Tackling the flavour puzzles using the CMS experiment

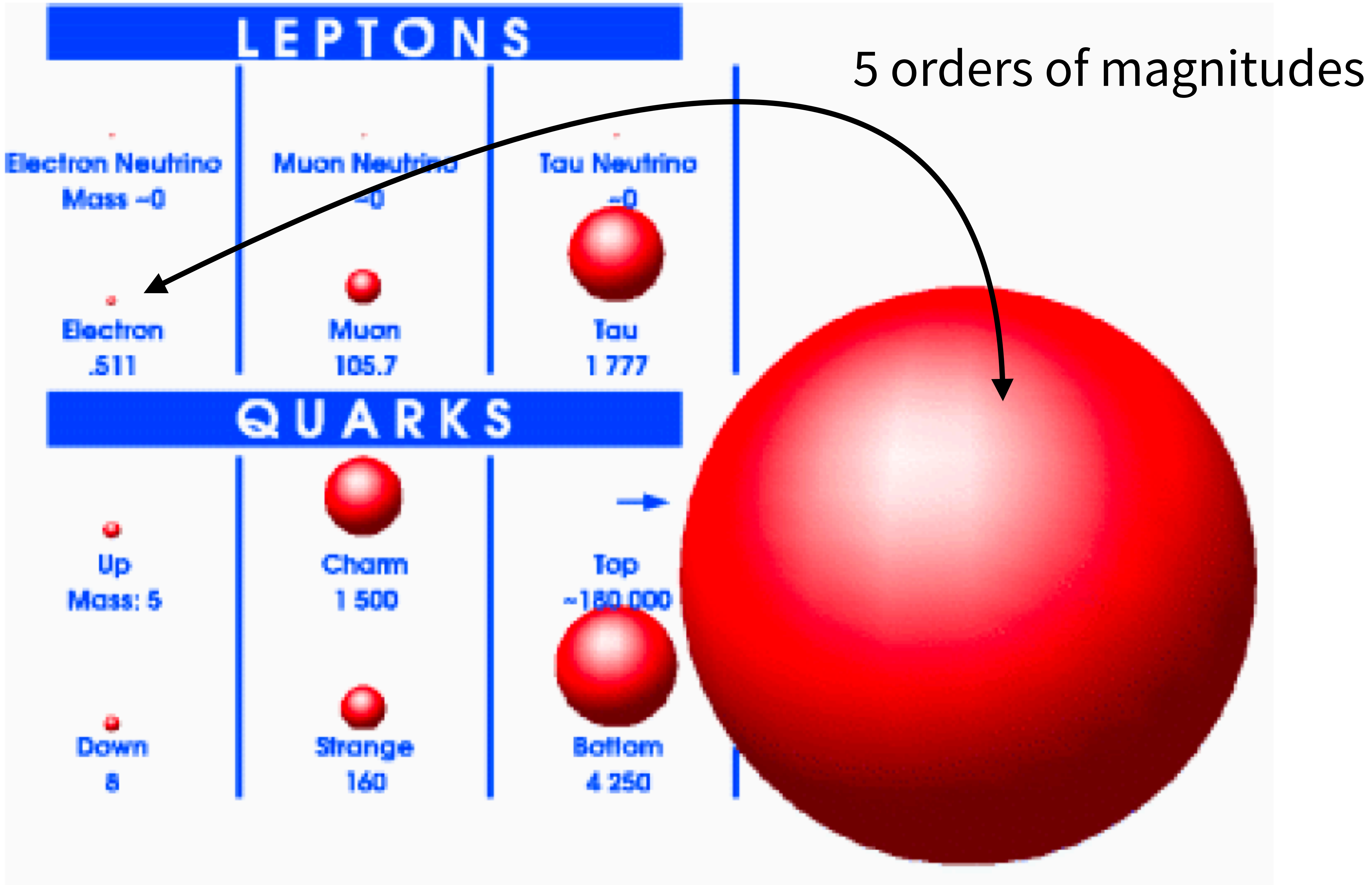
— My research path at UZH & future plans

UZH seminar
25 Sep 2023

Flavour Puzzles

Strange patterns of quarks and leptons as we see in the SM

- Doublet x 3 generations
- Similarity between quark and lepton sector
- Vastly different masses



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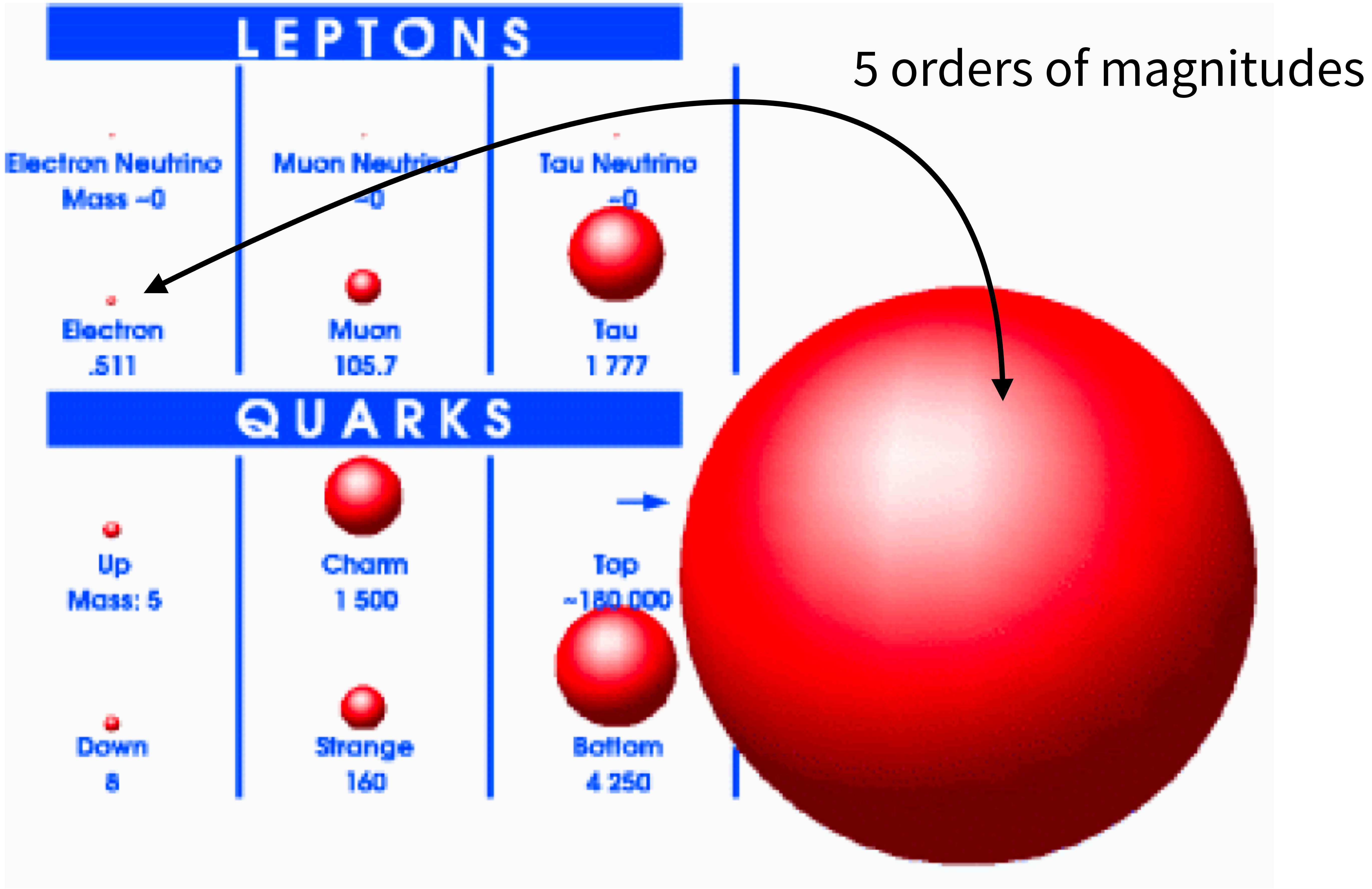

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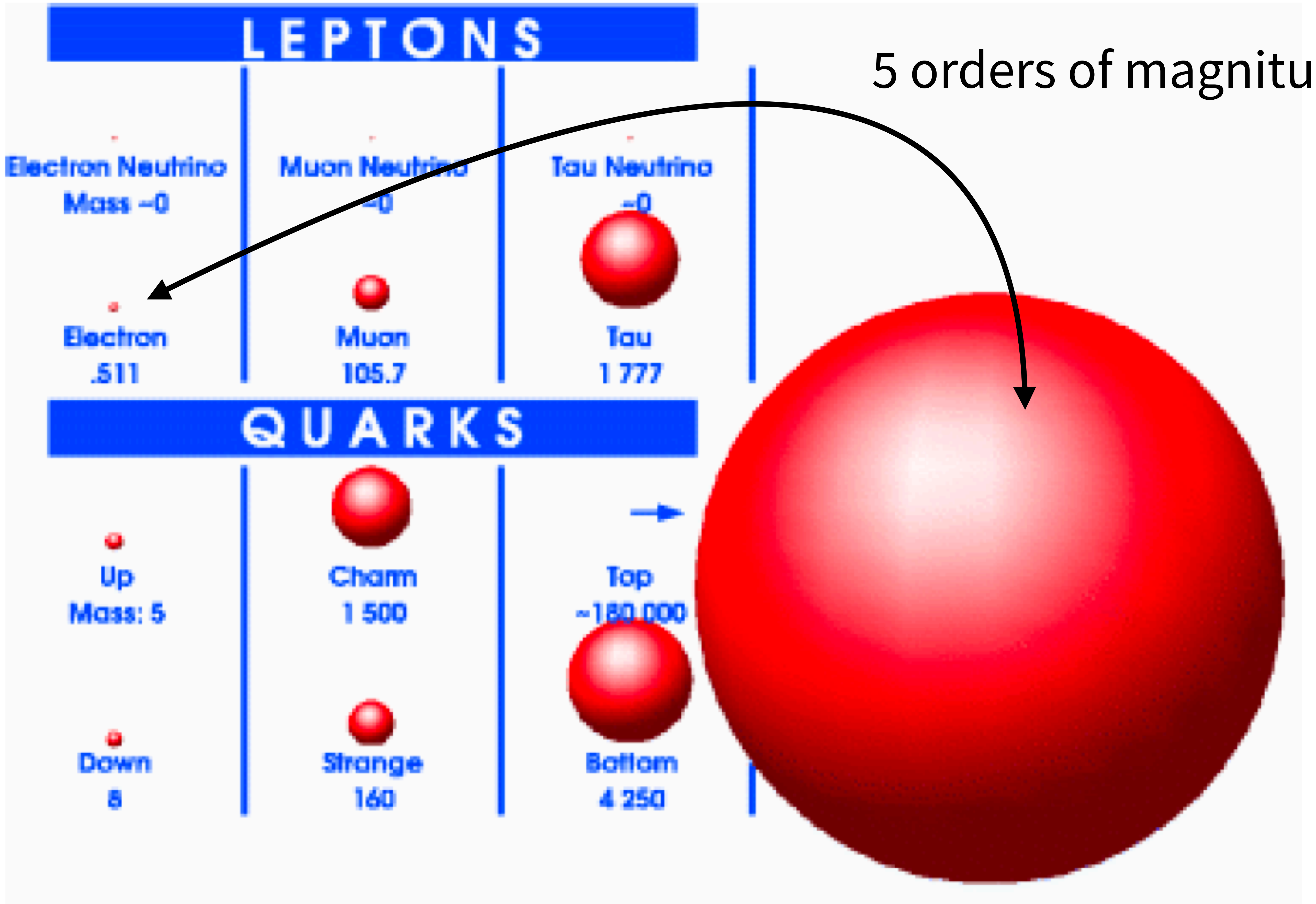
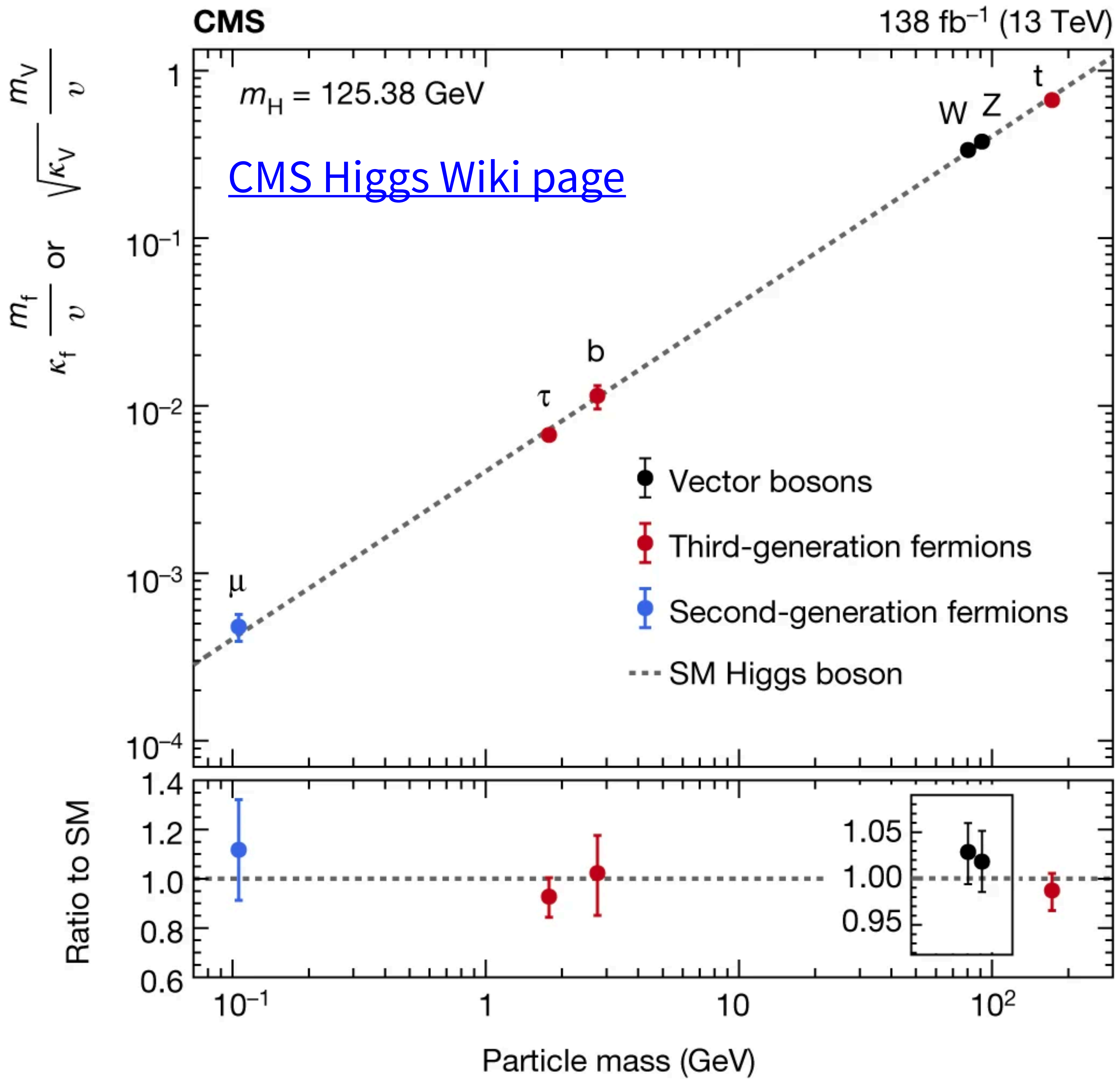


5 orders of magnitudes



[CMS Higgs Wiki page]

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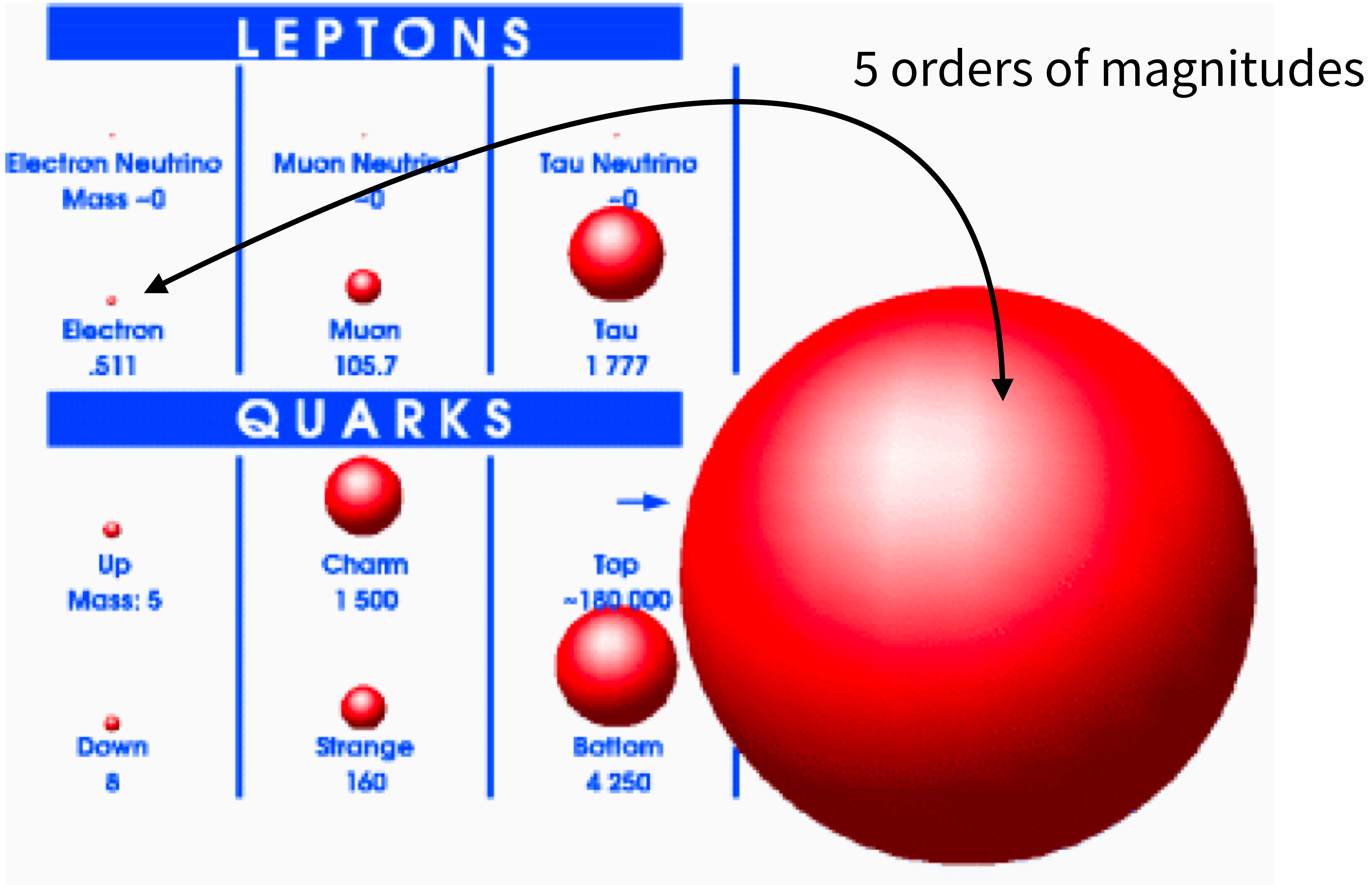

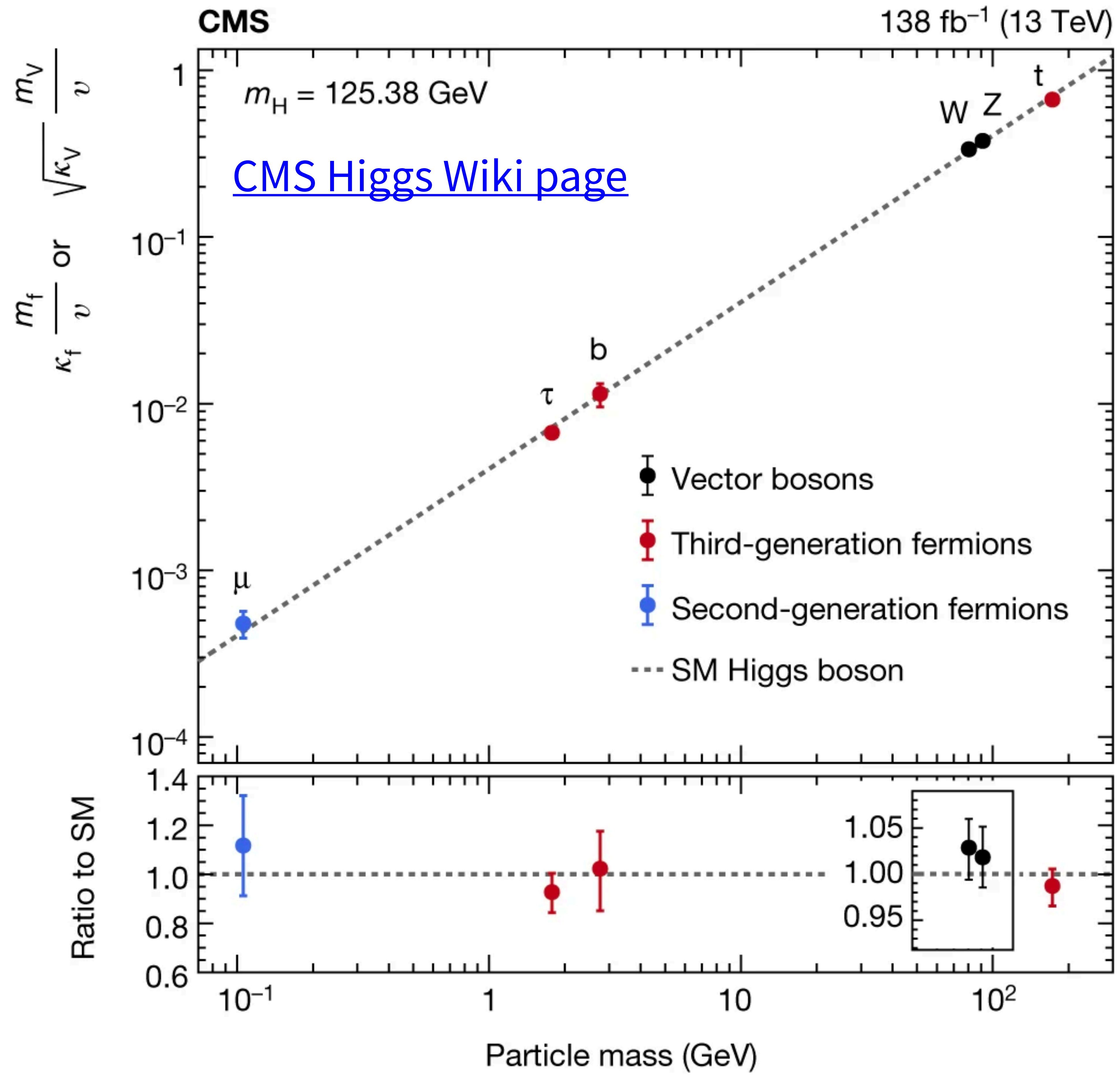

Postponing our questions:

Why do Higgs boson couplings span at least 5 orders of magnitude?

This leads to a speculation:

At high energy scale (i.e. at the beginning of the universe), there existed microscopic interaction that couples differently depending on the fermion flavour and could have shaped the **flavour structure**

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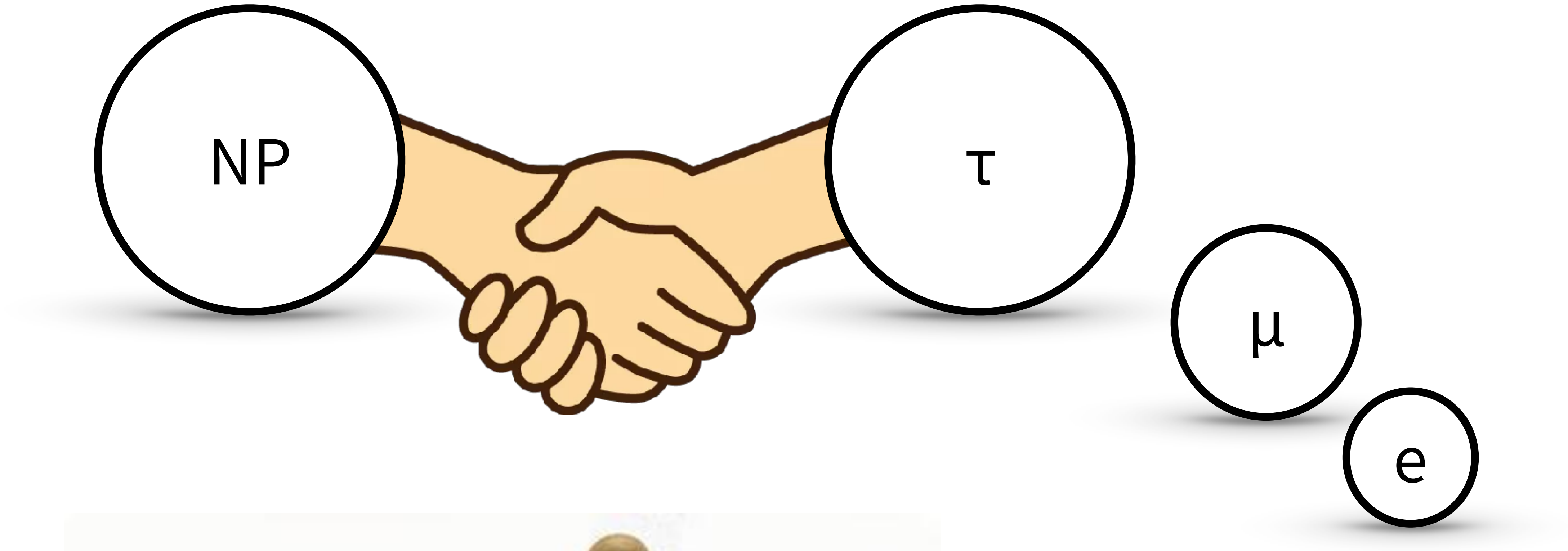

Fermions

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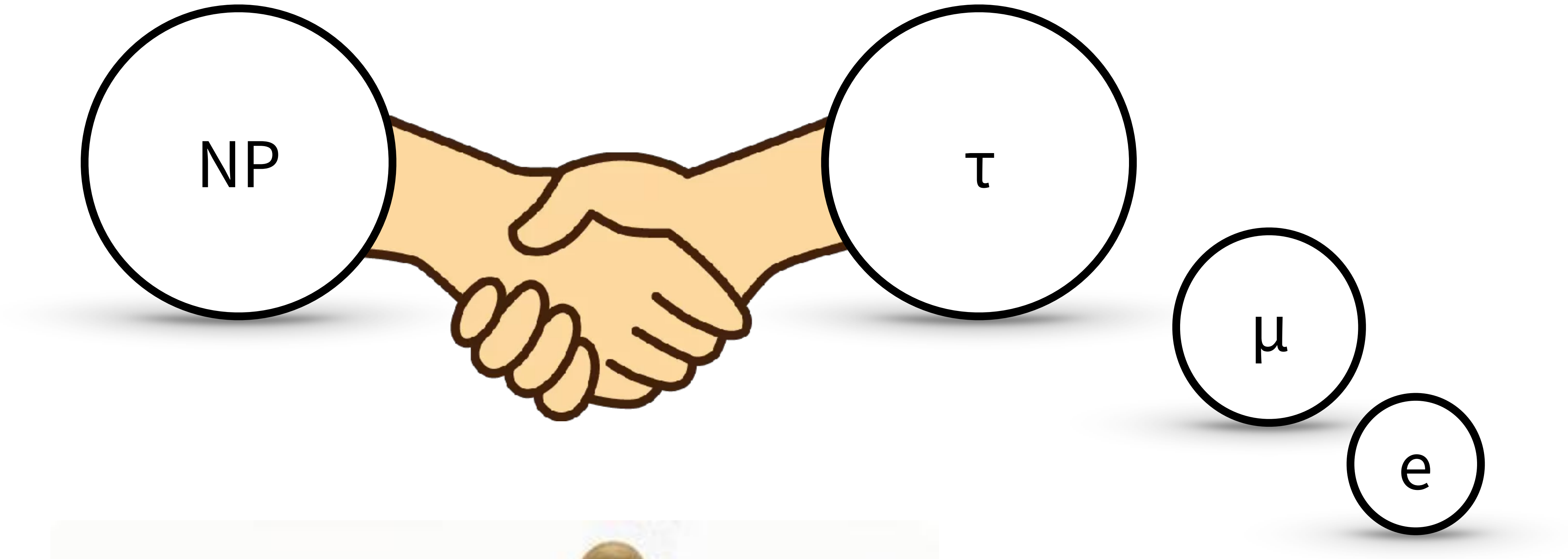
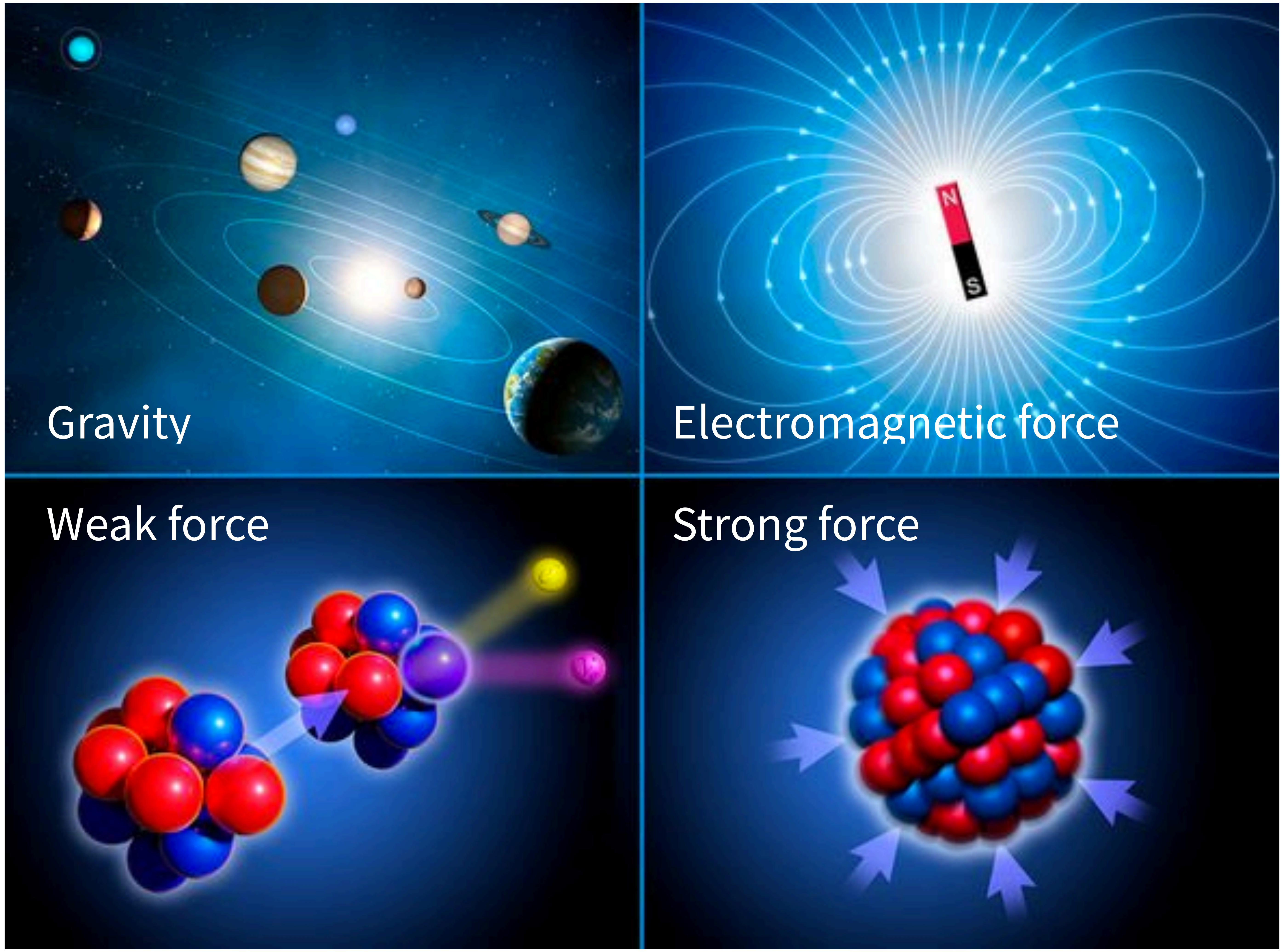


5th force
My goal: Discover such force at CMS

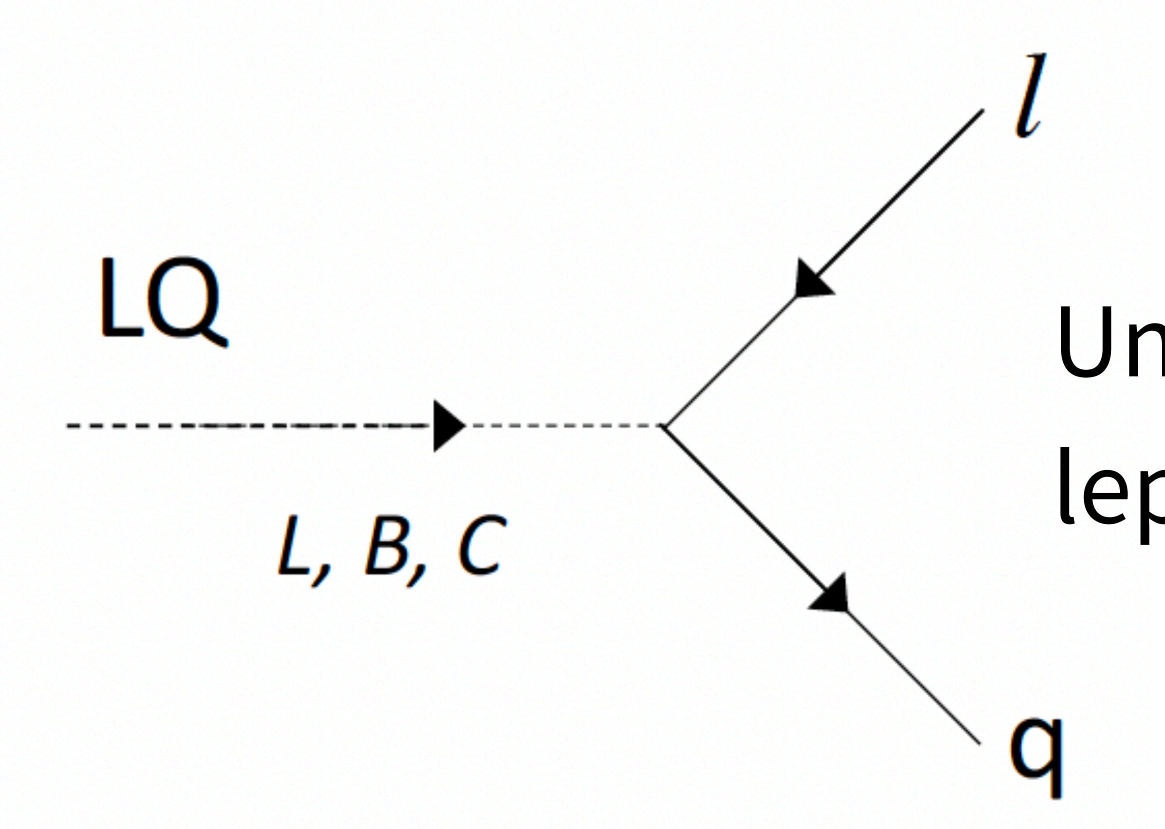


How to find it — going higher in energy

LHC — Largest & highest-energy particle collider

Leptoquark Search

Hypothetical boson (spin 0 or 1)
that couples to quark & lepton



Unification of the
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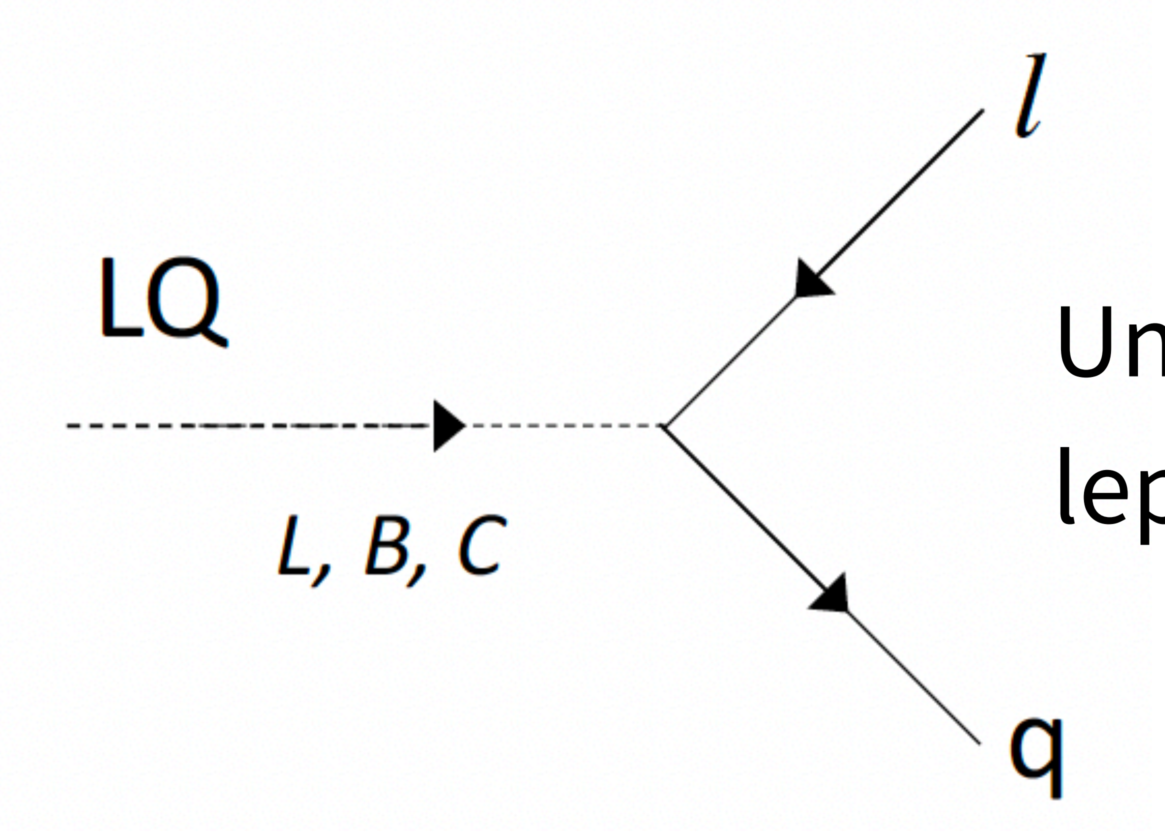

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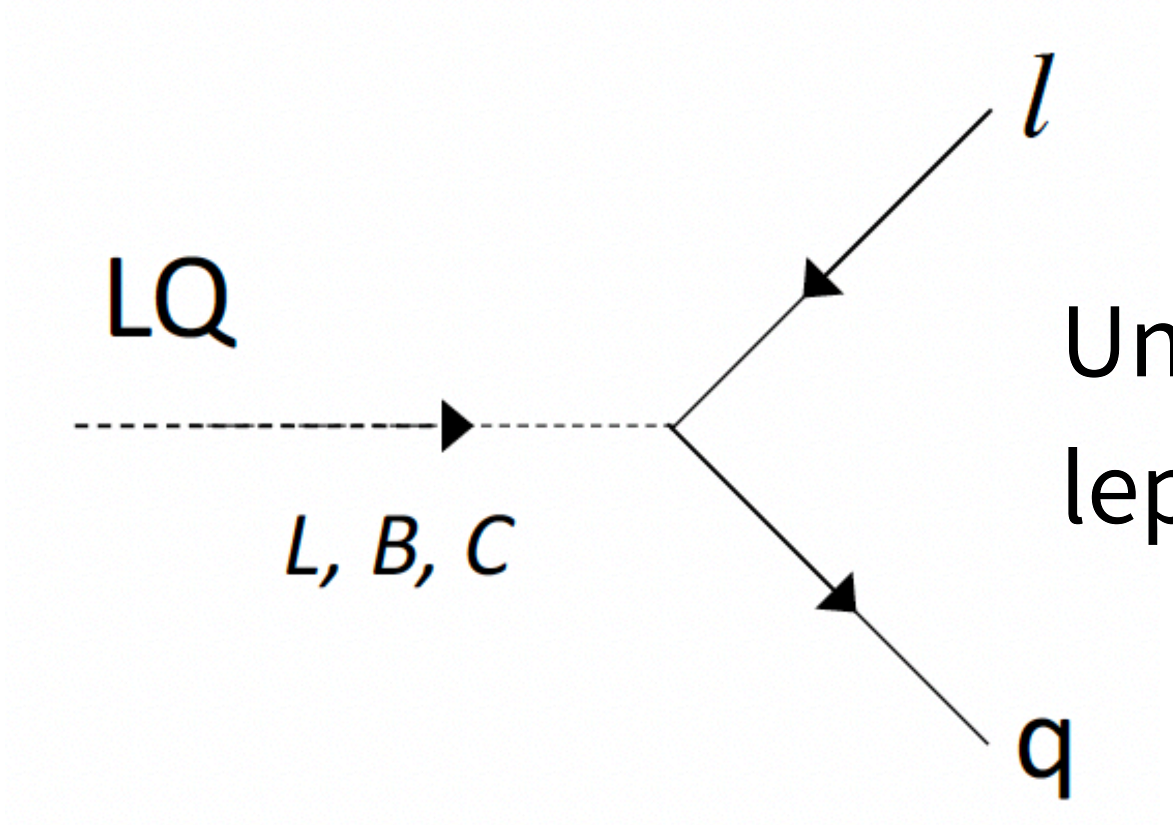

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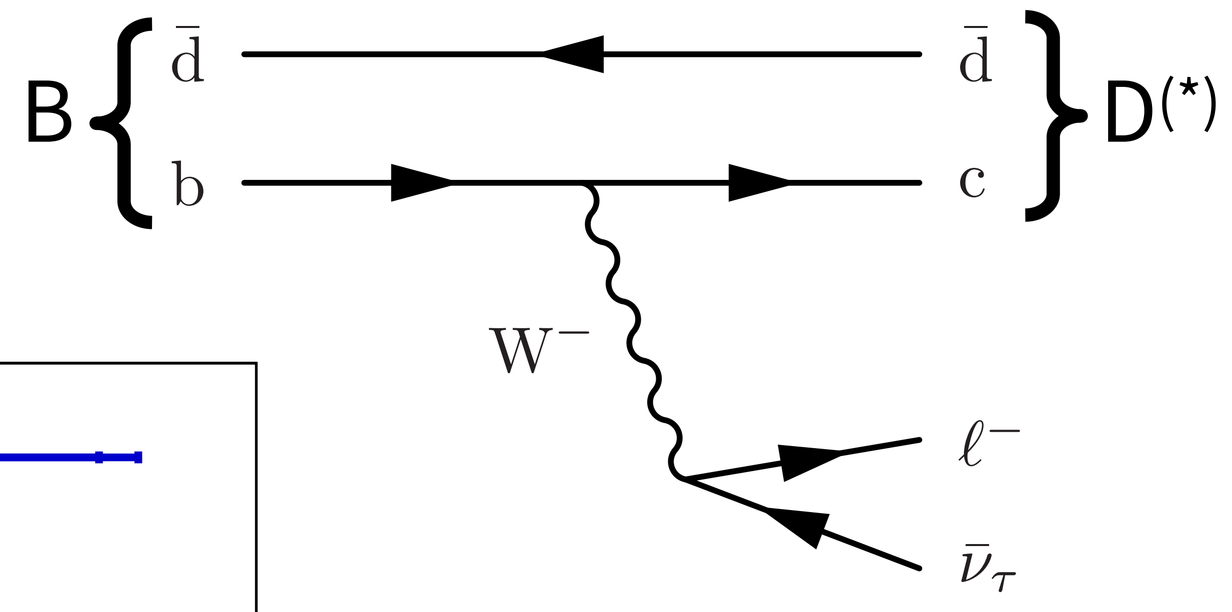

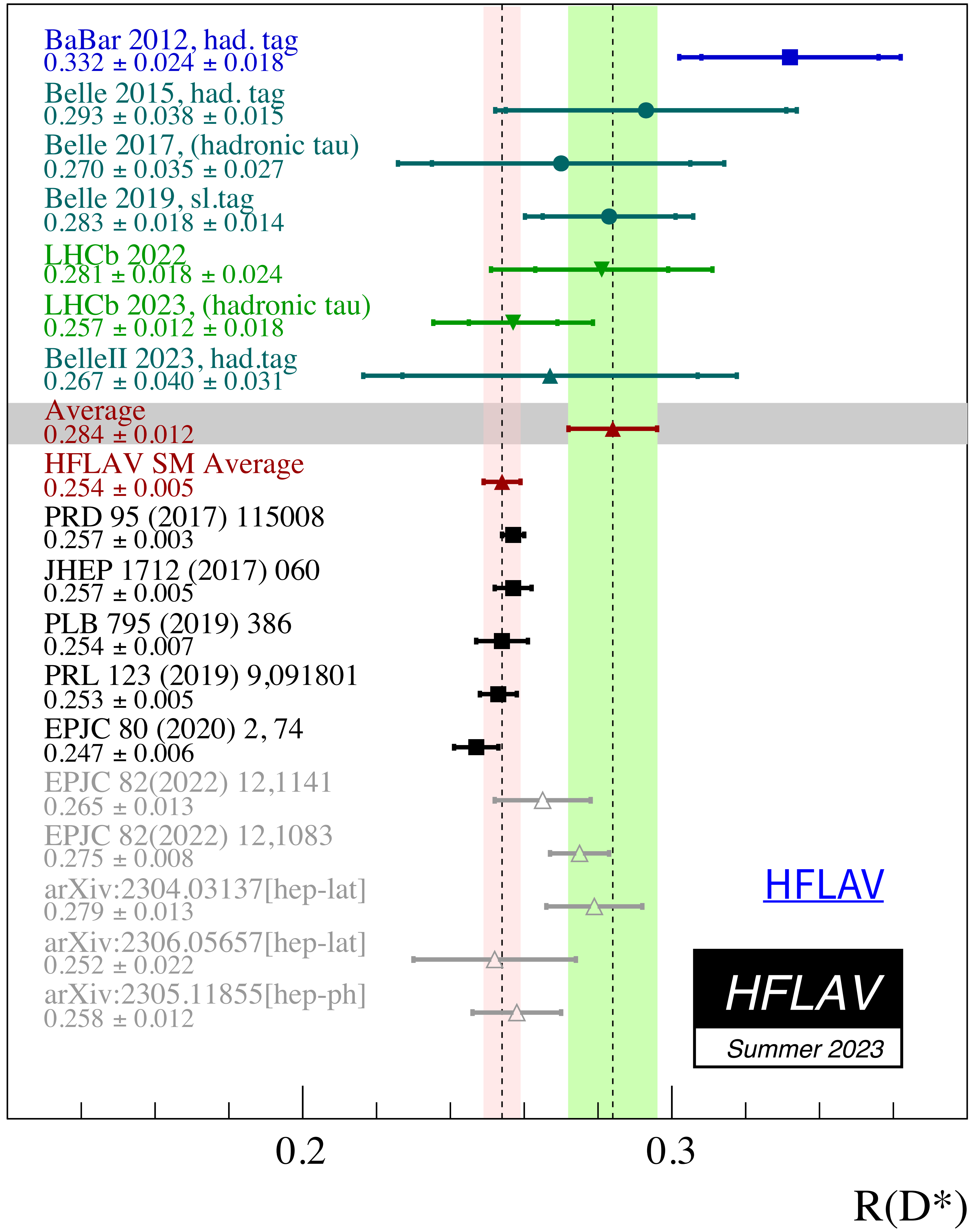

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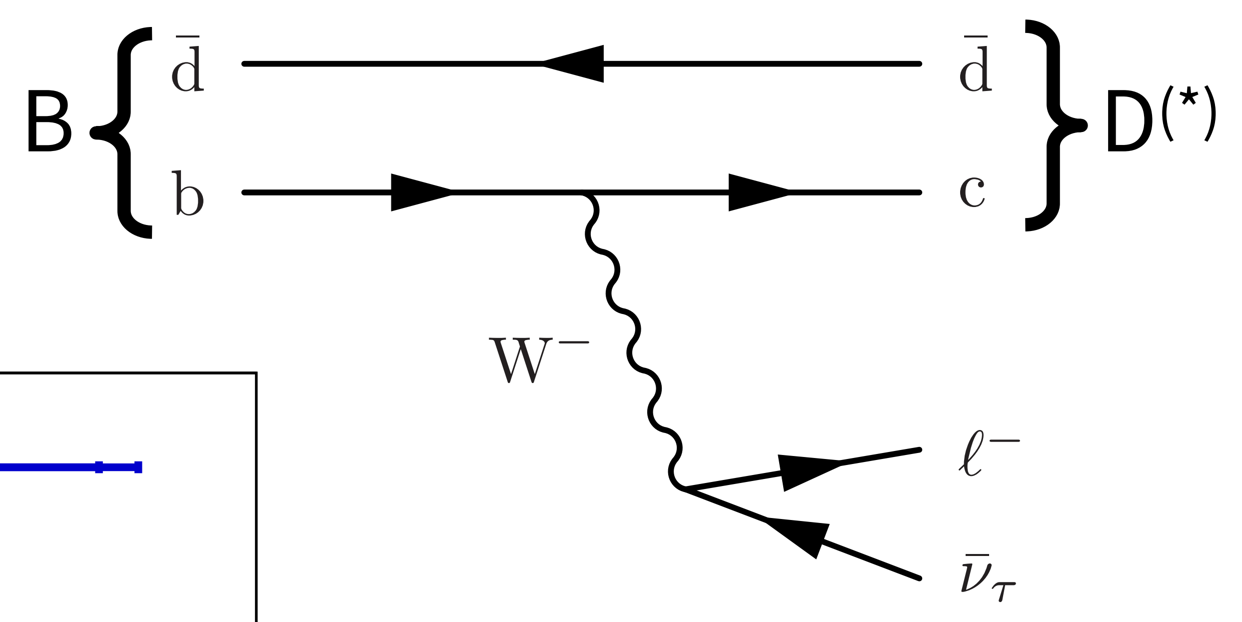

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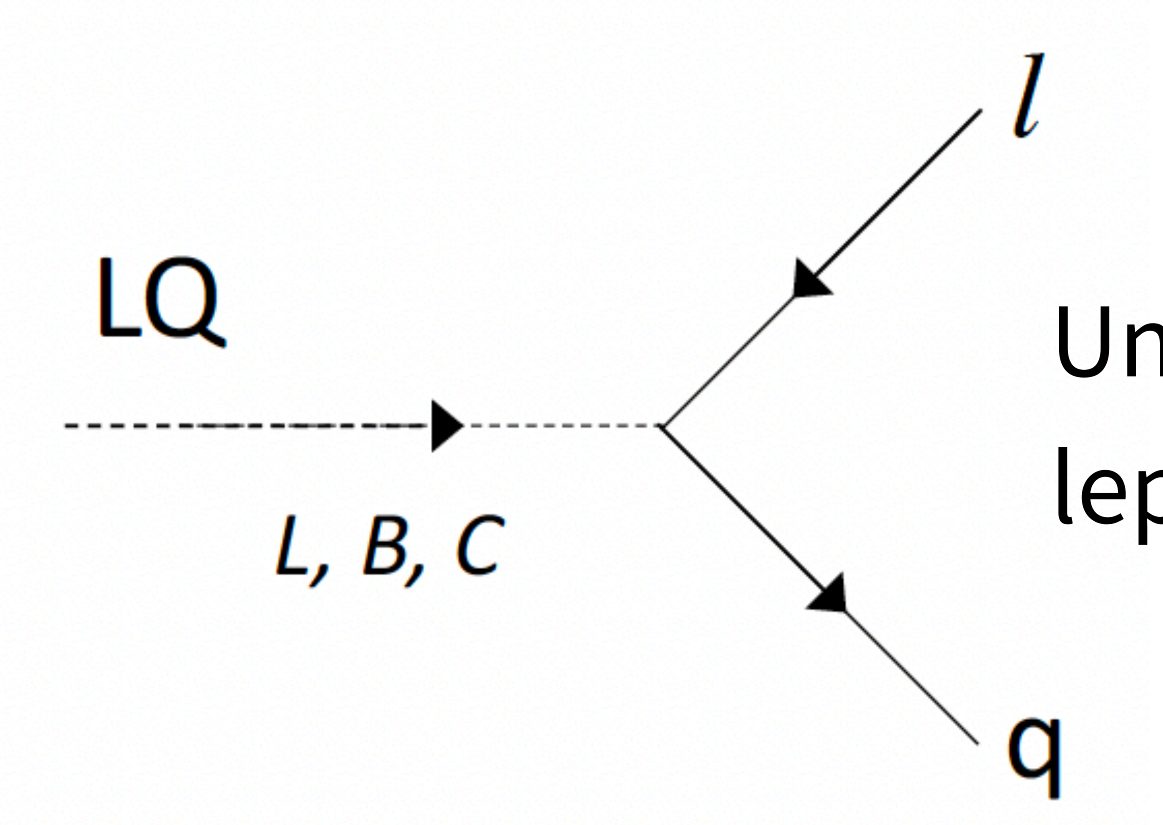

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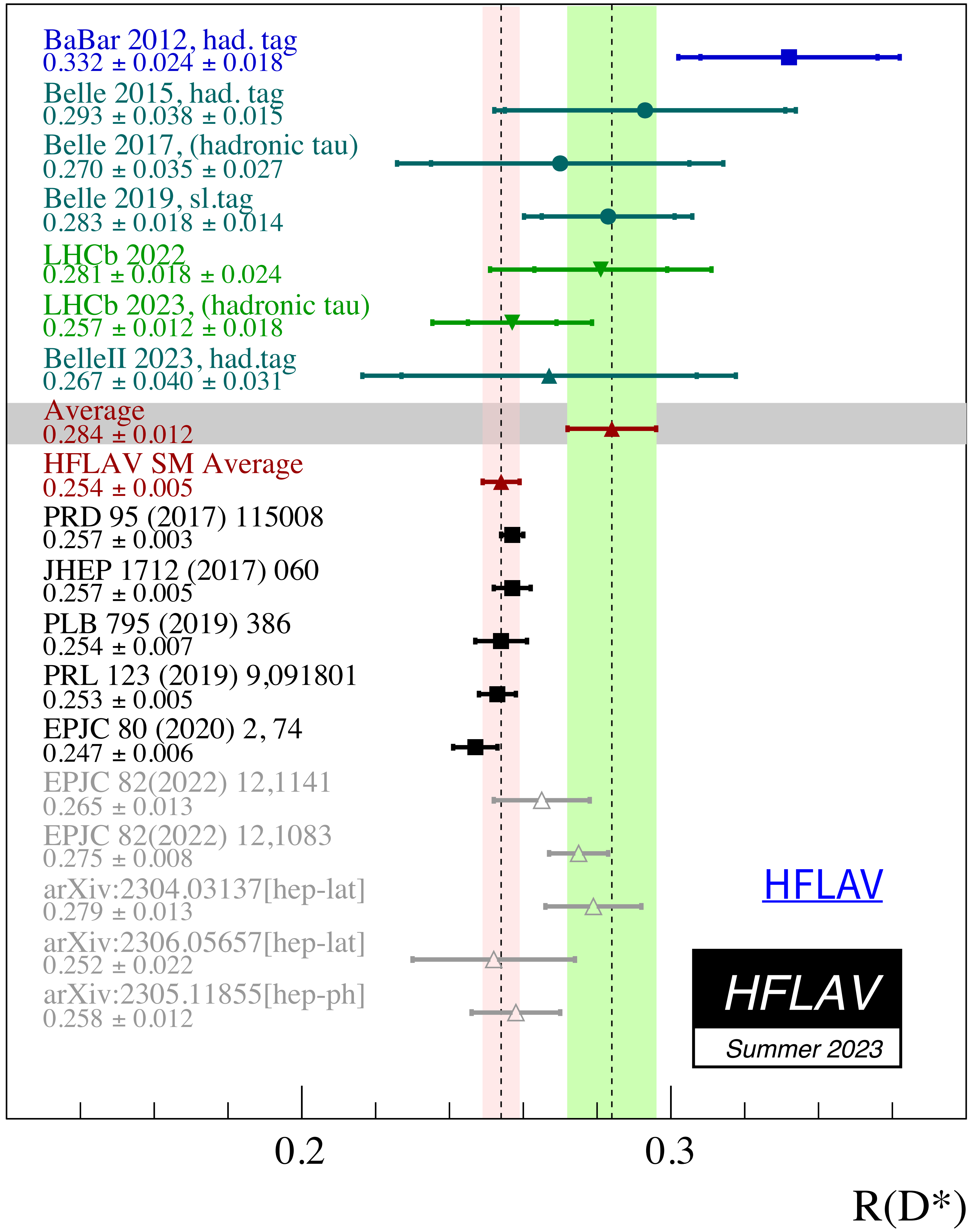

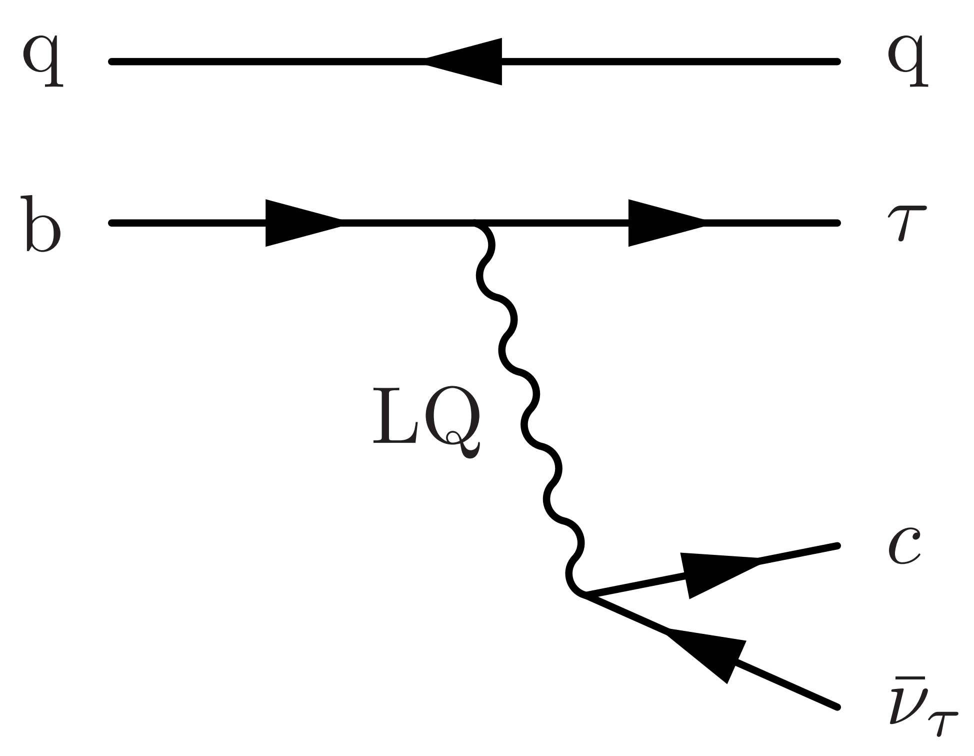

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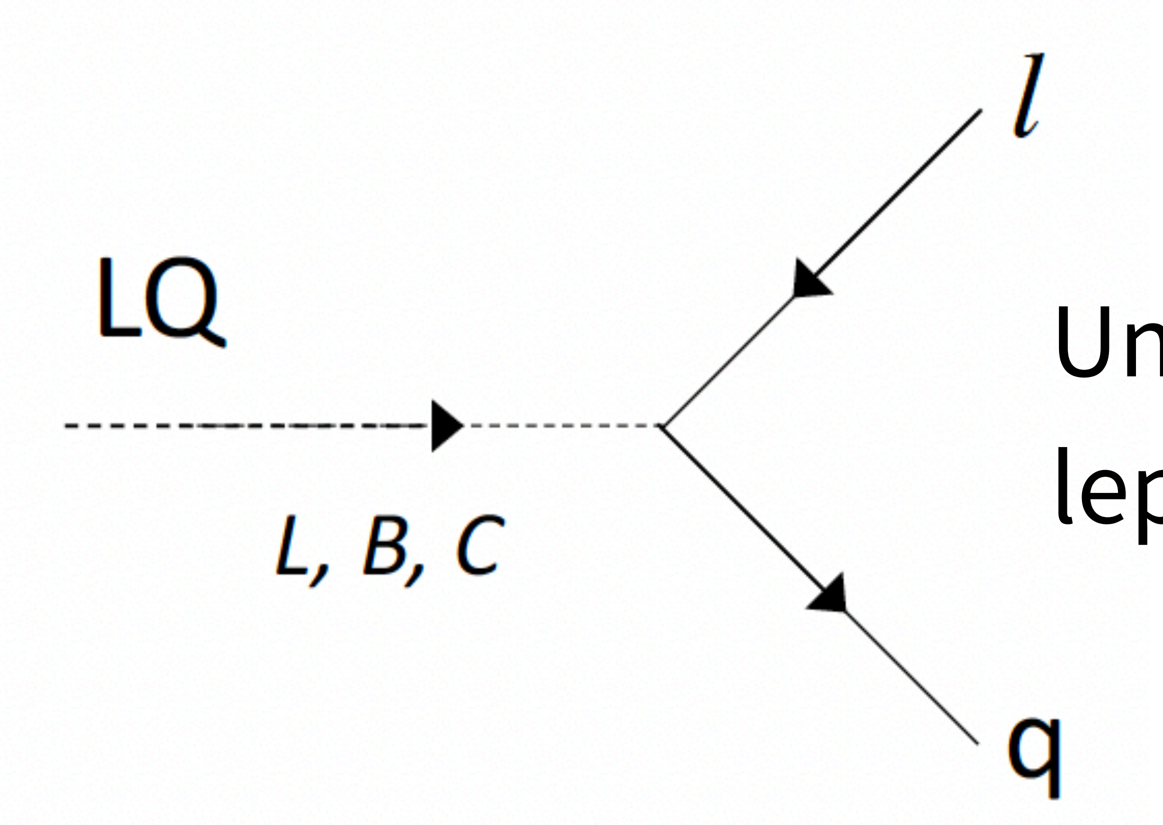

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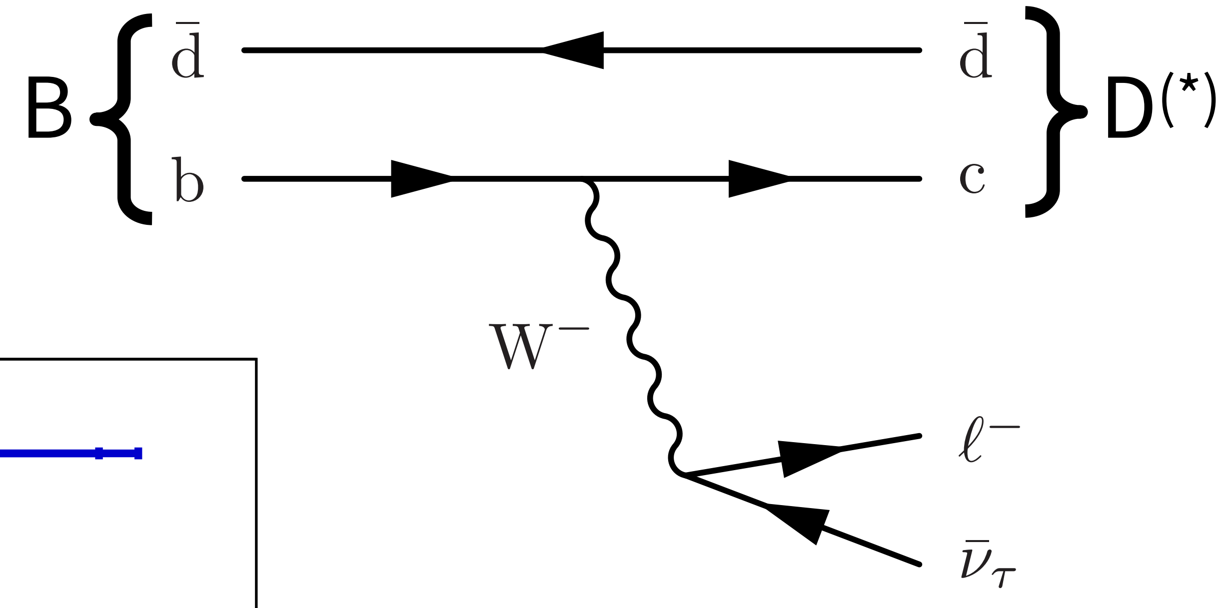

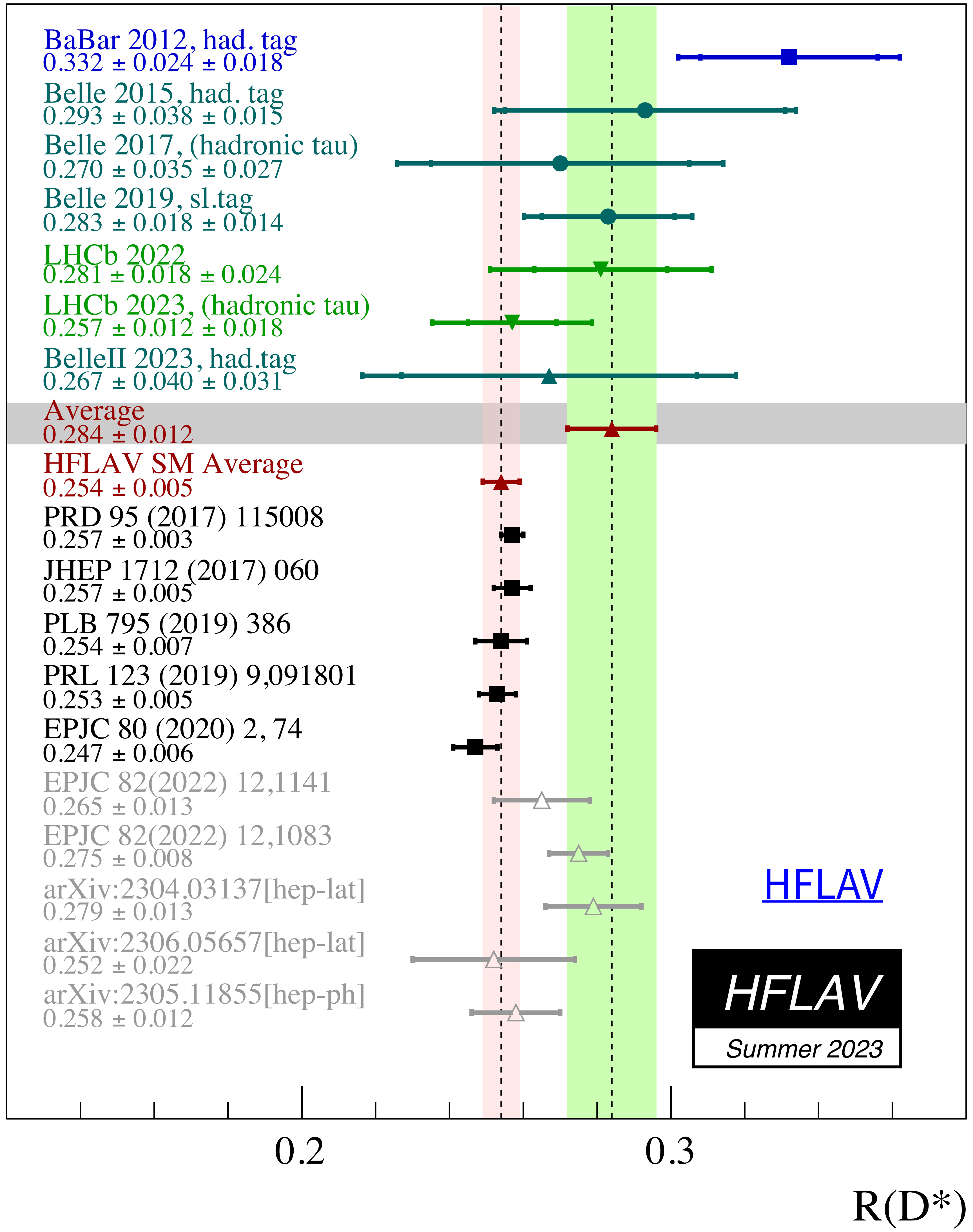

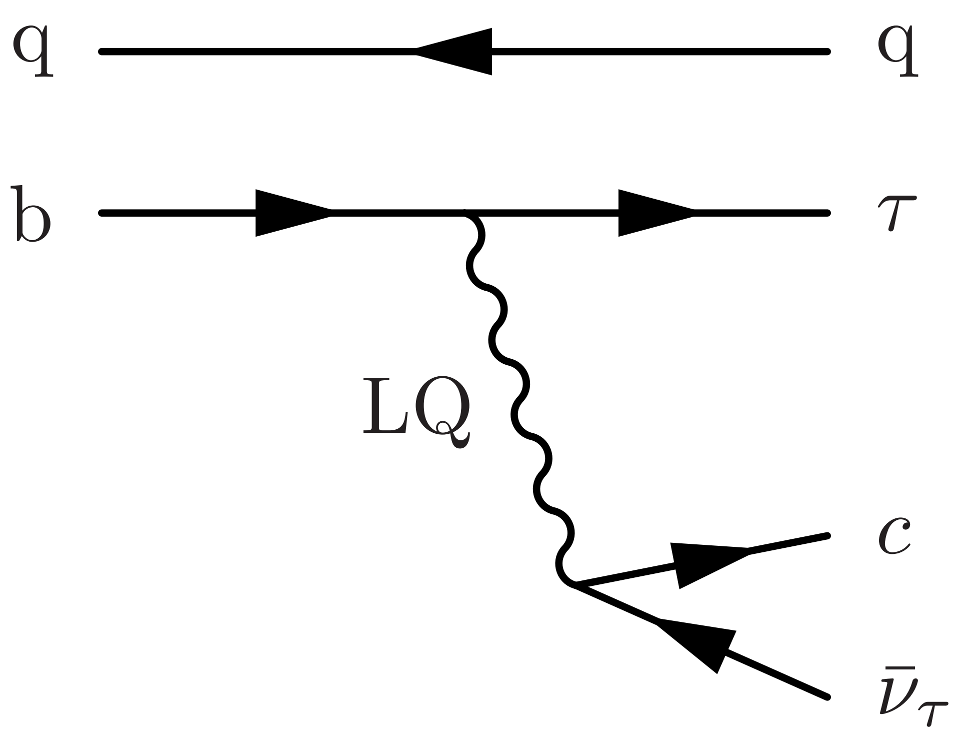

LQ should be at O(1) TeV
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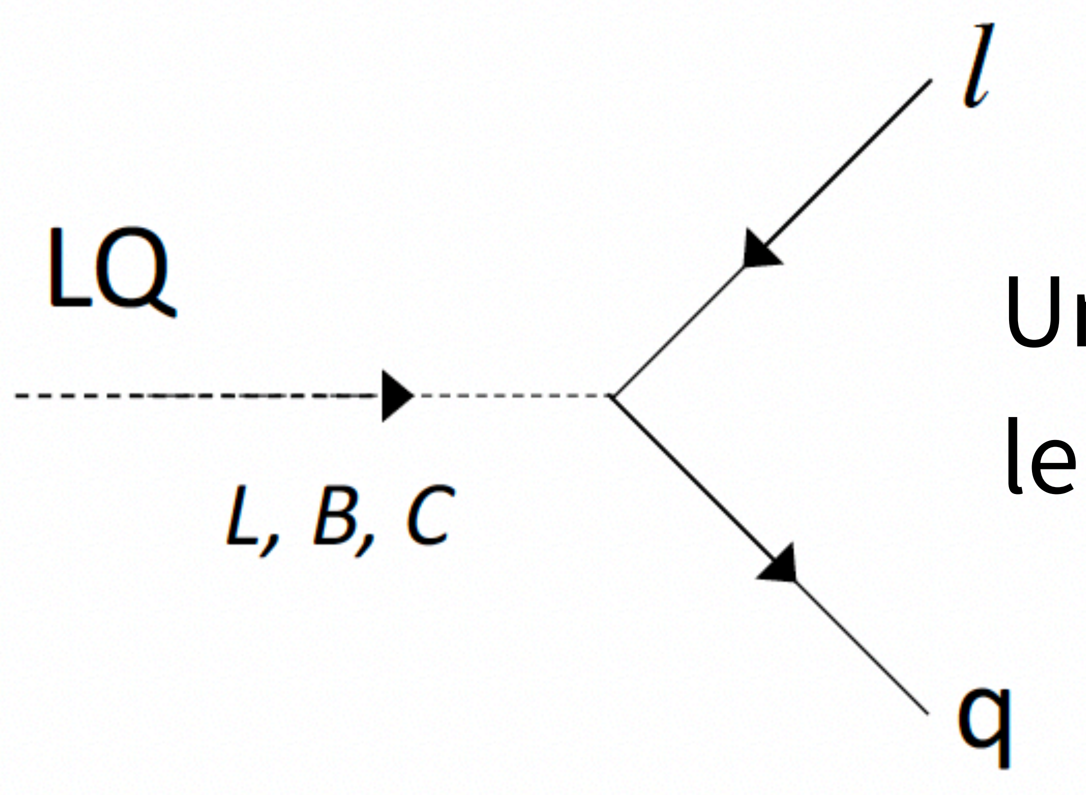

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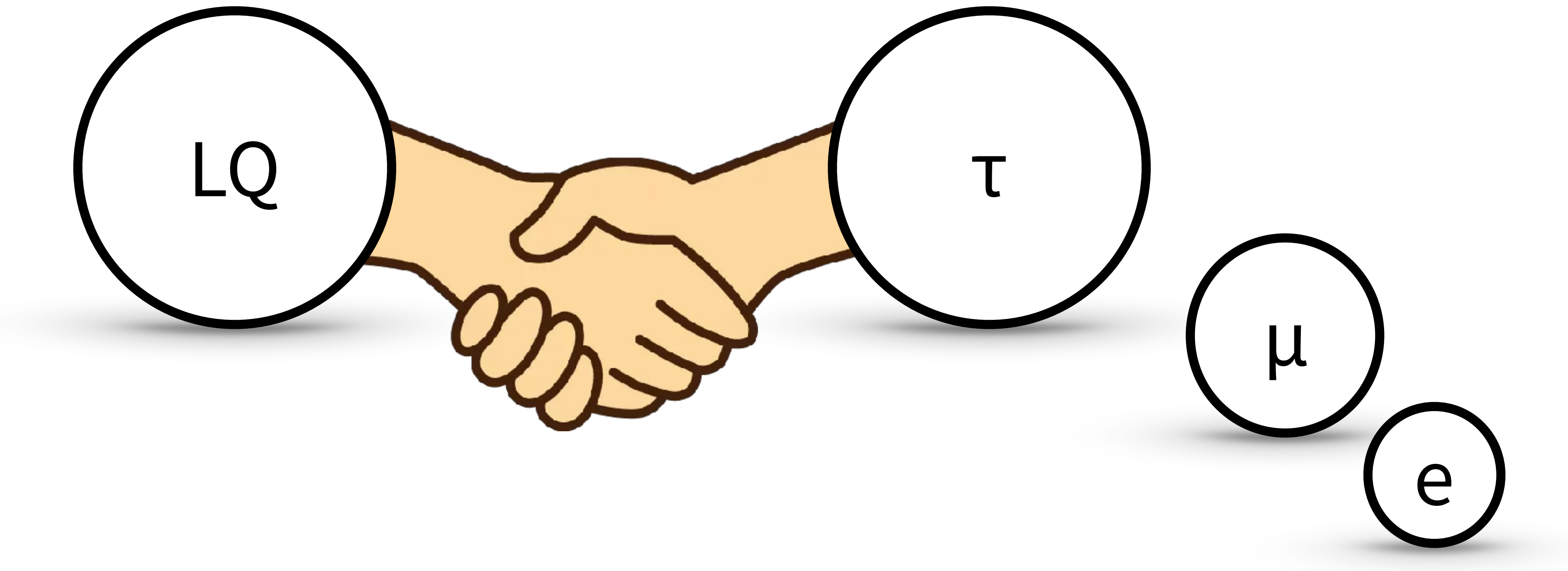

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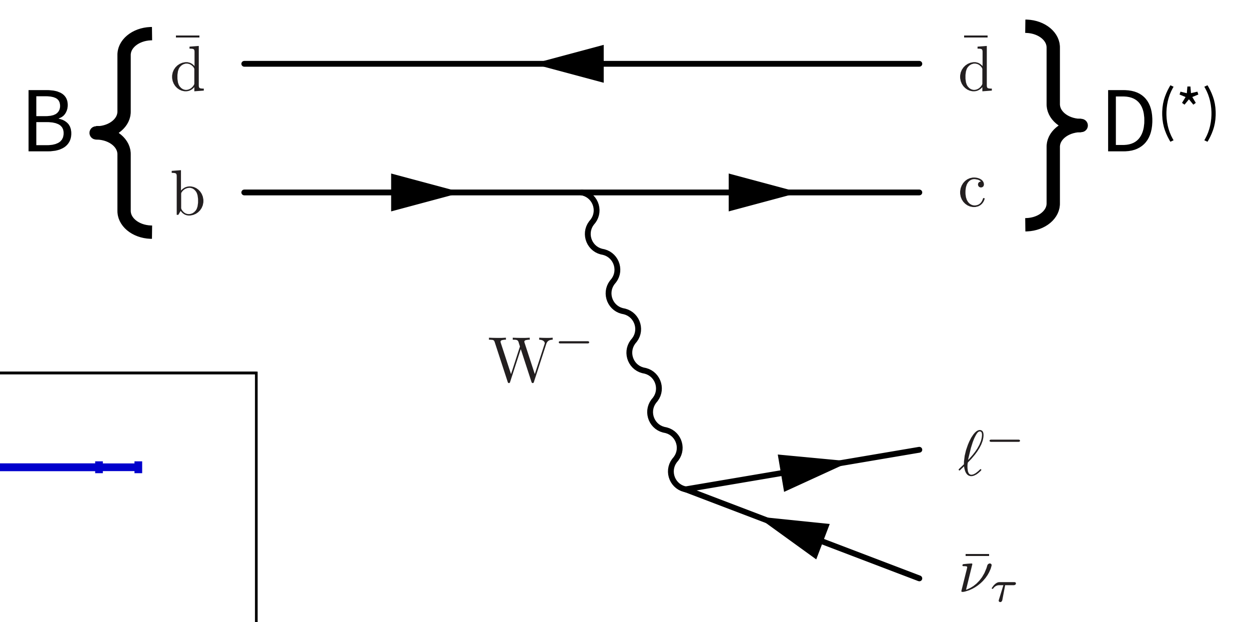

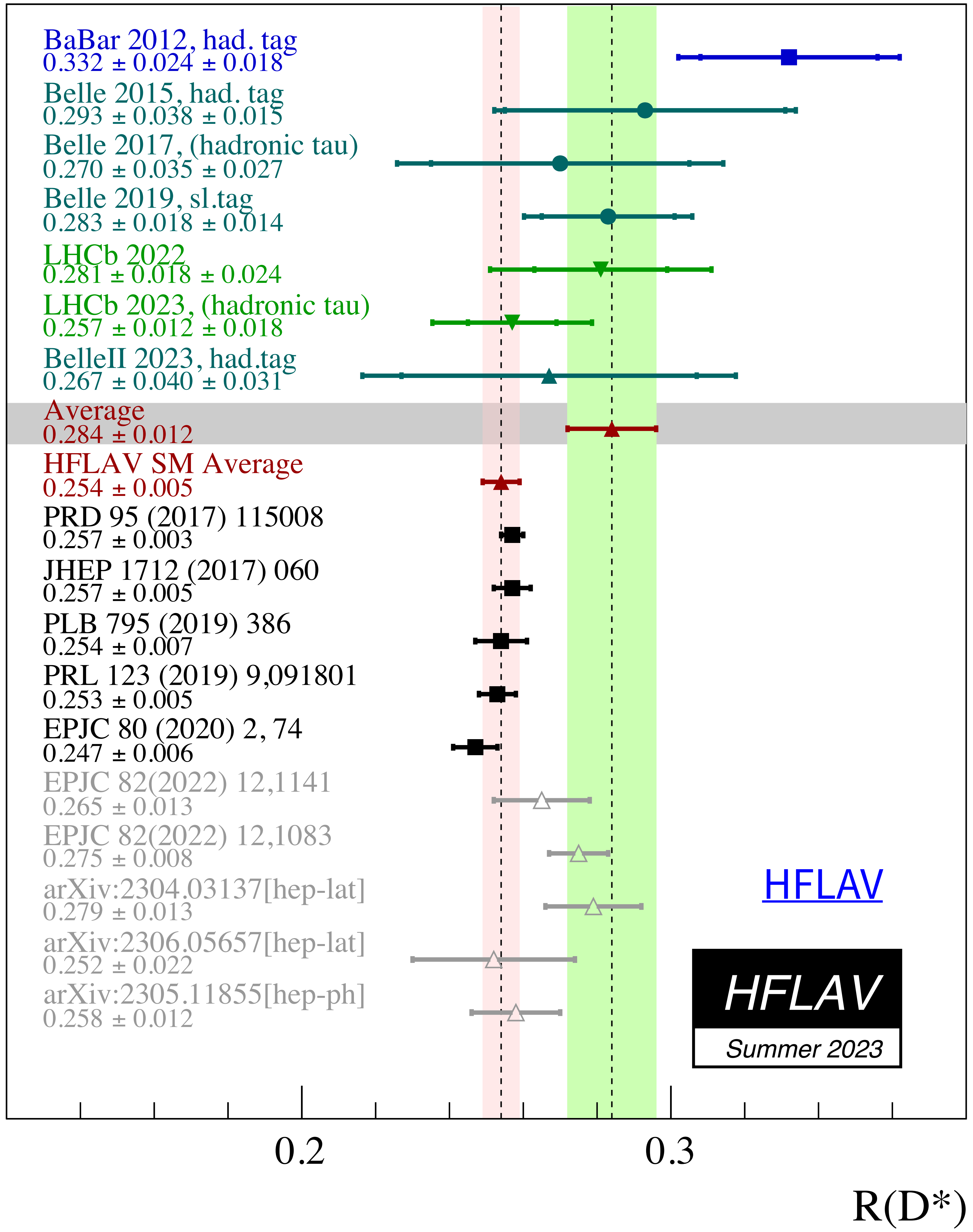

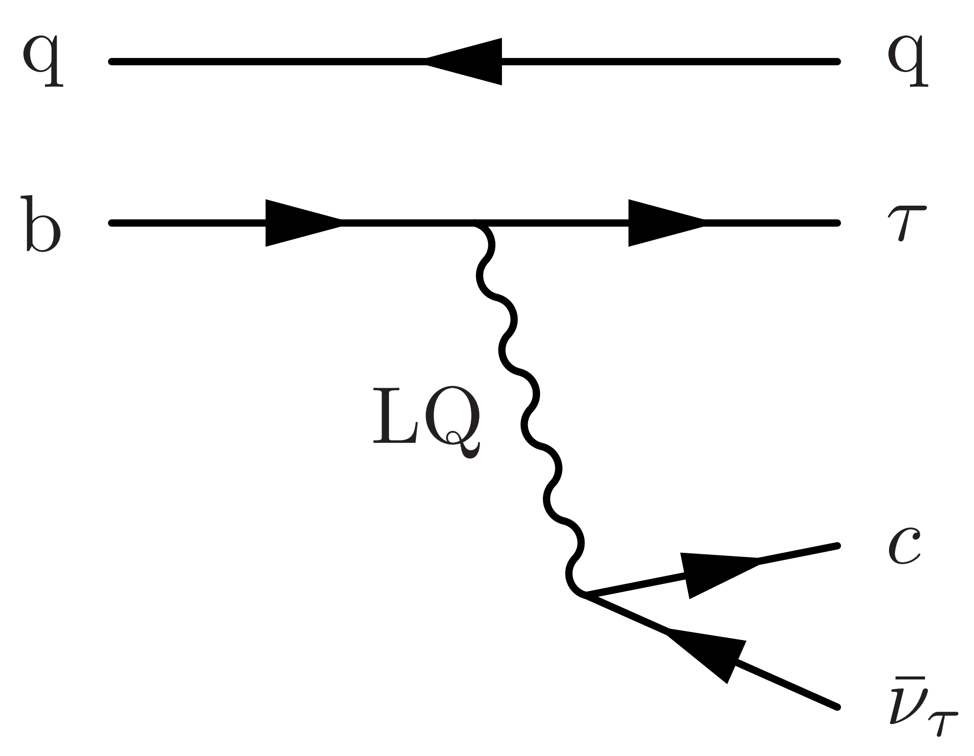

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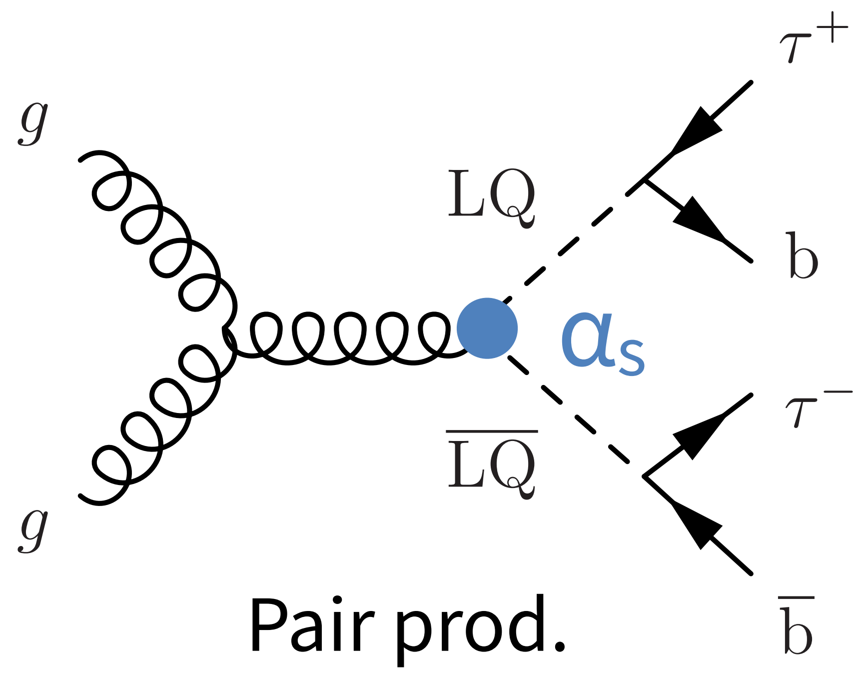
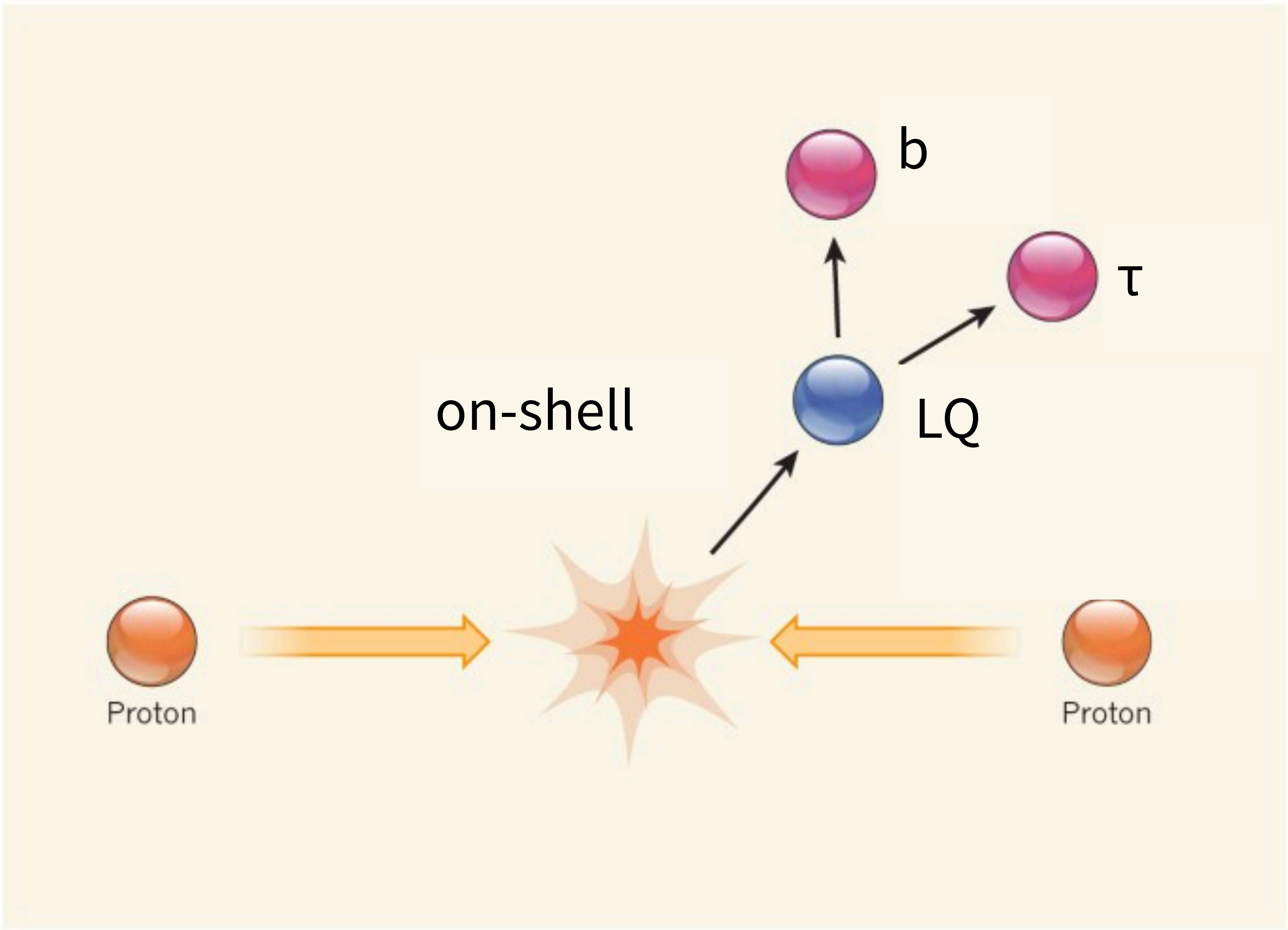
Direct search for LQ that couples to the third generation (bτ)

When I started



was the only process that people looked for (large cross-section)



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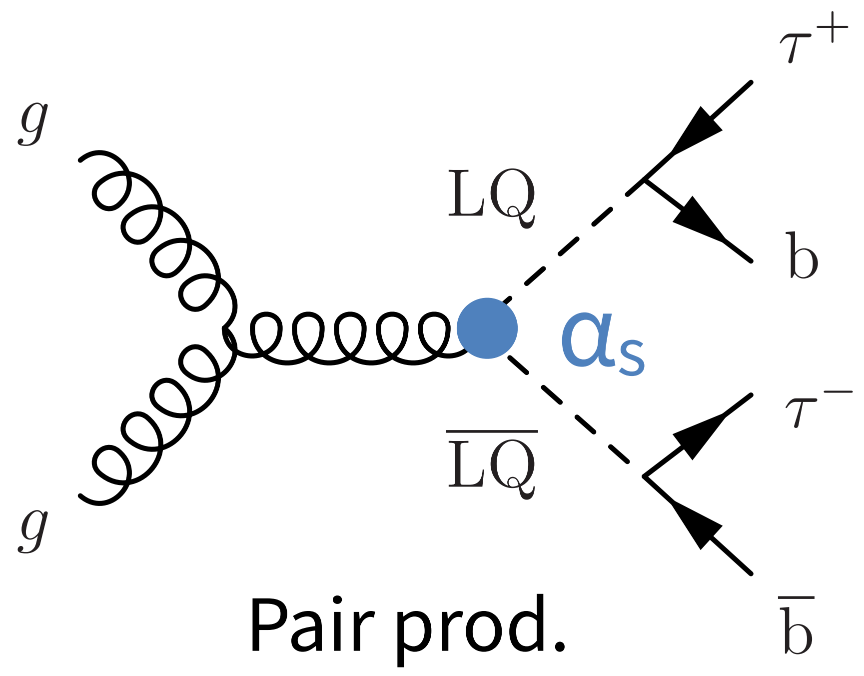

Pair prod.

