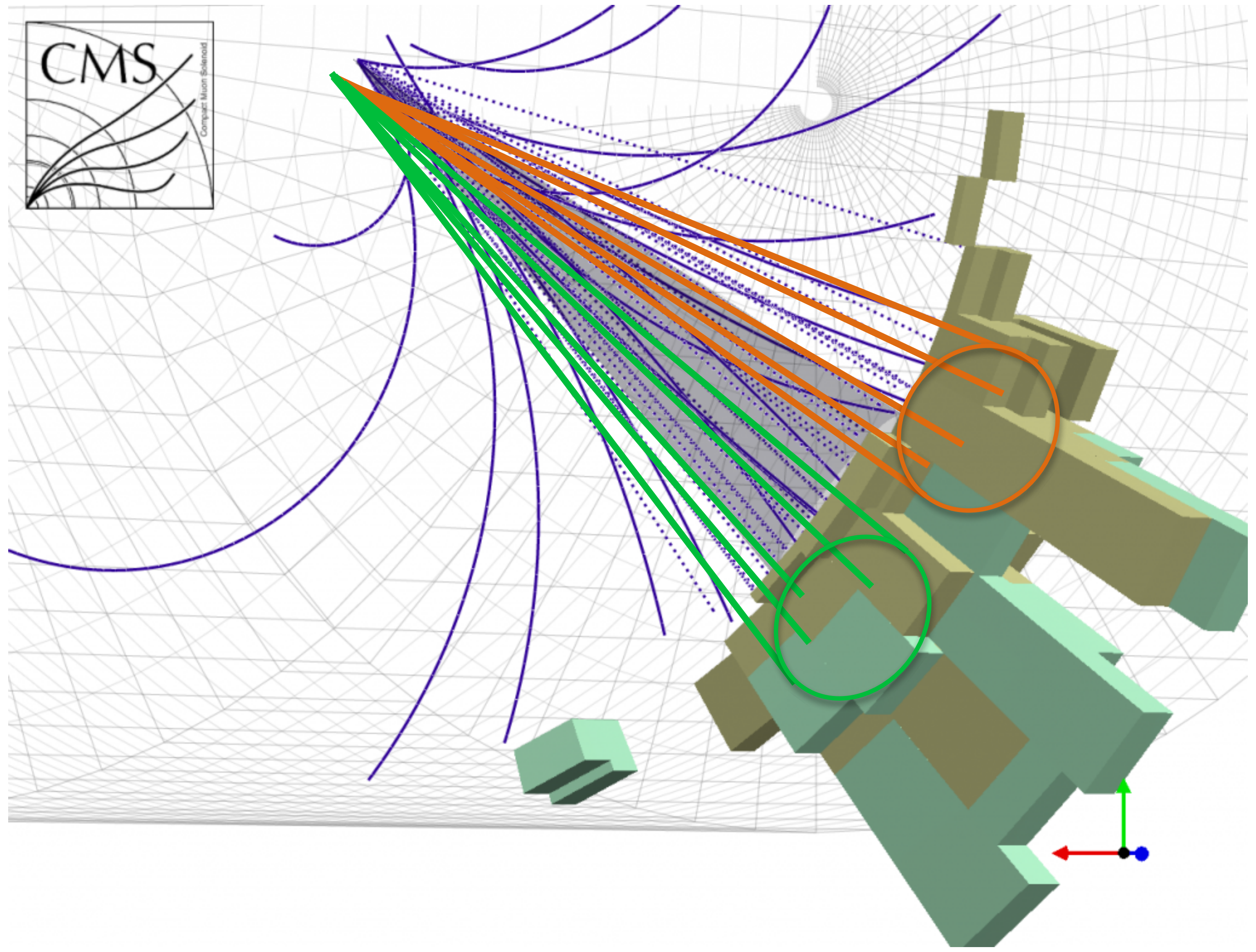
Boosted resonance searches at CMS and their long-term impact

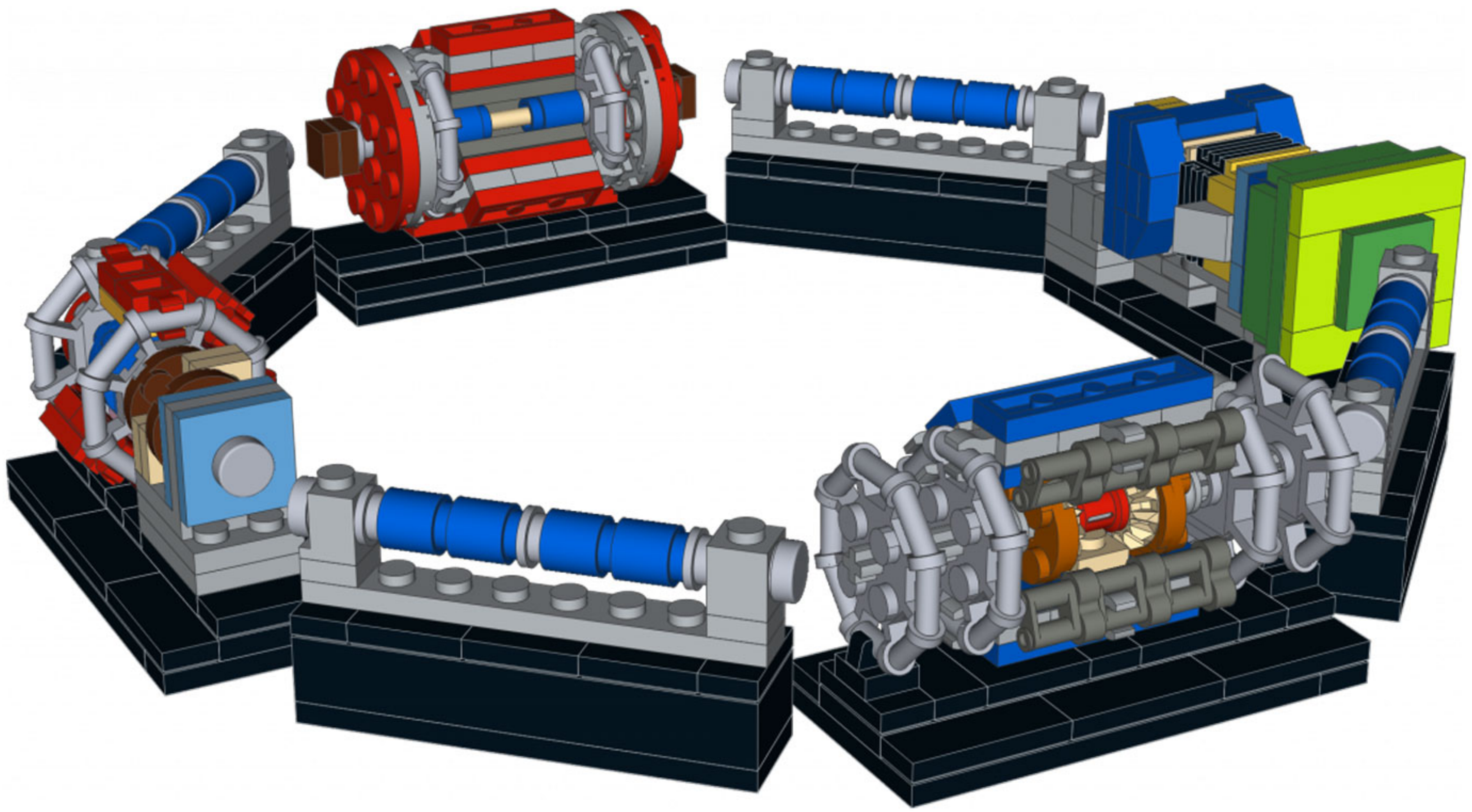


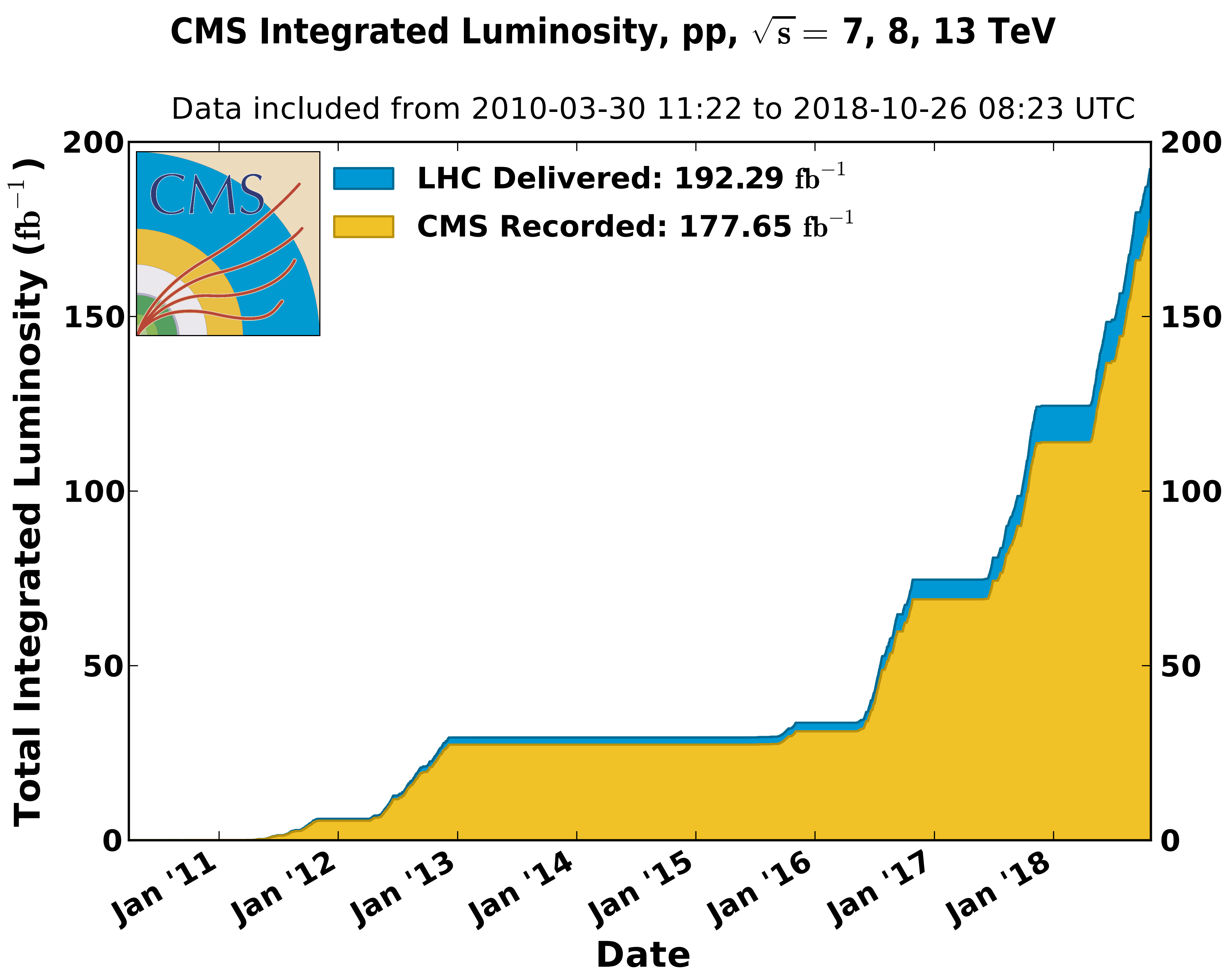
Clemens Lange (CERN)

Fermilab Wine & Cheese Seminar
15th January 2021

Going to highest energies…

- The Large Hadron Collider (LHC) is the world's largest and **highest-energy** particle accelerator





- Delivered $\mathscr{L}$ = 163 fb^{-1} of proton-proton collisions at $\sqrt{s}$ = 13 TeV
- Exceeded most of its design parameters, producing collisions 49% of the time in 2018

Image: Nathan Readioff

… creating a big mess

My needle in the haystack

- Finding a **very heavy and extremely rare resonance** in events like that

My needle in the haystack

> Finding a **very heavy and extremely rare resonance** in events like that

Why?

My needle in the haystack

> Finding a **very heavy and extremely rare resonance** in events like that

Why?

> Try to find a possible explanation to the big difference between **weak force** and **gravity**?

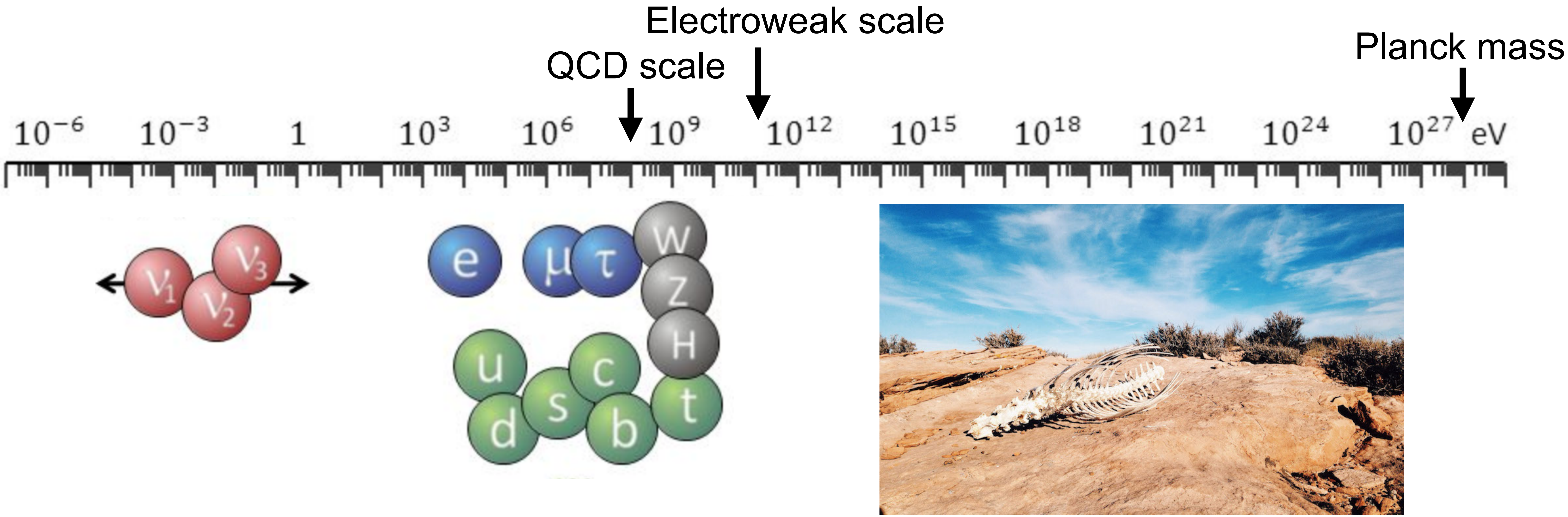
$$\mu^2 = \lambda v^2 = \frac{\lambda}{g^2} 4M_W^2 \sim 10^4 \text{ GeV}^2 \ll M_{Pl} \sim 10^{38} \text{ GeV}^2$$

Electroweak scale — Planck scale

- Referred to as **hierarchy problem**
- In other words — why is the **Higgs boson** so **light**?

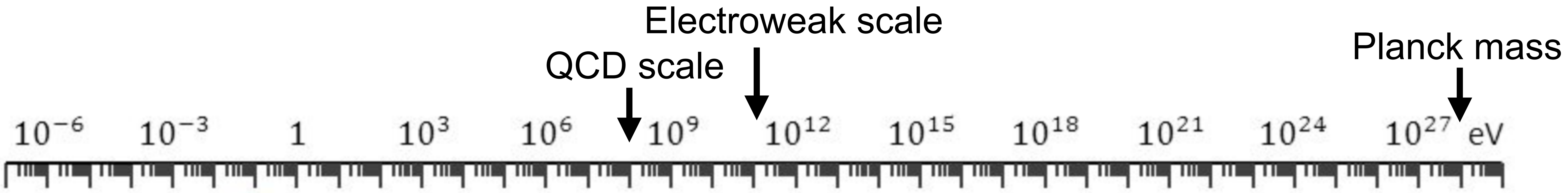
> „Natural" explanation would be that SM is replaced by another theory at the TeV scale: $\mu^2 \sim (\text{heavier scale})^2$ ➜ **new particles**

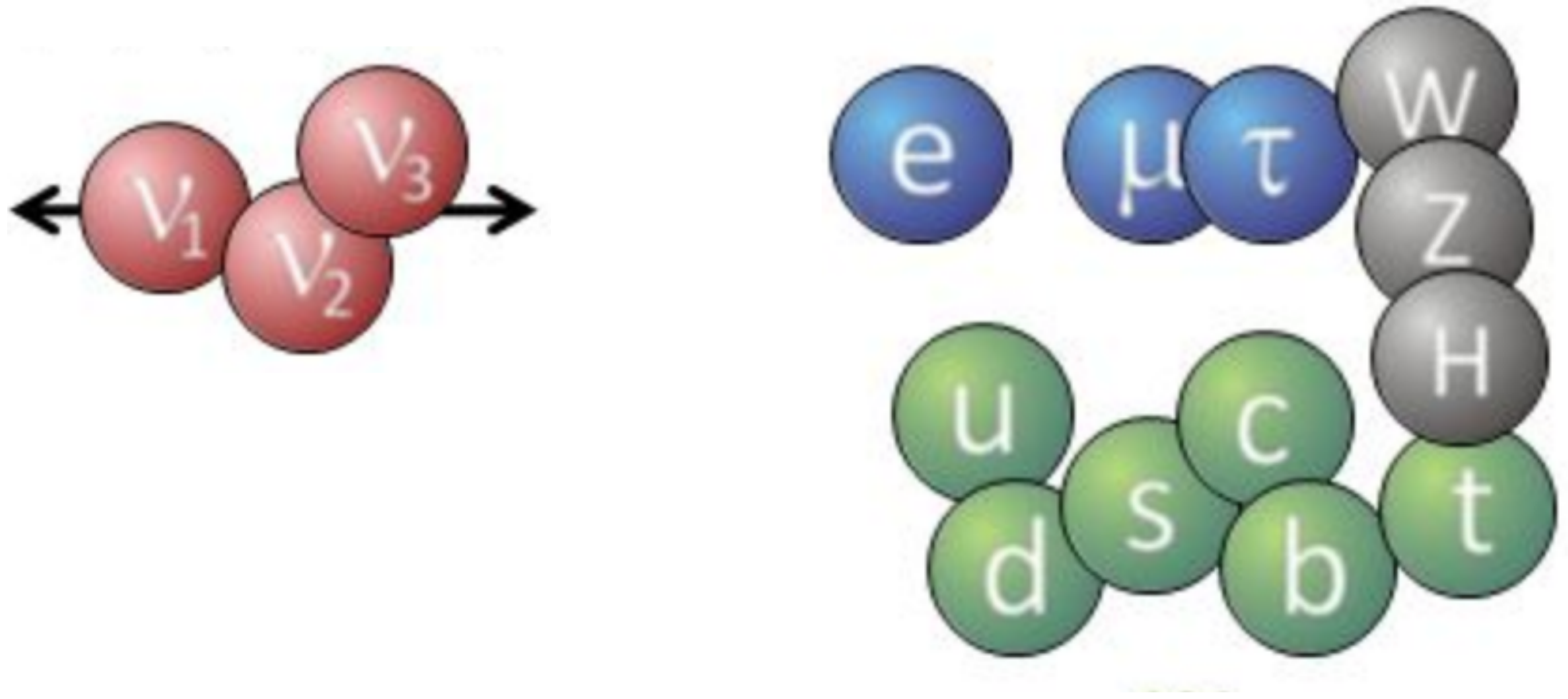
More on the hierarchy problem



No idea what's happening in this range

More on the hierarchy problem



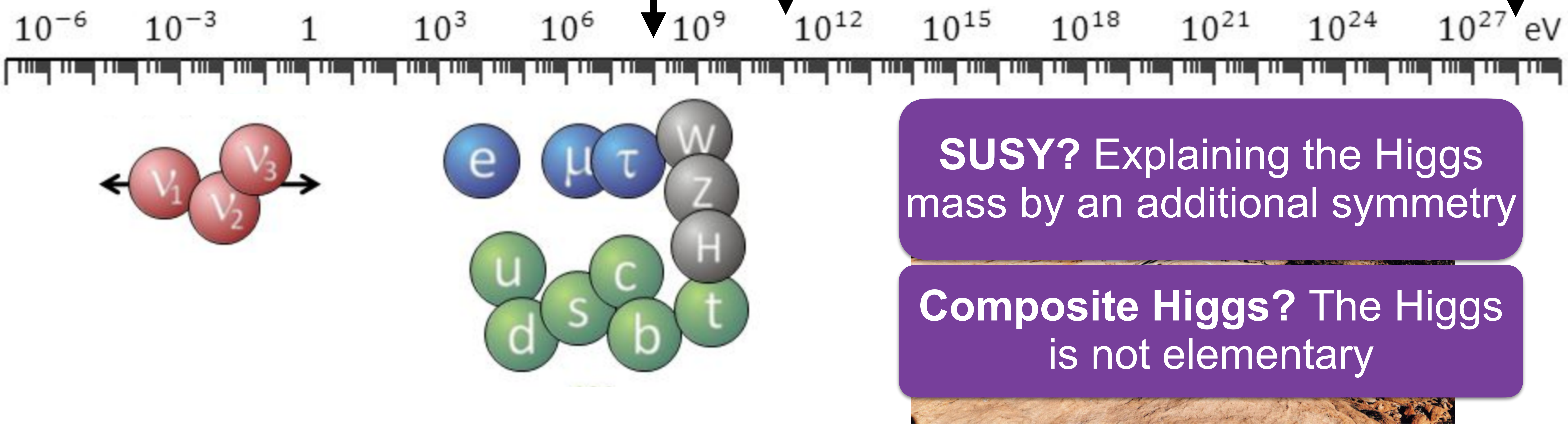


SUSY? Explaining the Higgs mass by an additional symmetry

No idea what’s happening in this range

More on the hierarchy problem

Electroweak scale
QCD scale
Planck mass



SUSY? Explaining the Higgs mass by an additional symmetry

Composite Higgs? The Higgs is not elementary

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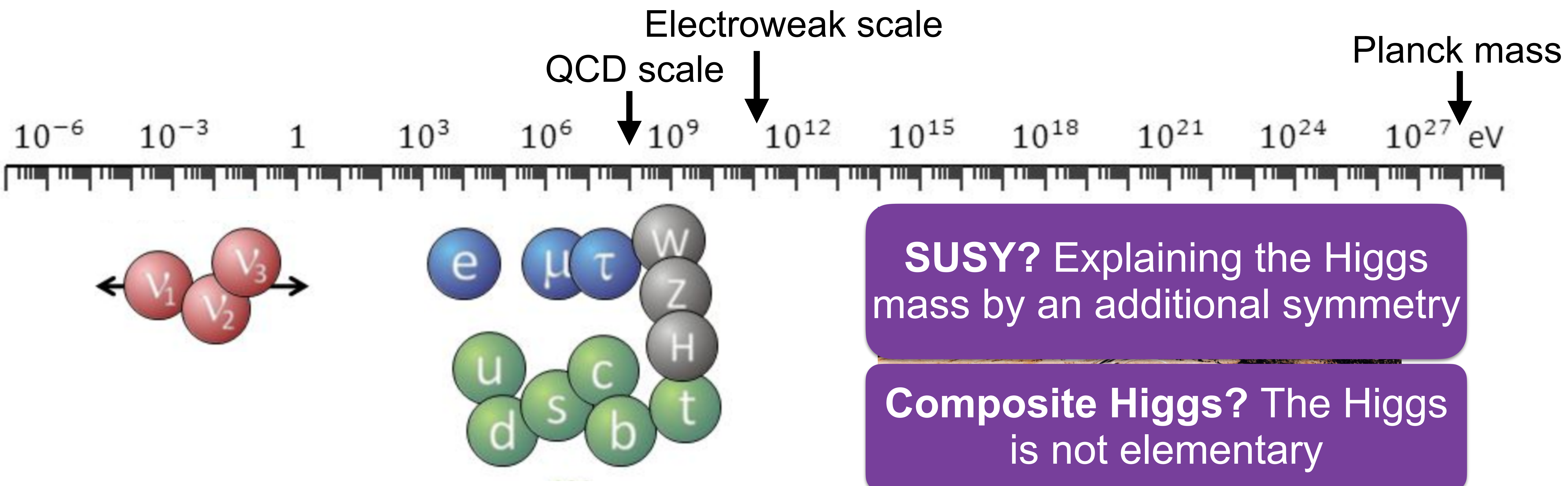
More on the hierarchy problem