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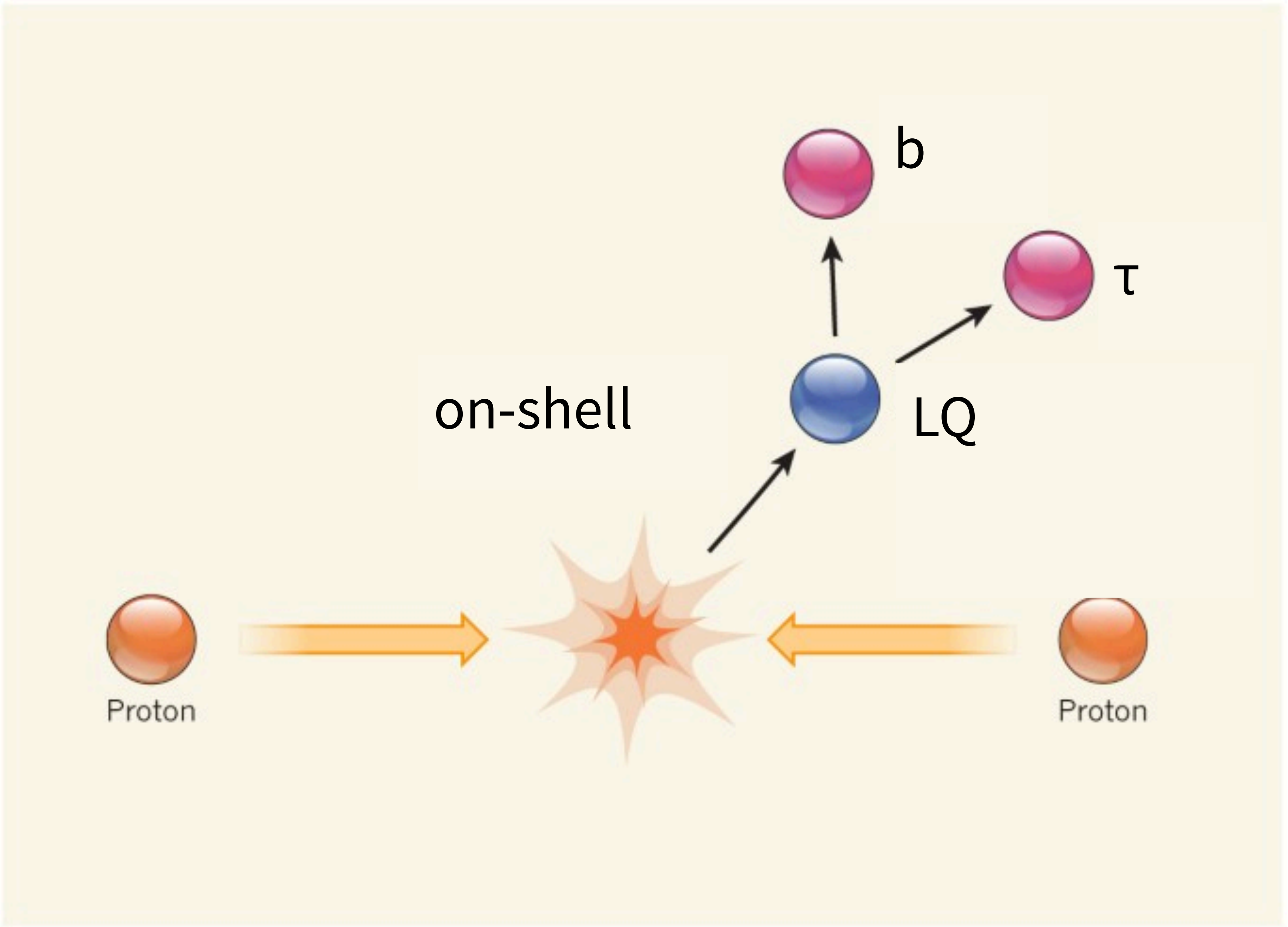
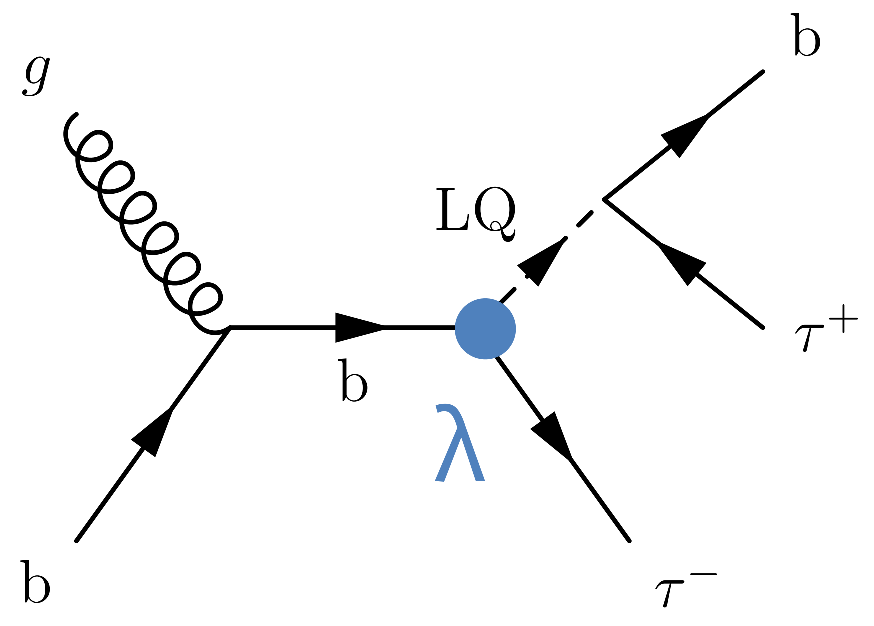


After discussing with Gino's group



Single prod.

turns out to be also important

- Cross-section ∝ λ^2
- To explain B-anomalies, we need large λ → this process also becomes relevant

Analysis Flow

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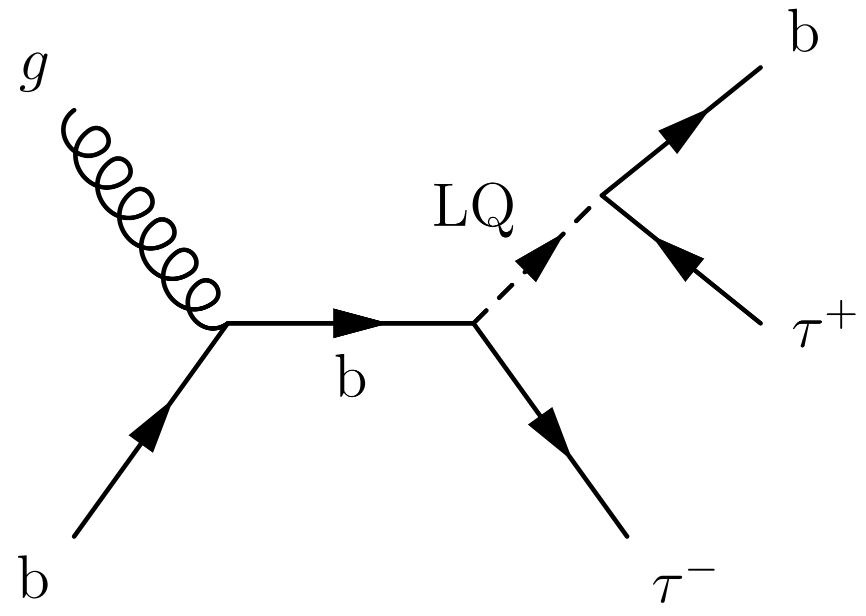

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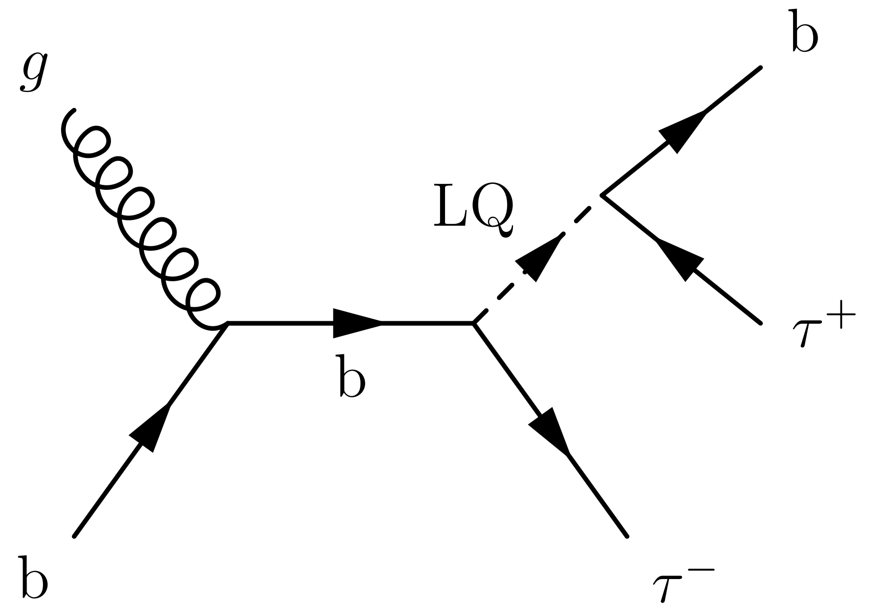

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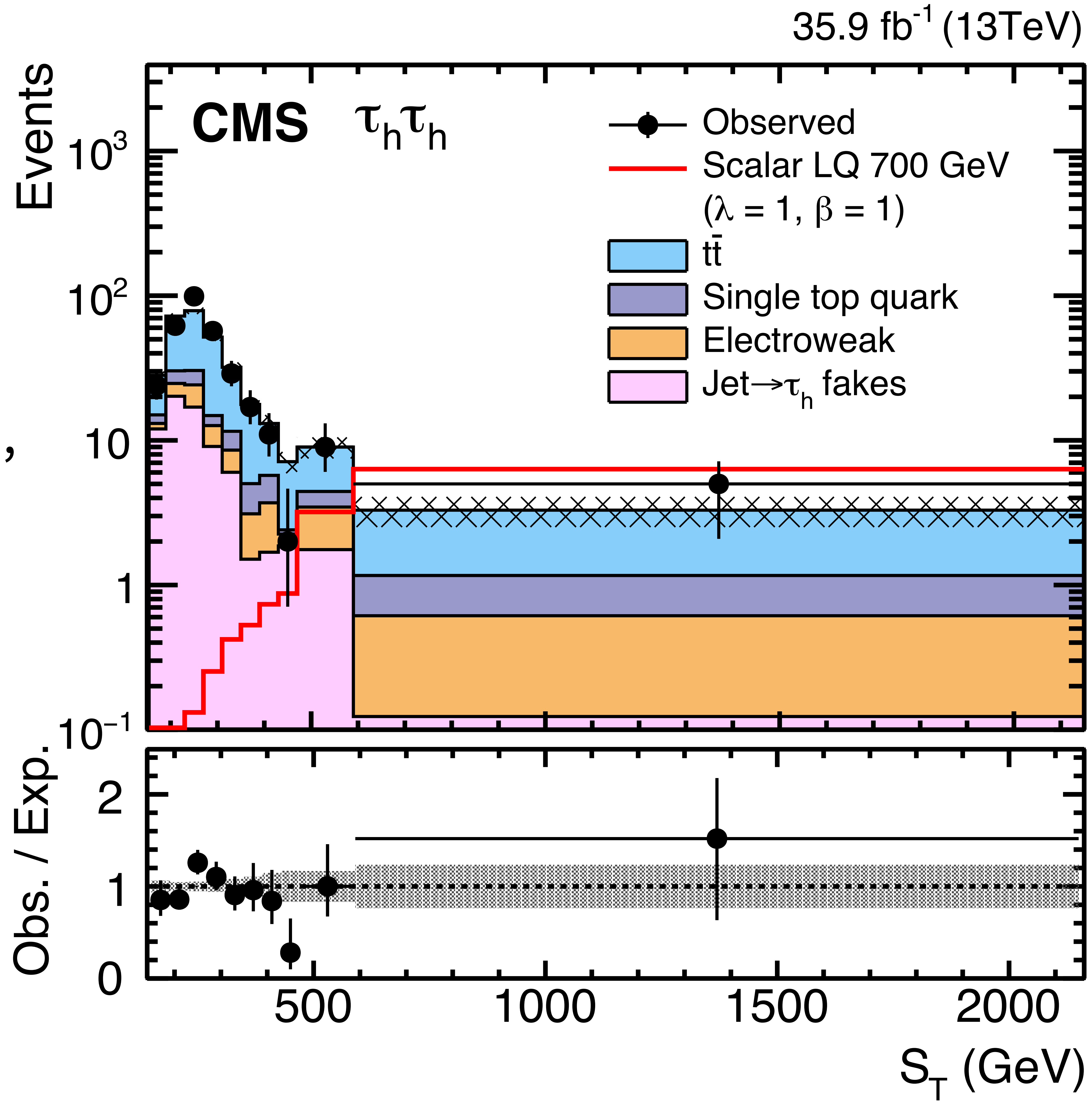

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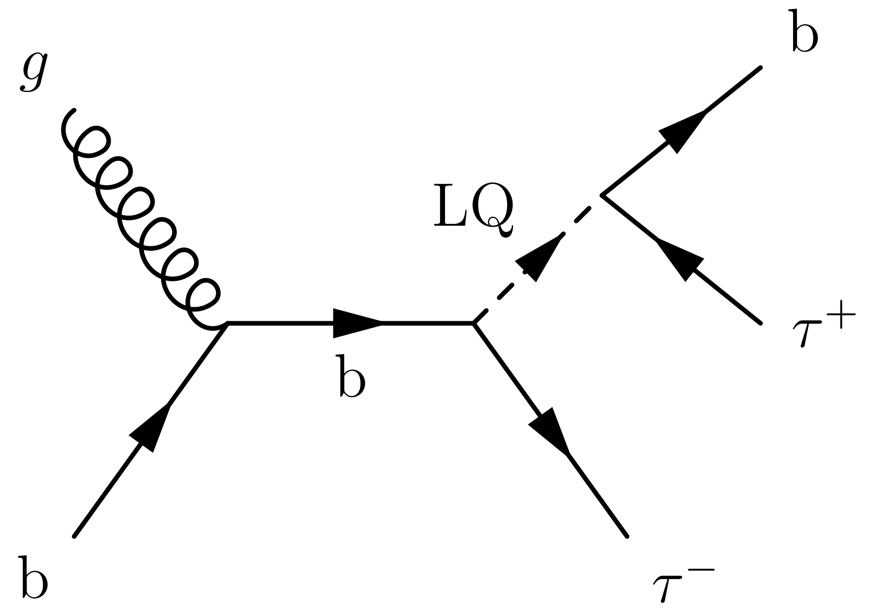

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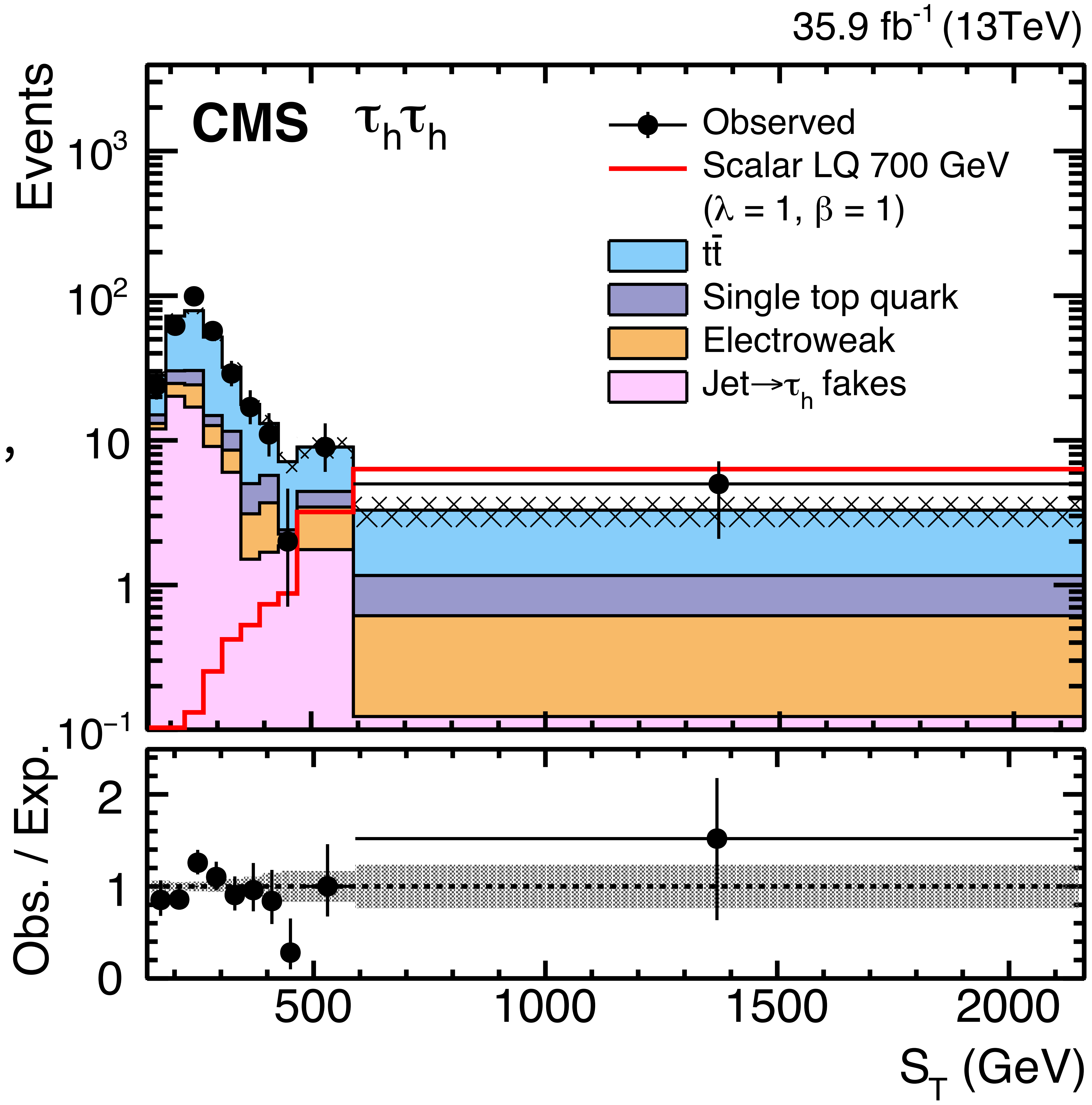

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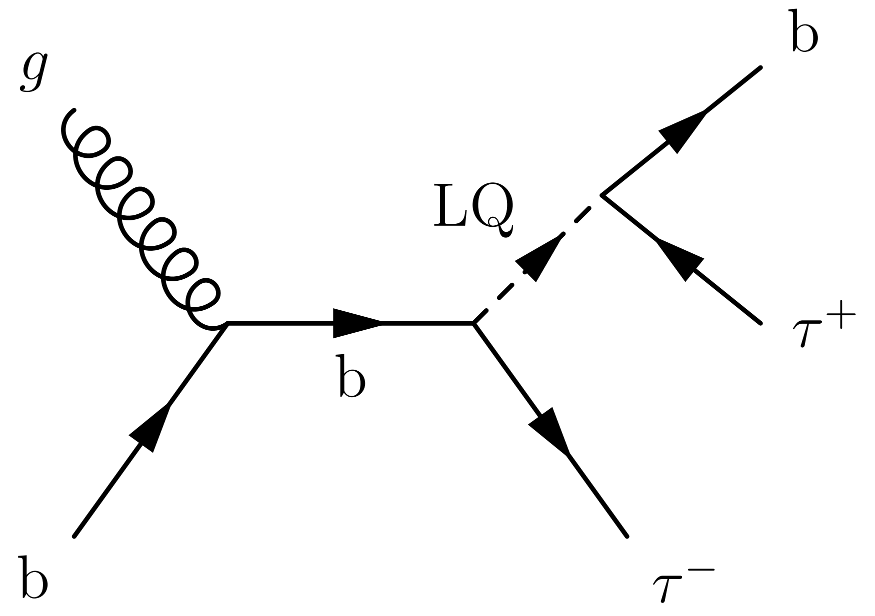

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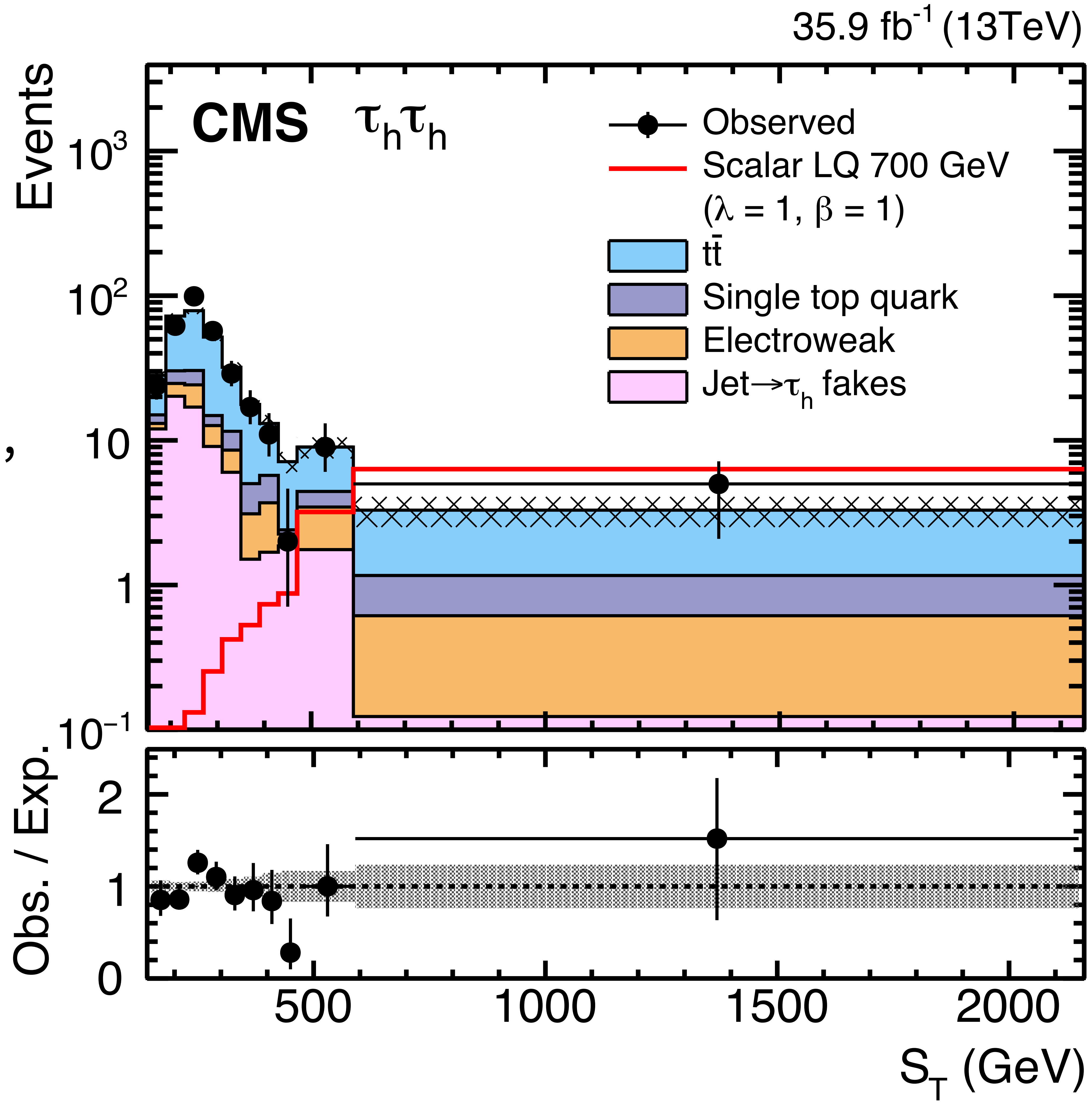

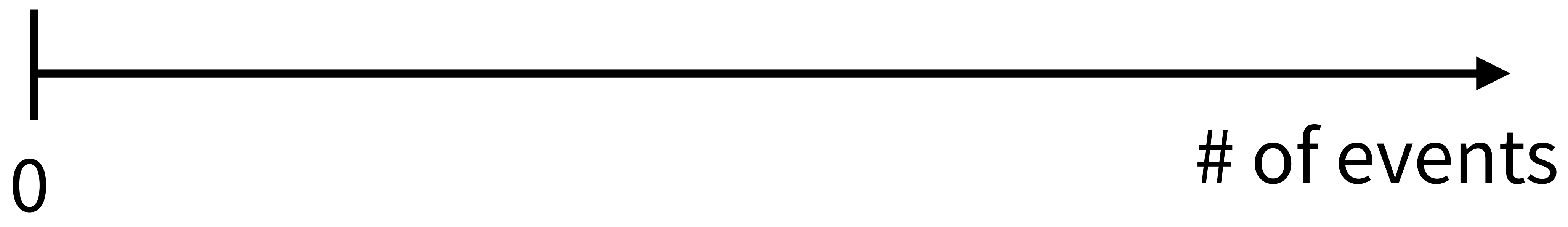

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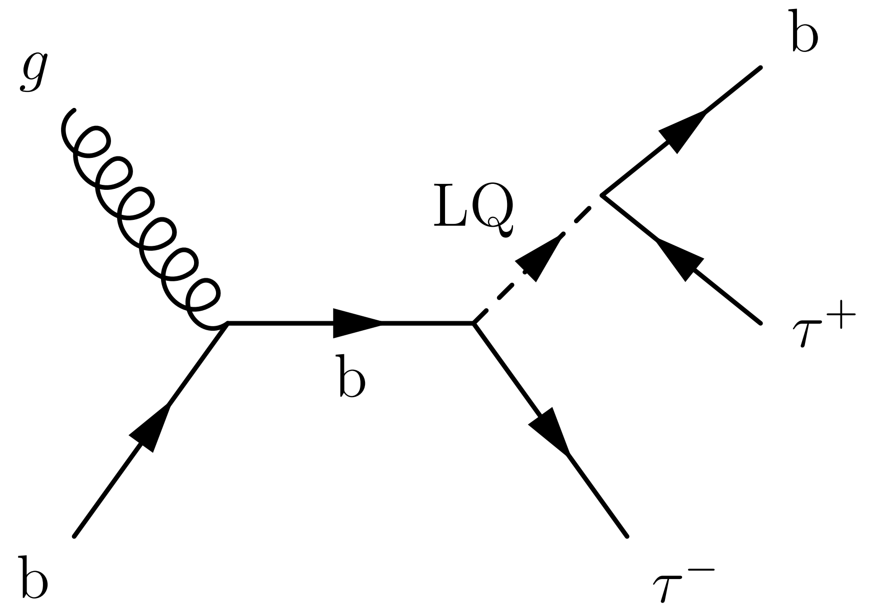

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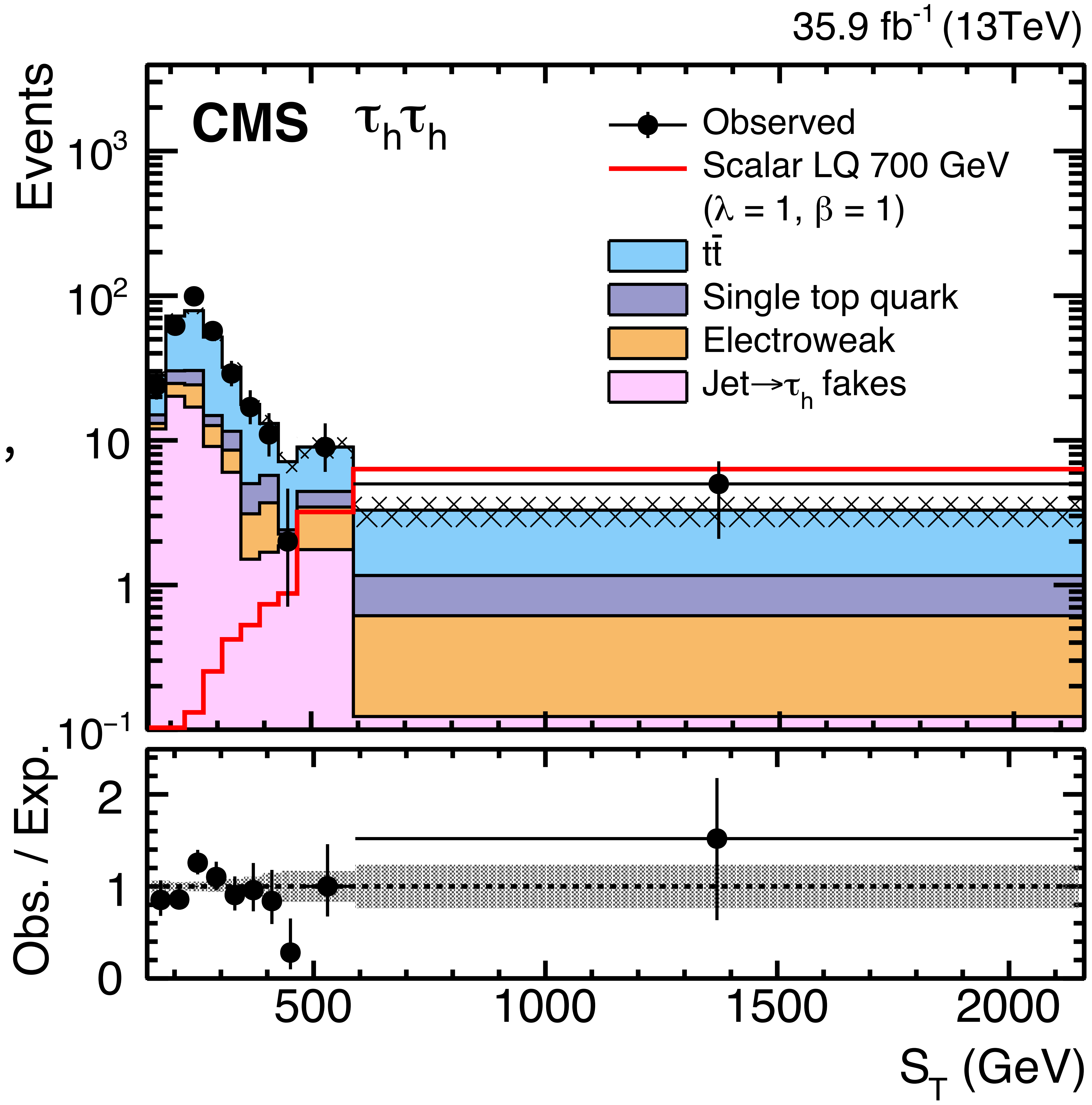

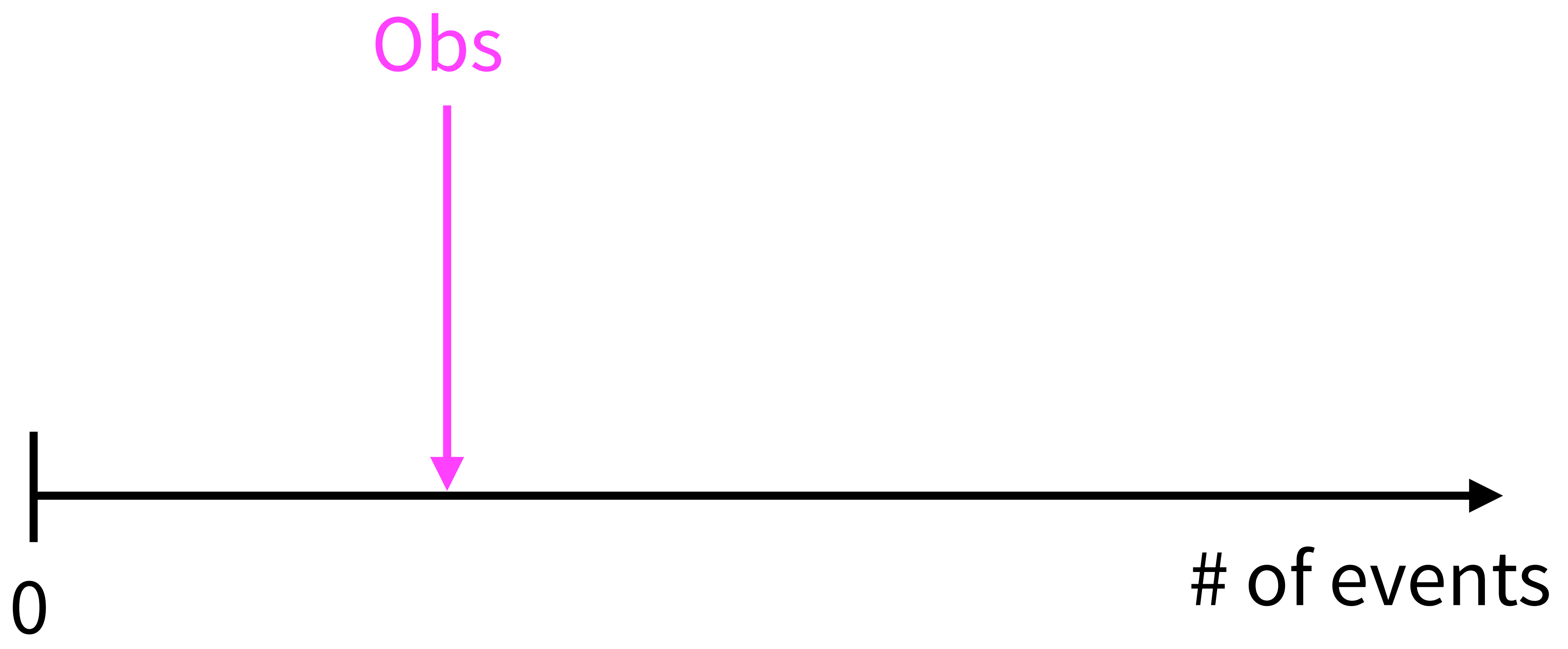

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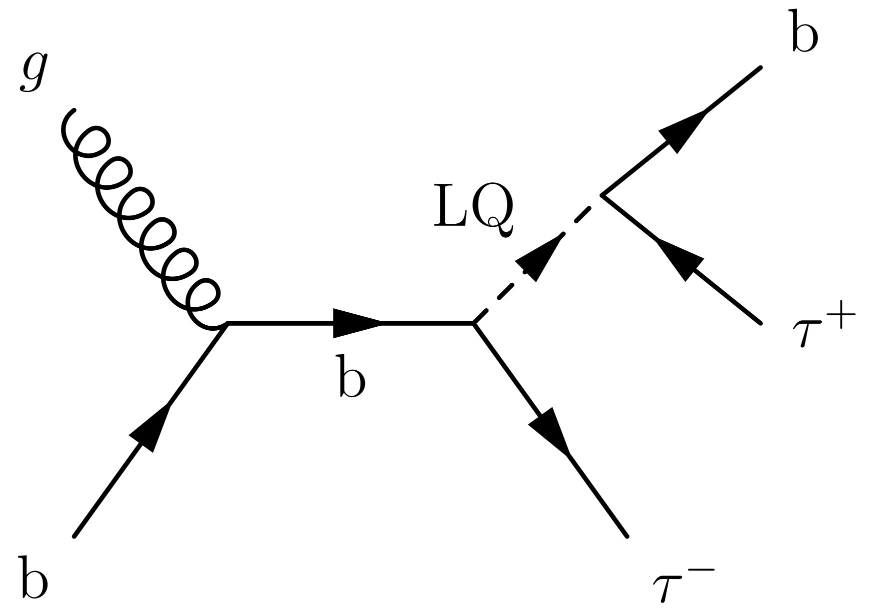

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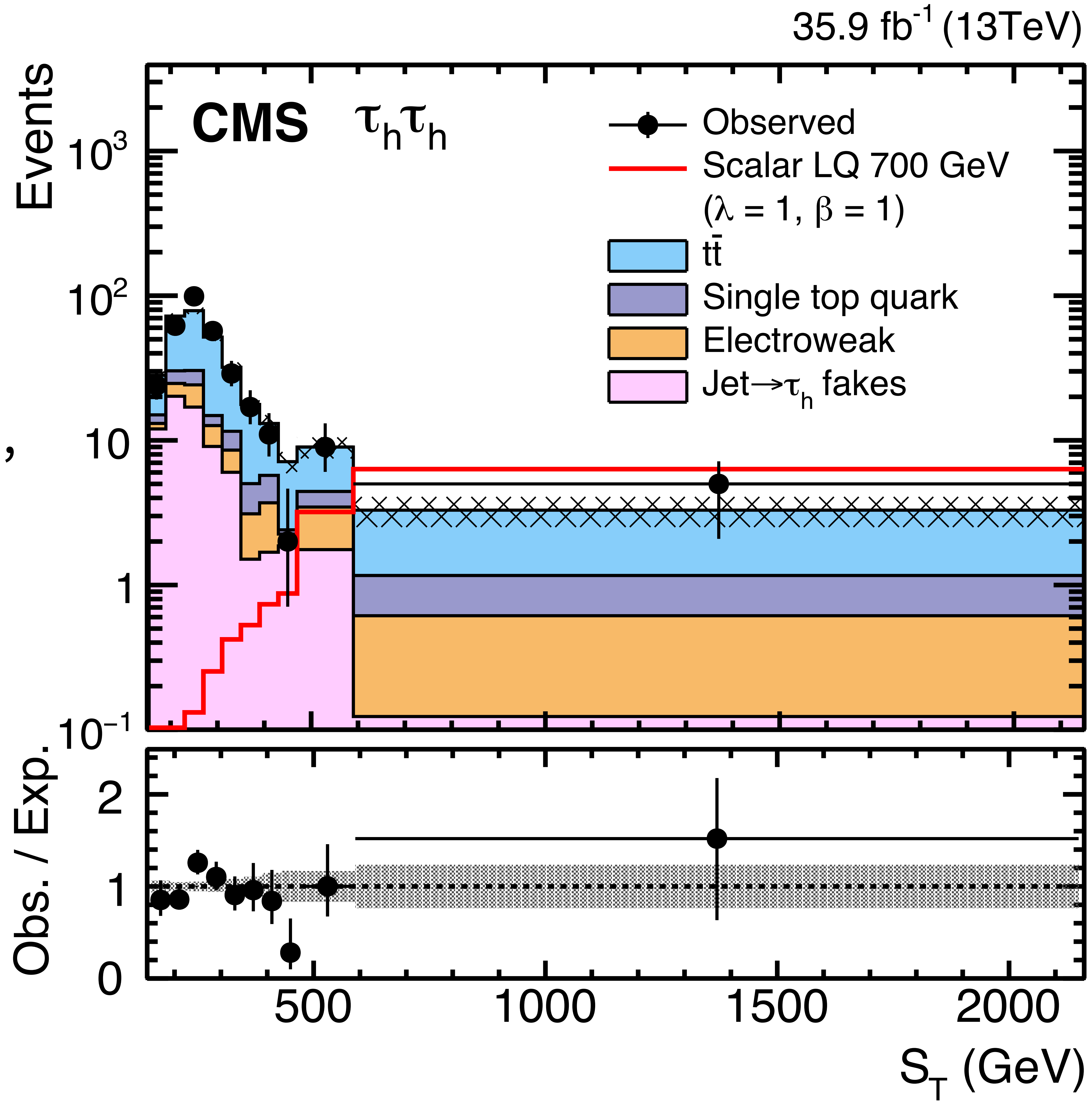

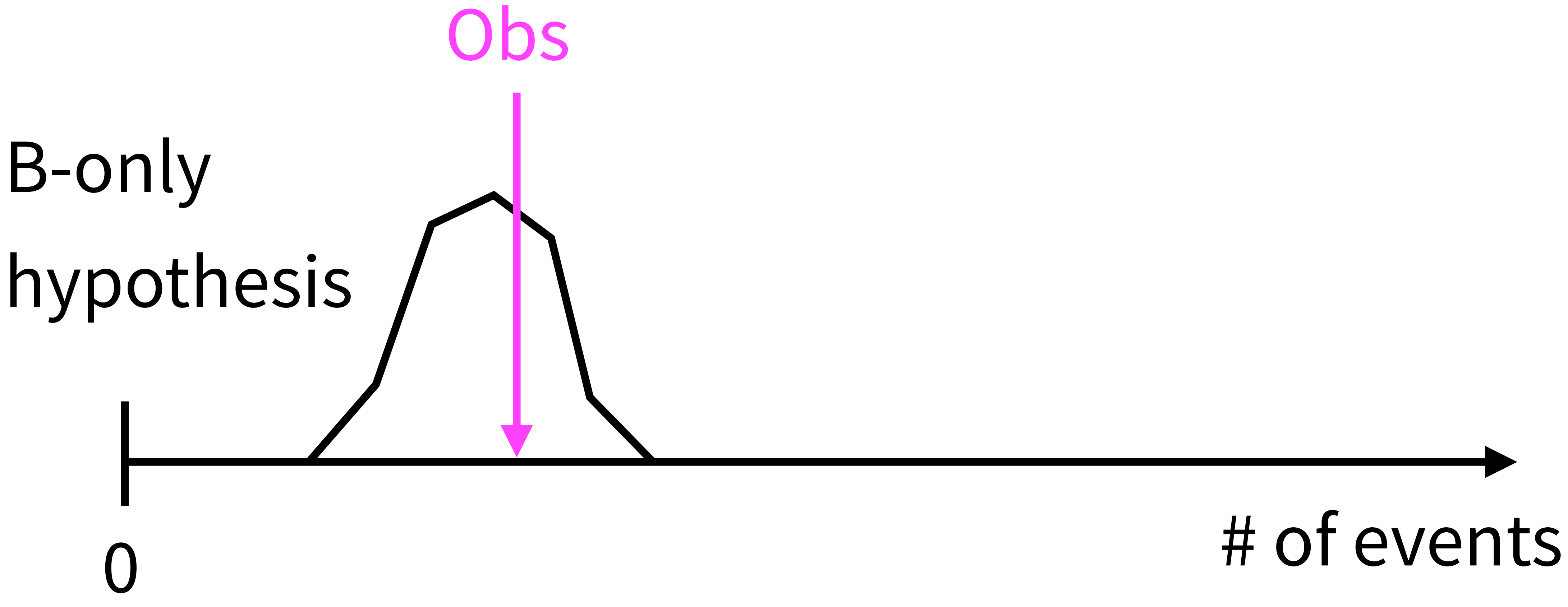

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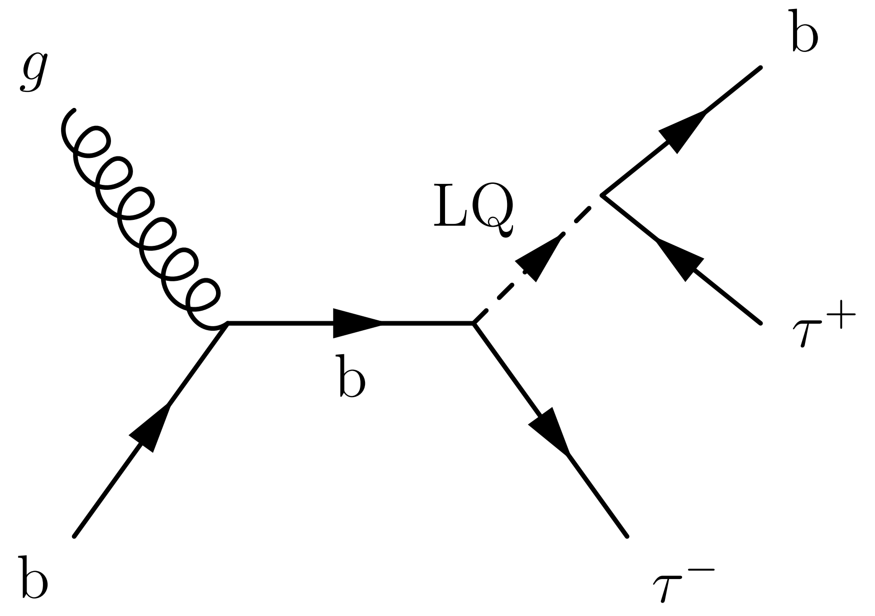

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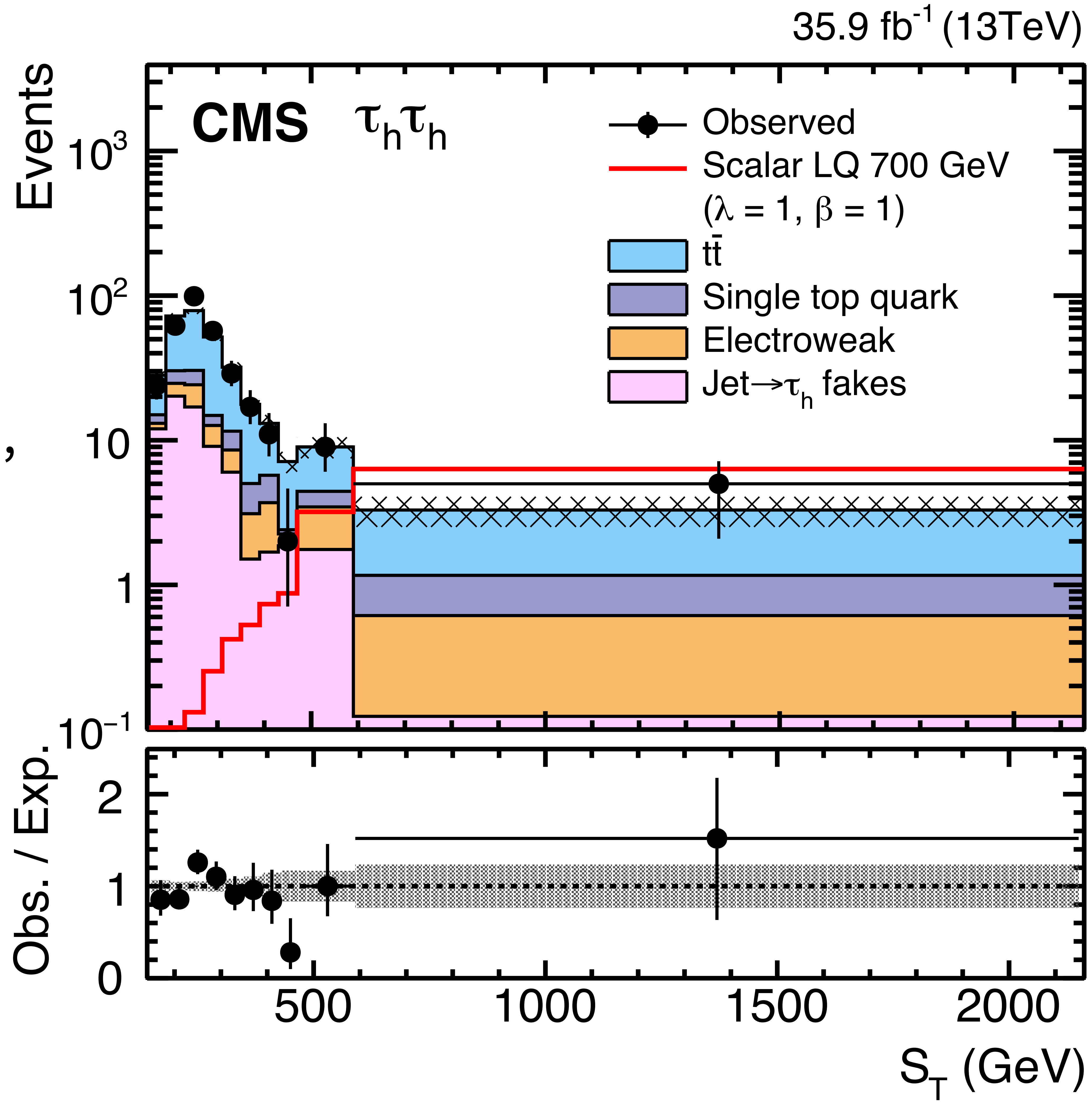

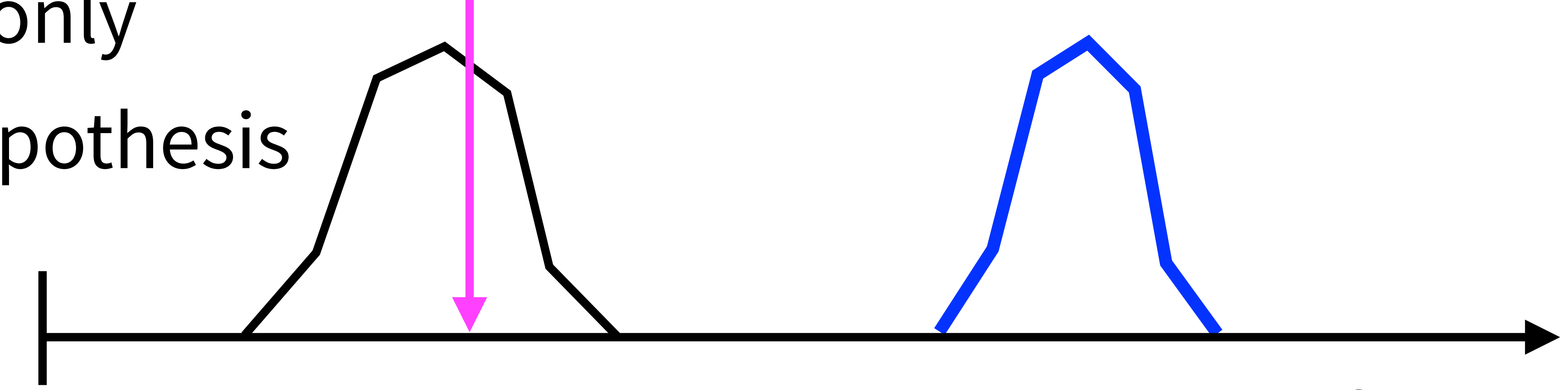

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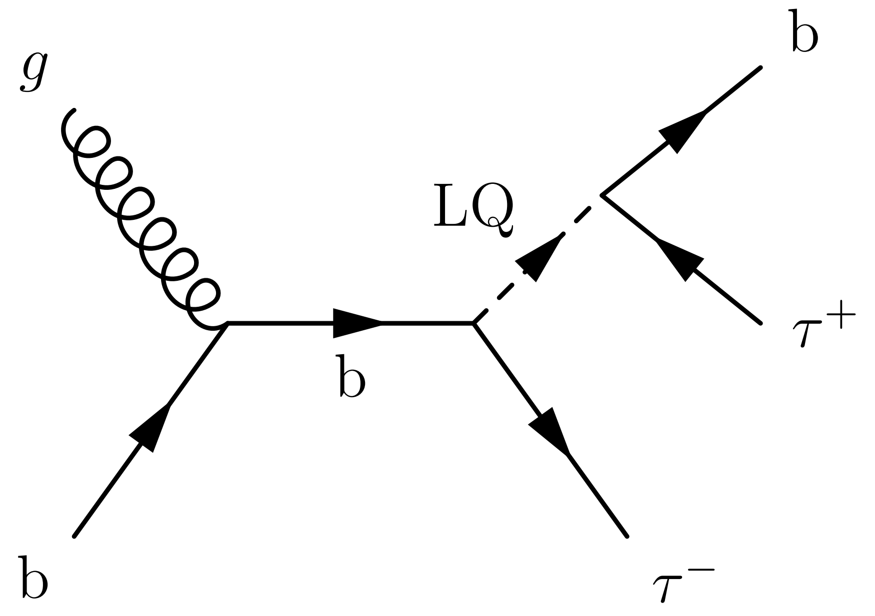

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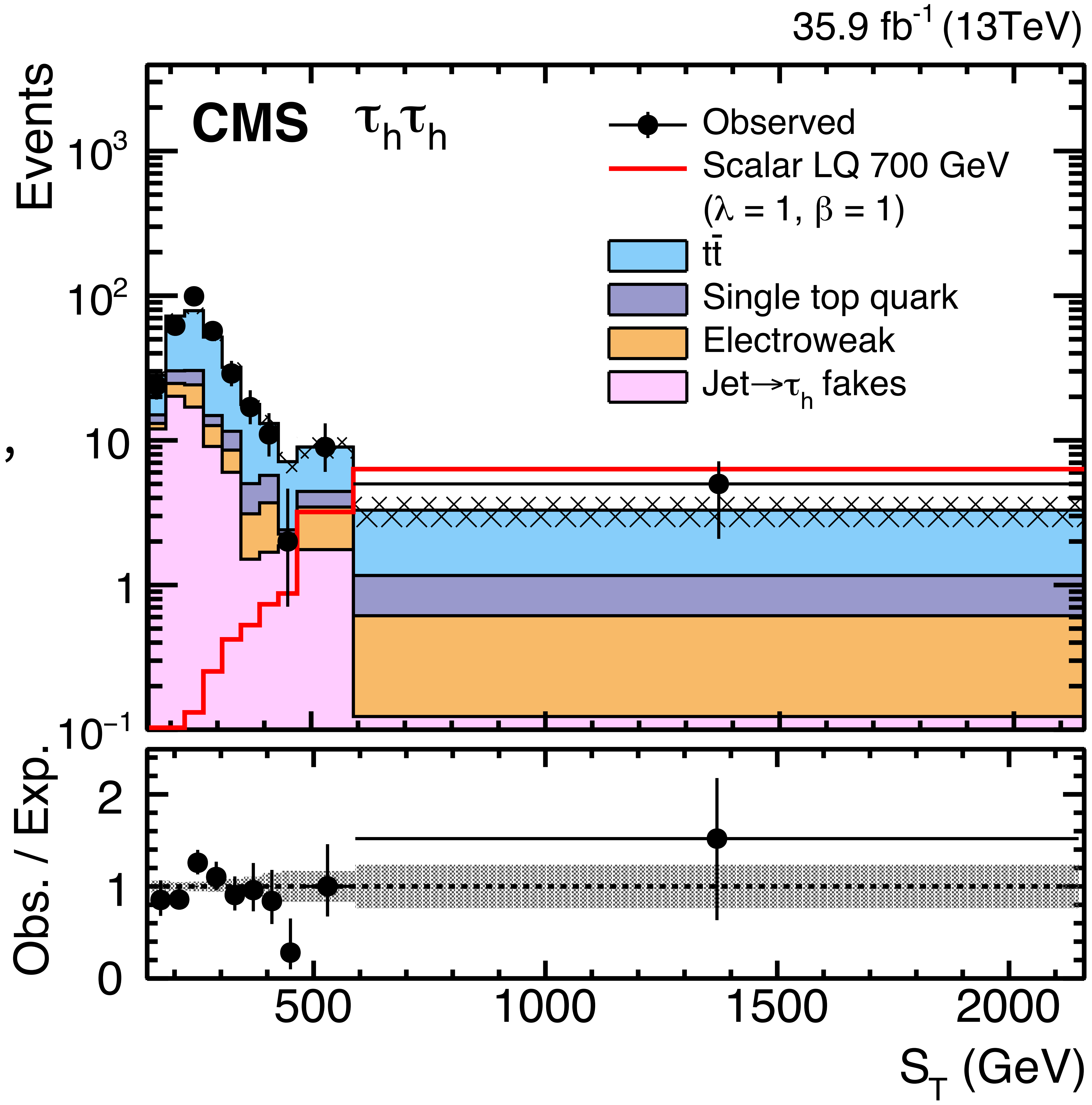

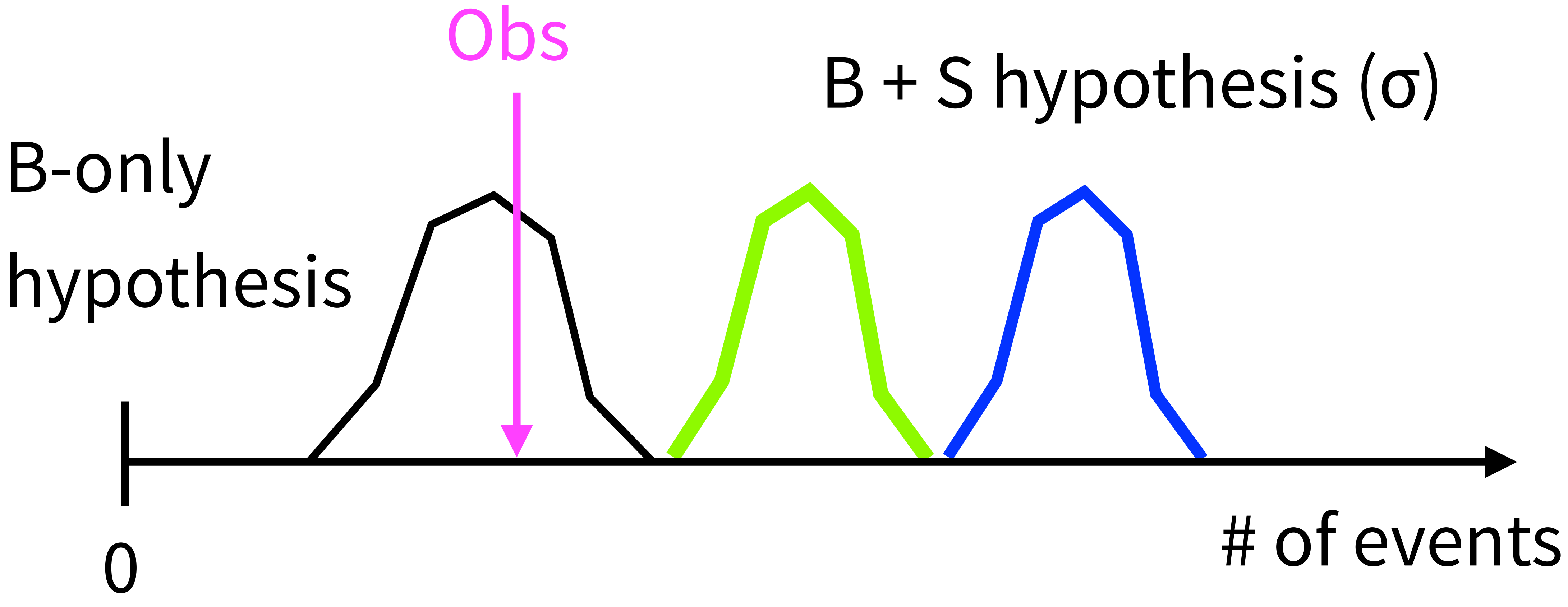

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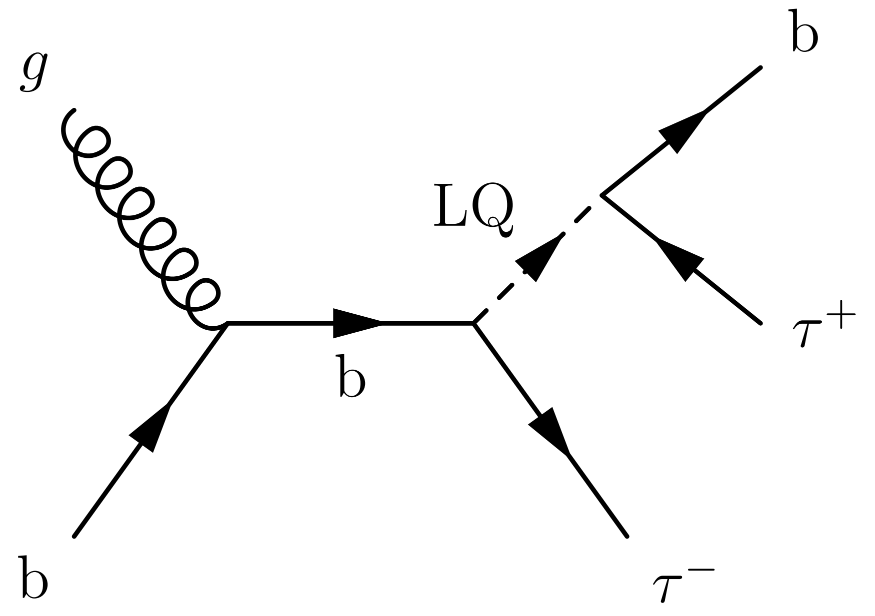

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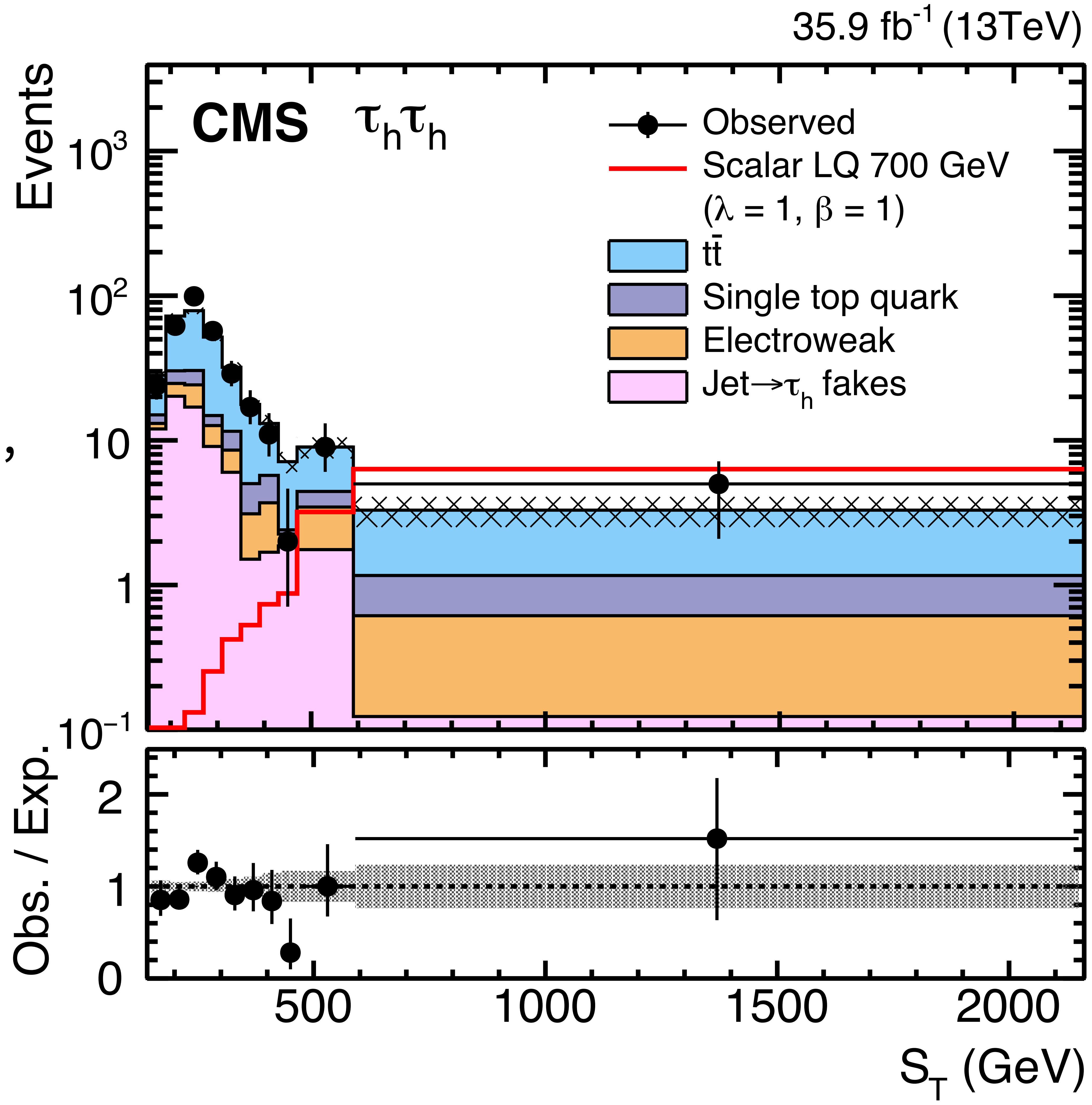

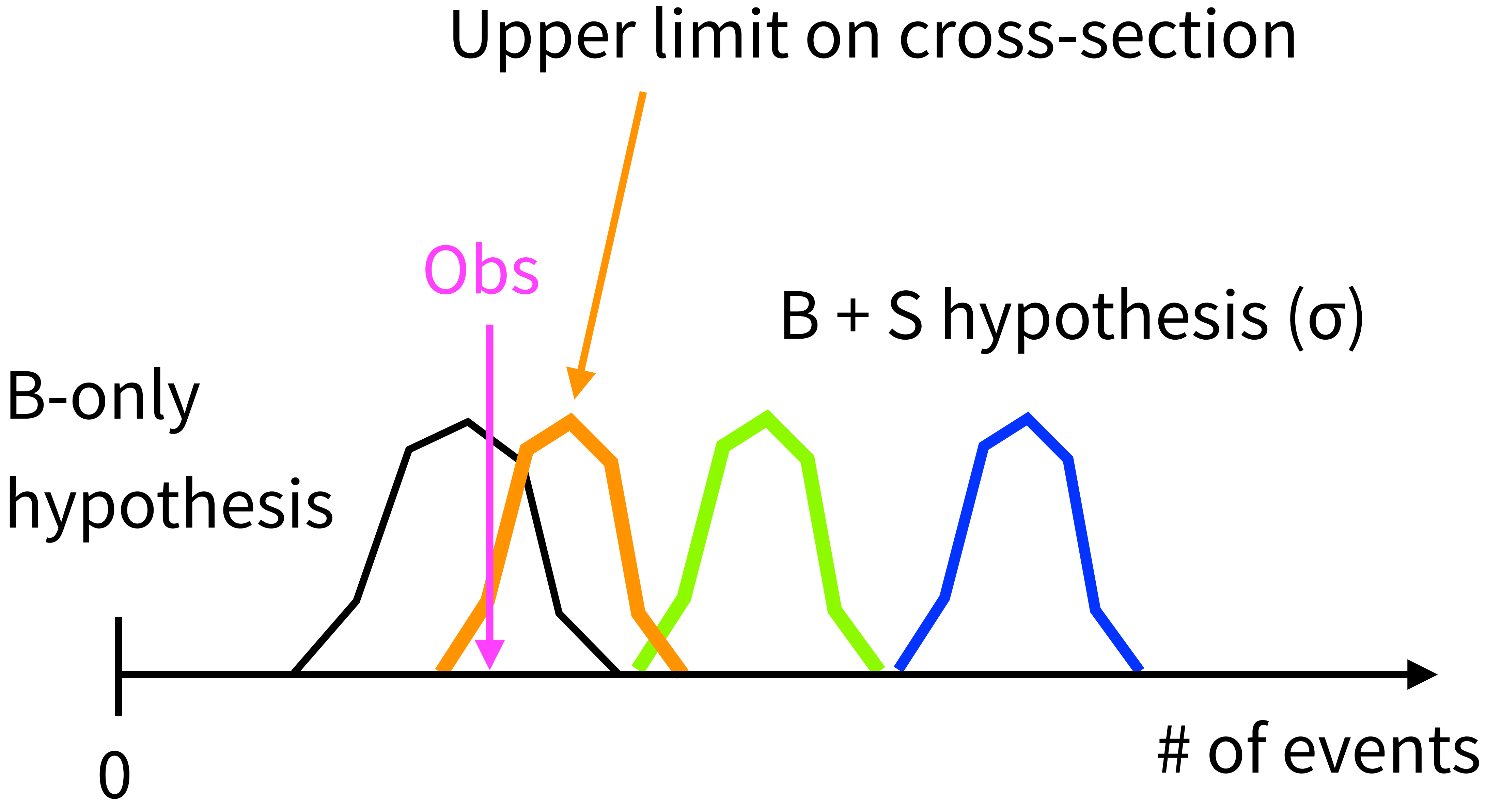

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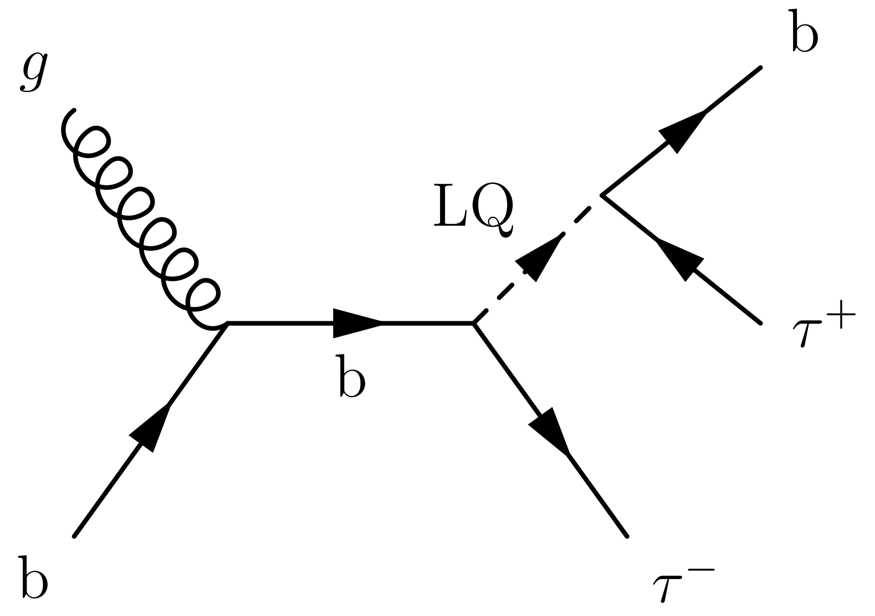

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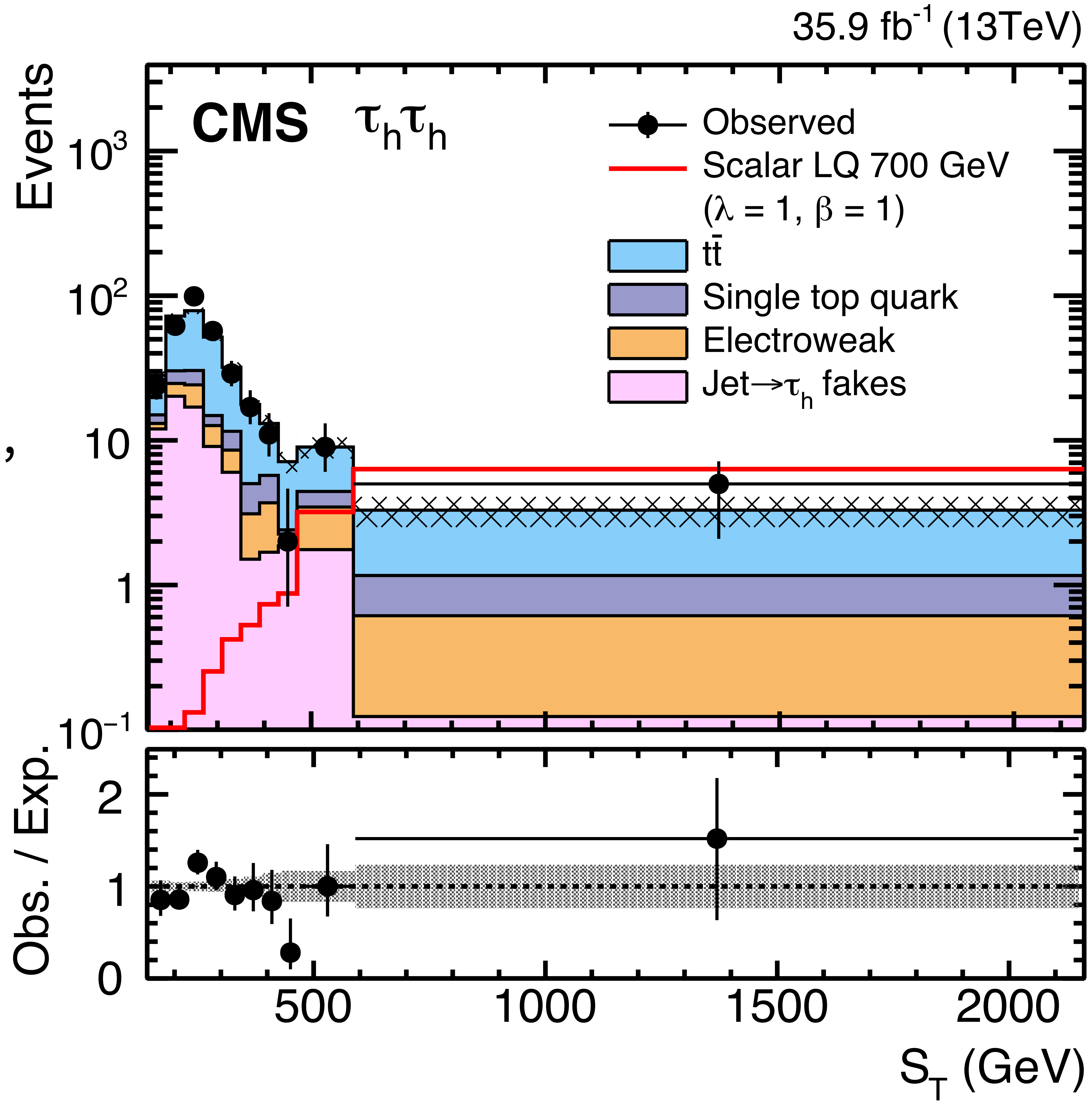
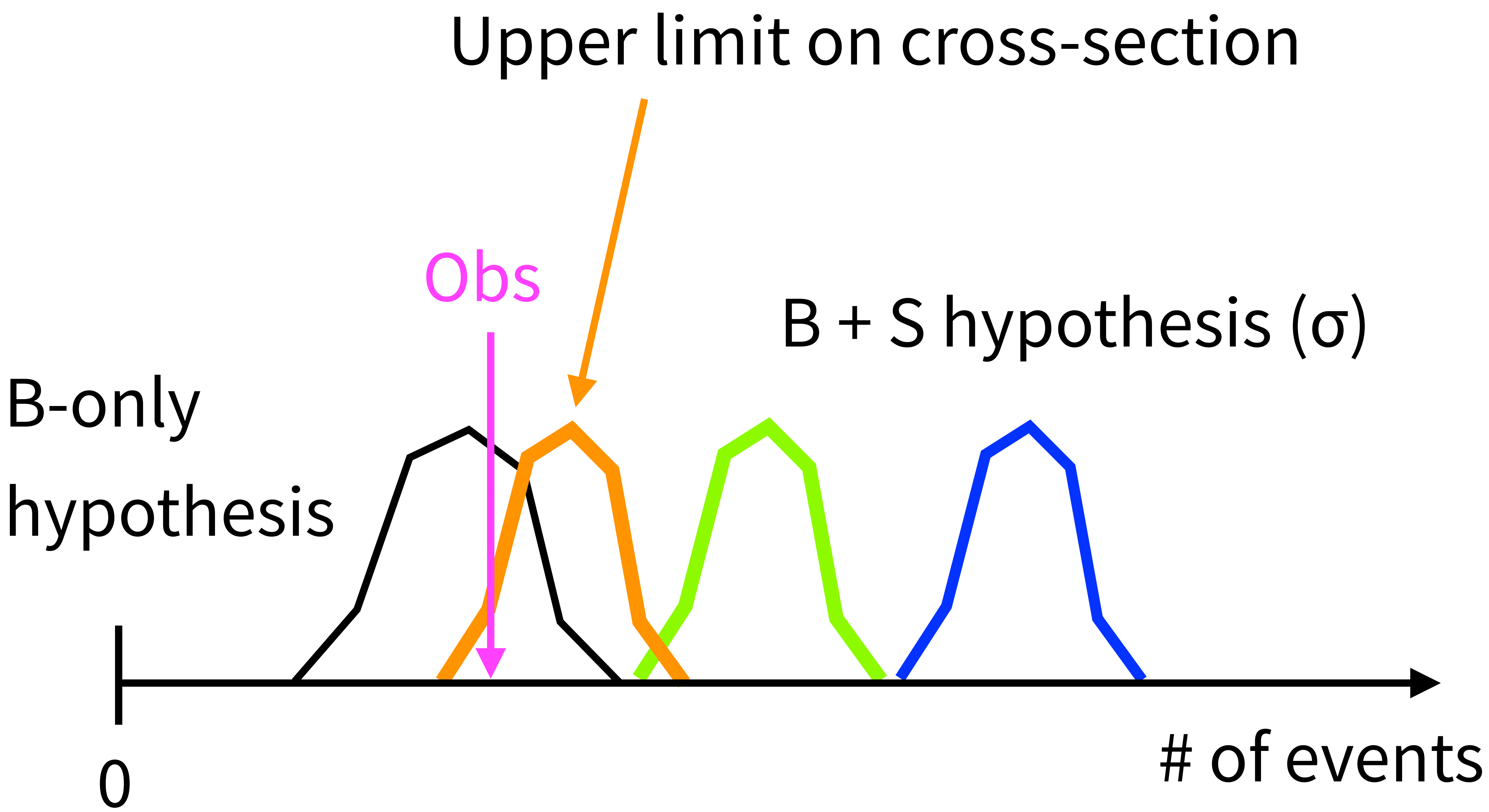
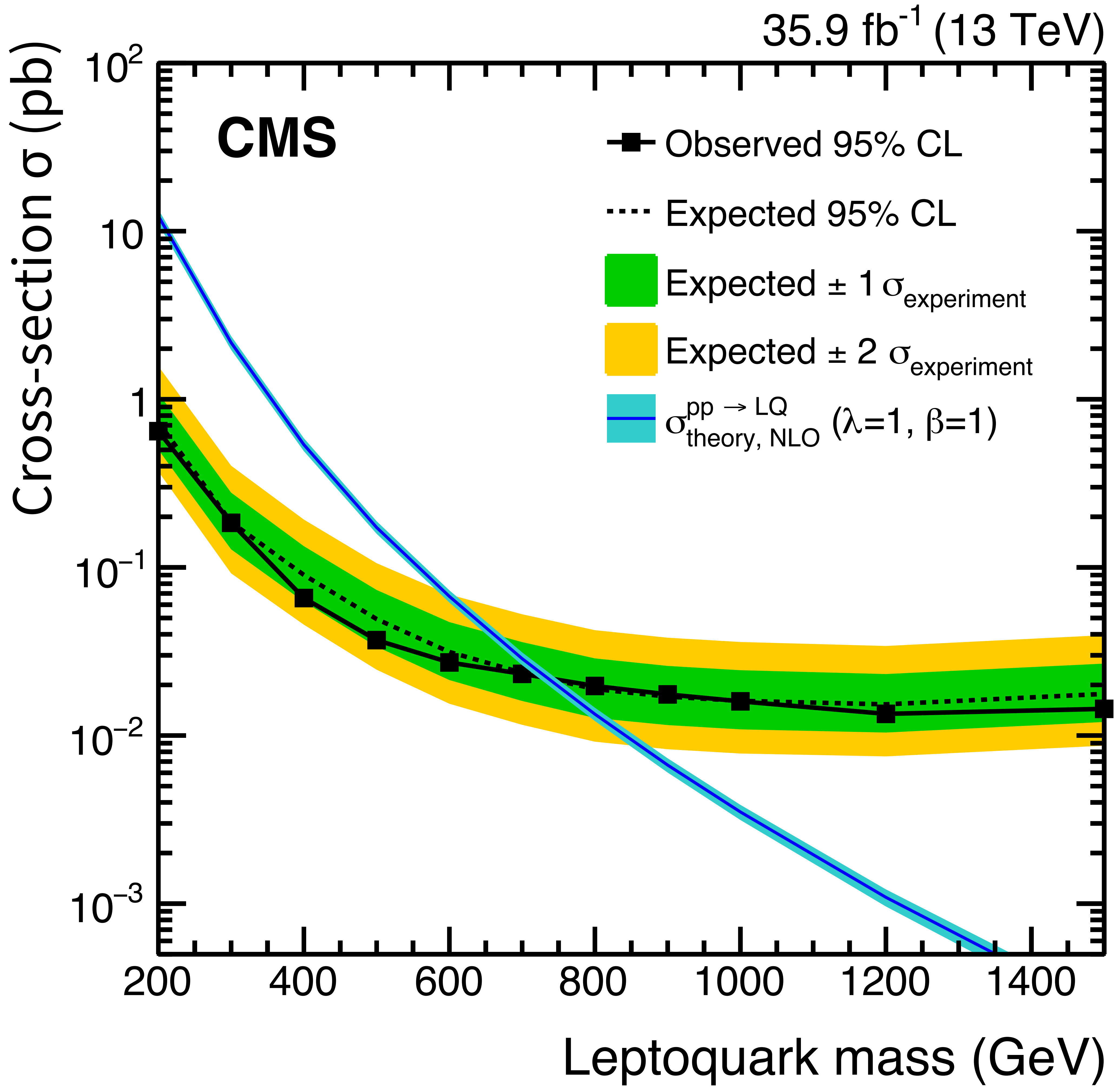


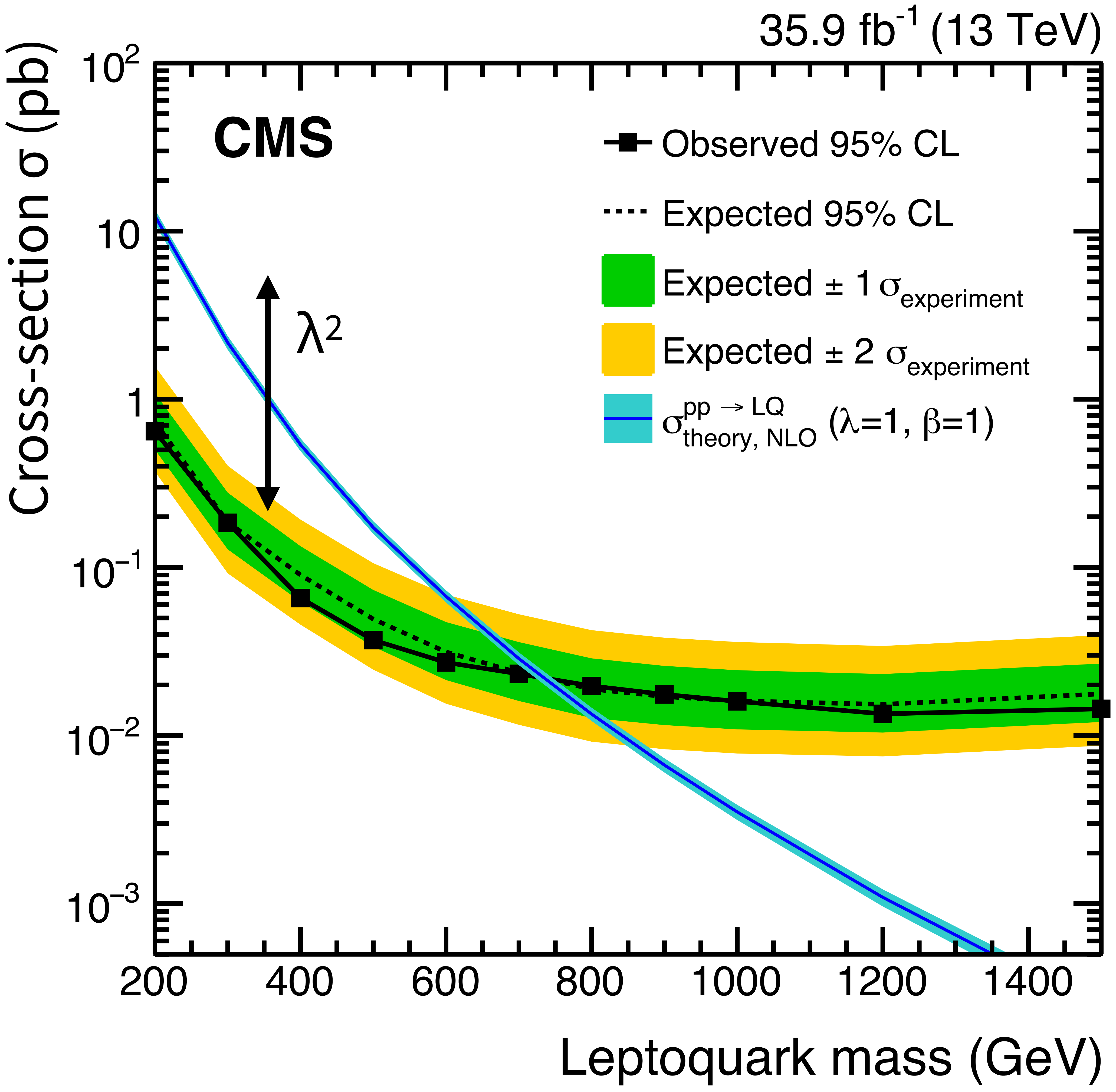


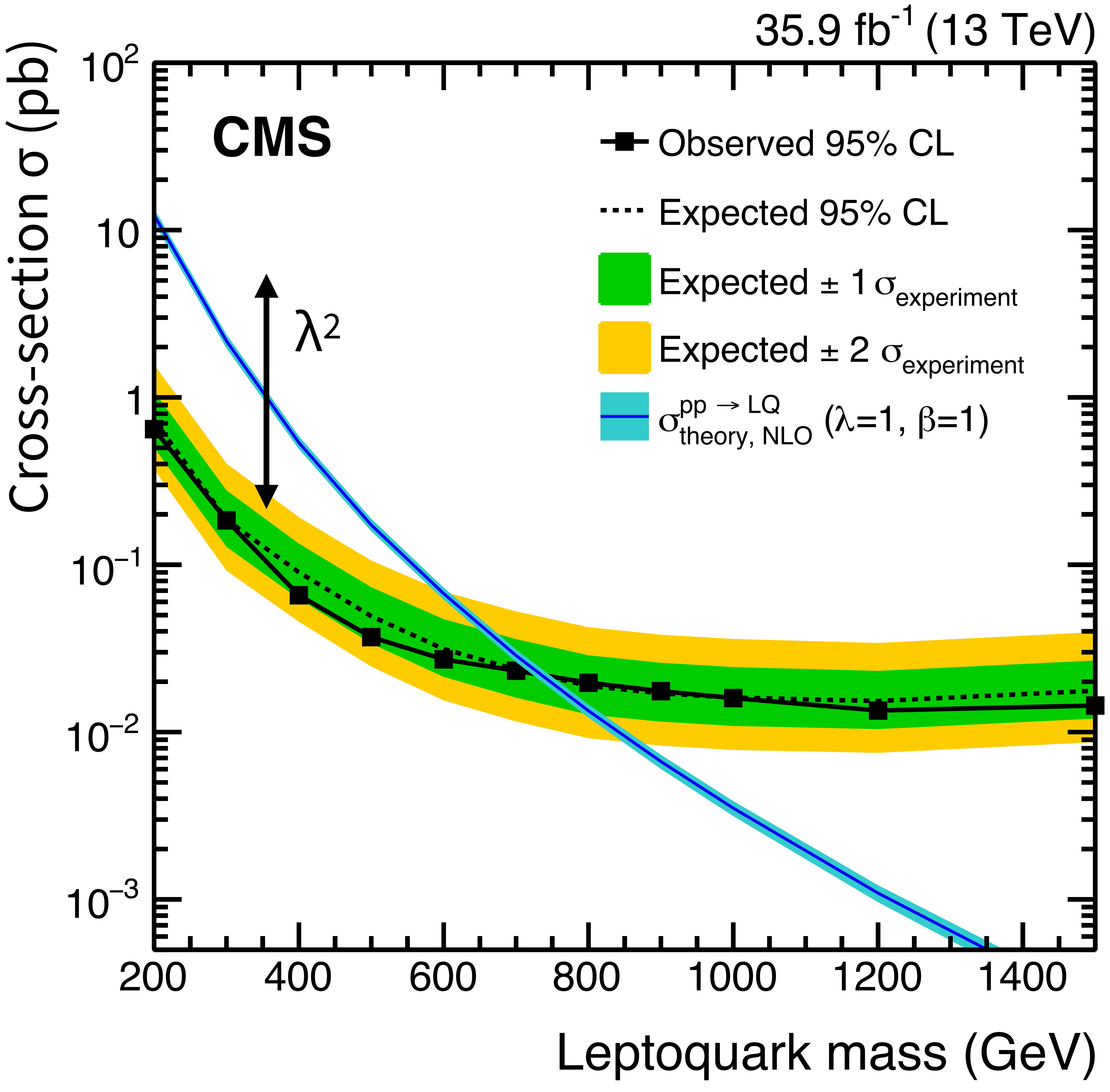
Naively speaking … we define,

- $CL = P(N < N_{obs}|B+S) / P(N < N_{obs}|B)$
- Reject signal if CL < 5%



35.9 fb^{-1} (13 TeV)
CMS
Observed 95% CL
Expected 95% CL
Expected ± 1 $\sigma_{experiment}$
Expected ± 2 $\sigma_{experiment}$
$\sigma^{pp \to LQ}_{theory, NLO}$ (λ=1, β=1)
Cross-section σ (pb)
Leptoquark mass (GeV)
200
400
600
800
1000
1200
1400
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}


35.9 fb-1 (13 TeV)
CMS
Observed 95% CL
Expected 95% CL
Expected ± 1 σexperiment
Expected ± 2 σexperiment
σpp → LQ theory, NLO (λ=1, β=1)
λ2
Cross-section σ (pb)
Leptoquark mass (GeV)
200
400
600
800
1000
1200
1400
10-3
10-2
10-1
1
10
102


35.9 fb-1 (13 TeV)
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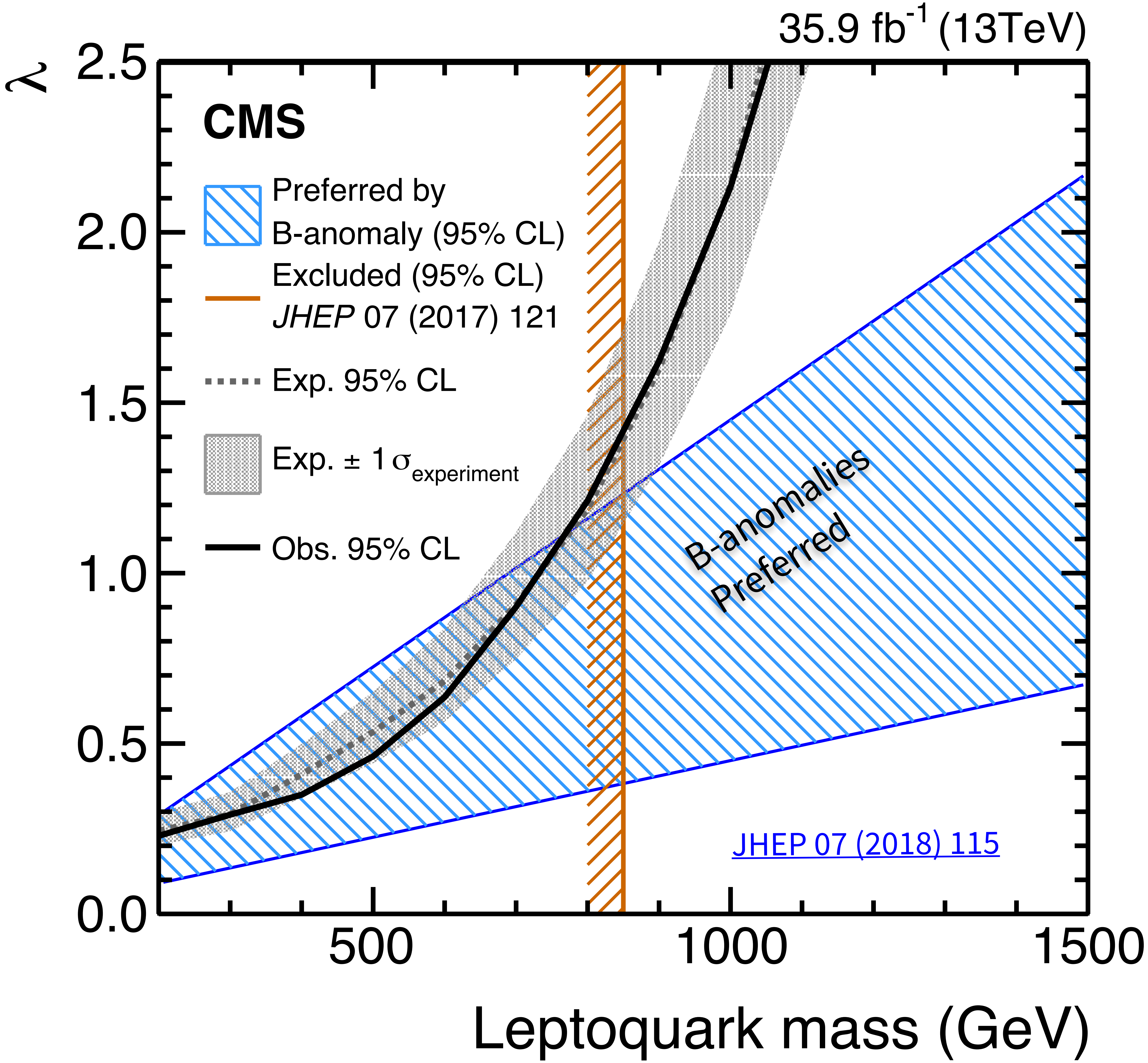
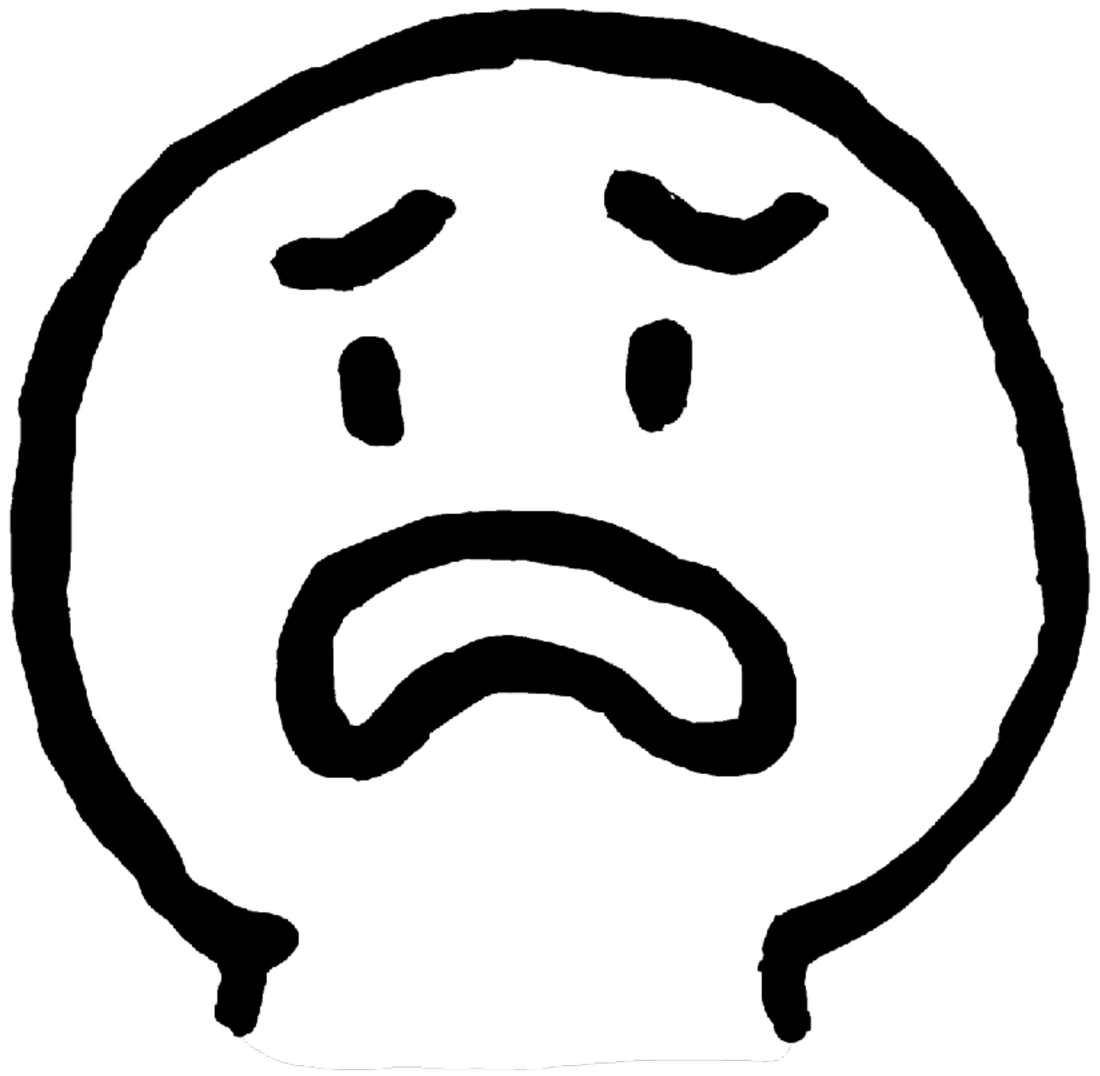
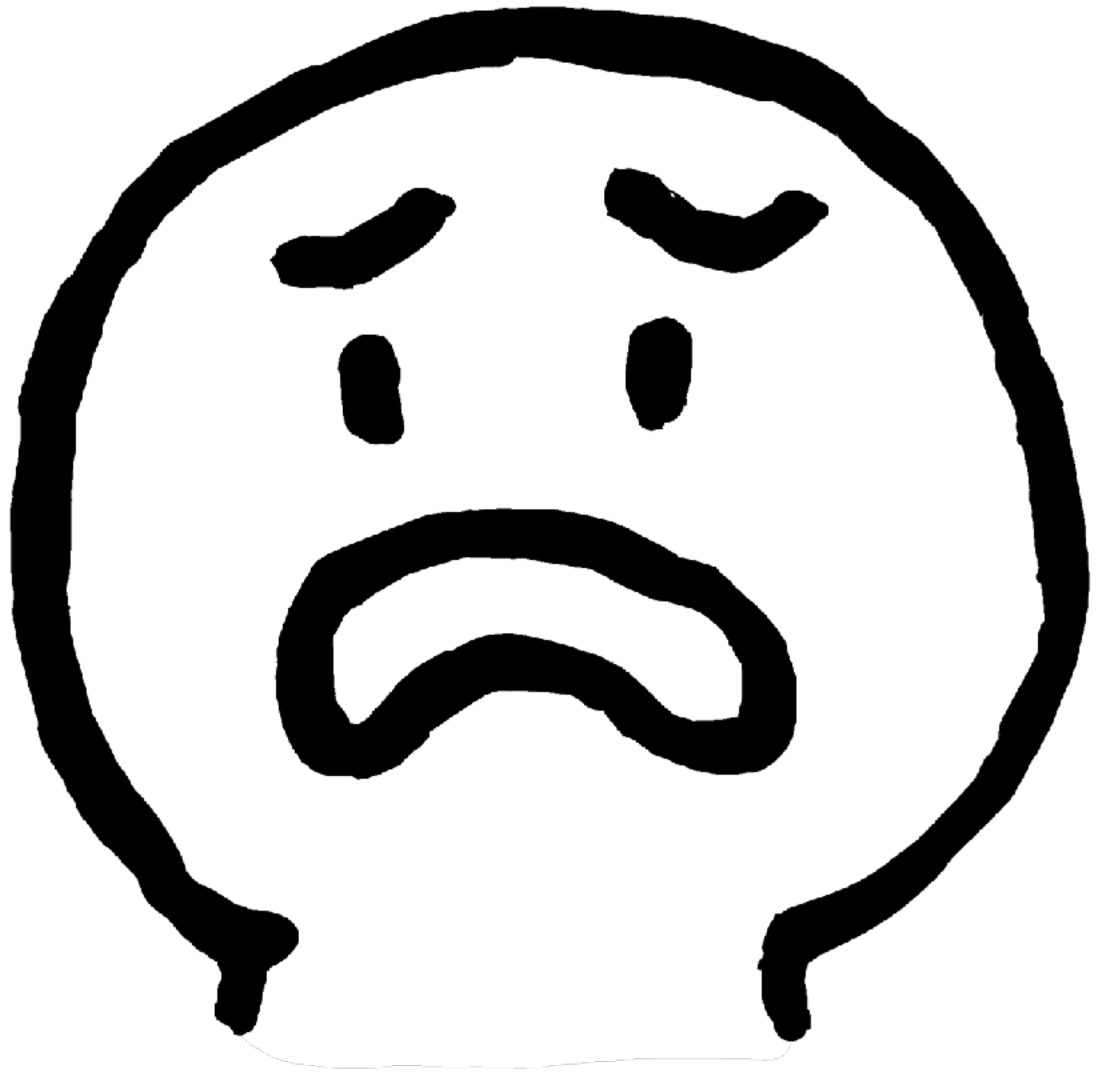
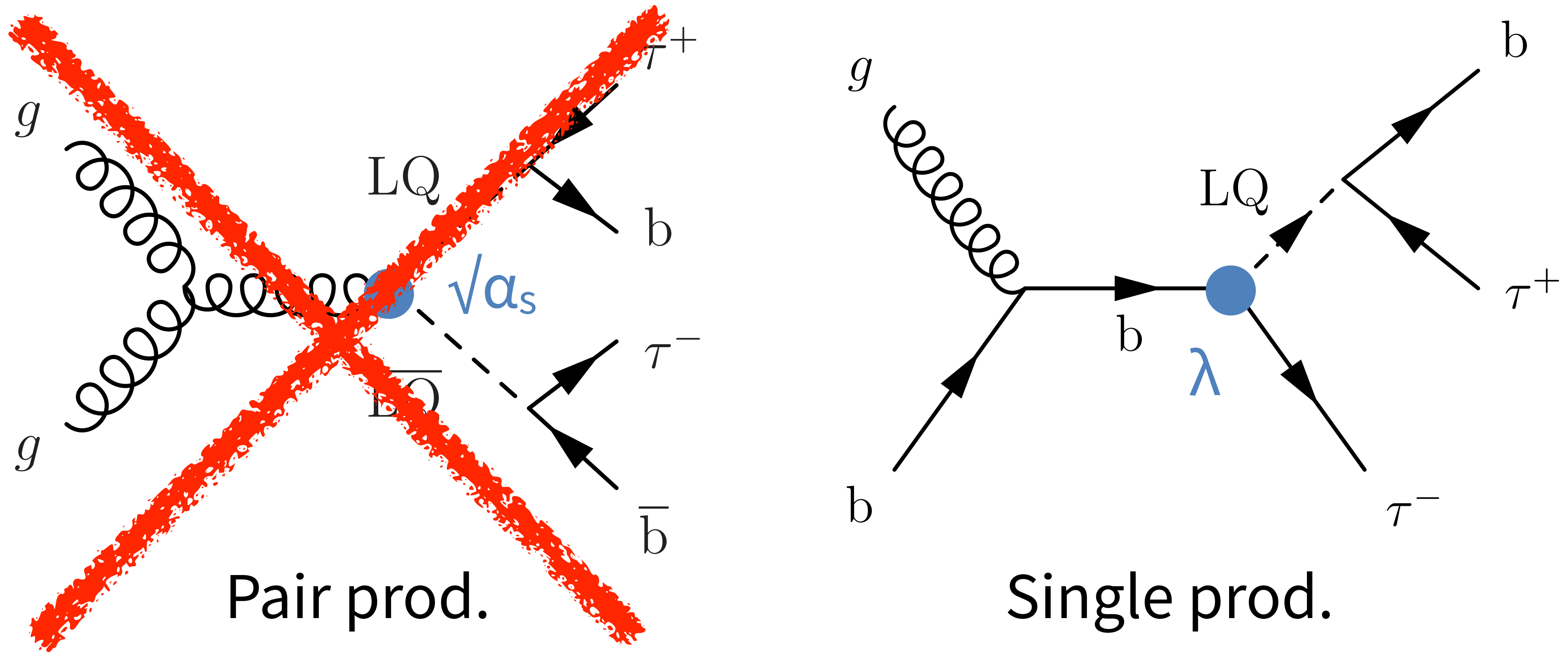
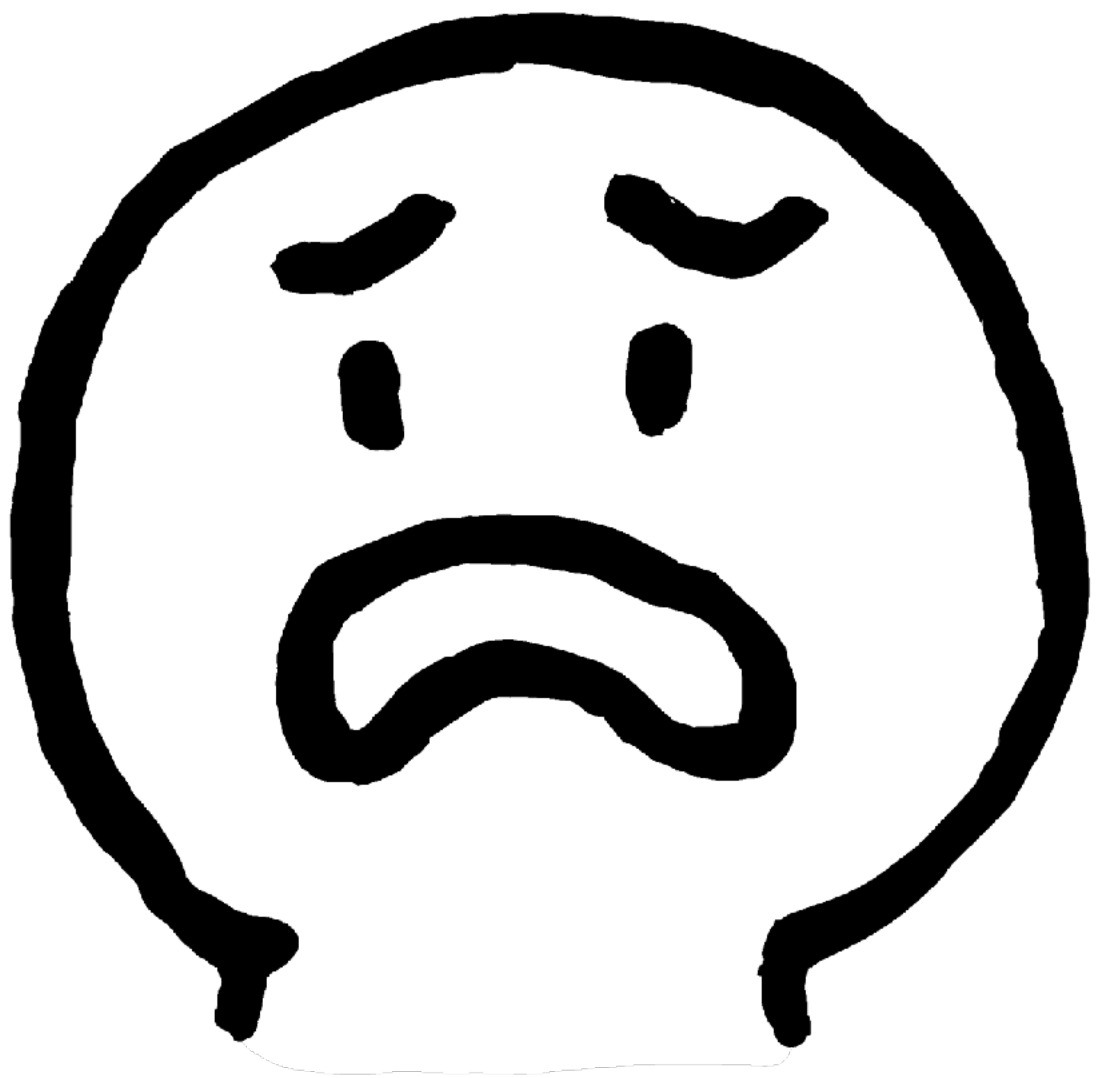

35.9 fb-1 (13TeV)
CMS
Preferred by
B-anomaly (95% CL)
Excluded (95% CL)
JHEP 07 (2017) 121
Exp. 95% CL
Exp. ± 1 σexperiment
Obs. 95% CL
B-anomalies
Preferred
JHEP 07 (2018) 115
λ
Leptoquark mass (GeV)

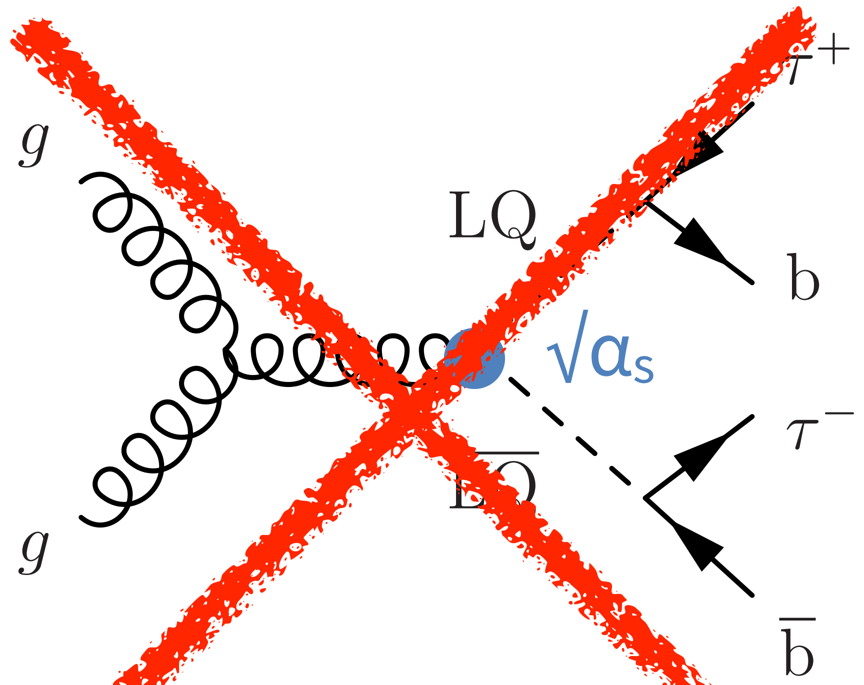






Pair prod. Single prod.





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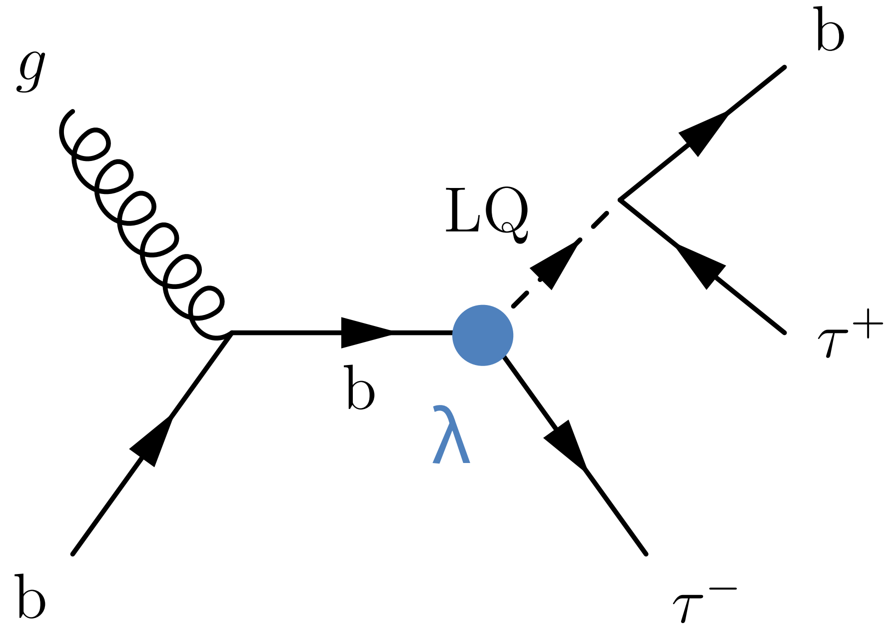
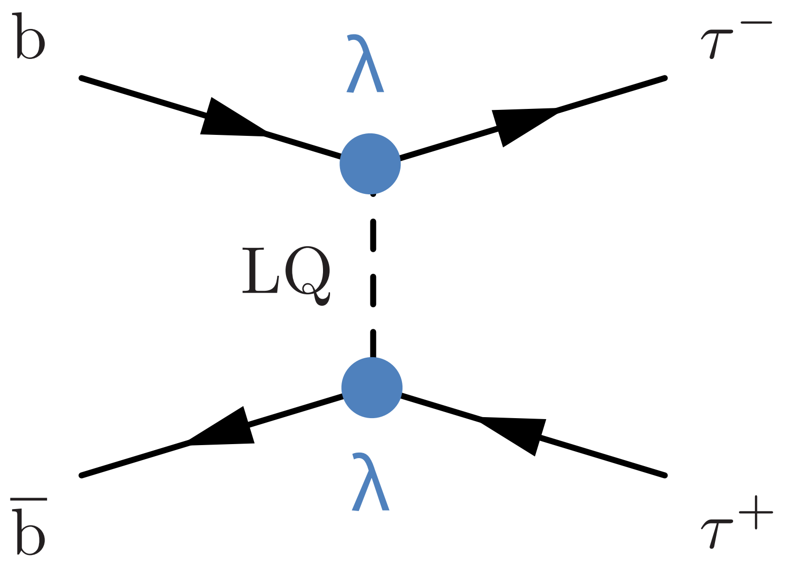


Single prod.

We are also ignoring …

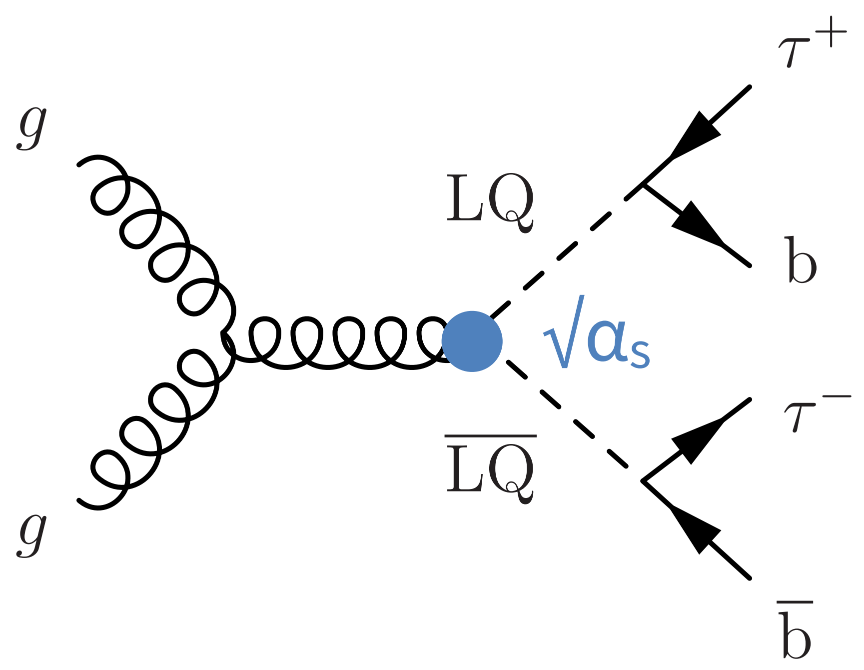


Non resonant

- Cross-section ∝ λ^4
- Particularly relevant when λ is large

More comprehensive analysis

We target all production modes **at once**



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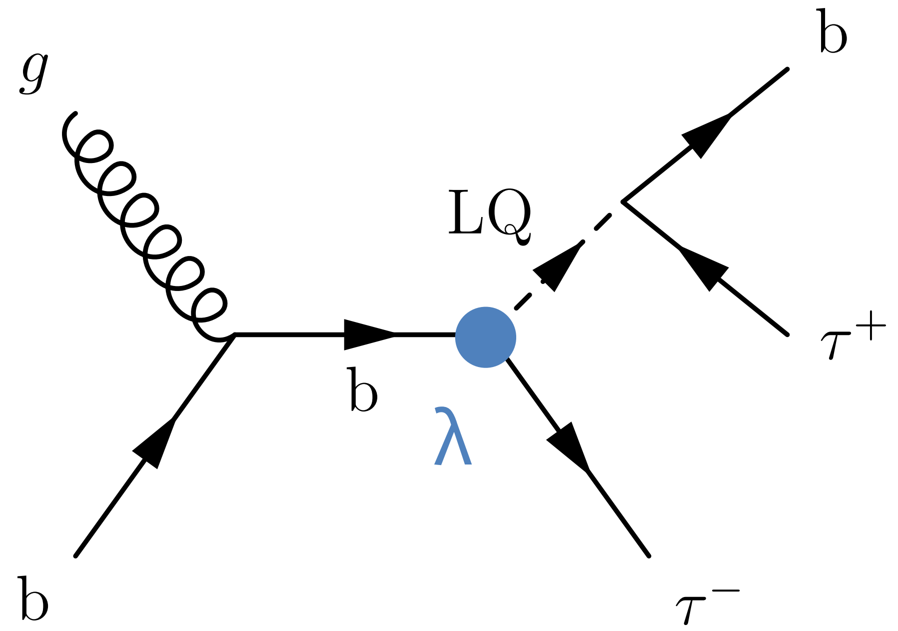
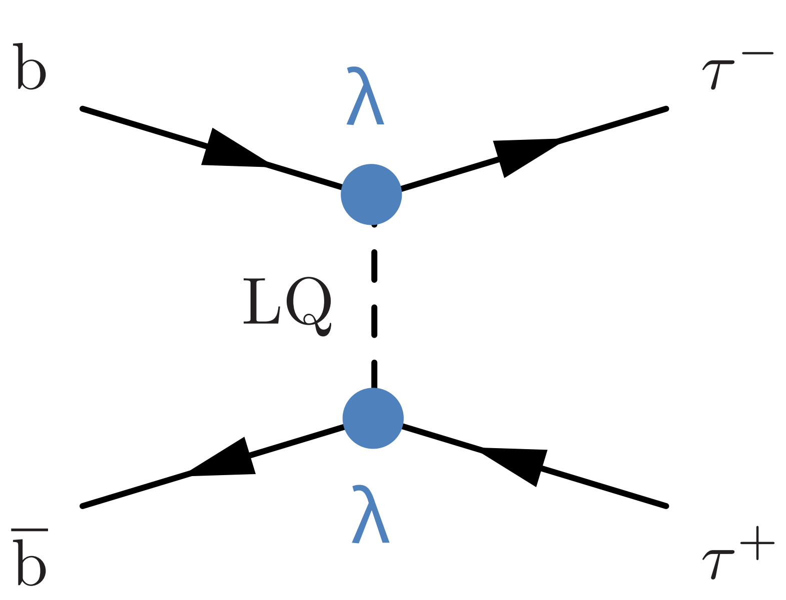


Single prod.



Non resonant

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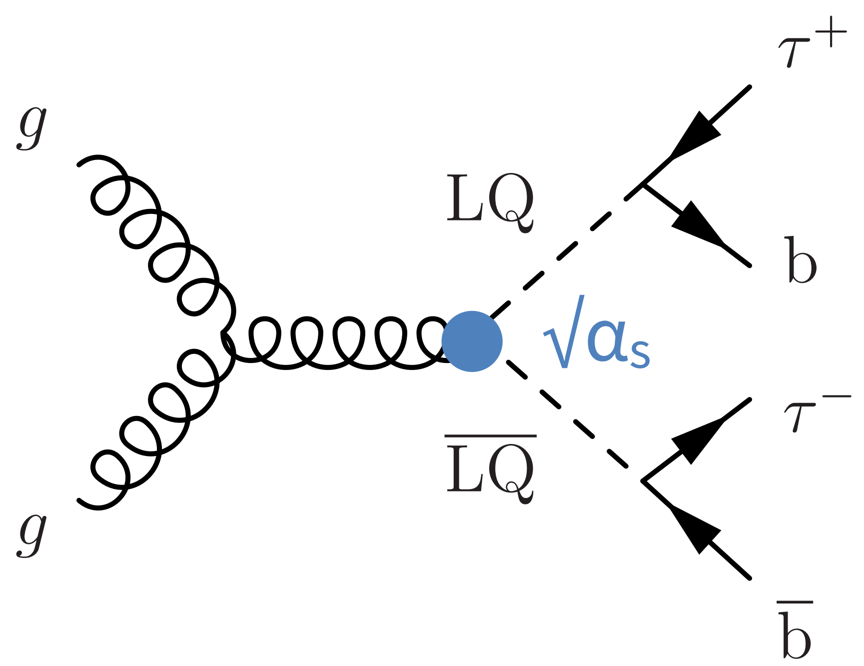
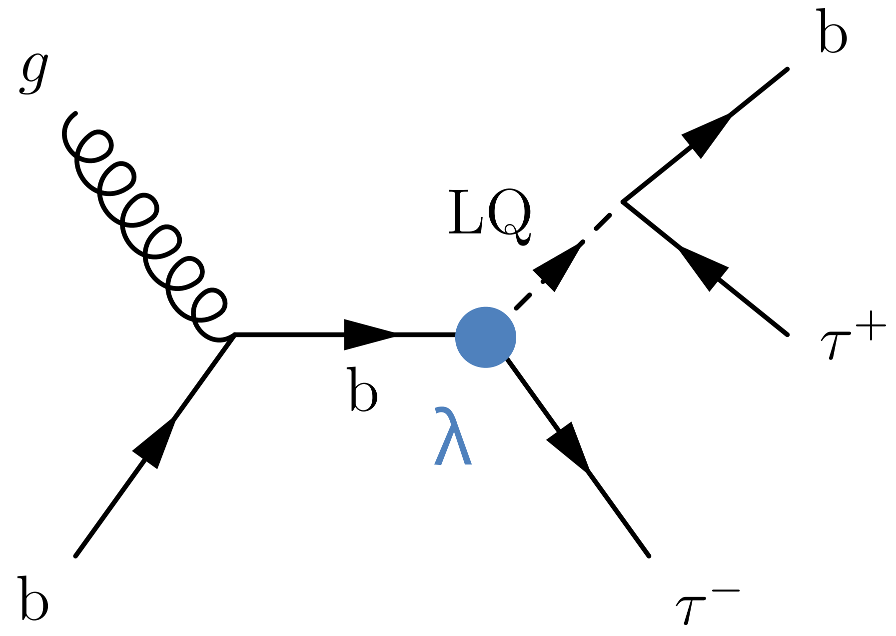
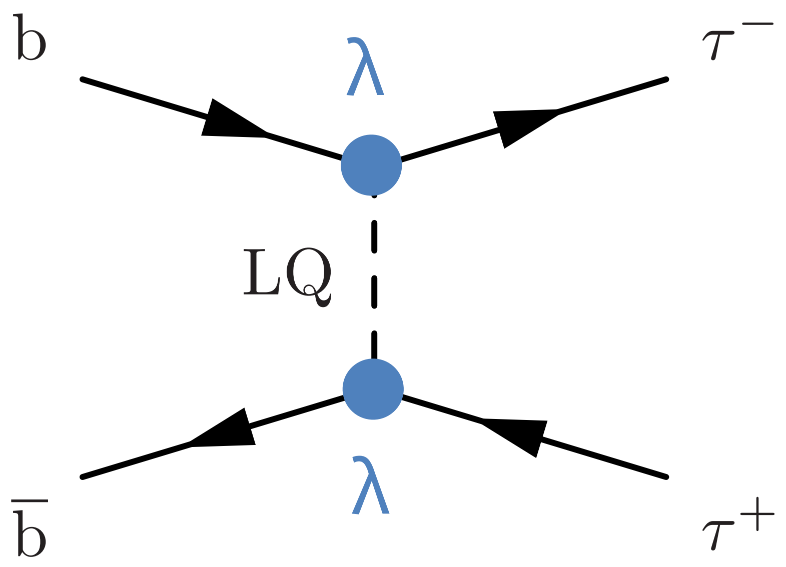


Pair prod.



Single prod.



Non resonant

When λ changes, we have different mixtures of pair/single/non-resonant
→ Signal distribution changes as a function of λ (and m_{LQ} too)

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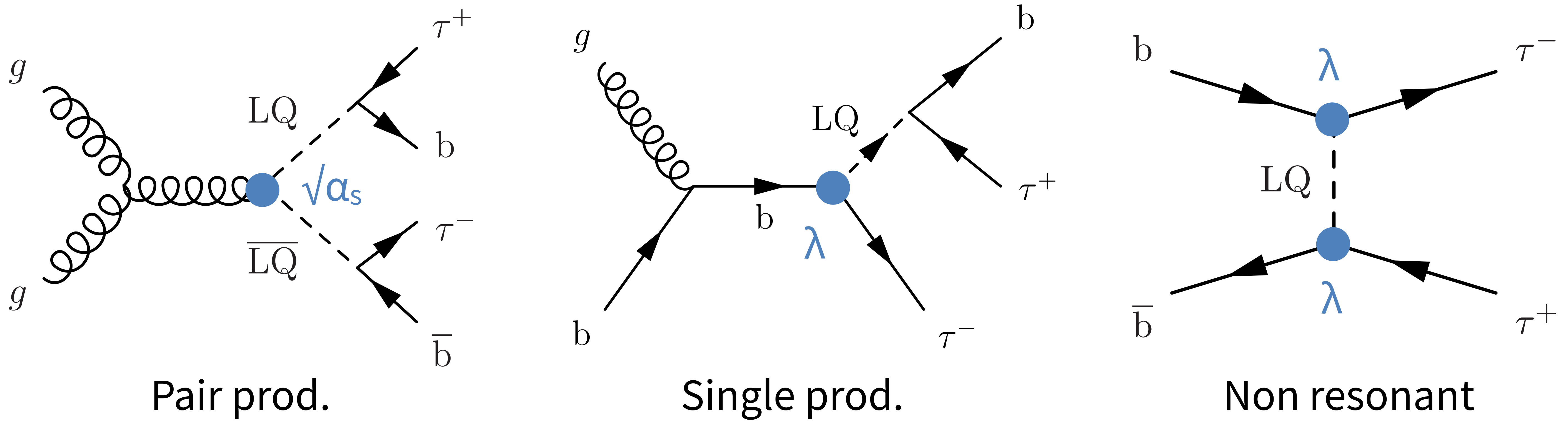

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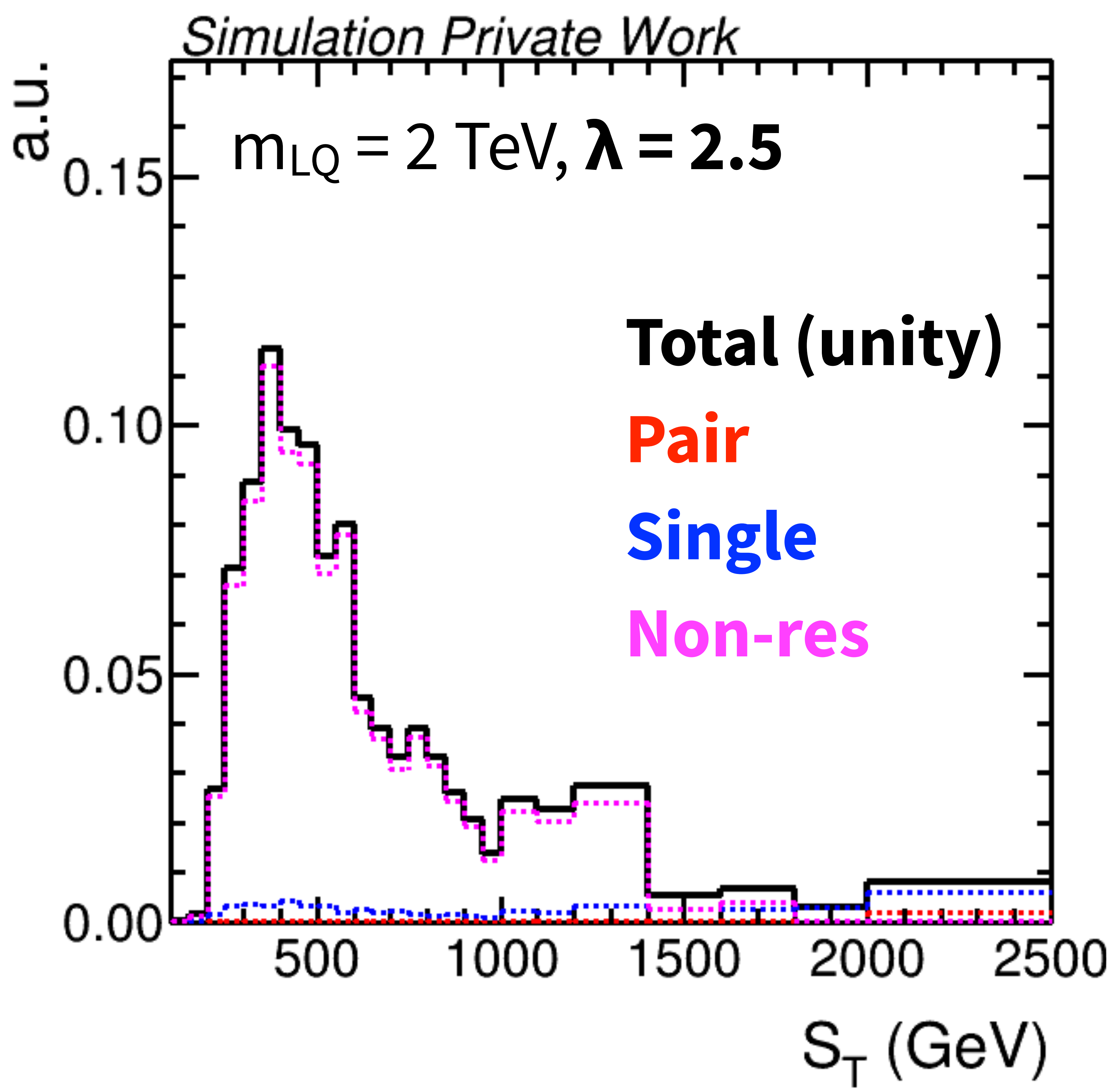

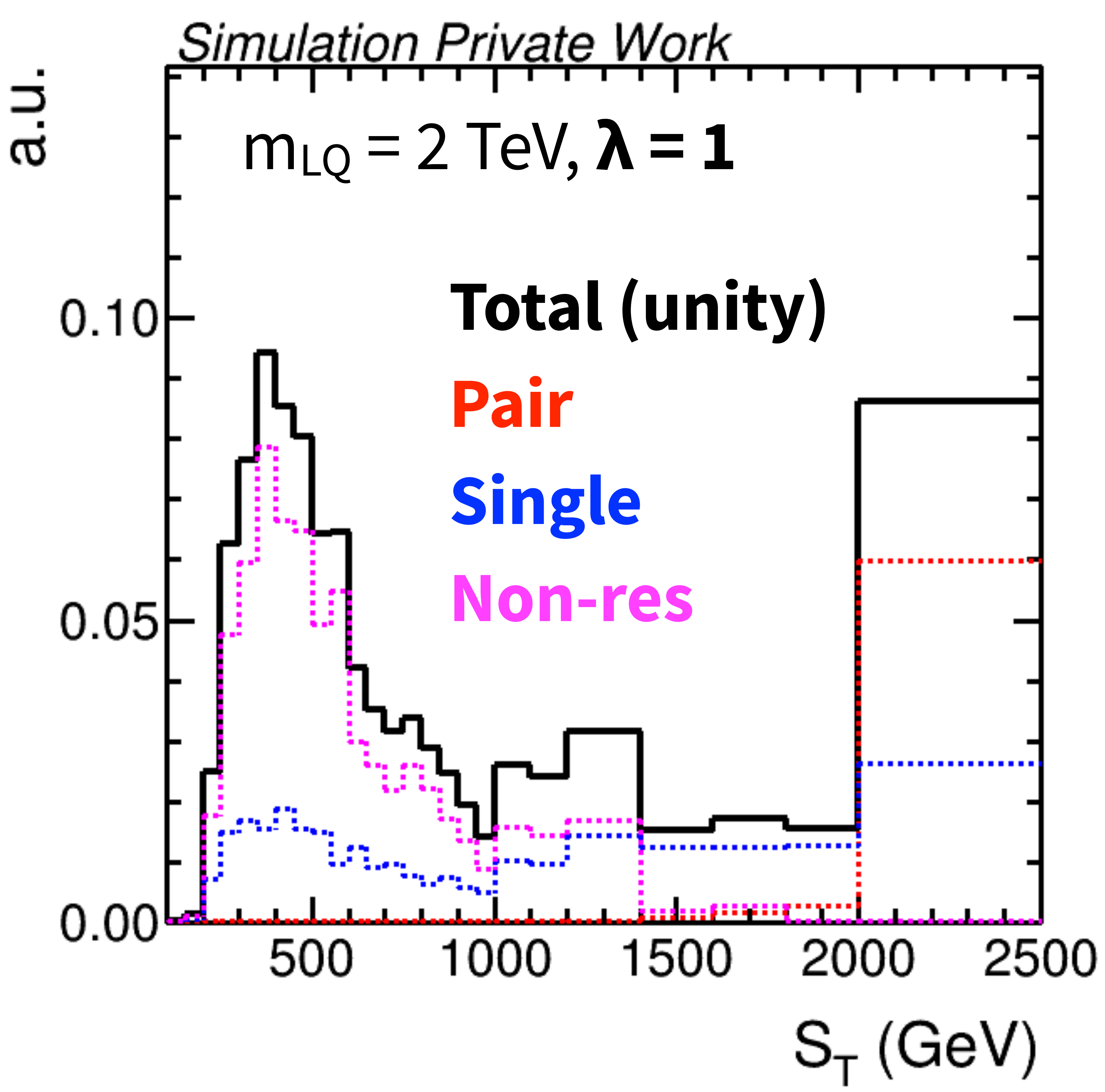

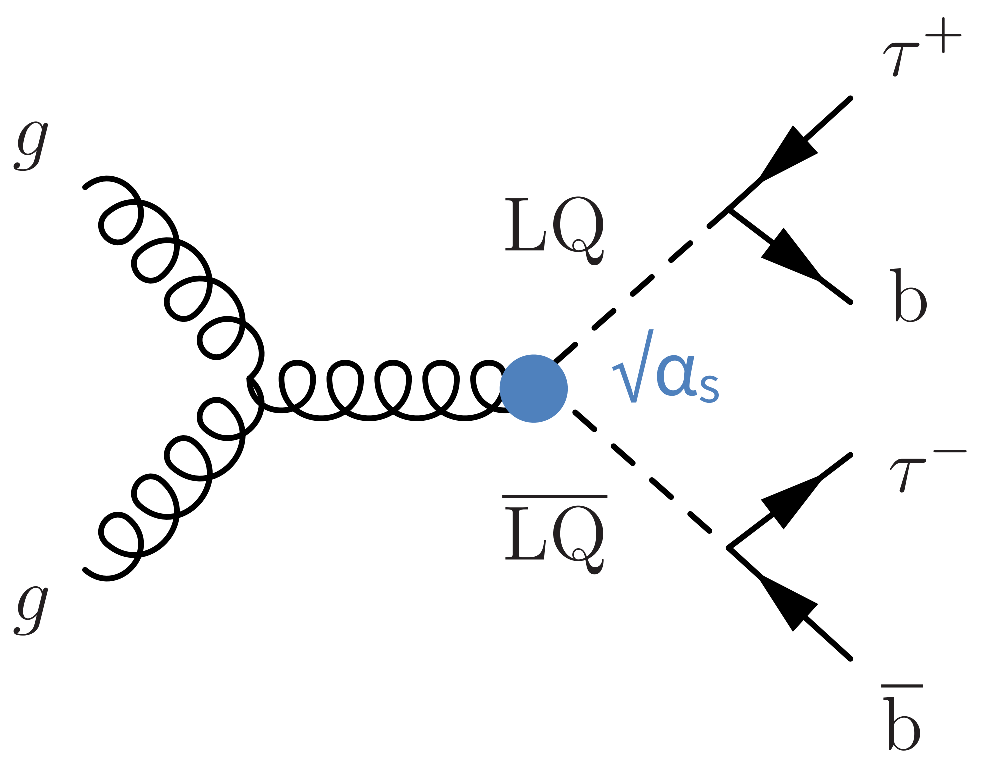

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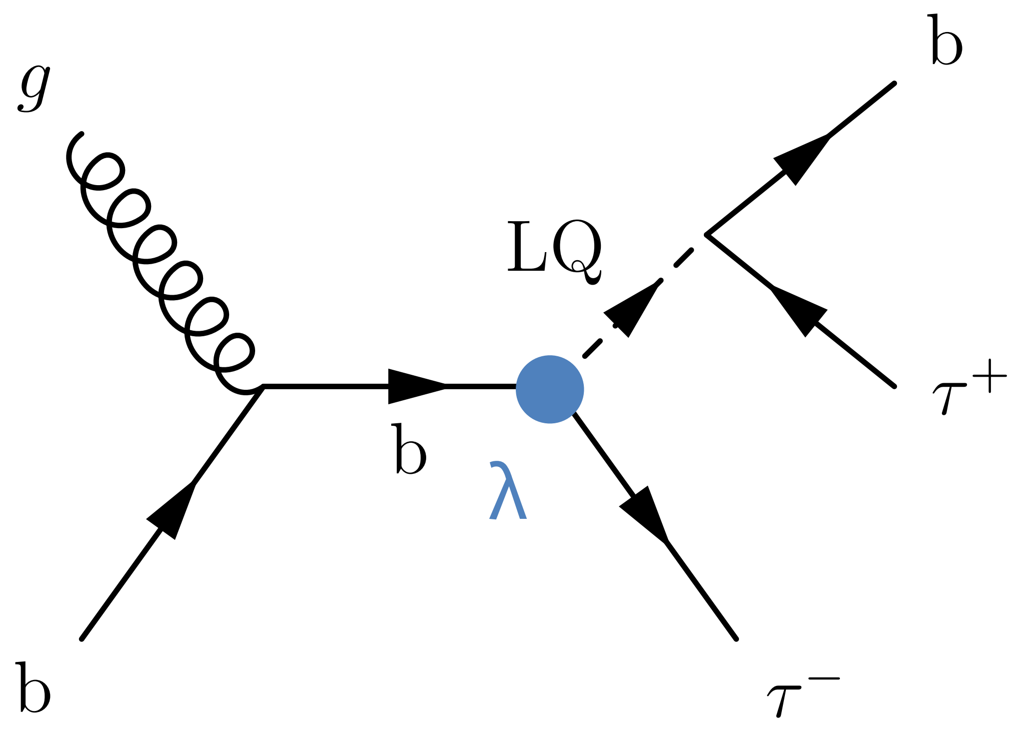
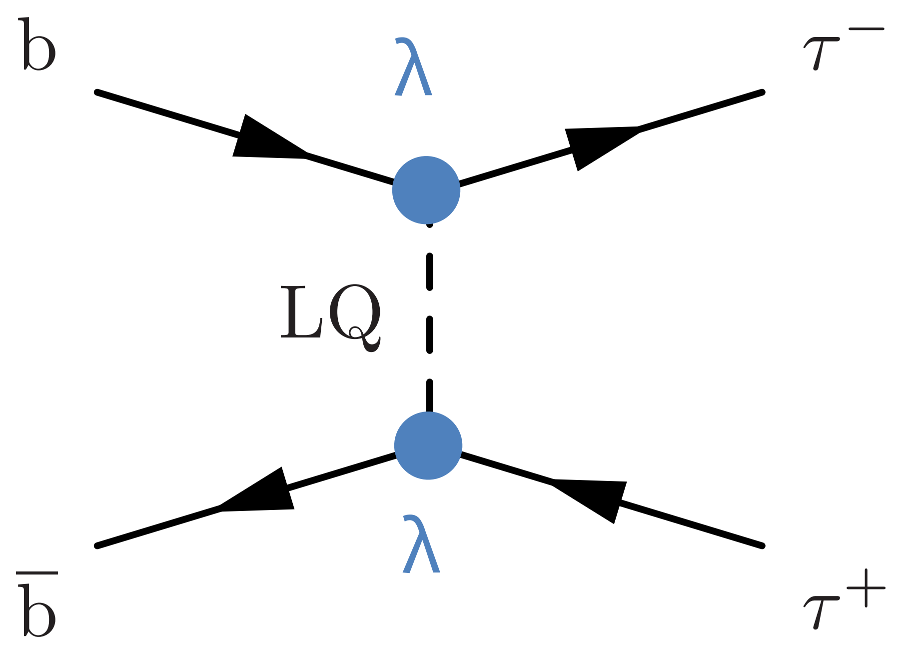


Single prod.



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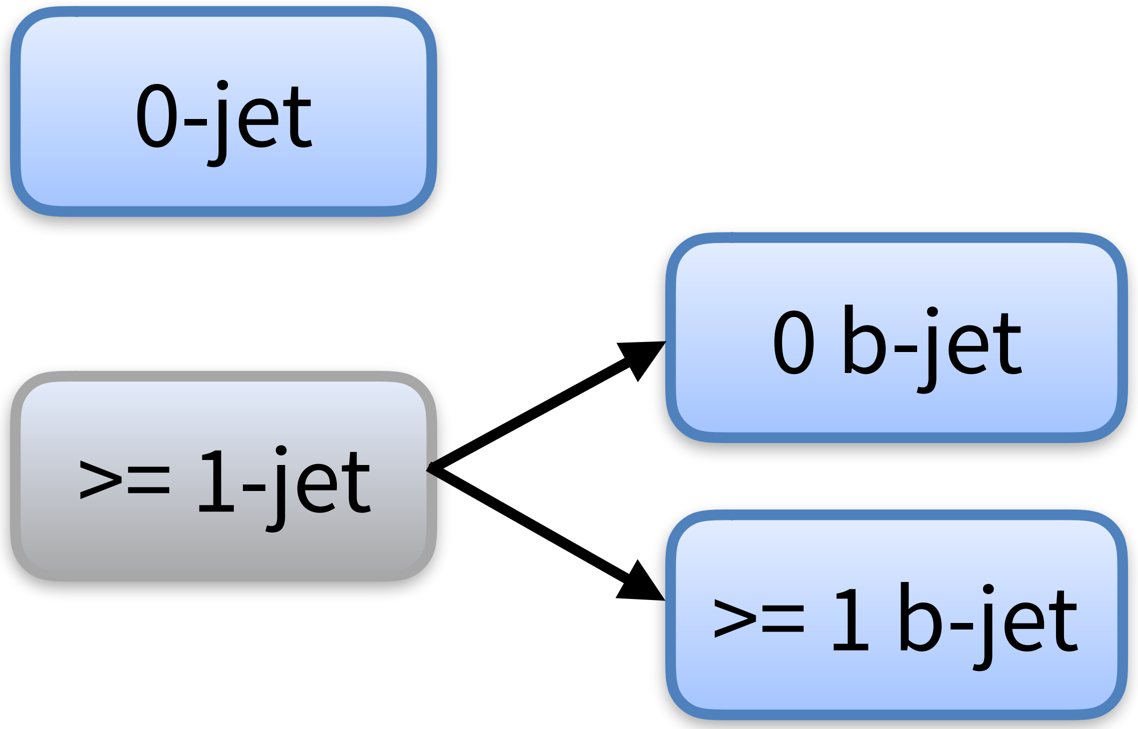

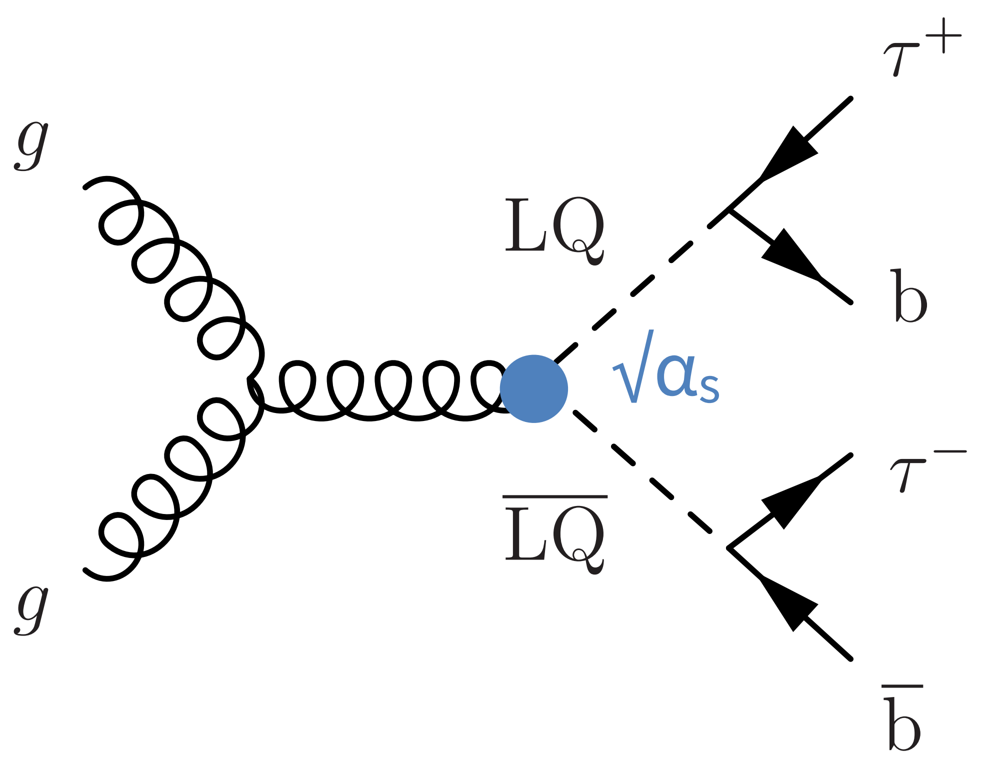

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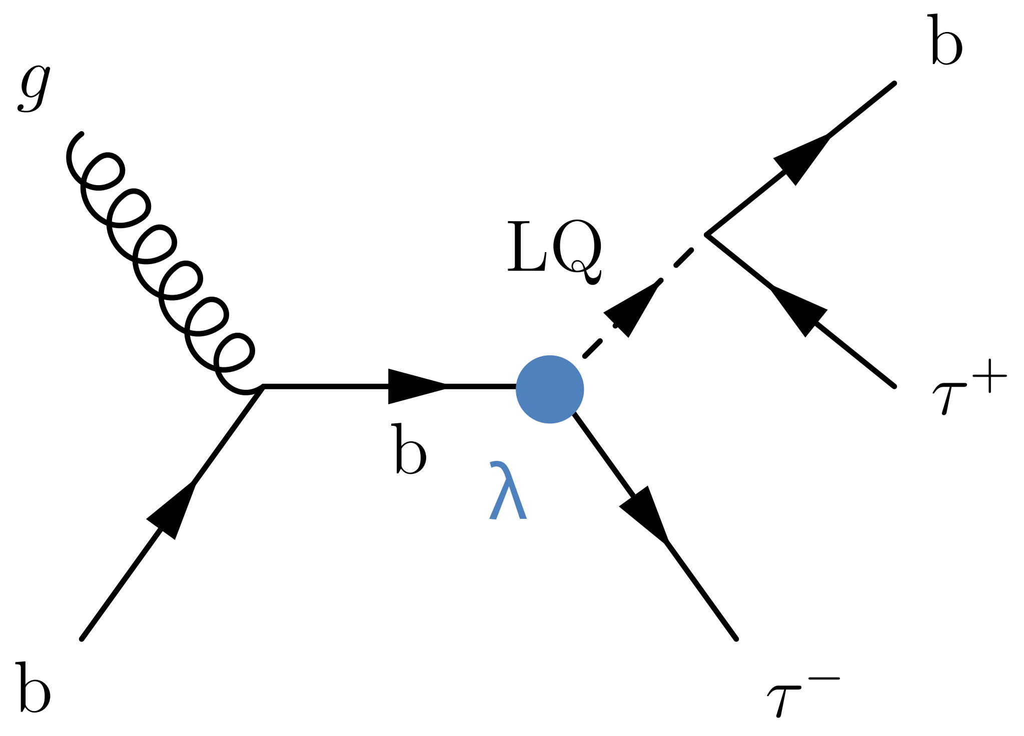

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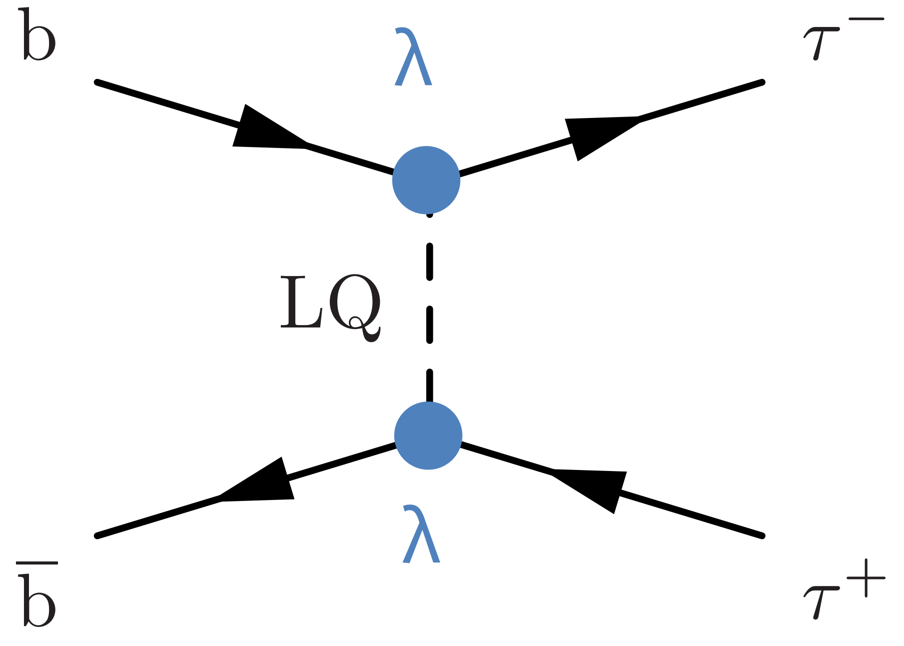
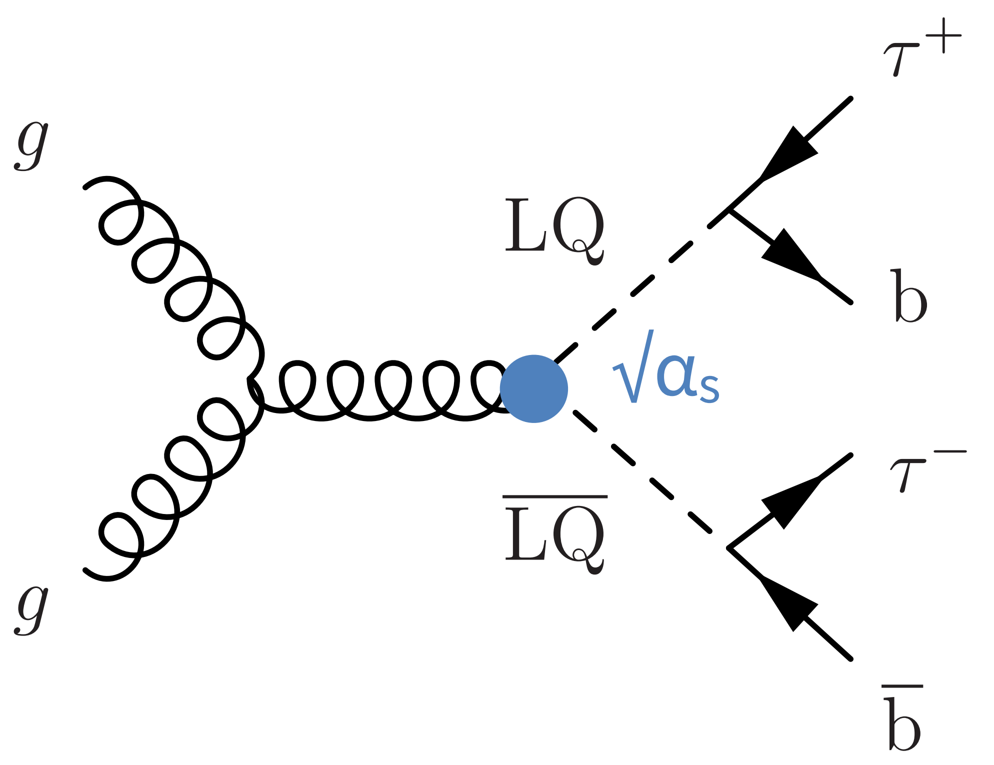


Non resonant



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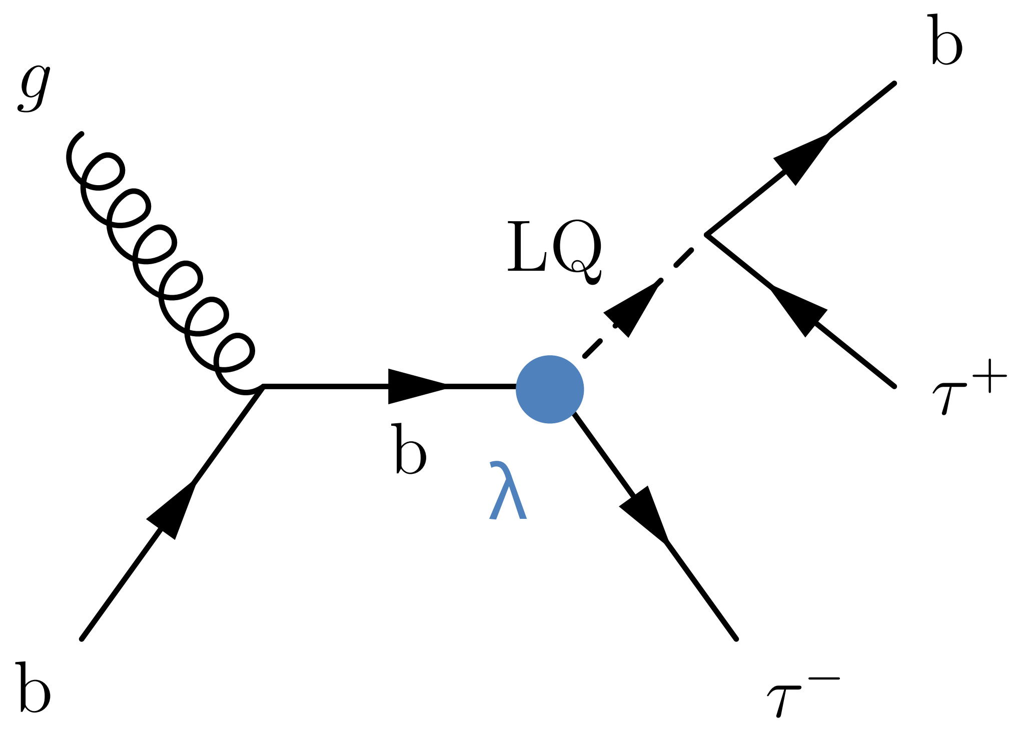
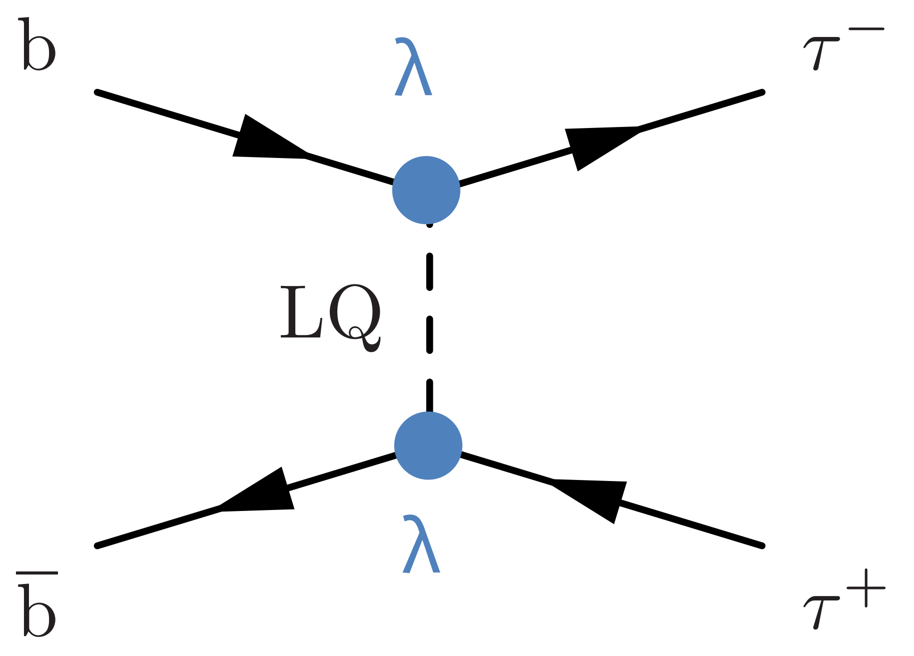


Single prod.



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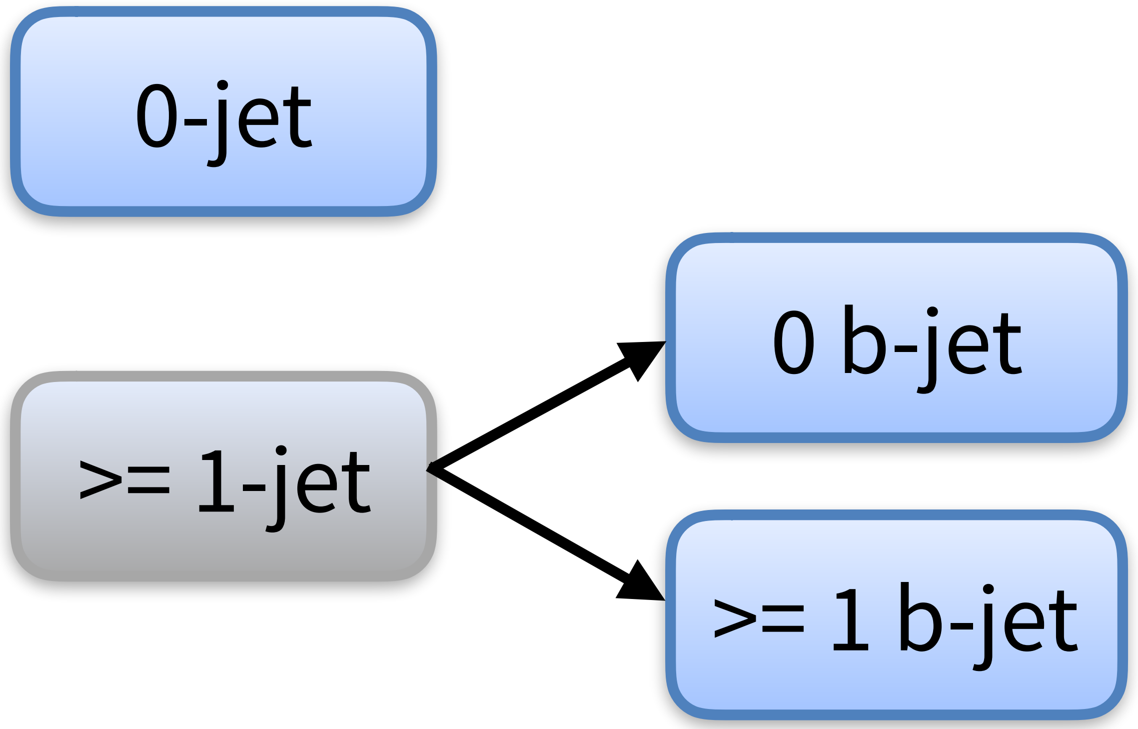

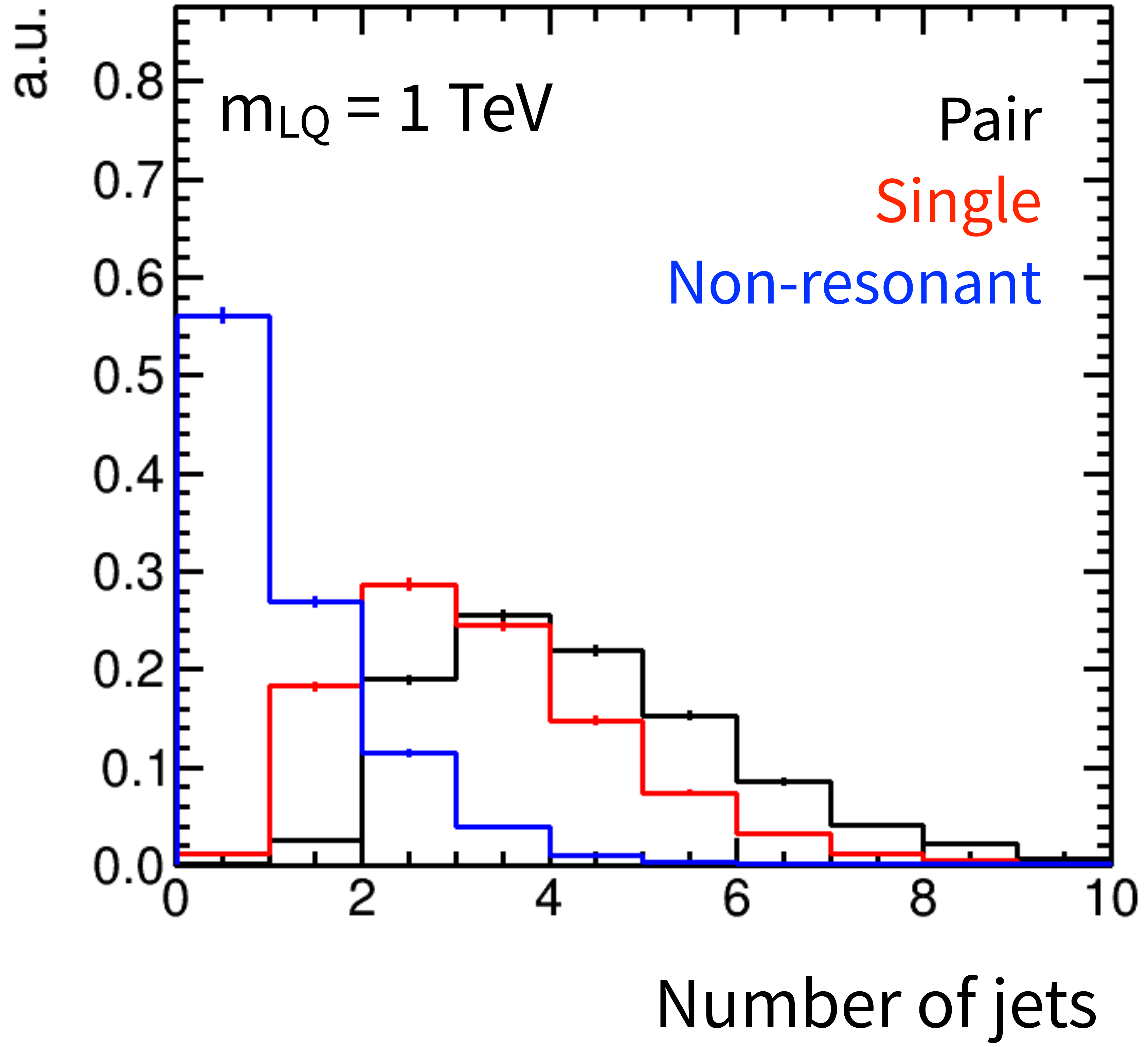

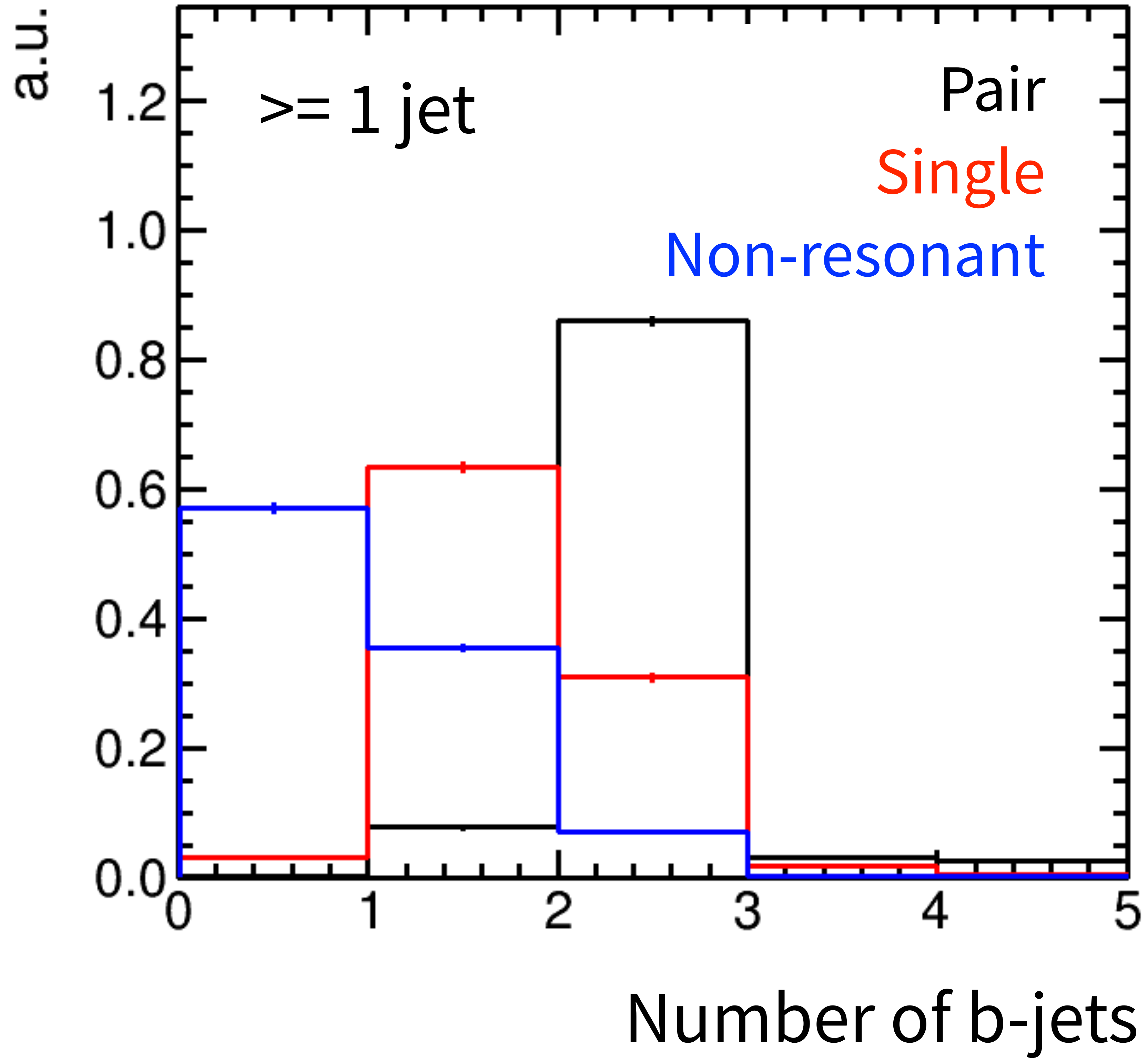

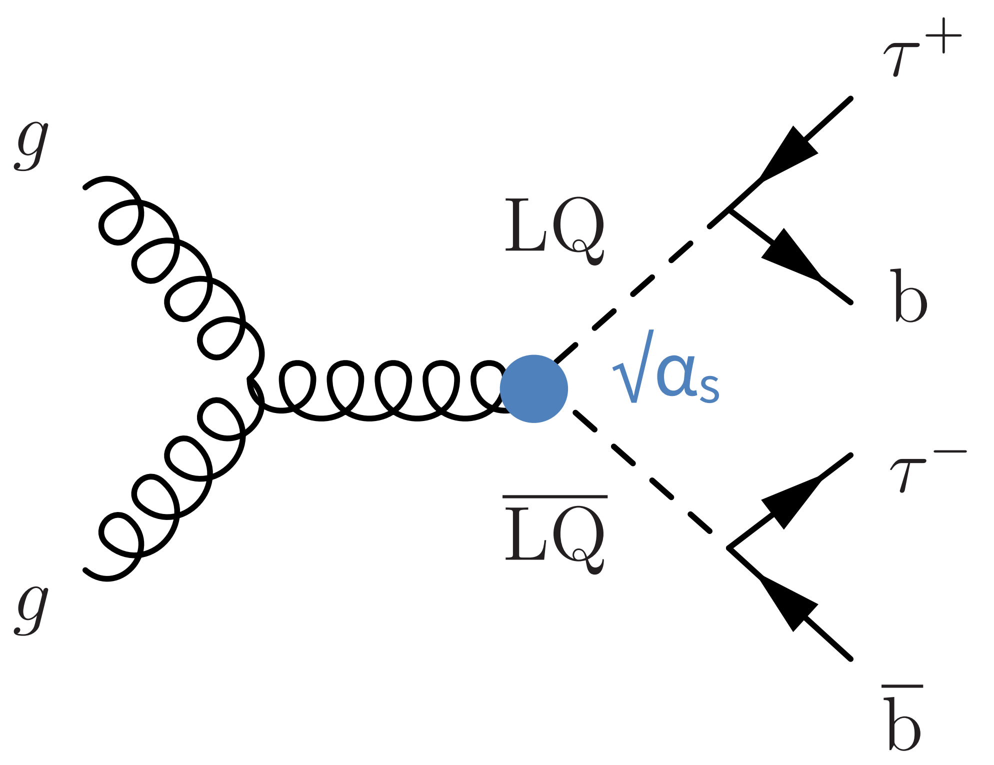

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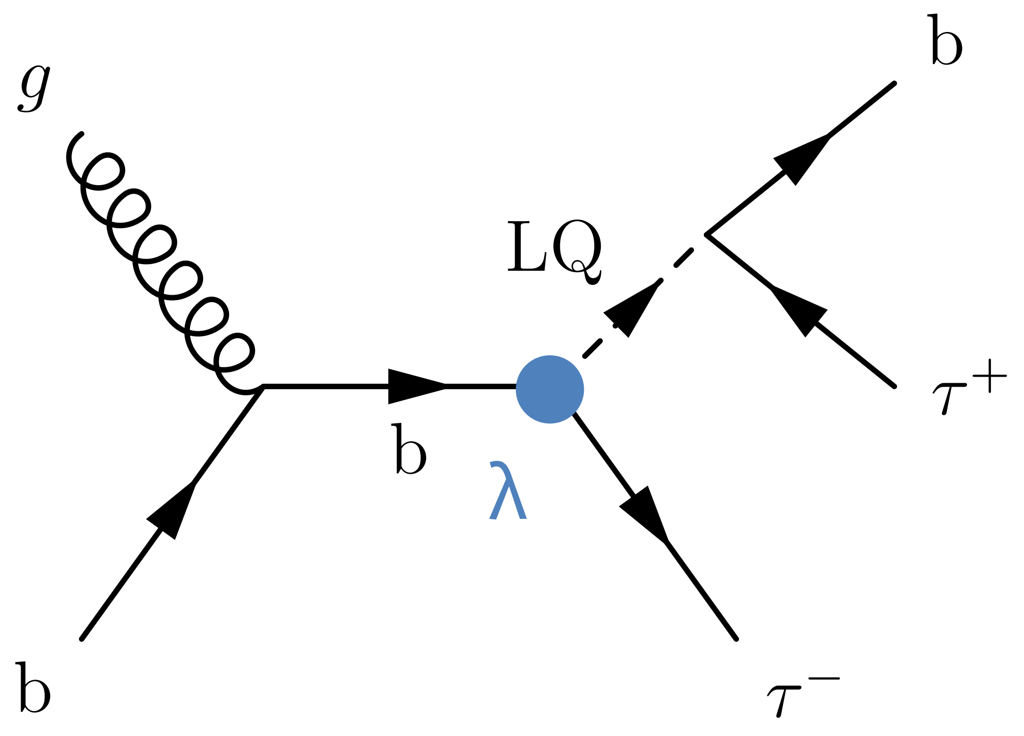

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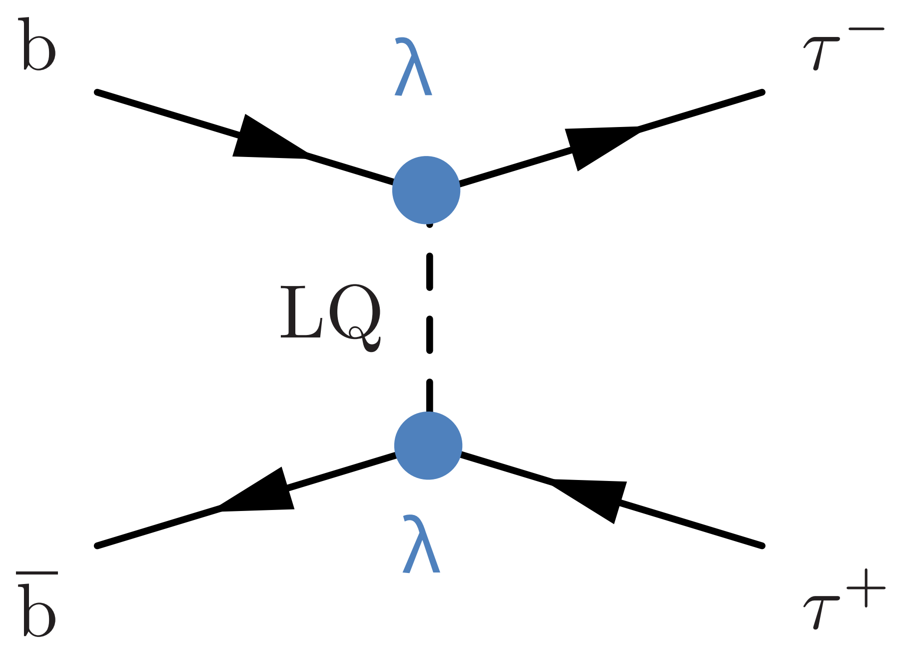