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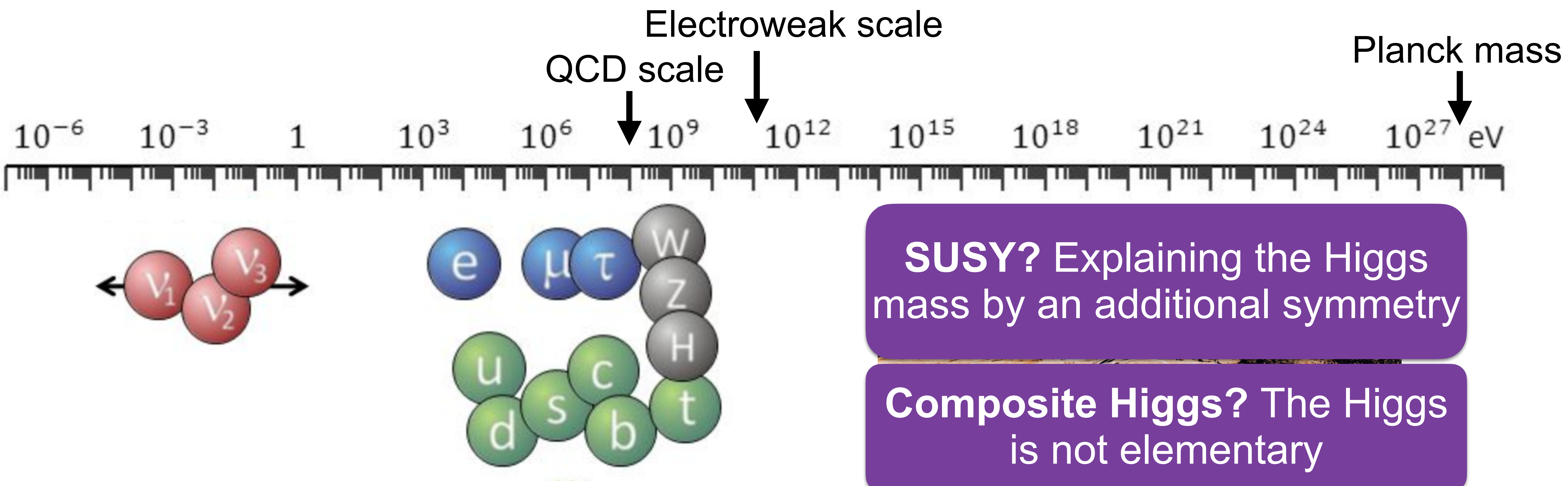
Large/warped extra dimensions? Gravity already strong at electroweak scale

More on the hierarchy problem



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Need to test these experimentally!

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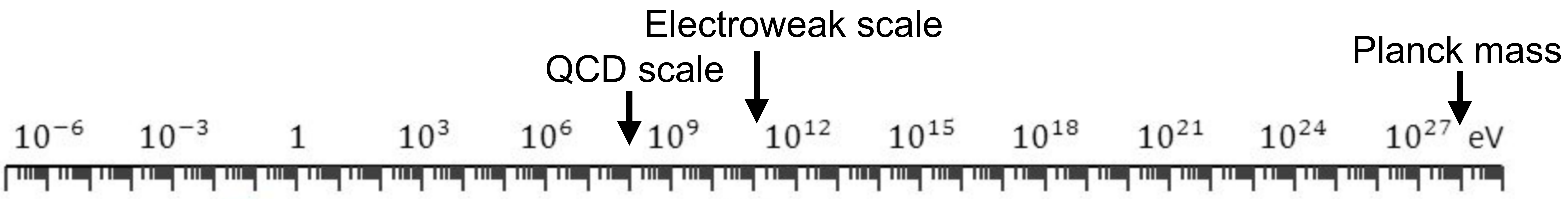

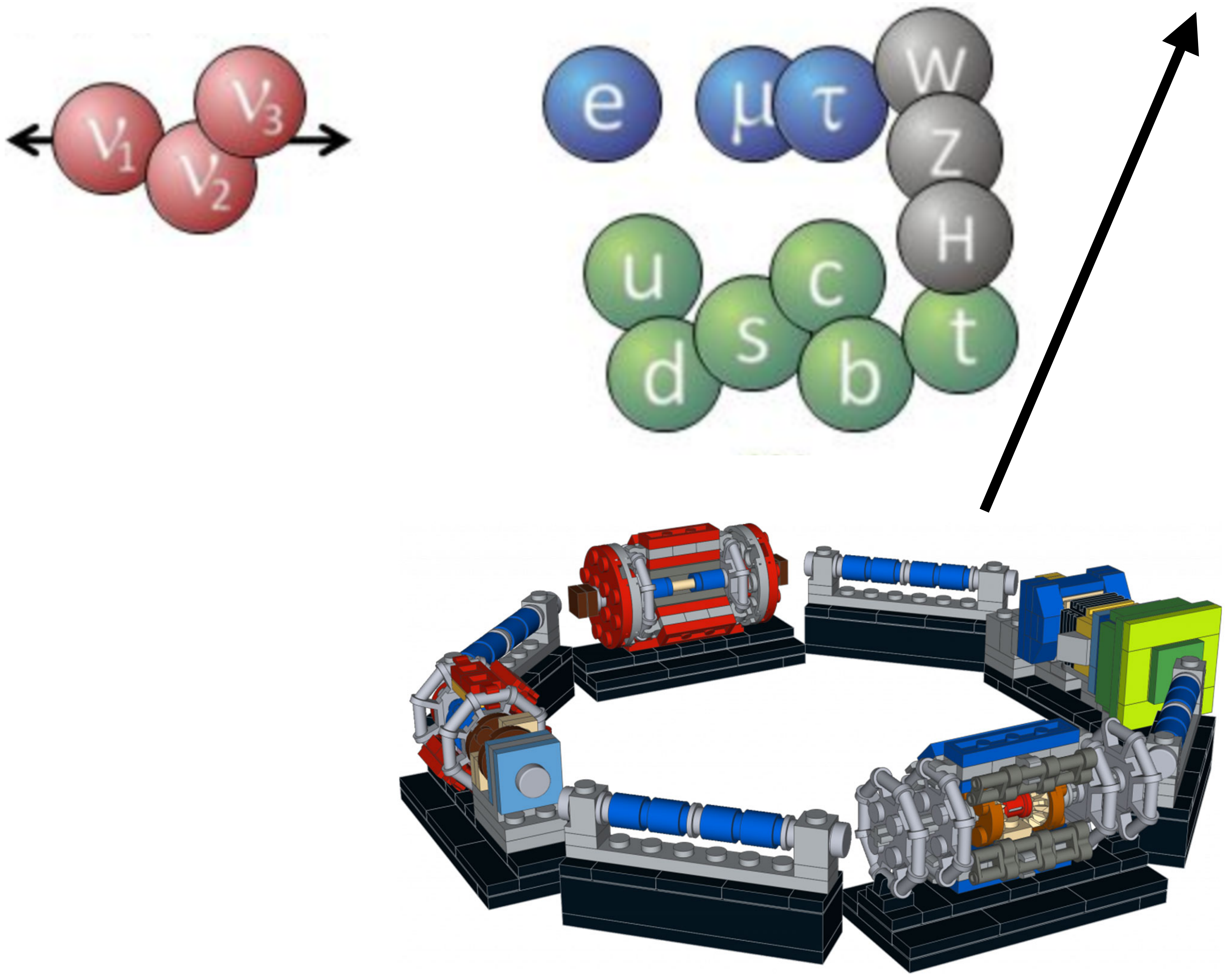

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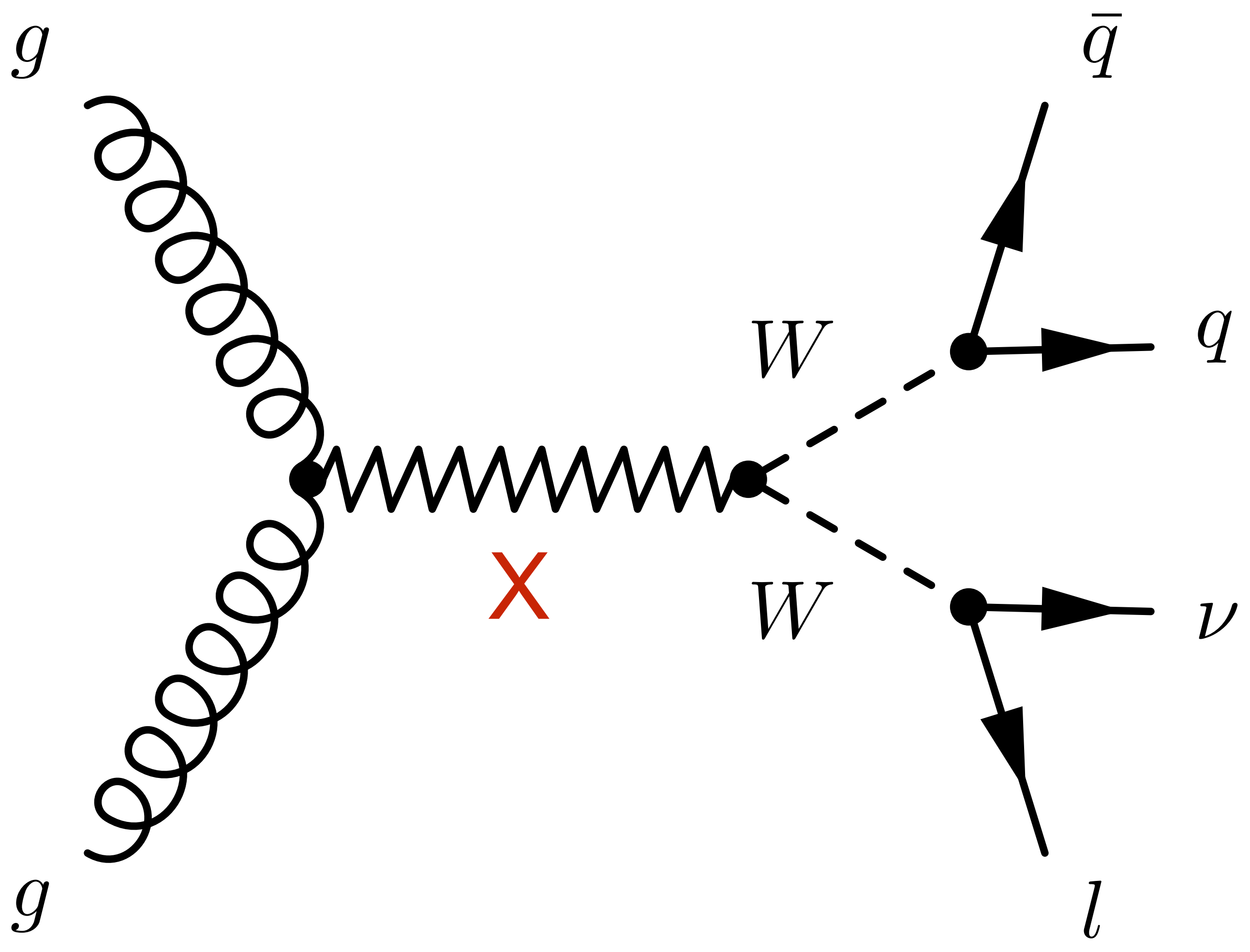
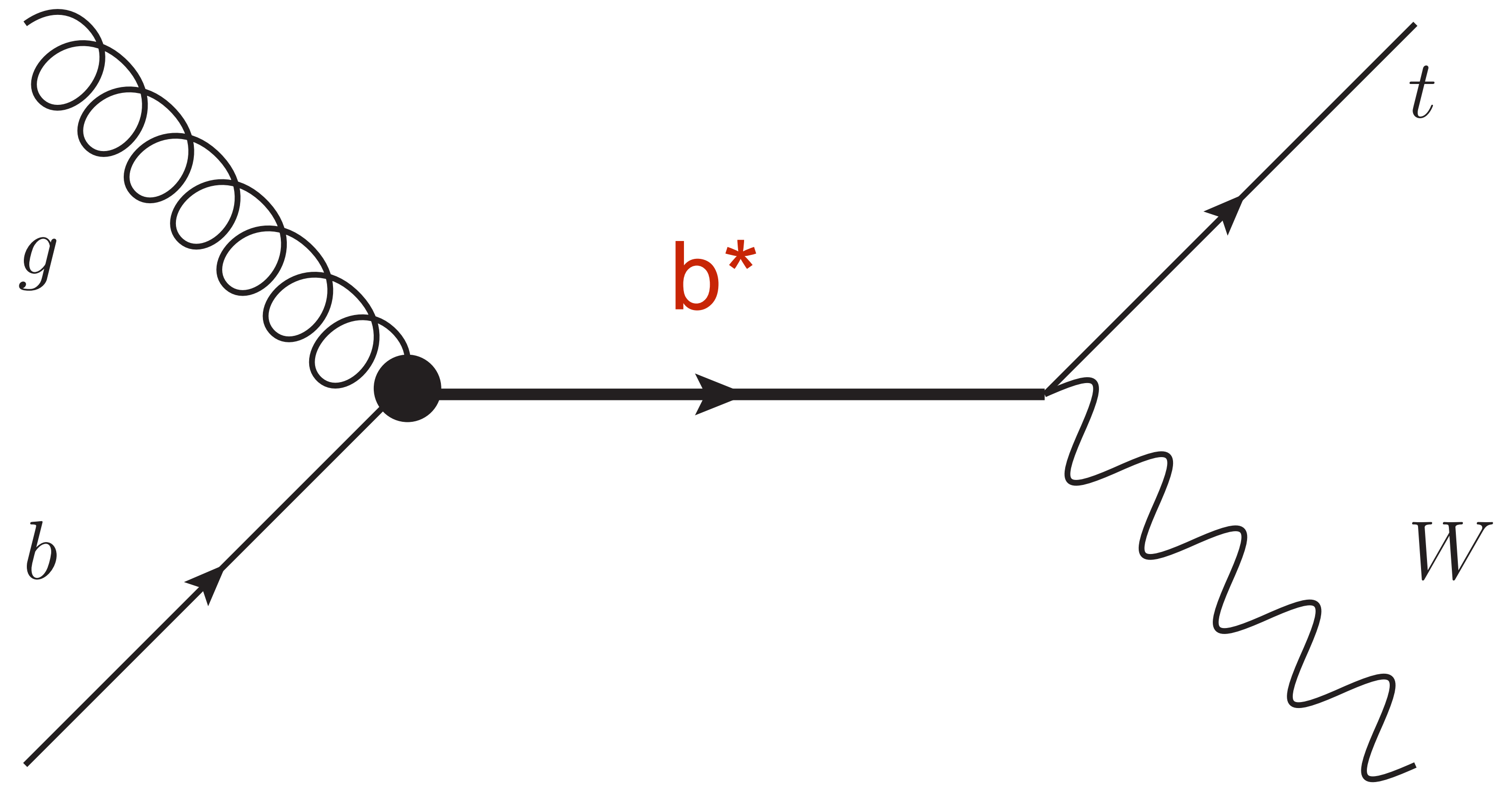
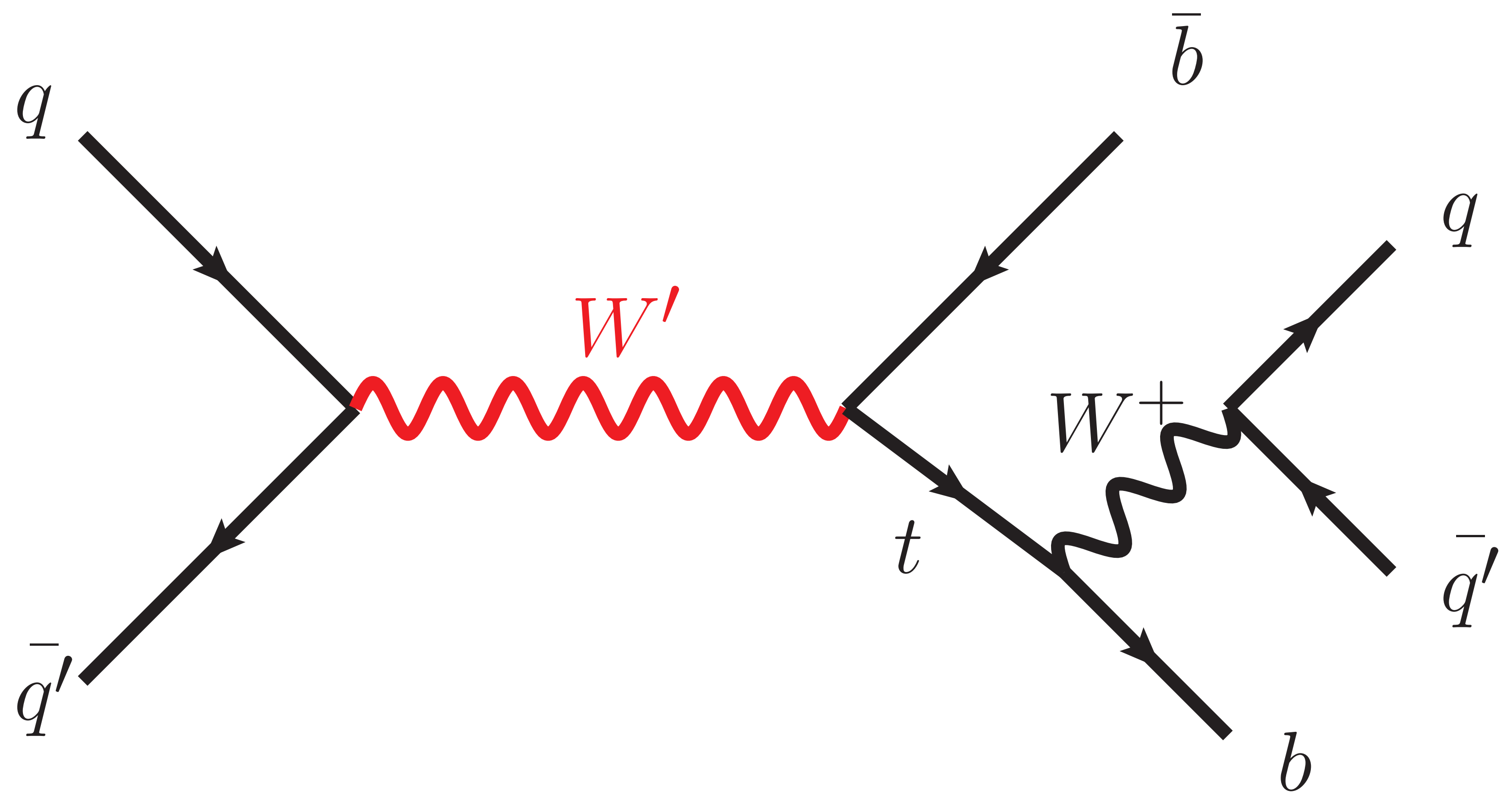
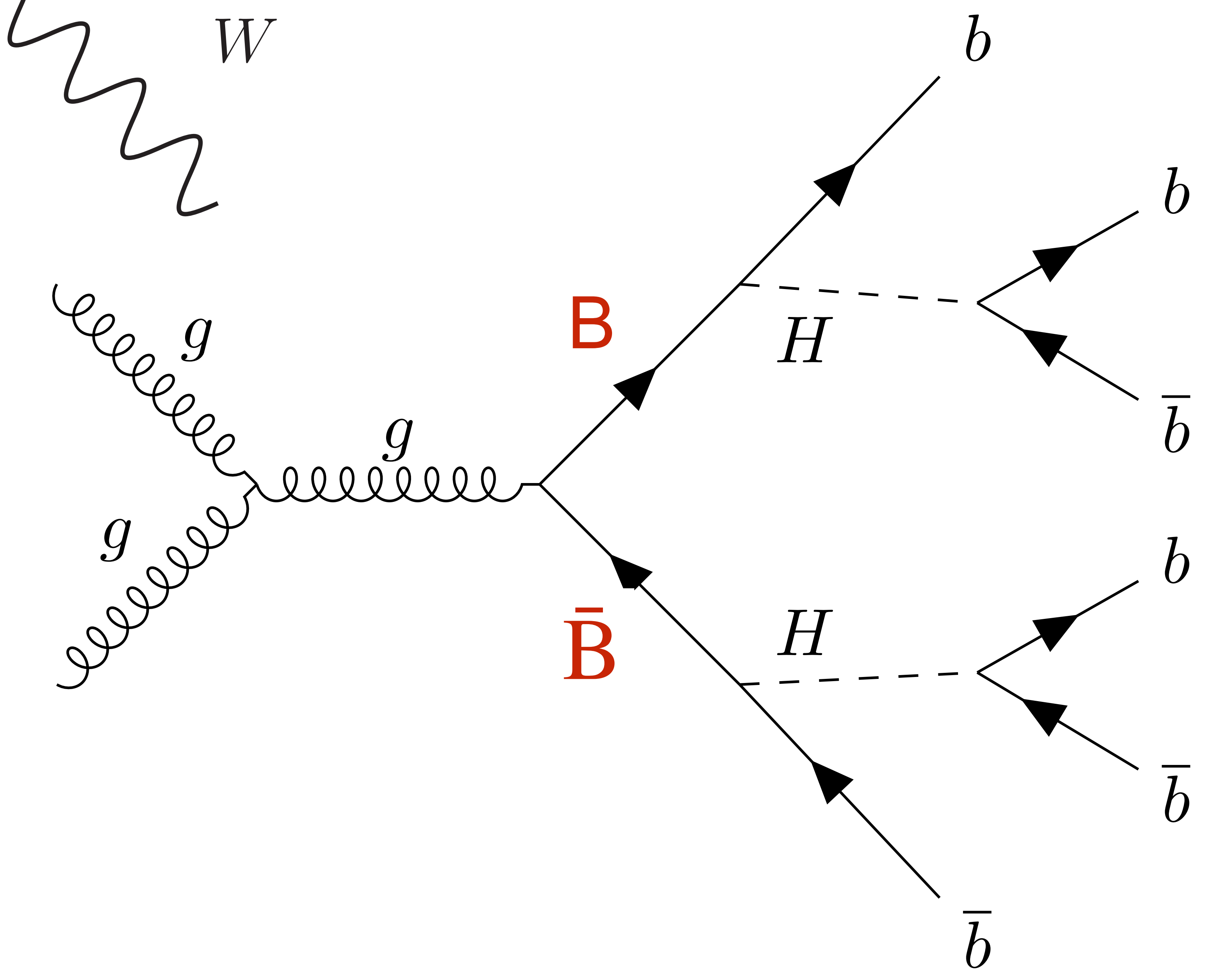
Examples of heavy resonances