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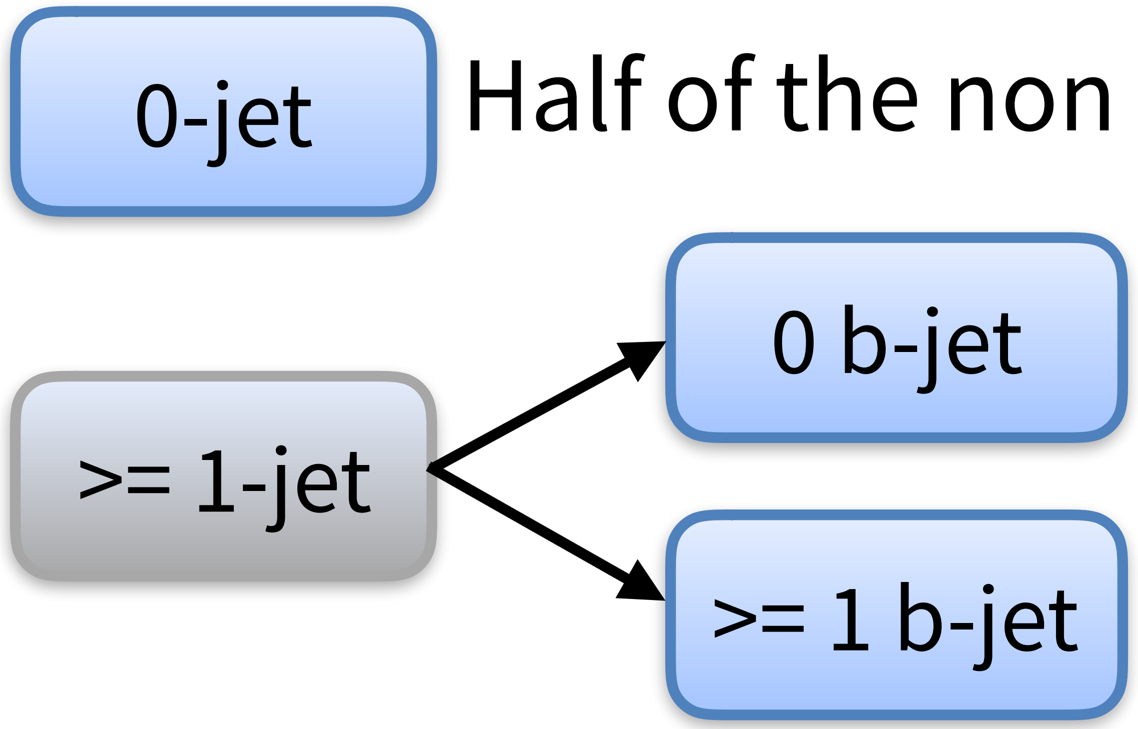
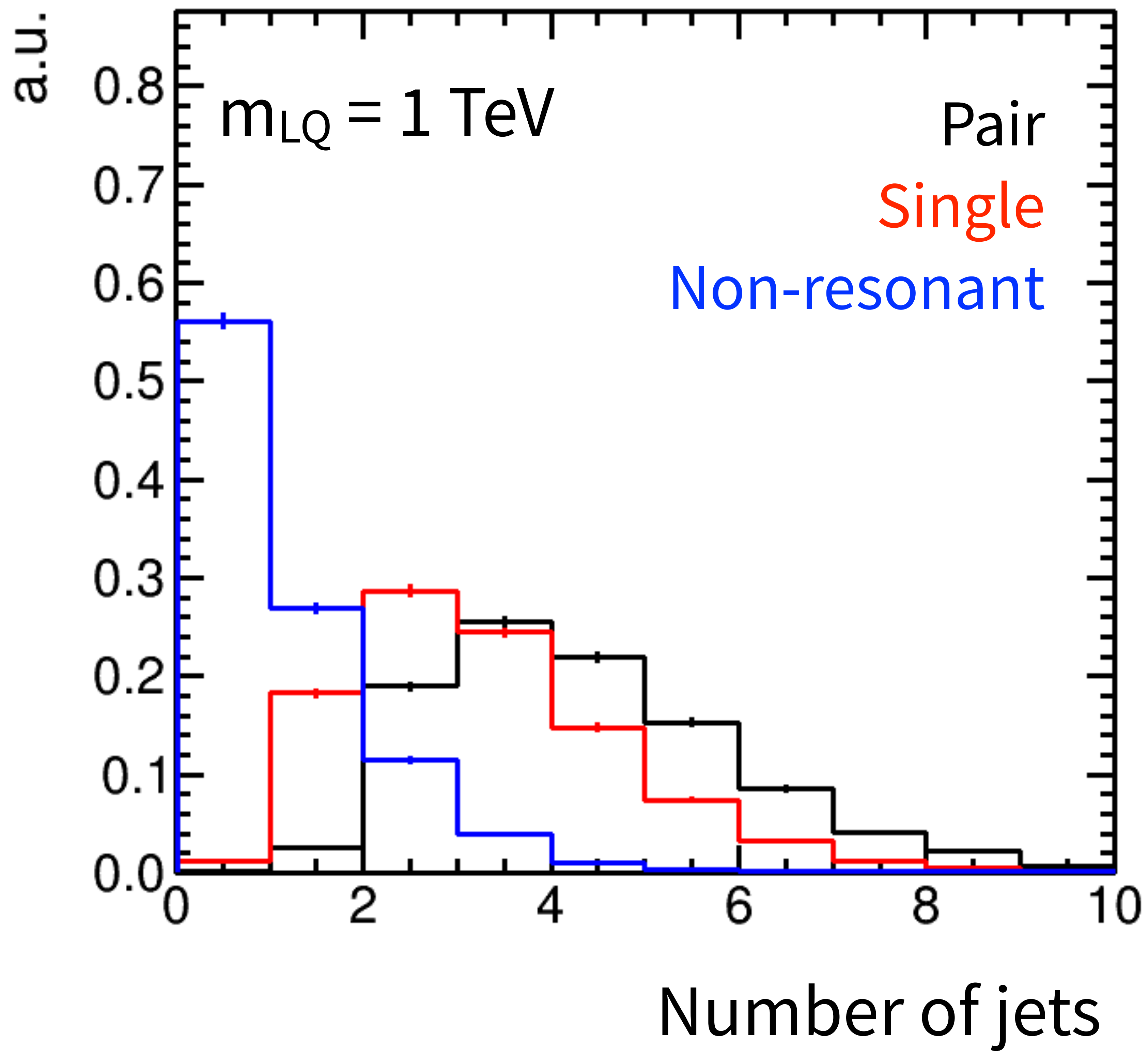
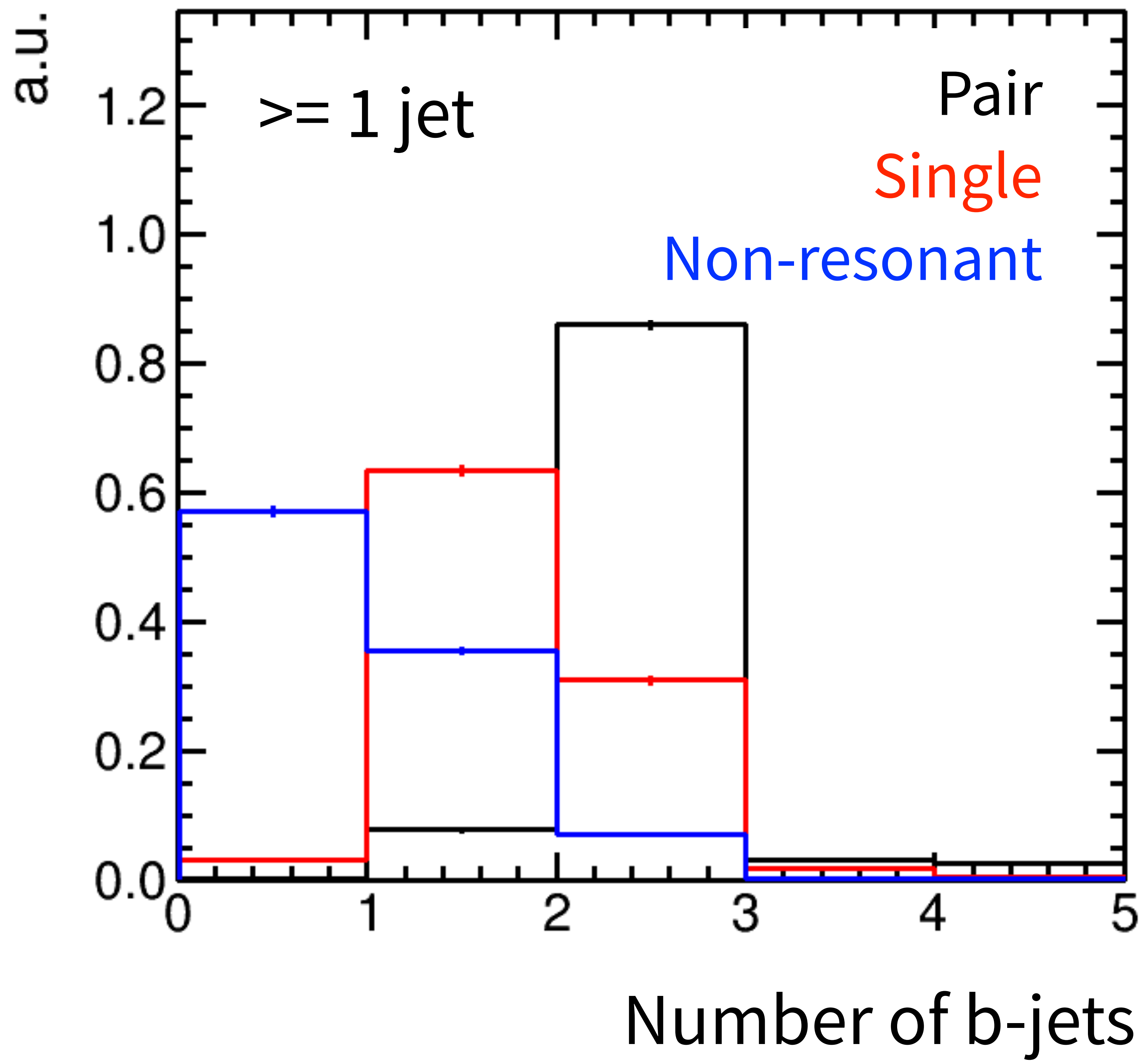
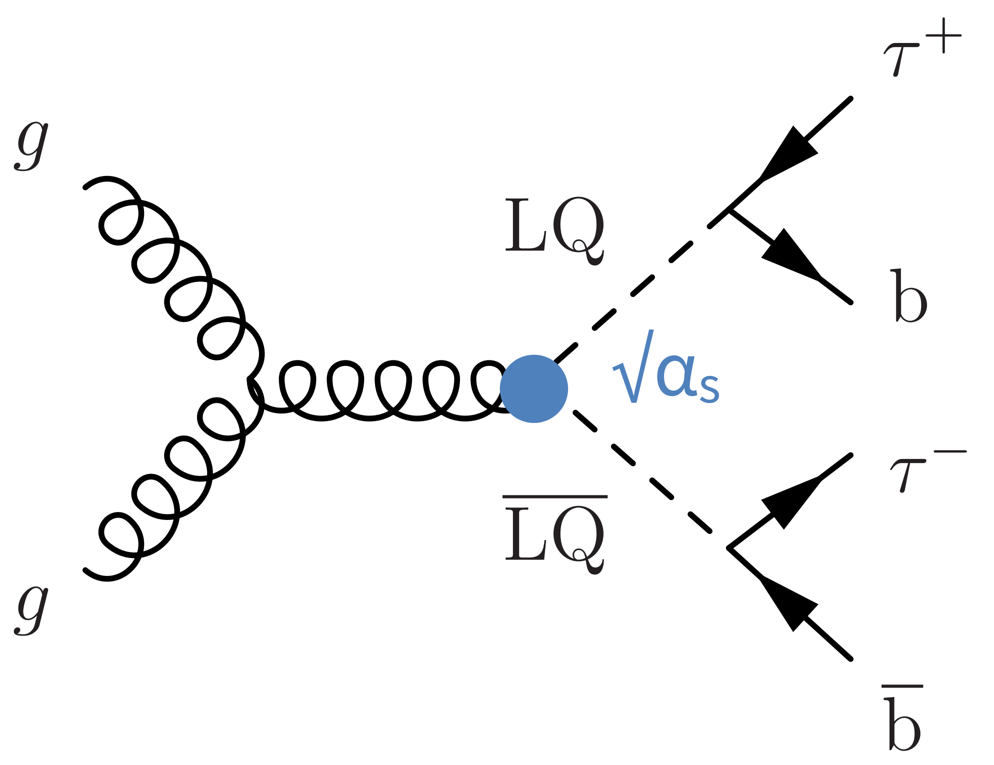


Half of the non resonant







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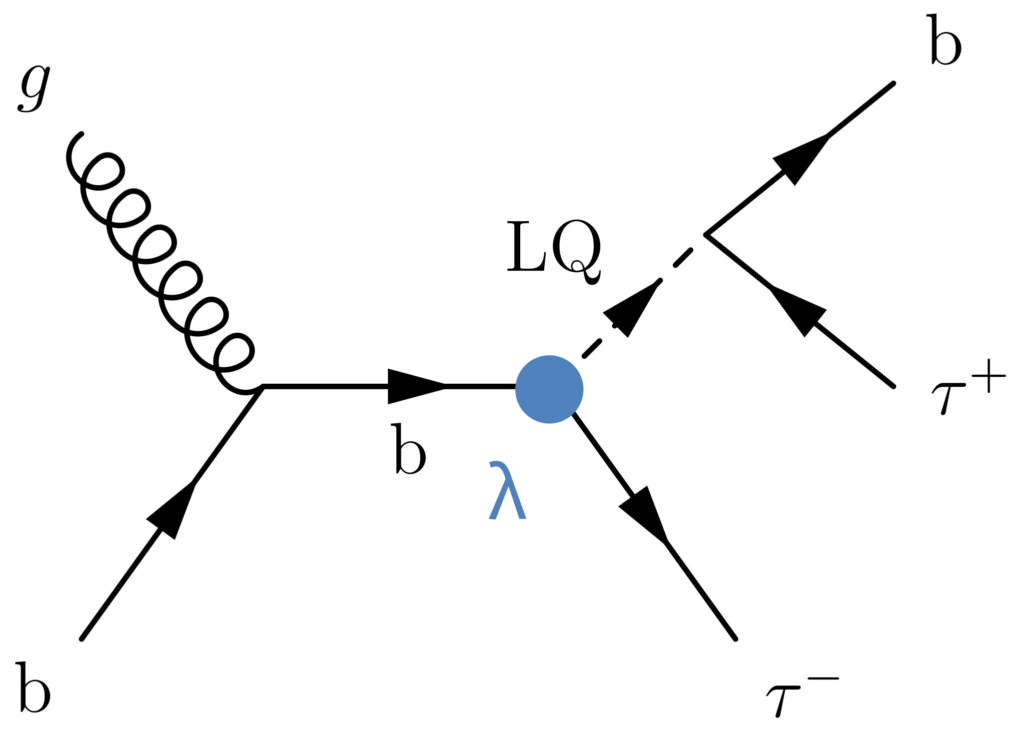
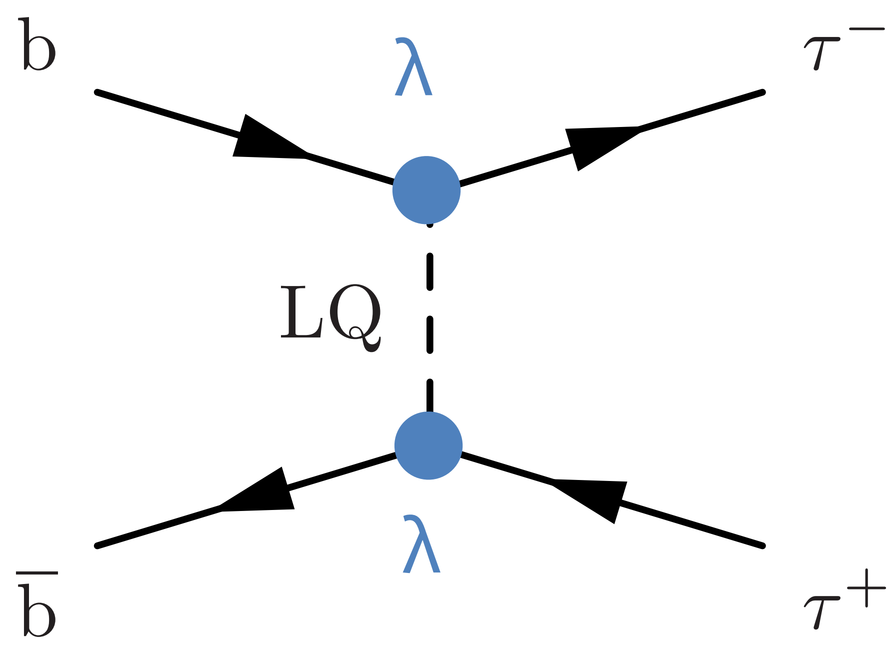


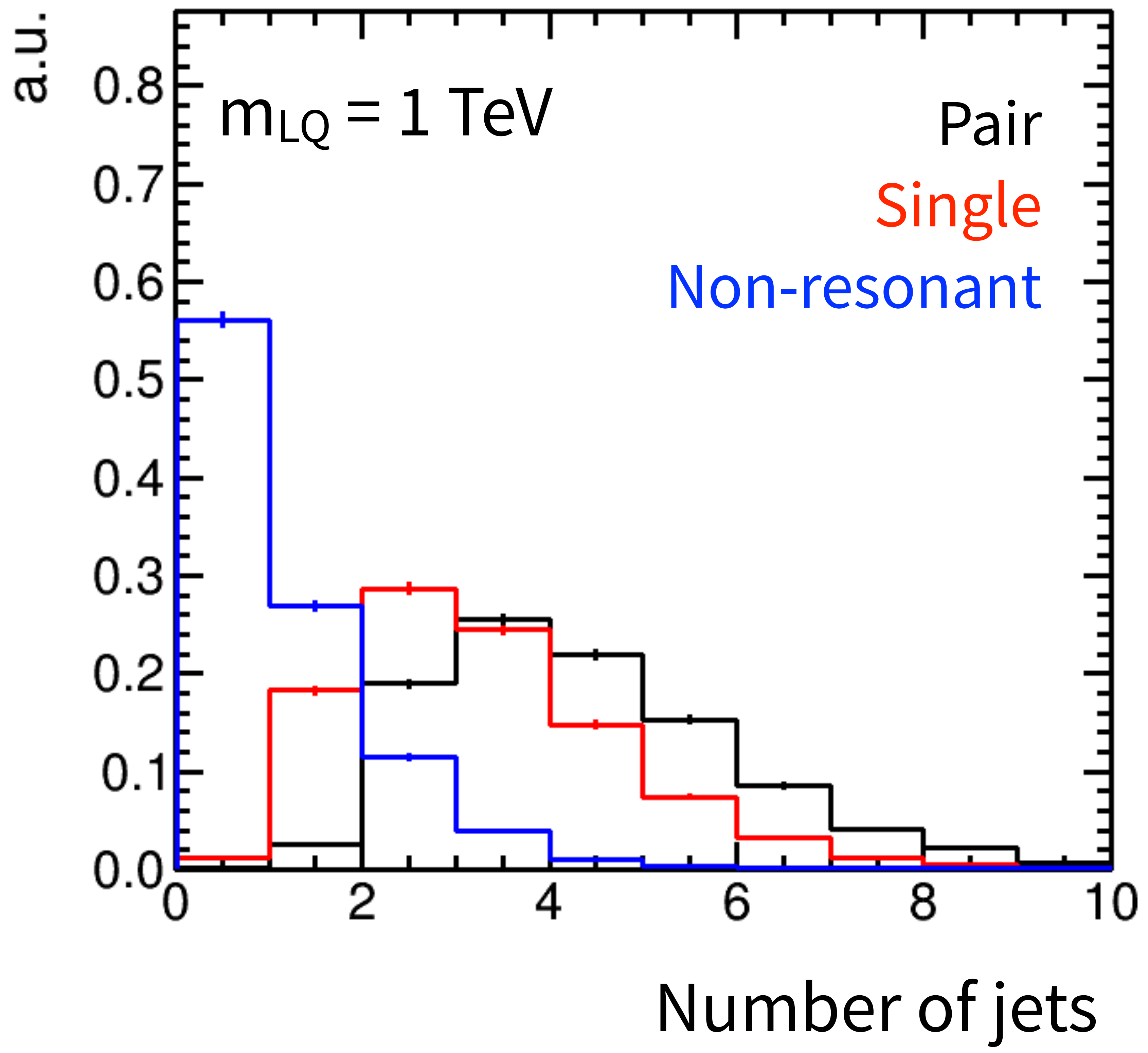
Single prod.

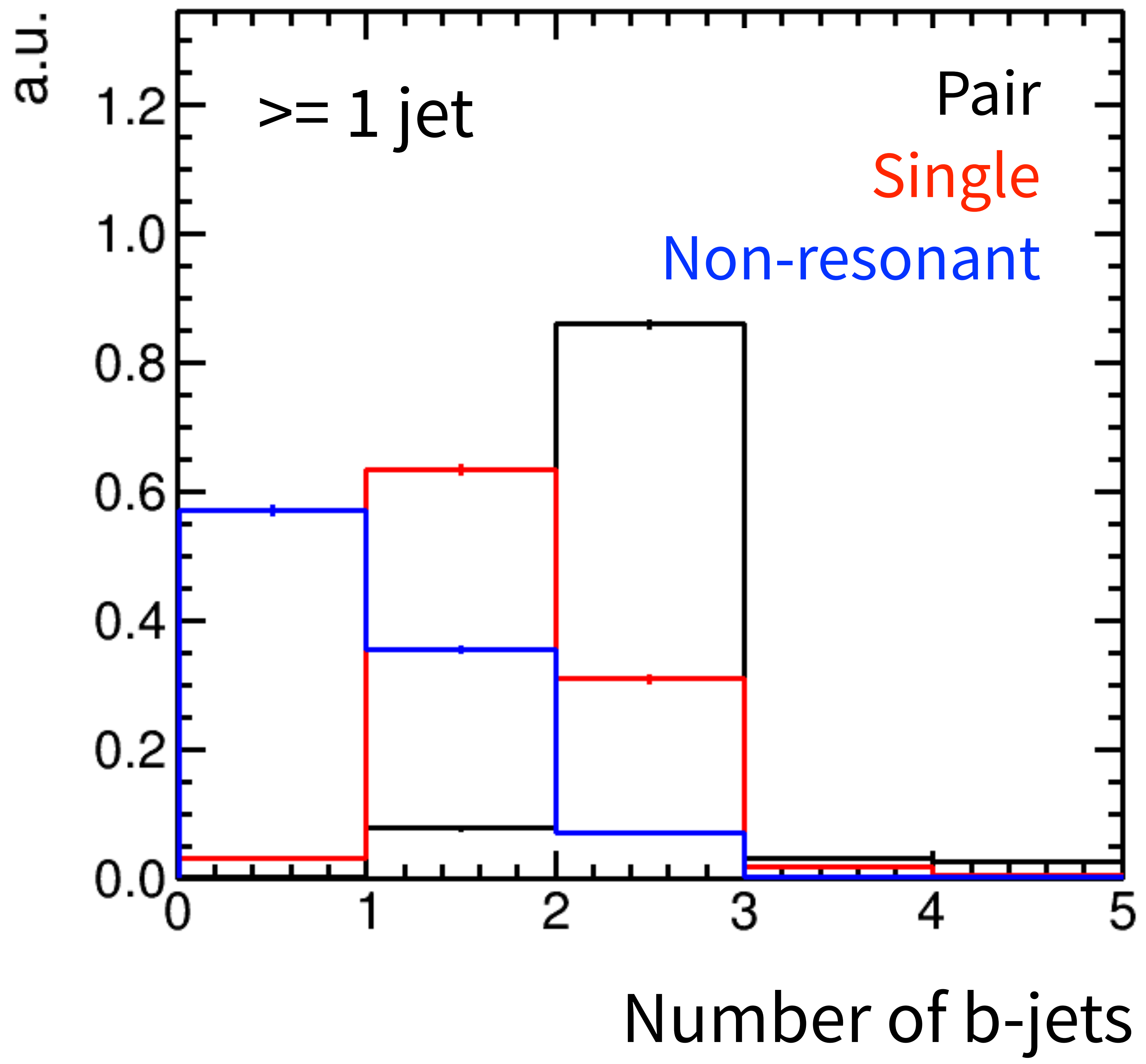


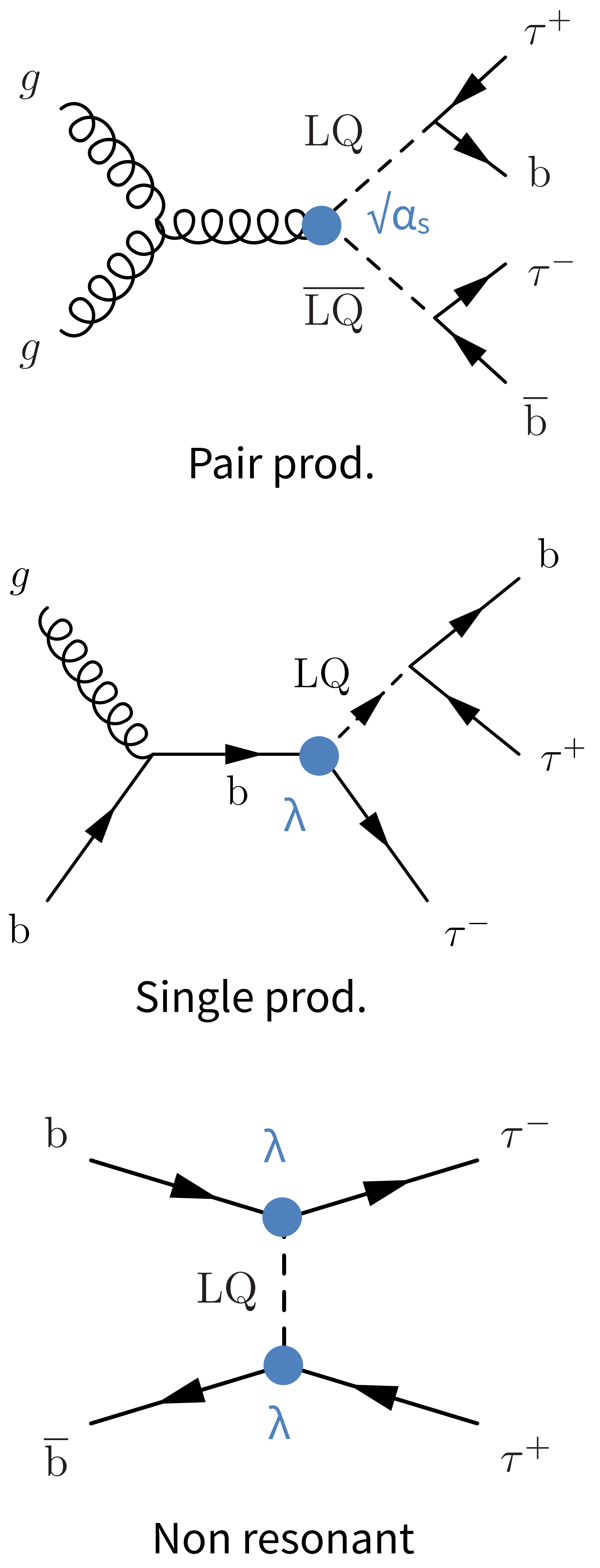
Non resonant

To maintain good sensitivity, we classify events based on the number of reconstructed (b-)jets → effectively increase S/B

- **0-jet**: Half of the non resonant
- **>= 1-jet**
  - **0 b-jet**: Another half of the non resonant
  - **>= 1 b-jet**







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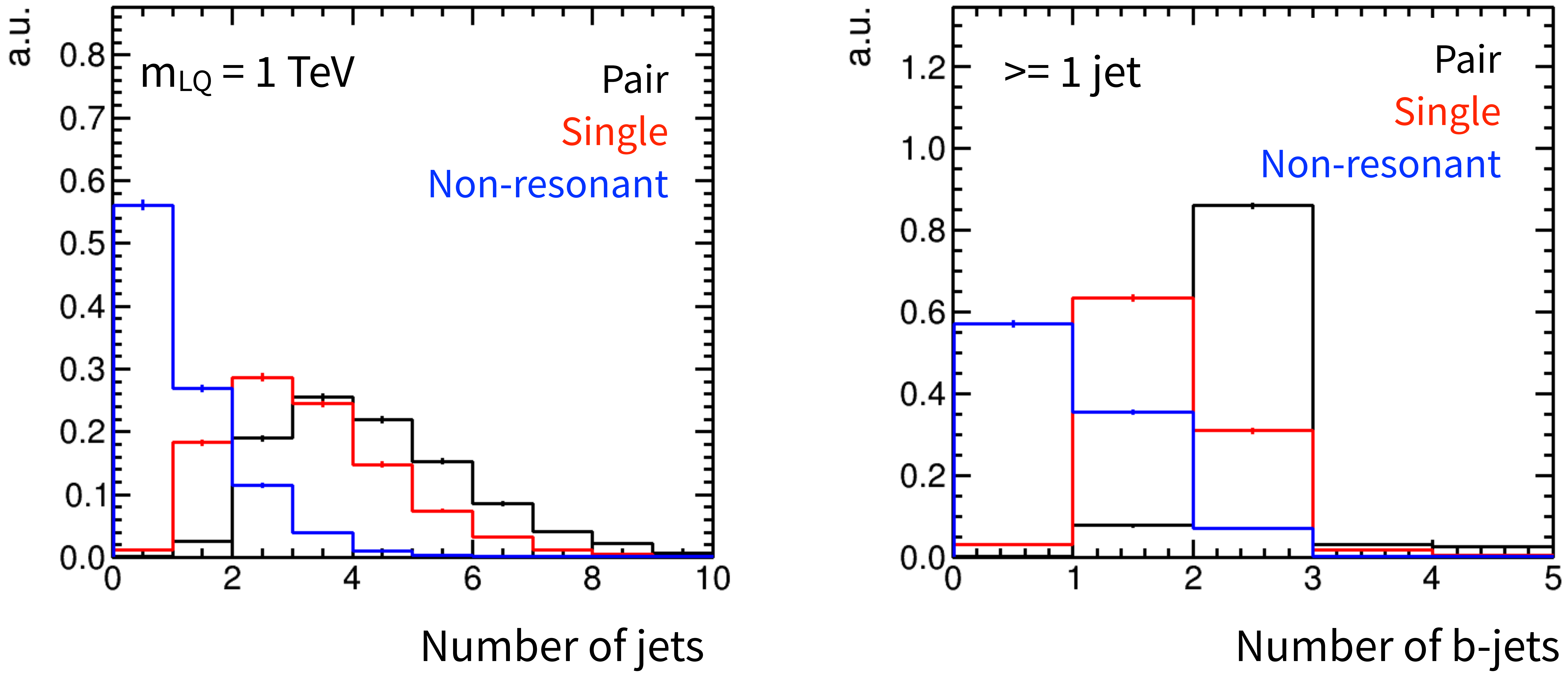
0-jet — Half of the non resonant

>= 1-jet → 0 b-jet — Another half of the non resonant

>= 1-jet → >= 1 b-jet — Single + Pair



Analysis Flow

[Ex: for 0 b-jet category, because we see excess!]

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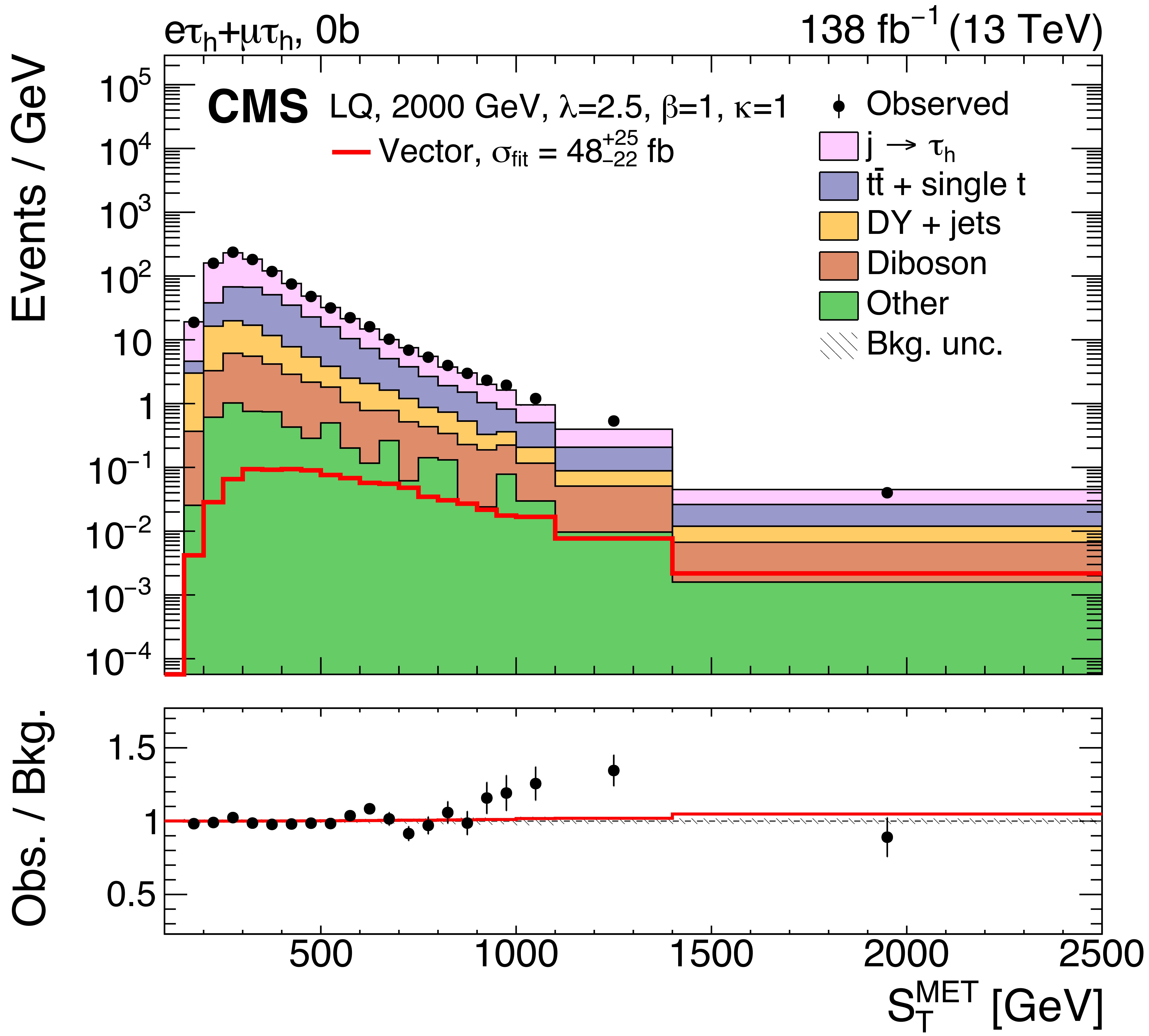

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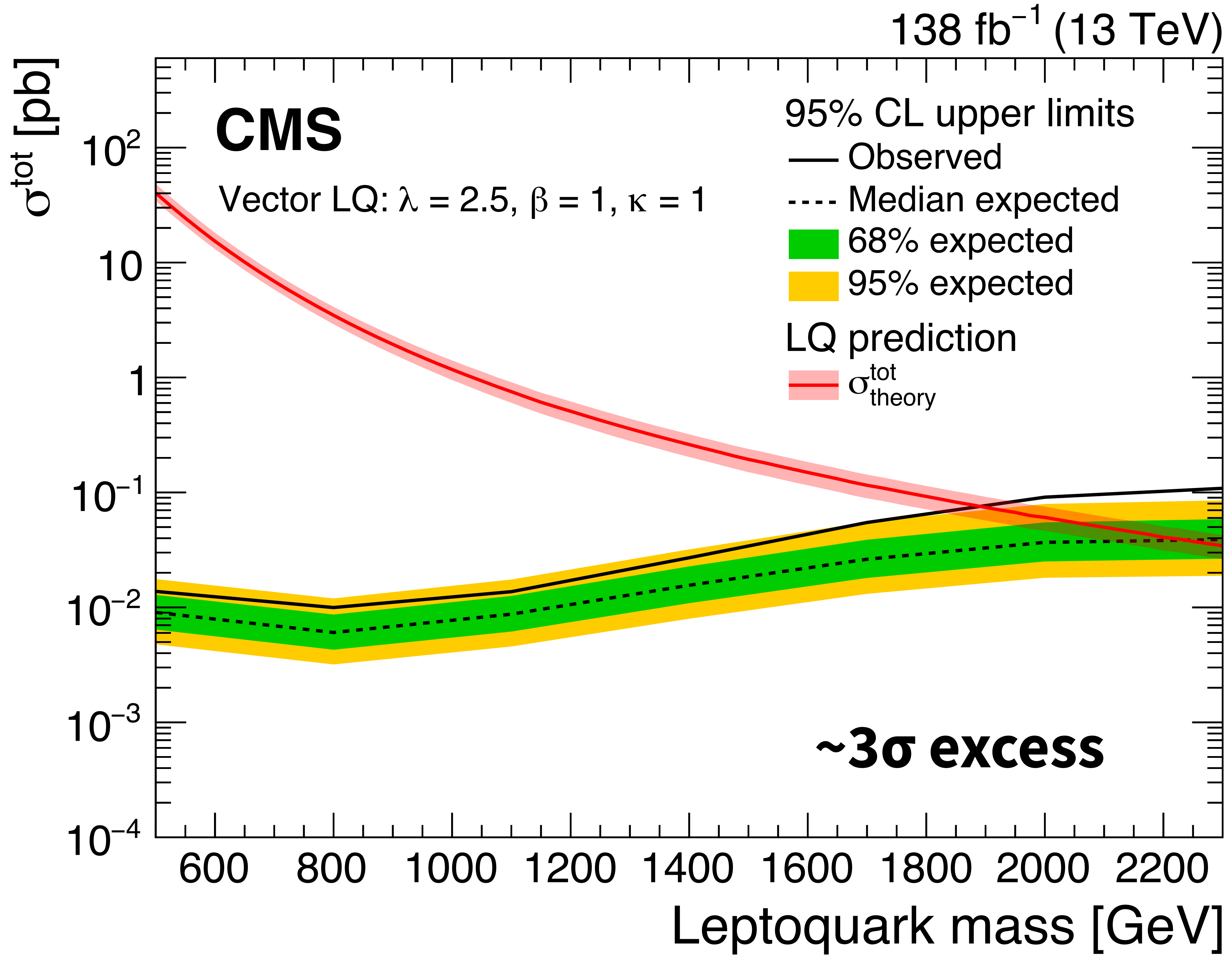

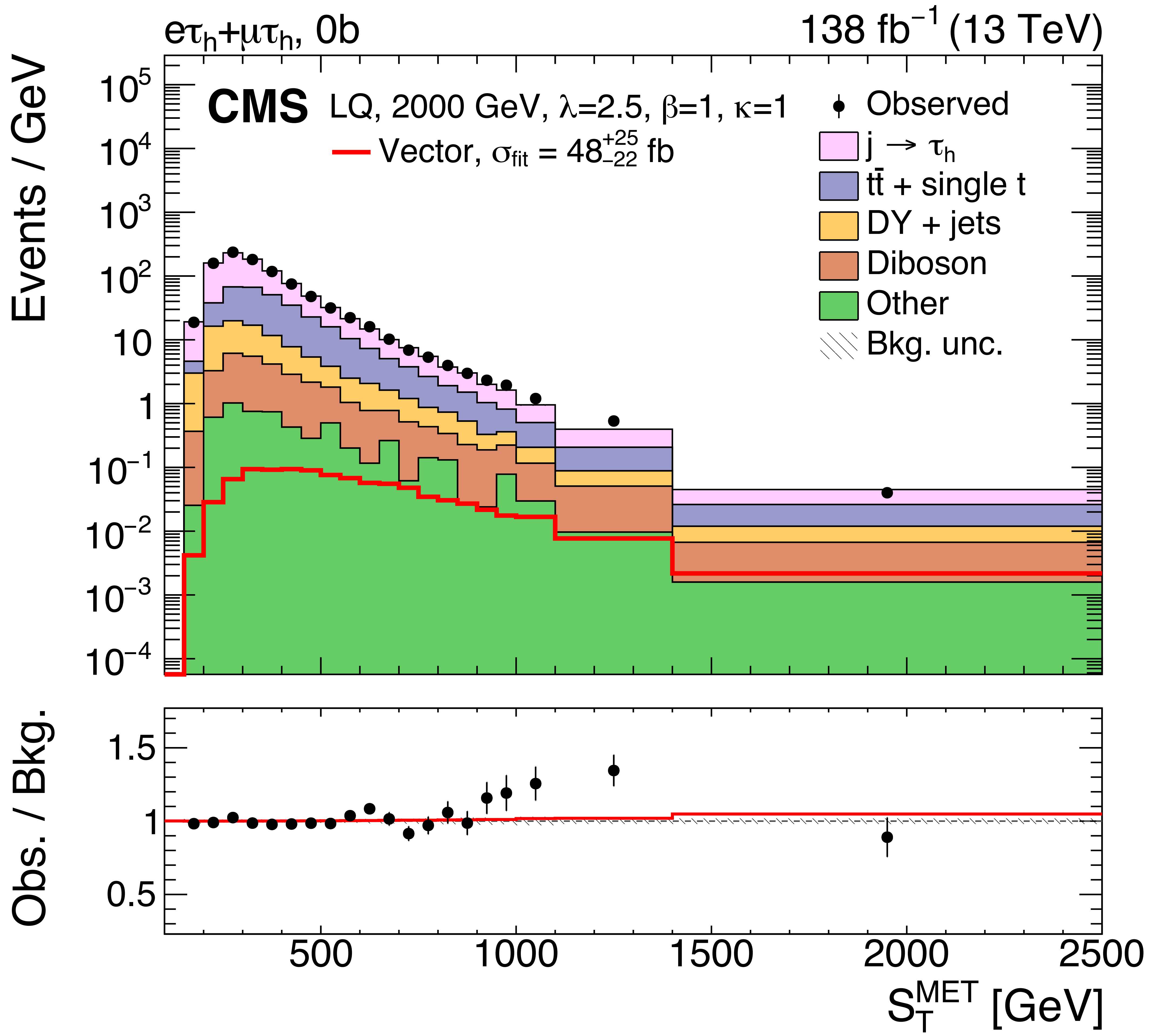

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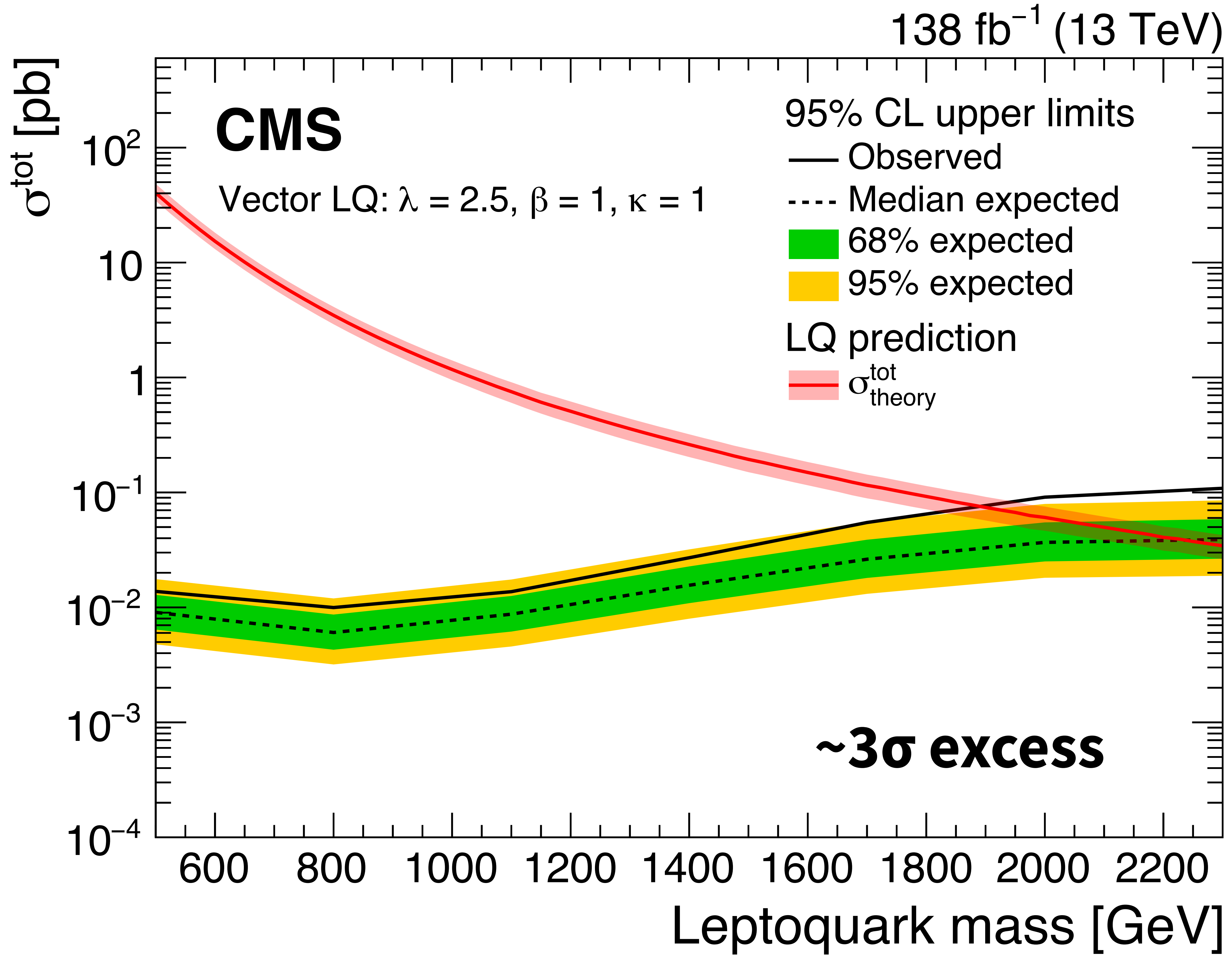

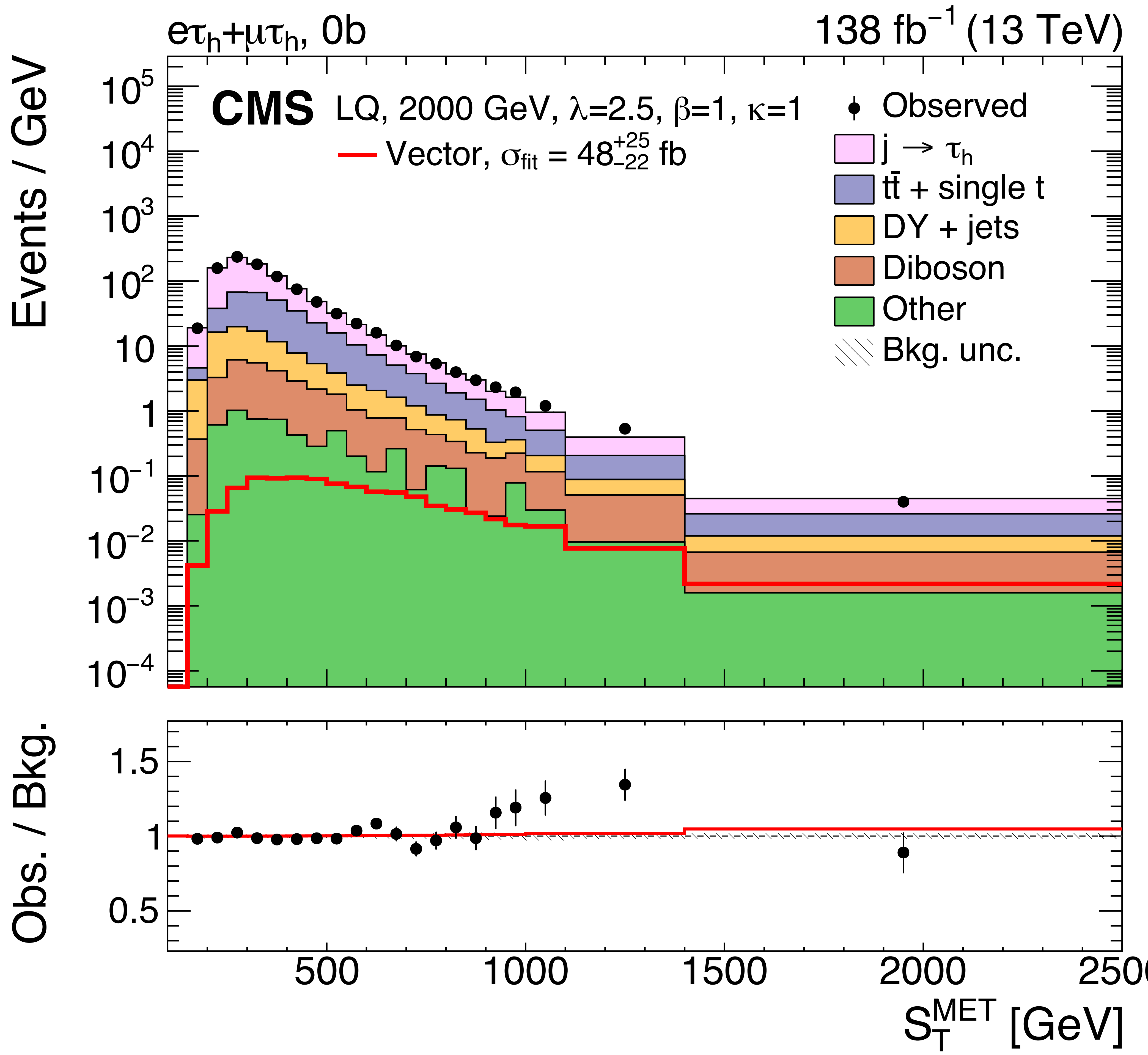

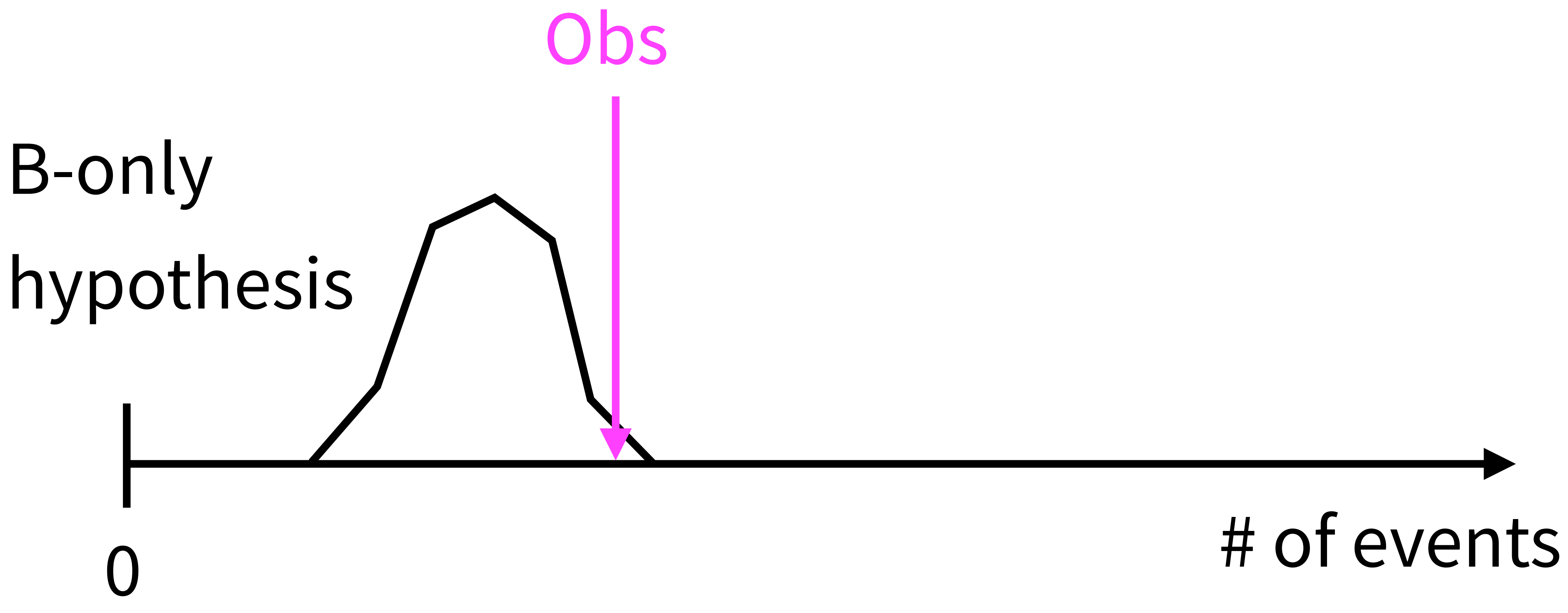

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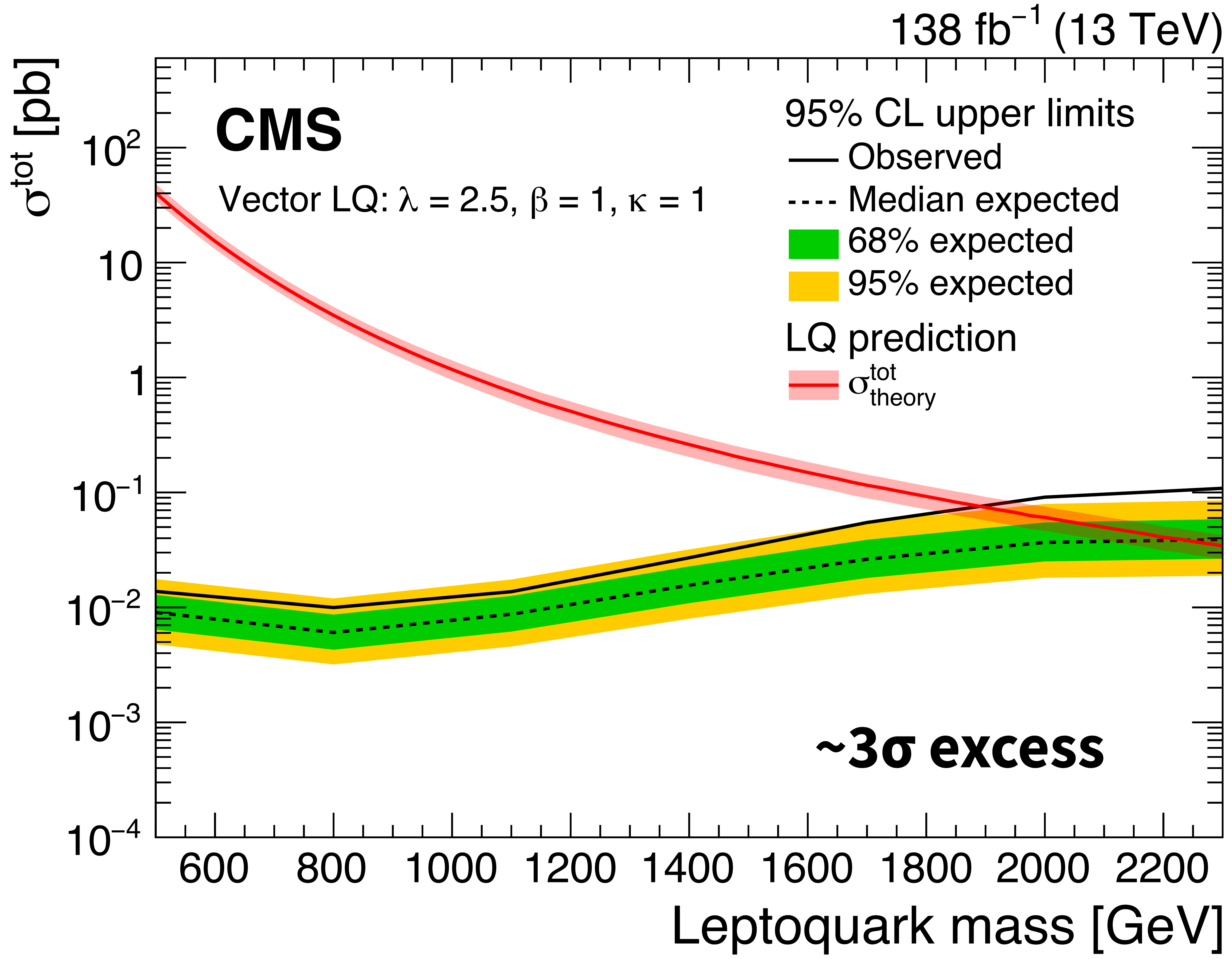

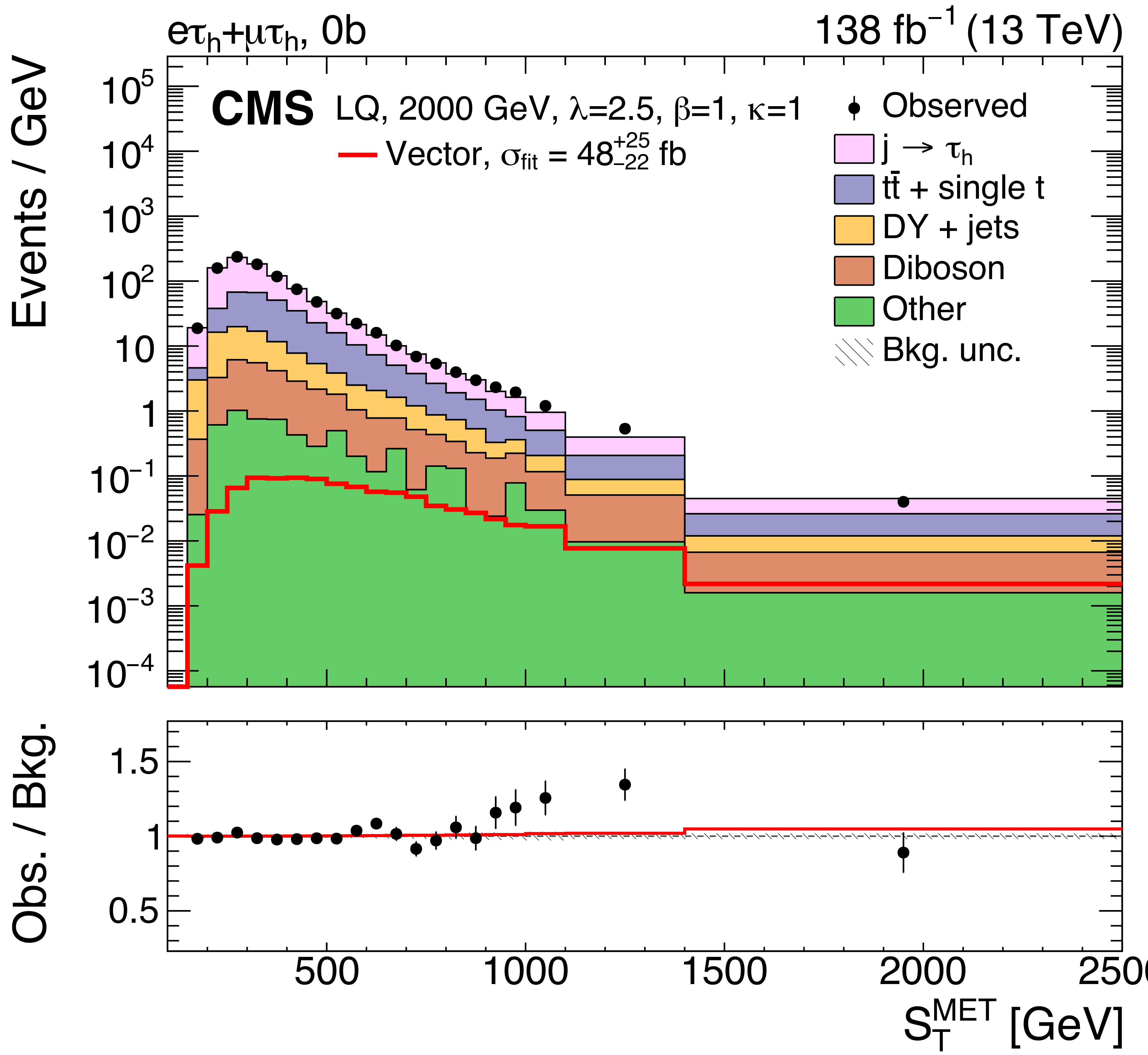

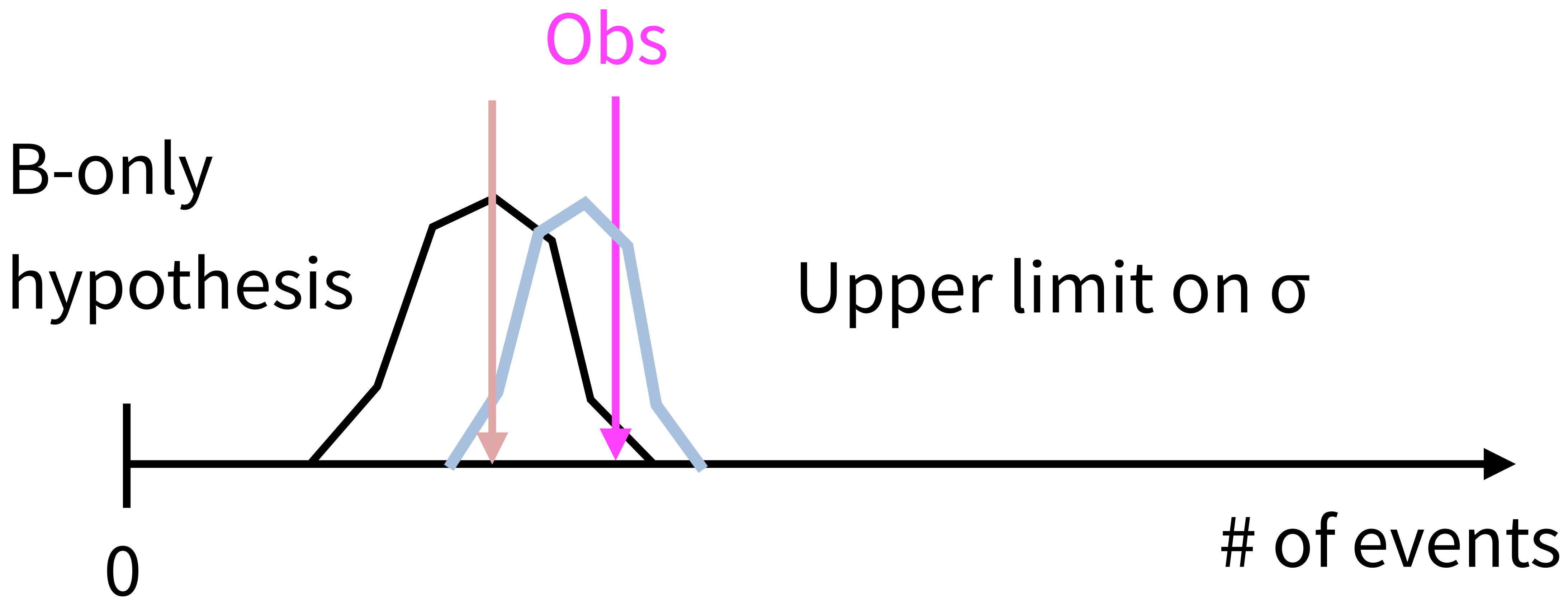

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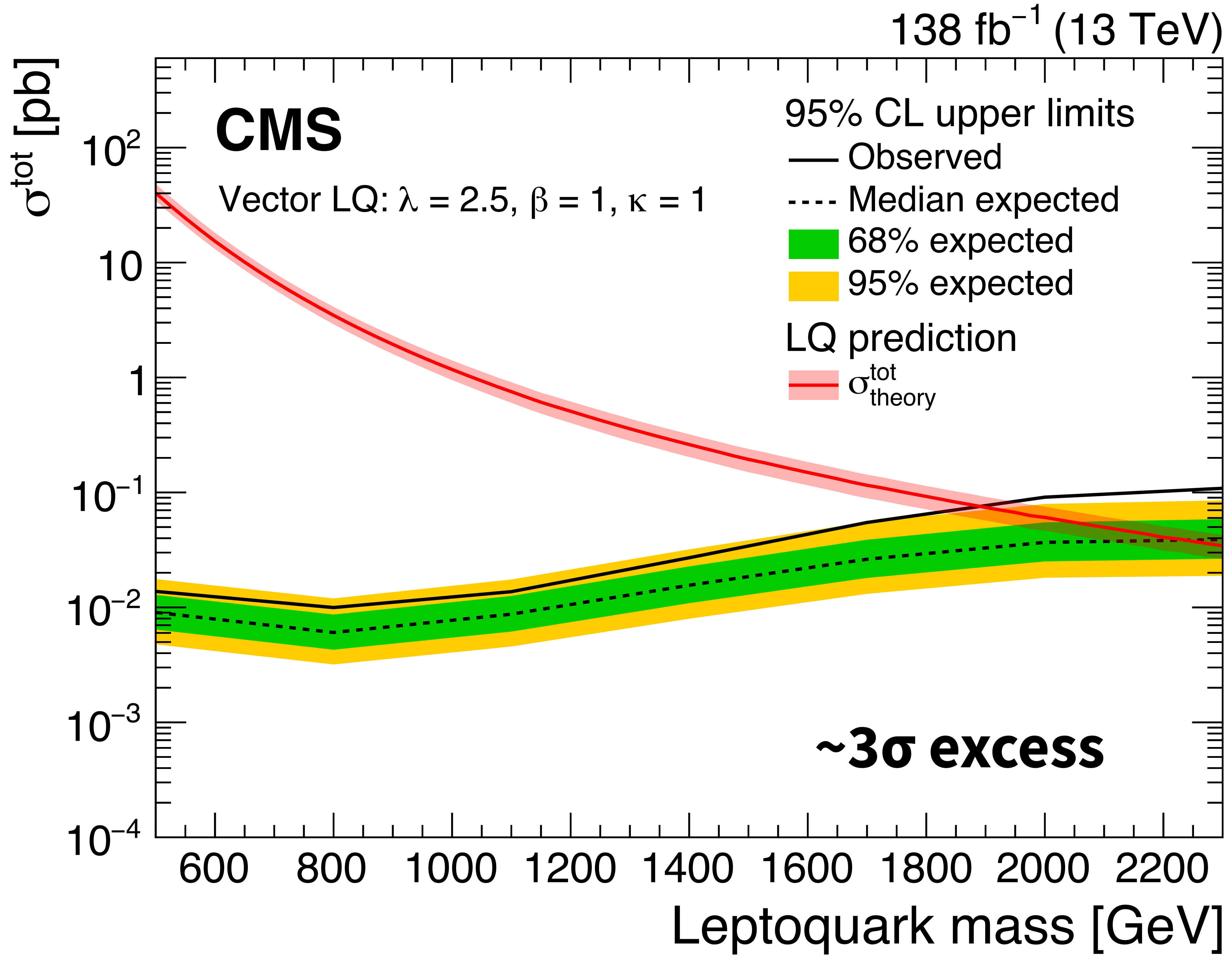
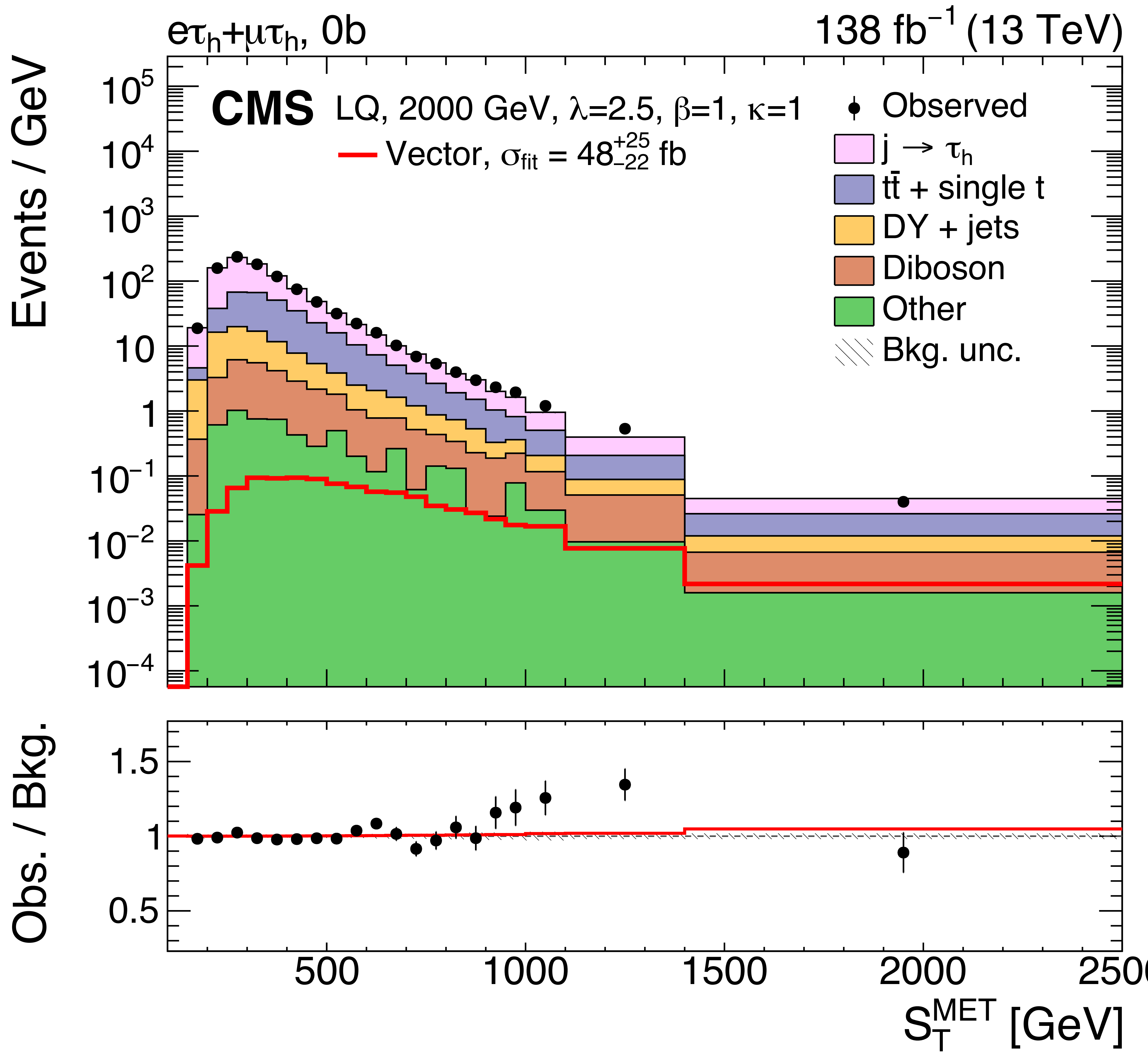
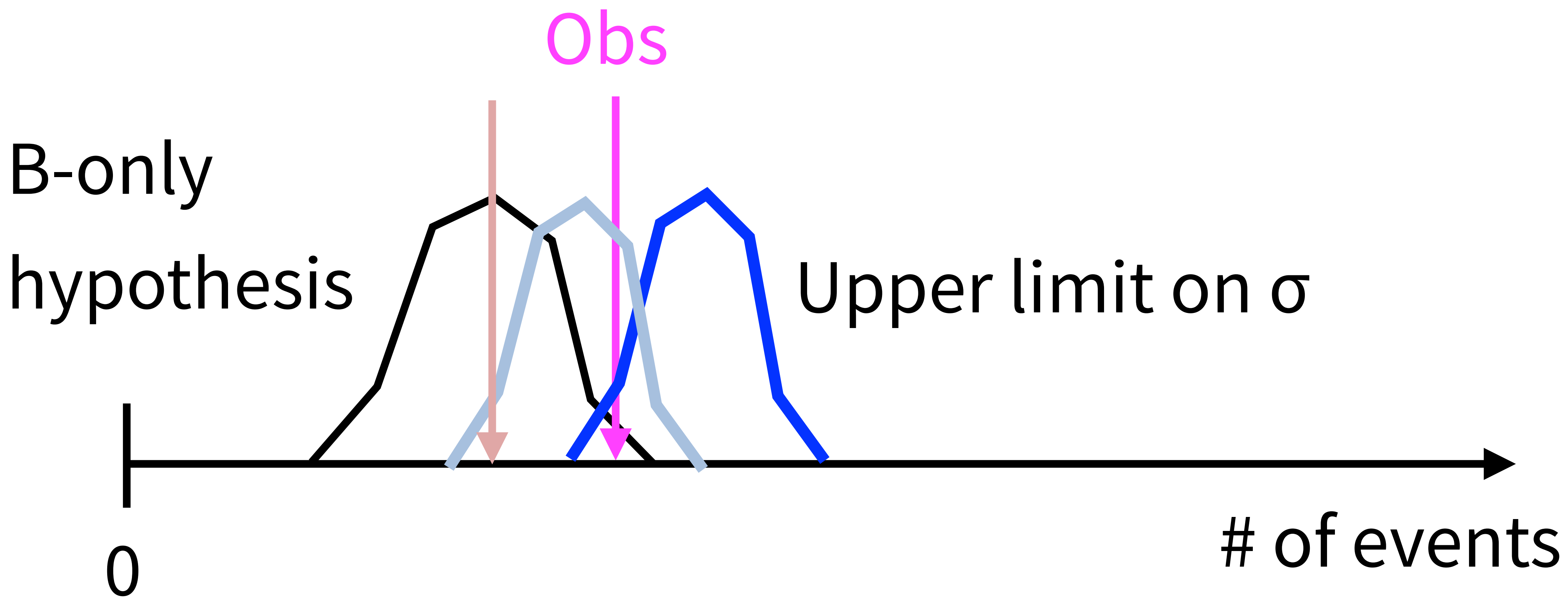
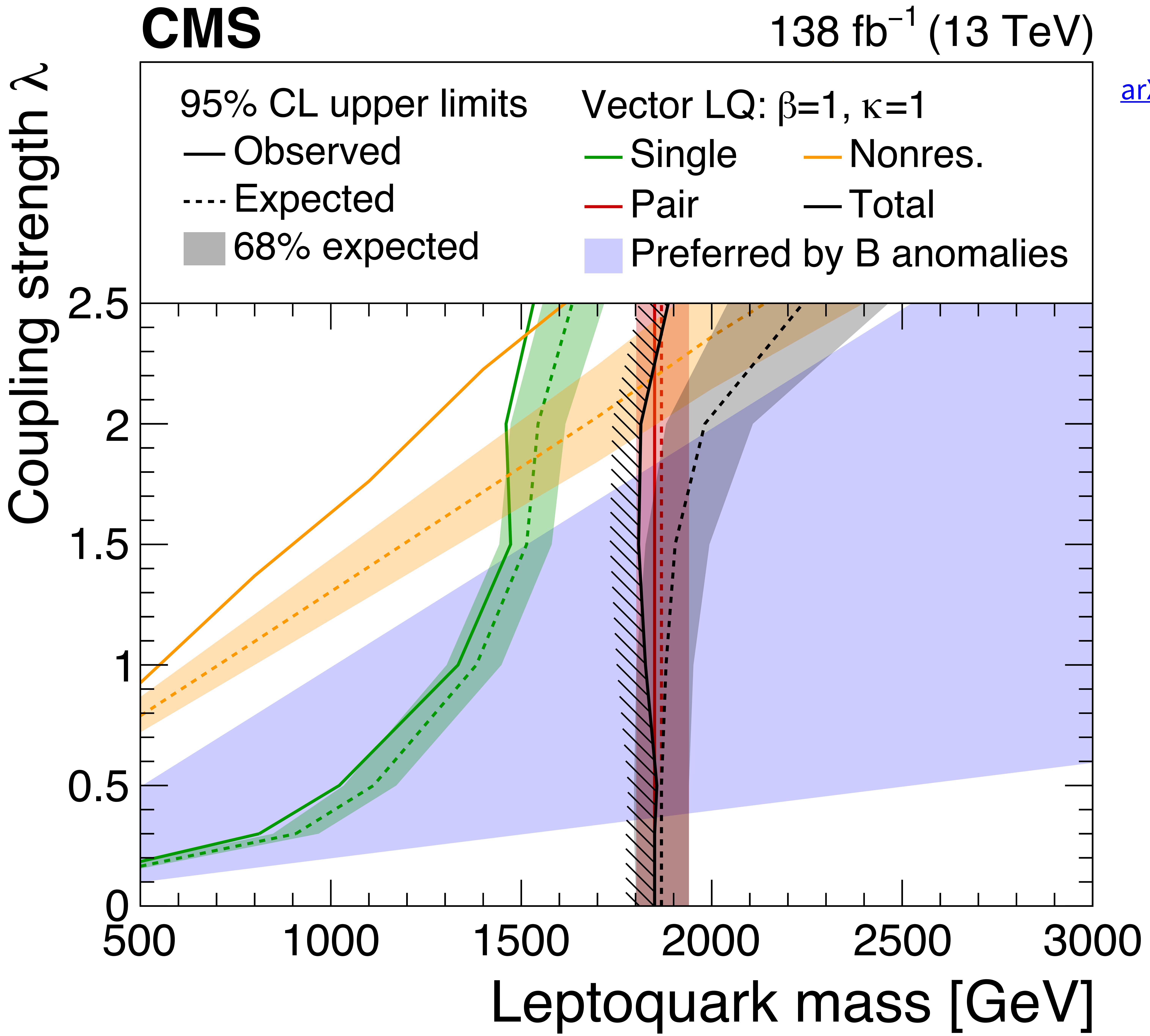
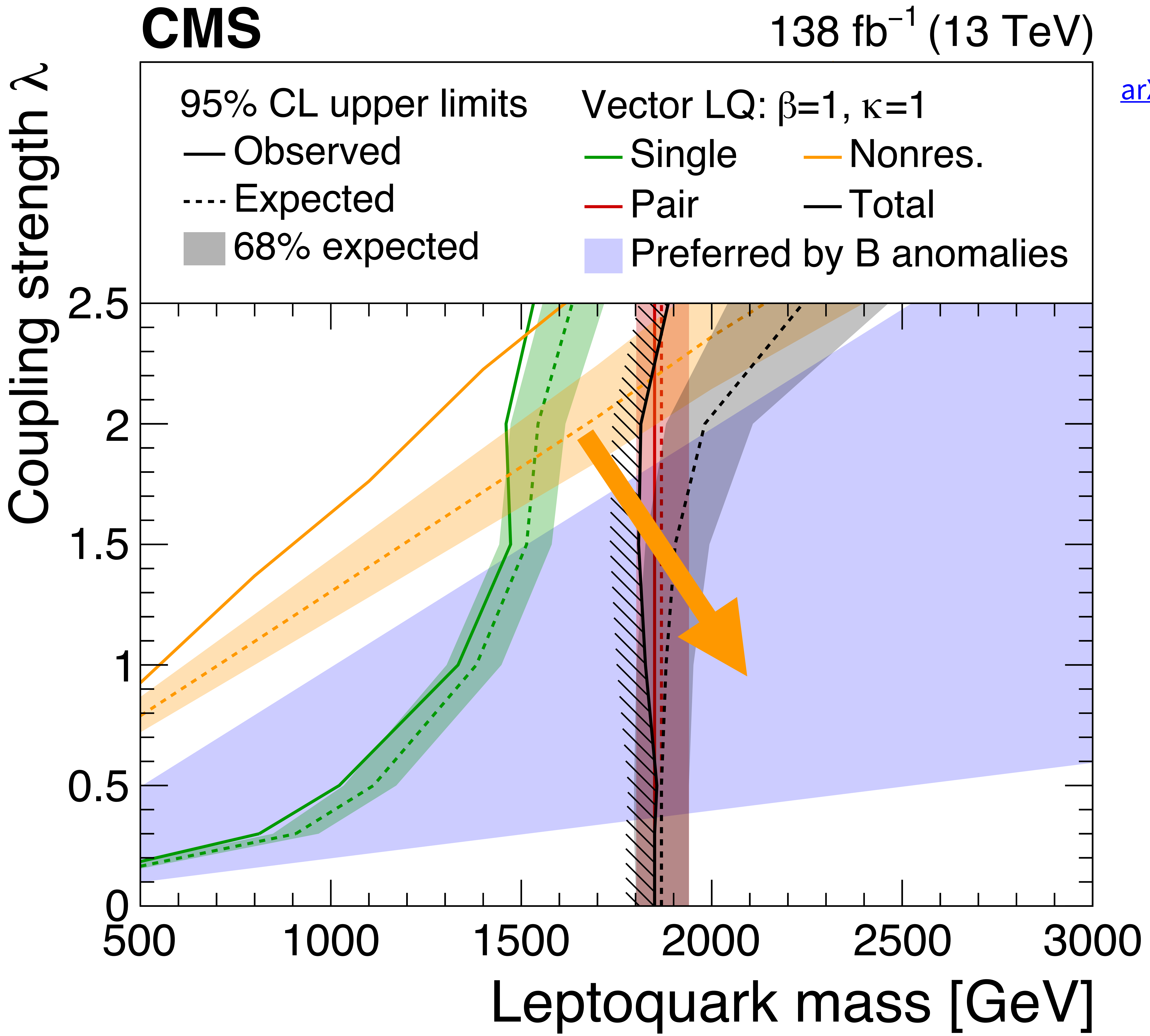








arXiv:2308.07826



[arXiv:2308.07826](https://arxiv.org/abs/2308.07826)

Why energy-frontier experiment is powerful even if we have statistically much less than B-factory experiment (LHCb)

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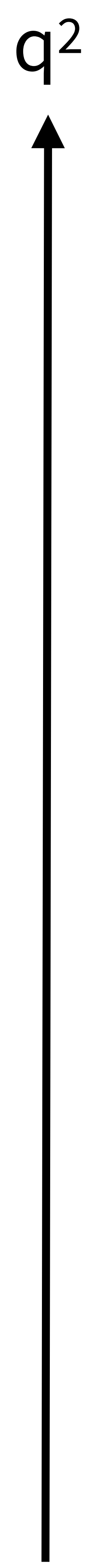

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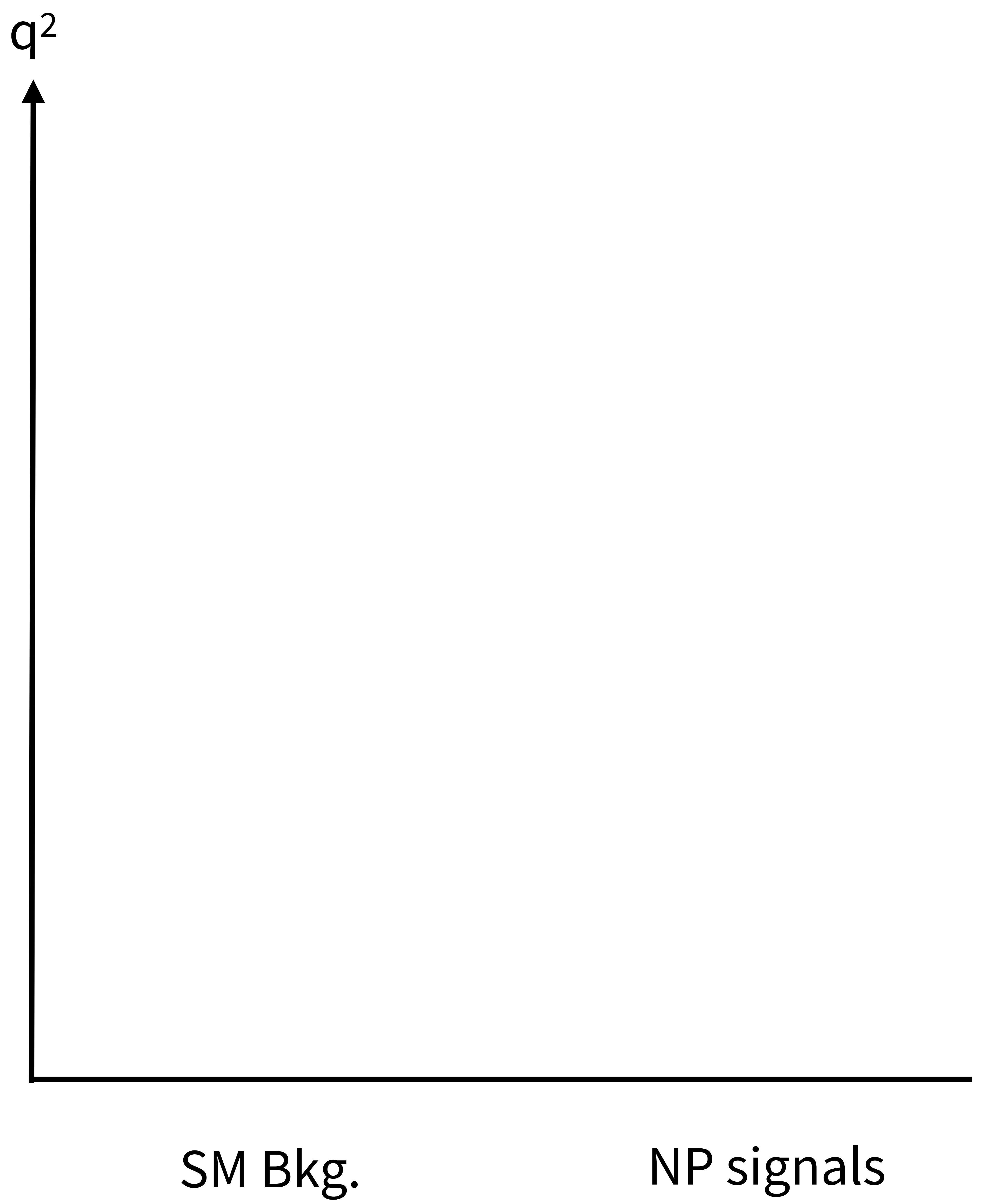

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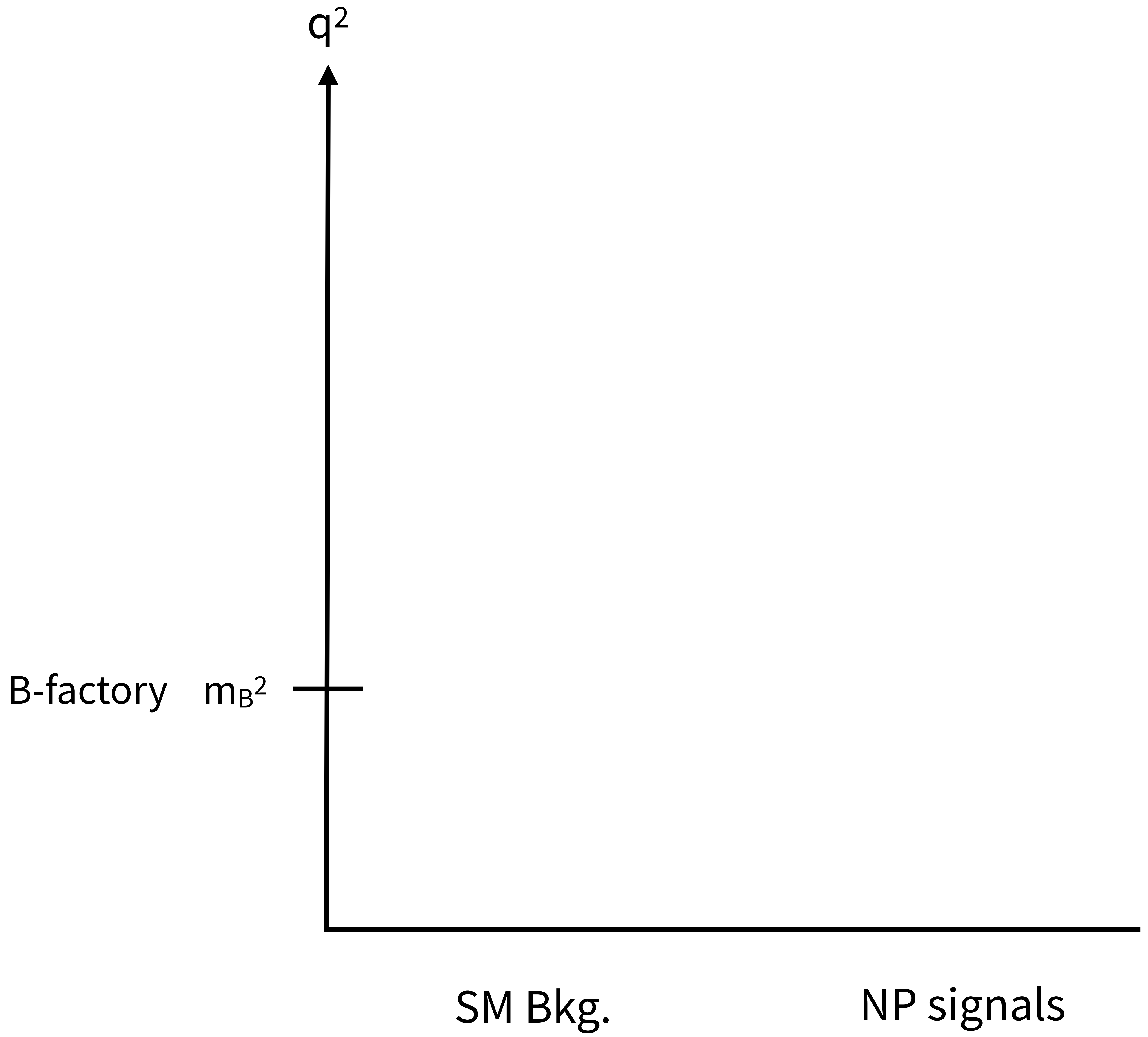

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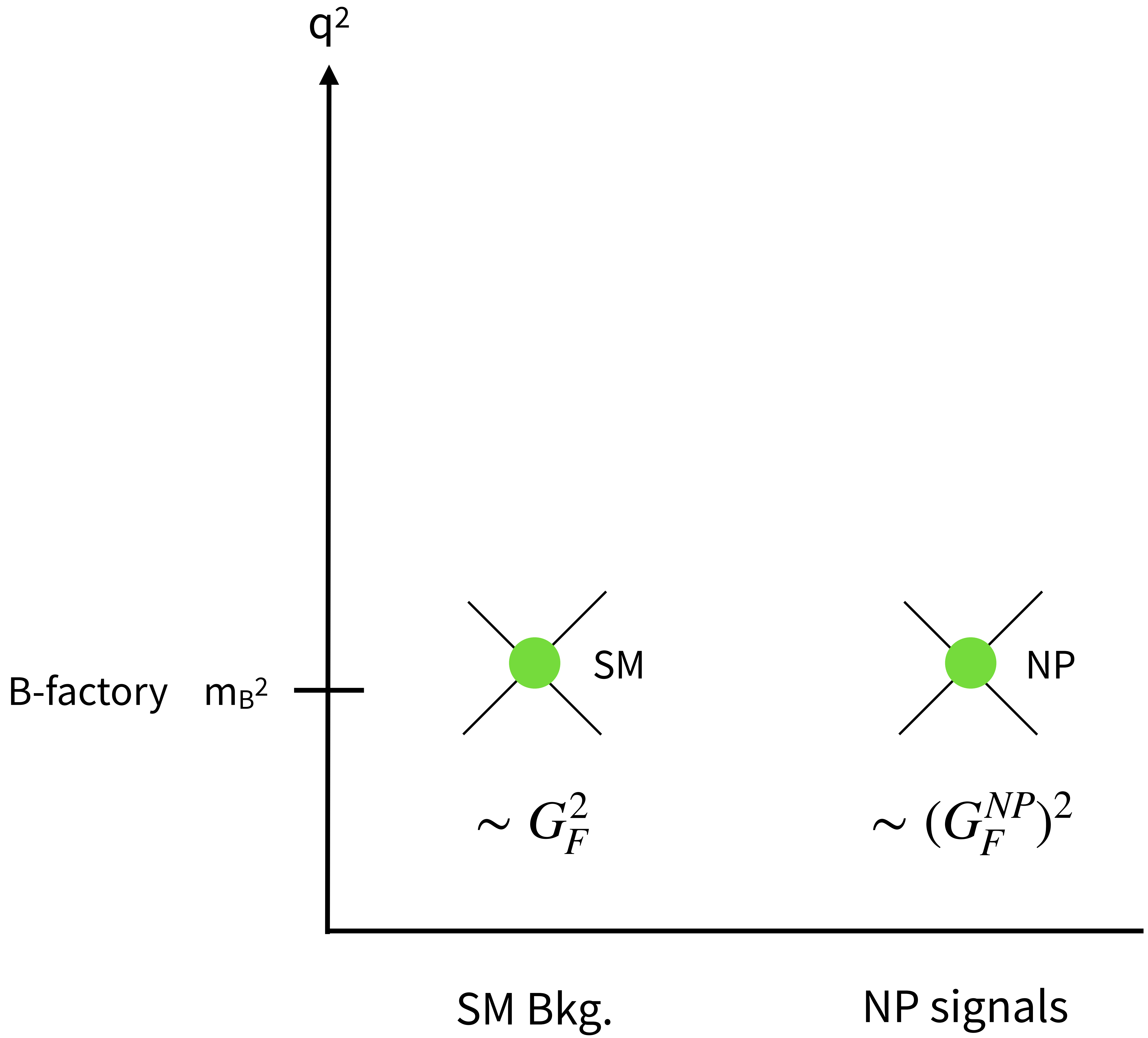

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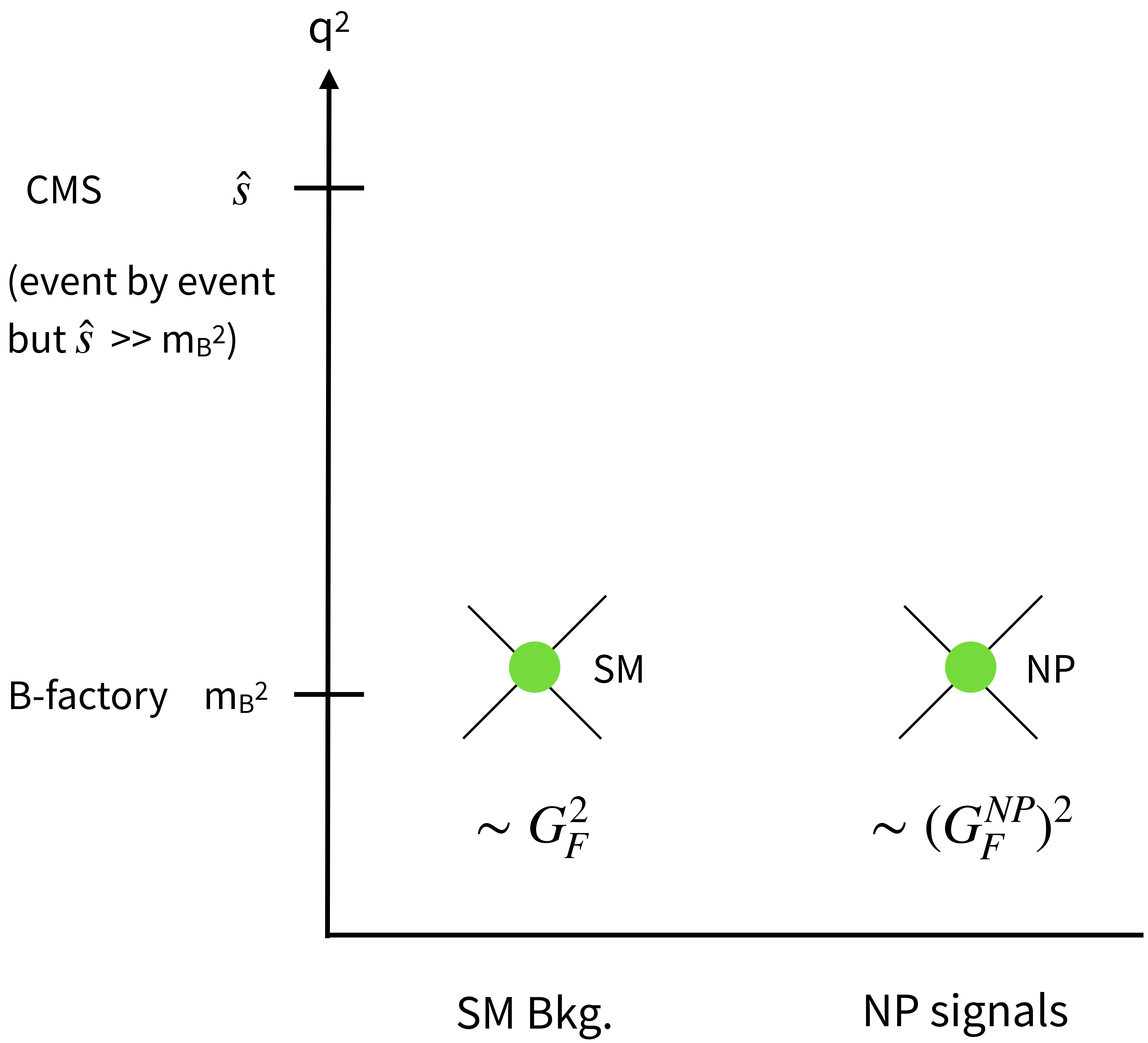

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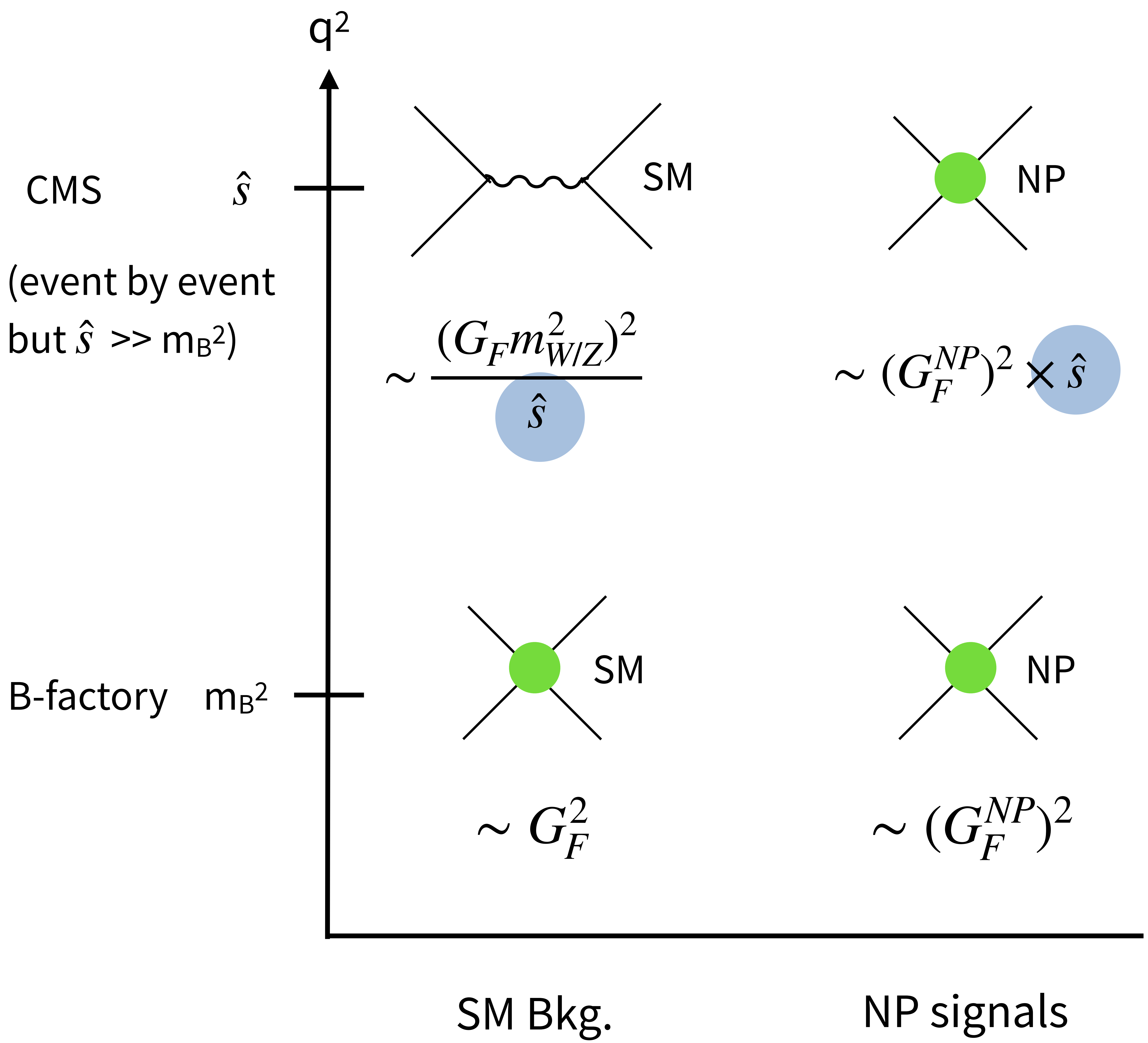

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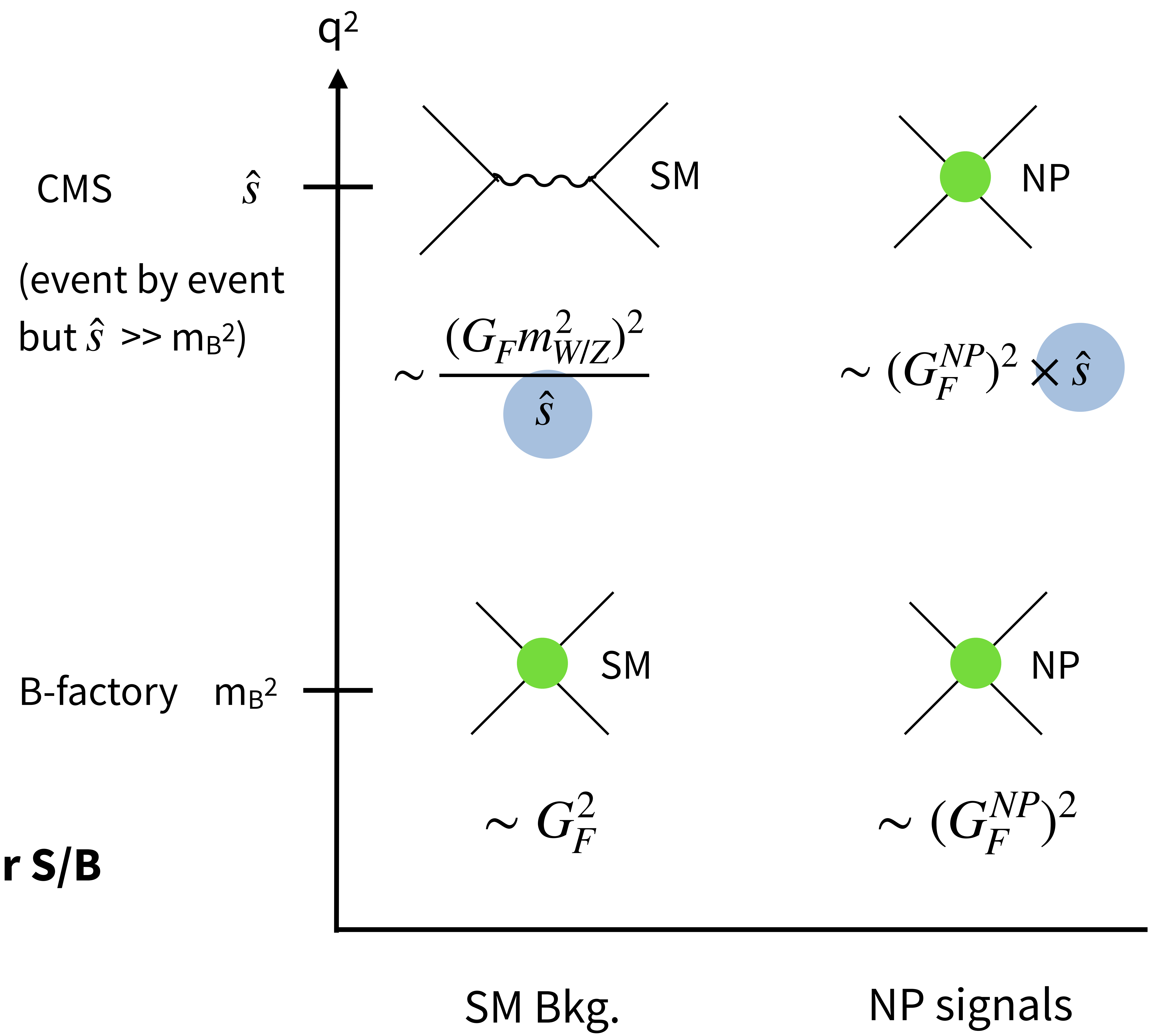

We can test new physics with much better S/B

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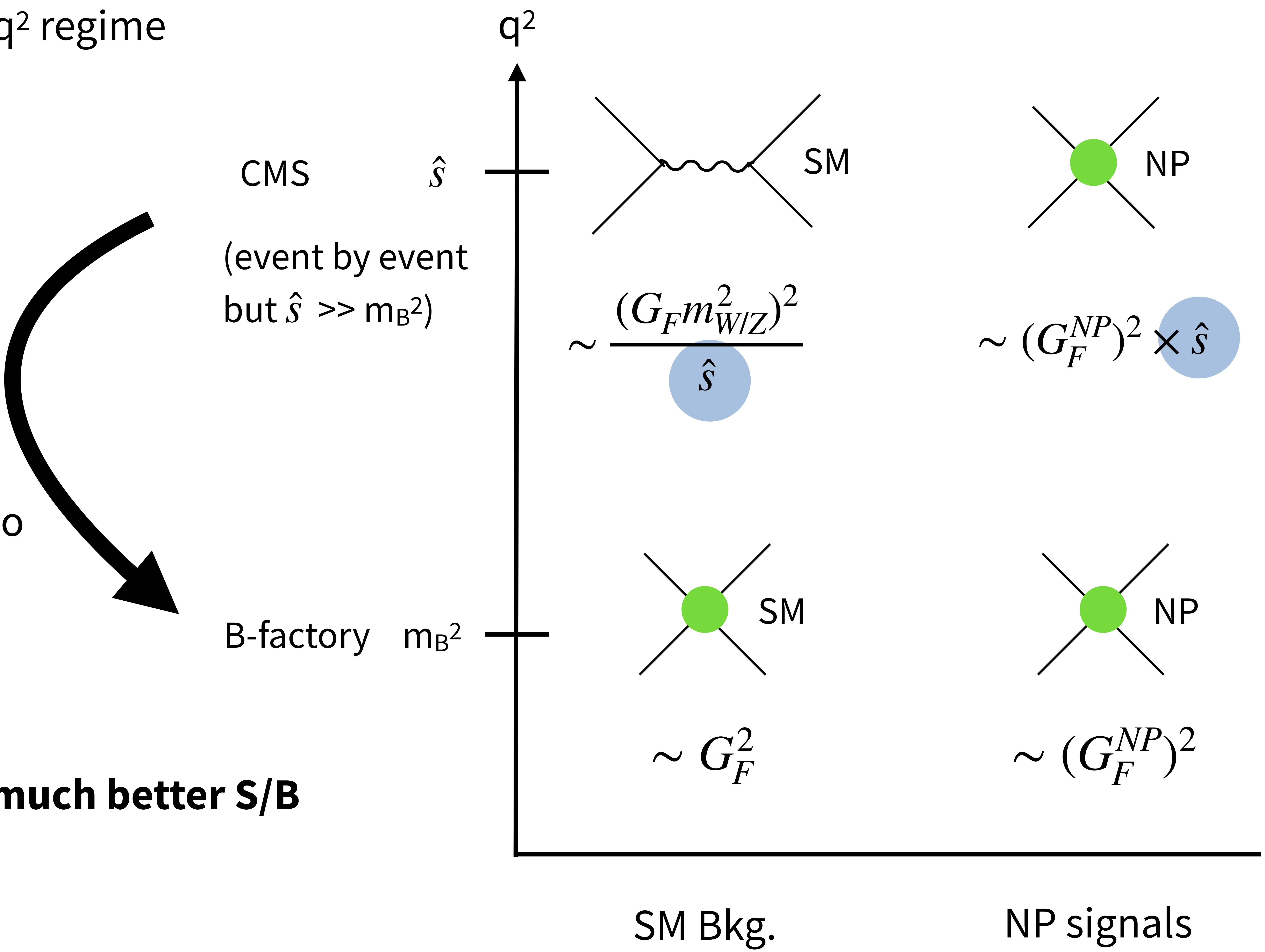
Can CMS also do B-physics measurement even if we are not designed to do so?



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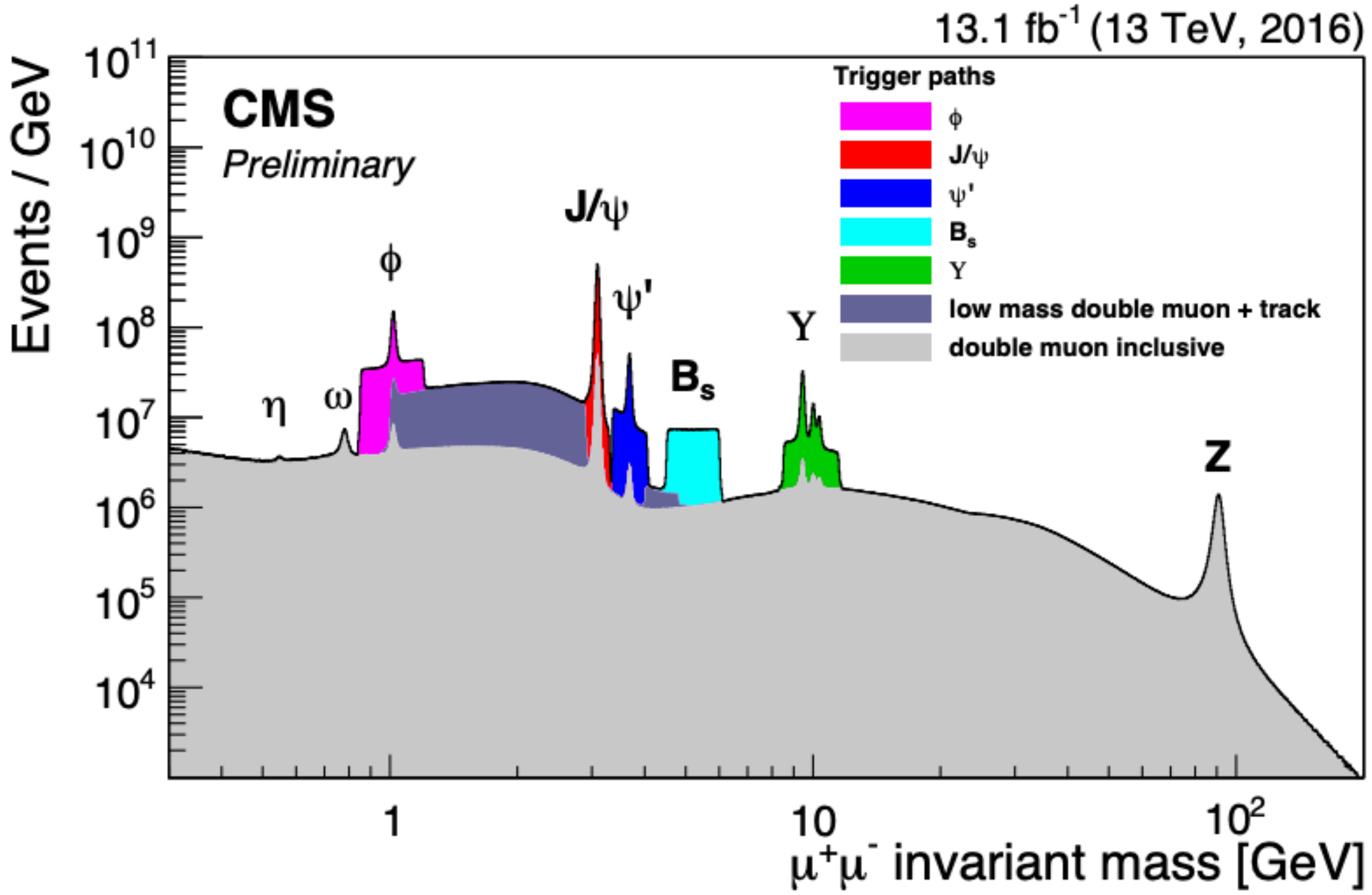
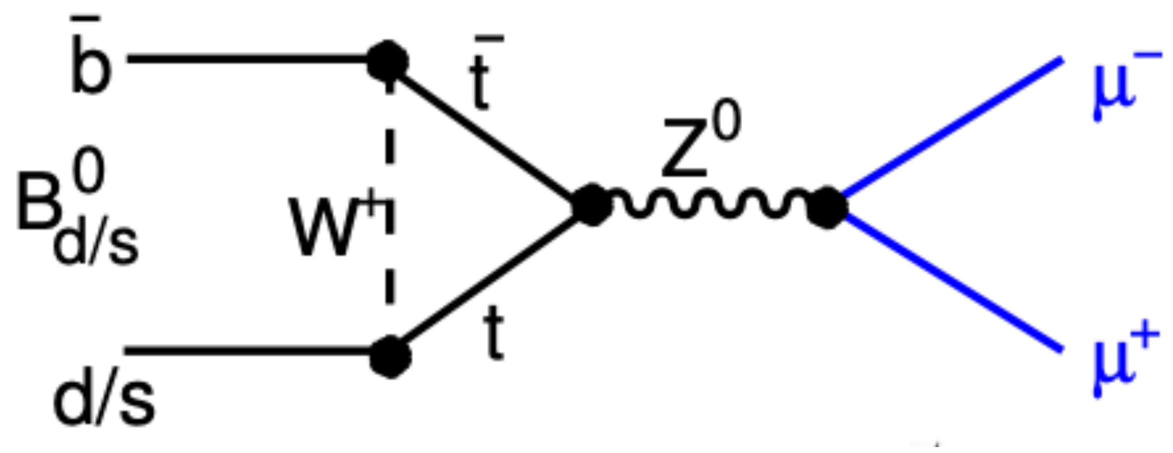
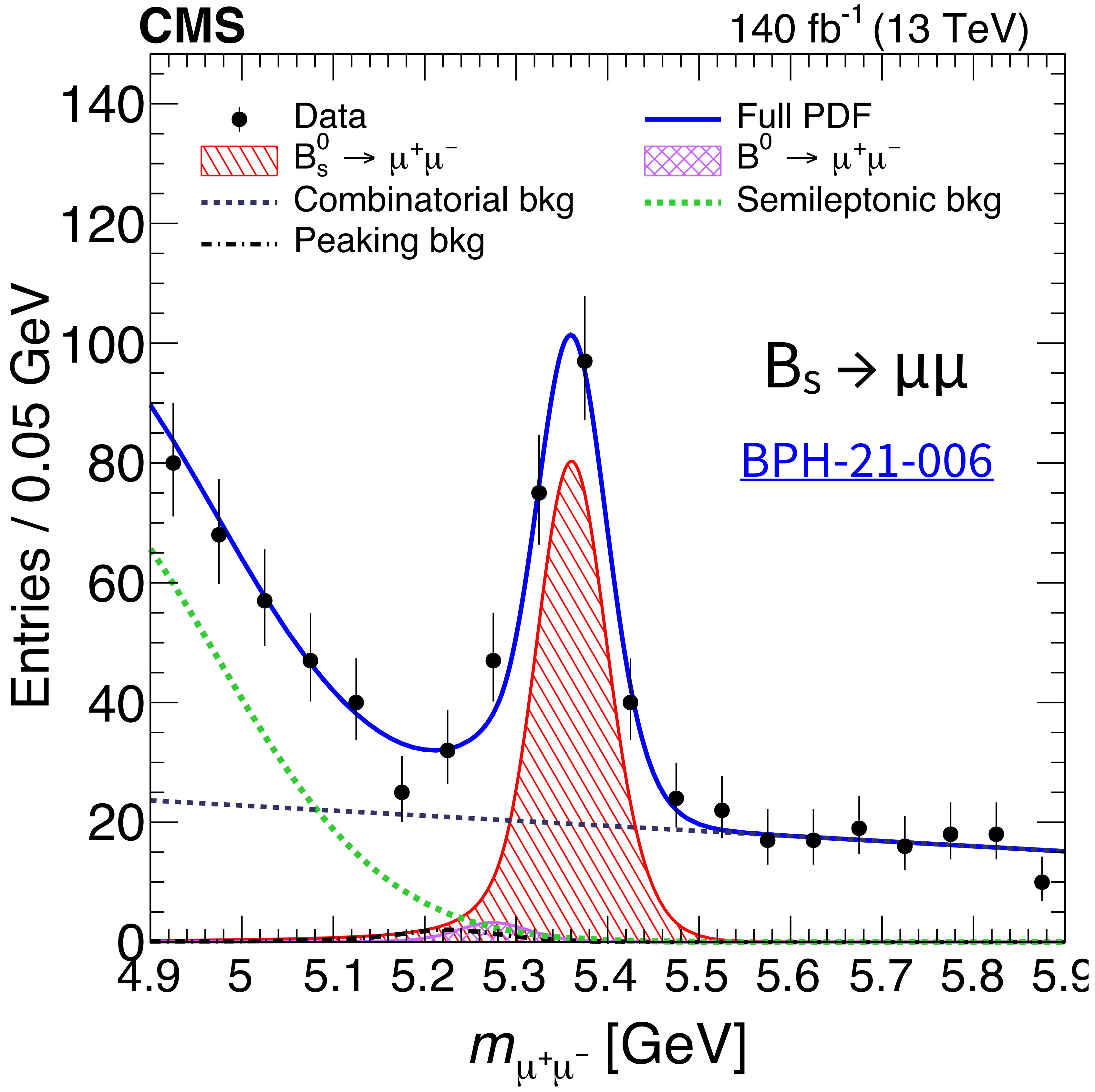
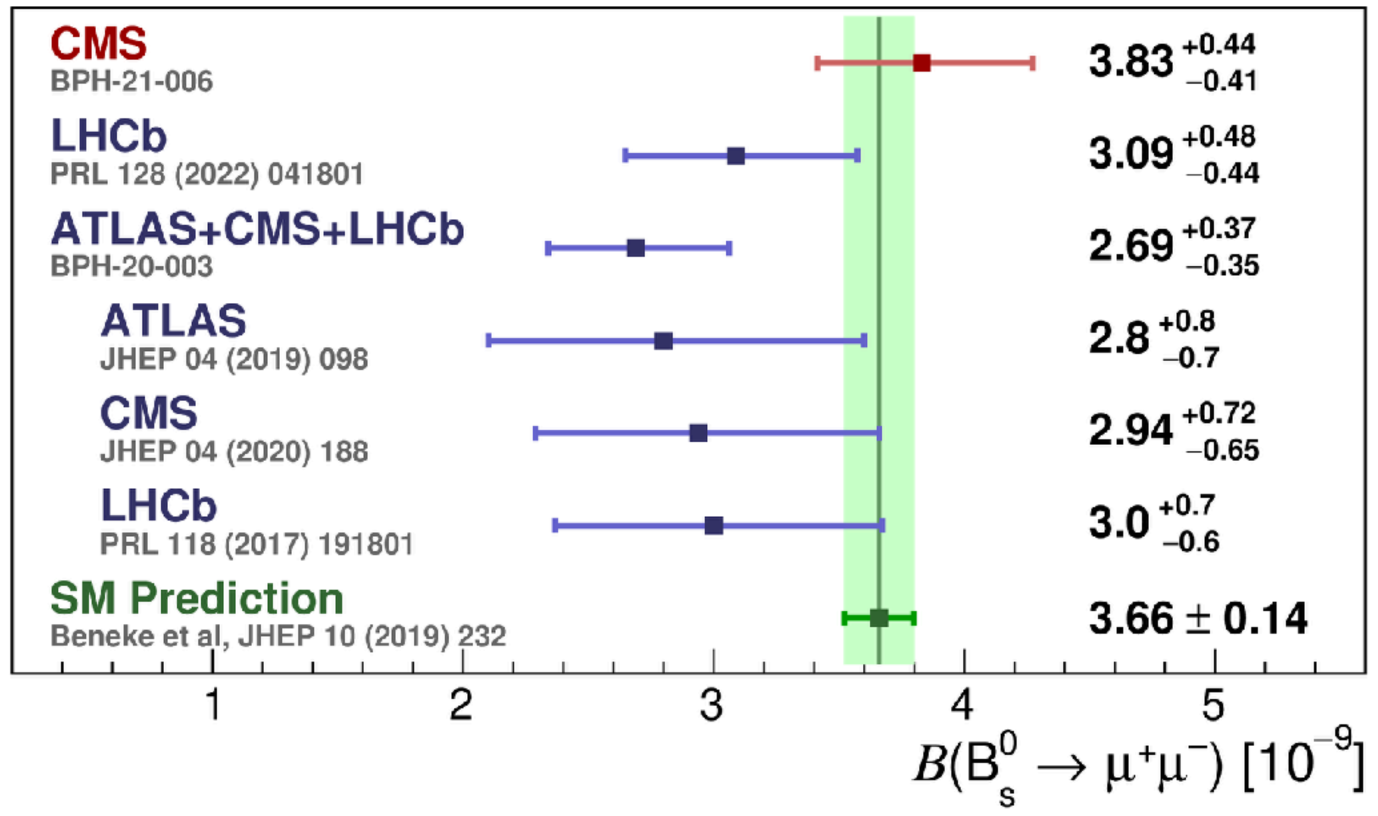


DP-2016/059

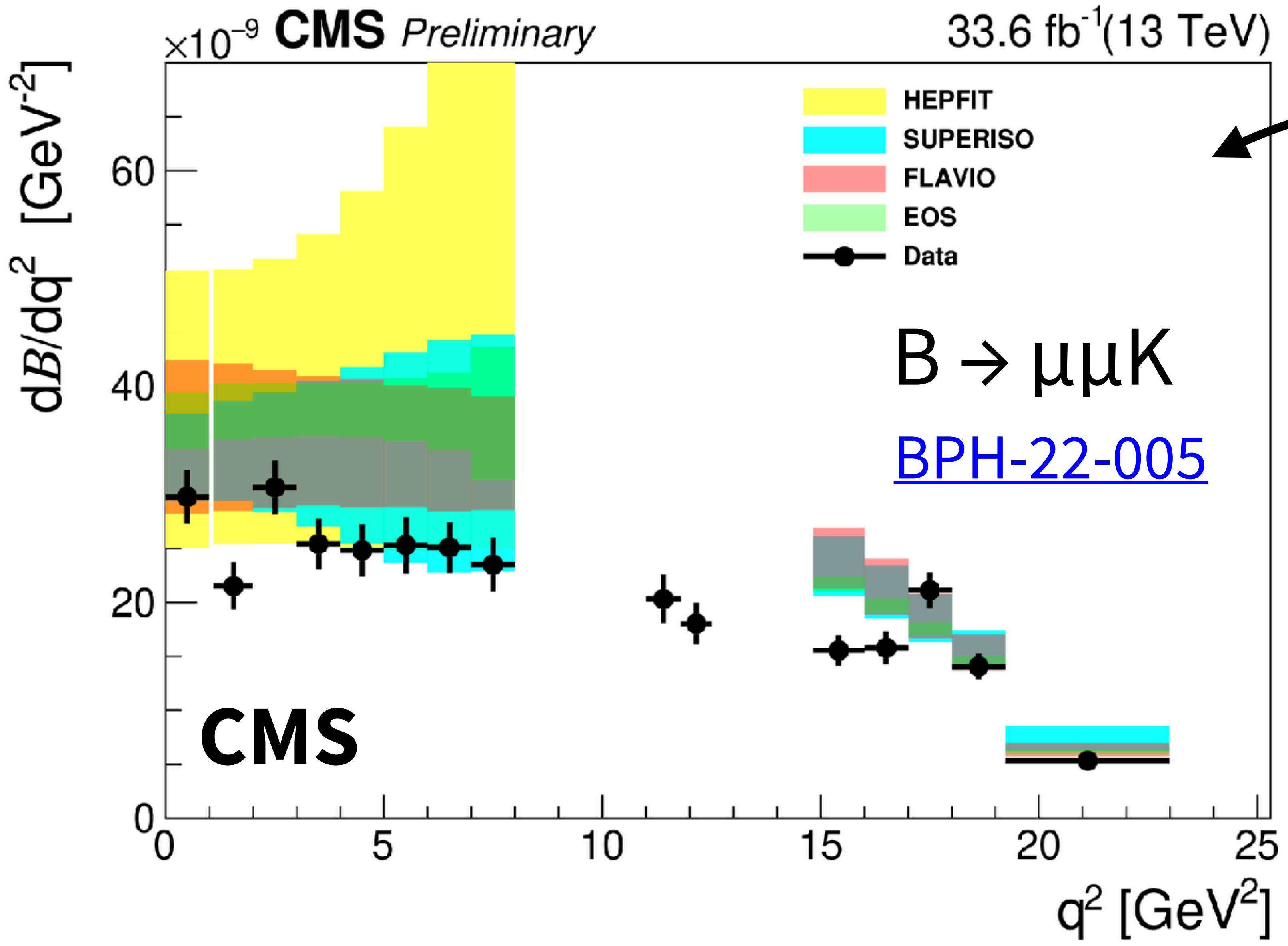
Br($B_s \to \mu\mu$) measurement

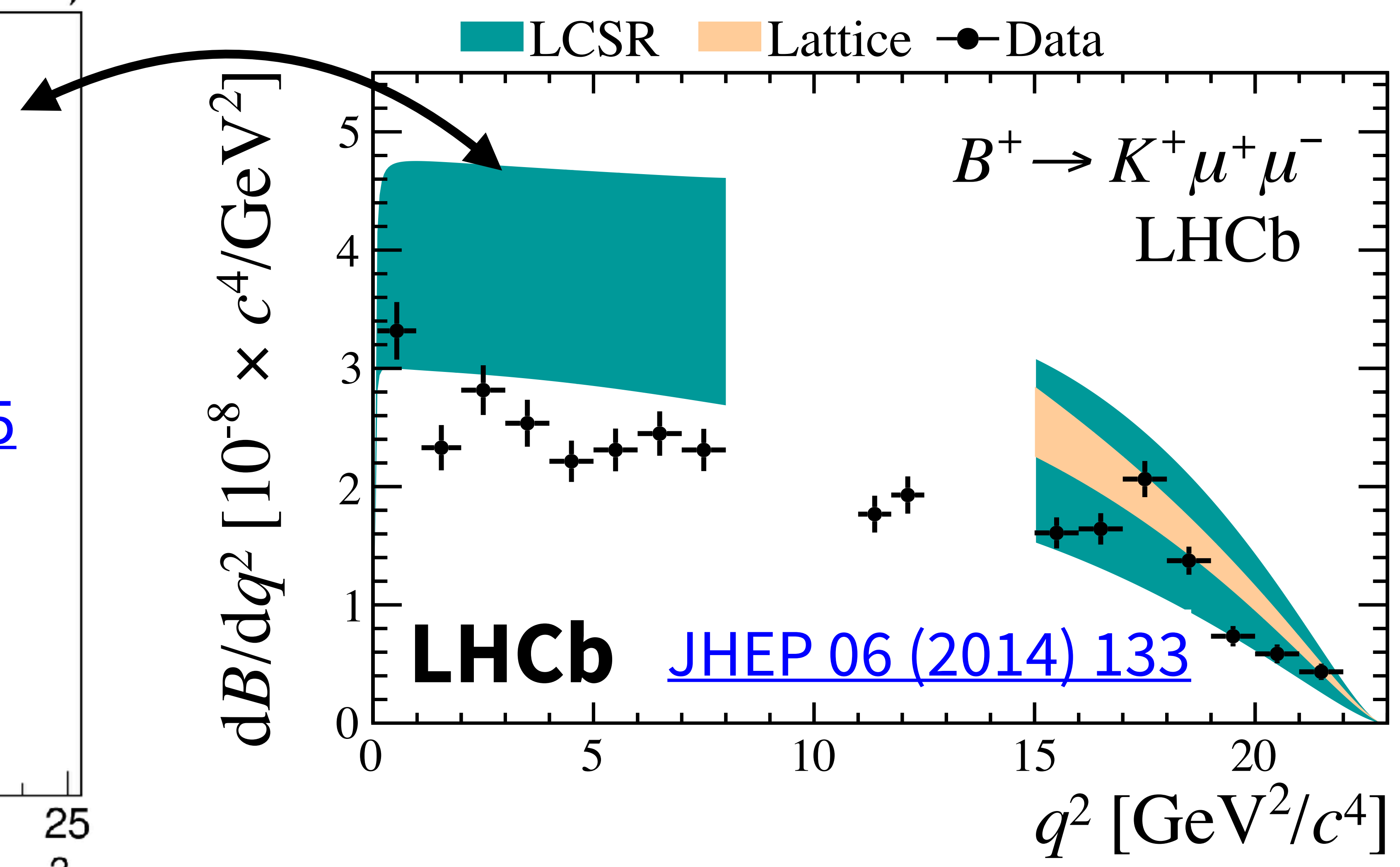






Differential Br(B → Kμμ) measurement





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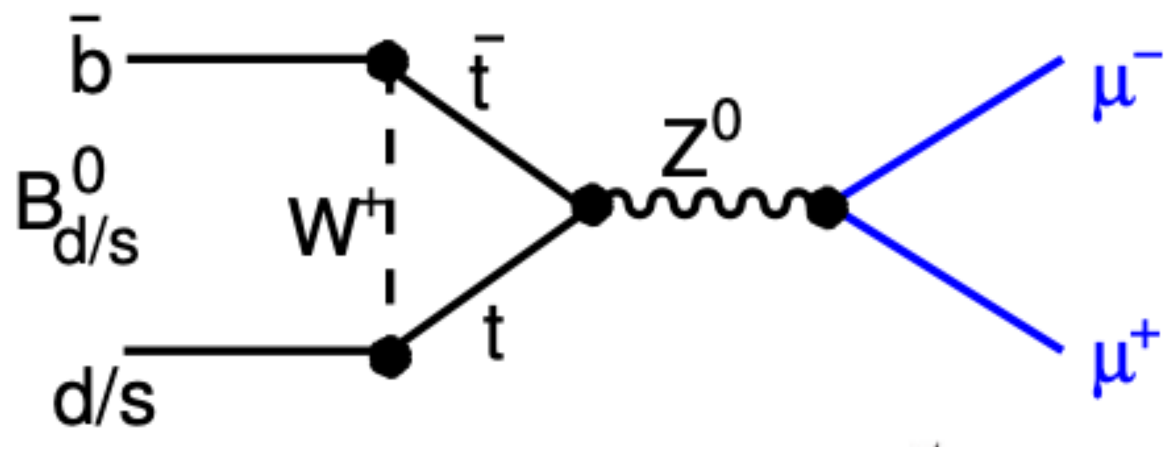

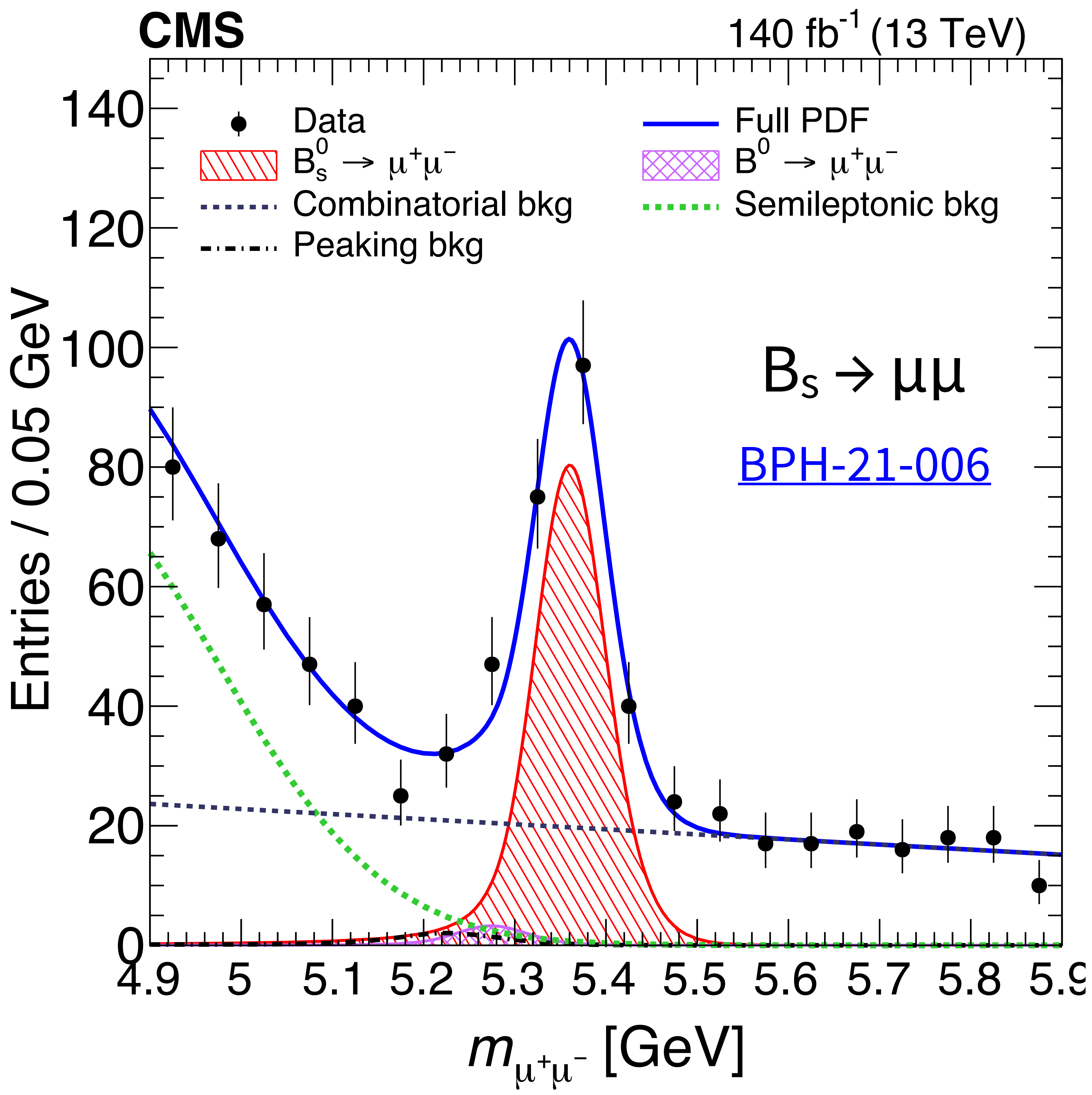

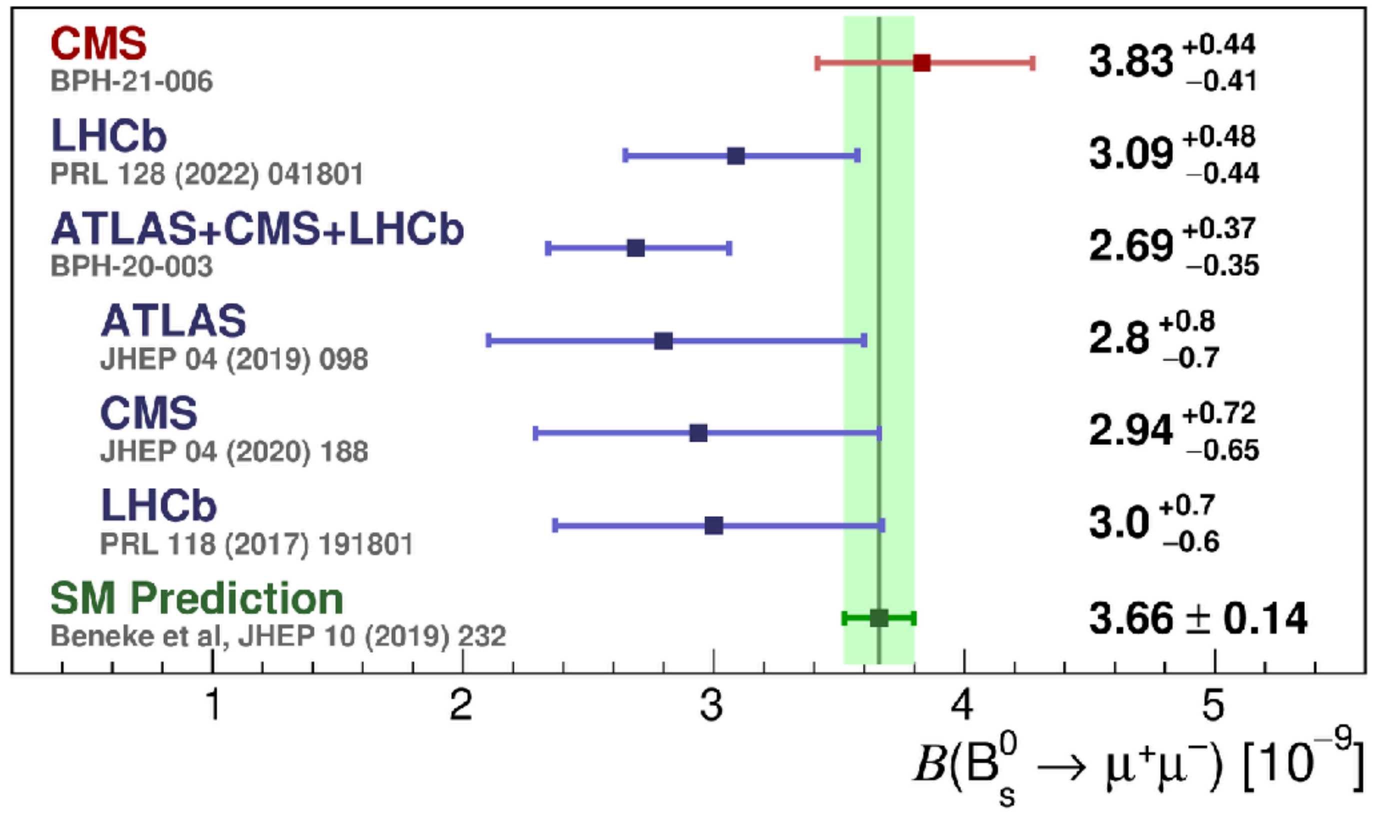

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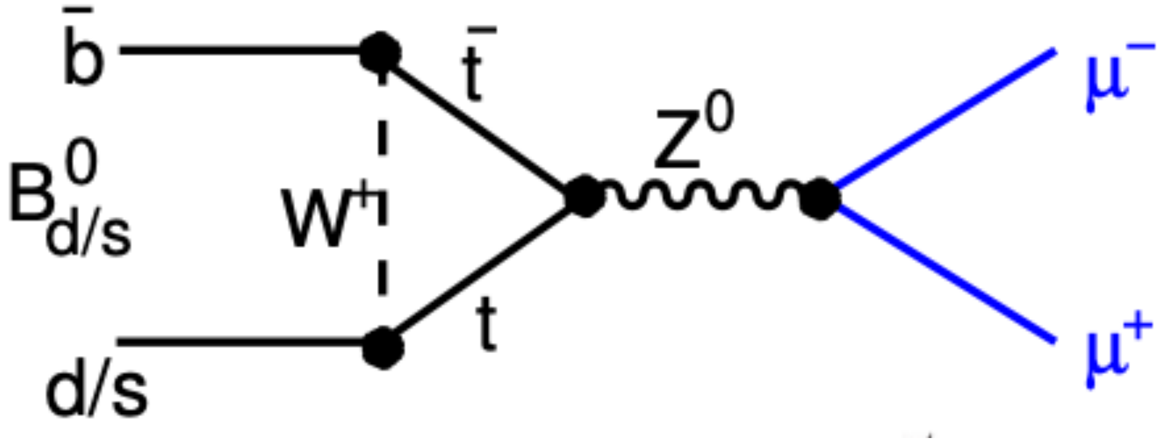

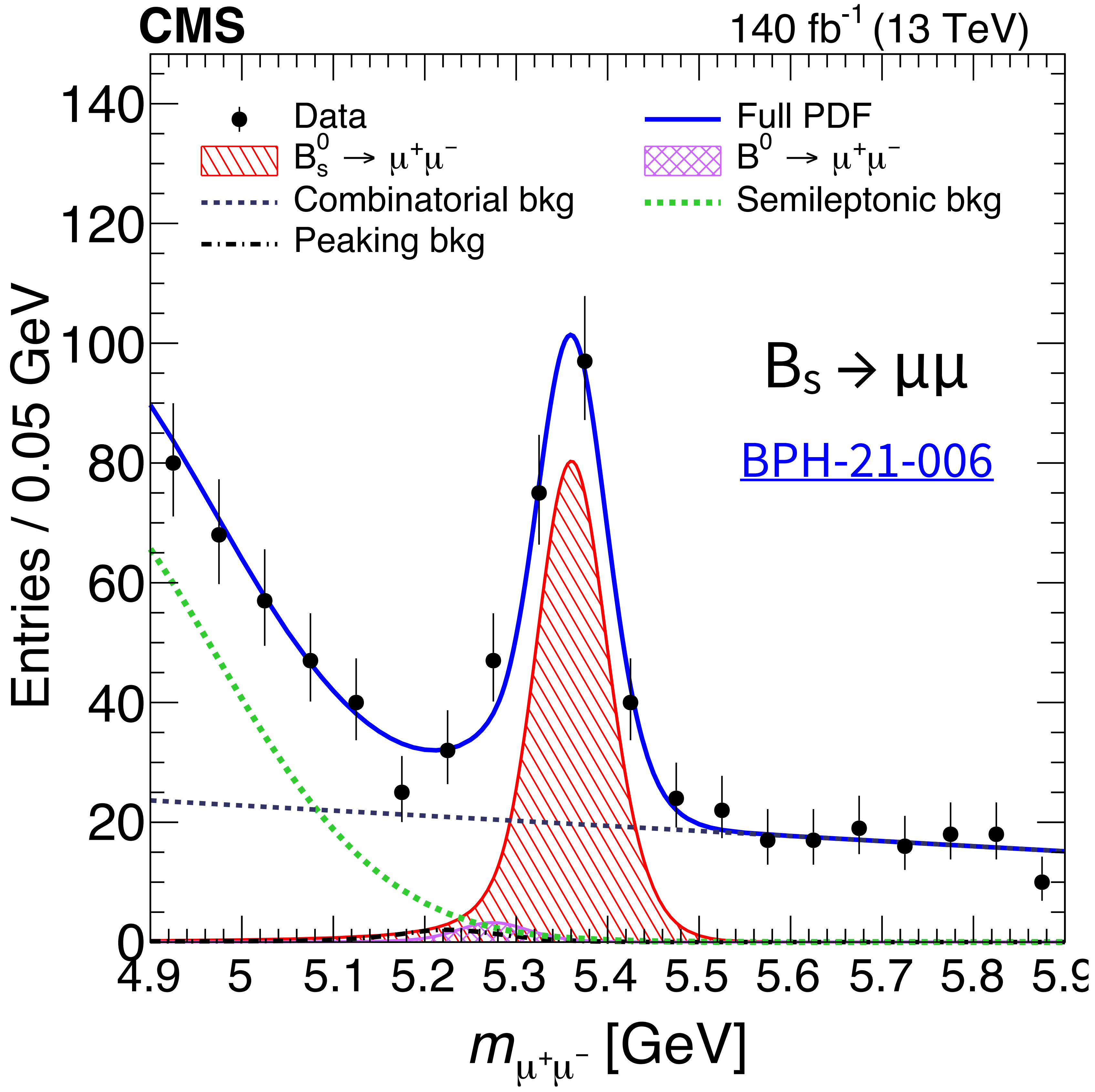

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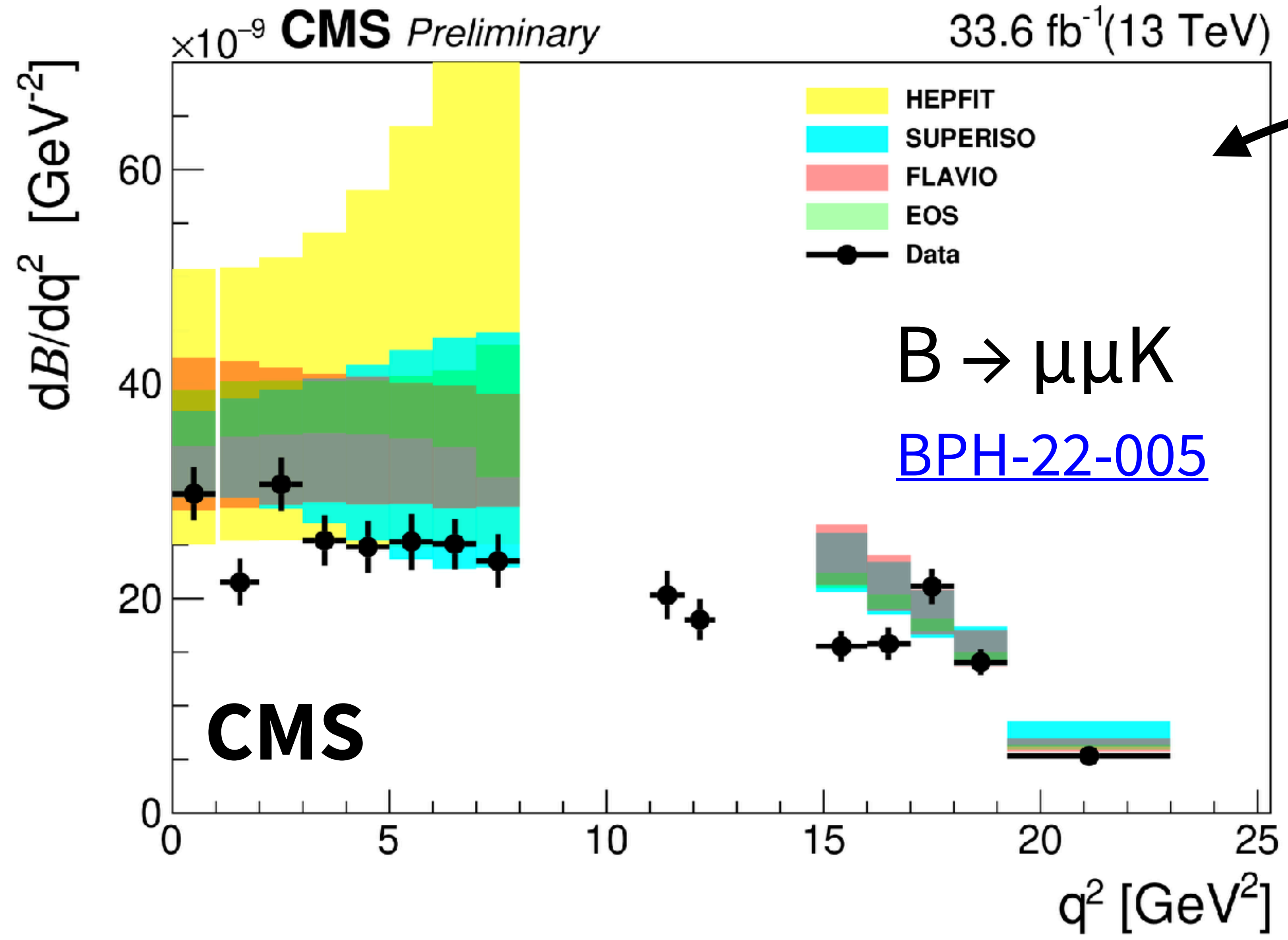
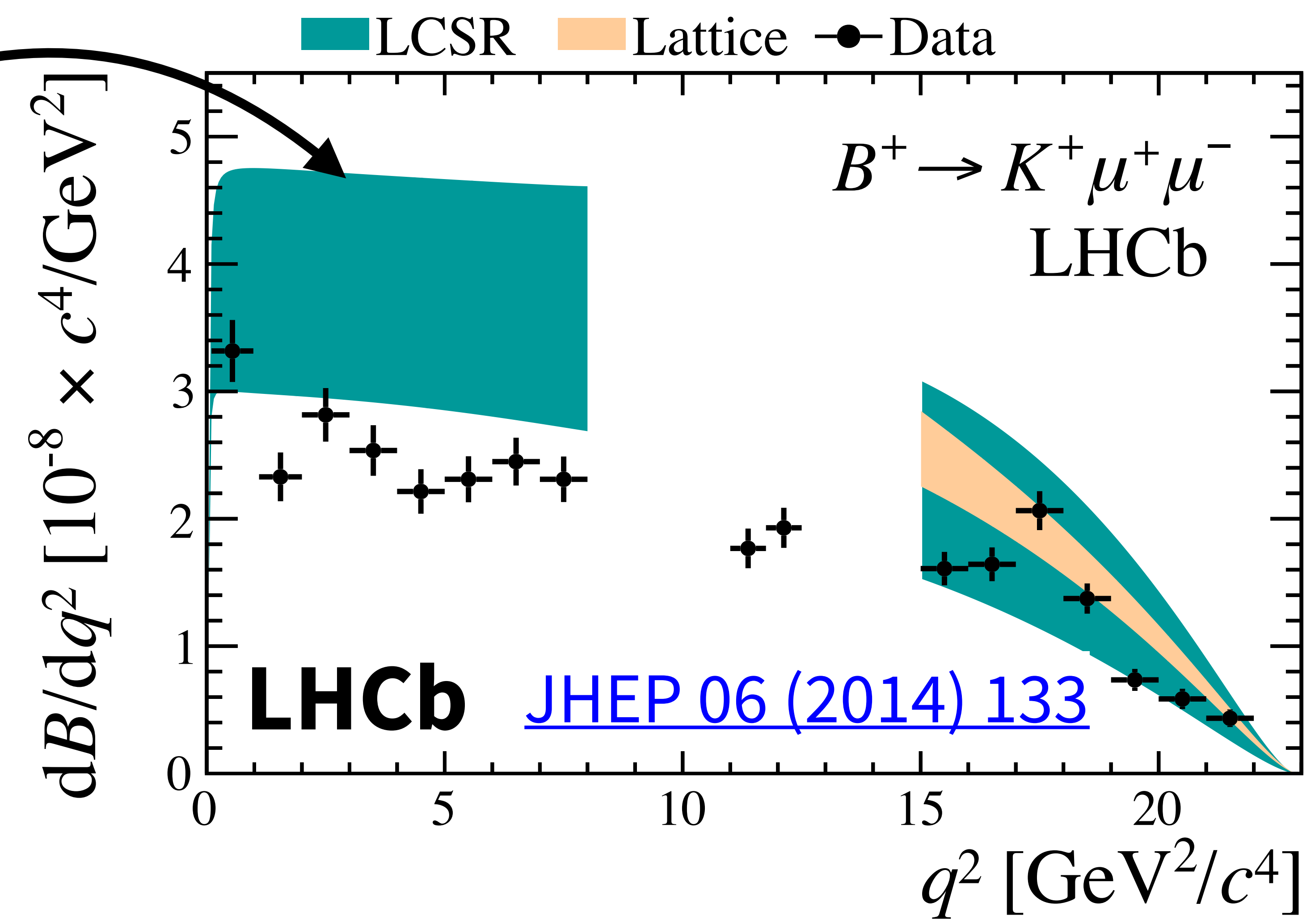
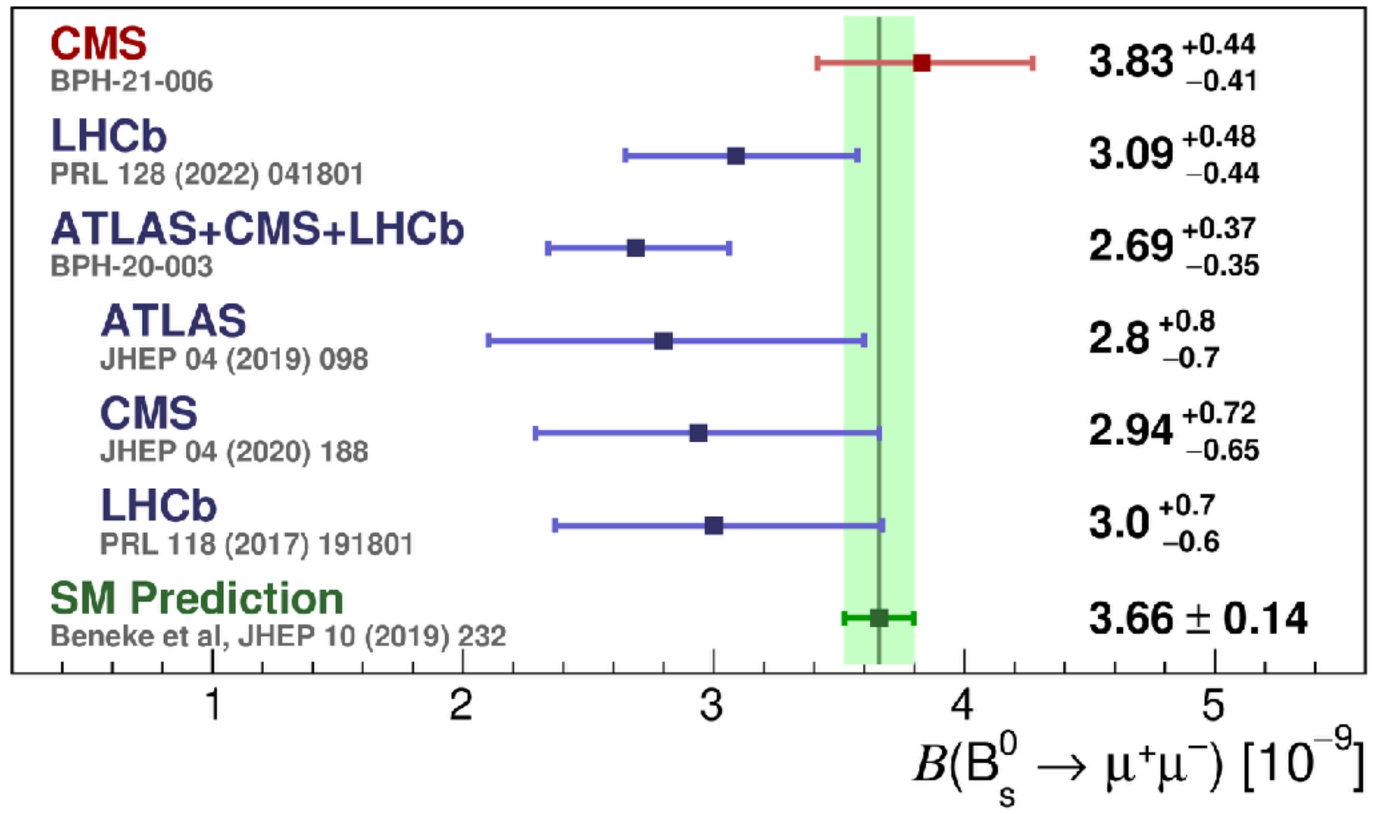
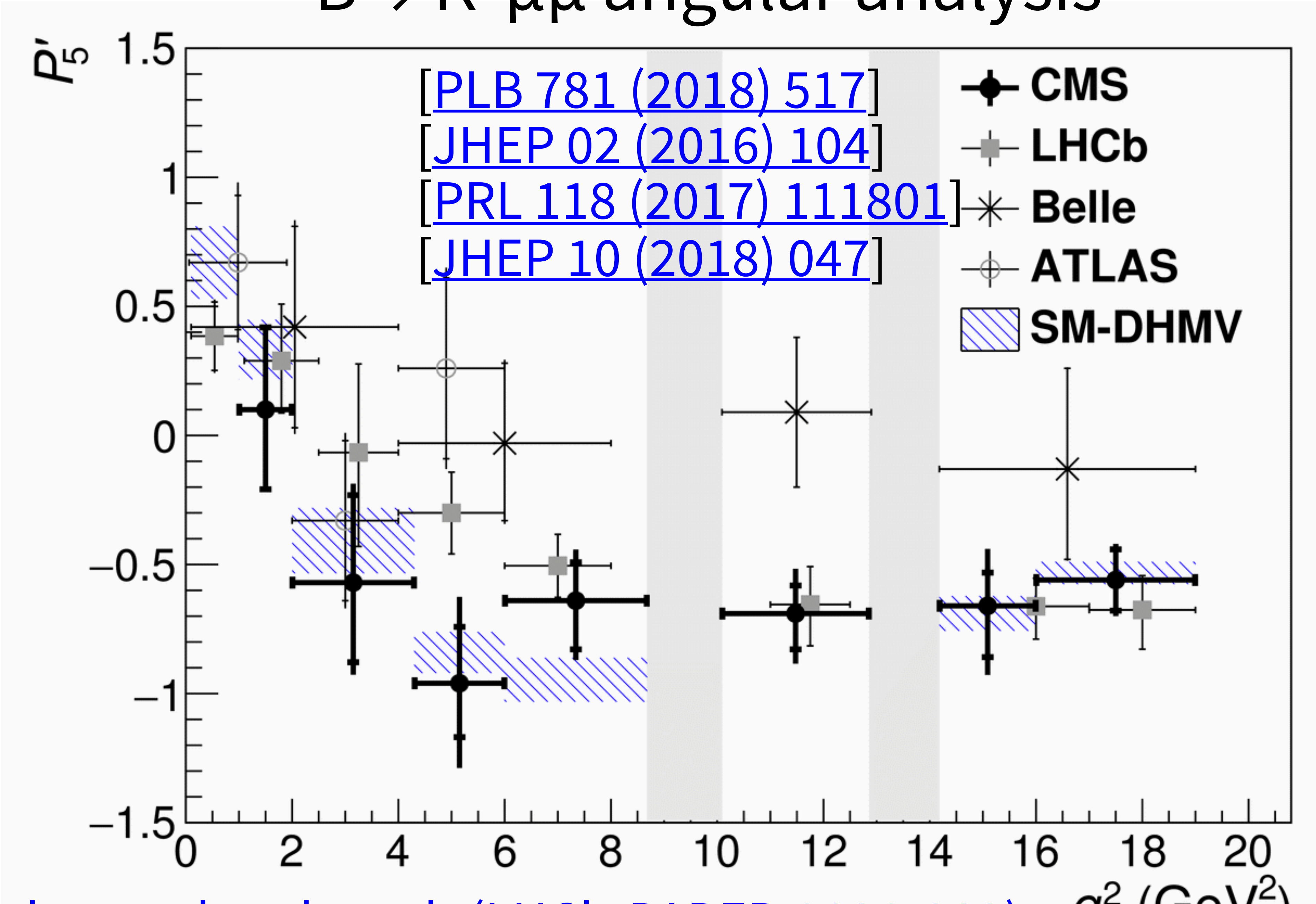






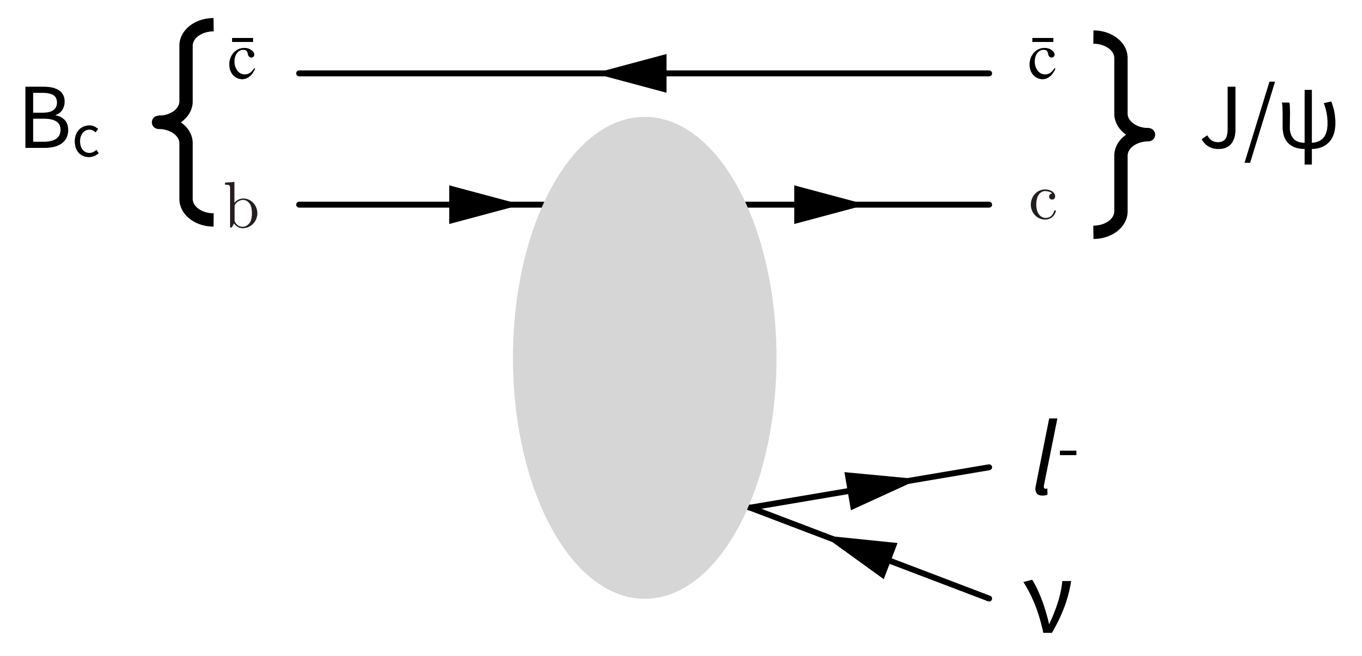
$B \to K^*\mu\mu$ angular analysis



LHCb has updated result (LHCb-PAPER-2020-002)

Extend our μμ program: R(J/ψ) analysis

$$\frac{\mathcal{B}(B_c \to J/\psi\tau\bar{\nu})}{\mathcal{B}(B_c \to J/\psi\mu\bar{\nu})}$$



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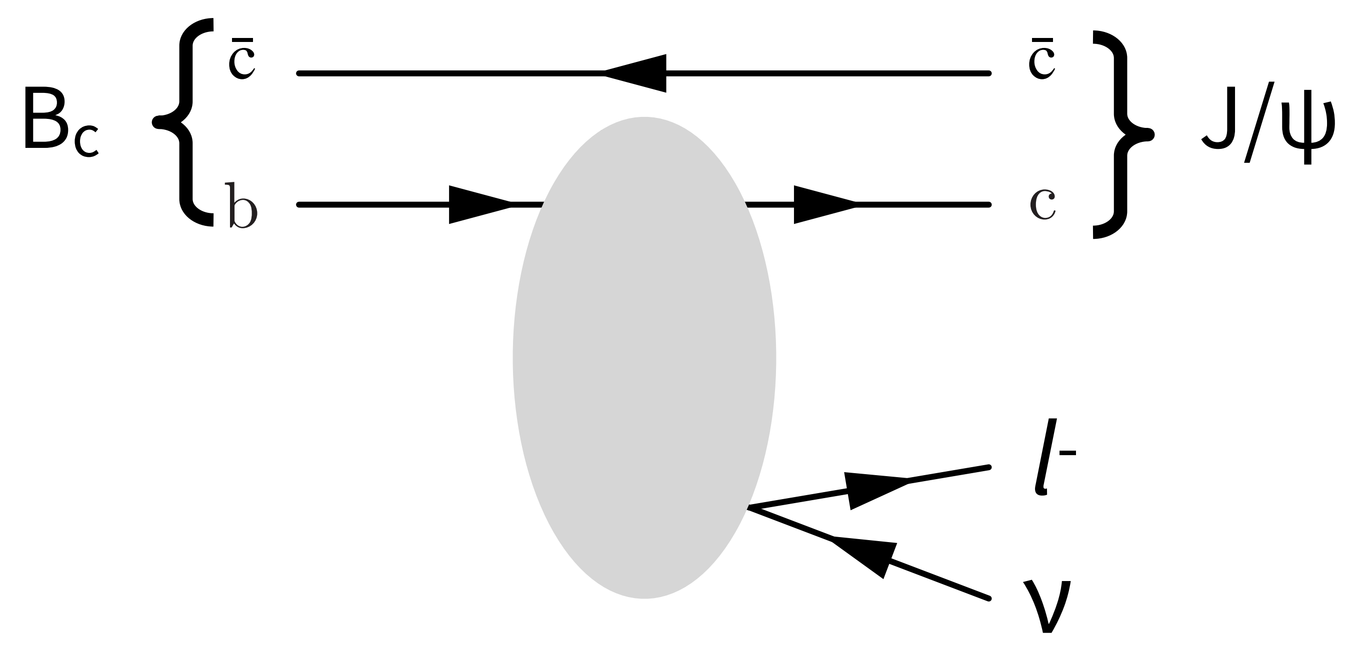

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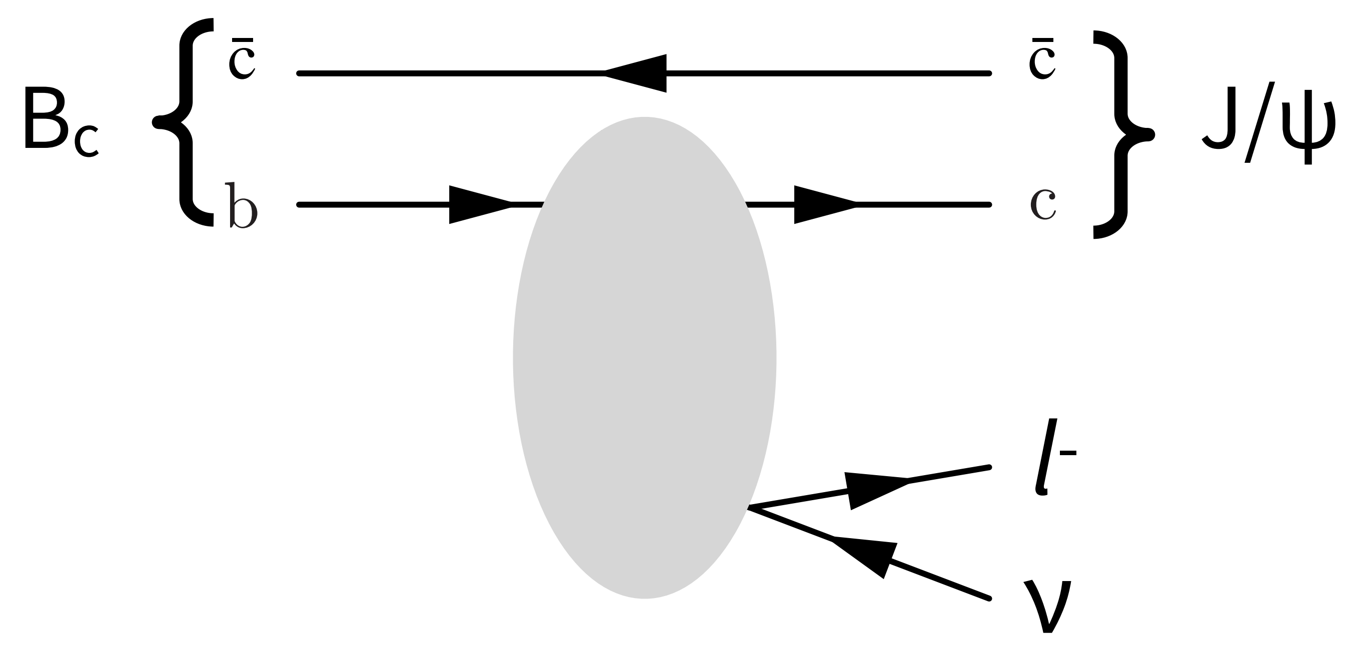

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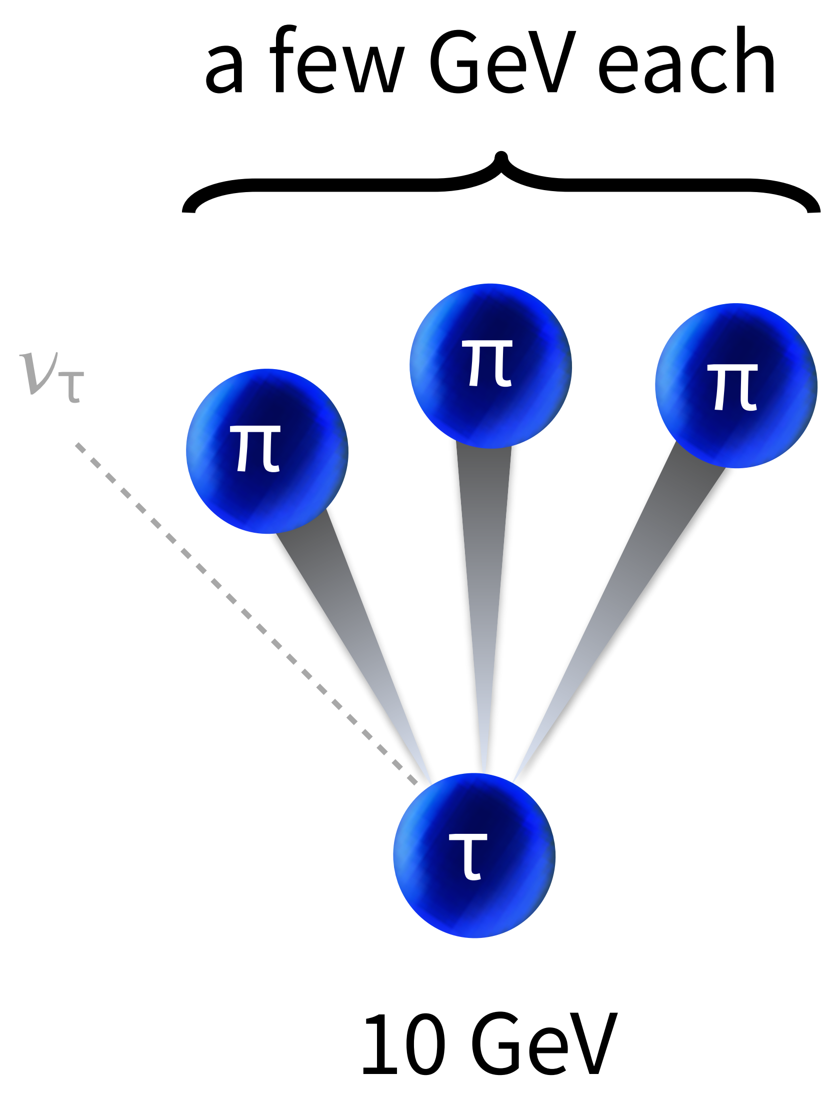

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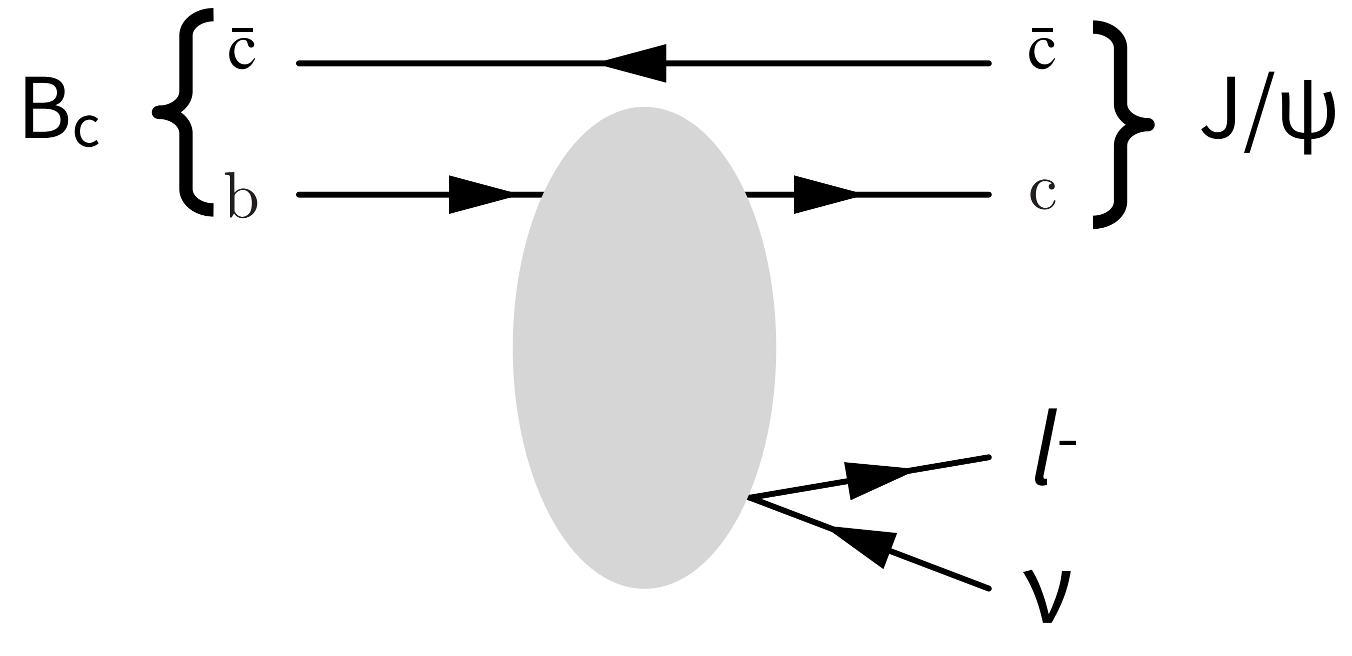

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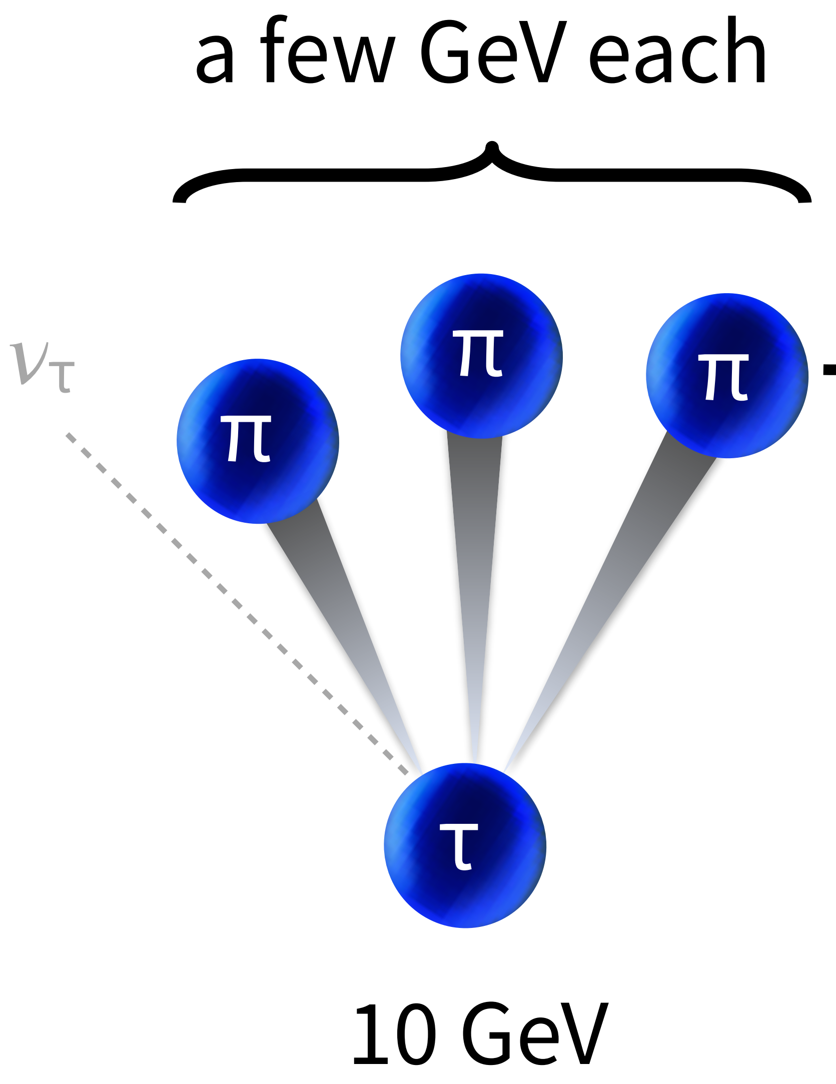
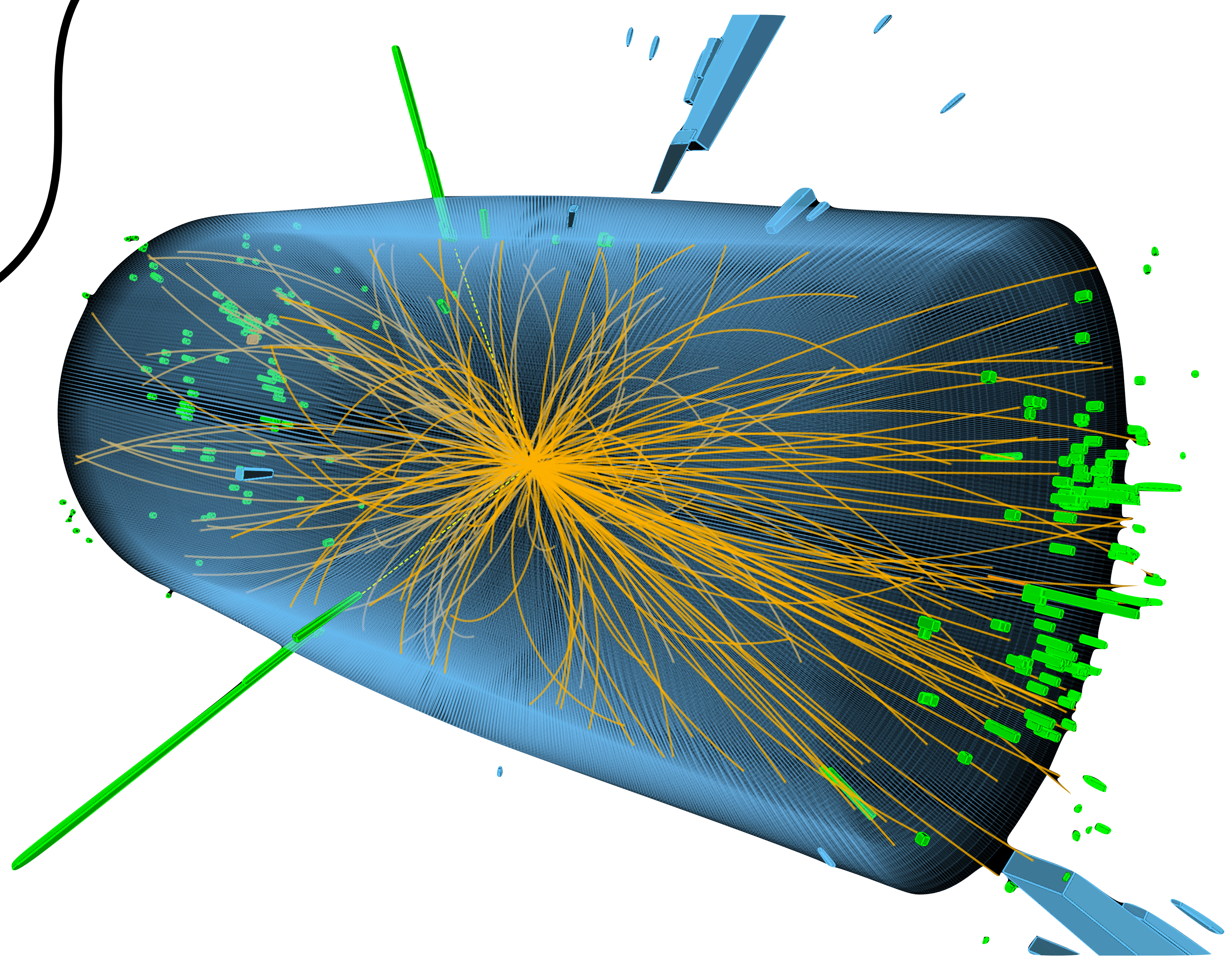


Ubiquitous at CMS



O(1000) pions, most of them having O(1) GeV momentum

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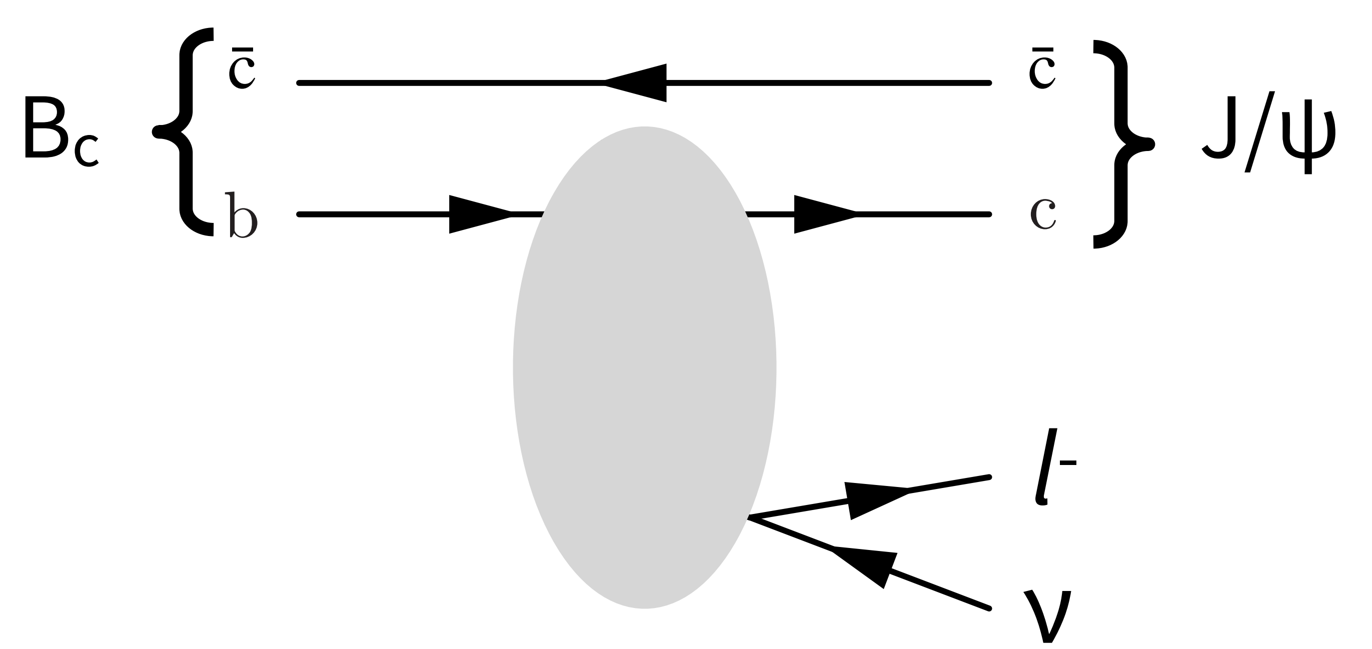

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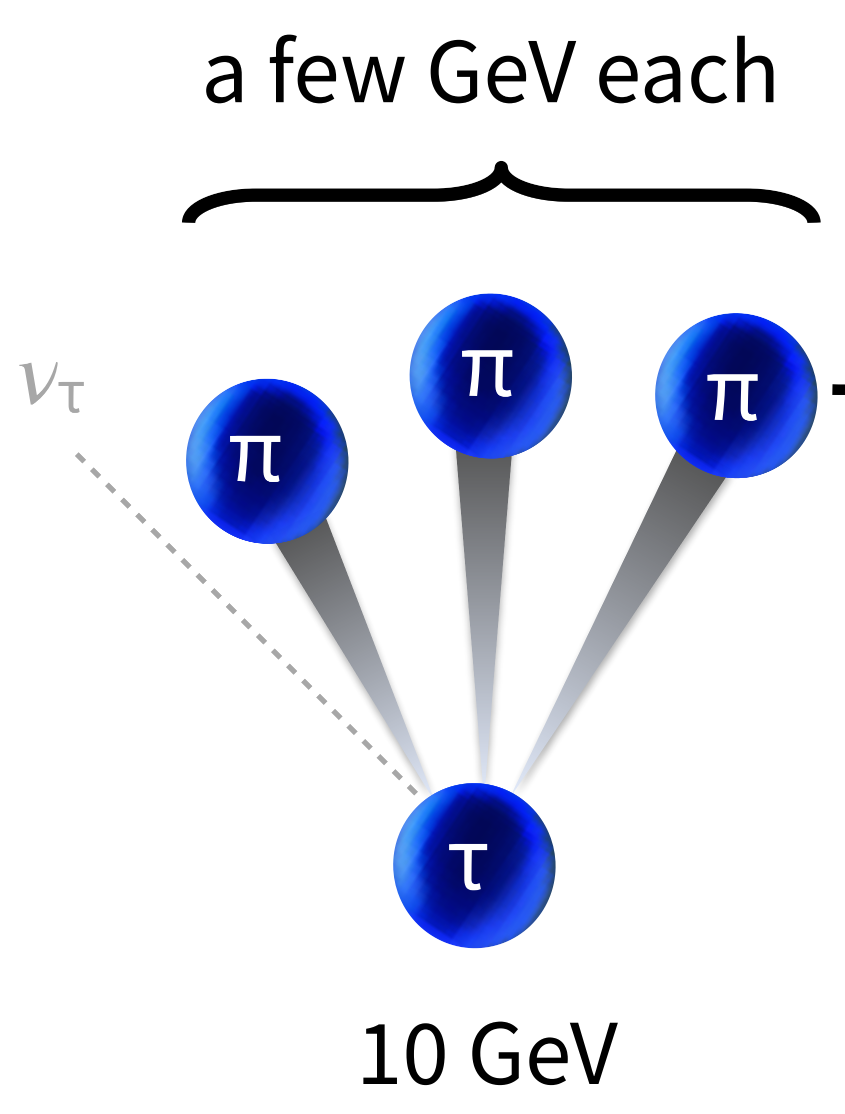

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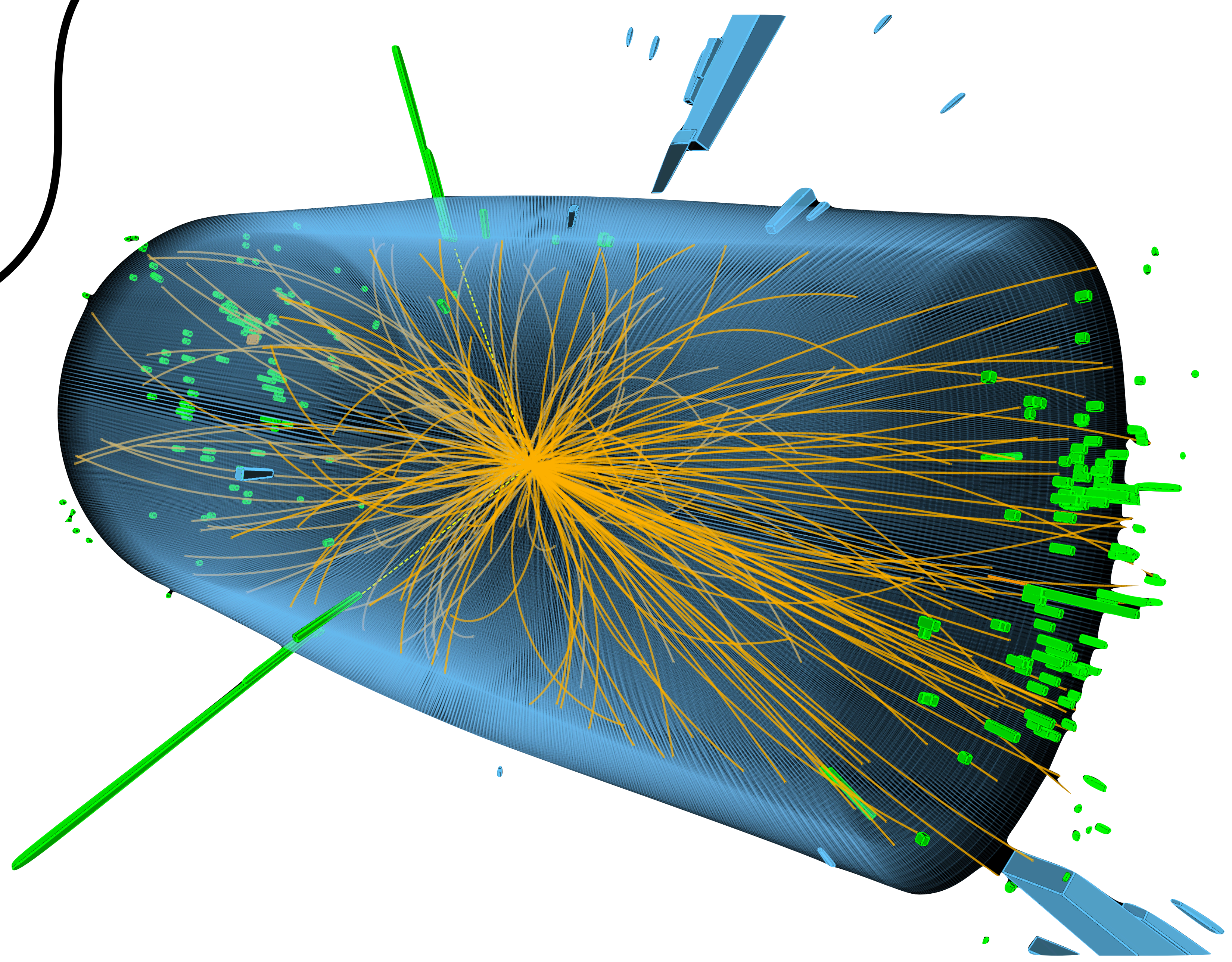

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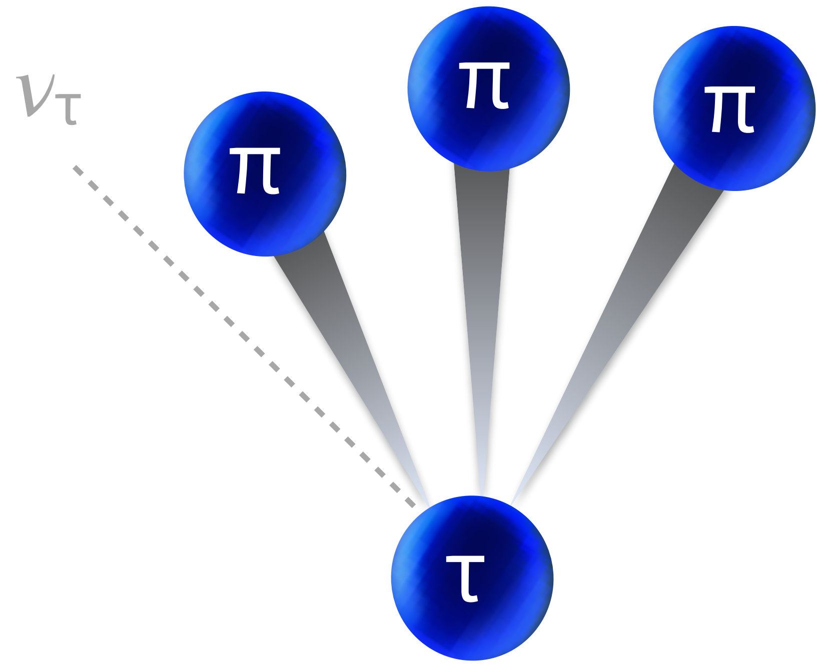
Finding 3 out of 1000 is very tough work
→ No algorithm has existed to efficiently identify this!