CMS-PAS-B2G-19-006
Phys. Lett. B 781 (2018) 327
Phys. Rev. D 102 (2020) 112004









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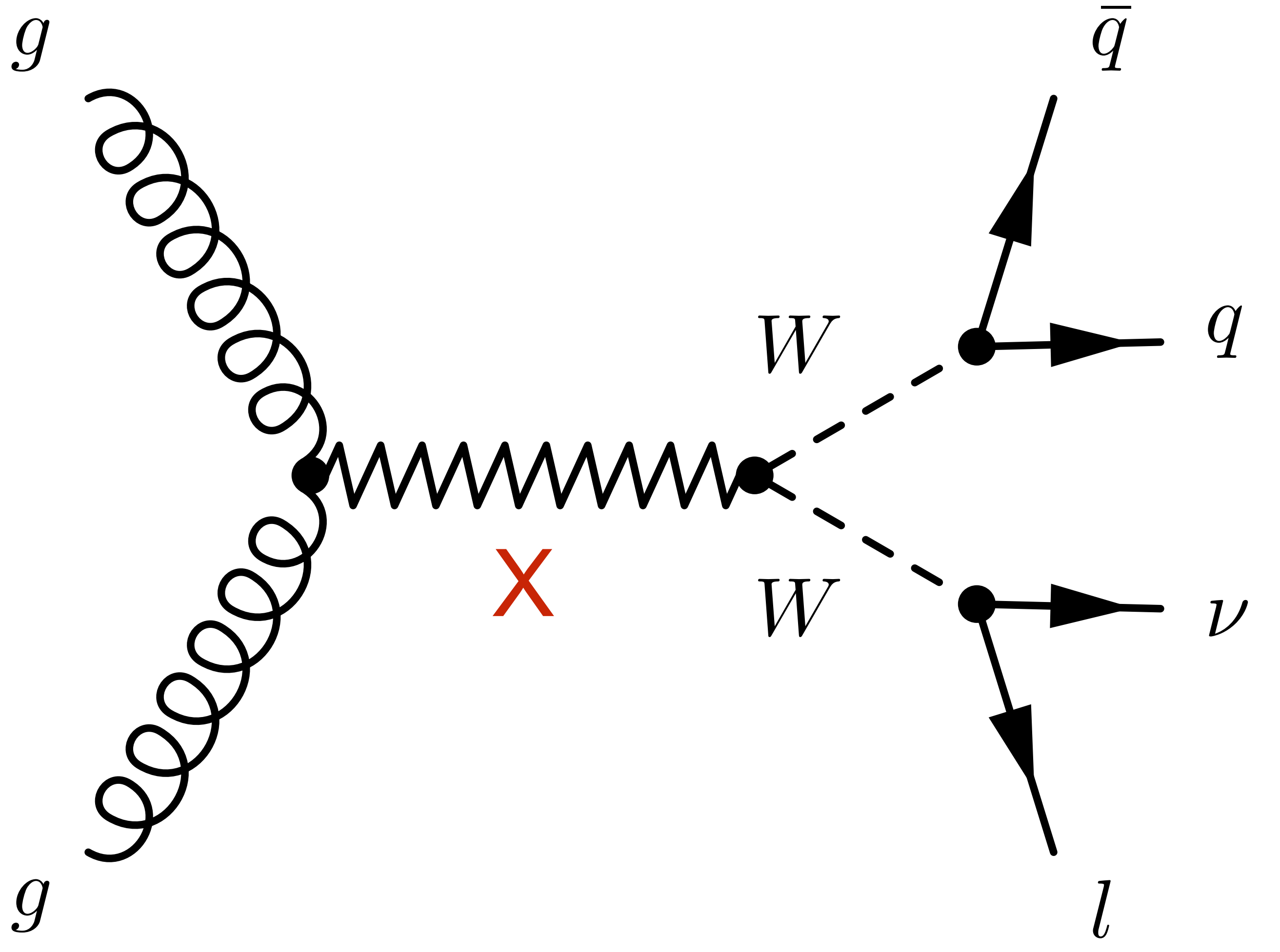
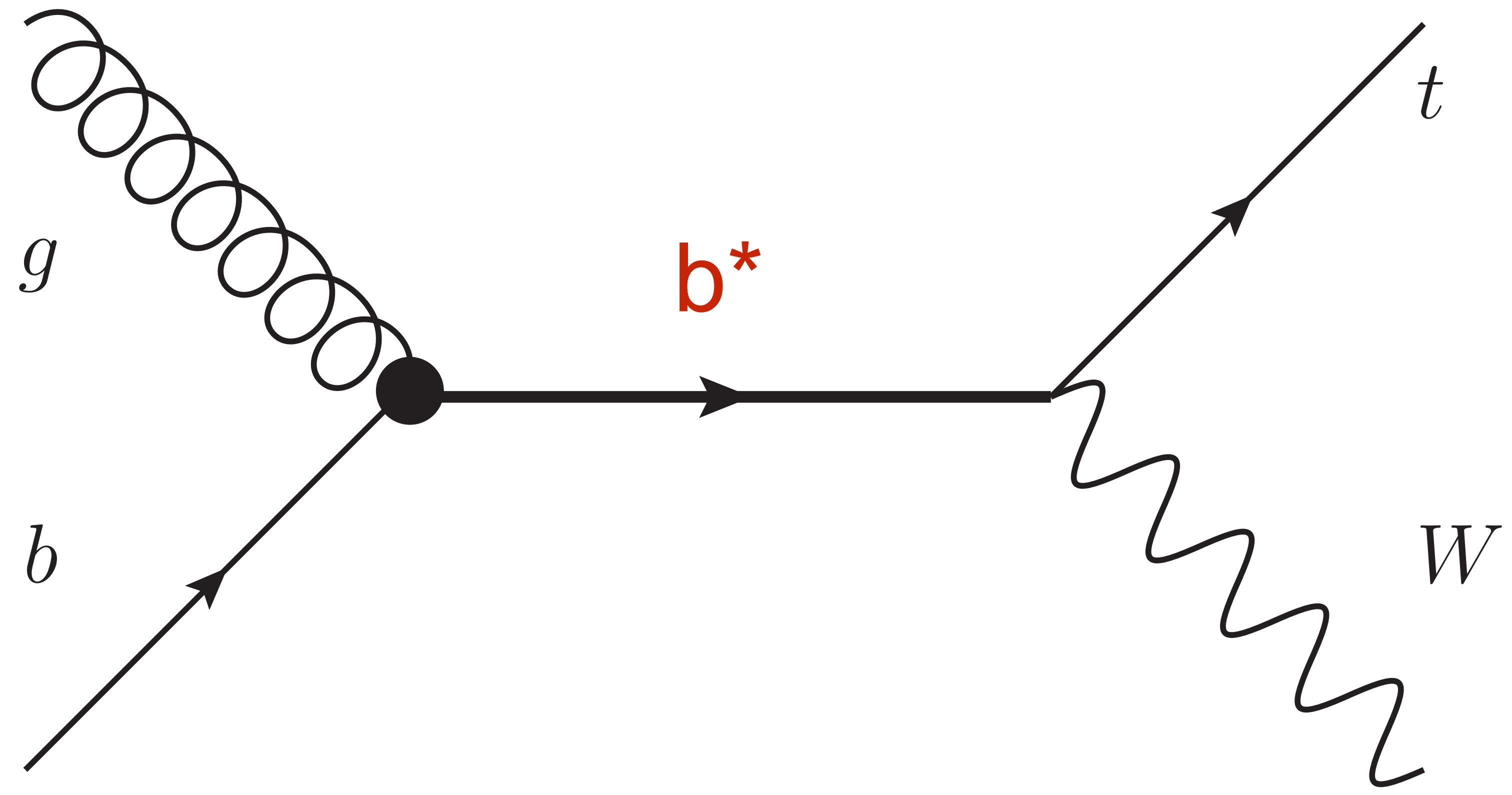
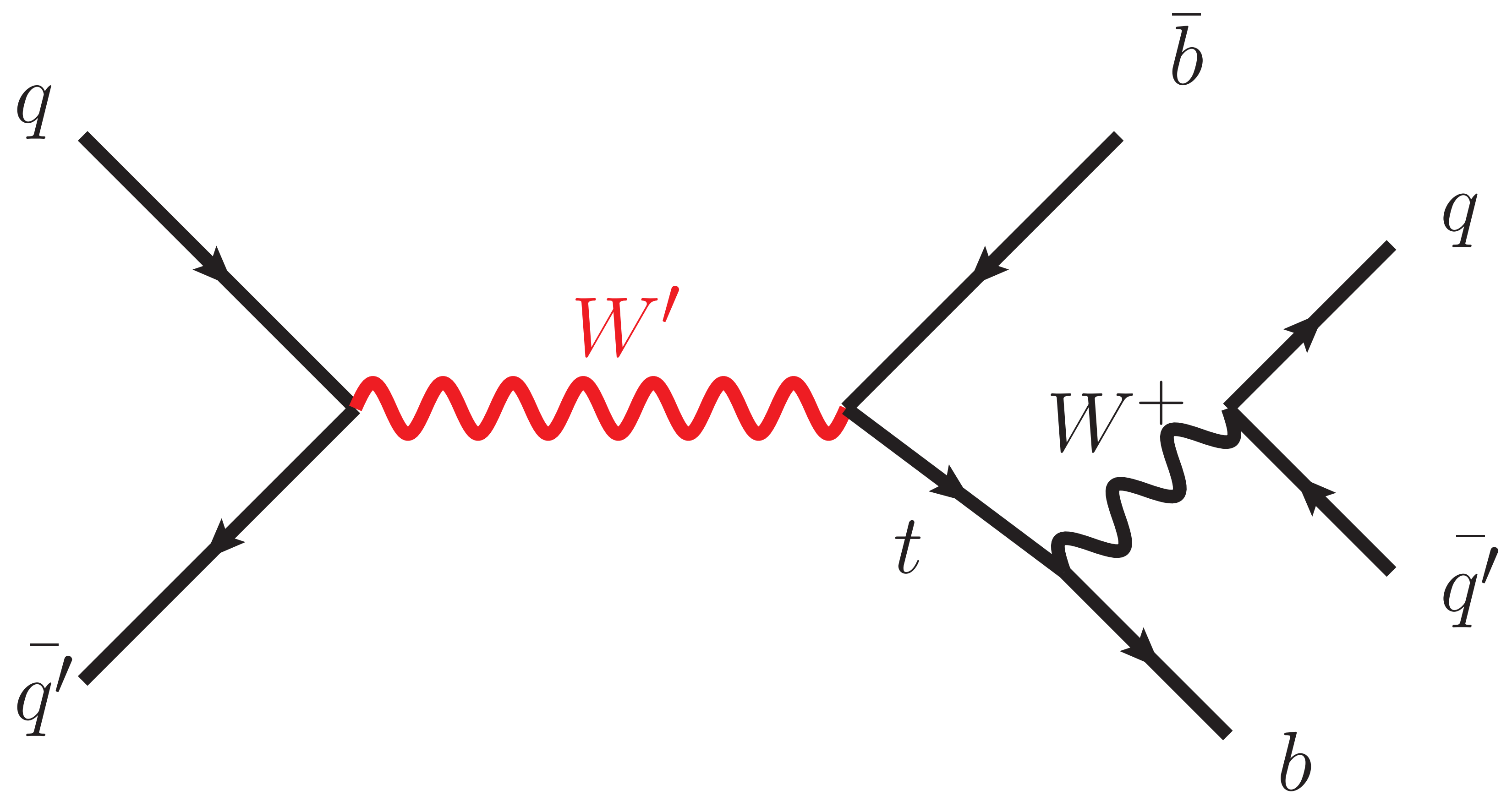
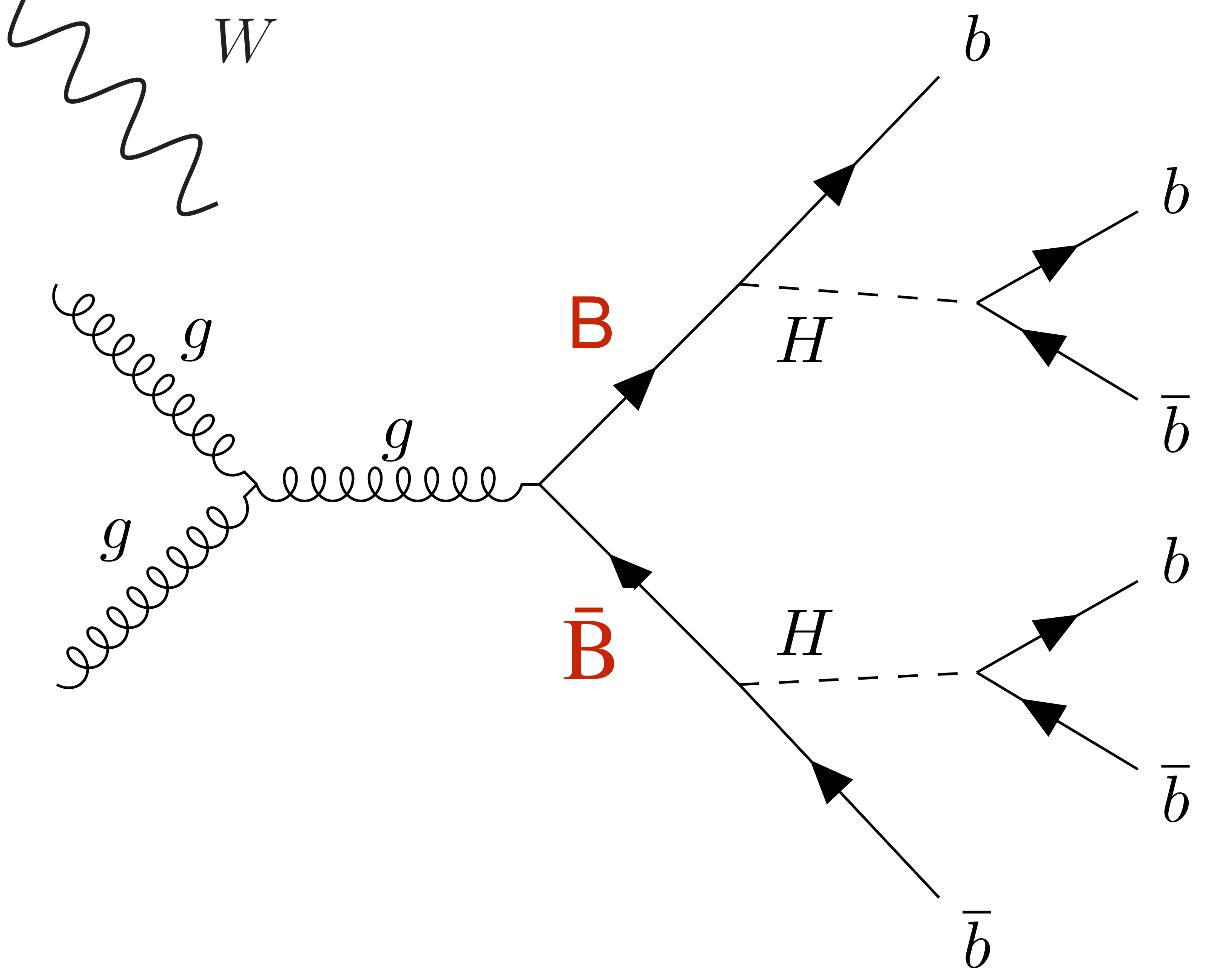




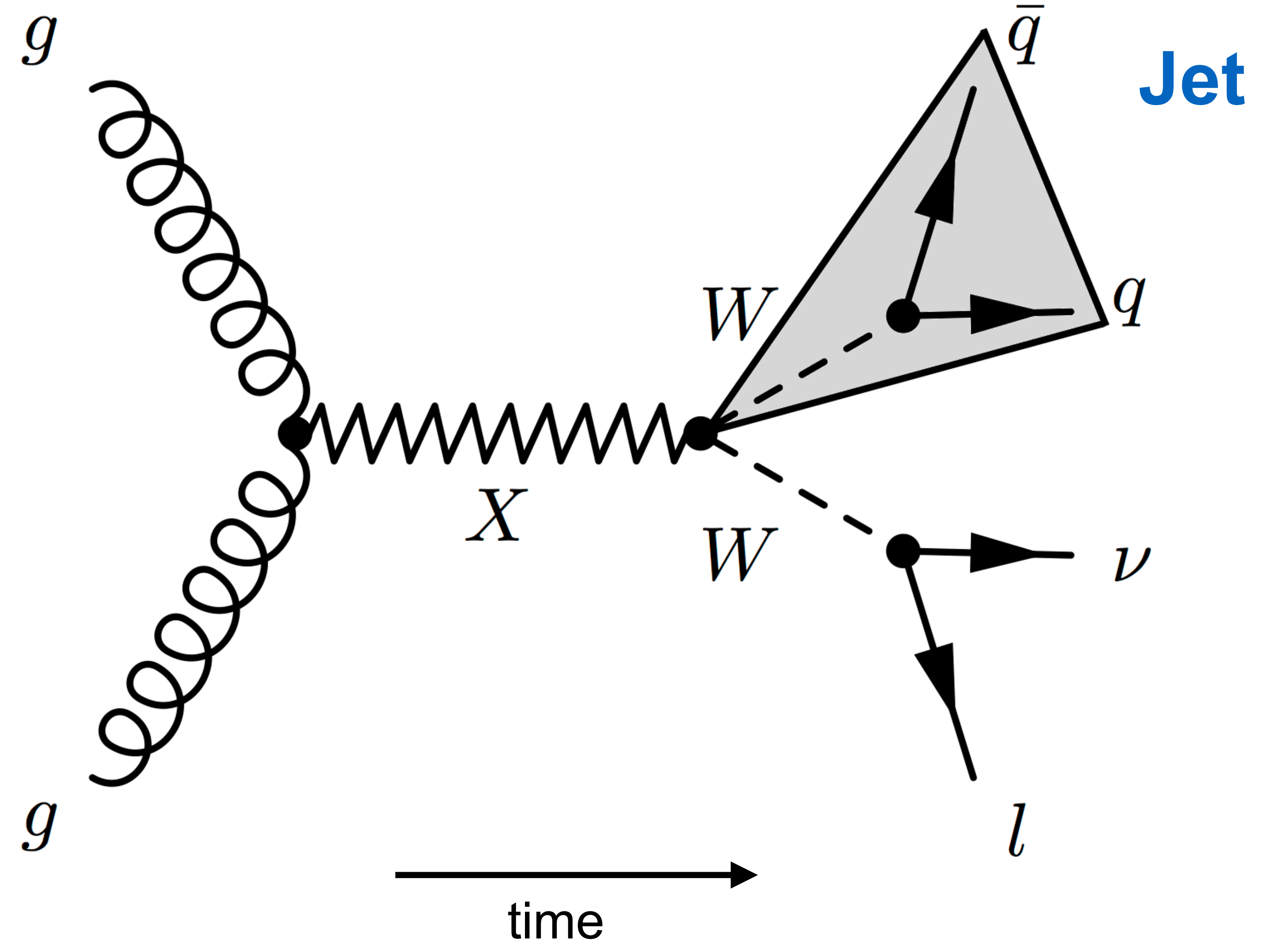


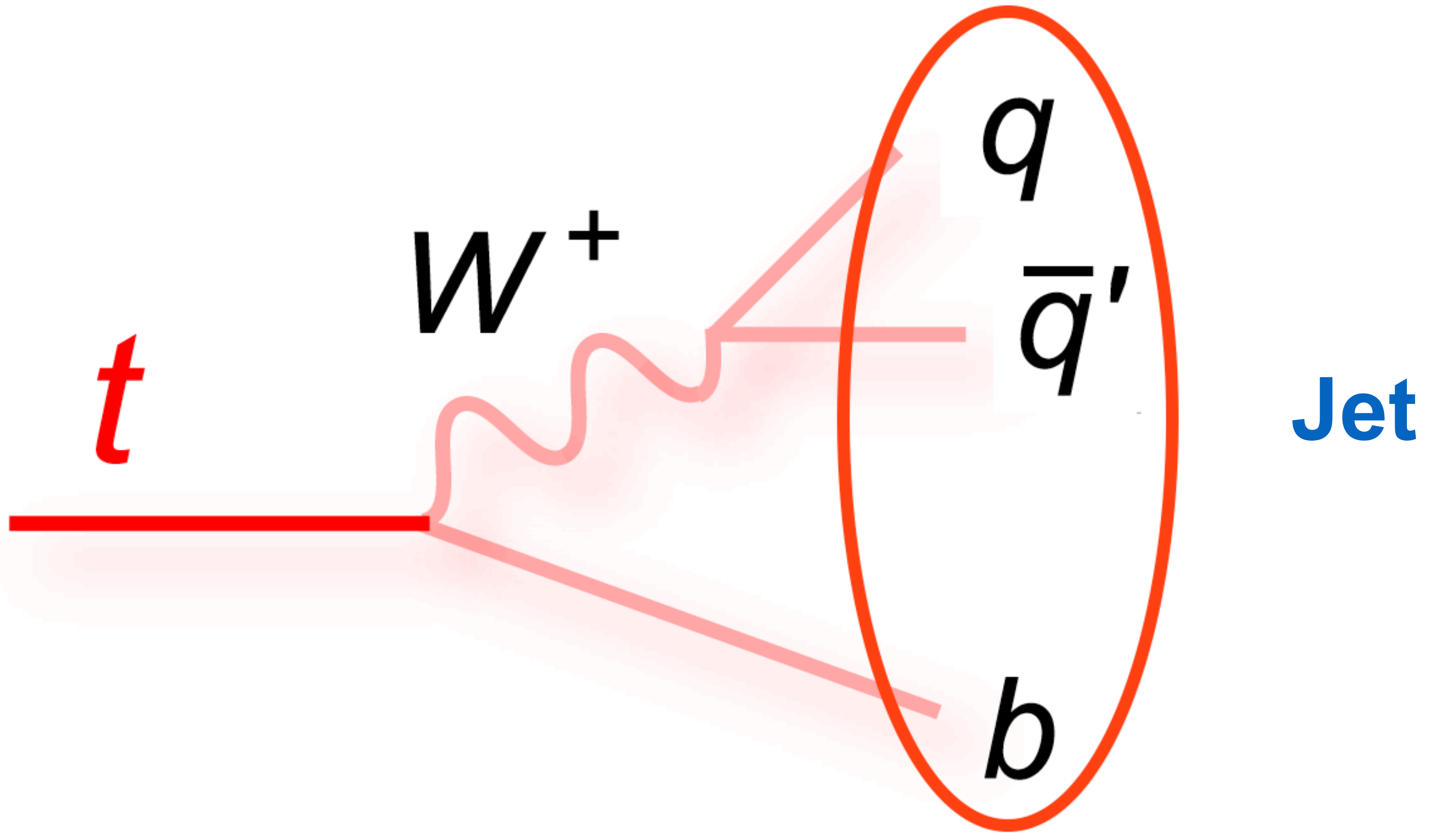


All the unknown particles X, W', b*, B etc. are very heavy: m ≥ 1 TeV

A heavy resonance decaying

- In the examples shown, resonance decays to **massive bosons (W, Z, H)** or also **top quarks**
- These **decay further**, since they are not stable
- They predominantly decay to a **pair of quarks** (bosons) or **three quarks** (top)
- This leaves a lot of energy to the quarks due to $E_{\mathrm{decay}} \approx m_X c^2$ and they will be **close in space**
- The quarks **hadronize** and form so-called **jets**