Built a new algorithm to identify low-momentum τ

Target τ → πππν



Try to find **combination of three pions** that …

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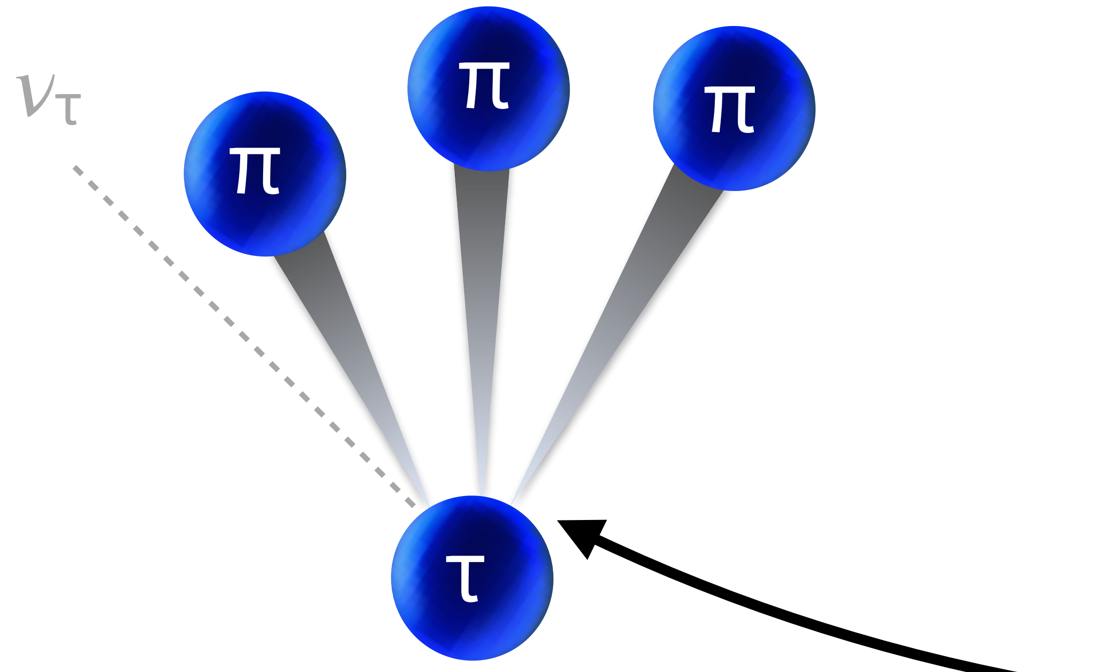

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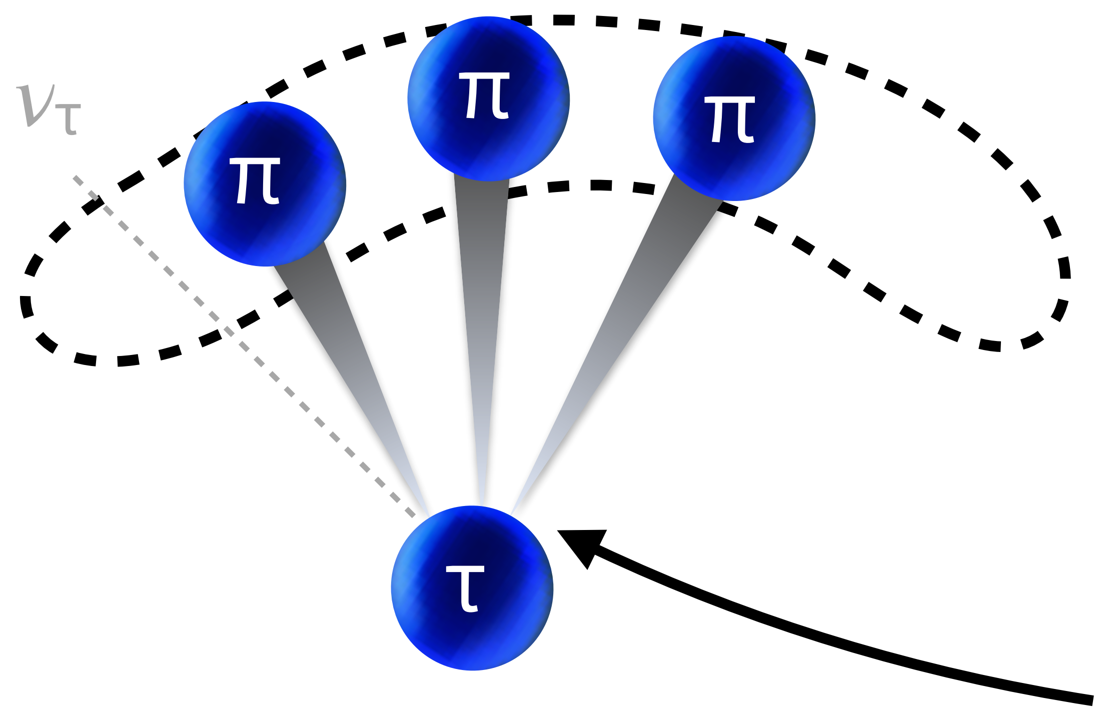

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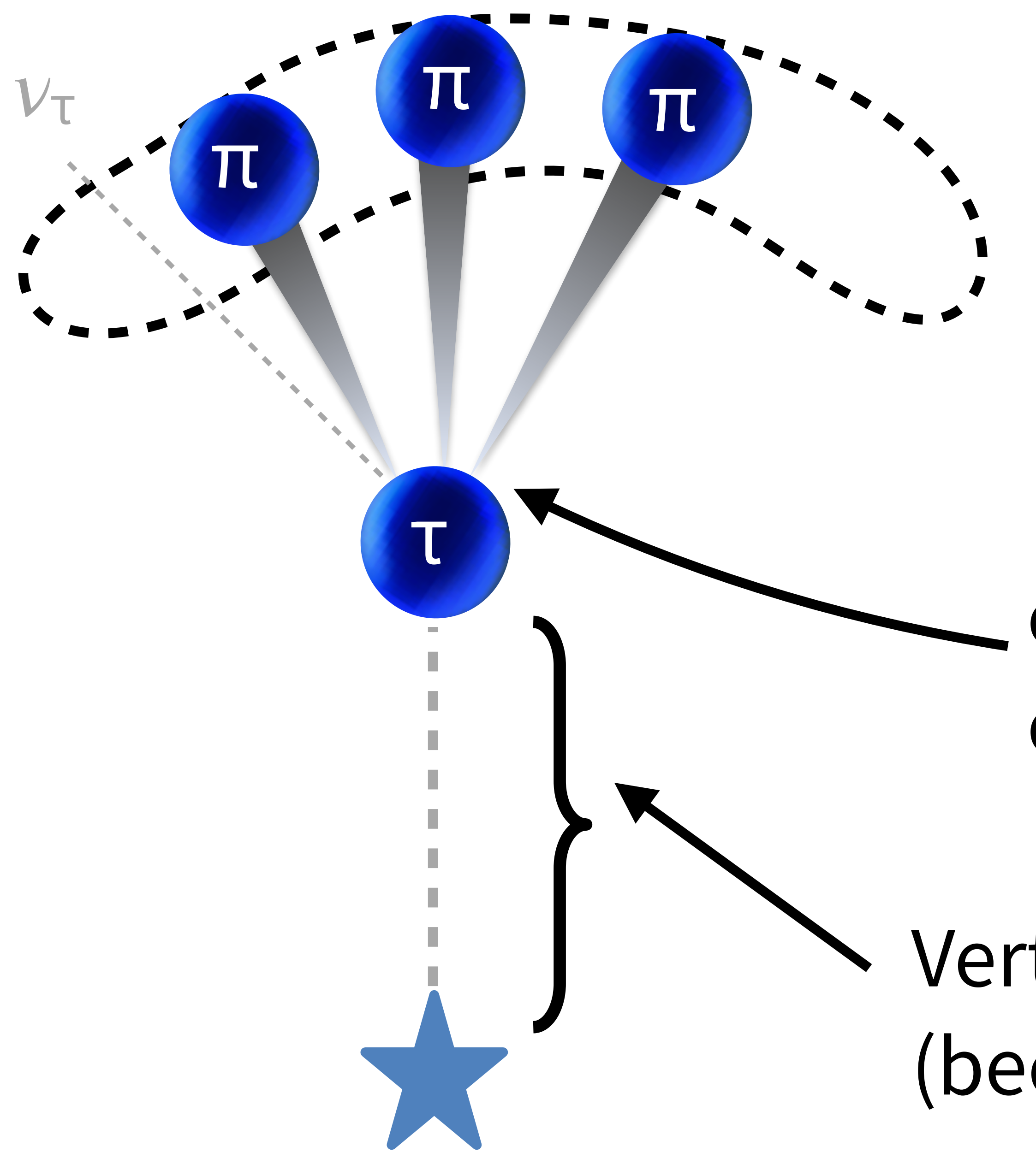

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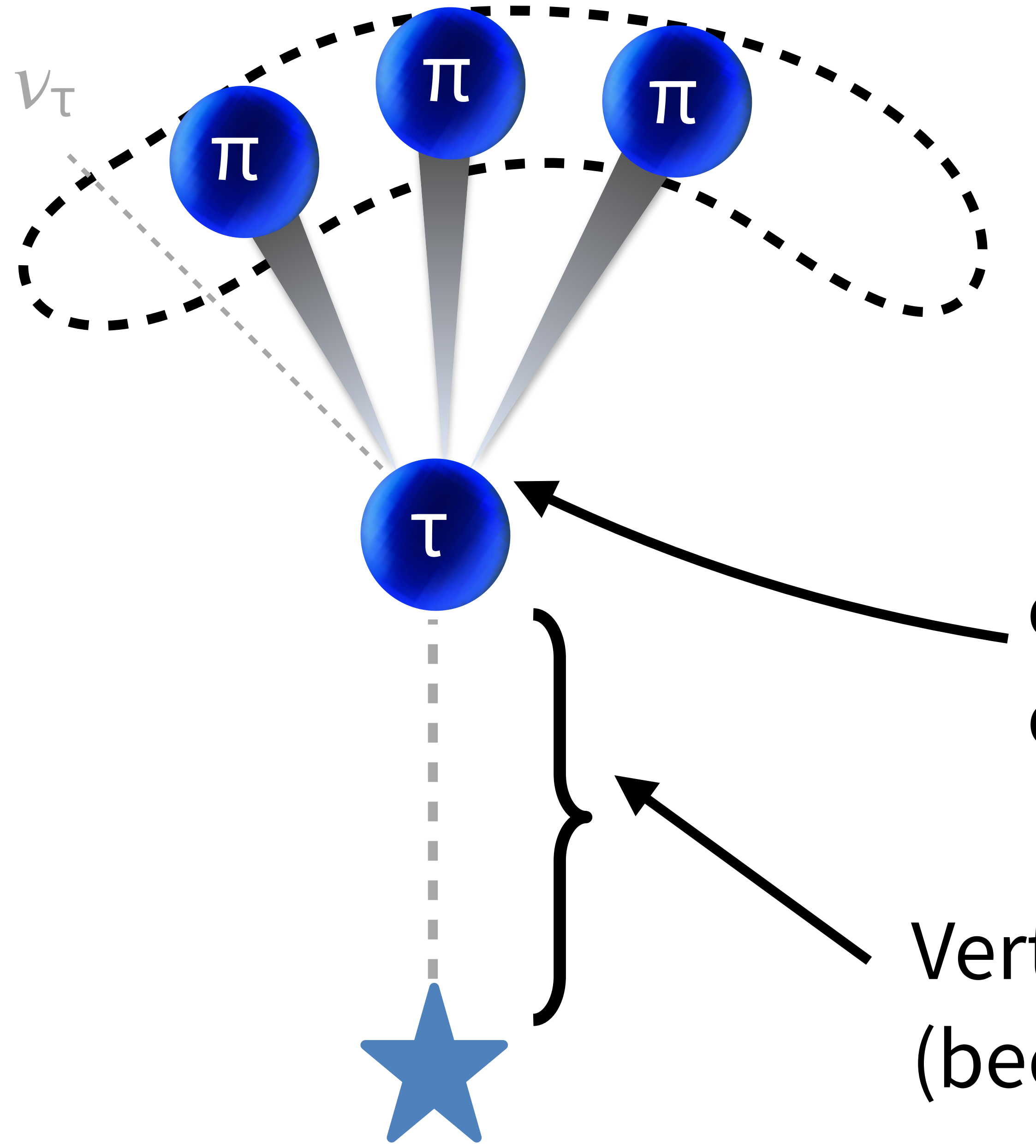

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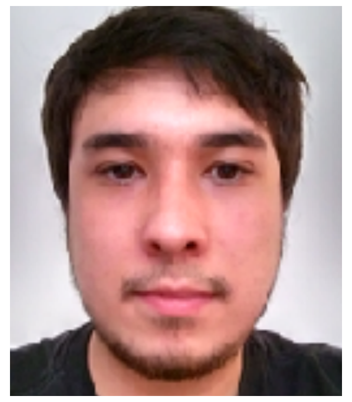
C. Galloni


V. Mikuni

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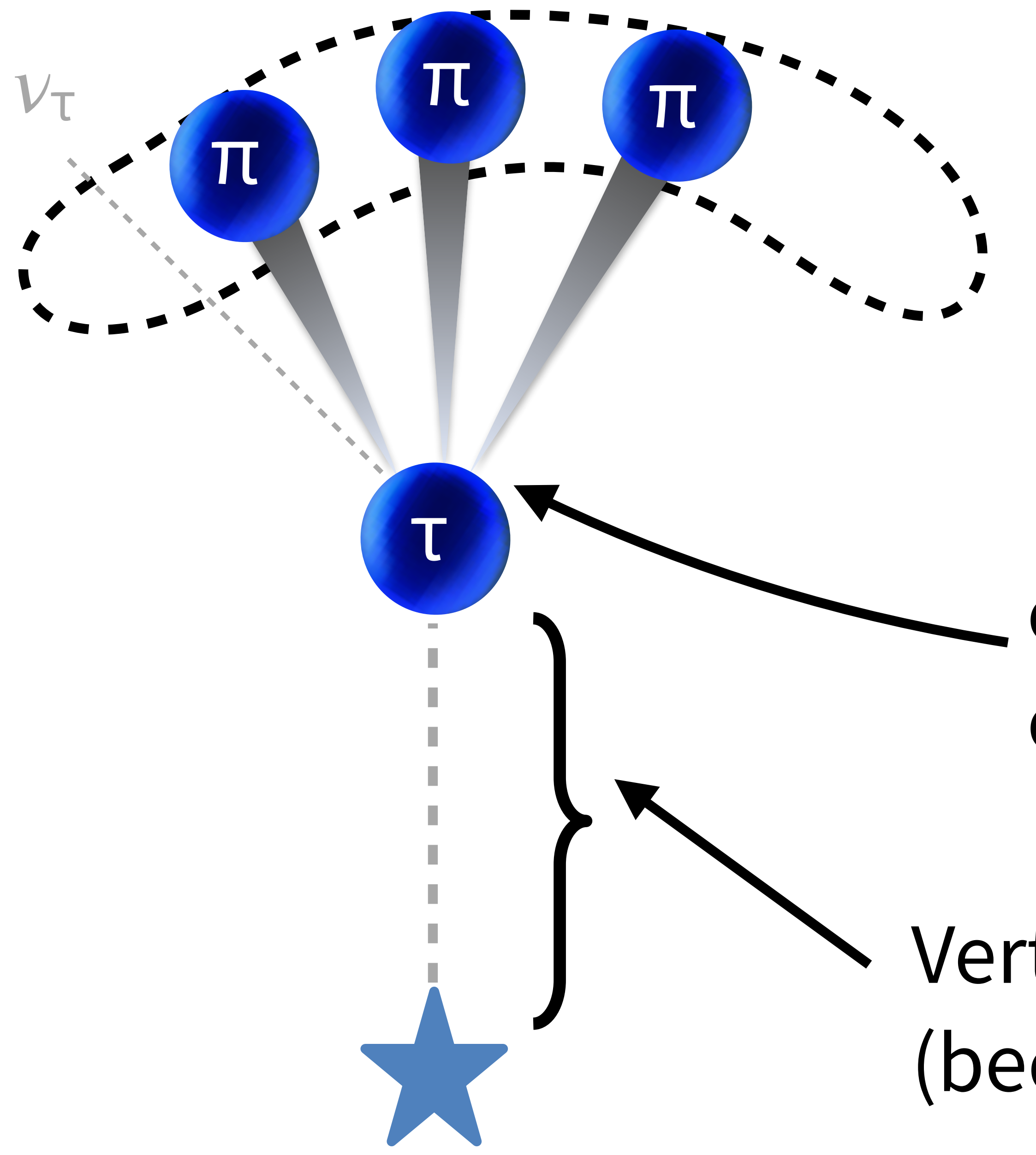

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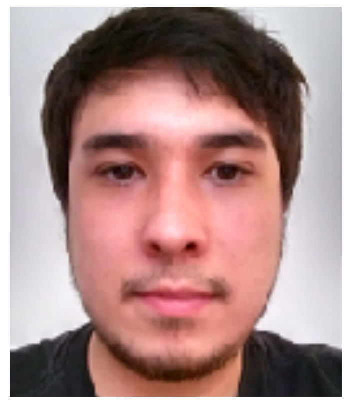

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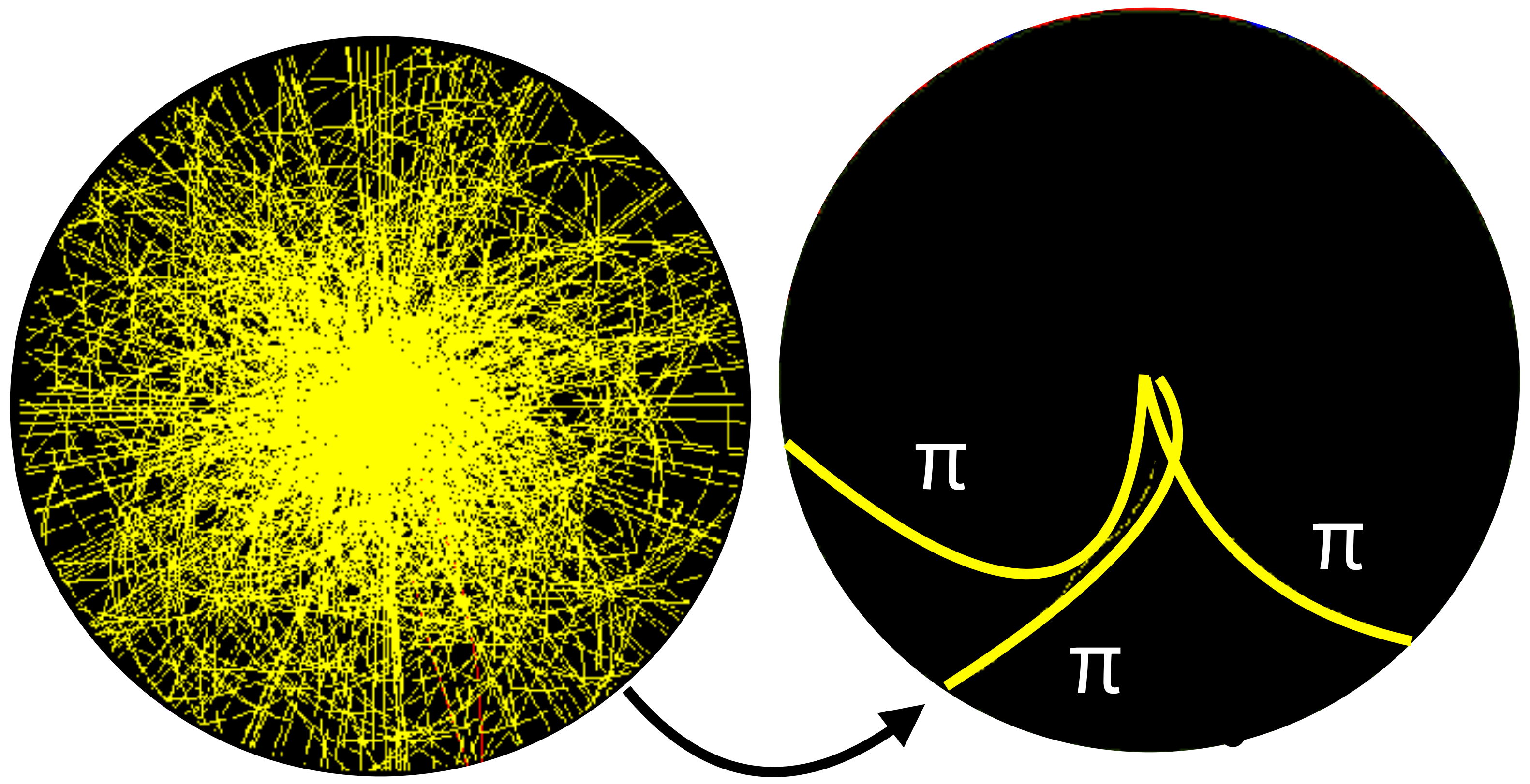

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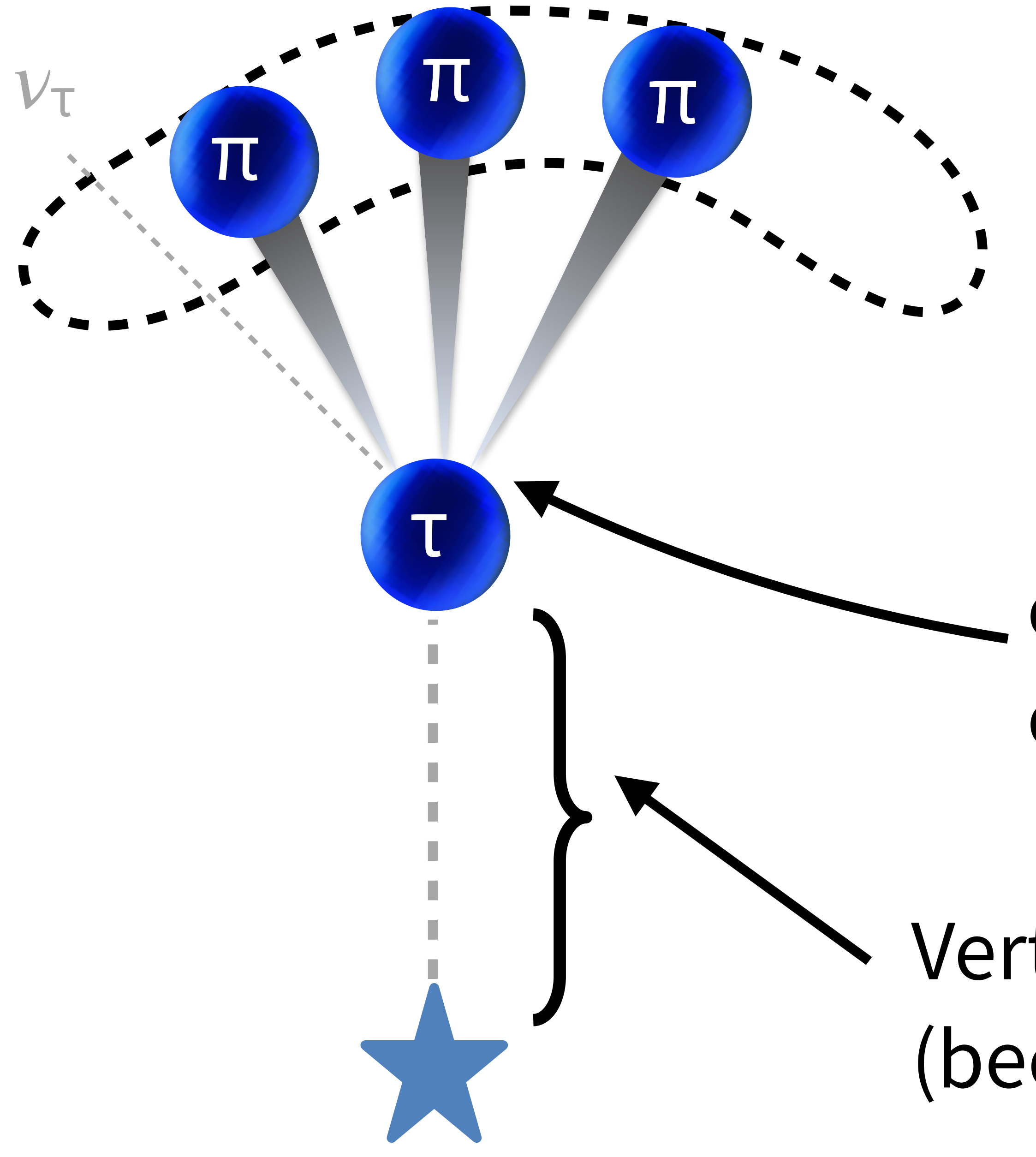

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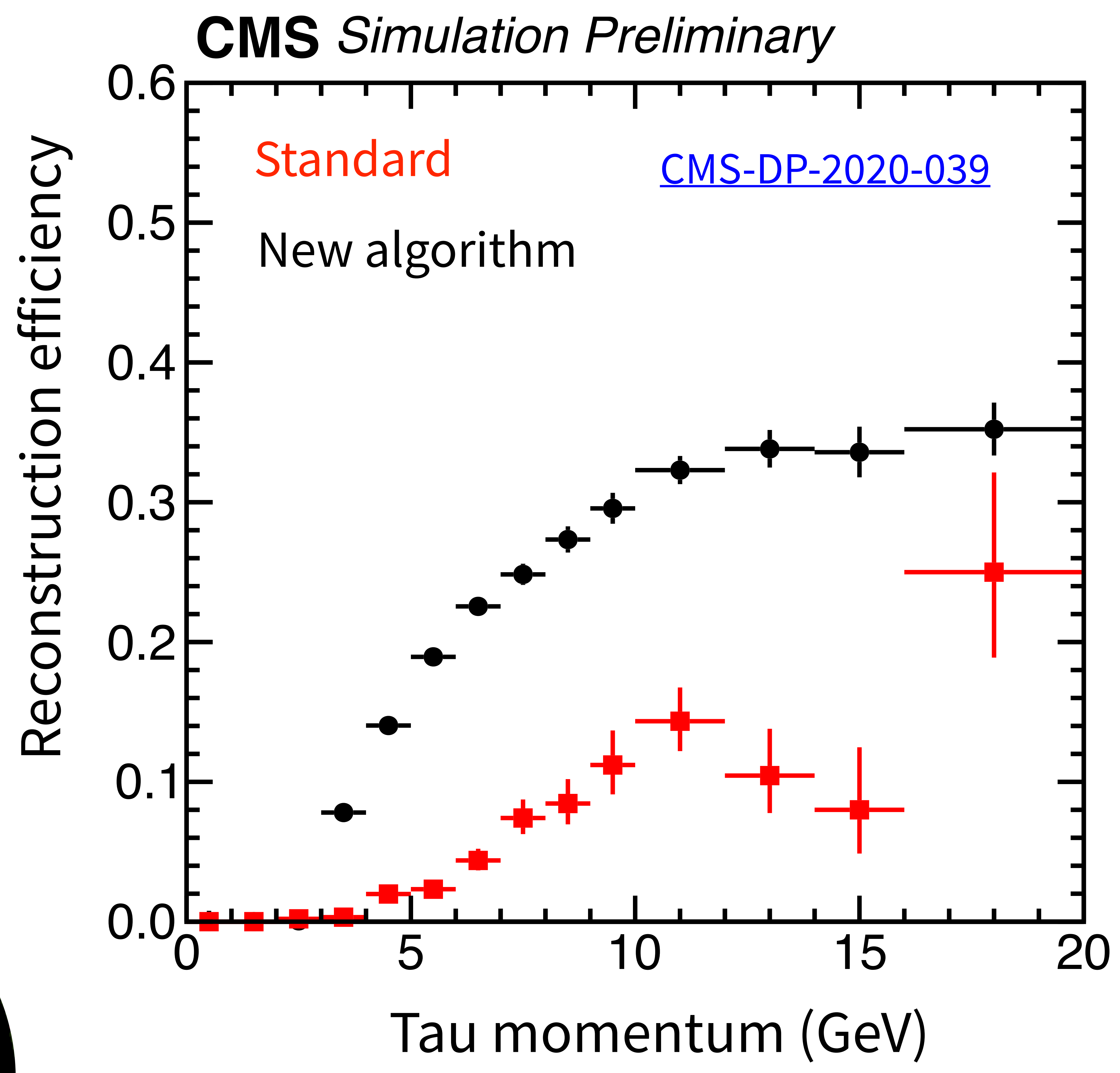

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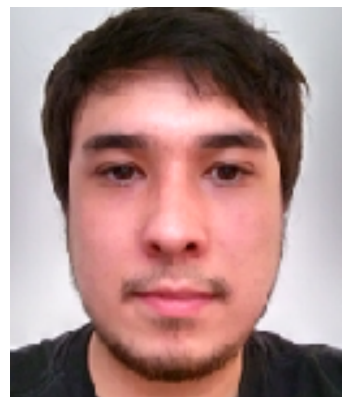

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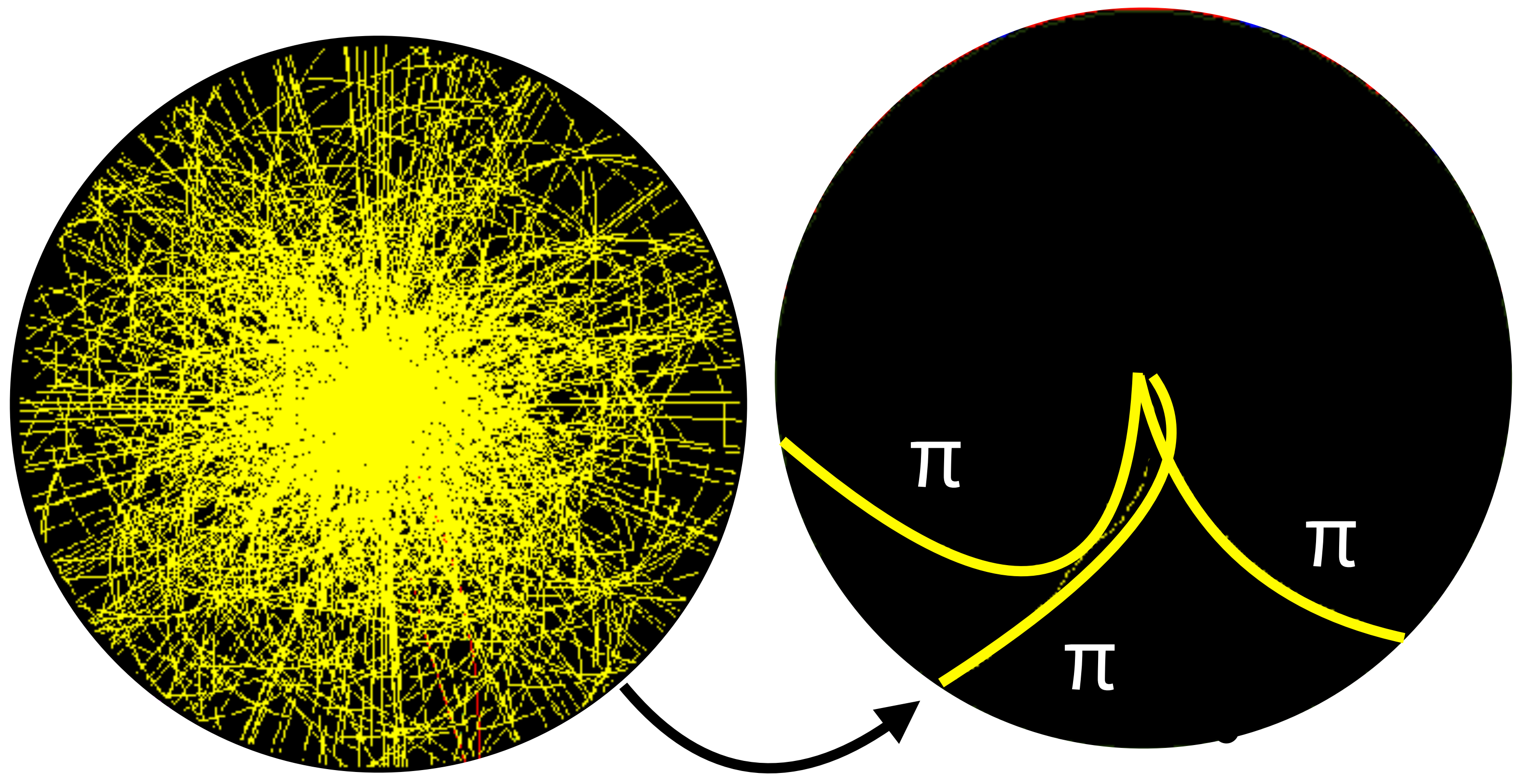

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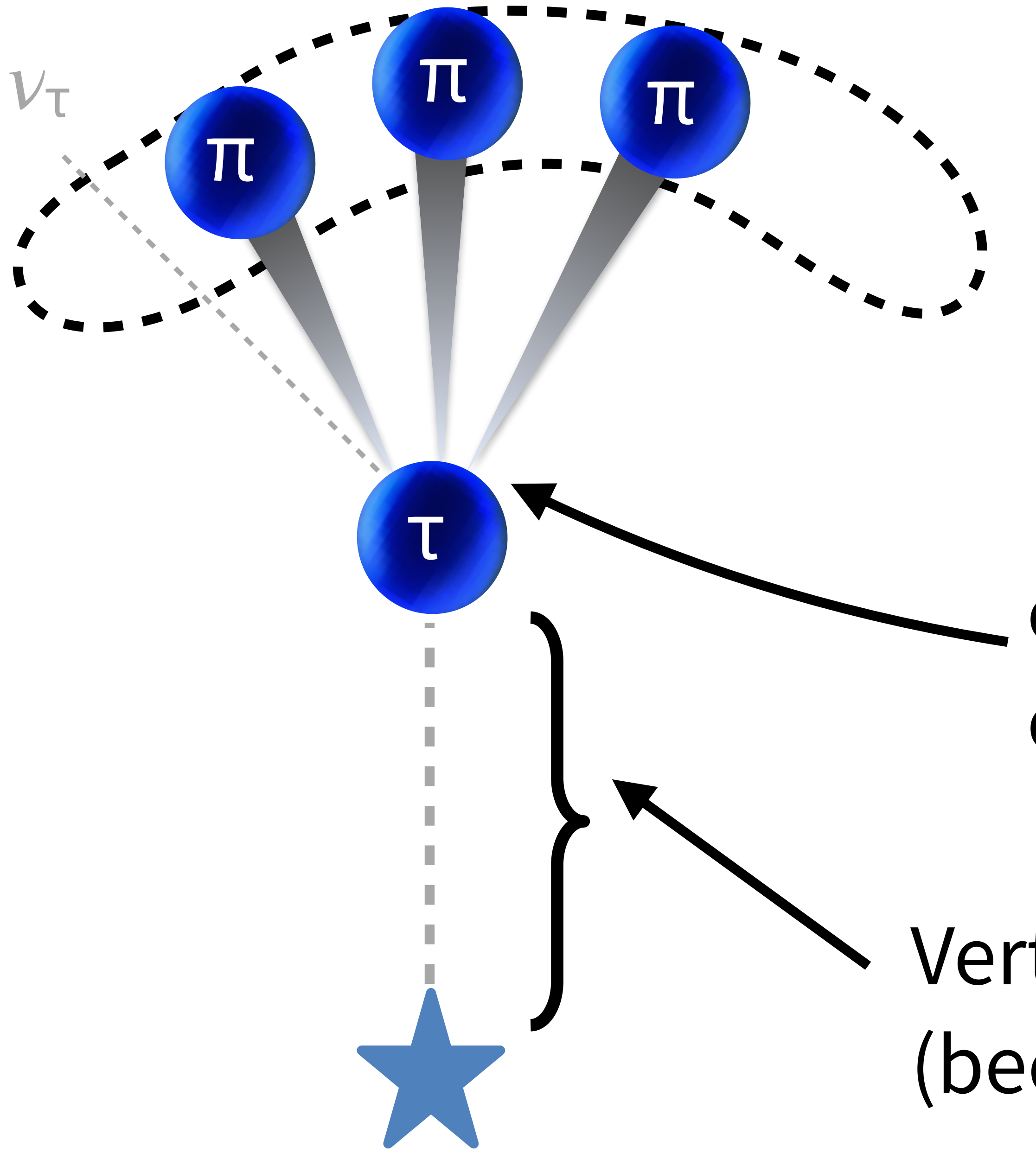

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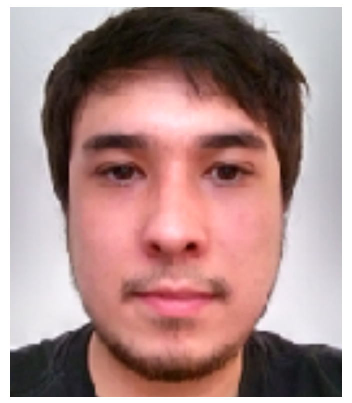

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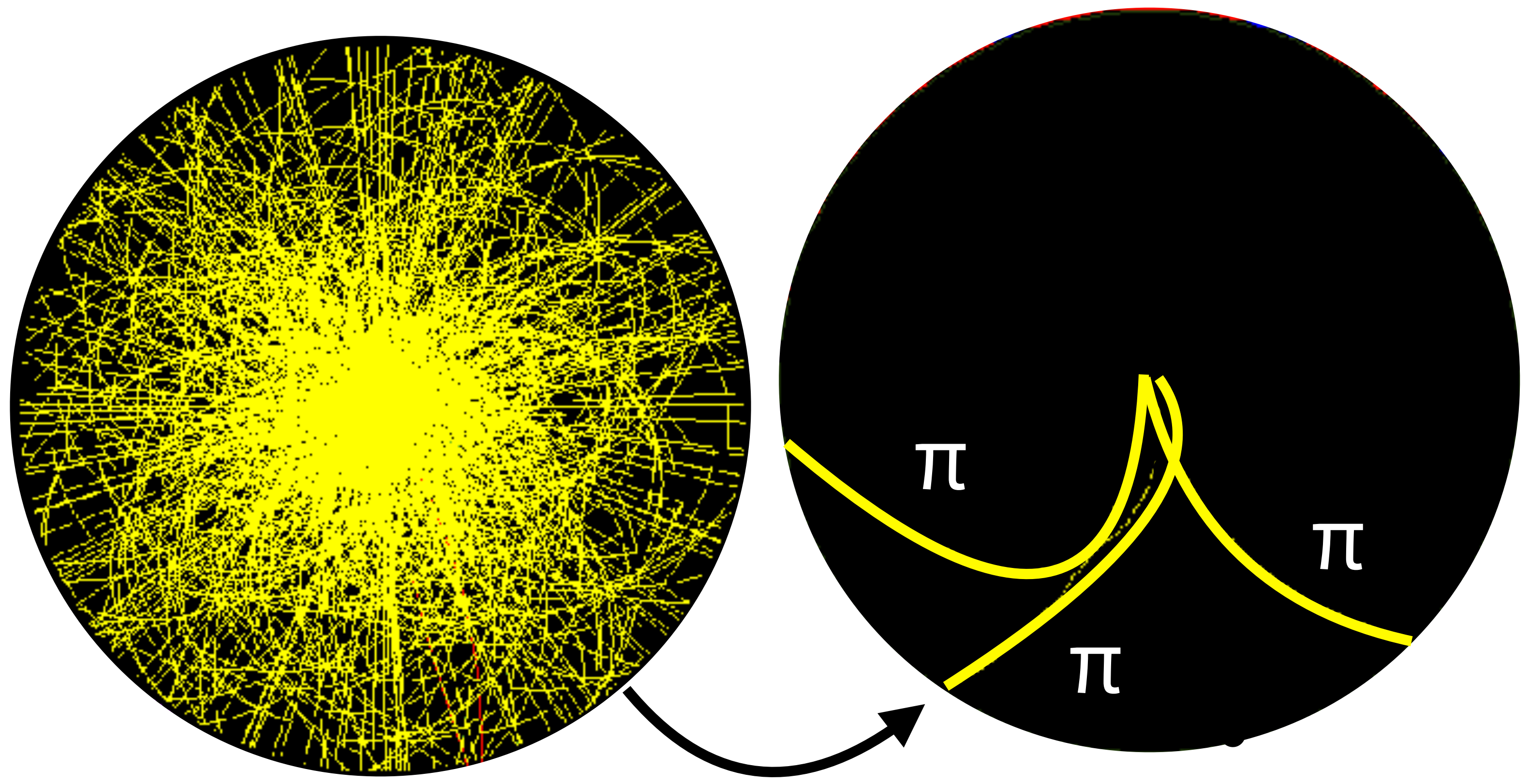

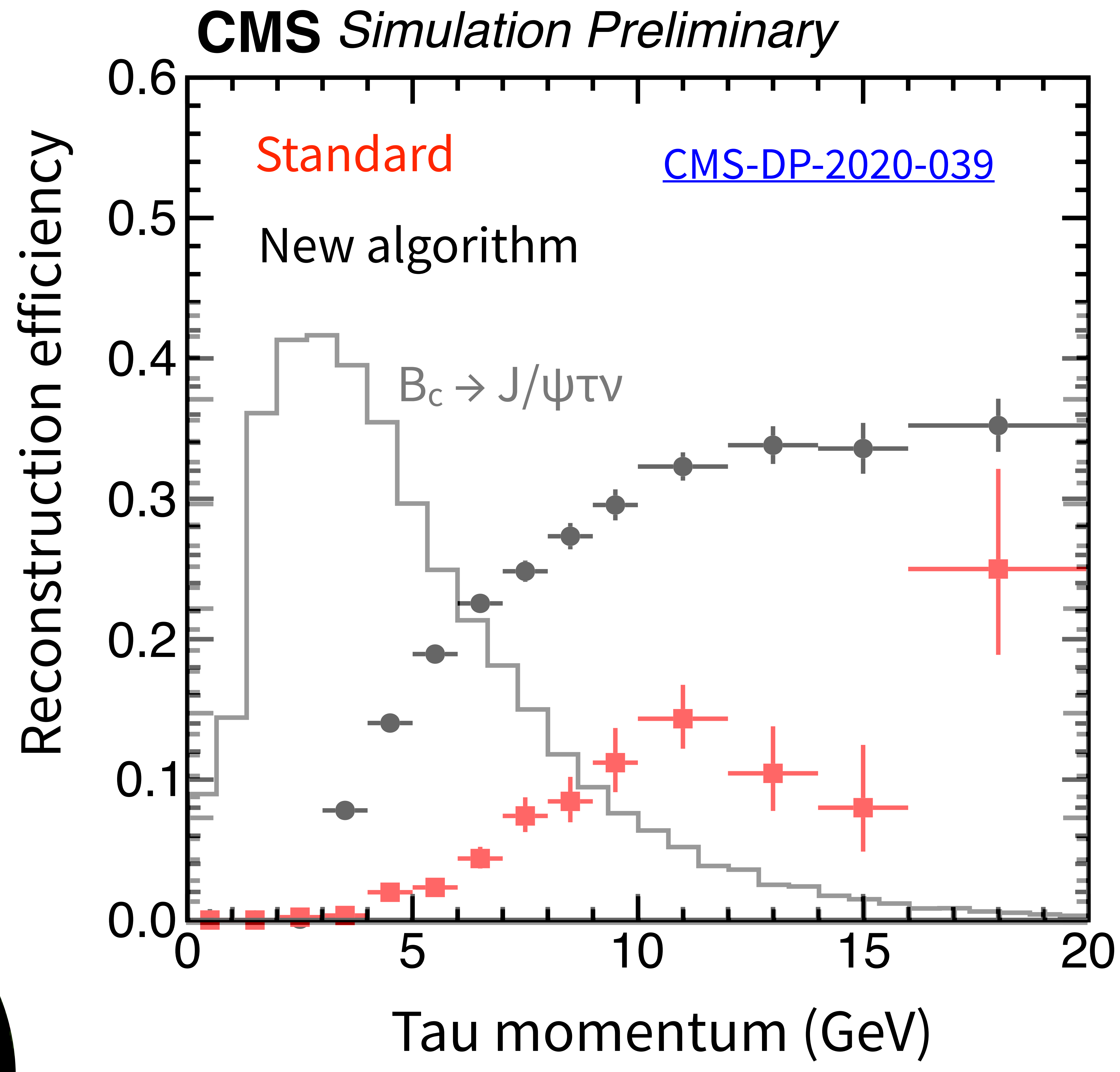

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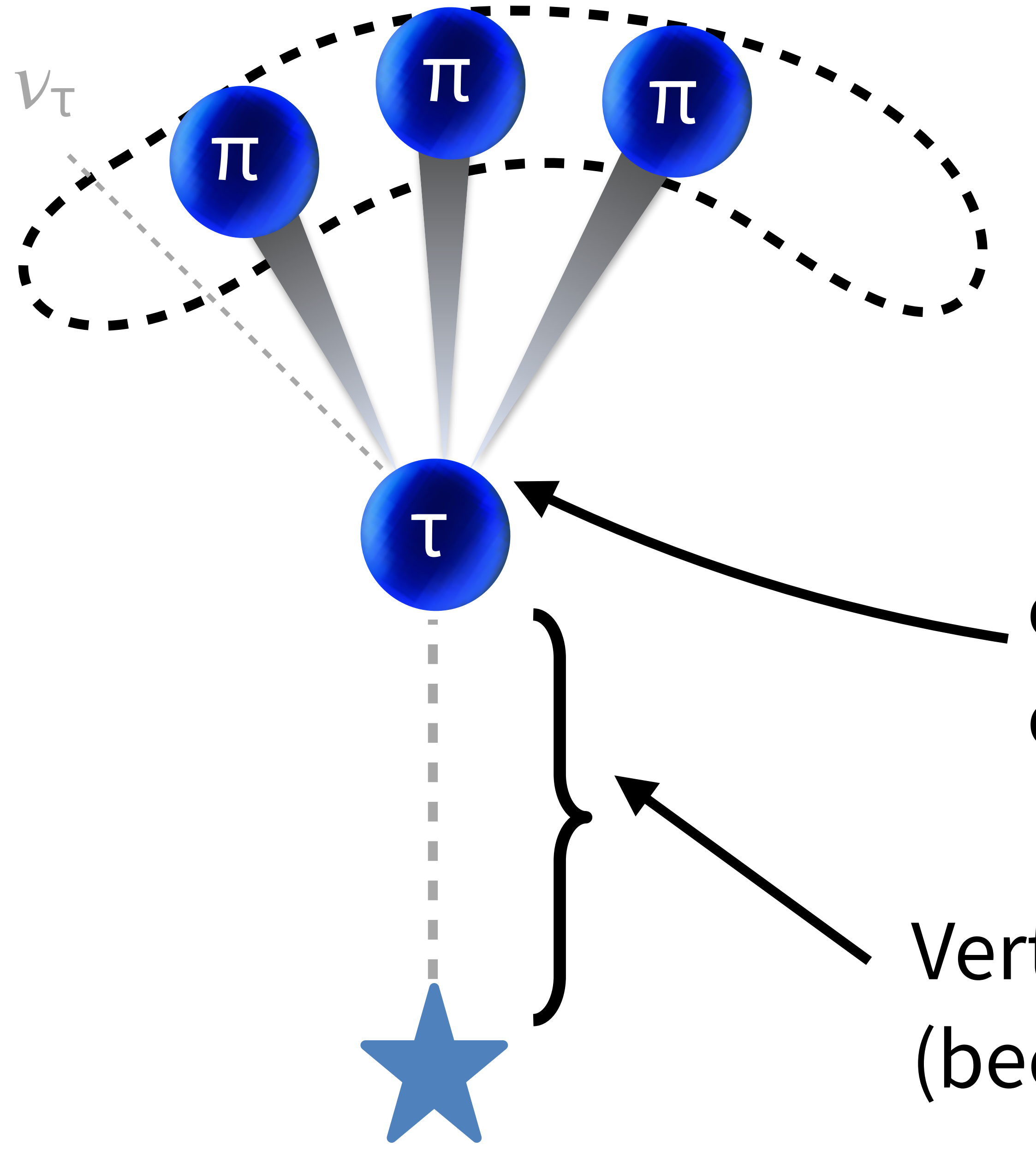

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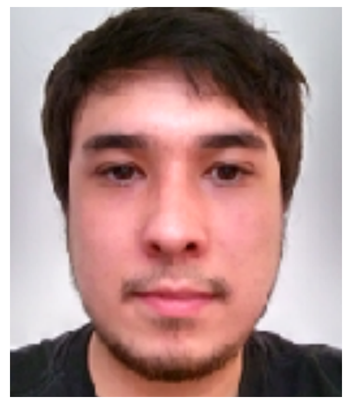

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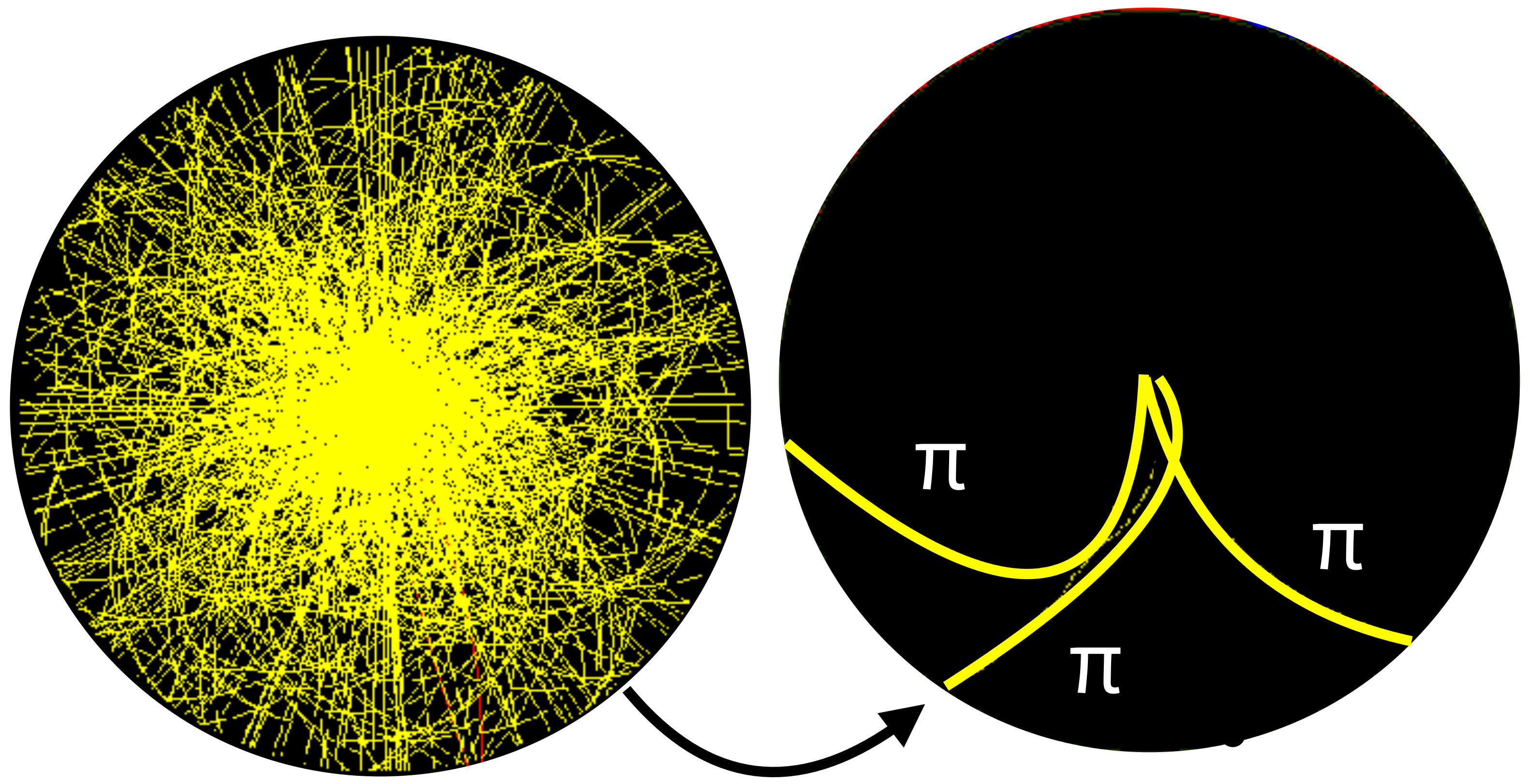
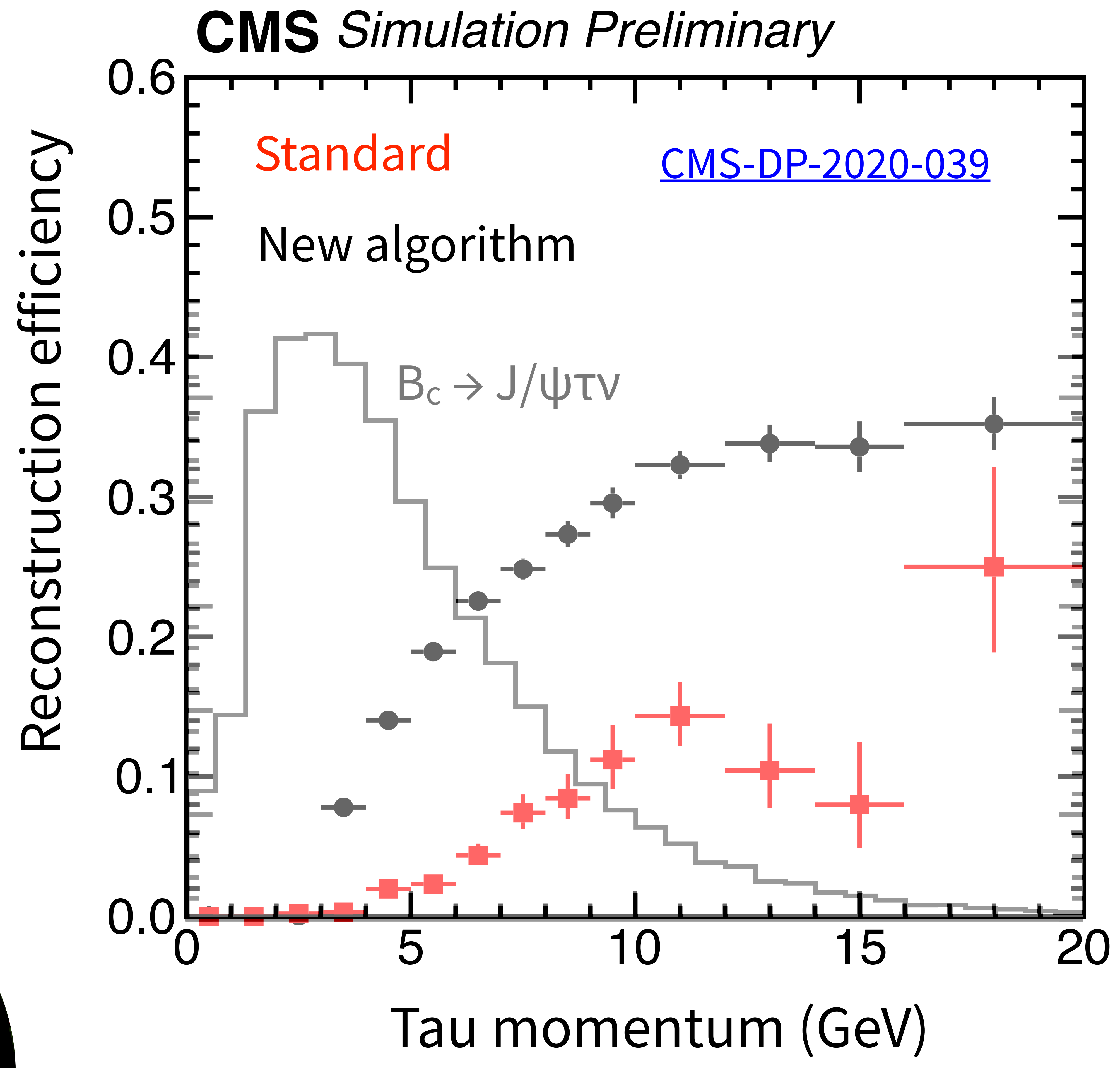
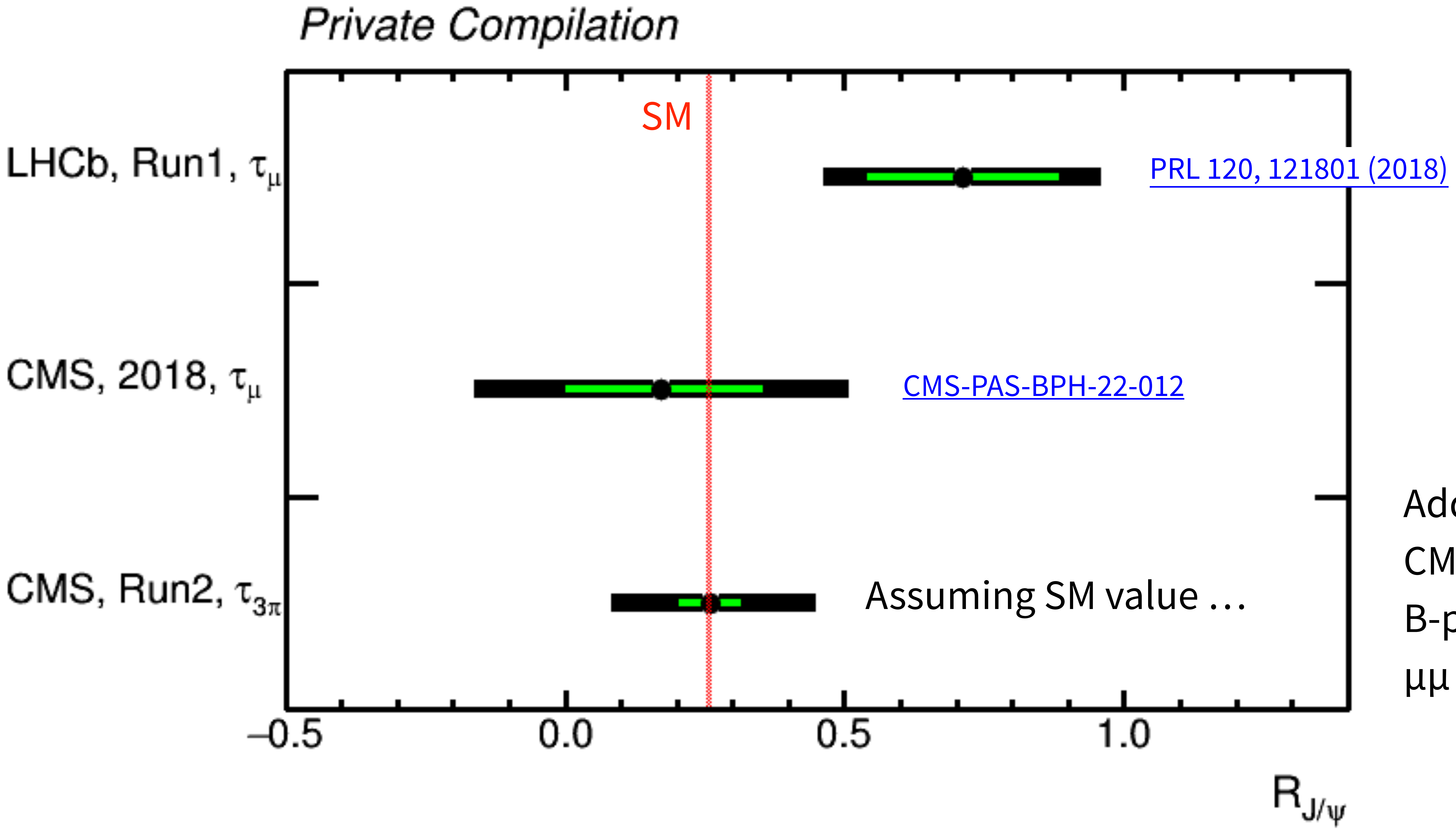




→ Factor 5 gain in terms of signal efficiency

I'm leading $R_{J/\psi} = \dfrac{\mathcal{B}(B_c \to J/\psi\tau\nu)}{\mathcal{B}(B_c \to J/\psi\mu\nu)}$ which is close to completion



Add another example of the CMS' excellent capability for B-physics using the μμ final state!

Low-p_T tau reco. opened up new possibilities for CMS

- B-physics measurements with taus

M. Huwlier

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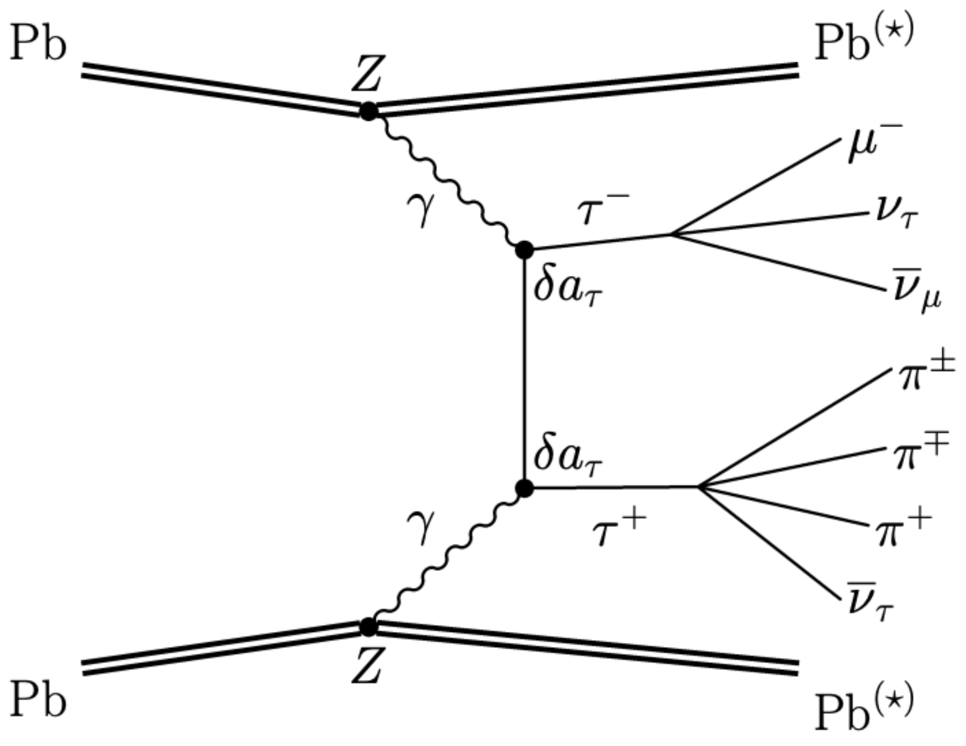

arXiv:2206.05192

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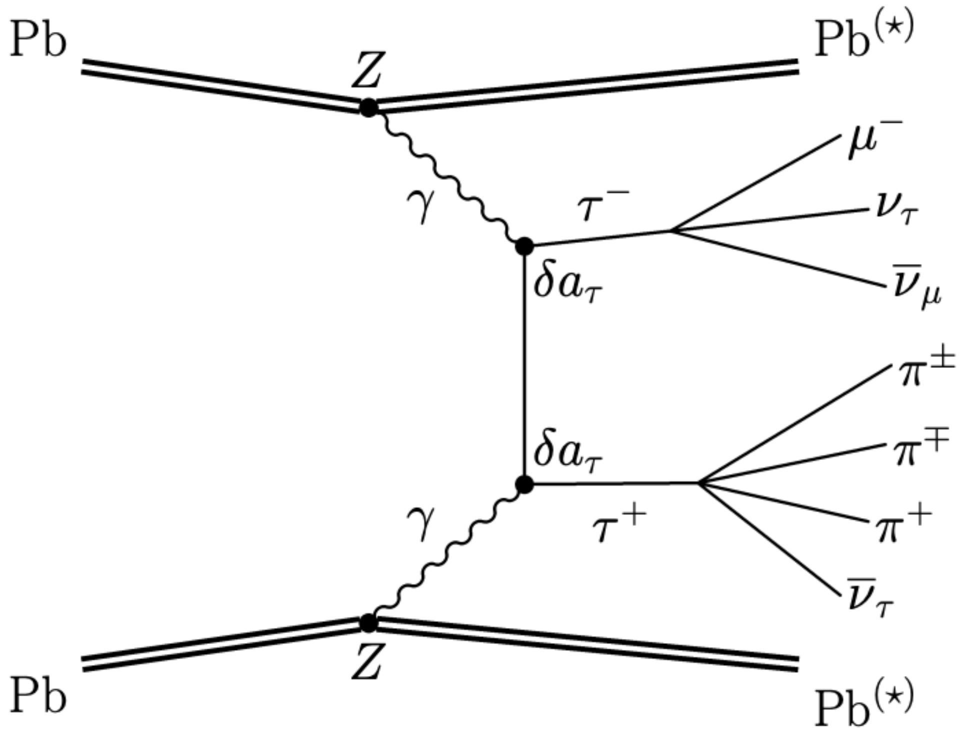
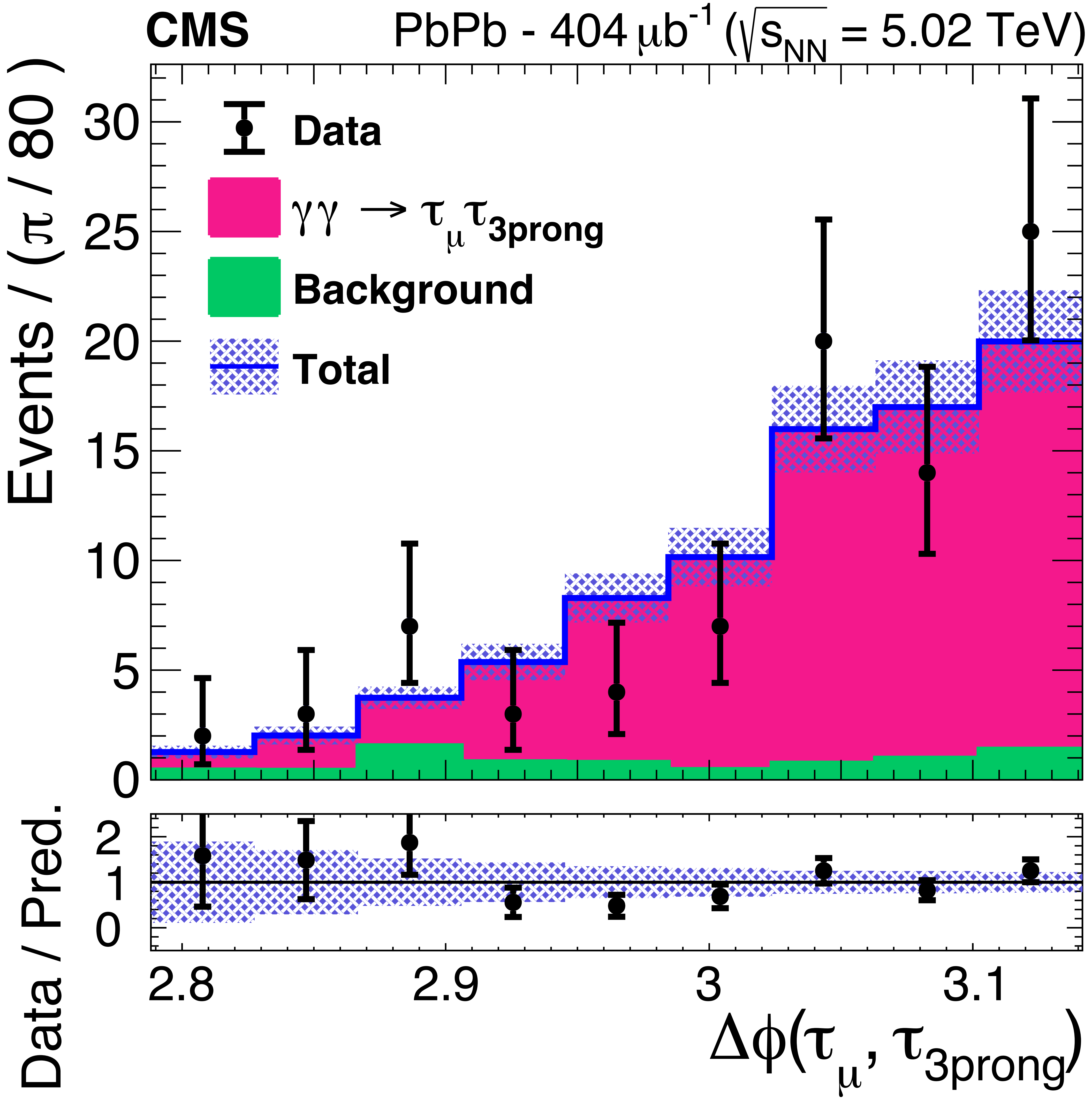


First observation at the LHC after the last measurement from LEP (2004)



arXiv:2206.05192

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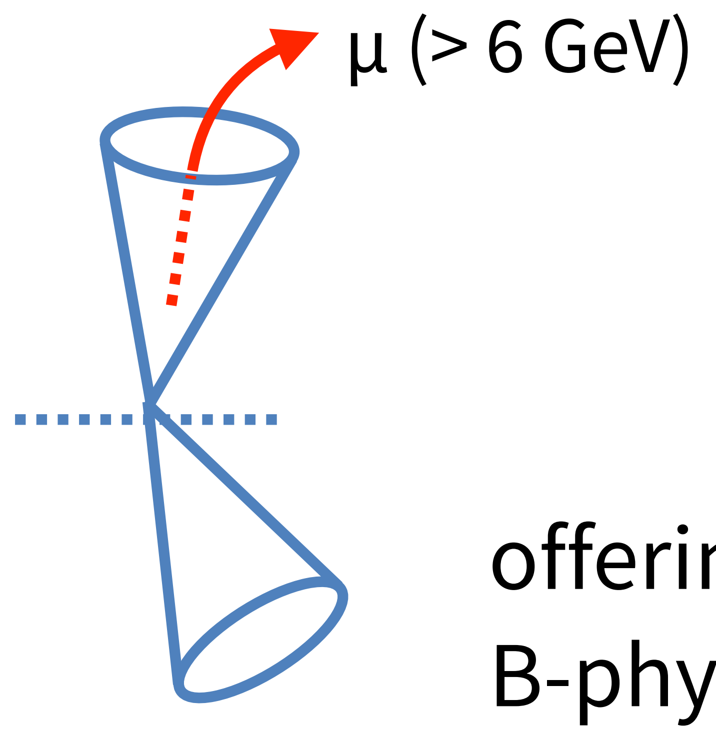

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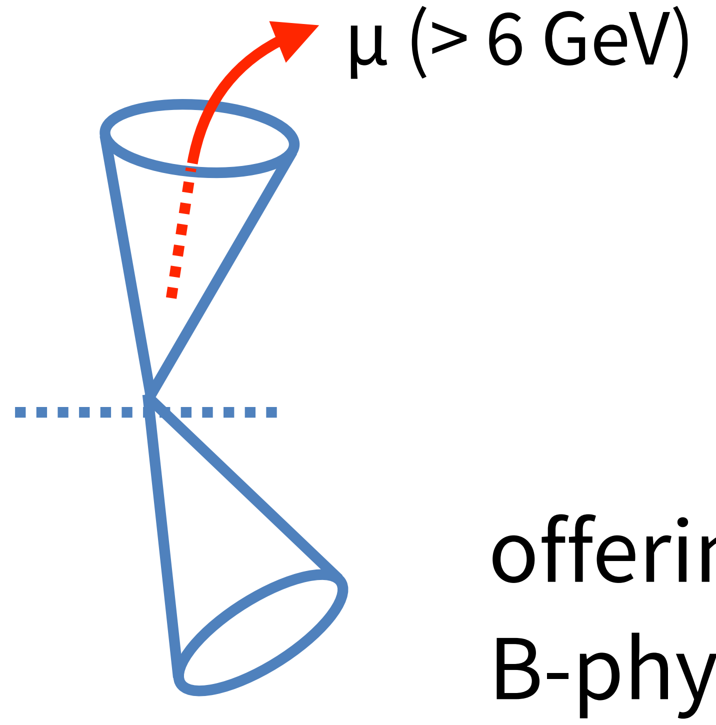

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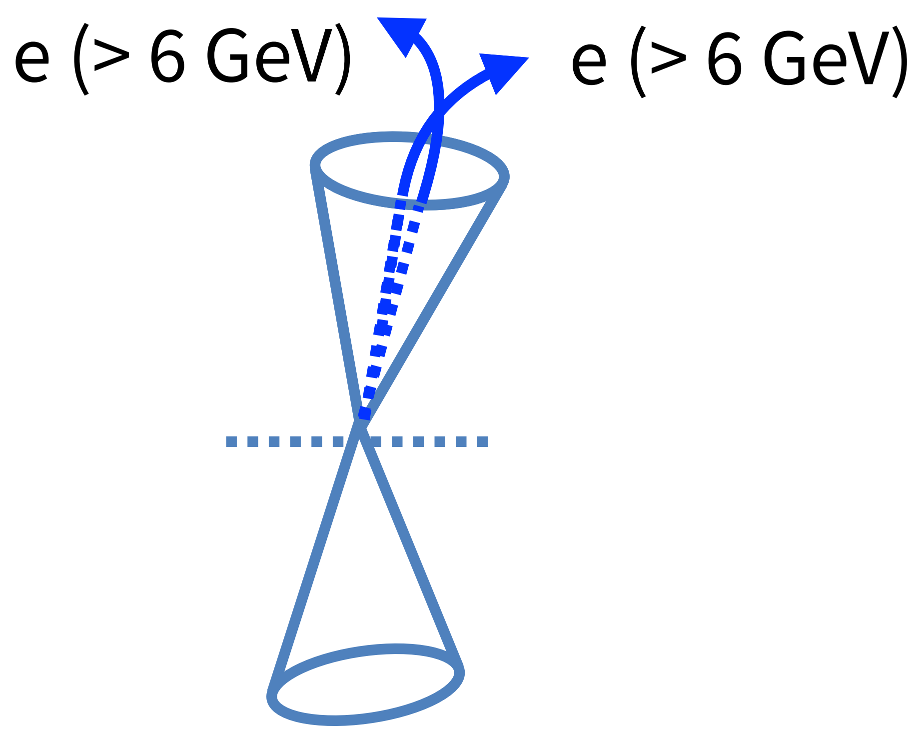

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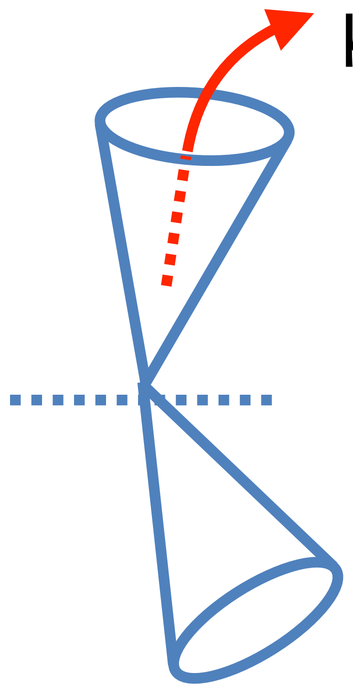

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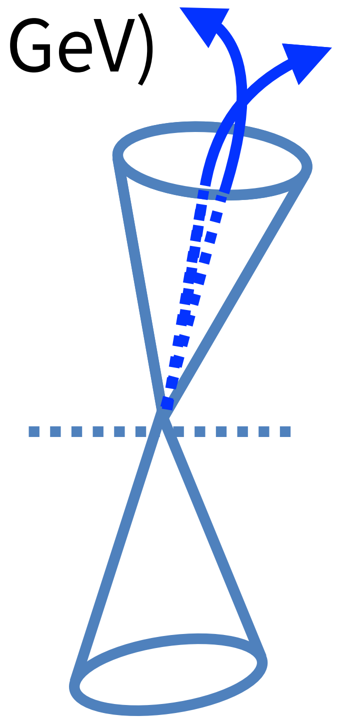
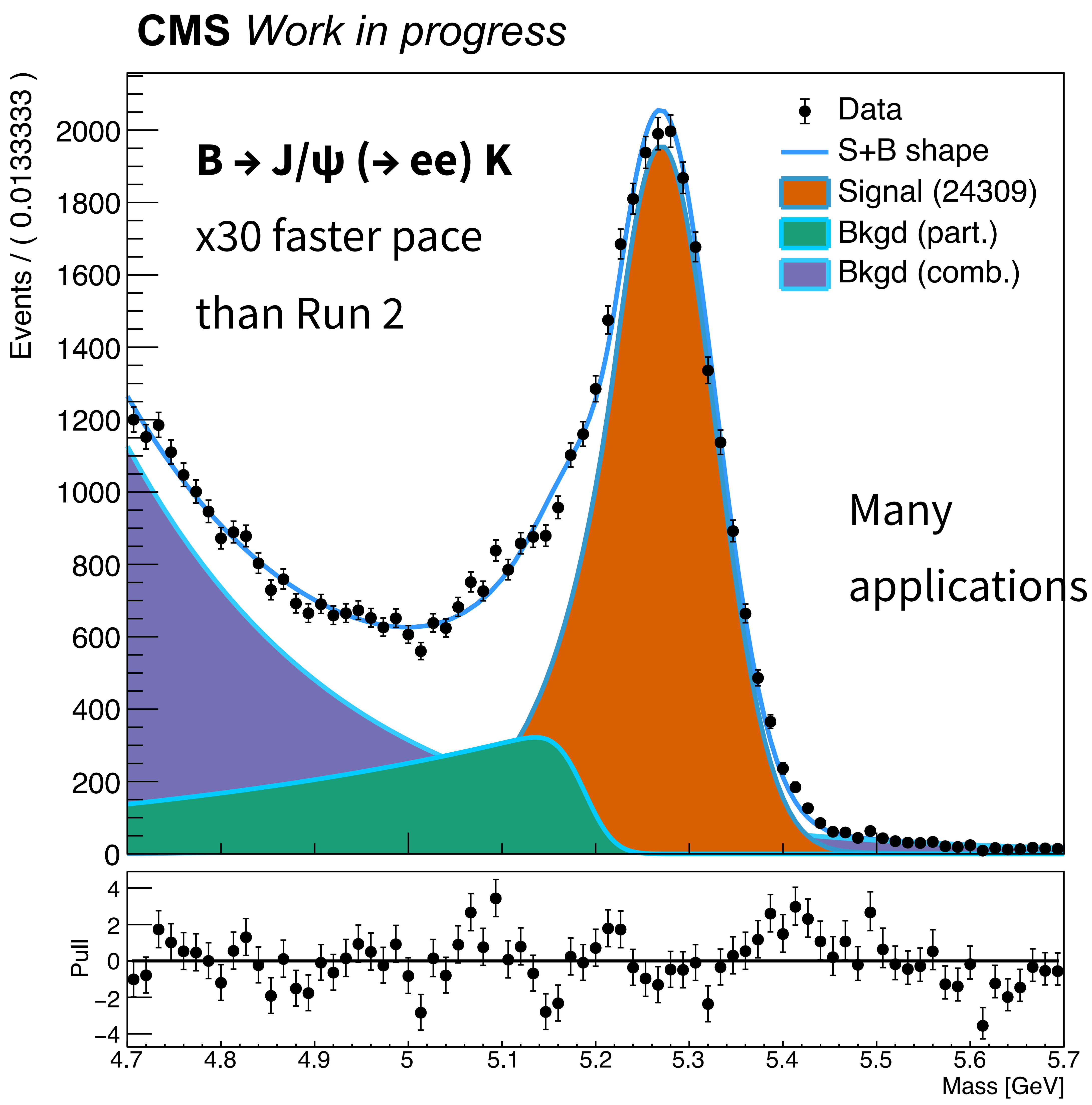
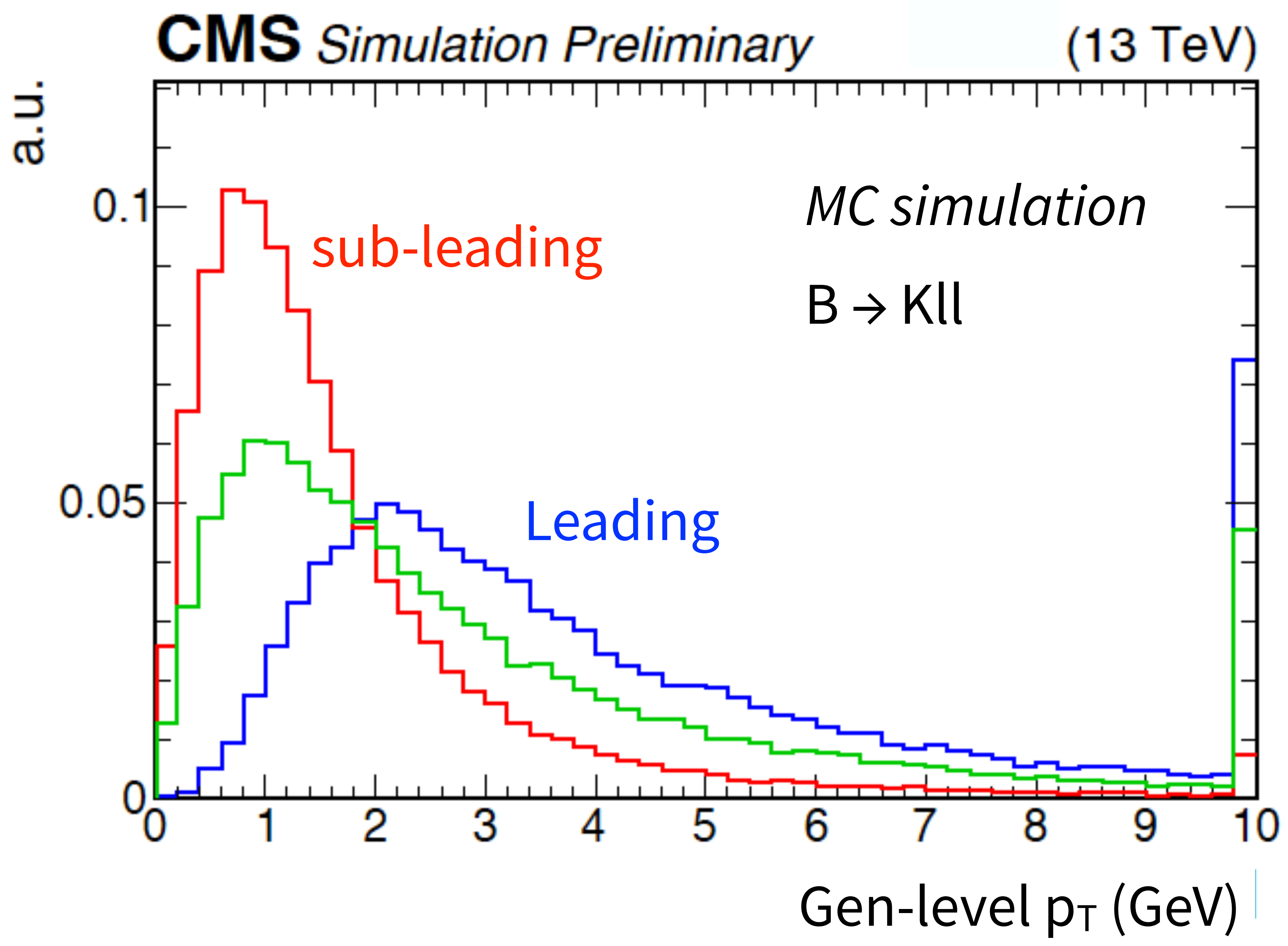




Many applications …

Low p_T electron reconstructions

Need to deal with low-p_T electrons



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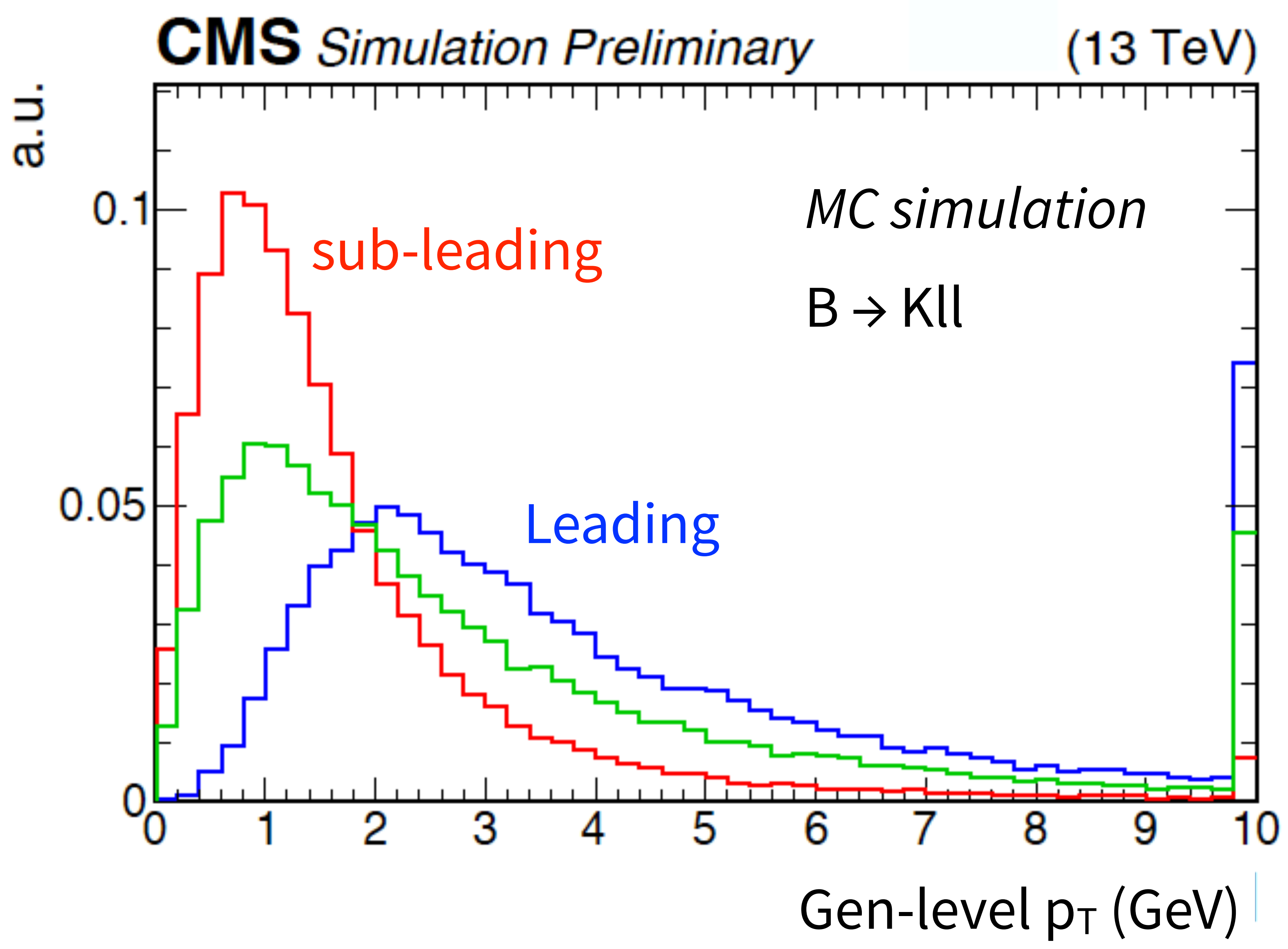

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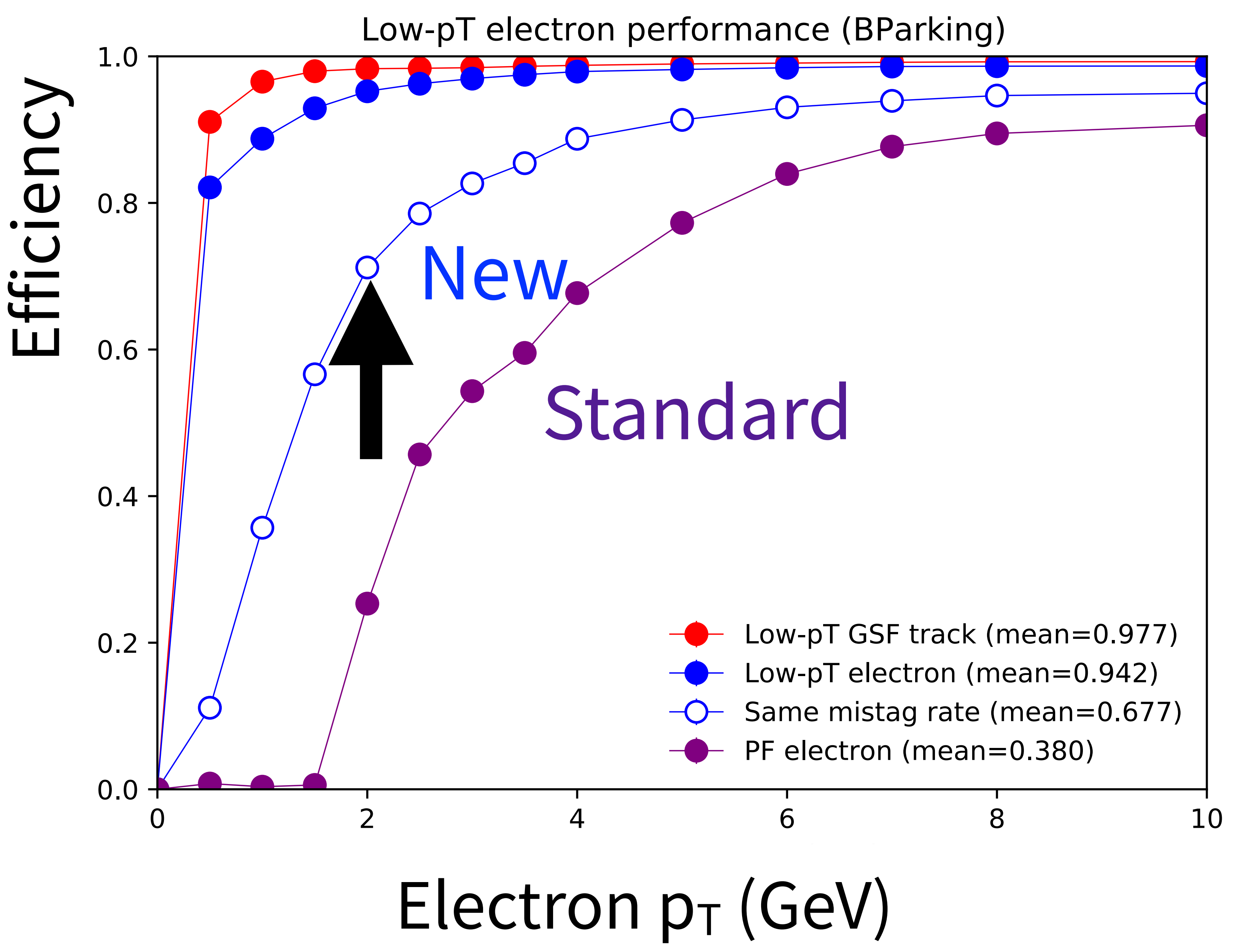

CMS-DP-2019-043

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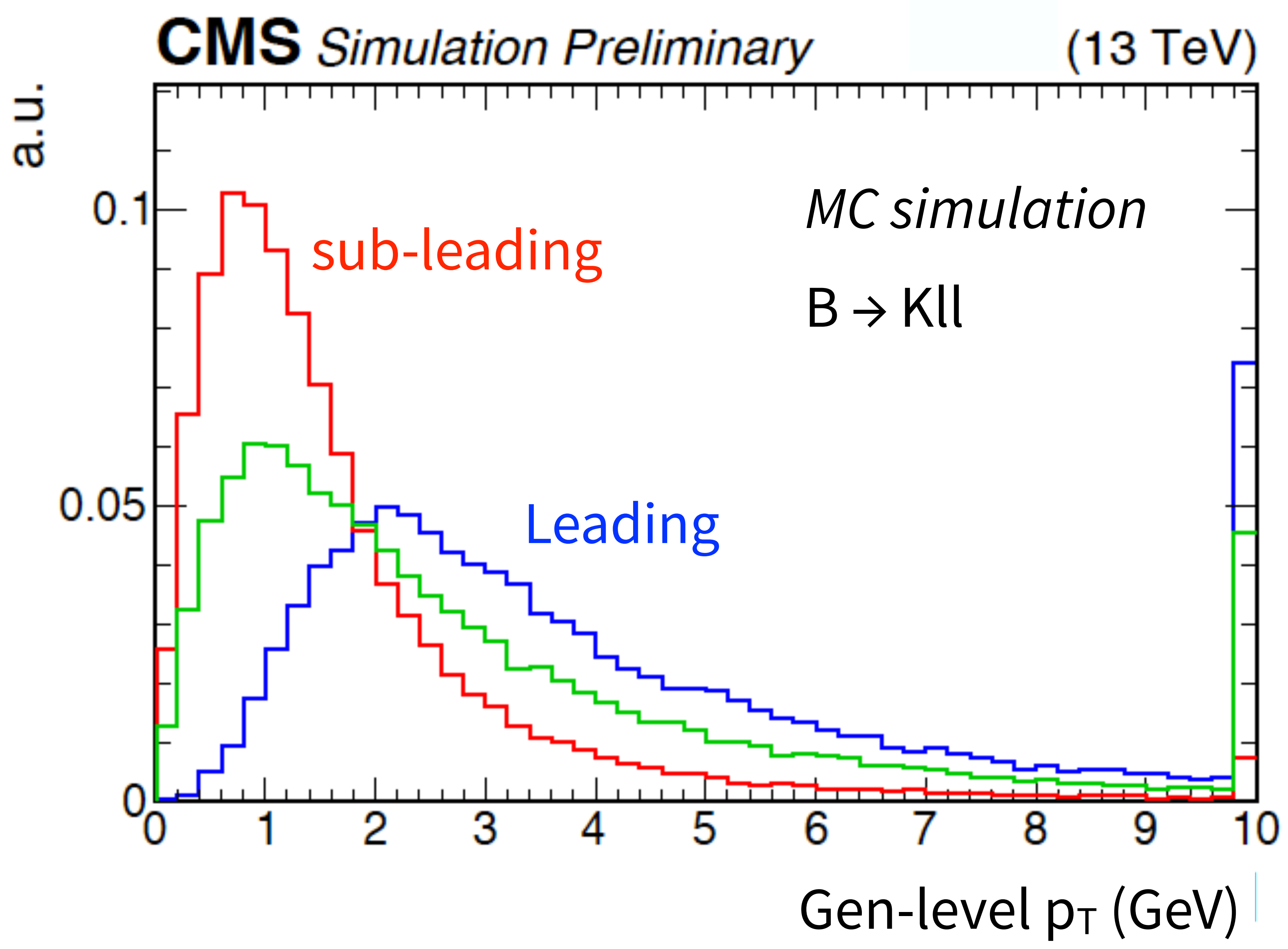

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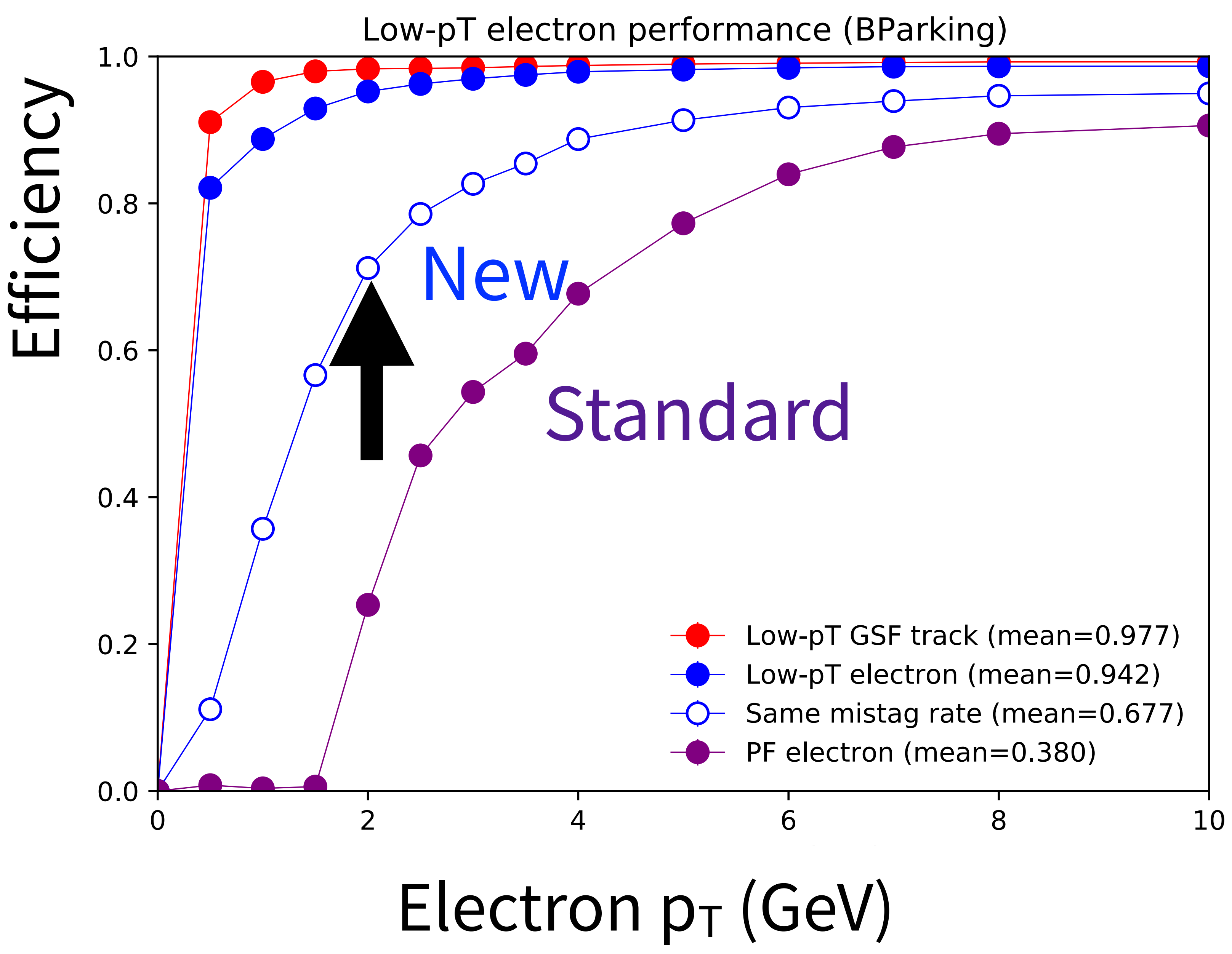

CMS-DP-2019-043

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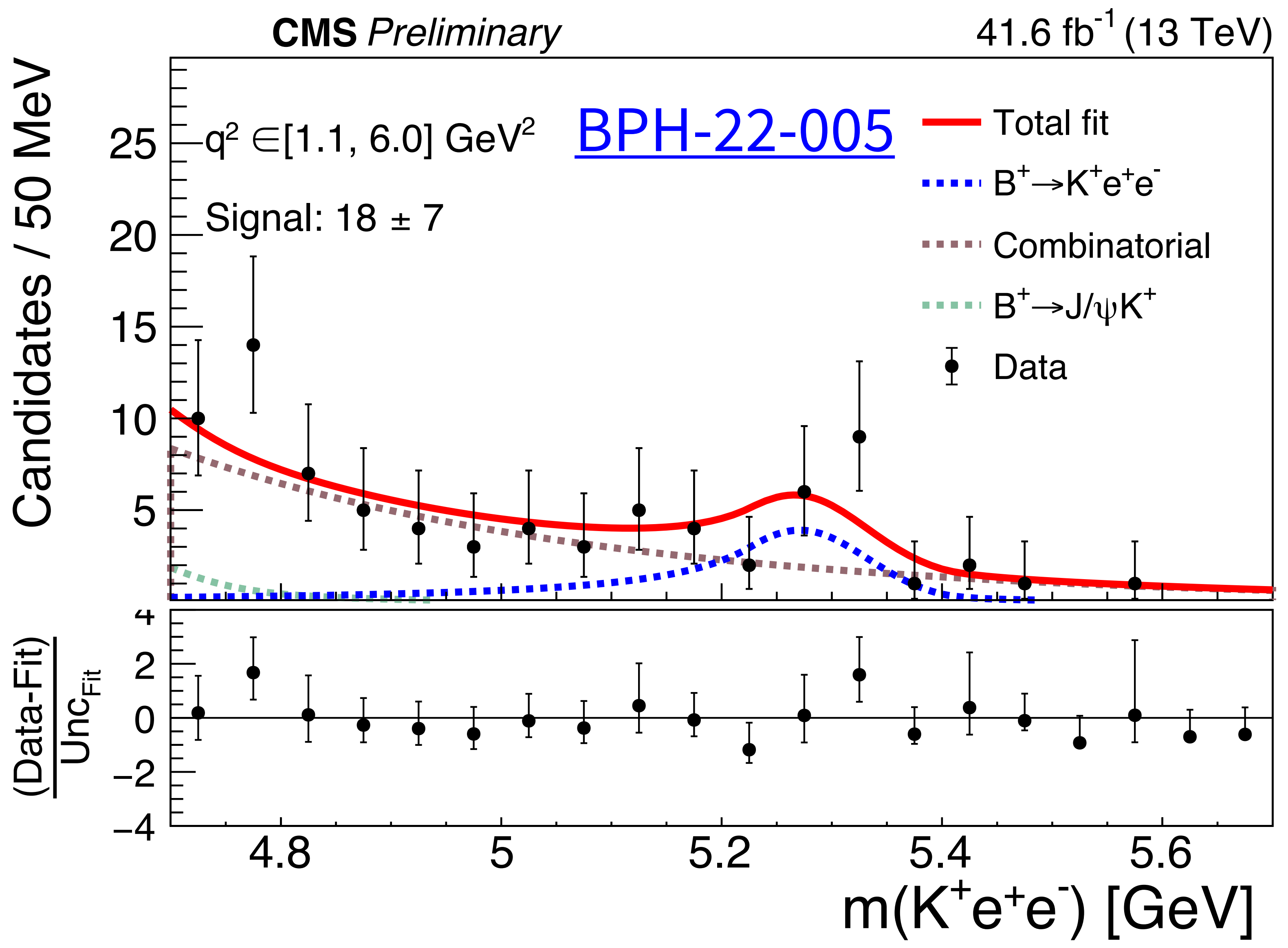

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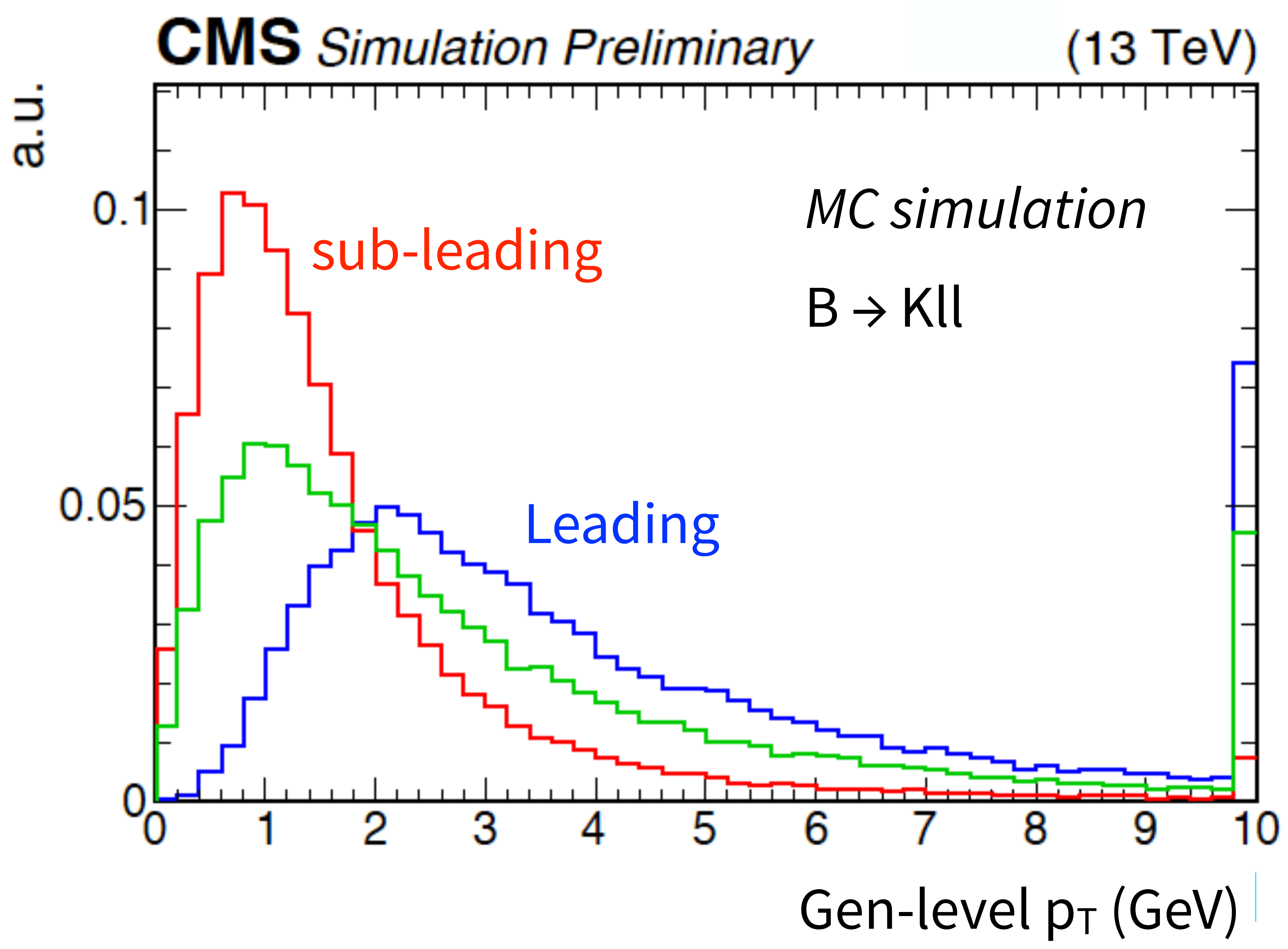

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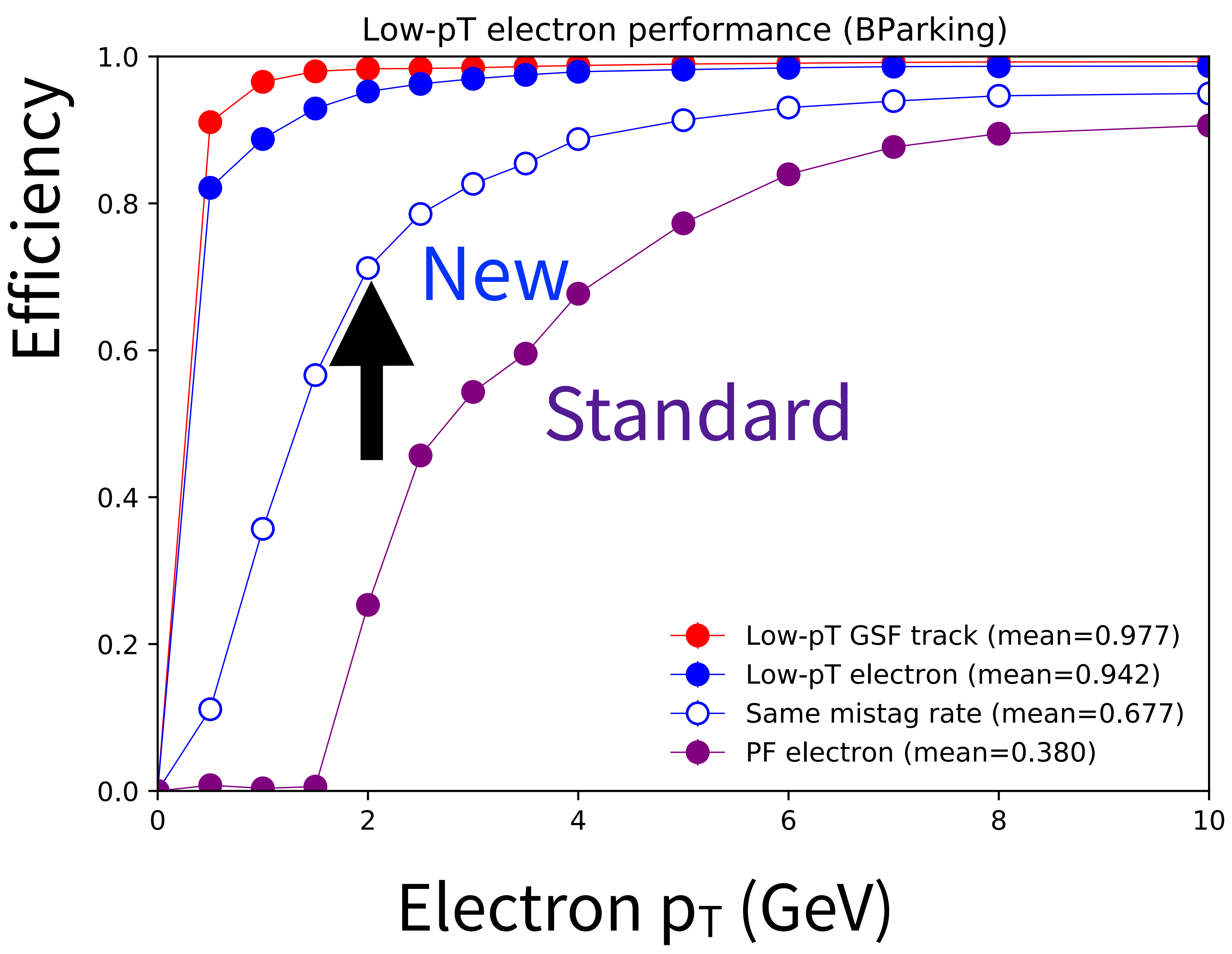

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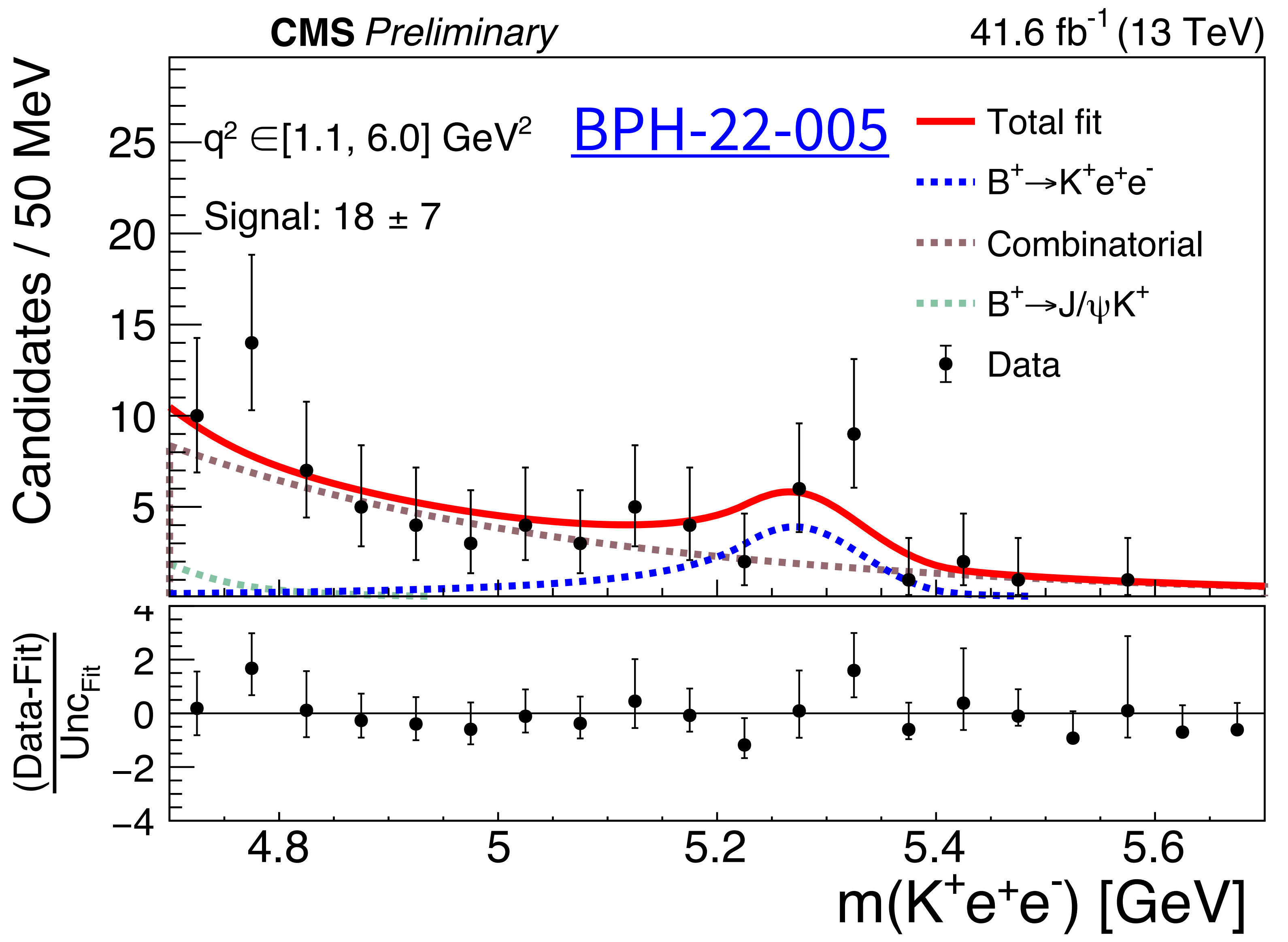

→ will definitely improve with data being taken by ee trigger

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High-Luminosity LHC (HL-LHC) upgrade

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LFU test ($\tau\tau$ v.s $\mu\mu$ or ee) at high-energy scale

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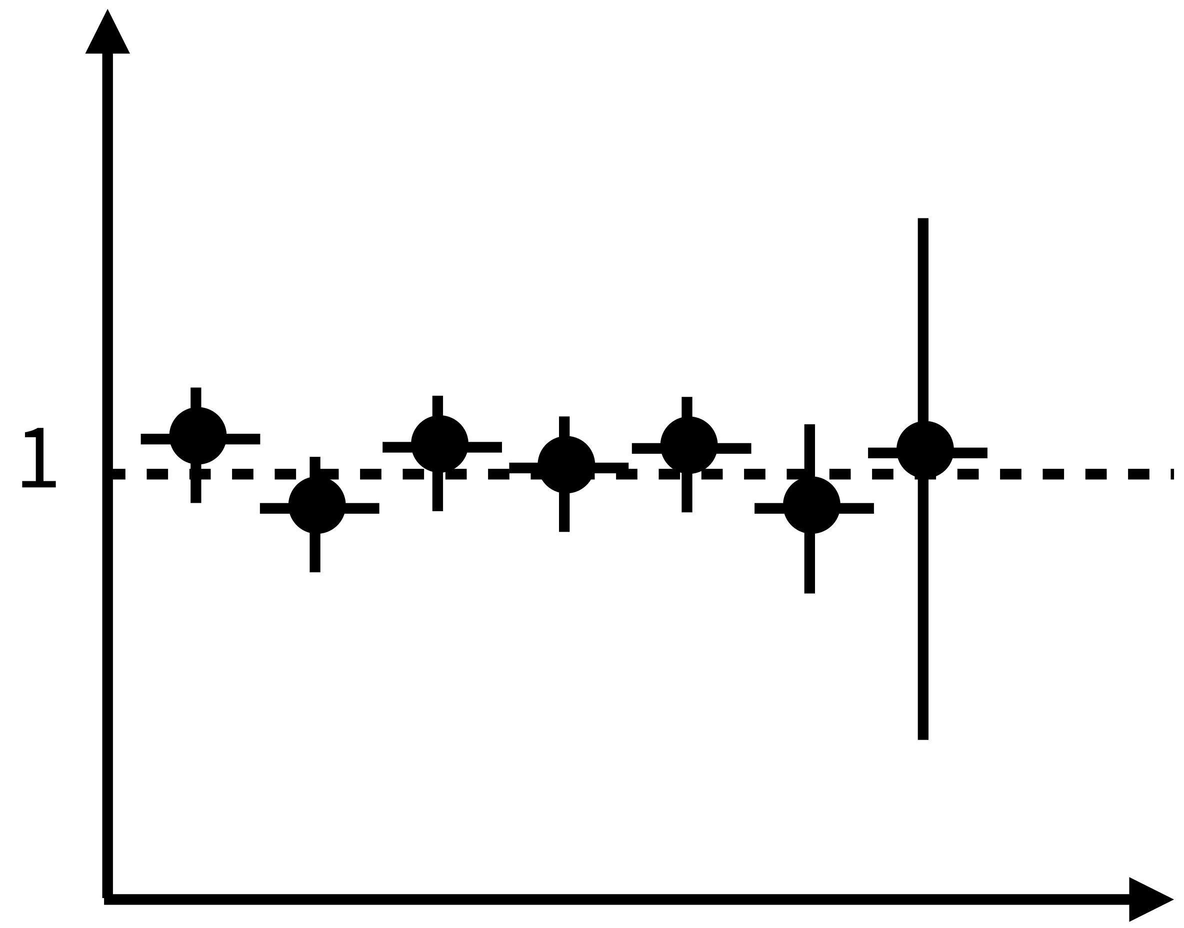

Cancel several systematic uncertainties (e.g. PDF, cross-sections)

m_{ll} (GeV)

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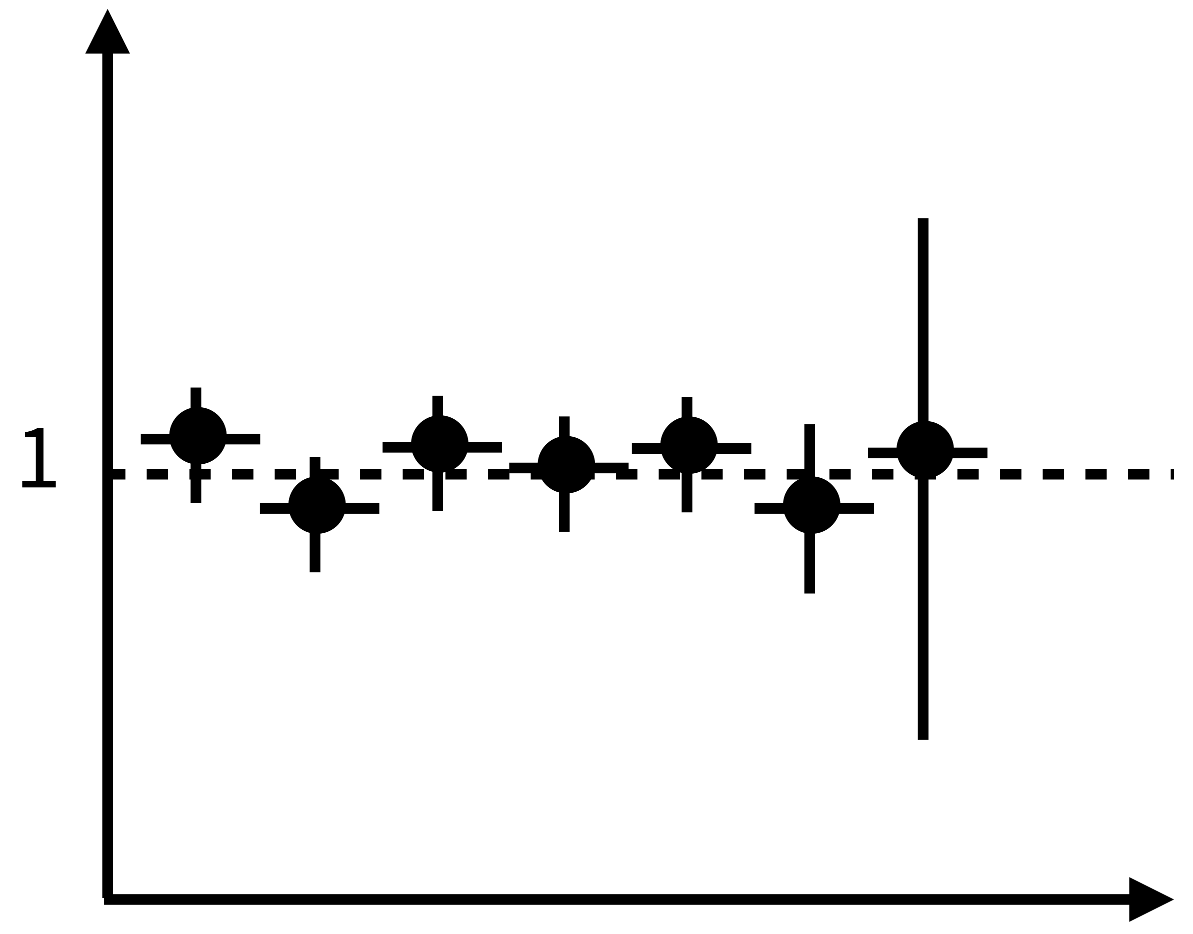

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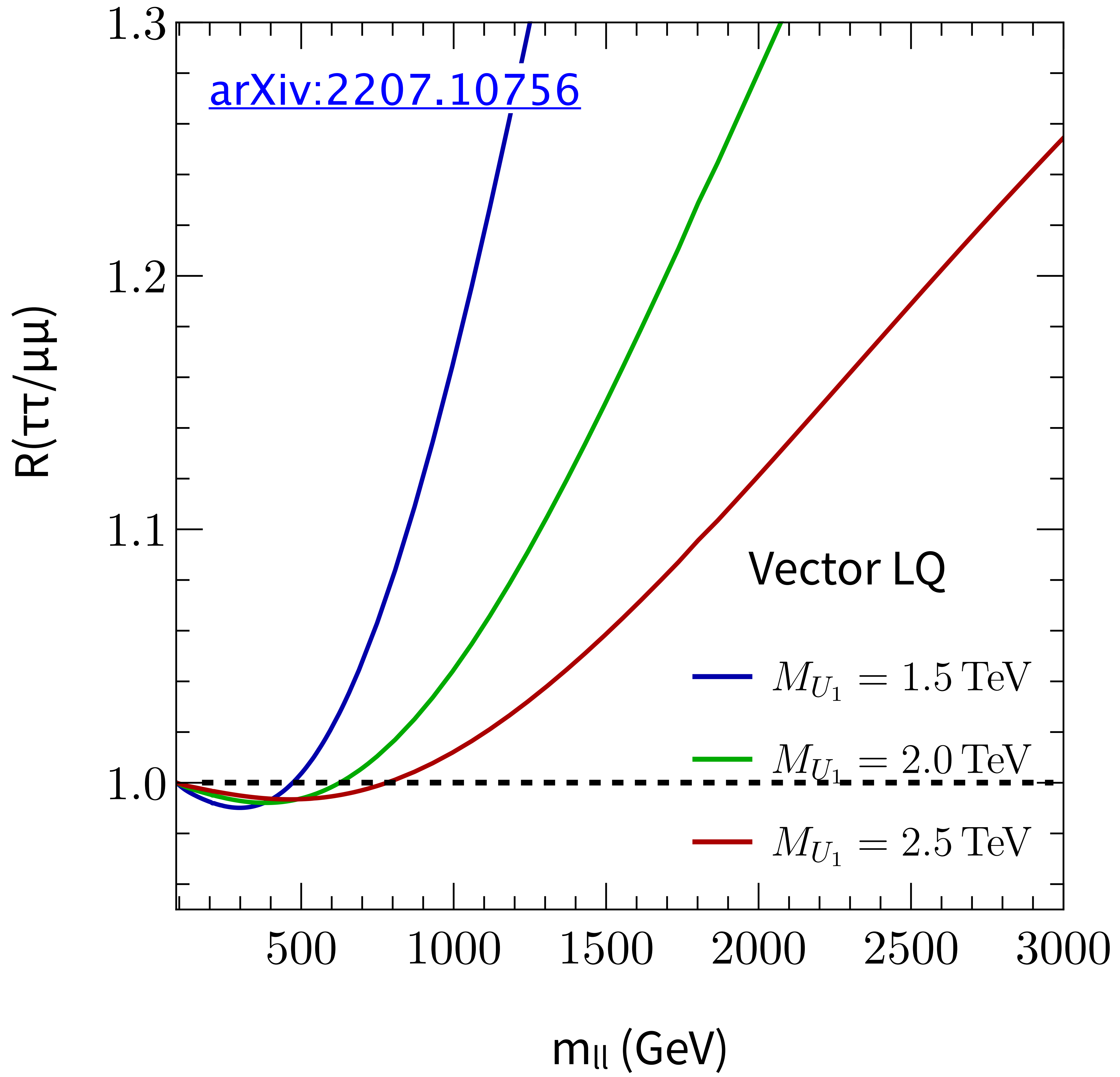

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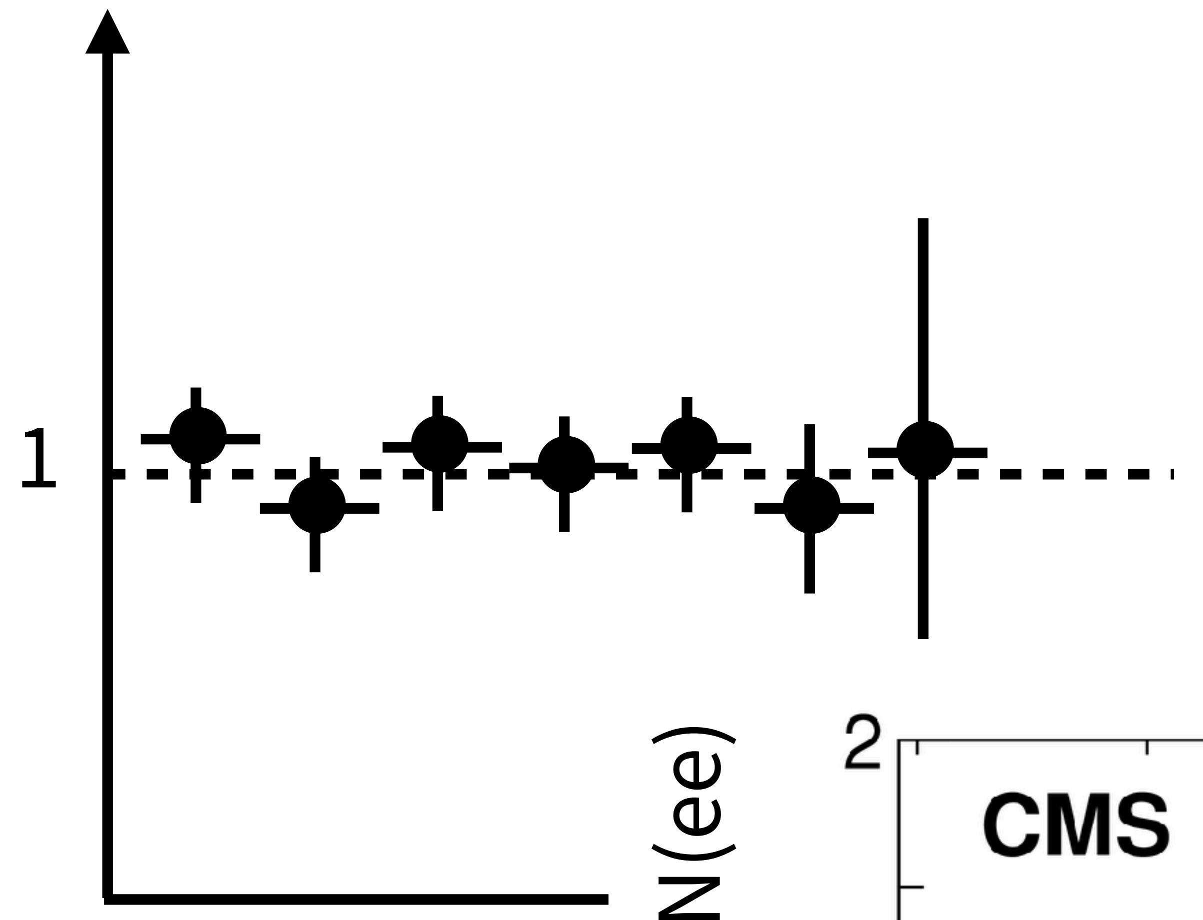

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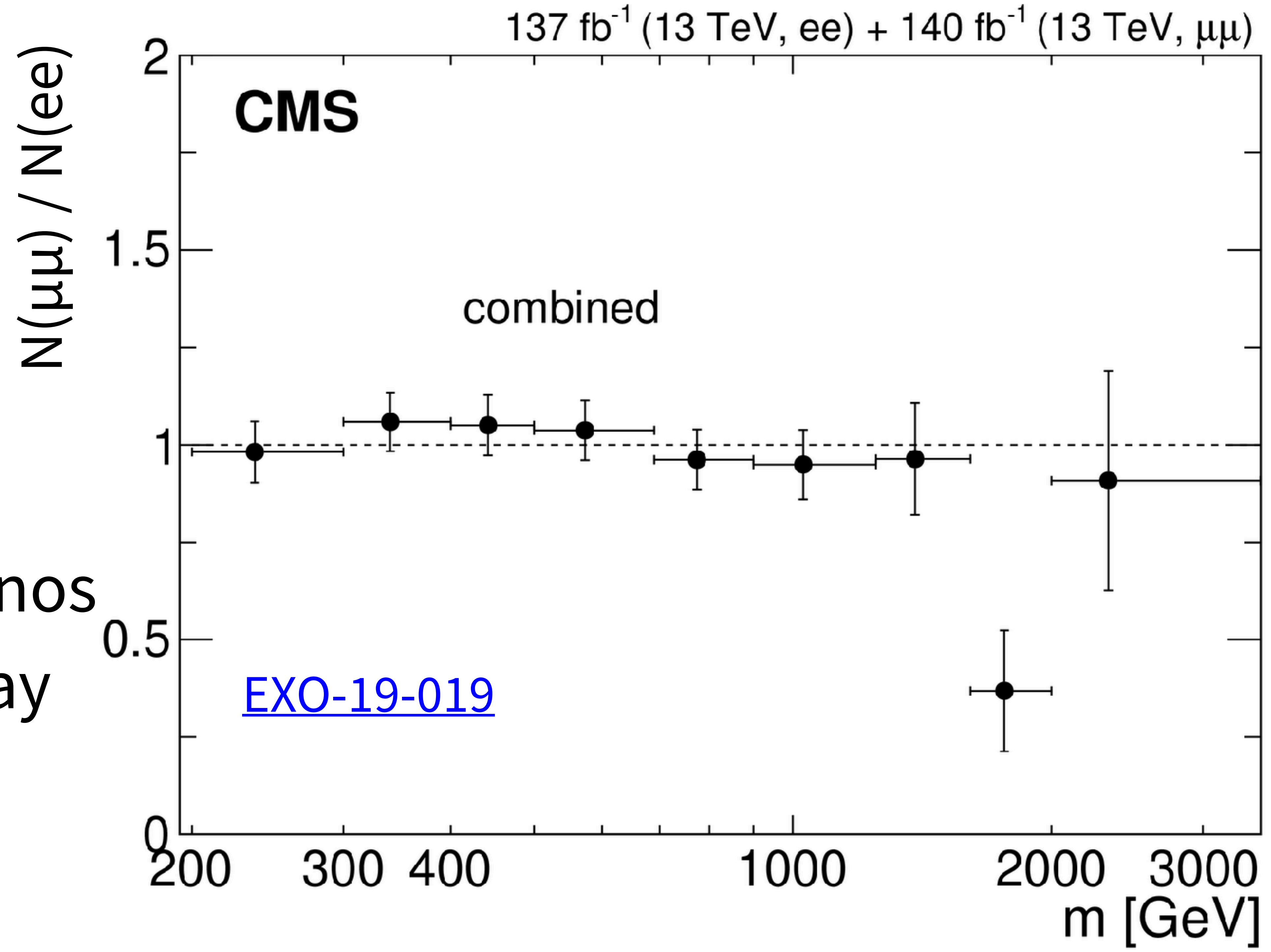

Not trivial due to neutrinos from tau decay

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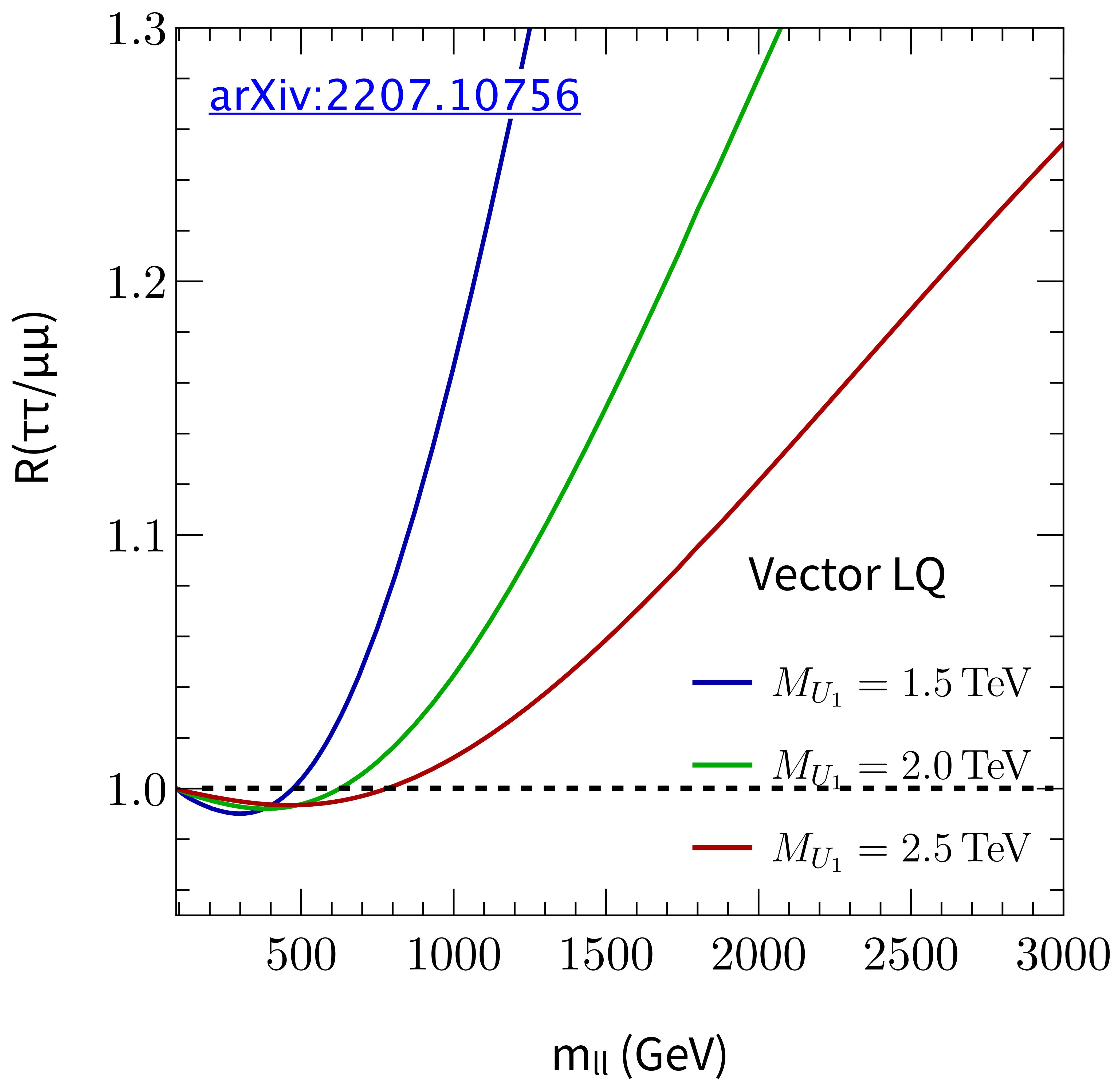

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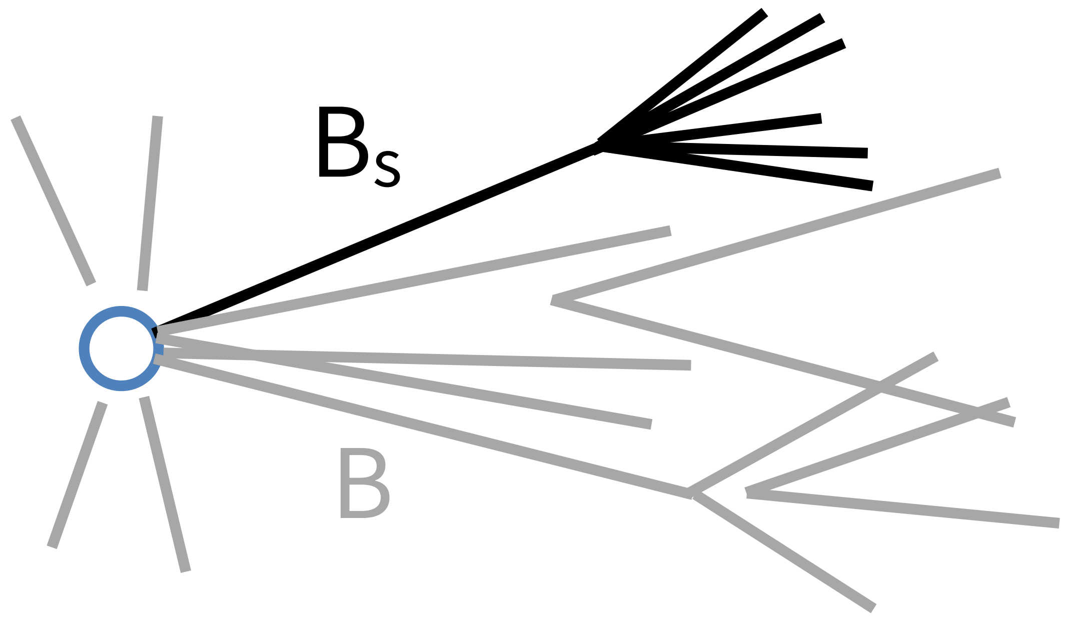

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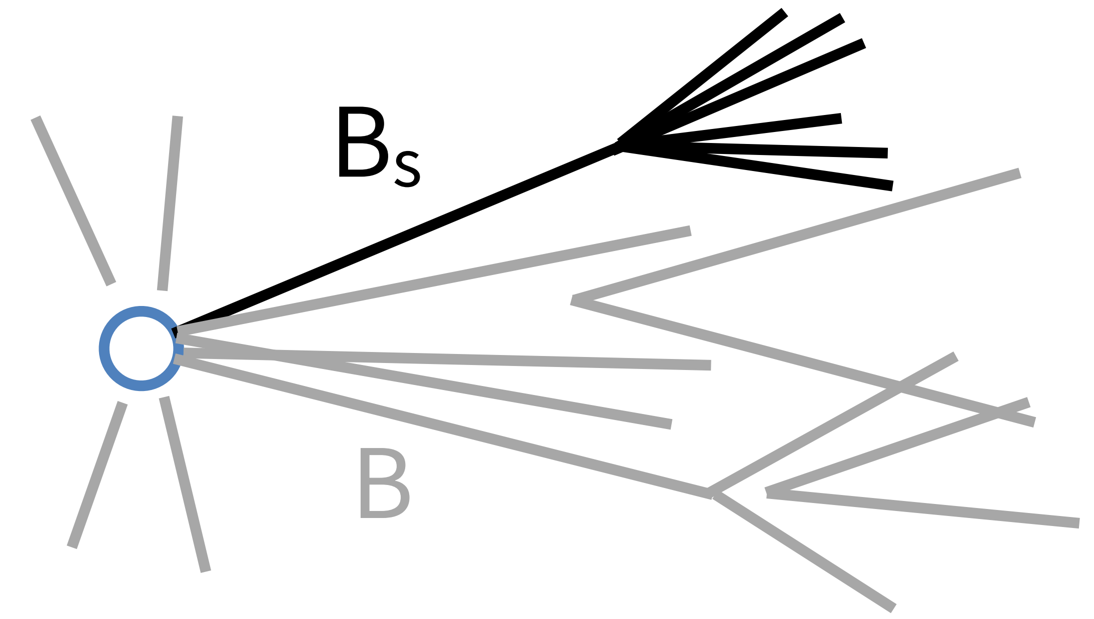

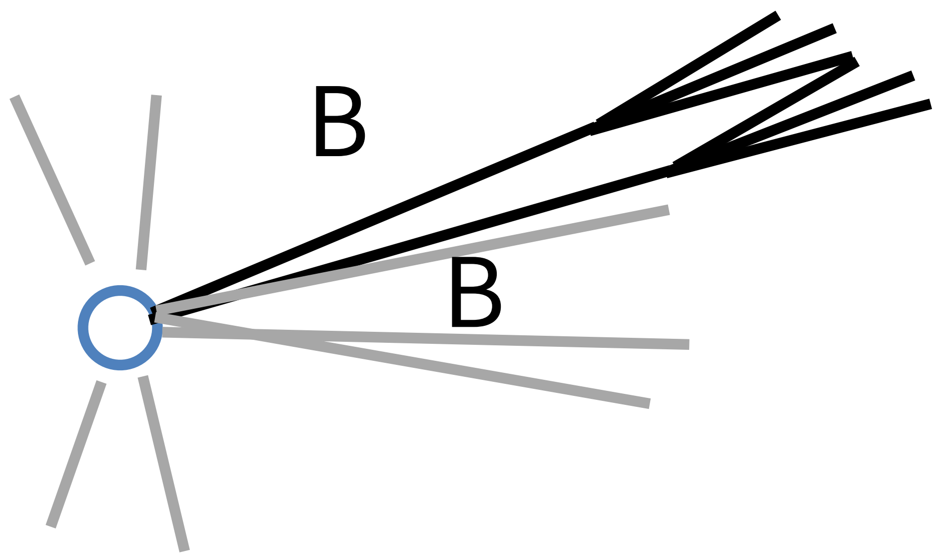

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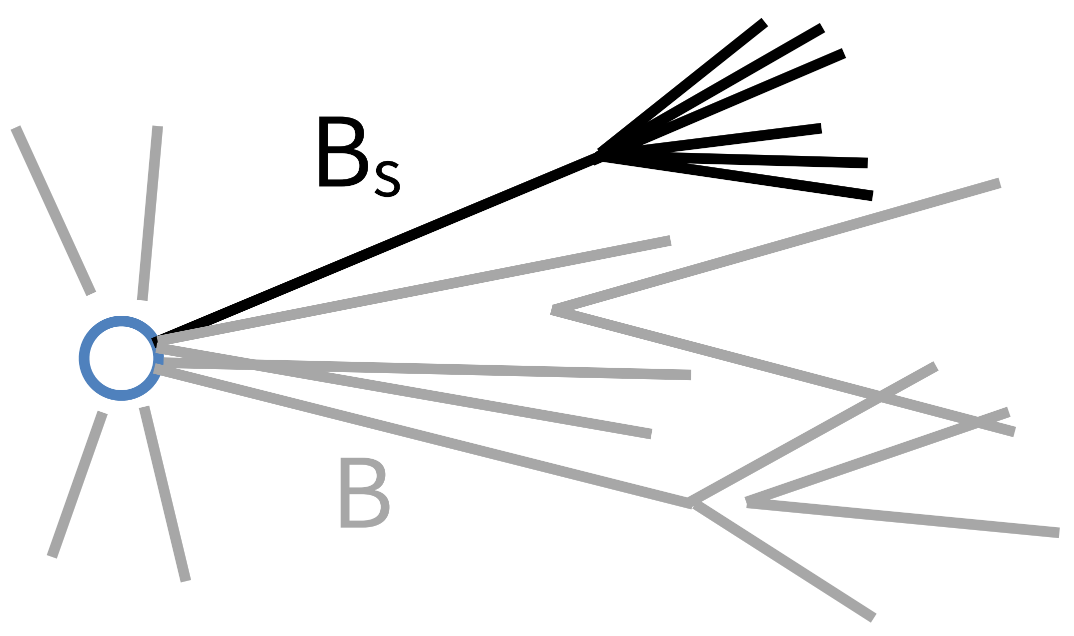

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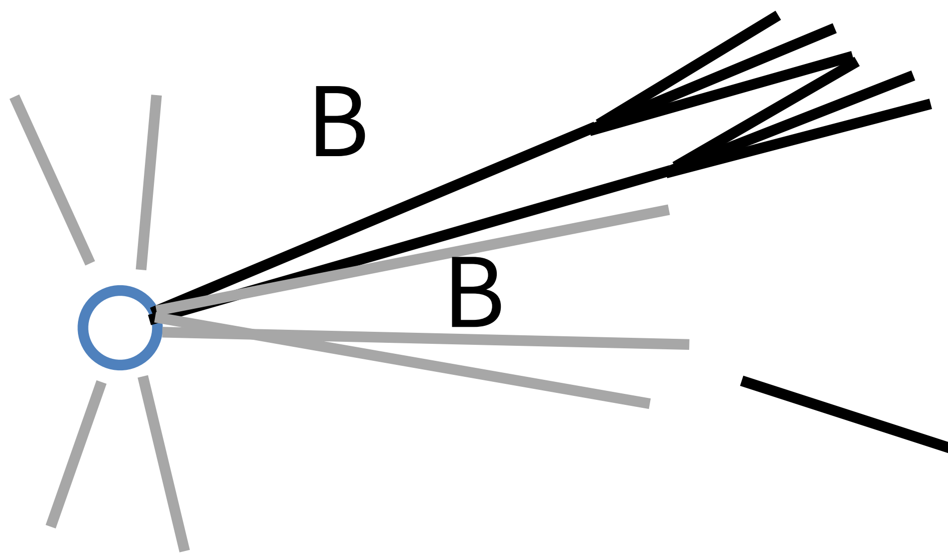

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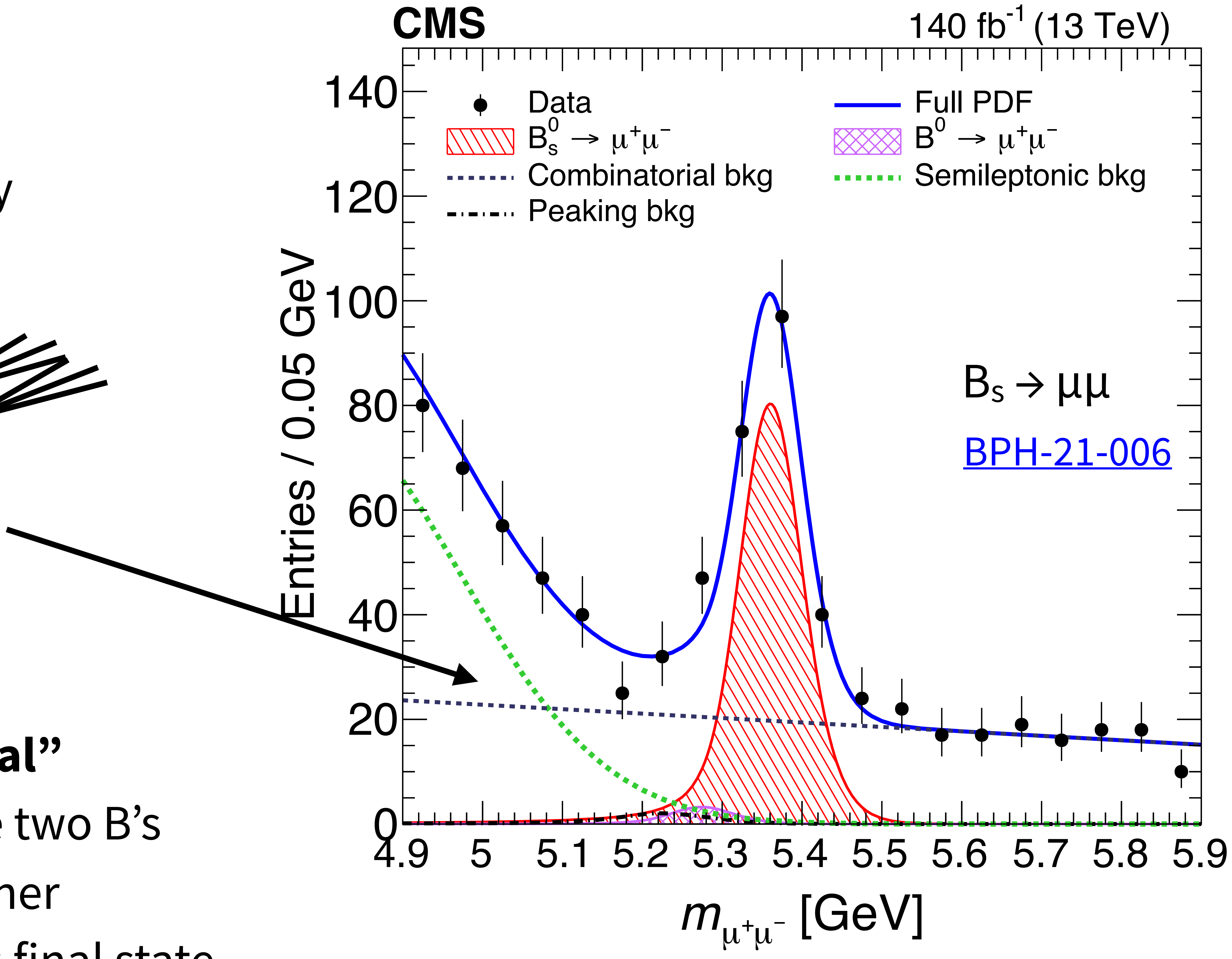

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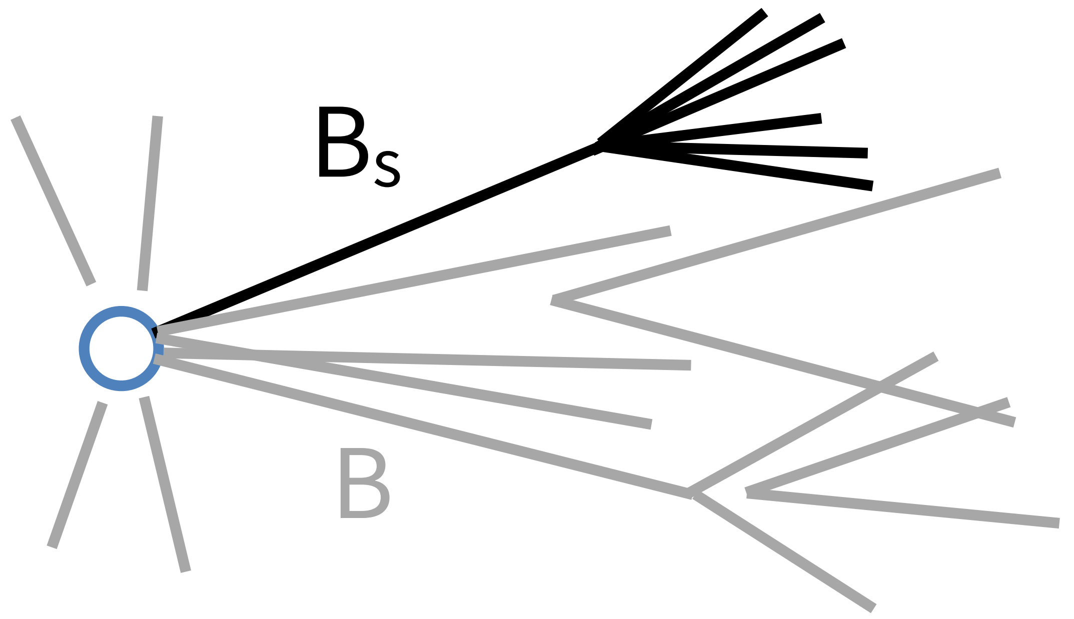

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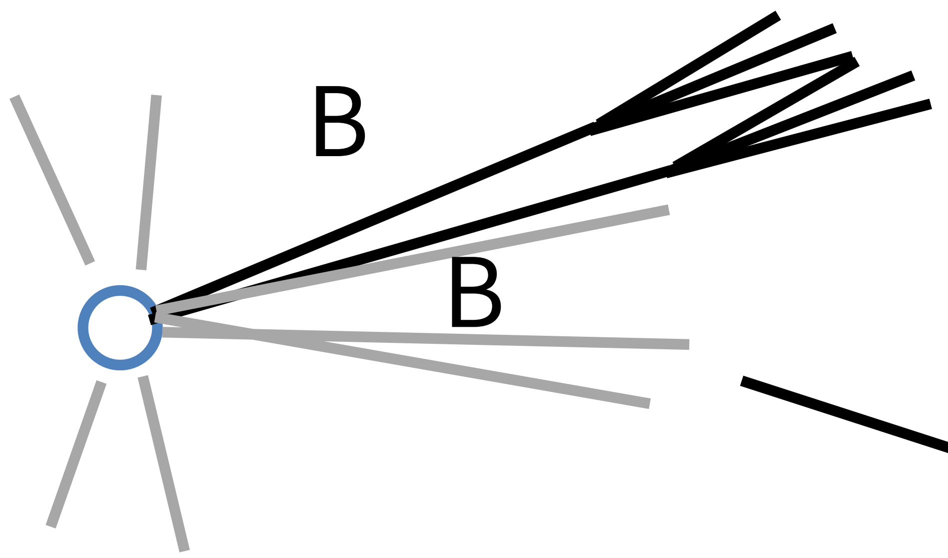

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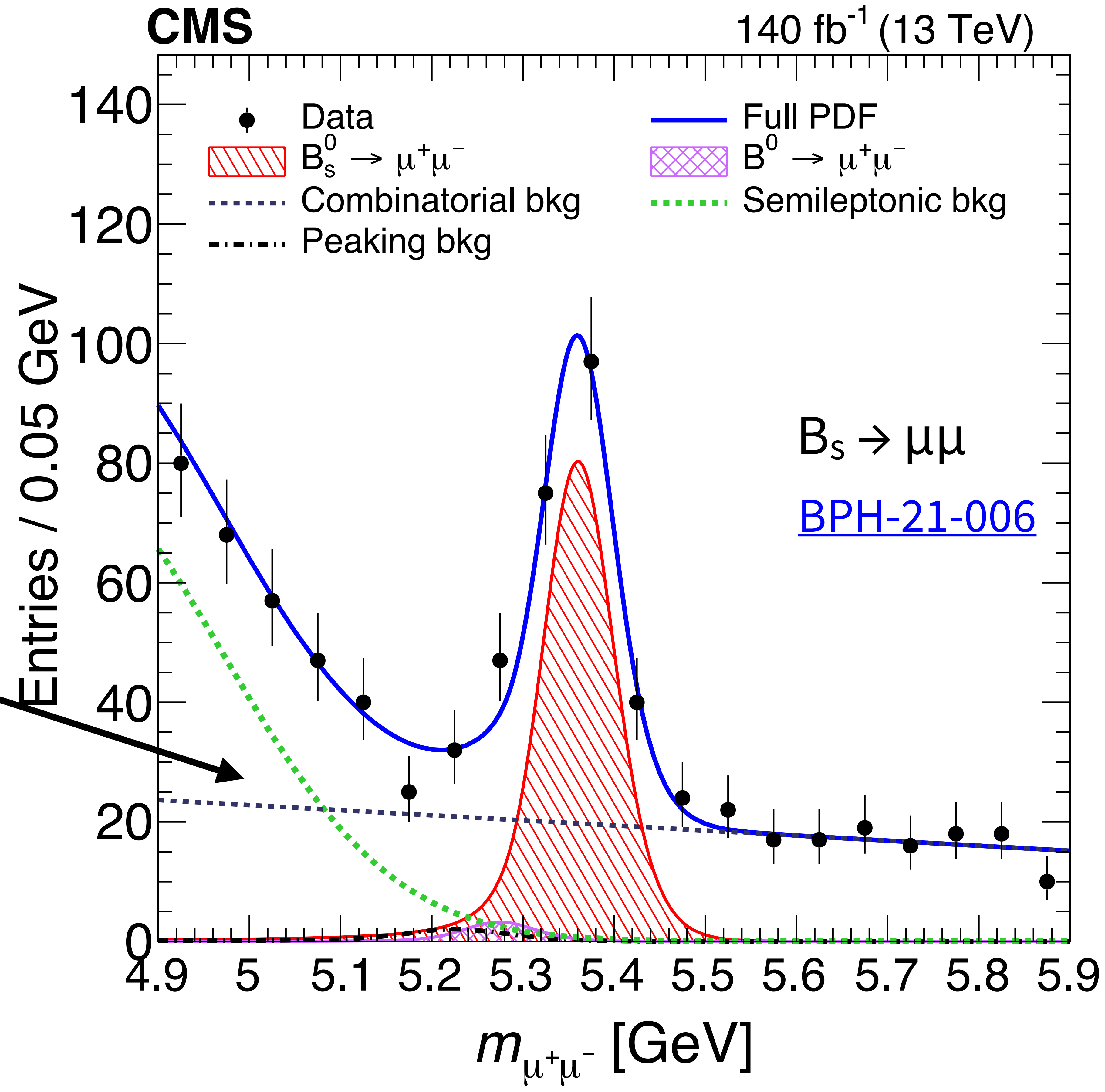
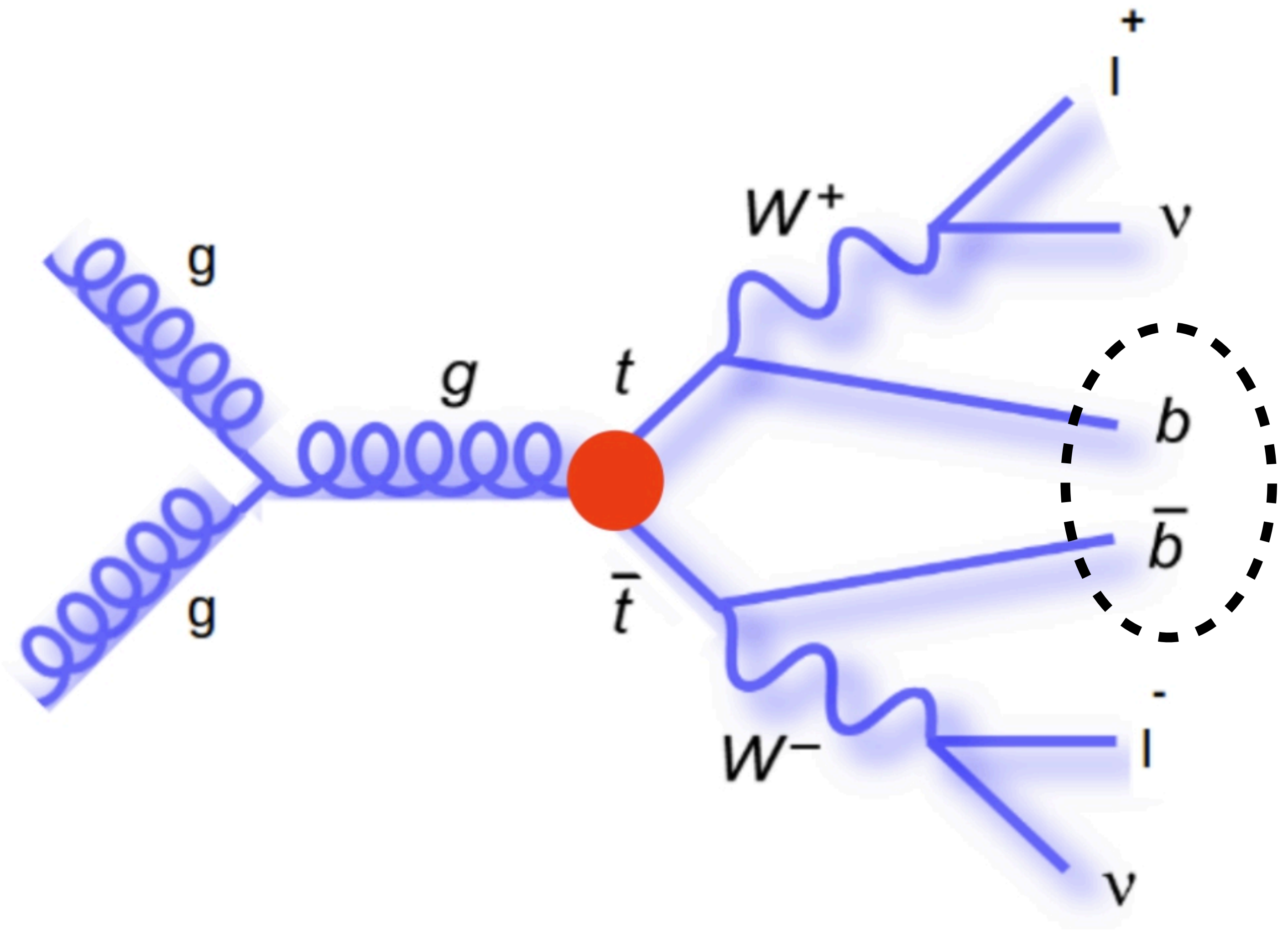


- So far, only weak constraint from LHCb: B($B_s \to \tau\tau$) < 6.8 x 10^{-3} PRL 118, 251802 (2017)

Idea: use $t\bar{t}$ to measure $B(B_s \to \tau\tau)$



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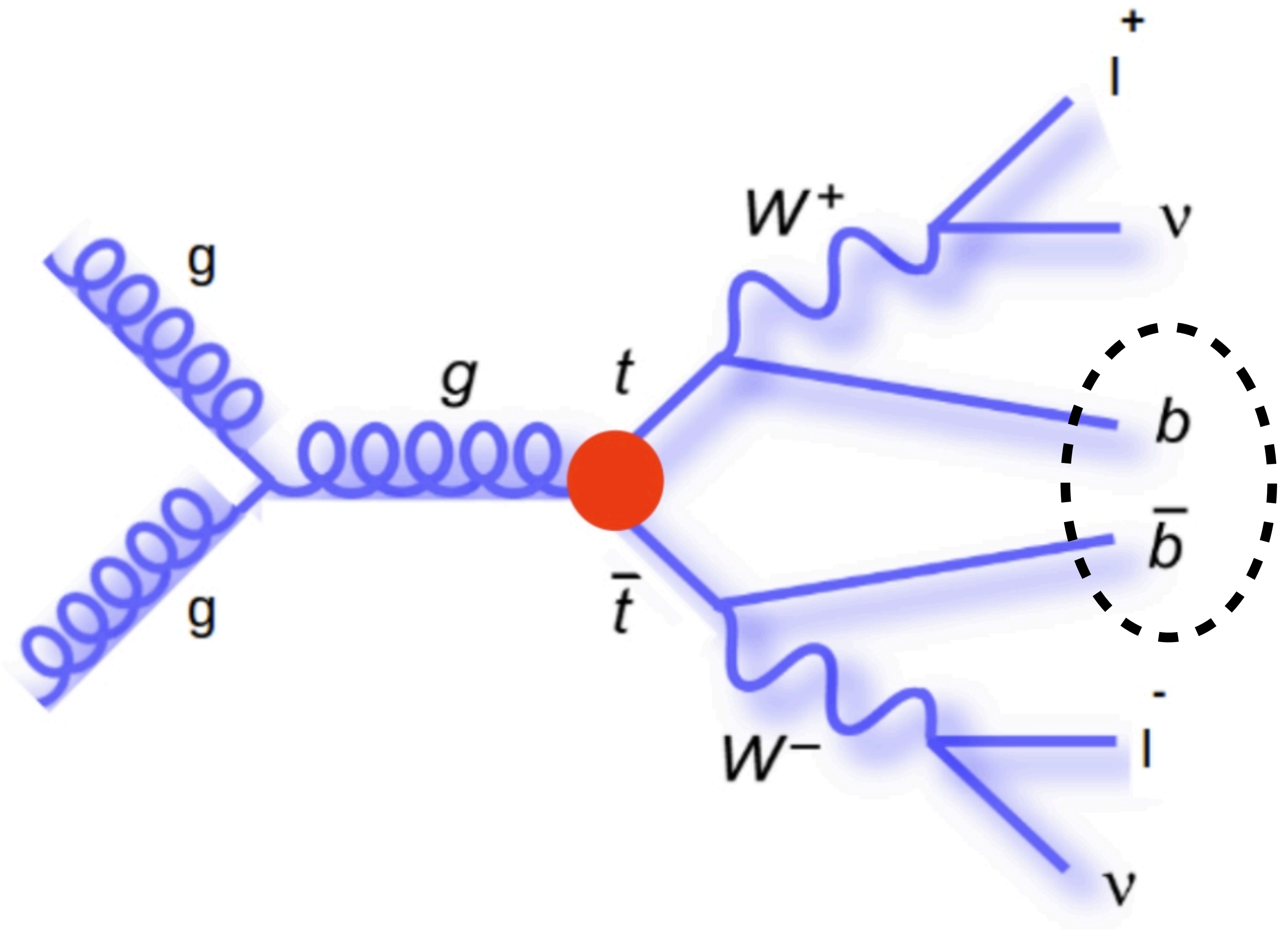

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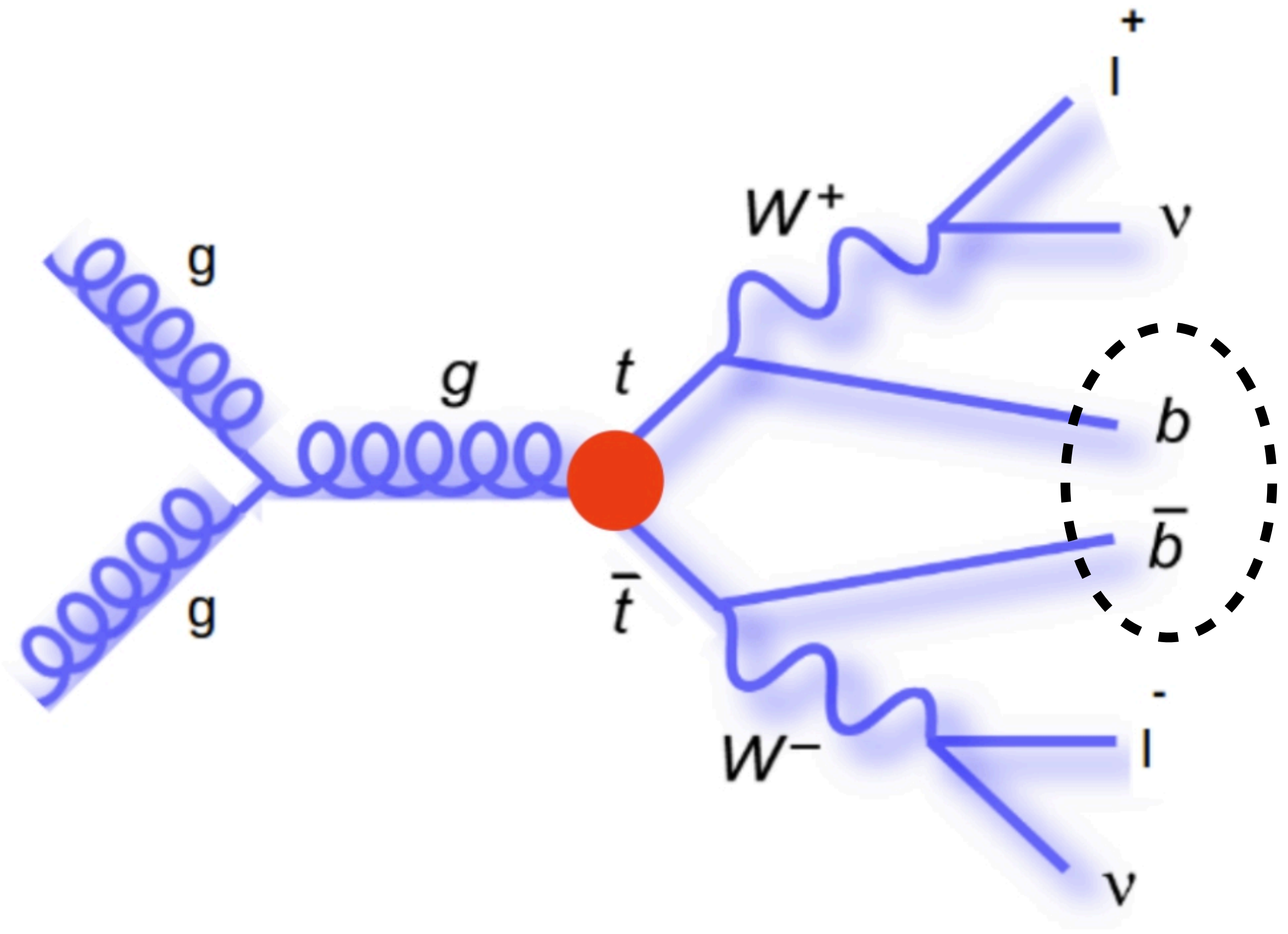