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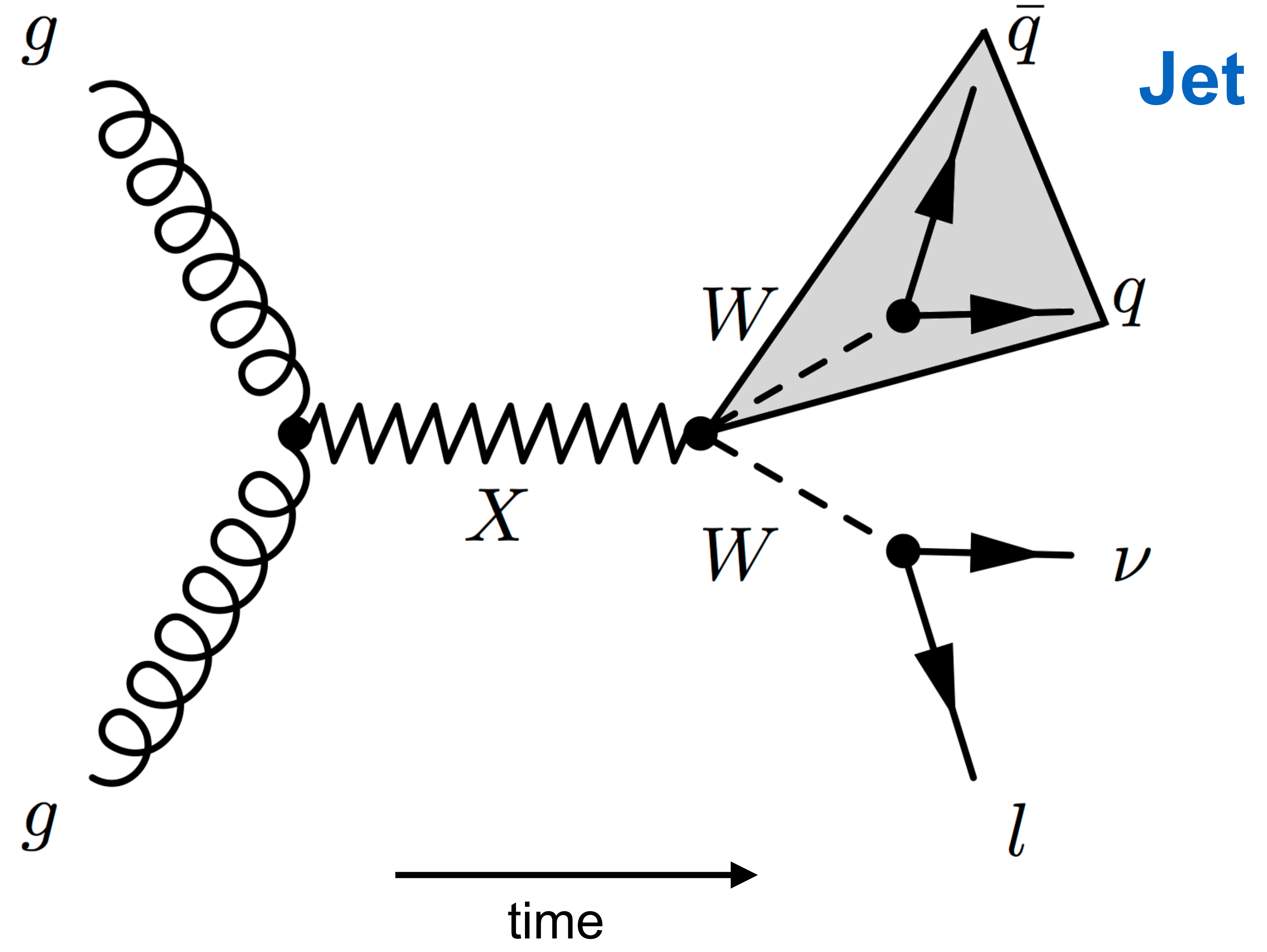
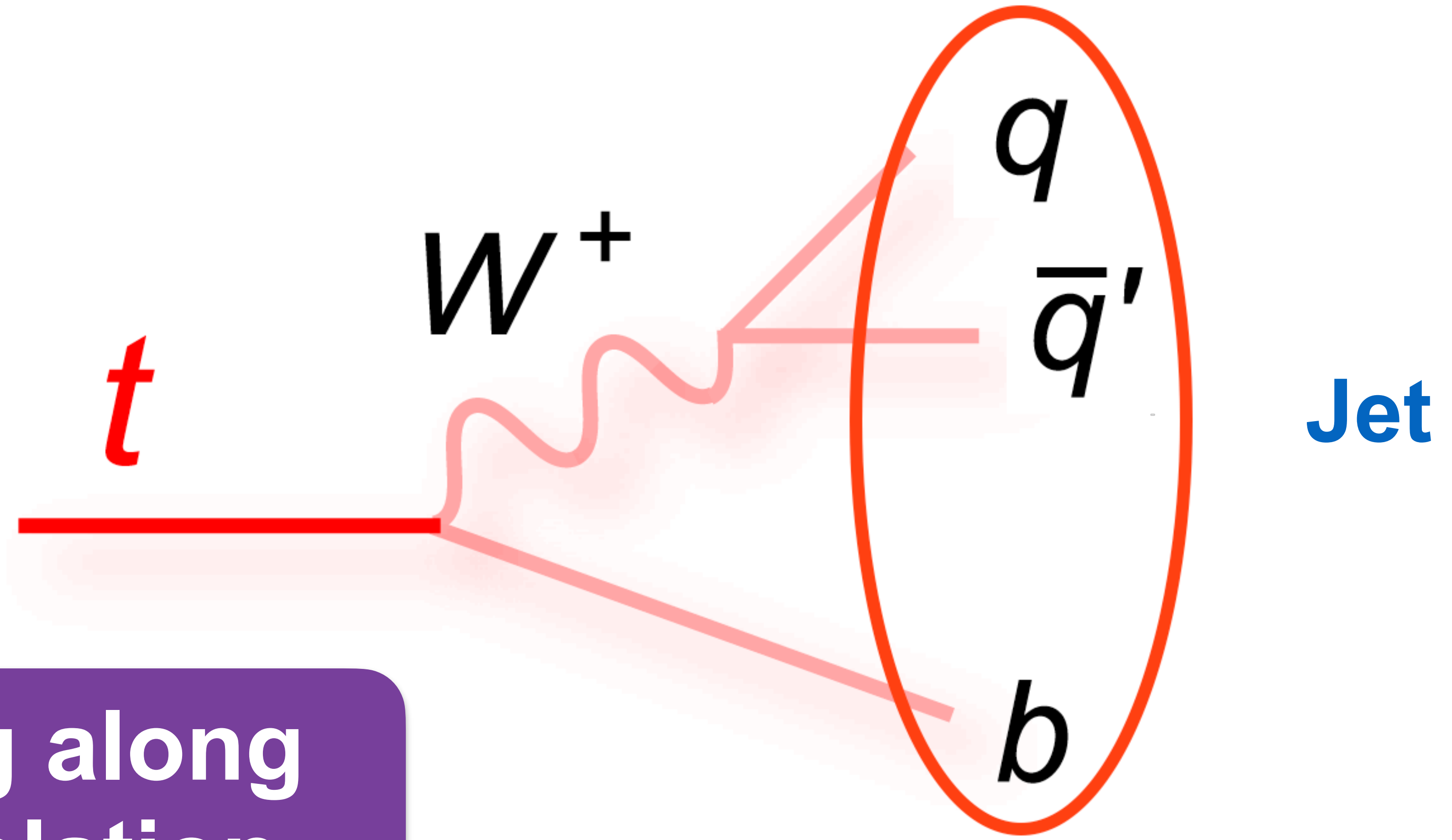
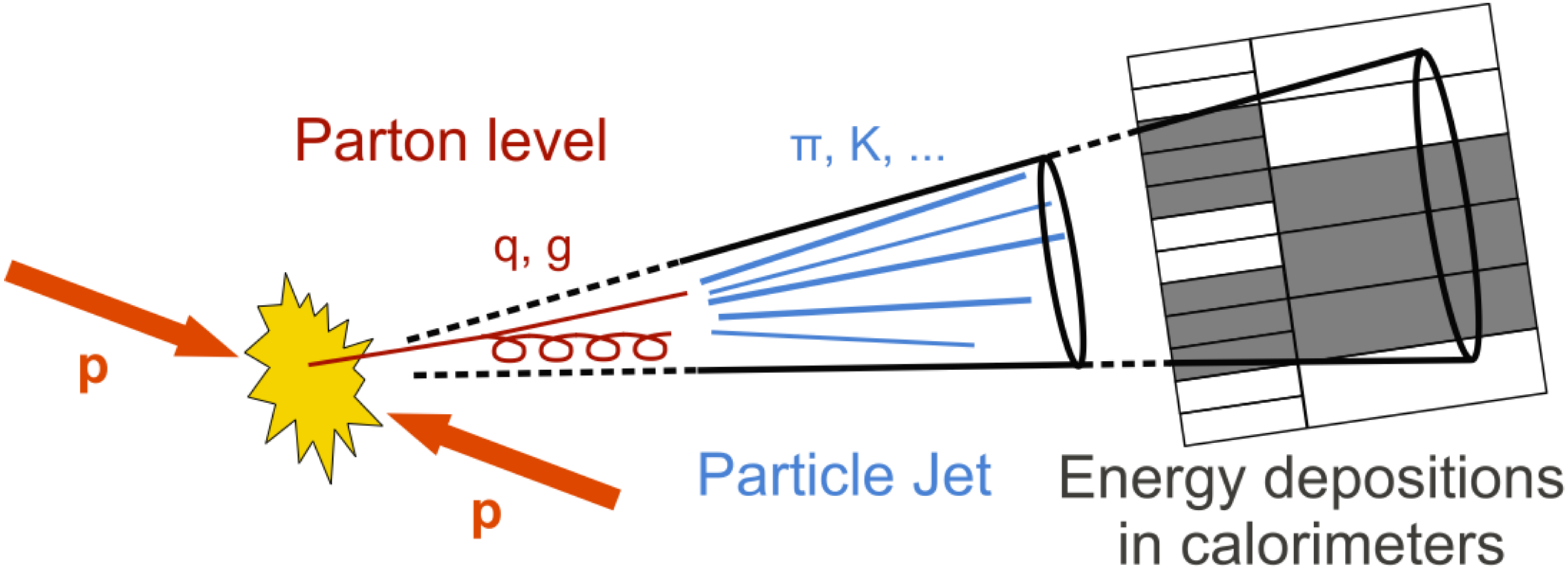




Note: leptonic decay channels bring along other challenges such as lepton isolation

What is a jet?

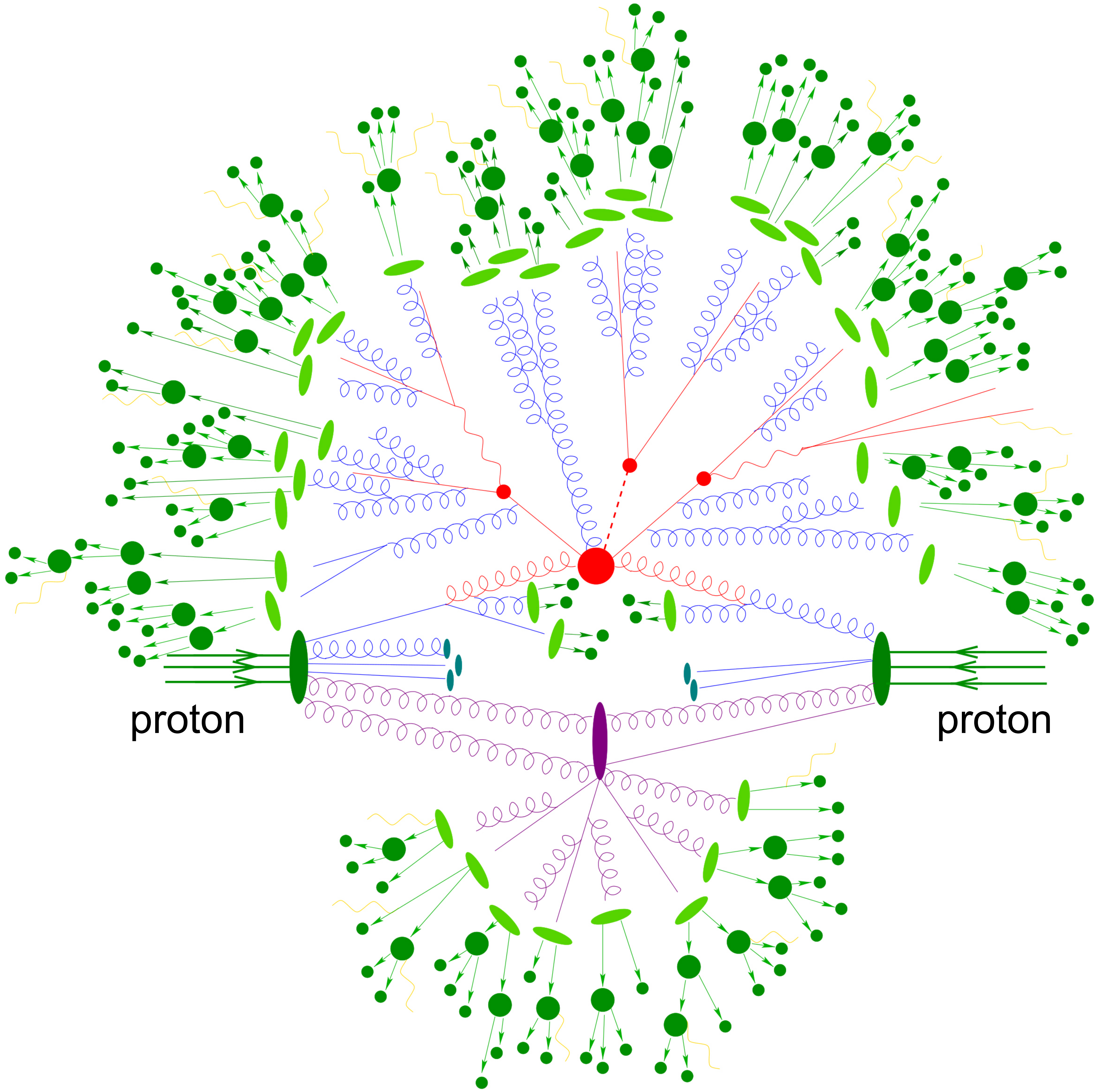


- **Object** defined by jet **clustering algorithm**
- Provides **link** between **theory predictions** and **experimental observations**
- Theory: quarks/partons ➜ *hadronization* ➜ particles (p, n, η, λ, π, …)
- Experiment: sensor signals ➜ reconstruction ➜ tracker hits, calorimeter entries (➜ particles (neutral/charged hadrons, ɣ, …))

What's going on in a jet

- Jets are very messy objects
- This is due to a phenomenon called **confinement**
- A quark/gluon cannot exist on its own
- It "pulls" in other quarks and gluons to **form hadrons** - this is due to the **strong force**
- Several of the **particles** created this way **decay further** until stable particles have been created

$$(\tau_{\mathrm{had}} = \Lambda_{\mathrm{QCD}}^{-1} = 3 \cdot 10^{-24}\ \mathrm{s})$$



Example of a *single* proton-proton collision—now imagine more than 30 on average at the same time

Fat jet or not

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- "Standard" jets in CMS: use **anti-k_T algorithm** with R = 0.4 ("AK4 jets")
- Approximation: all particles within $\Delta R := \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = c$ will be **reconstructed as a single jet** with cut-off parameter $R = c$

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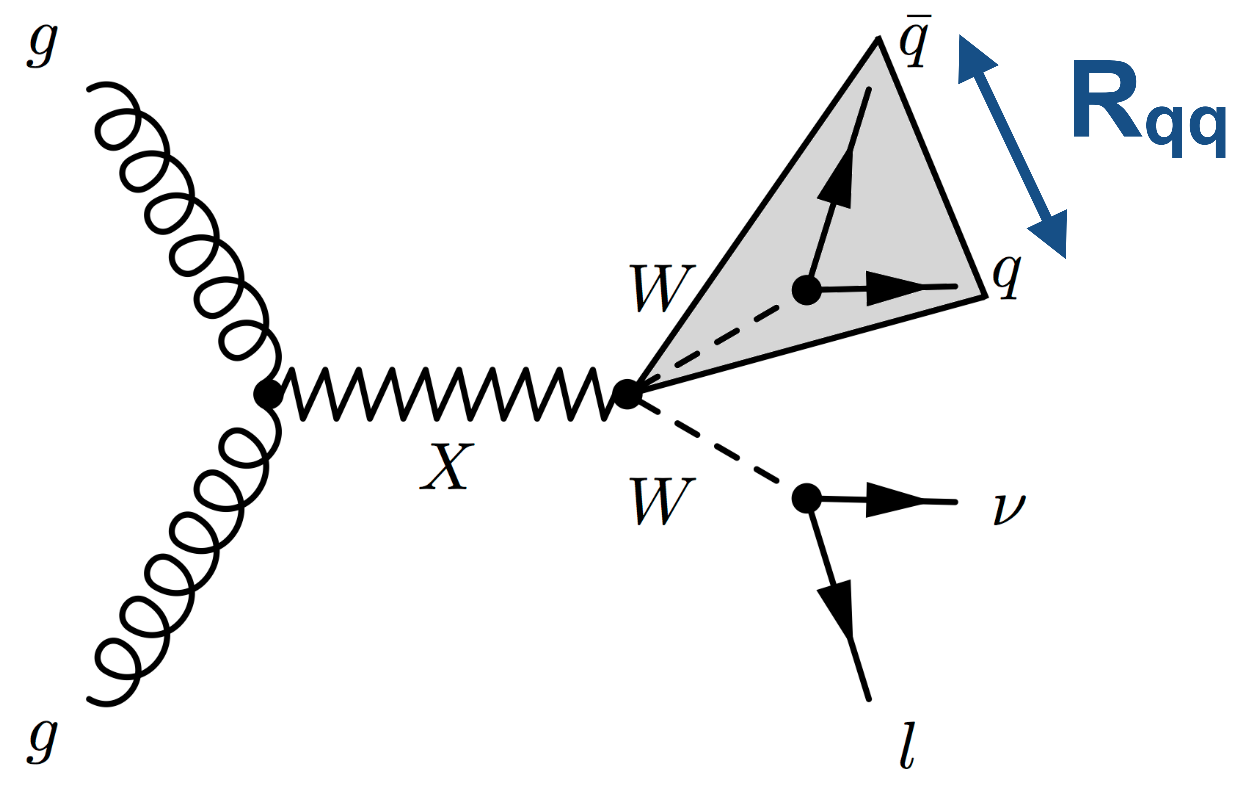
- For a W-boson decay: $R_{qq} \approx 2\frac{m_W}{p_T^W}$
  - Example: resonance of mass 1 TeV bosons (m = 100 GeV) from the decay will on average have p_T~0.4 TeV ➜ R_{qq} ≈ 0.5
  - An AK4 jet could miss parts of the decay