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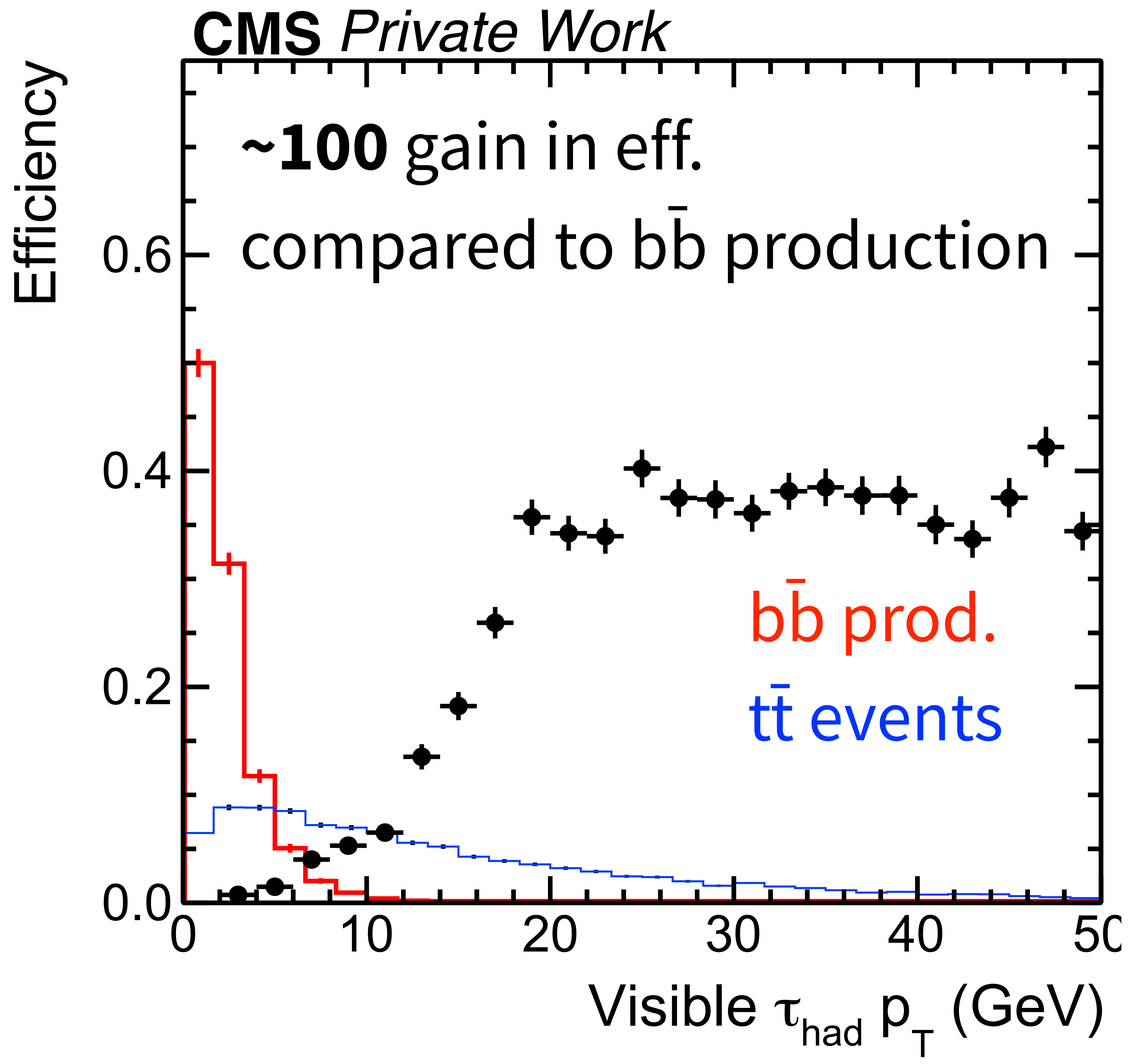

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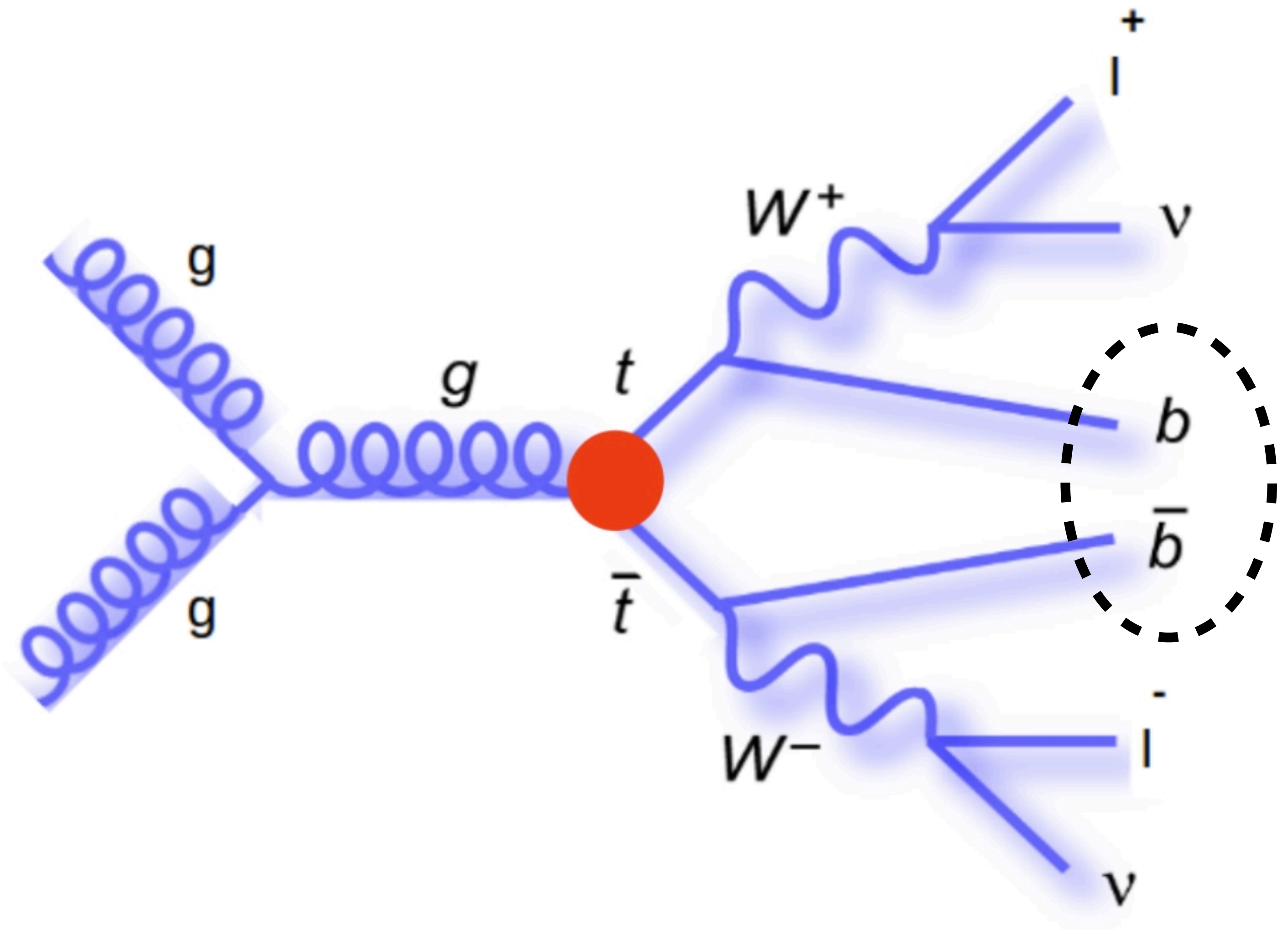

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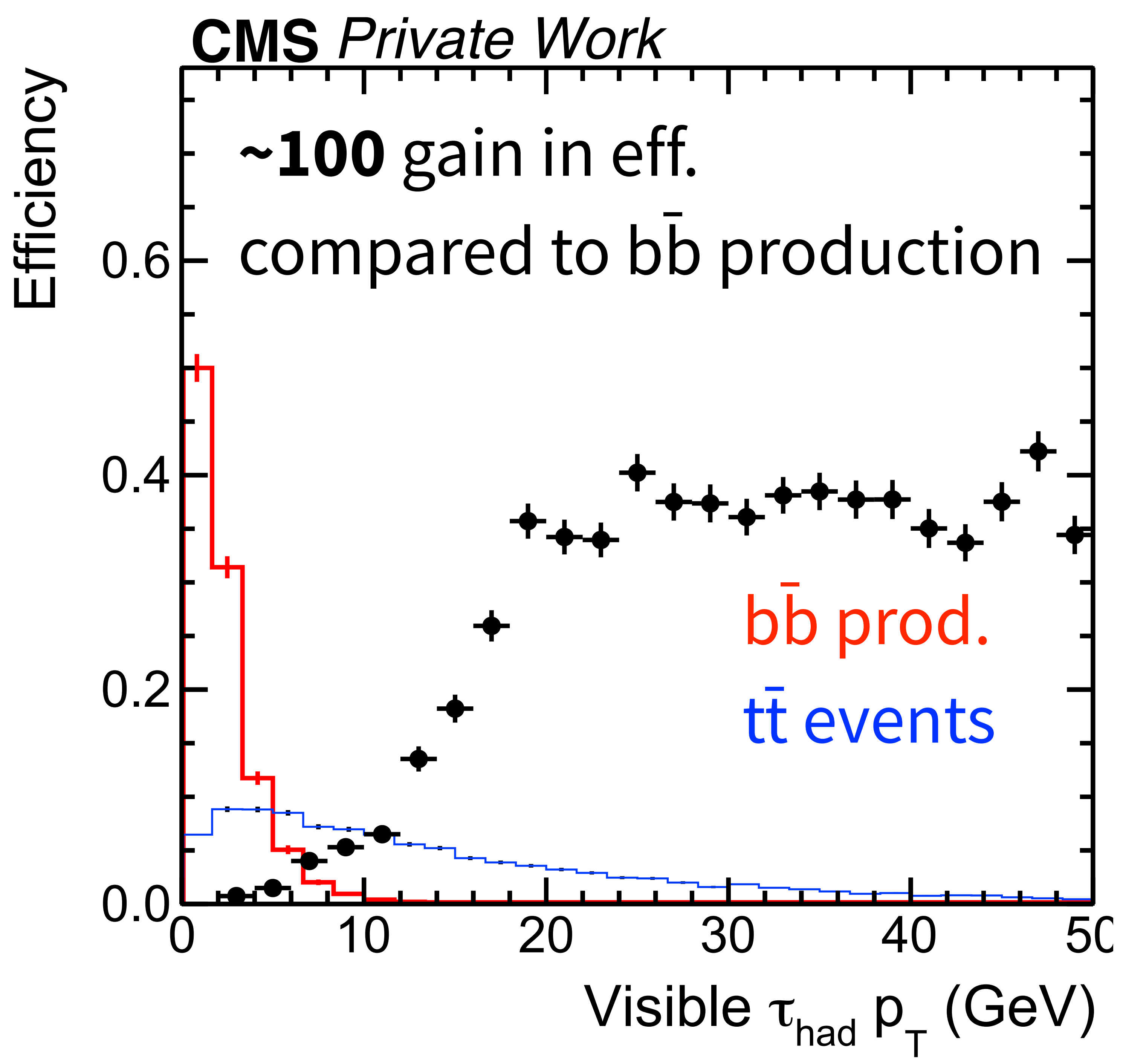

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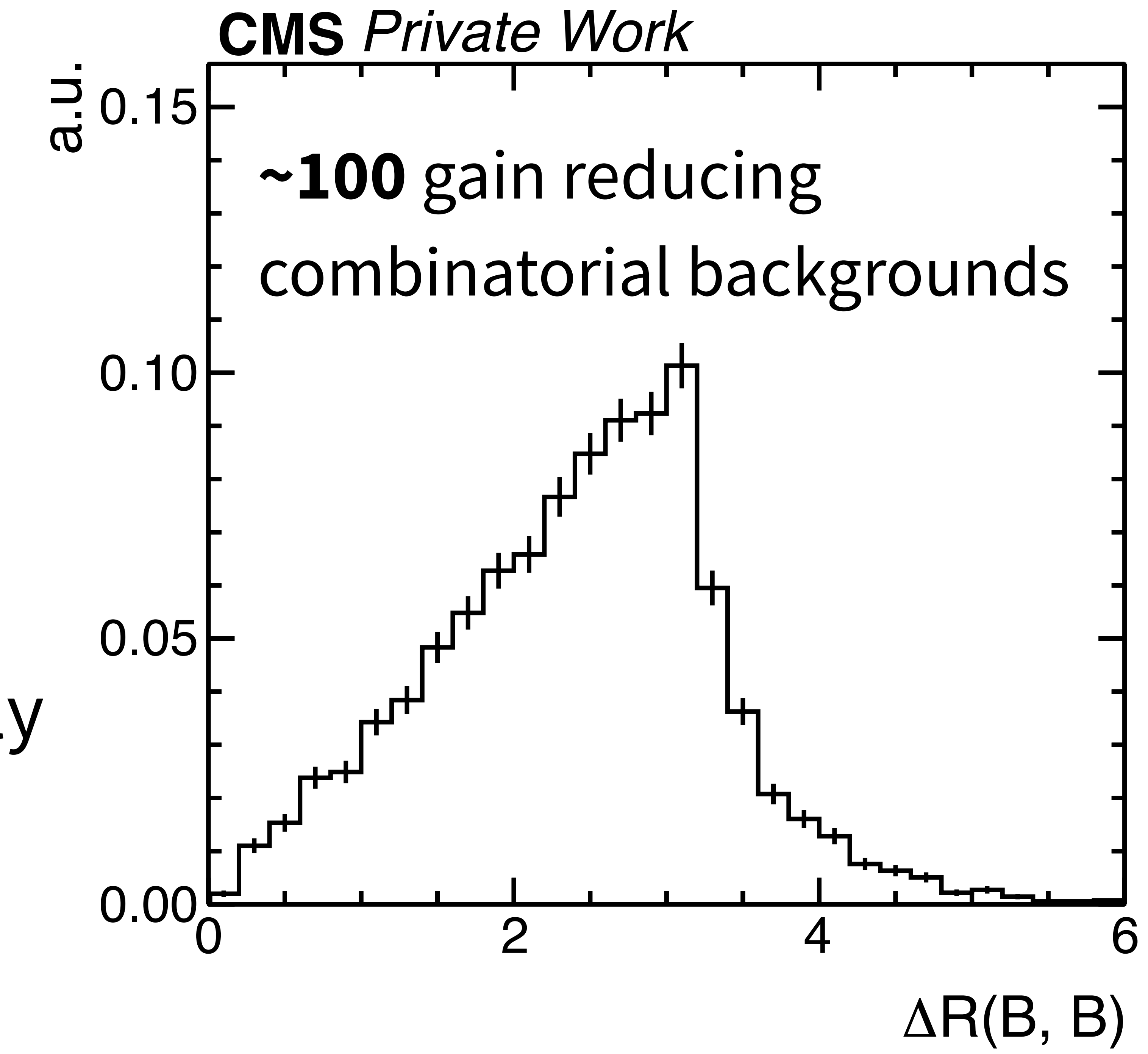

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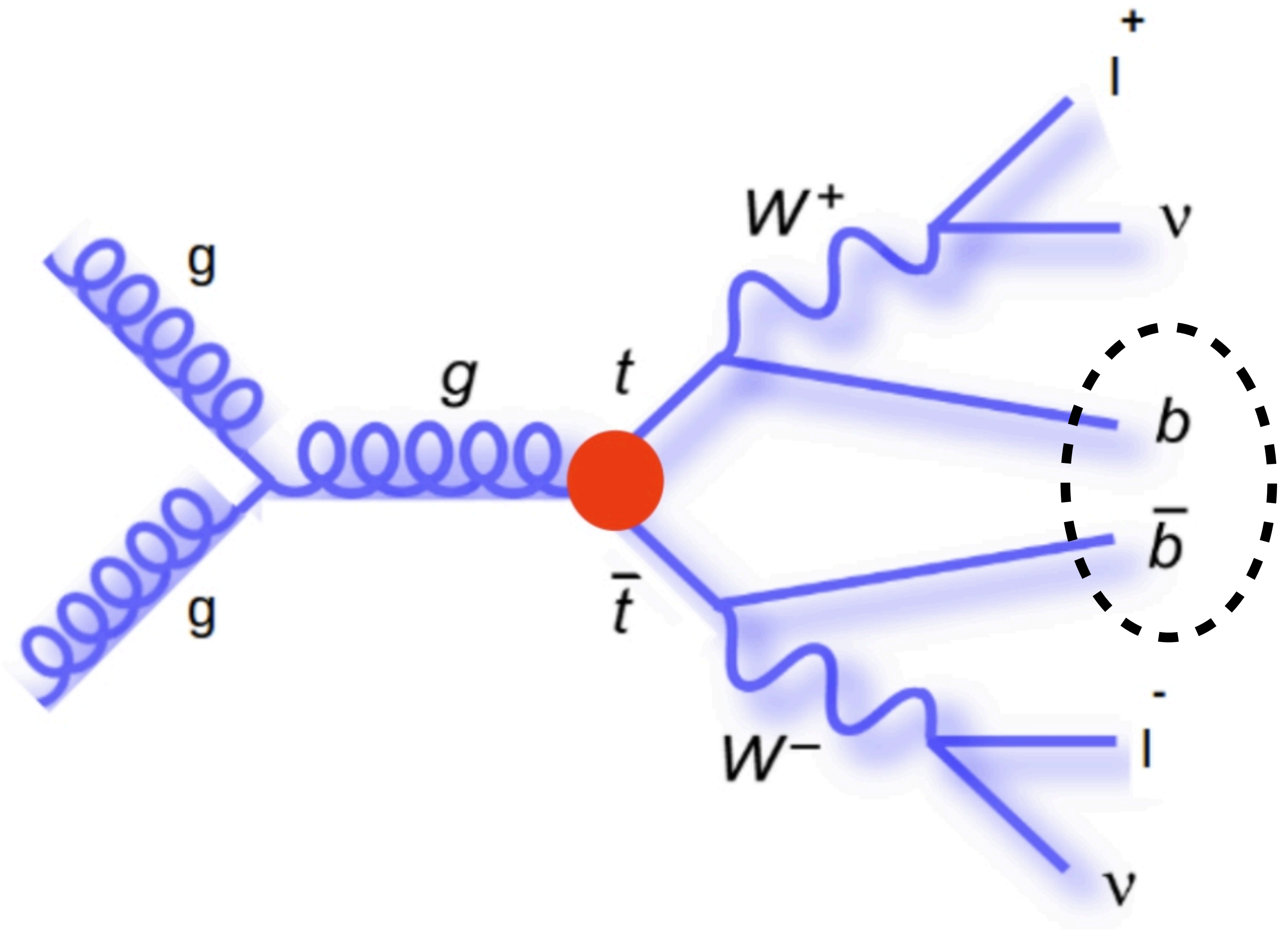

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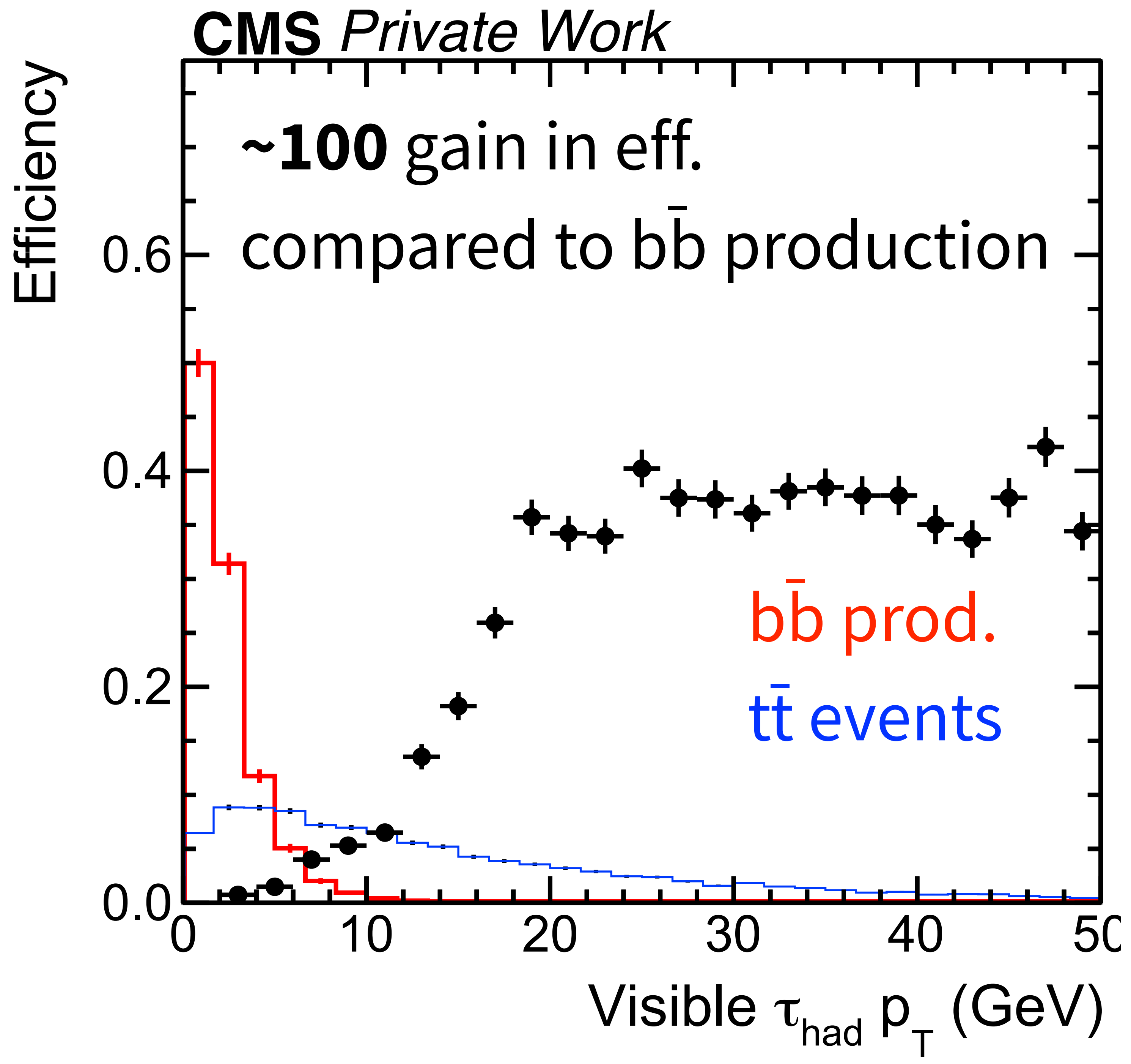

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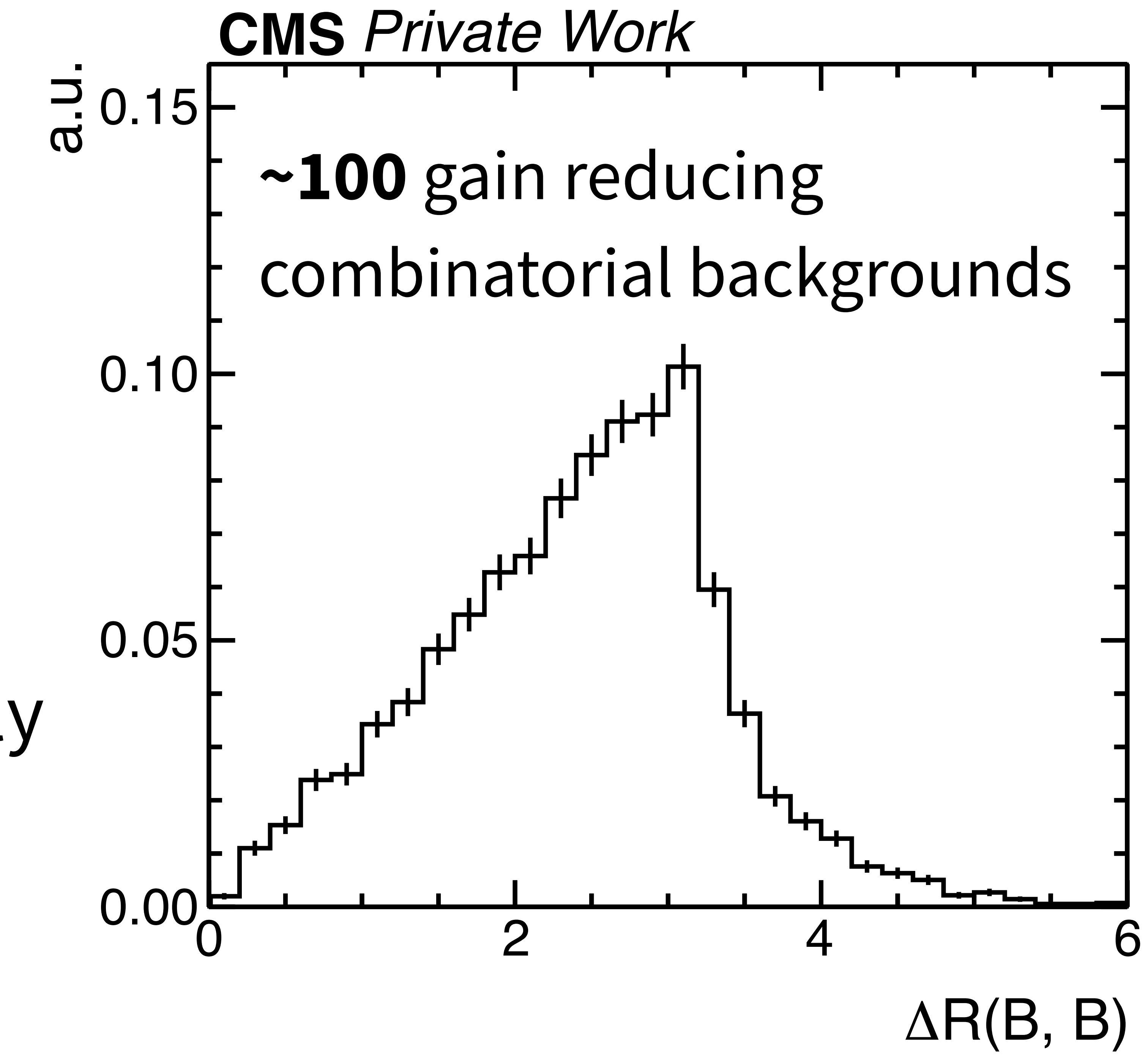

- Statistically speaking, we have much less Bs mesons collected than LHCb (~1%)
- But sensitivity wise, with these gains, we can be competitive
- Nobody thought possible from energy-frontier experiment!

Hadronically decaying tau (τ_h) triggers for the HL-LHC

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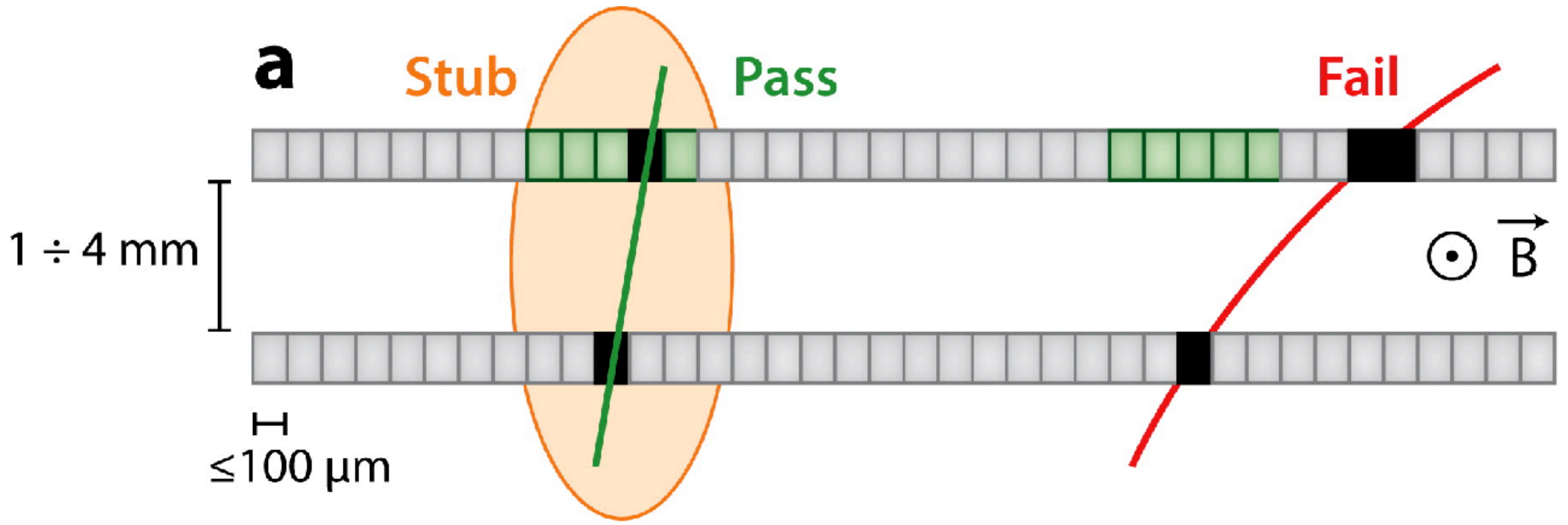

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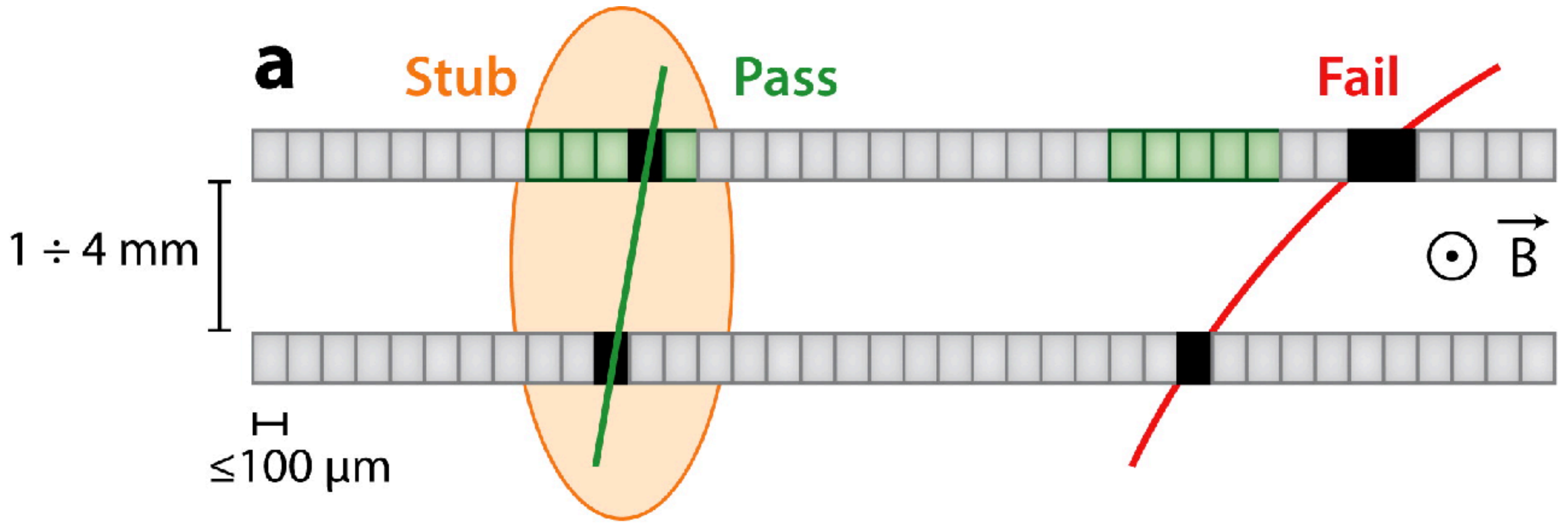

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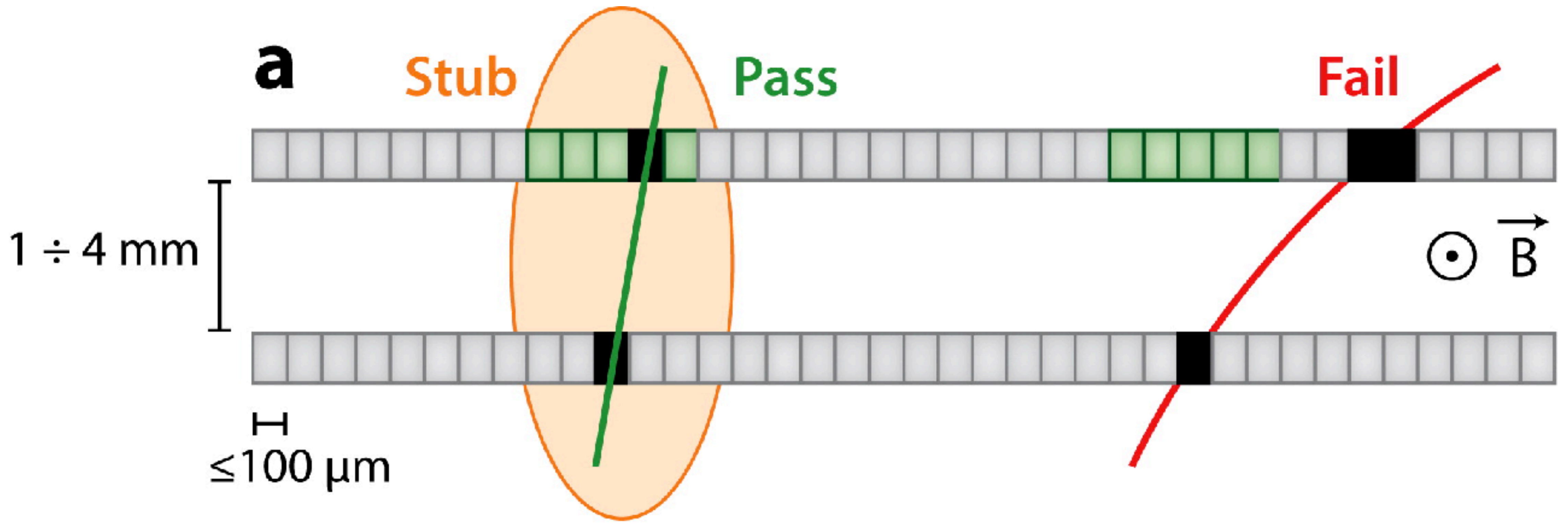

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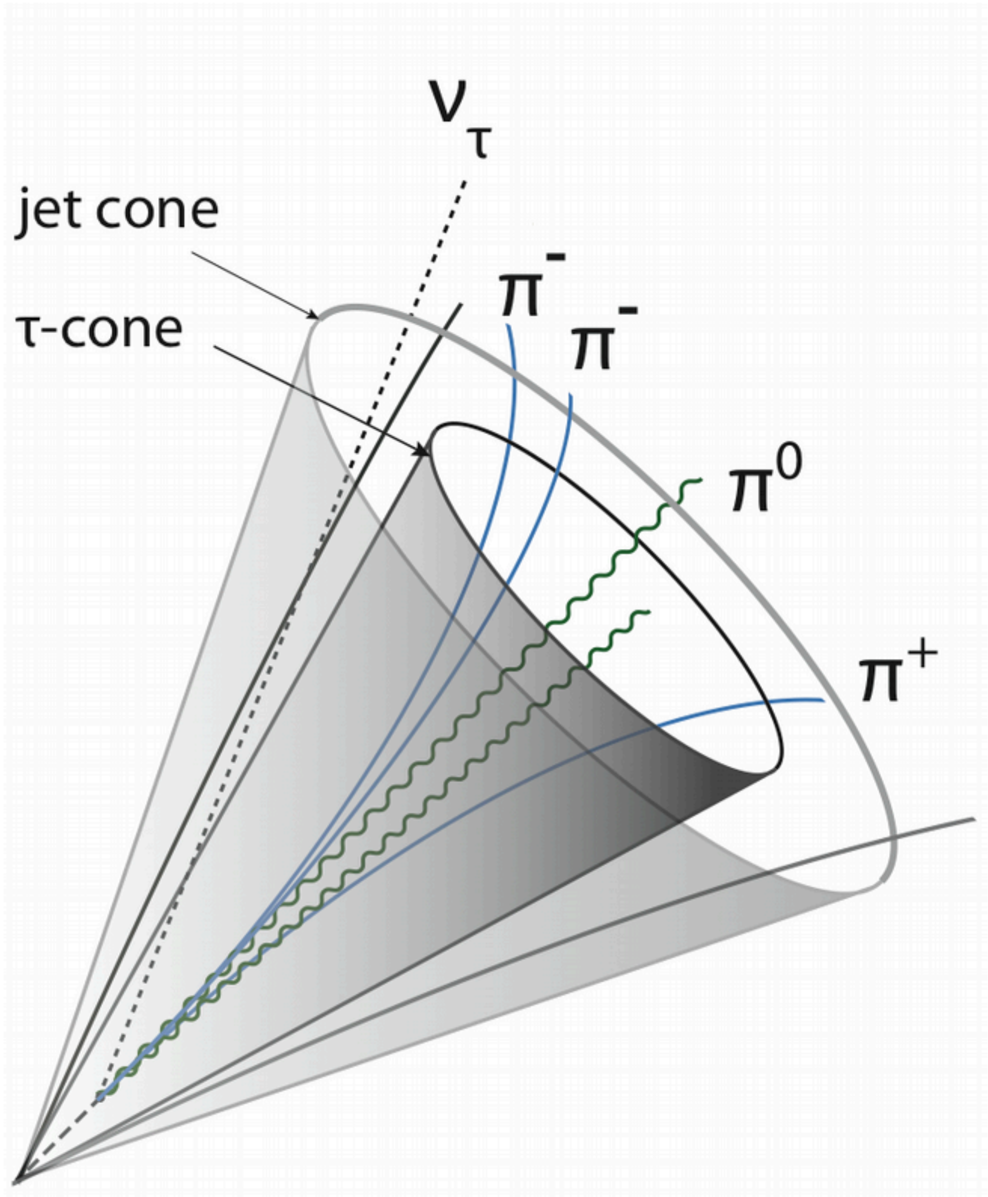

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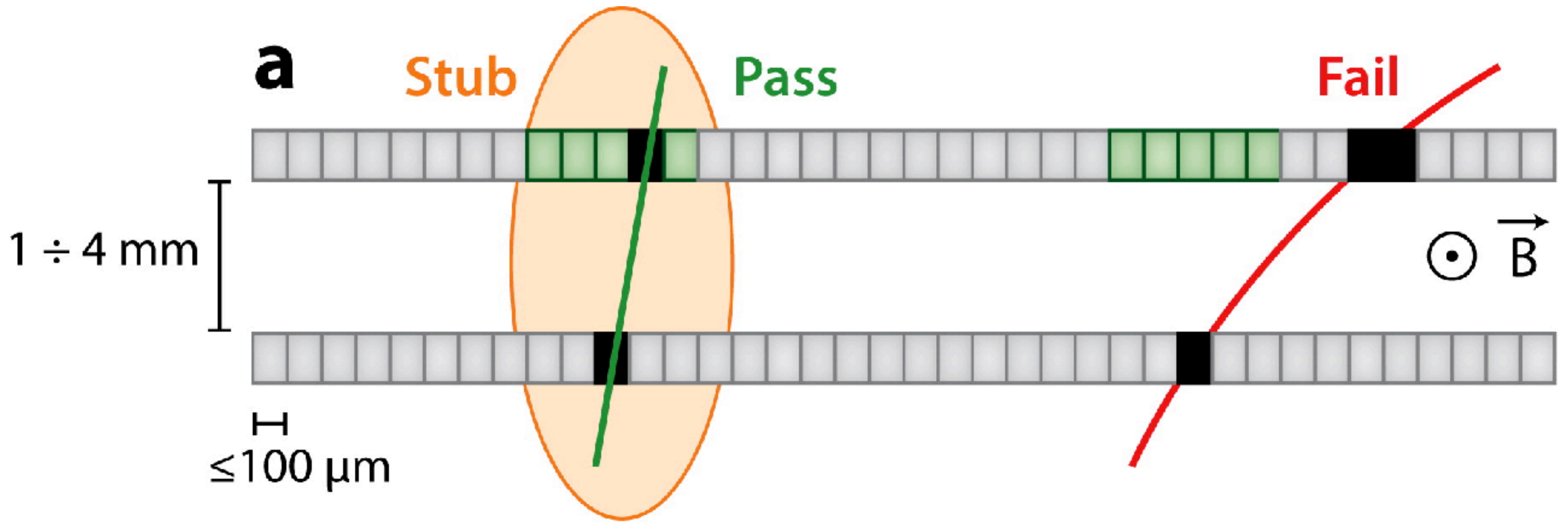

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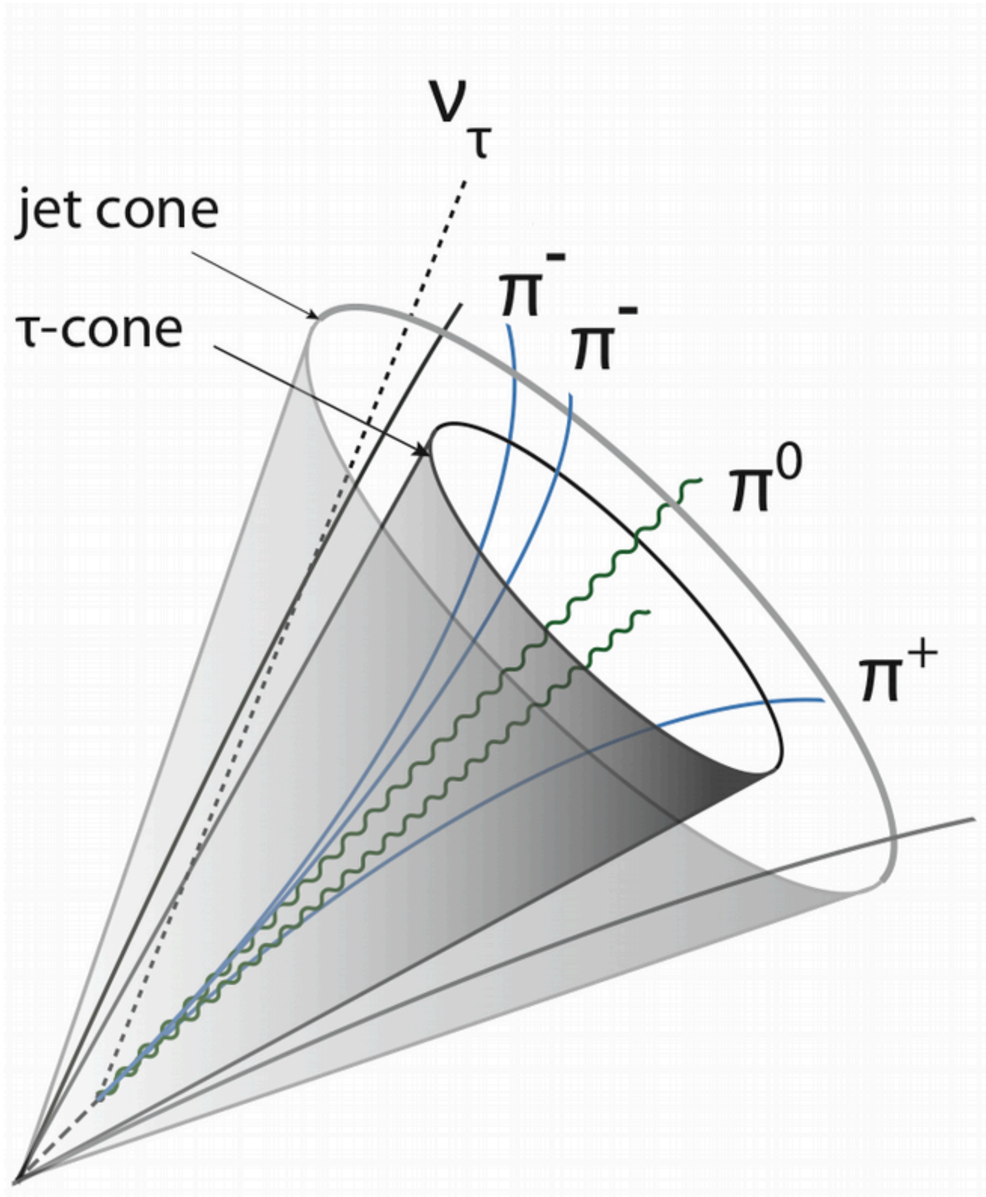
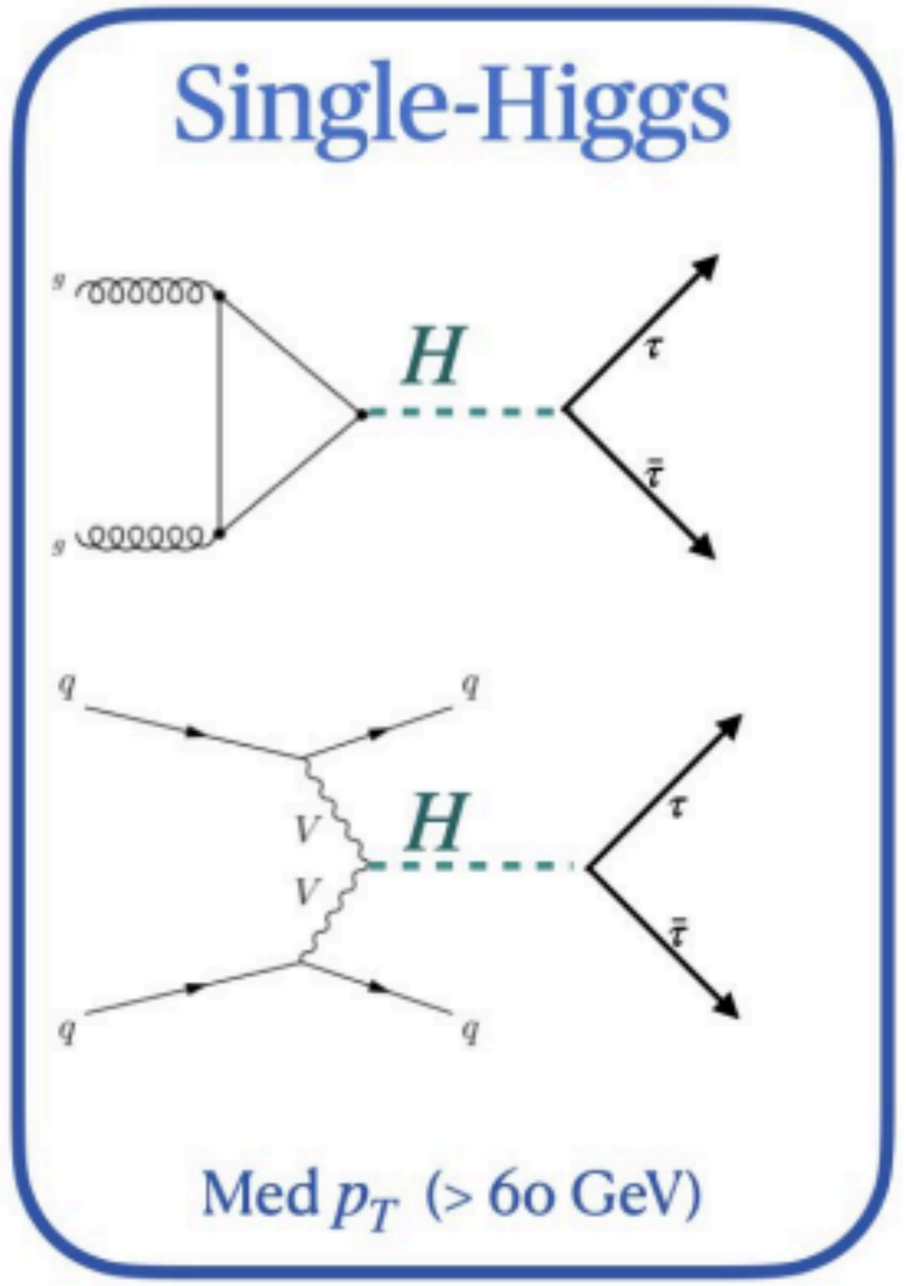
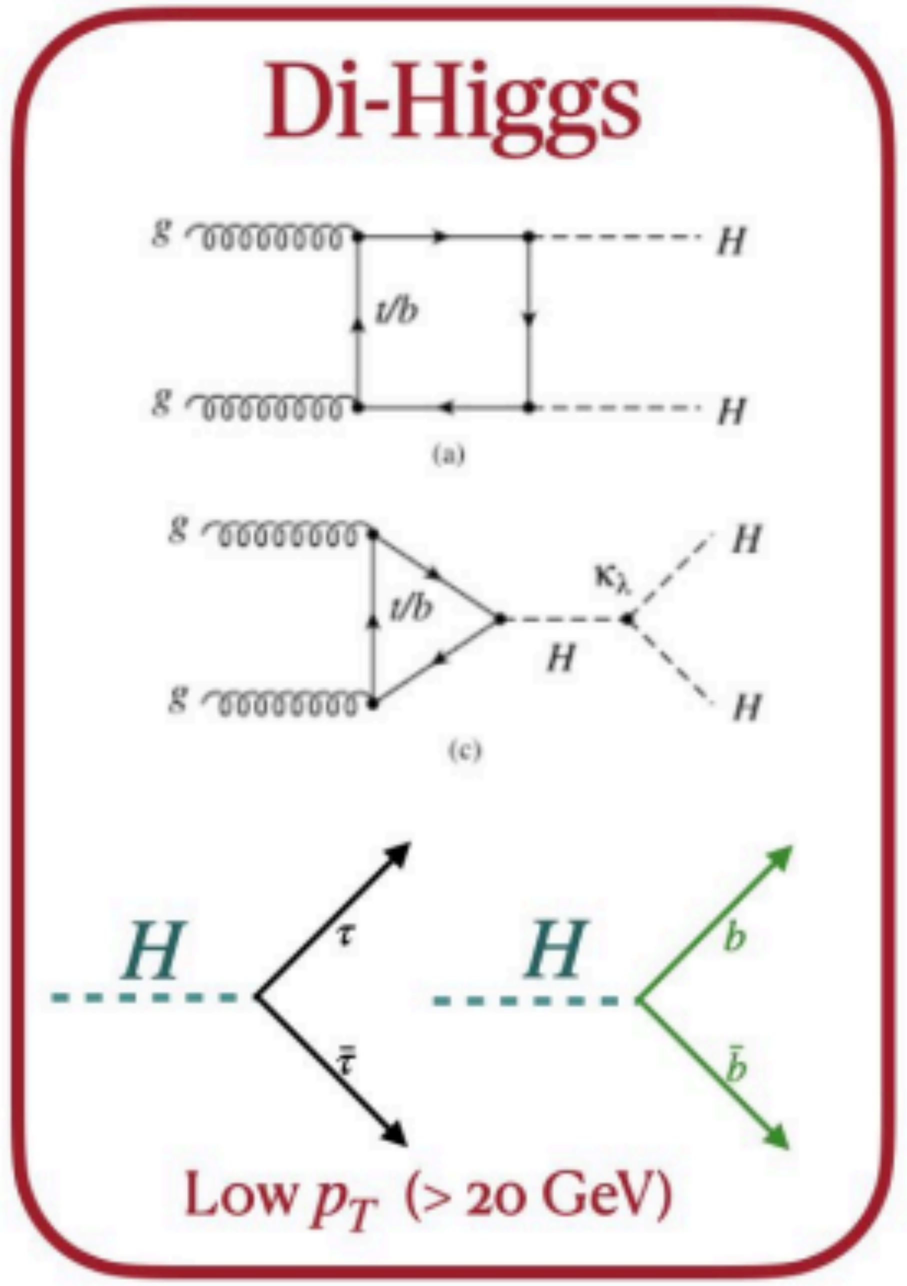


If made, this is going to be the first in hadron collider to trigger jets with **substructure** at L1! (ATLAS can't do this)

Develop H → $\tau_h \tau_h$ trigger for the HL-LHC





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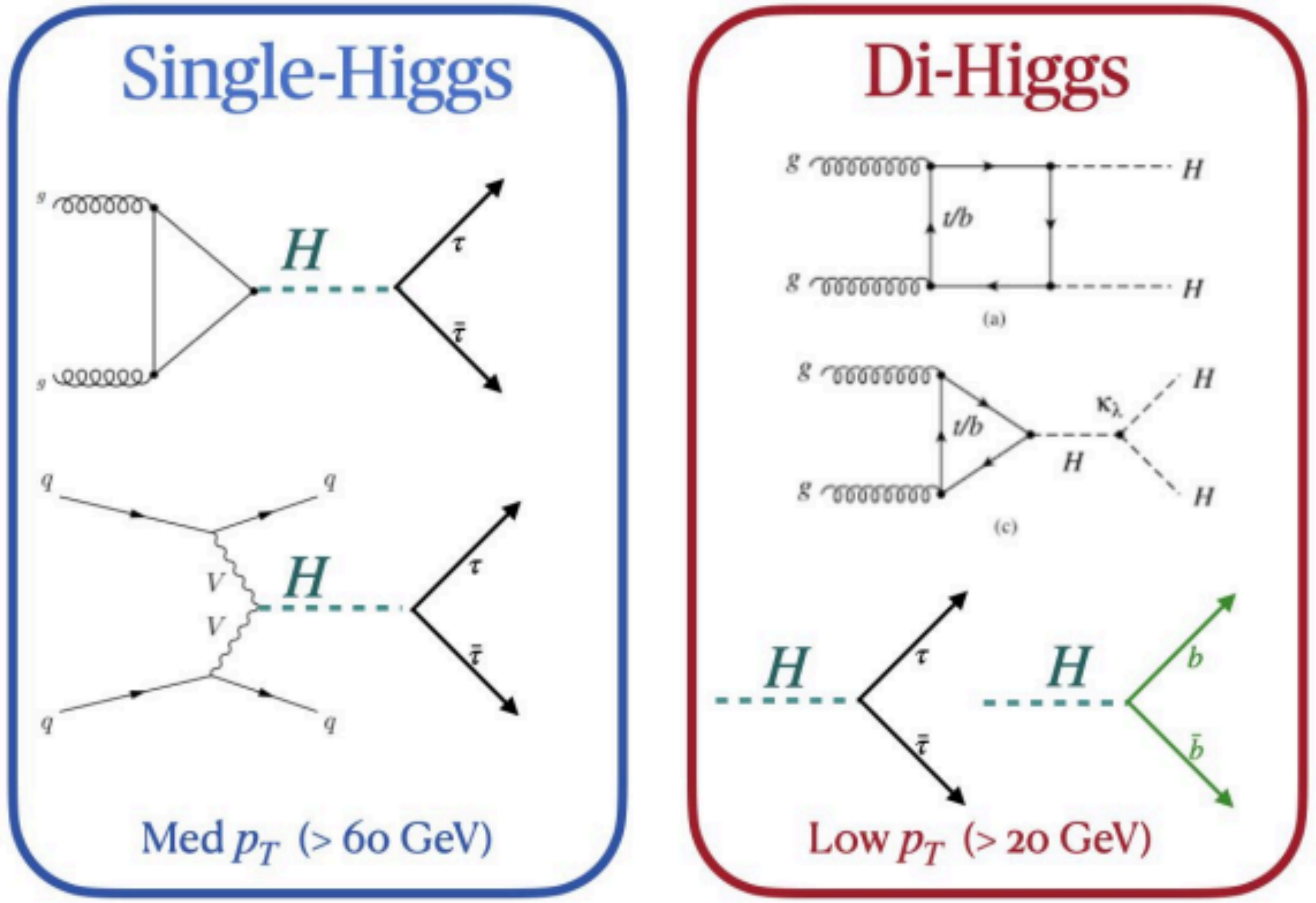

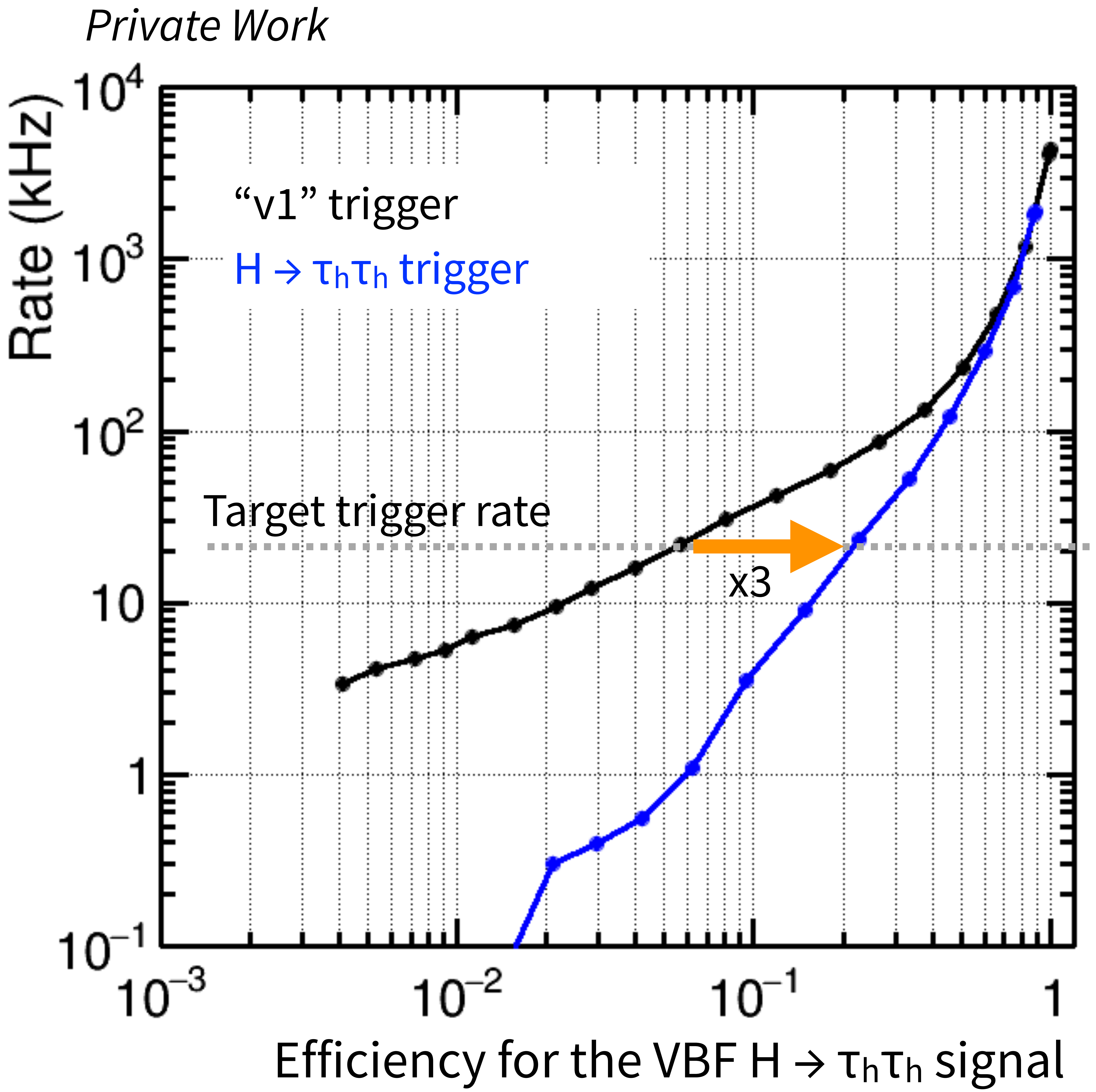

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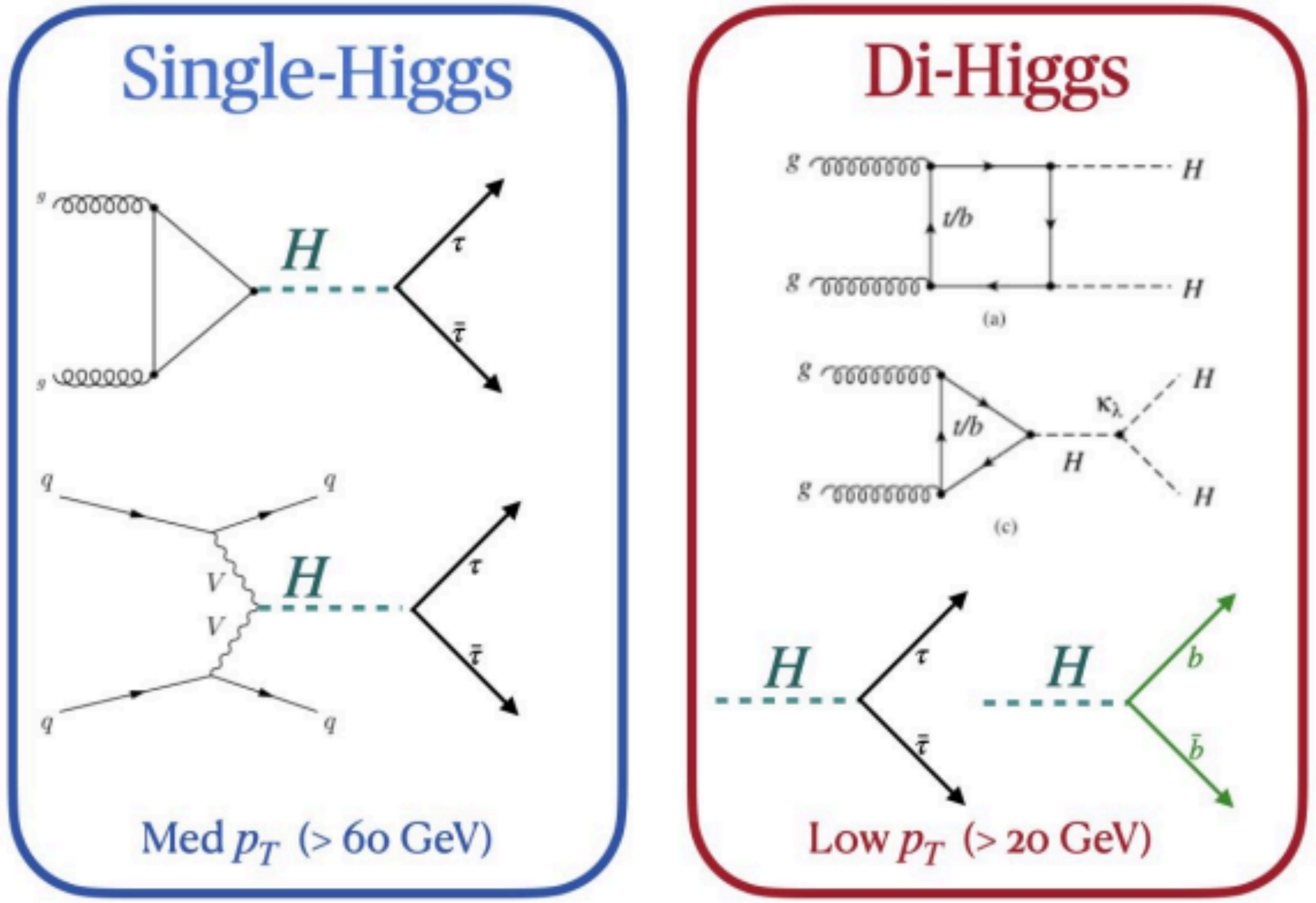
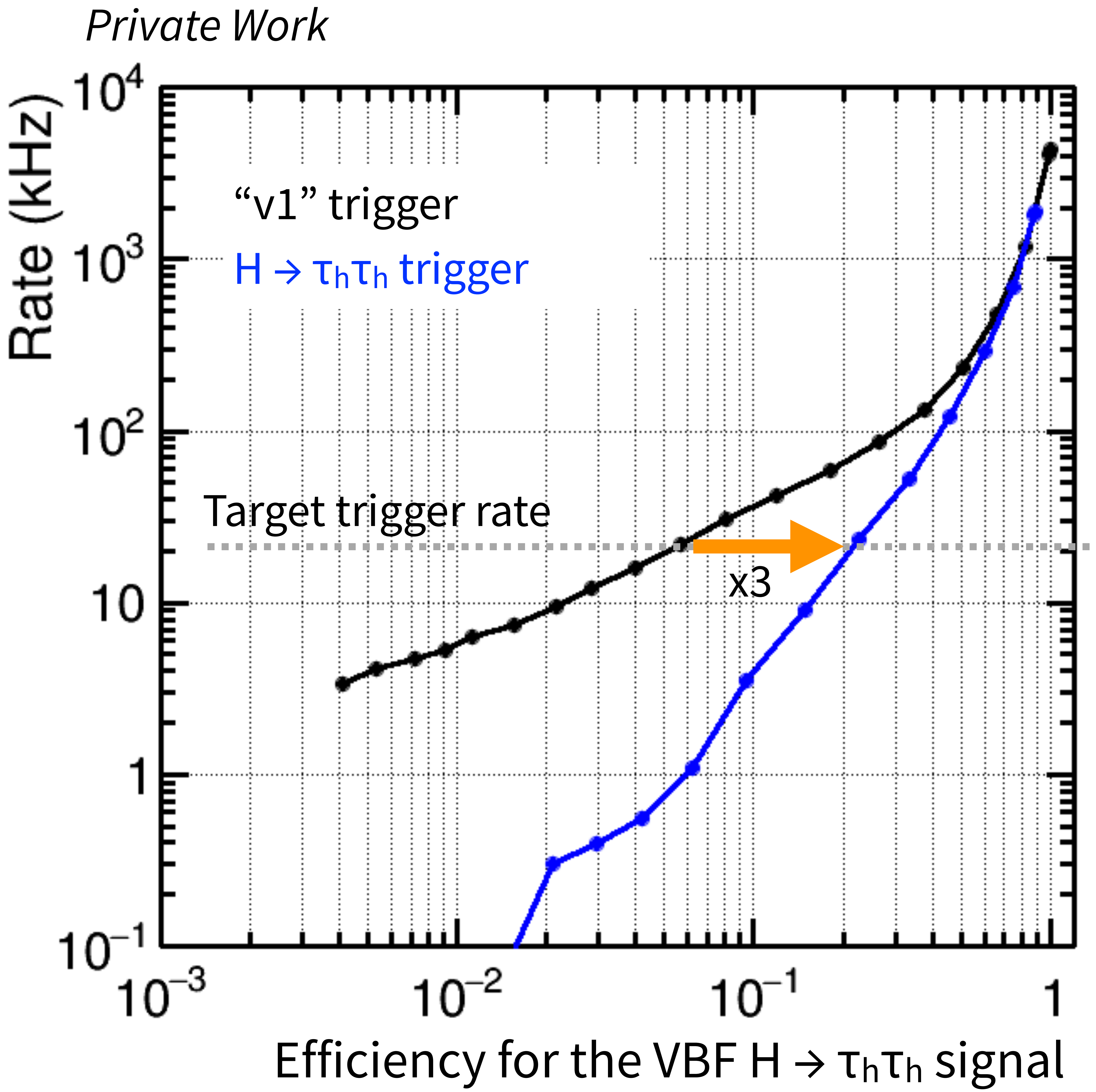


Potential game-changer for the λ_H measurement



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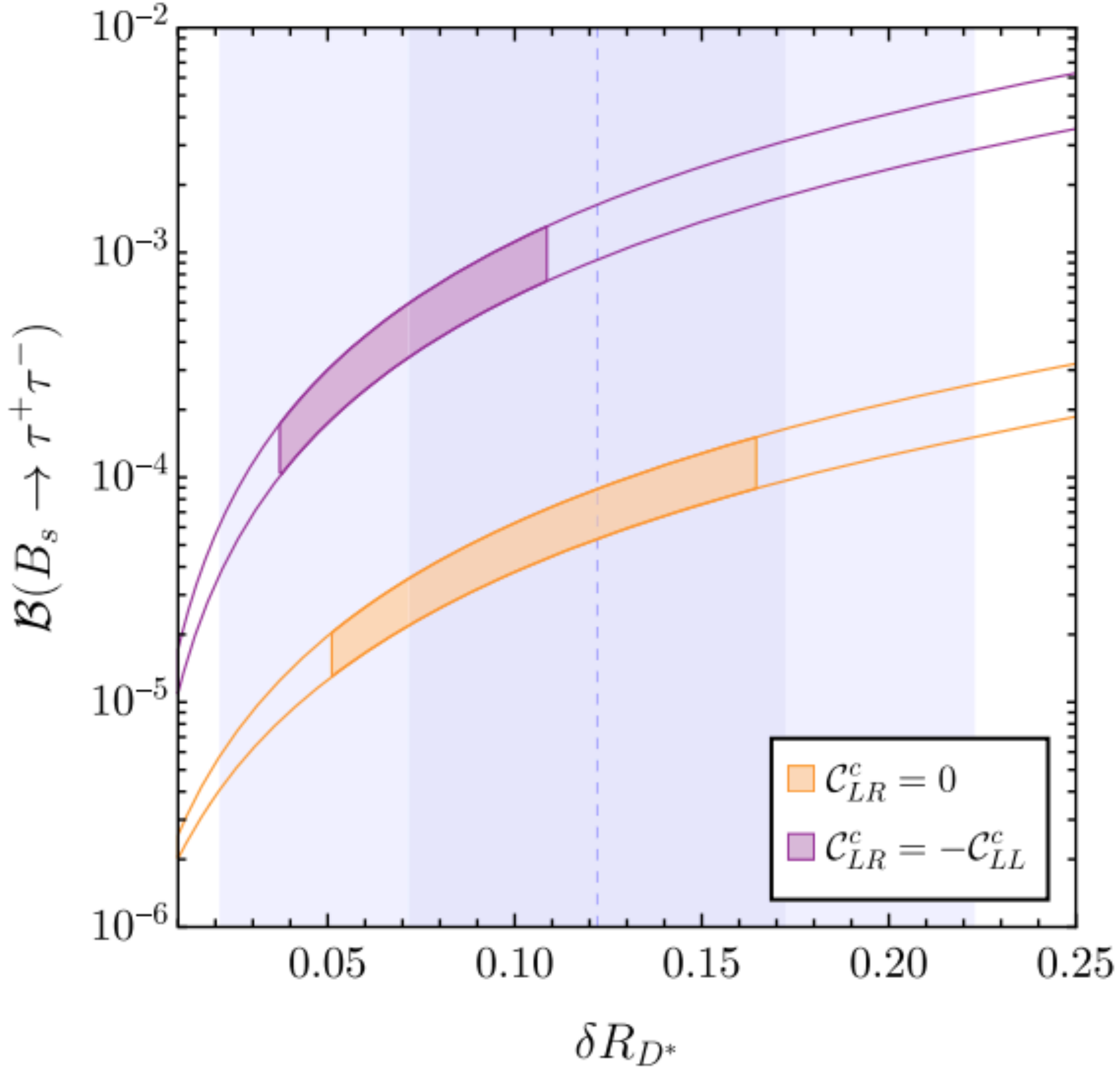
- We have been pioneering new object identification & new analysis ideas and will keep doing so

- We'll enjoy Run-3 and HL-LHC data, hoping to make a groundbreaking discovery!

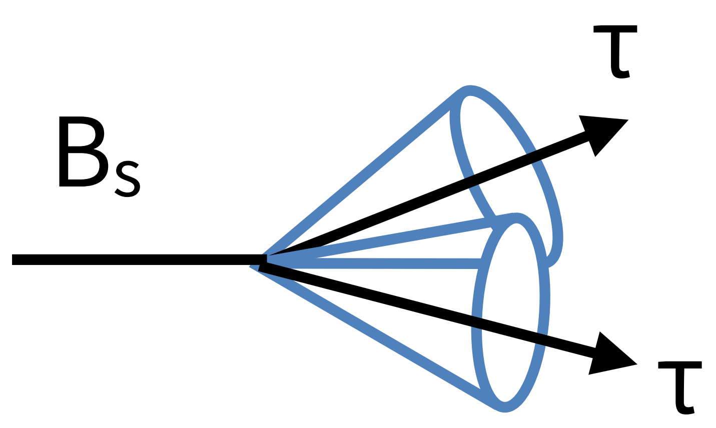
Thank you!



Aebischer, J., Isidori, G., Pesut, M. *et al.* Confronting the vector leptoquark hypothesis with new low- and high-energy data.
Eur. Phys. J. C **83**, 153 (2023).
https://doi.org/10.1140/epjc/s10052-023-11304-5

Difficulties

Two taus are produced in close vicinity (Lorentz boost)



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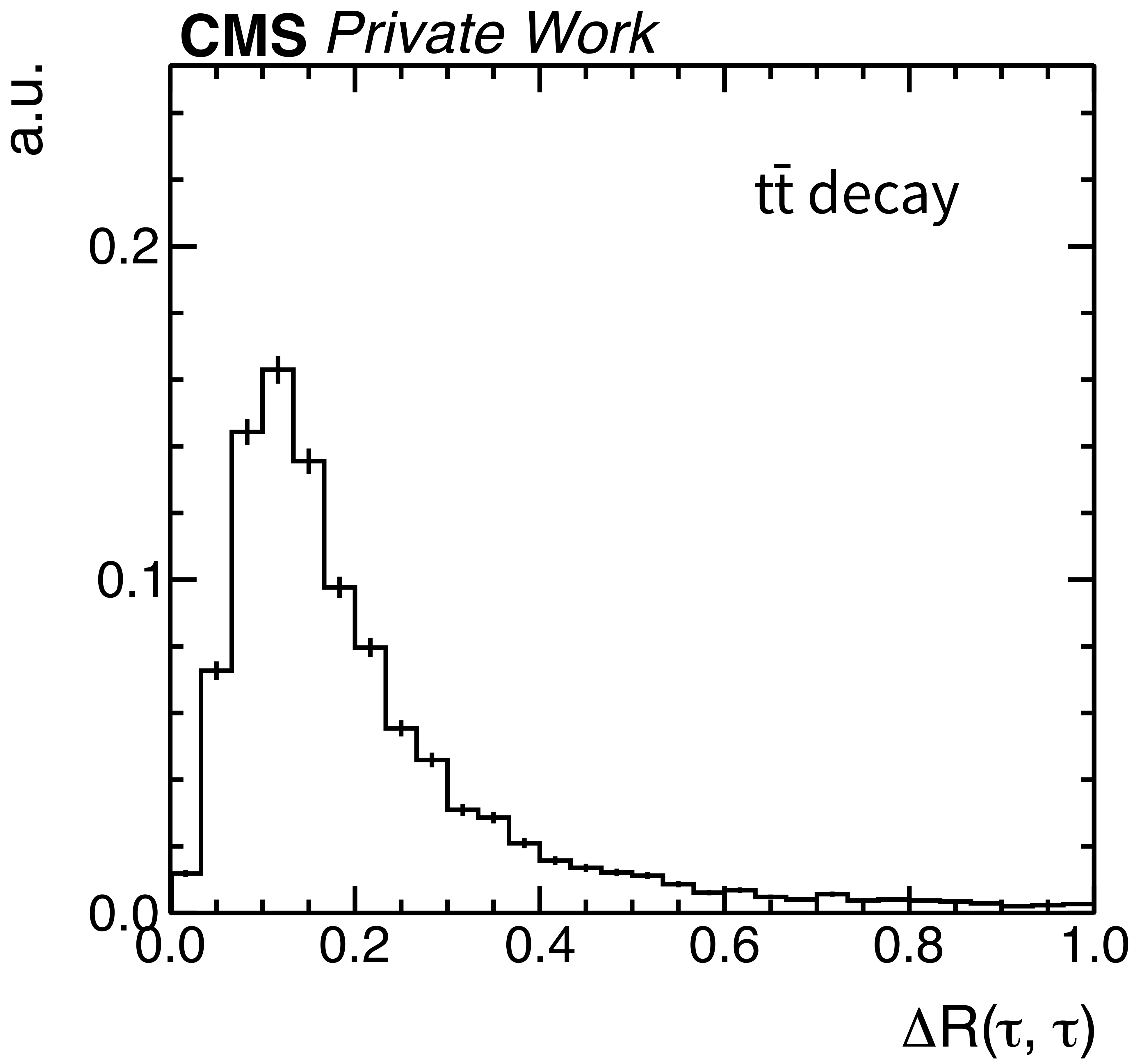

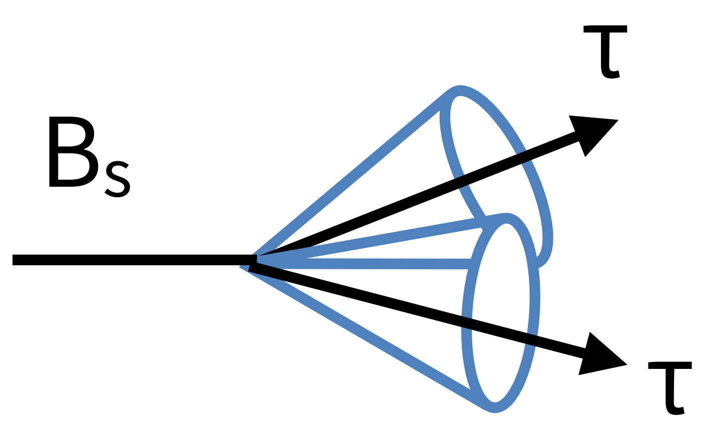

making it more challenging to reconstruct it

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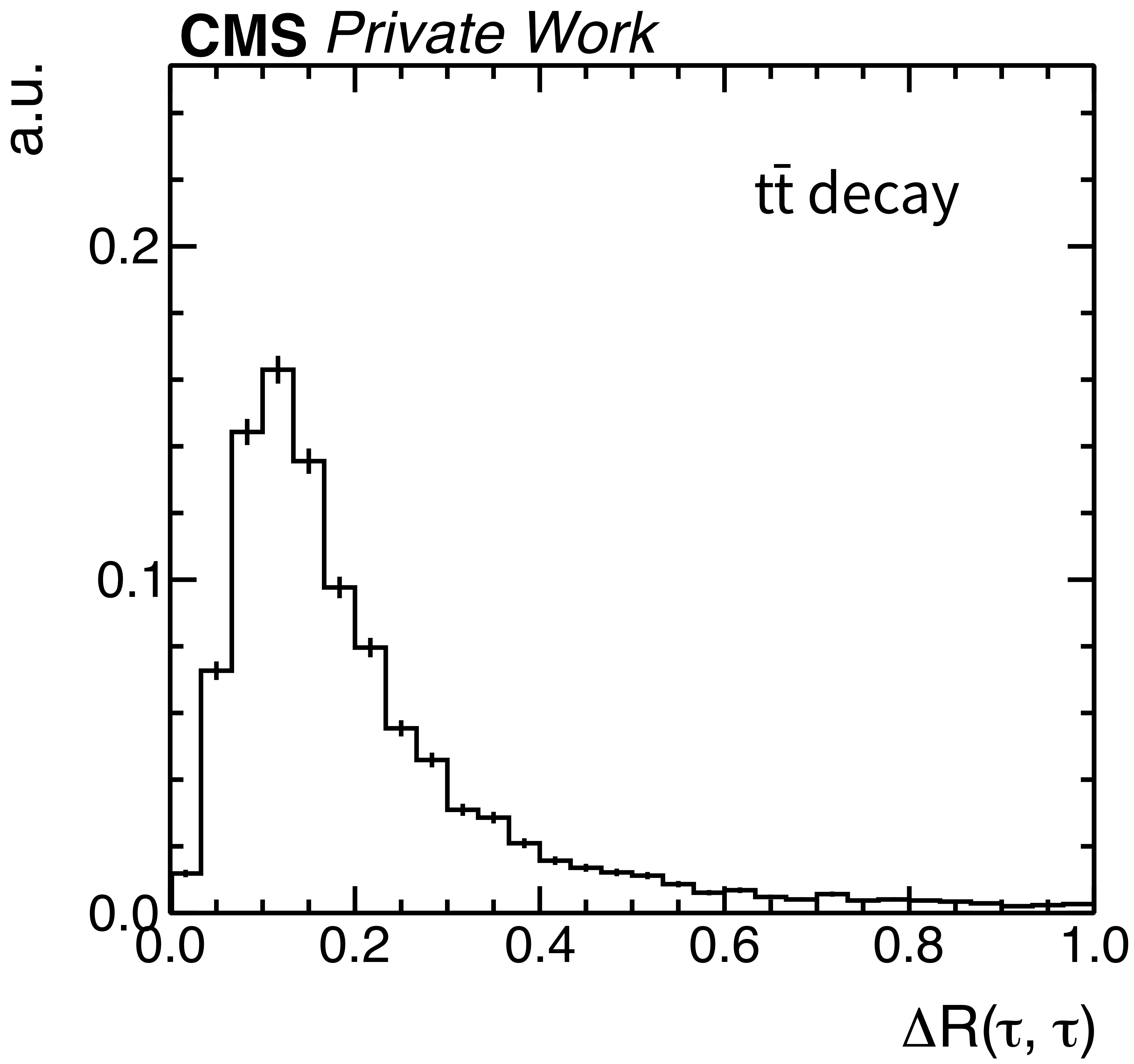

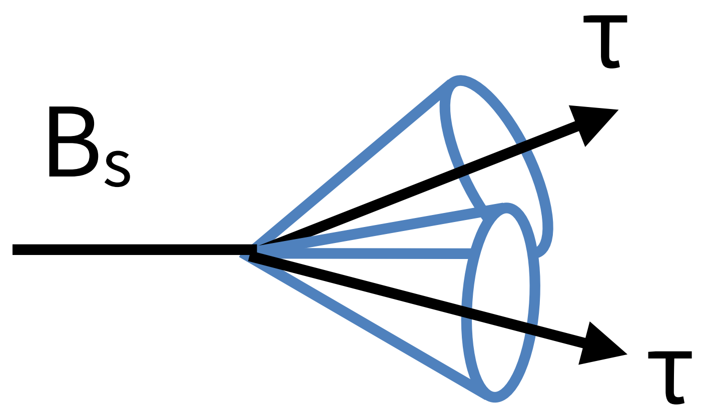

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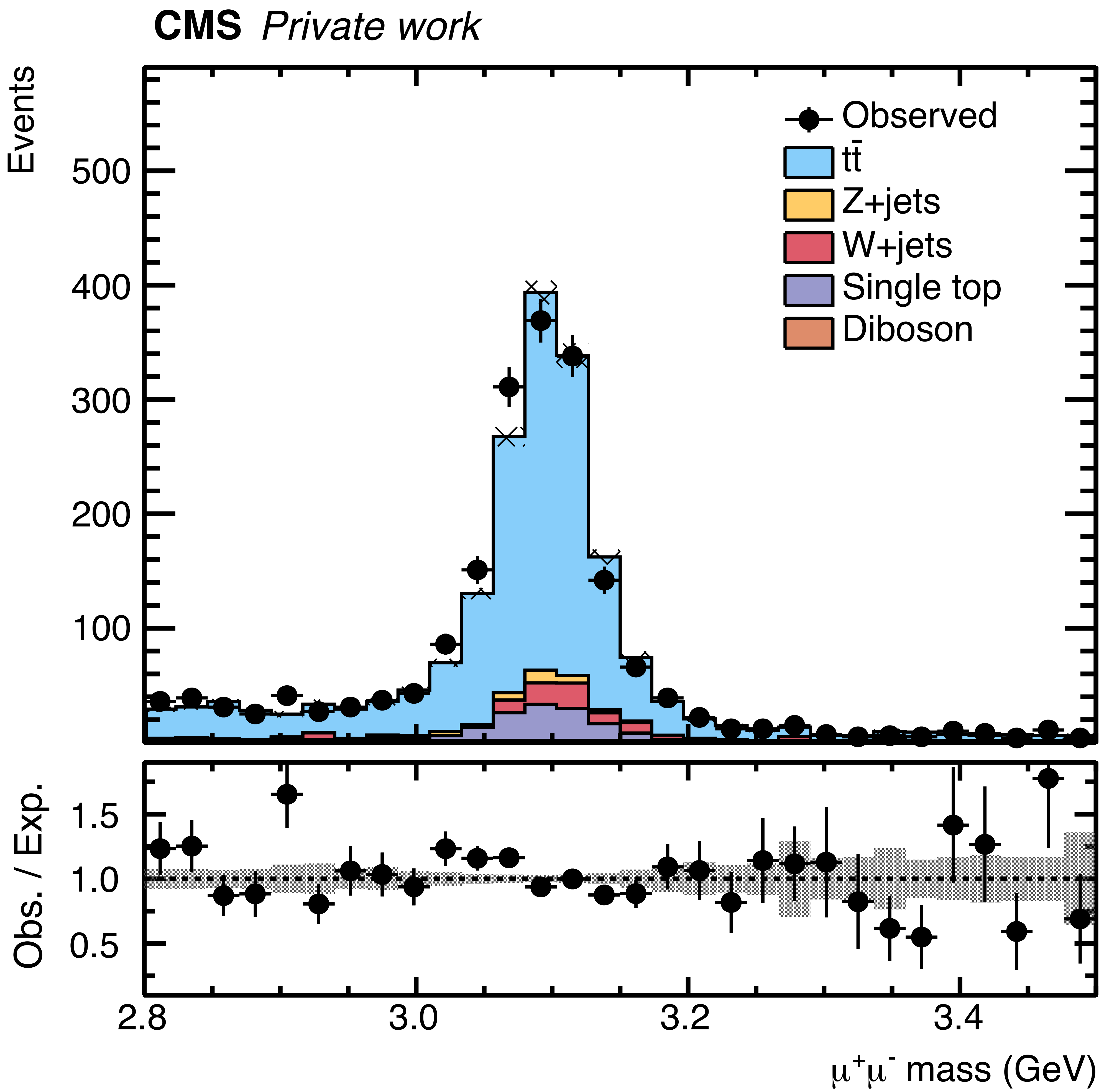
Proof-of-principle studies: Look at $B \to J/\psi + X$ in $t\bar{t}$ events using Run 2 data



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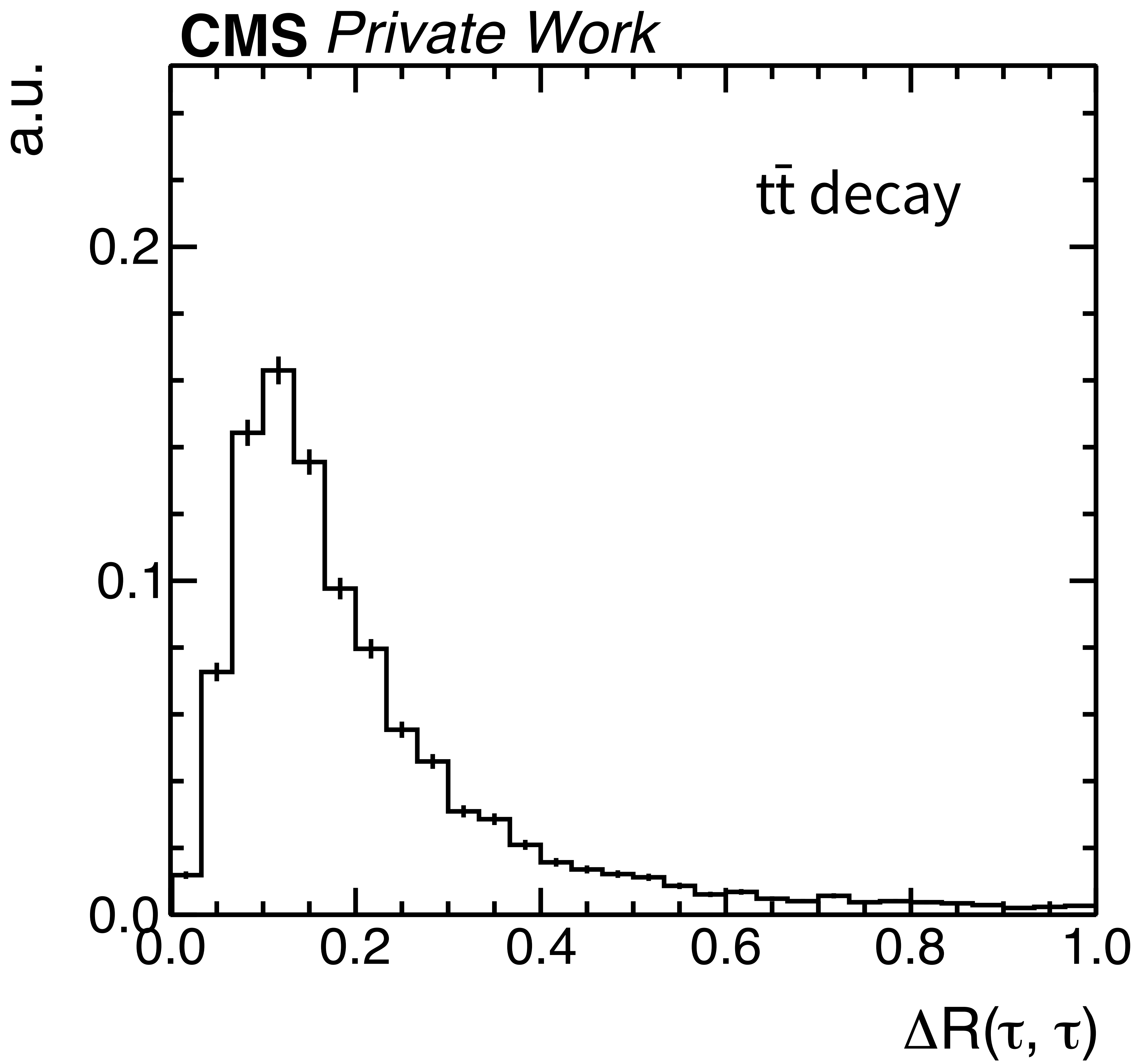

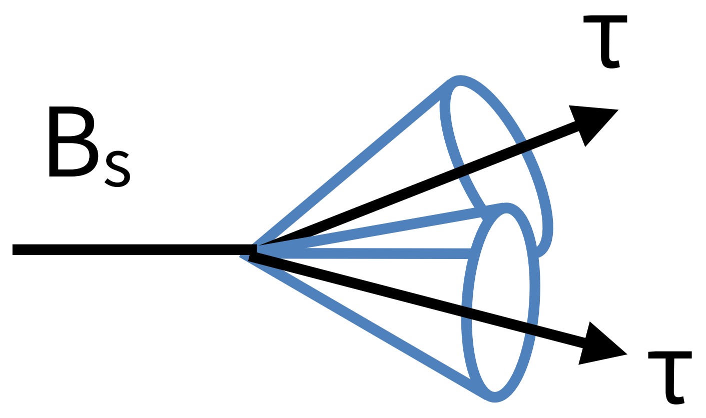

6 hadrons final state? (ML …)

making it more challenging to reconstruct it

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