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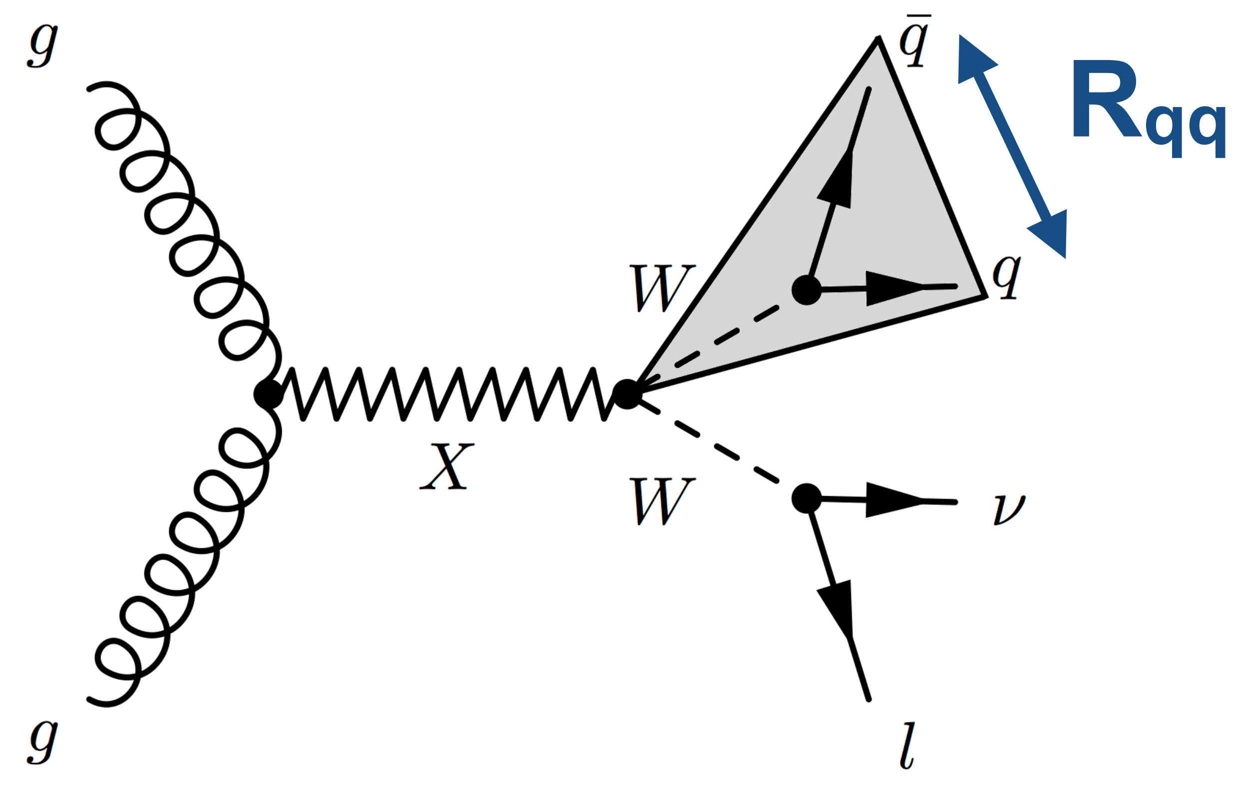
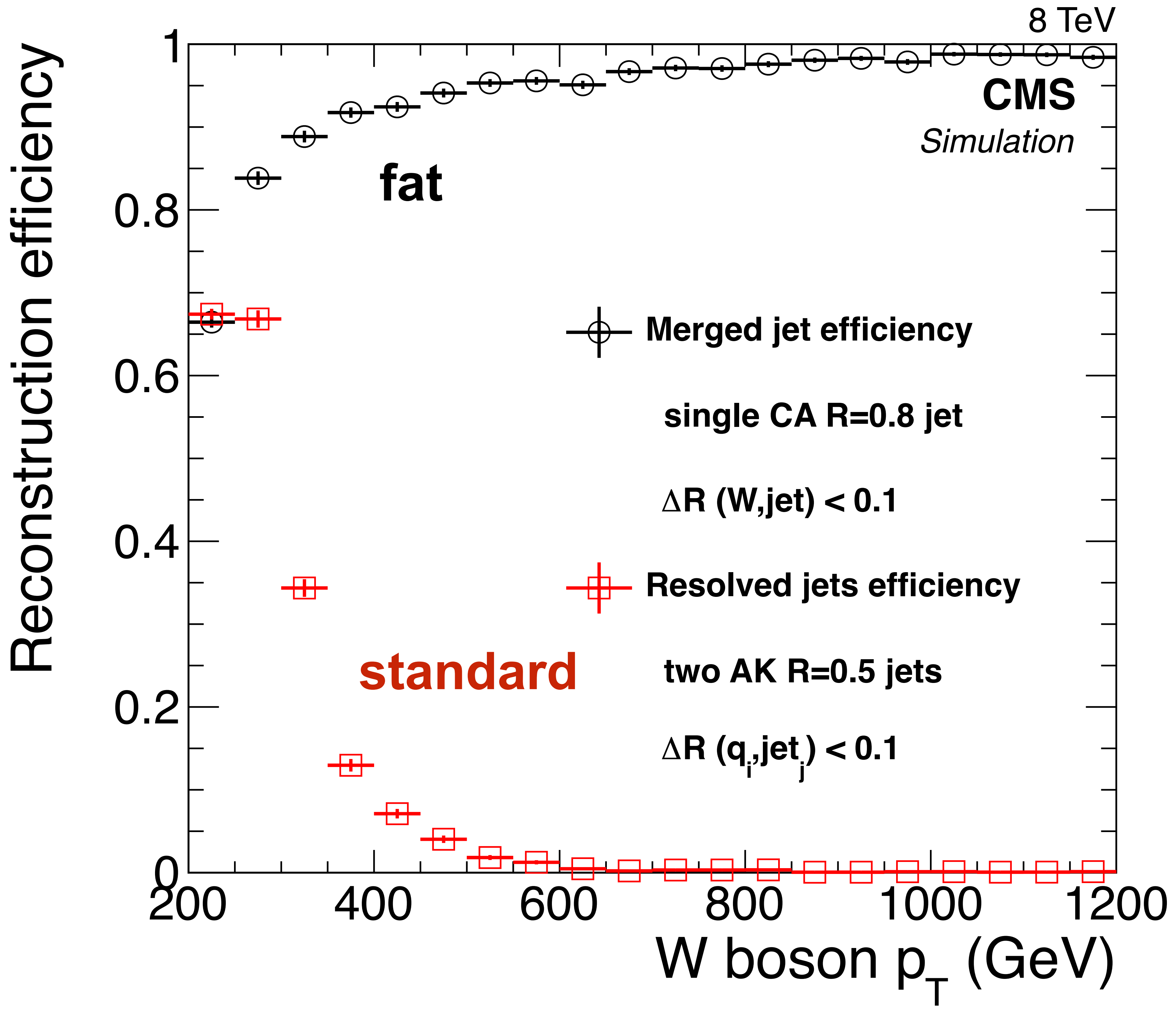
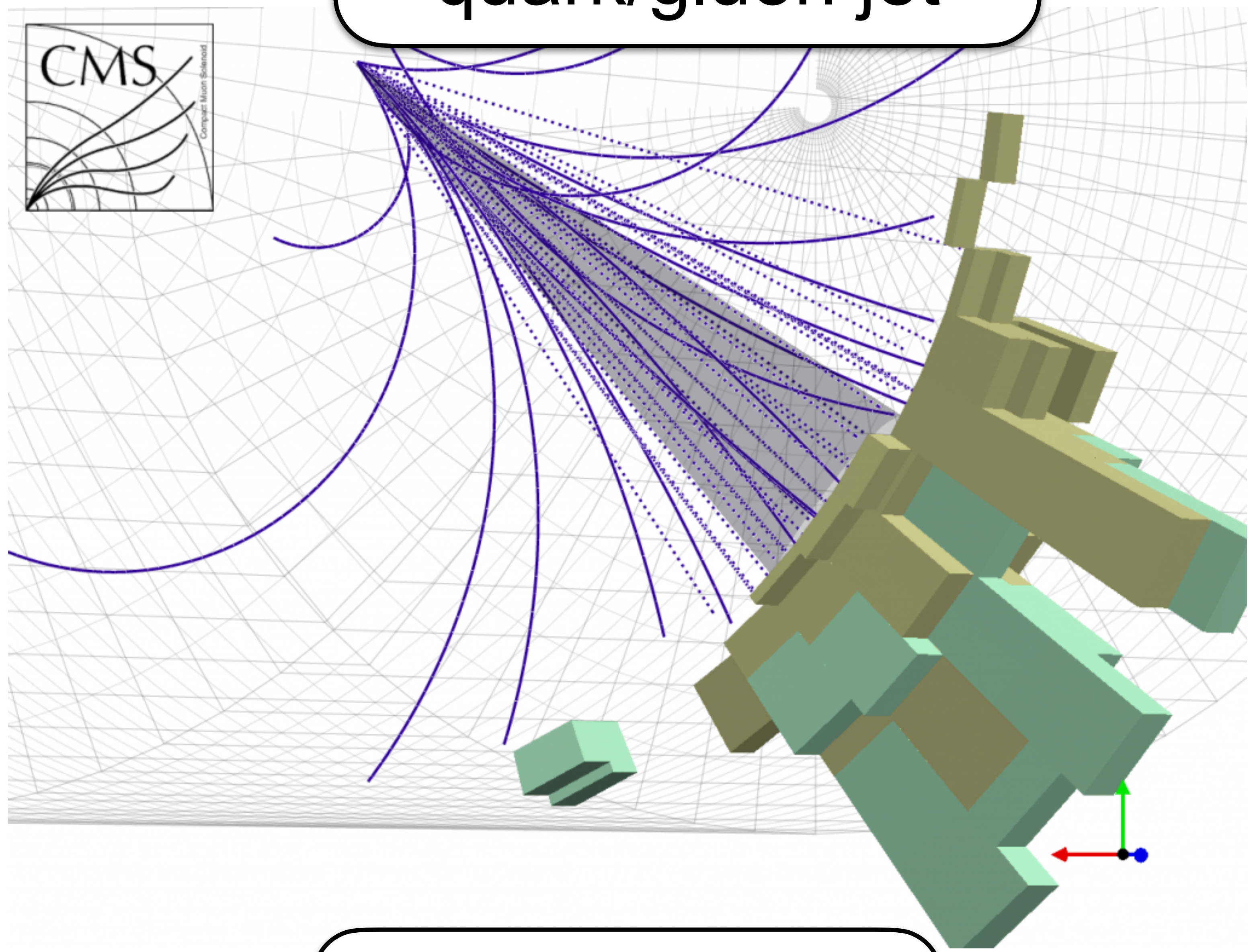
  - An AK4 jet could miss parts of the decay
- Use larger jet "radius" to **contain full decay** (usually R = 0.8, ➜ "AK8")



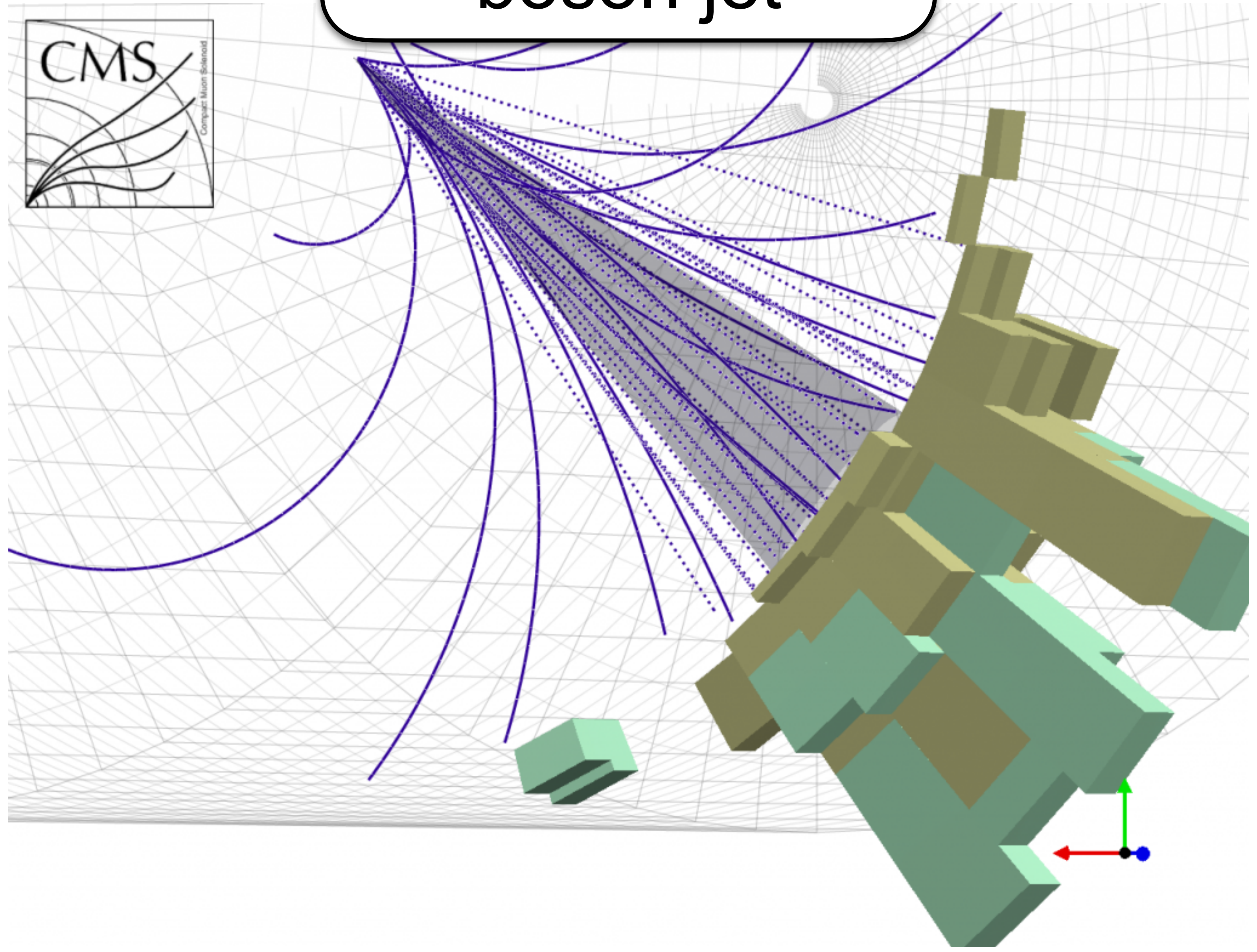


Boson/top quark jets vs. quark/gluon jets

quark/gluon jet

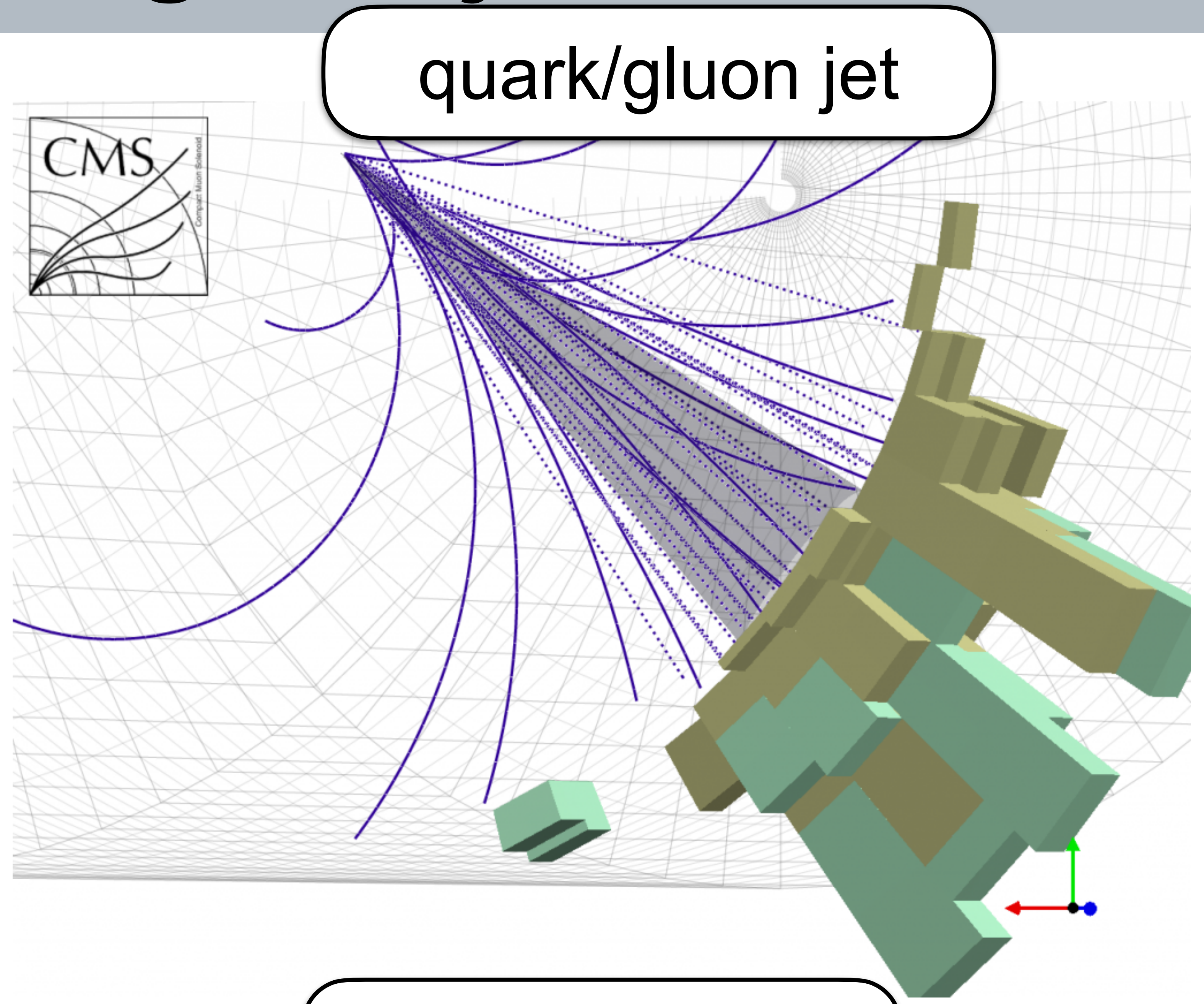


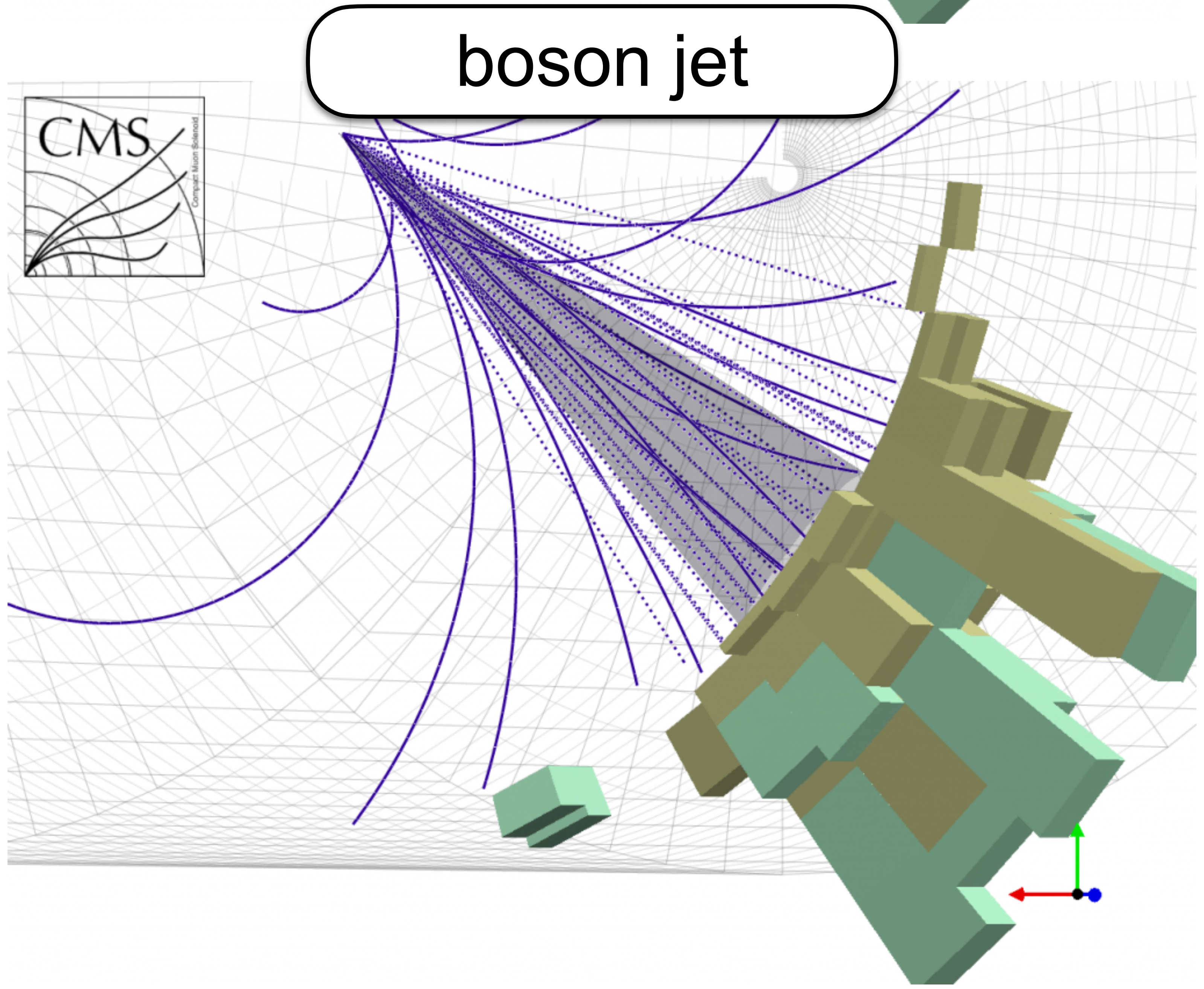
boson jet



Boson/top quark jets vs. quark/gluon jets

- At first look, it's the same as any other jet
- However, if you **look more closely**, you can find differences





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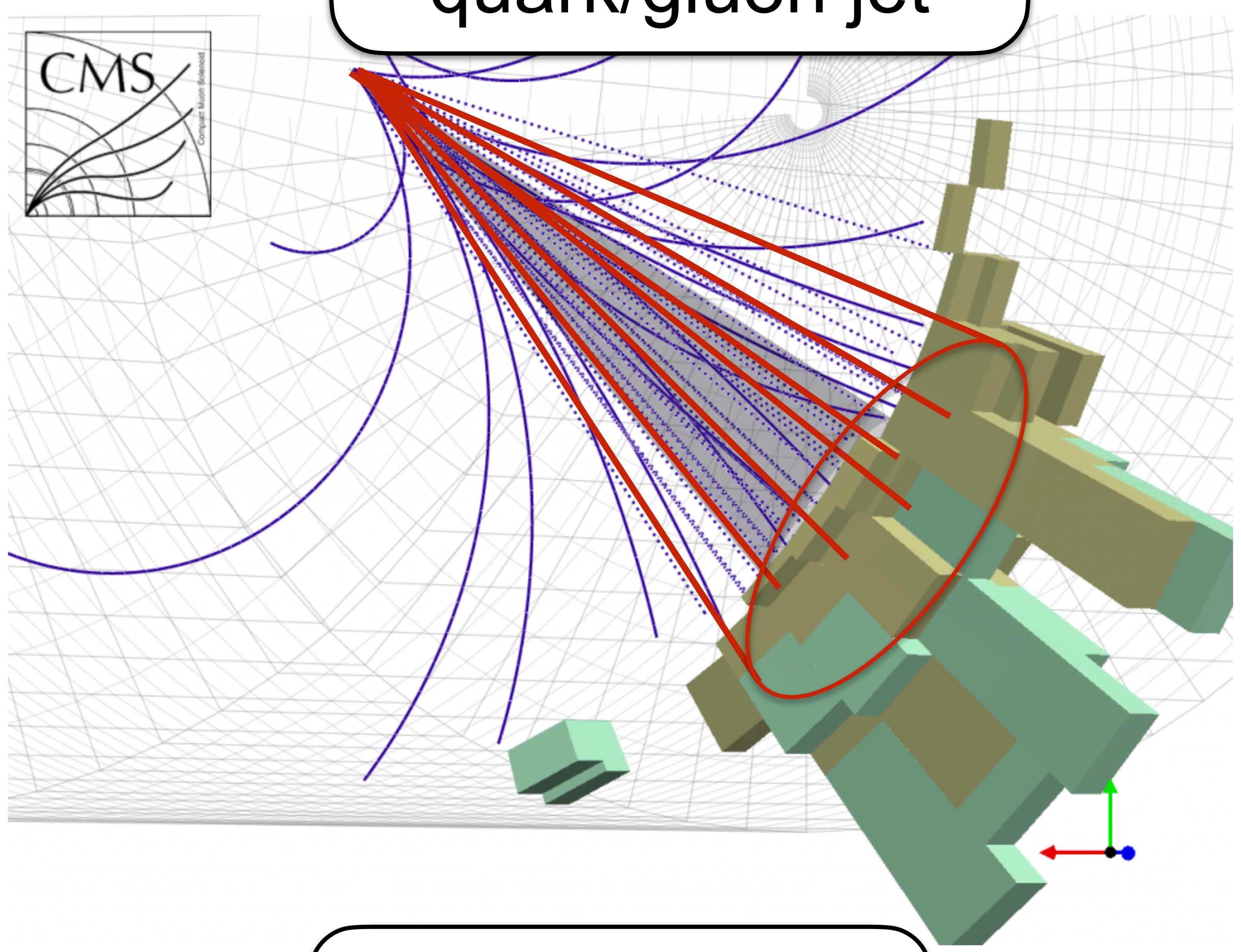

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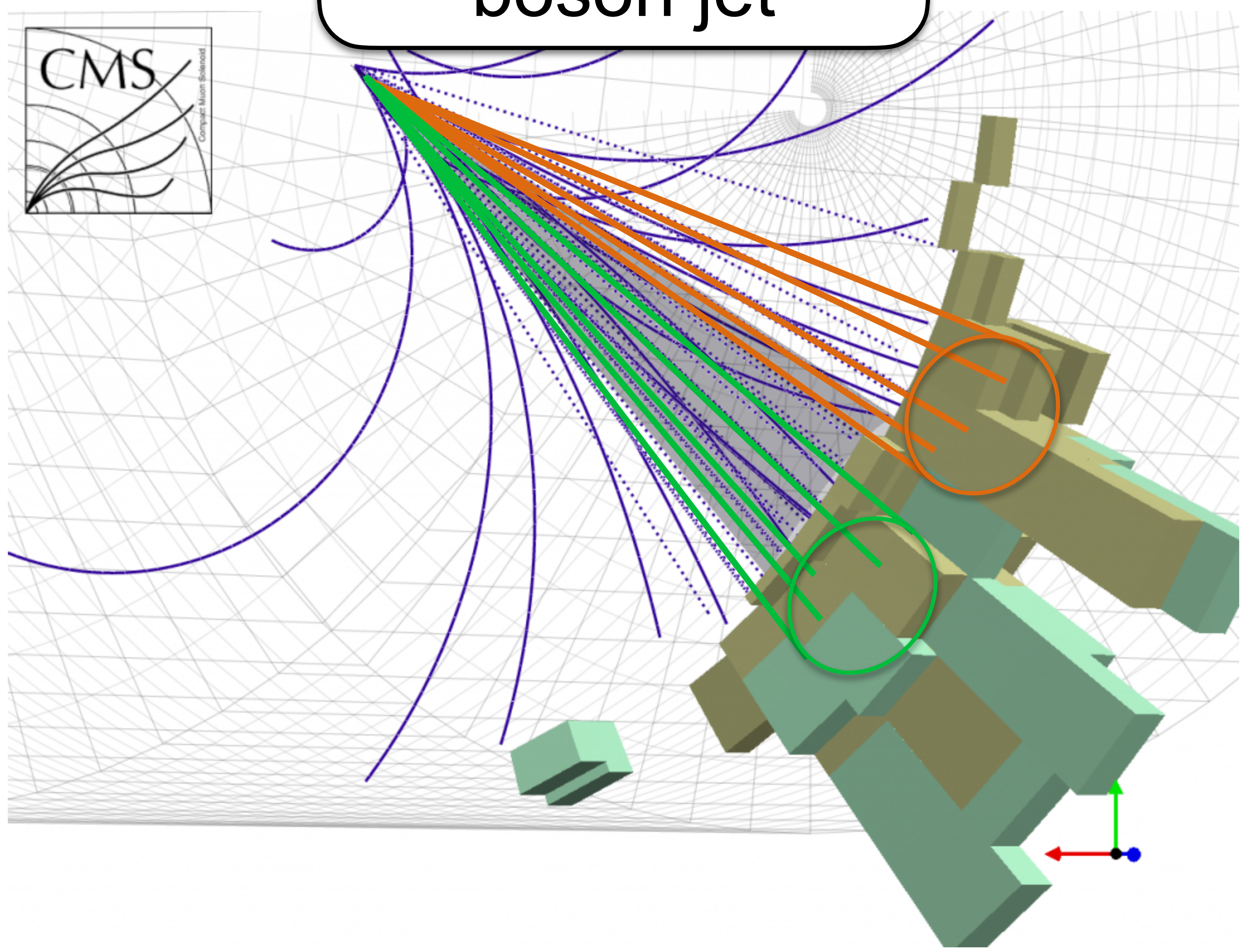

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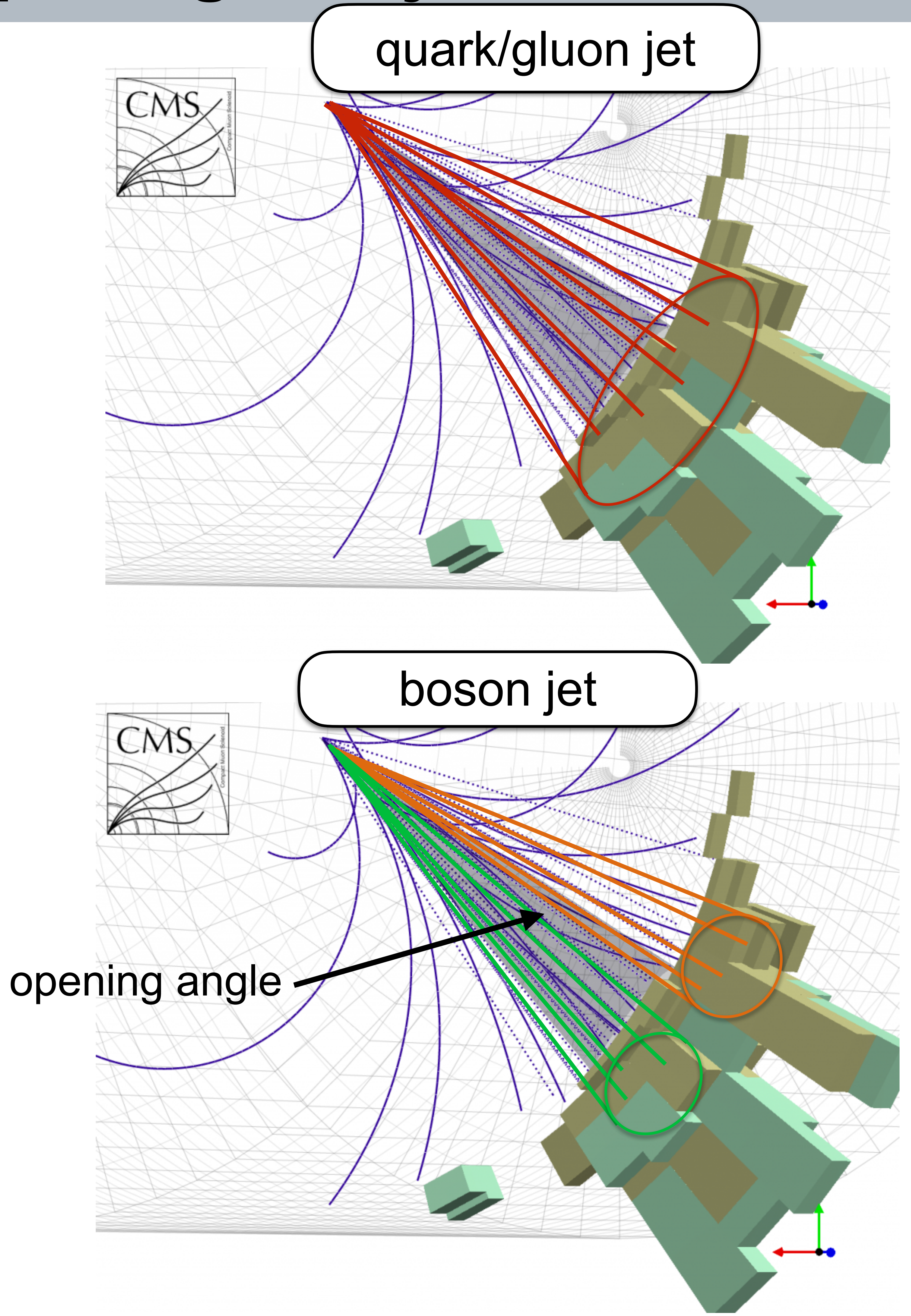
- The **opening angle** between two energy deposits relates to the **mass of the original particle**



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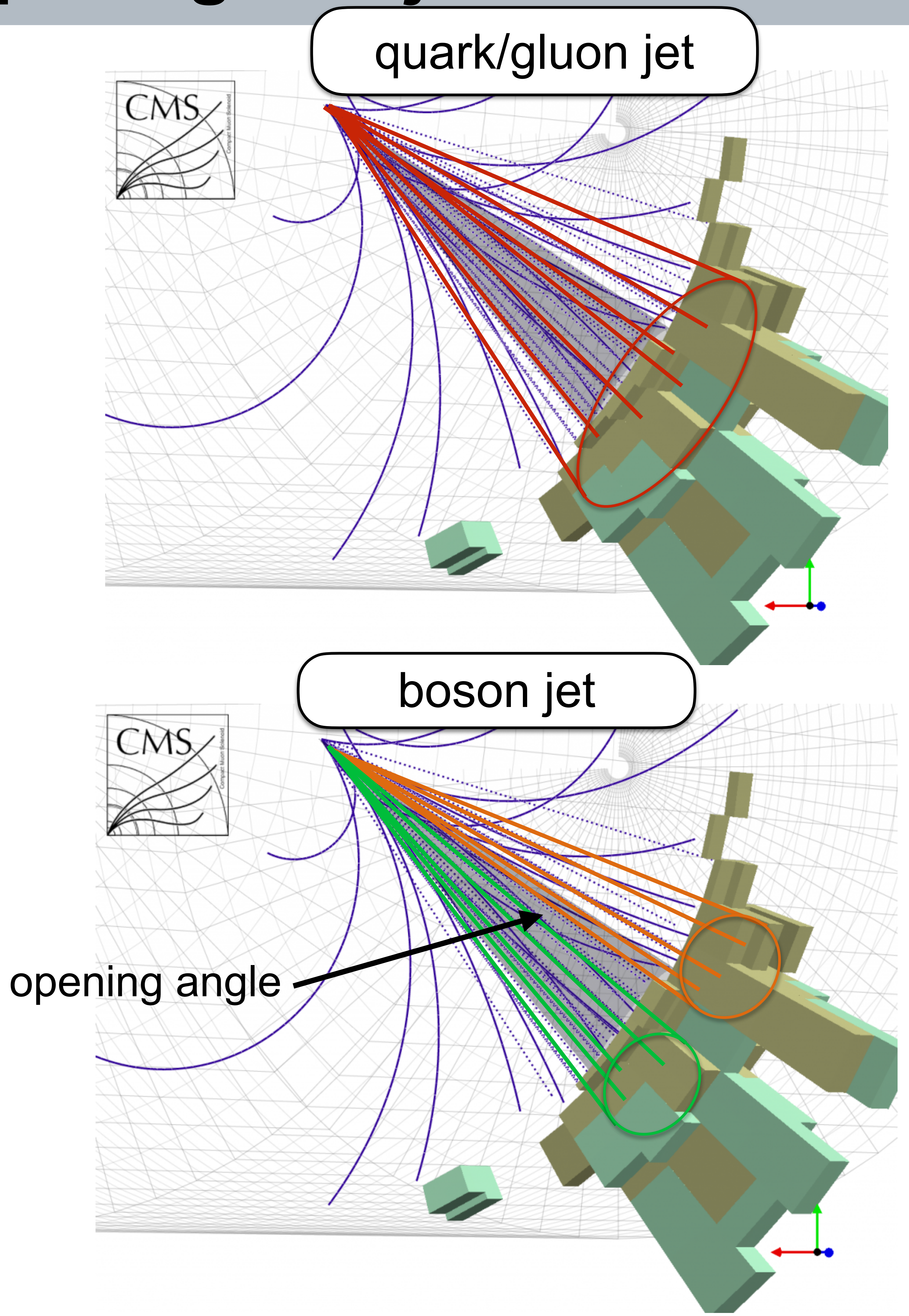
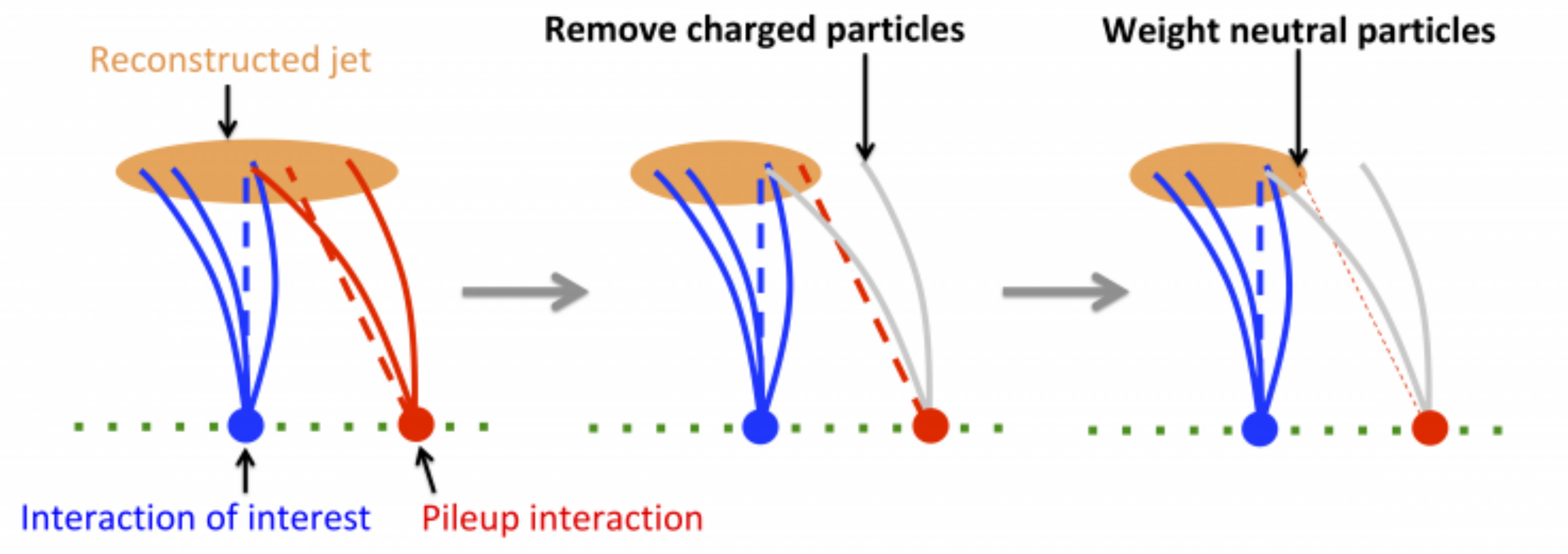
- You will find that the **energy deposits** inside the jet are centred around **two cores/axes** instead of just one
- The **opening angle** between two energy deposits relates to the **mass of the original particle**
- However, to be able to see that, we need to **clean up the jet**

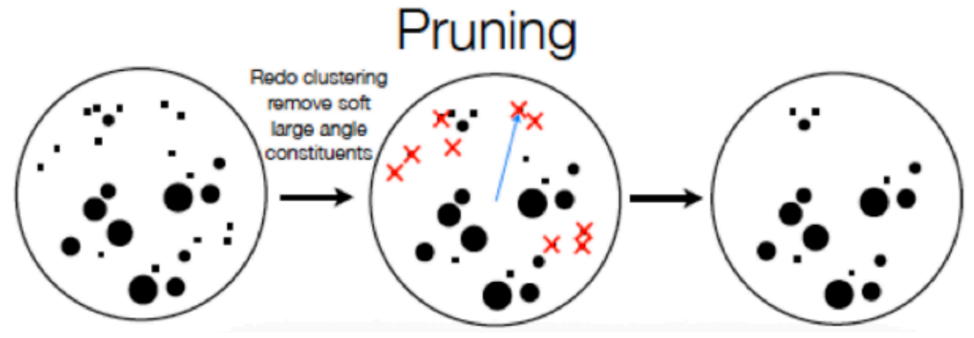


Cleaning up a jet

1. Remove pileup (PUPPI algorithm)



2. “Undo” hadronization ➜ groom the jet



Cleaning up a jet

- When looking at our **"massive" jets**, we are mostly interested in the **initial quarks**
- Attempt to **throw away low energy** and **large angle radiation** ➜ **"undo" hadronization**
- This process is called **grooming**
  - There are a few different algorithms to do that

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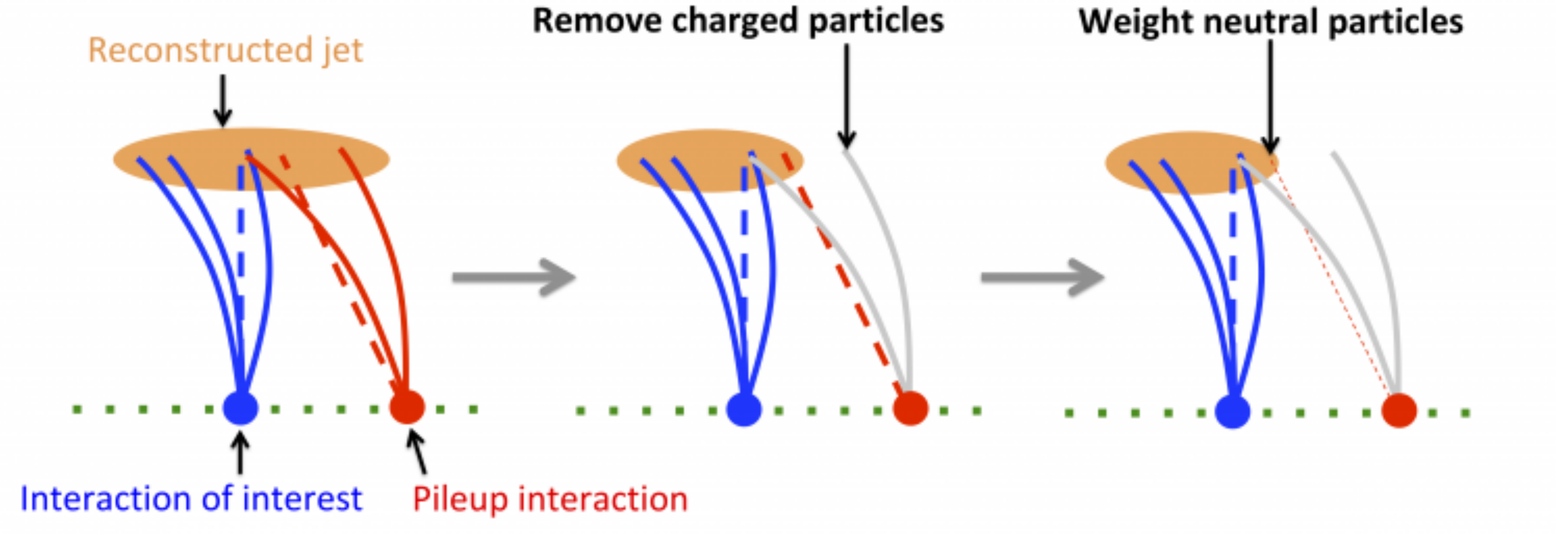

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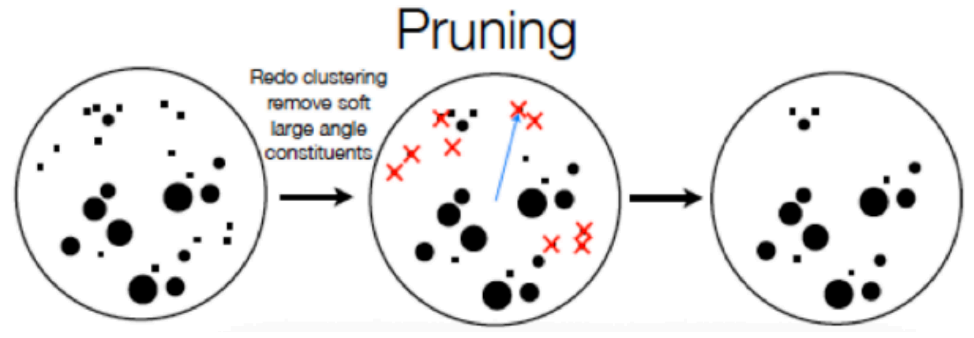

Cleaning up a jet

JINST 15 (2020) P09018
Phys. Rev. D 97 (2018) 072006

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- Attempt to **throw away low energy** and **large angle radiation** **➜ “undo” hadronization**
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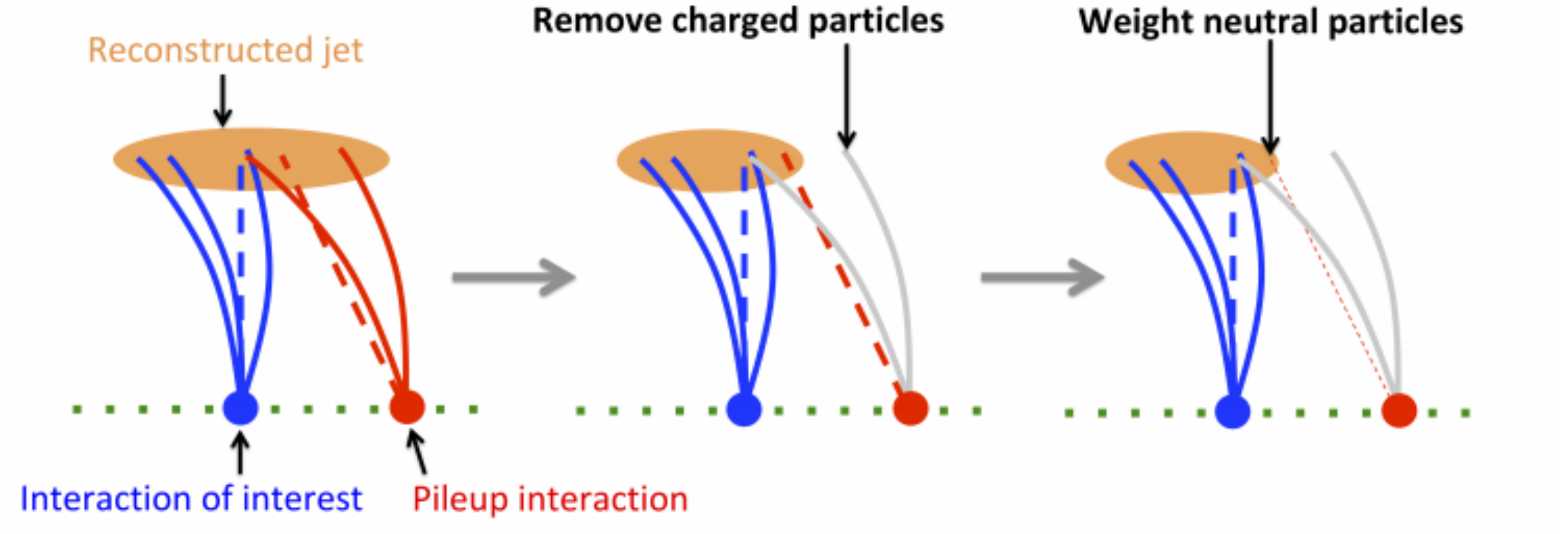
  - There are a few different algorithms to do that
- In CMS, the modified mass-drop tagger “soft drop” is commonly used

1. Remove pileup (PUPPI algorithm)



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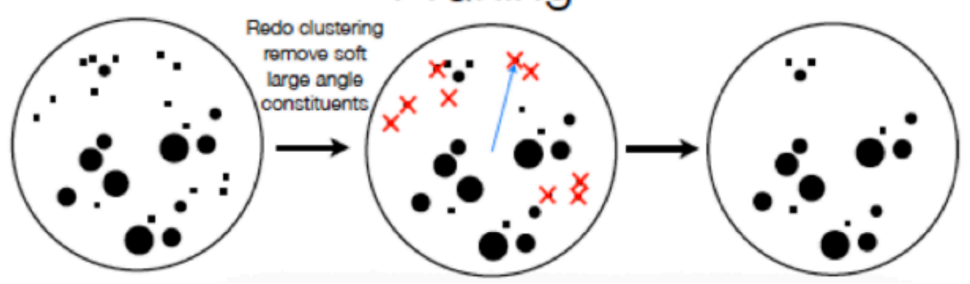
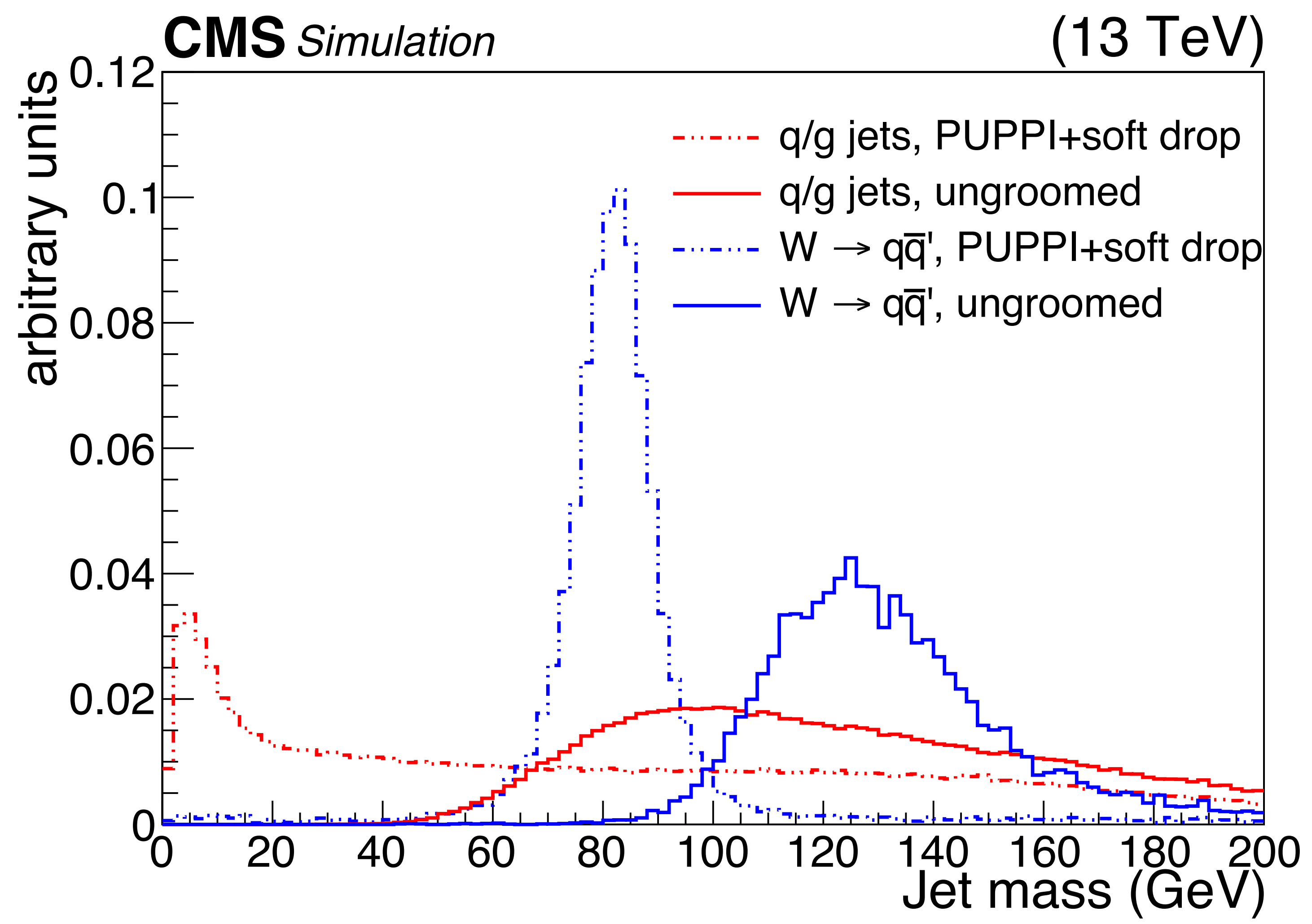
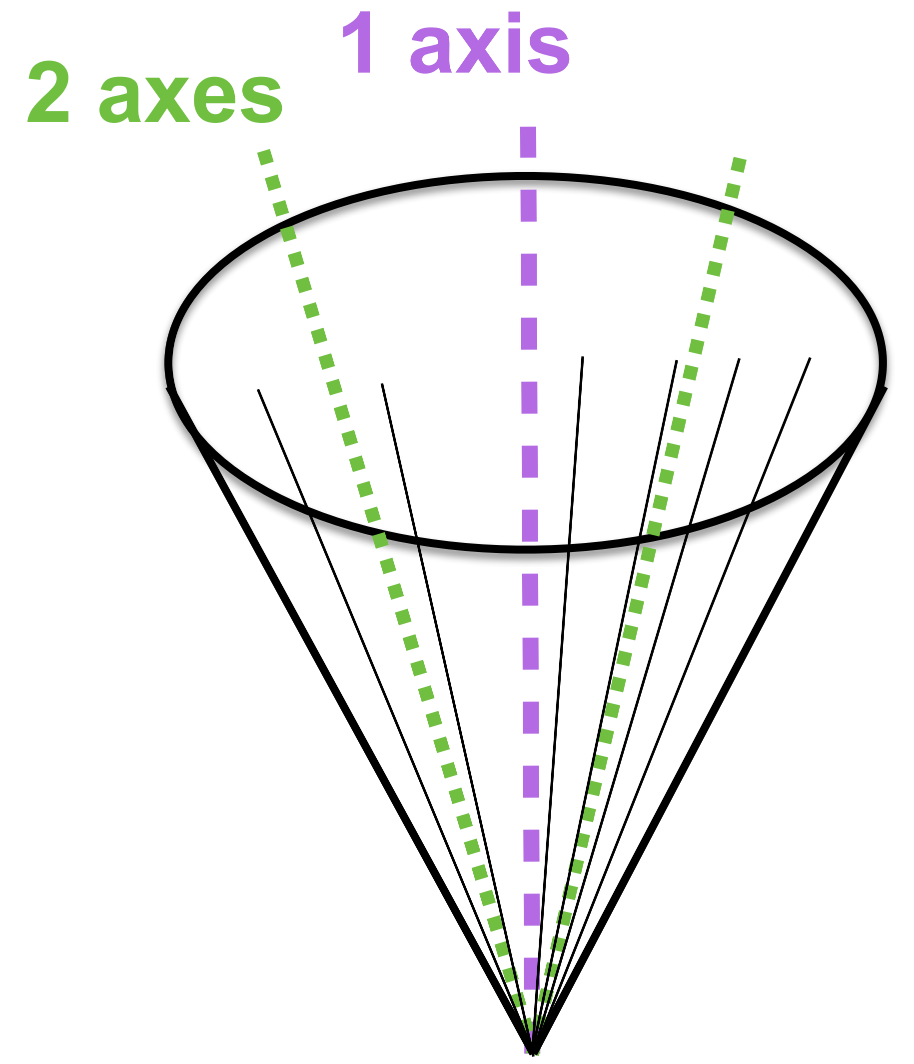
Pruning





There is more than just mass

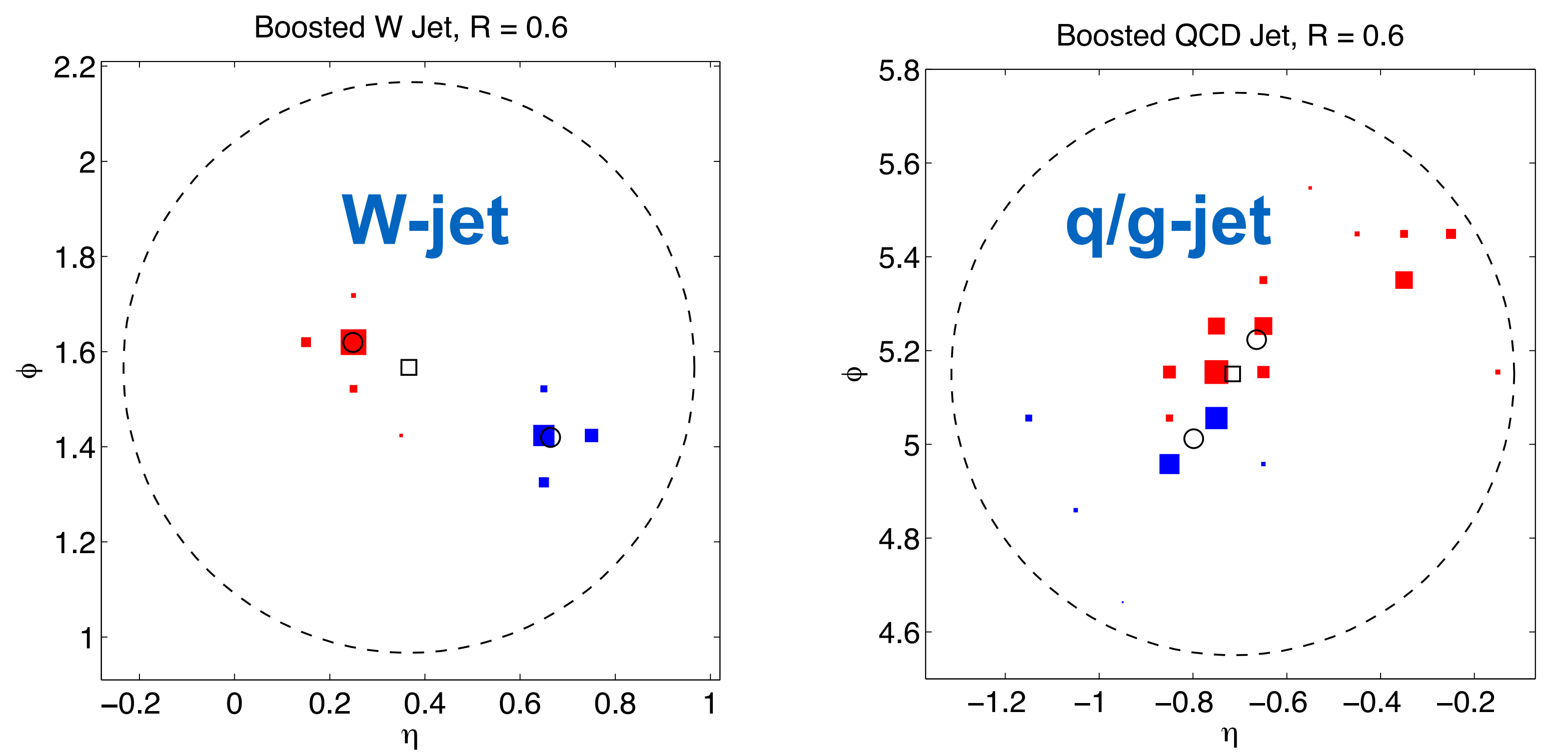
- Remember that I told you something about an opening angle between the decay products?
- We can also measure the **energy flow** inside a jet
- Estimate to what extent it is aligned along 2 or 3 momentum axes (or just 1)
- Again, there are a range of different algorithms
  - N-subjettiness (τ_N), energy correlation functions, machine-learned variables, …
- For τ_N (by now somewhat outdated):
  - ratio τ_2/τ_1 ➜ W/Z boson tagging
  - ratio τ_3/τ_2 ➜ top quark tagging



Calculate for a given hypotheses of N subjets:

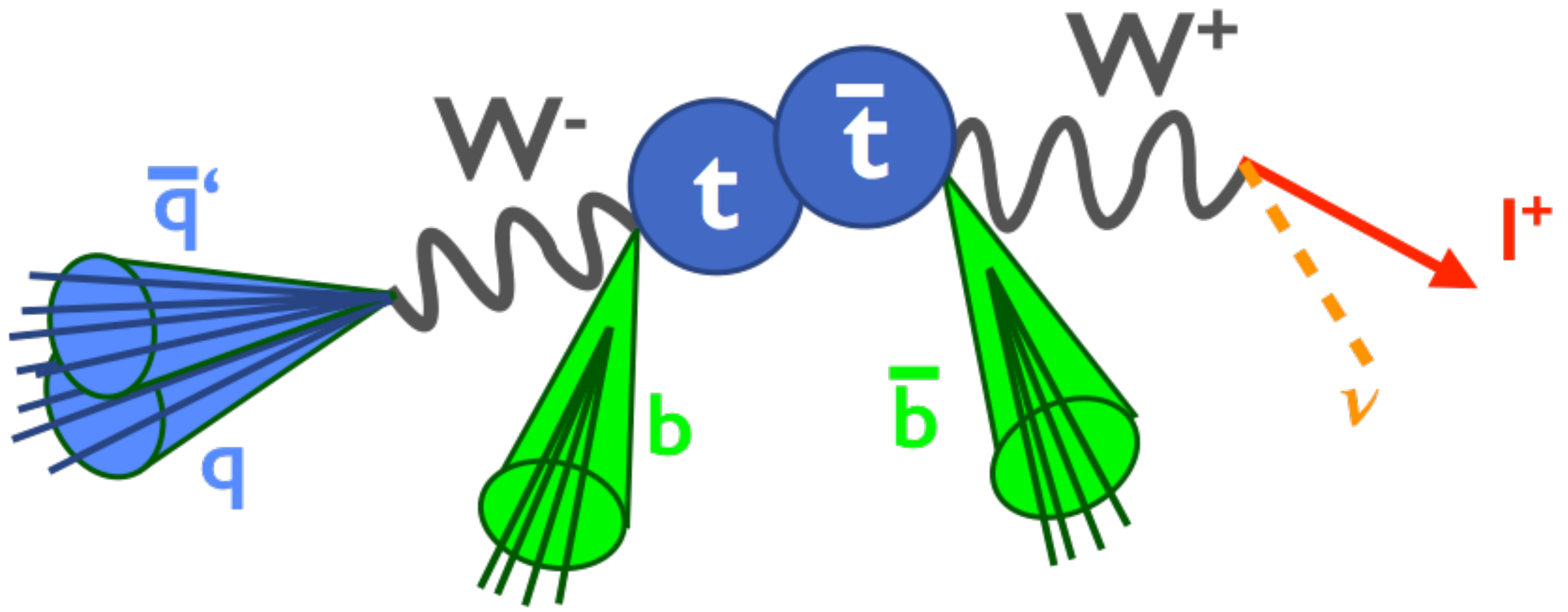
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{N,k})$$

normalization — sum over particles — minimise distance to candidate subjets

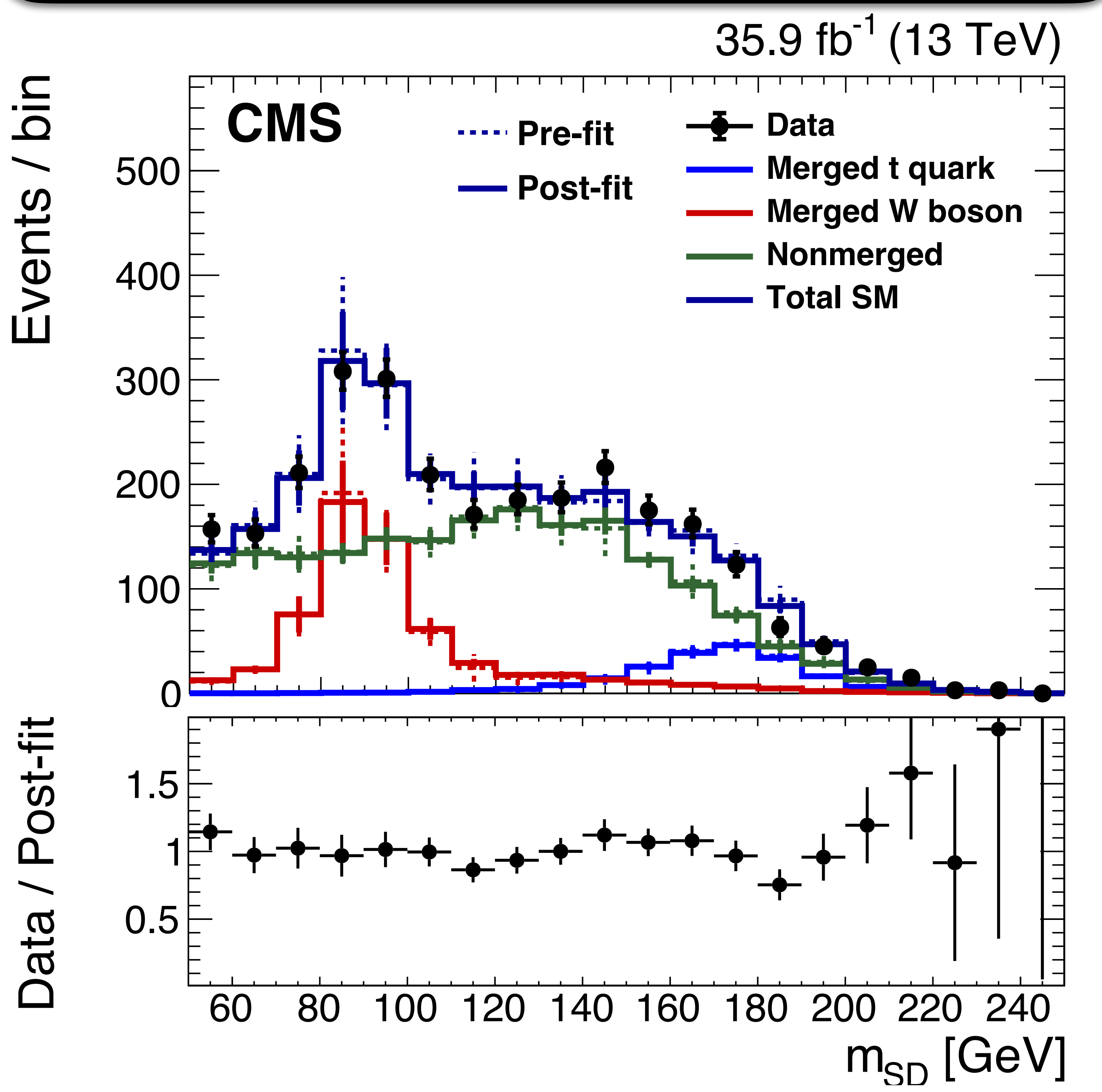


Confirming that this works

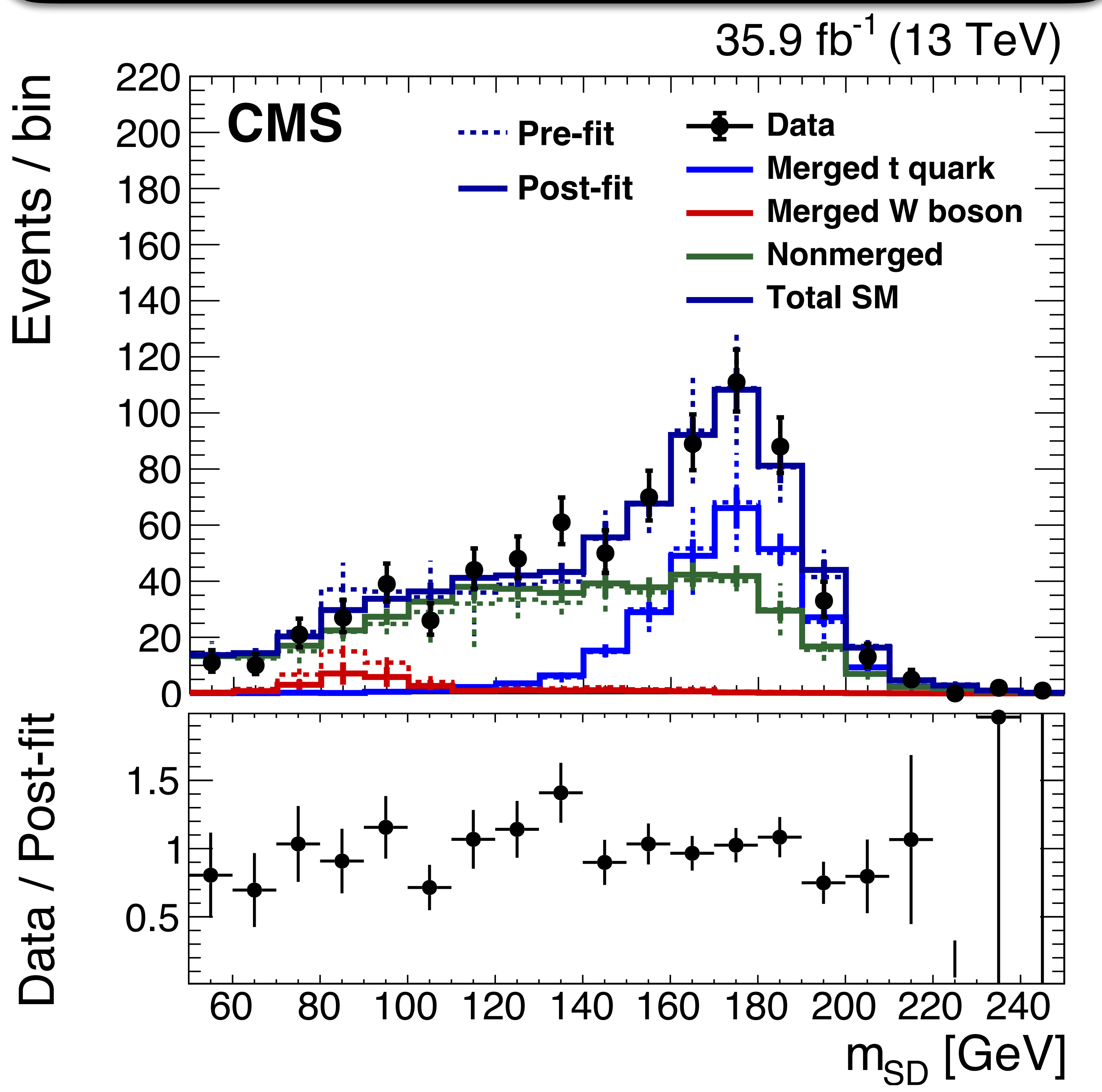
- Rather **complicated variables**, difficult to model ➜ need to validate in data
- Clean sample of W-boson jets: **top-antitop quark pairs** used for calibration (W-boson jet p_T ~ 200 GeV)



Pass W-boson discriminant



Pass top-quark discriminant



Using jet substructure in resonance searches

Two hot-off-the-press examples

Search for W’ ➜ tb

new!

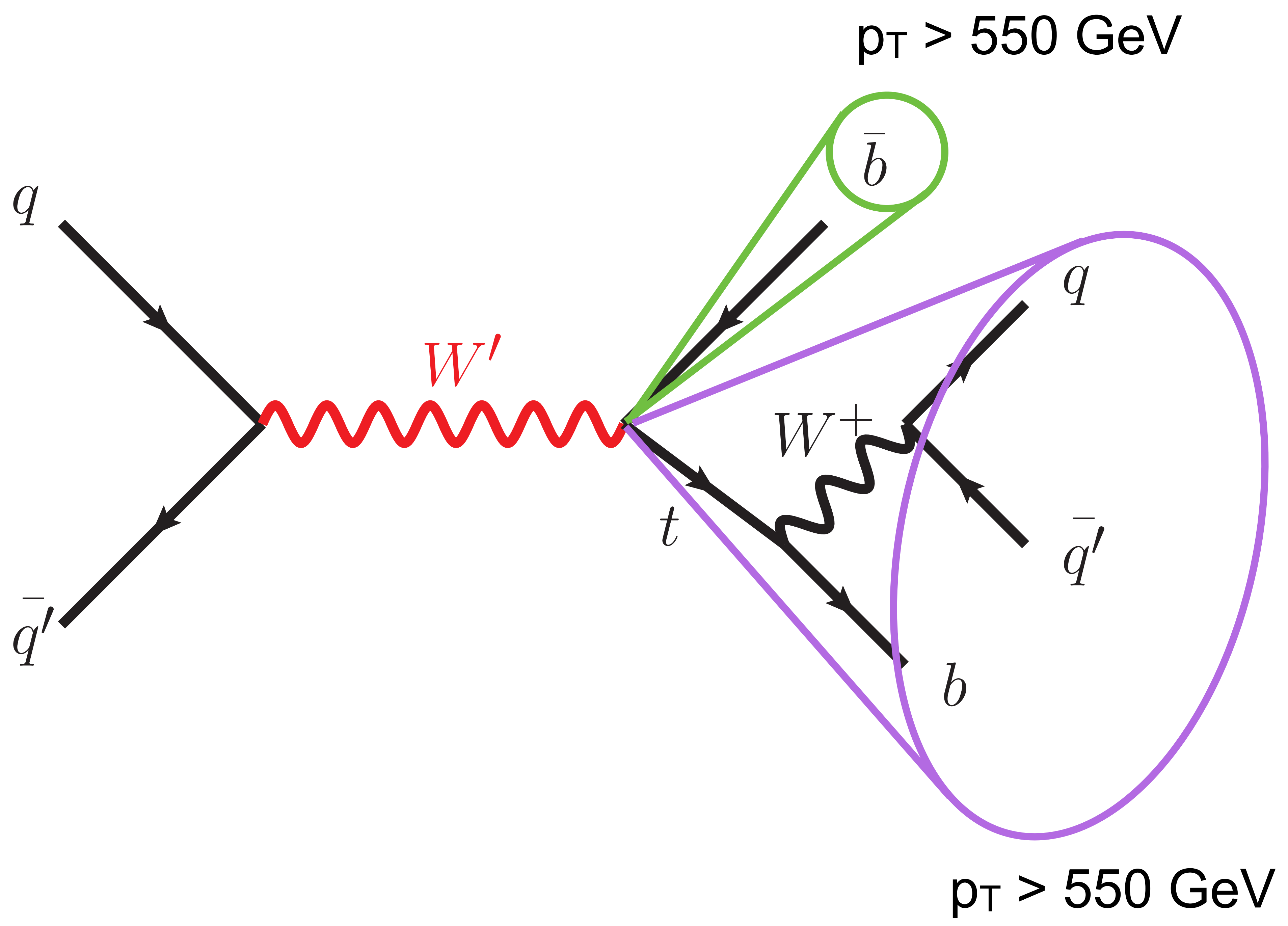
Topology:

- 1 high-p_T bottom-quark jet
- 1 high-p_T top-quark jet
- both are identified using dedicated deep neural network algorithms (DeepJet and DeepAK8)

Selection:

- One AK4 jet, p_T > 550 GeV, b tagged
- One AK8 jet, p_T > 550 GeV, top tagged, 105 < m_{SD} < 210 GeV
- Both well-separated from each other (back-to-back)

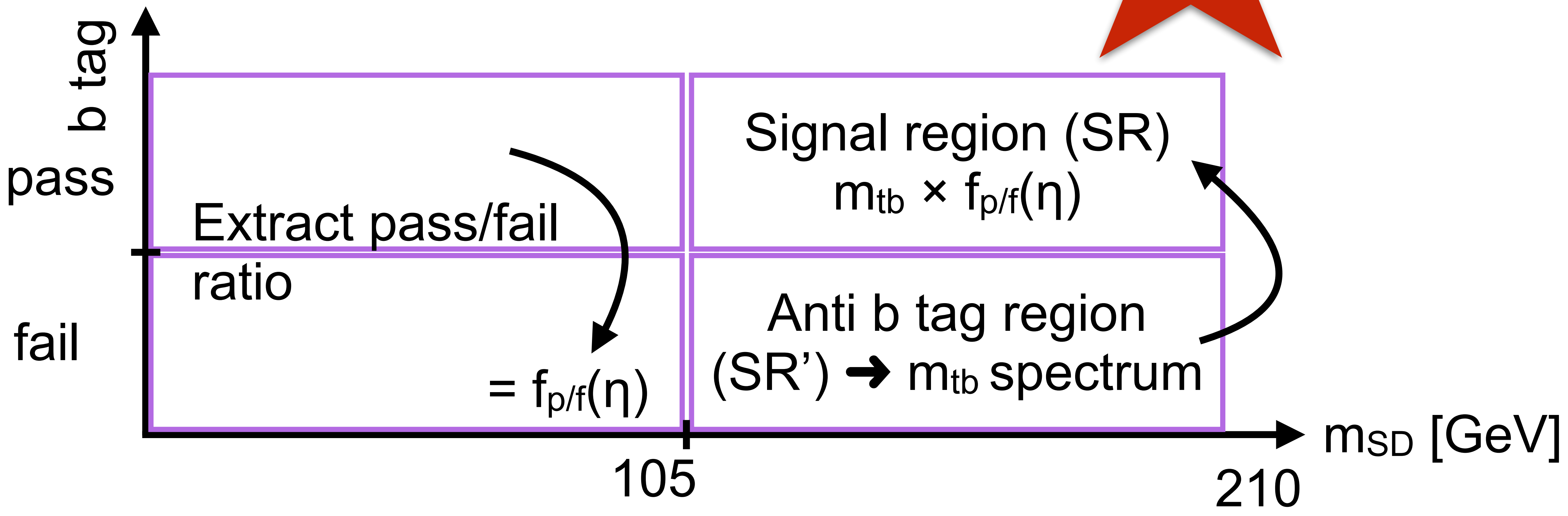
Define control and validation regions by inverting b/top tag requirements and using mass sidebands



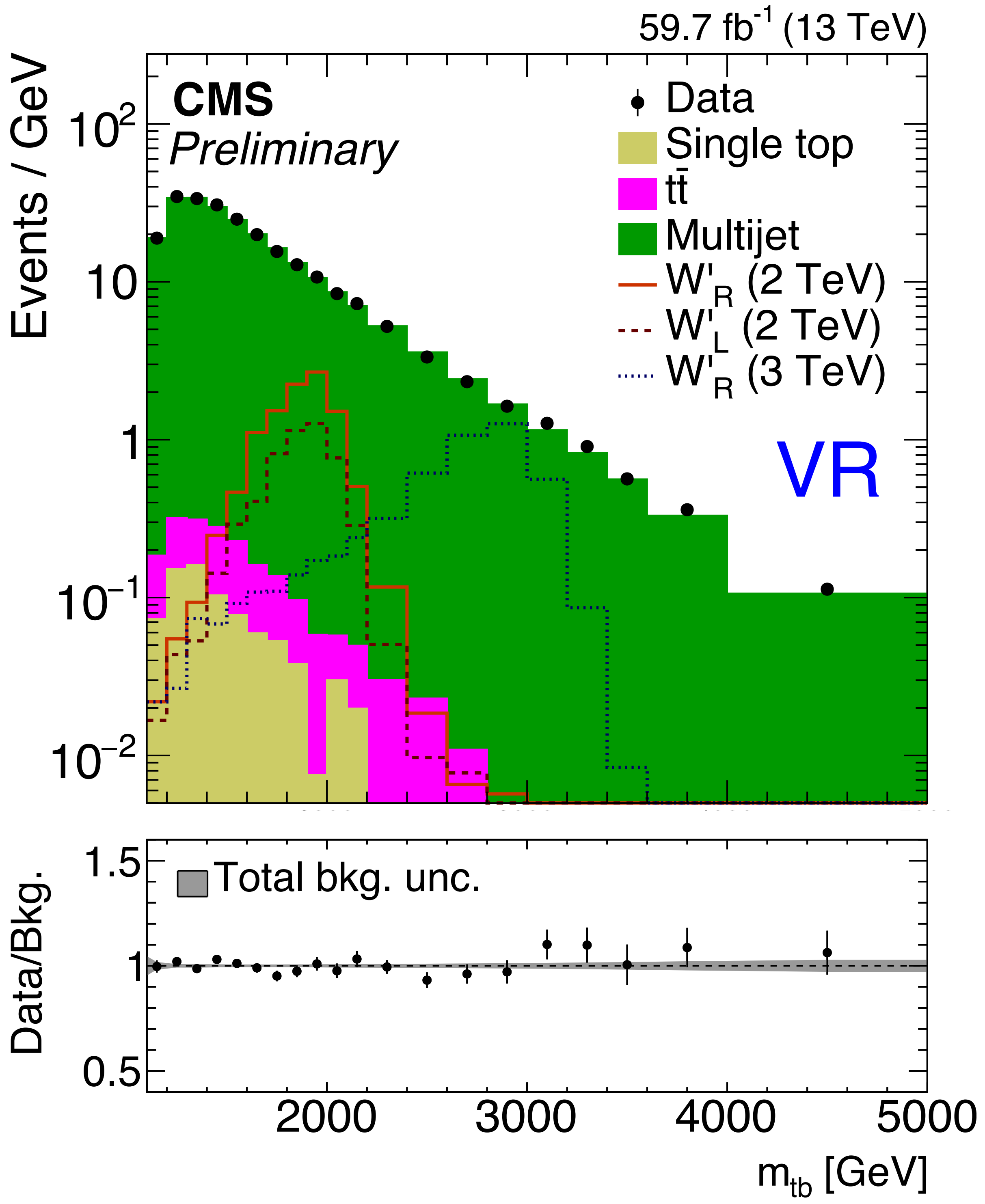
Search for W’ ➜ tb

new!

- Final discriminant: invariant tb mass (m_{tb})
- Background estimation of dominant multijet production:
  - In mass sideband (m_{SD} < 105 GeV), extract **b tag pass/fail ratio** as function of η of the AK4 jet
  - In signal mass window, invert b tag requirement (SR’) and multiply m_{tb} spectrum by pass/fail ratio to **predict multijet in signal region** (SR)
  - Validate procedure in top tag fail region (VR)



Multijet validation region



Search for W' ➜ tb

new!

- Final discriminant: invariant tb mass (m_{tb})
- Background estimation of dominant multijet production:
  - In mass sideband (m_{SD} < 105 GeV), extract **b tag pass/fail ratio** as function of η of the AK4 jet
  - In signal mass window, invert b tag requirement (SR') and multiply m_{tb} spectrum by pass/fail ratio to **predict multijet in signal region** (SR)
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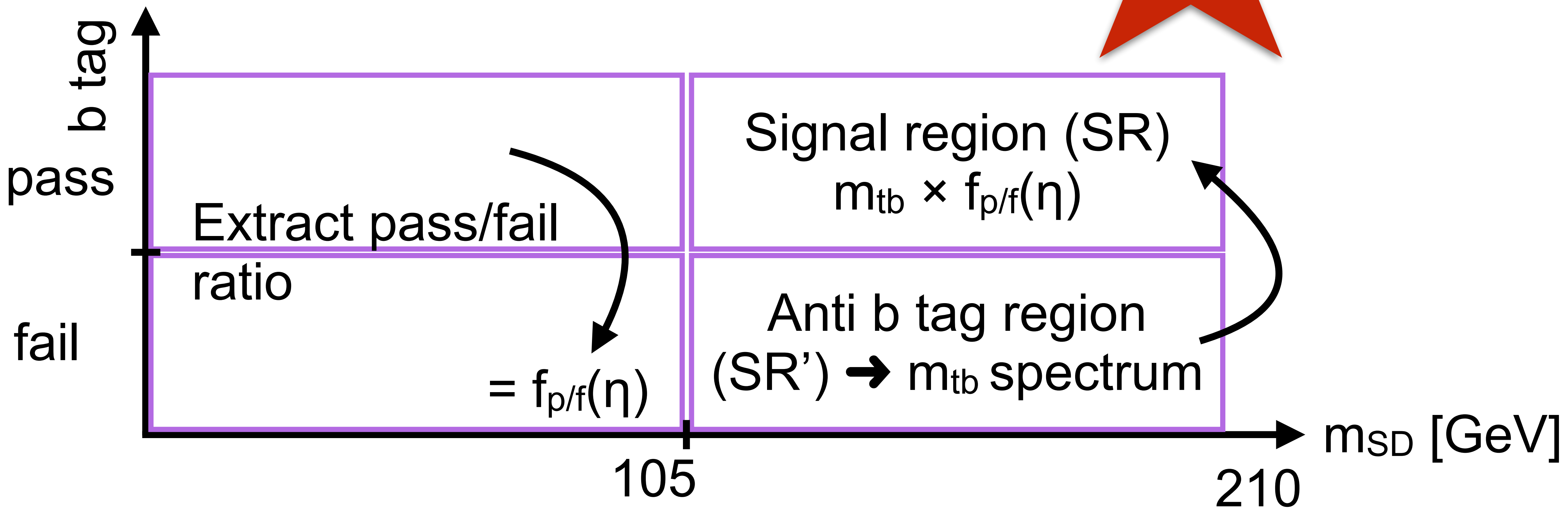

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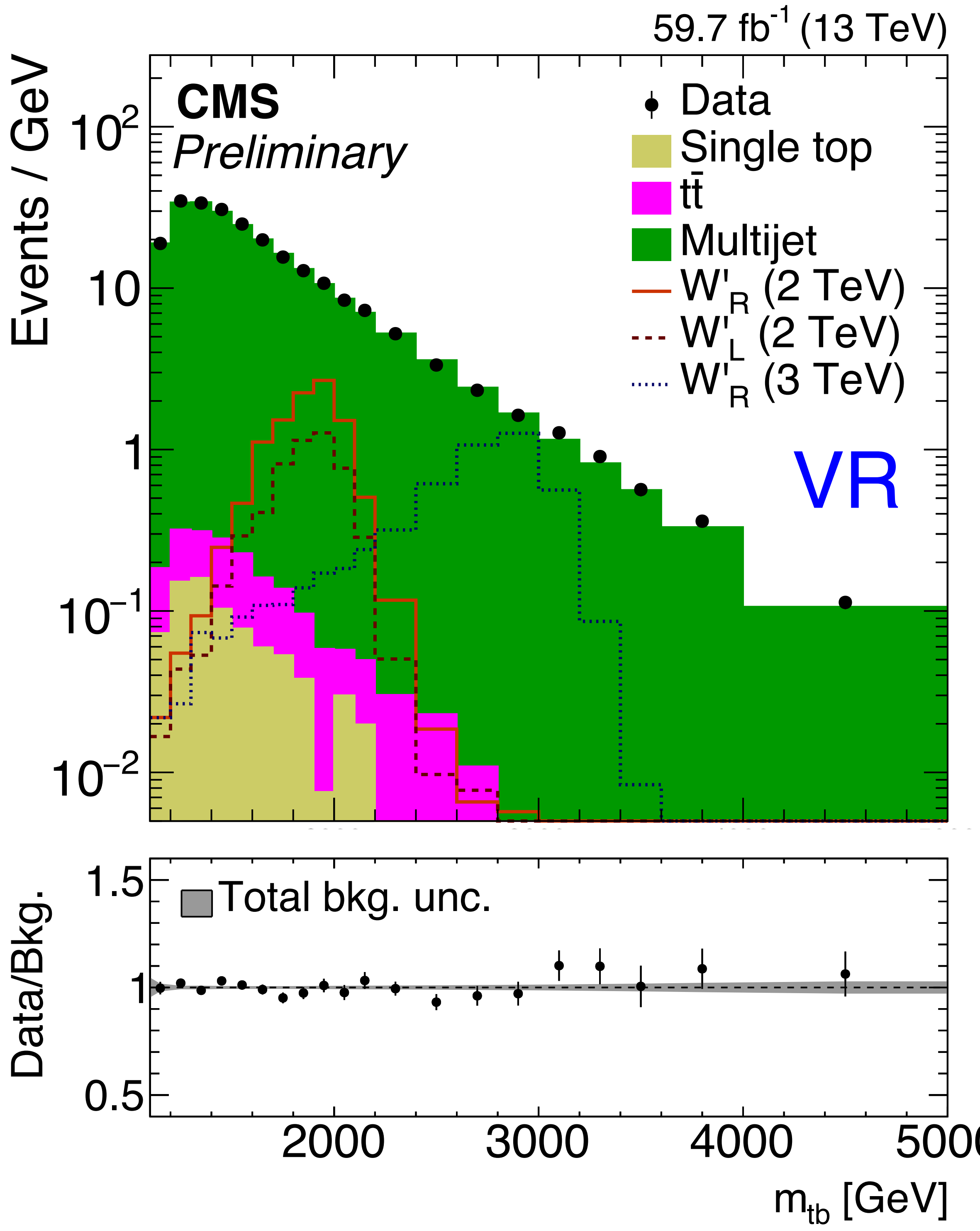
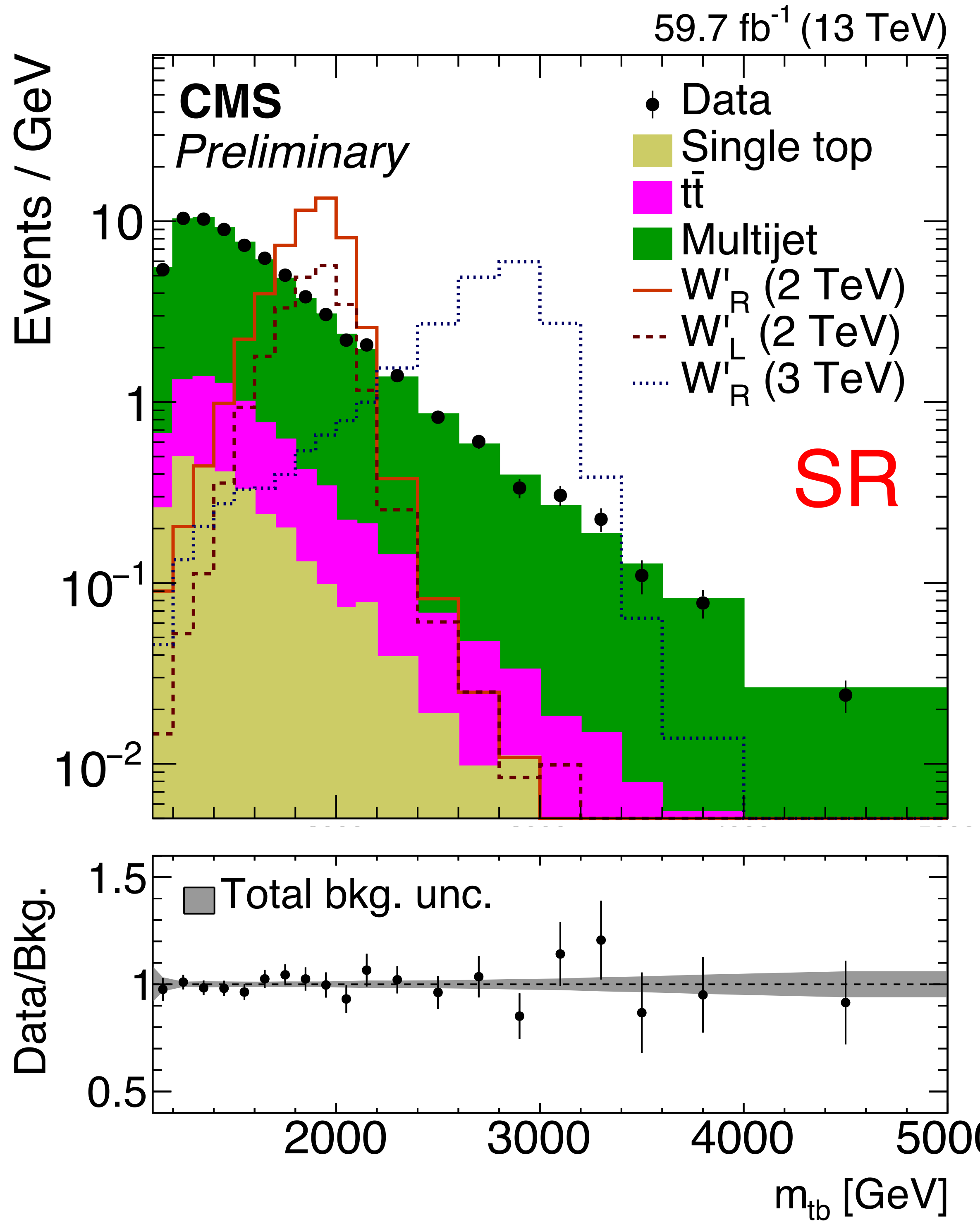


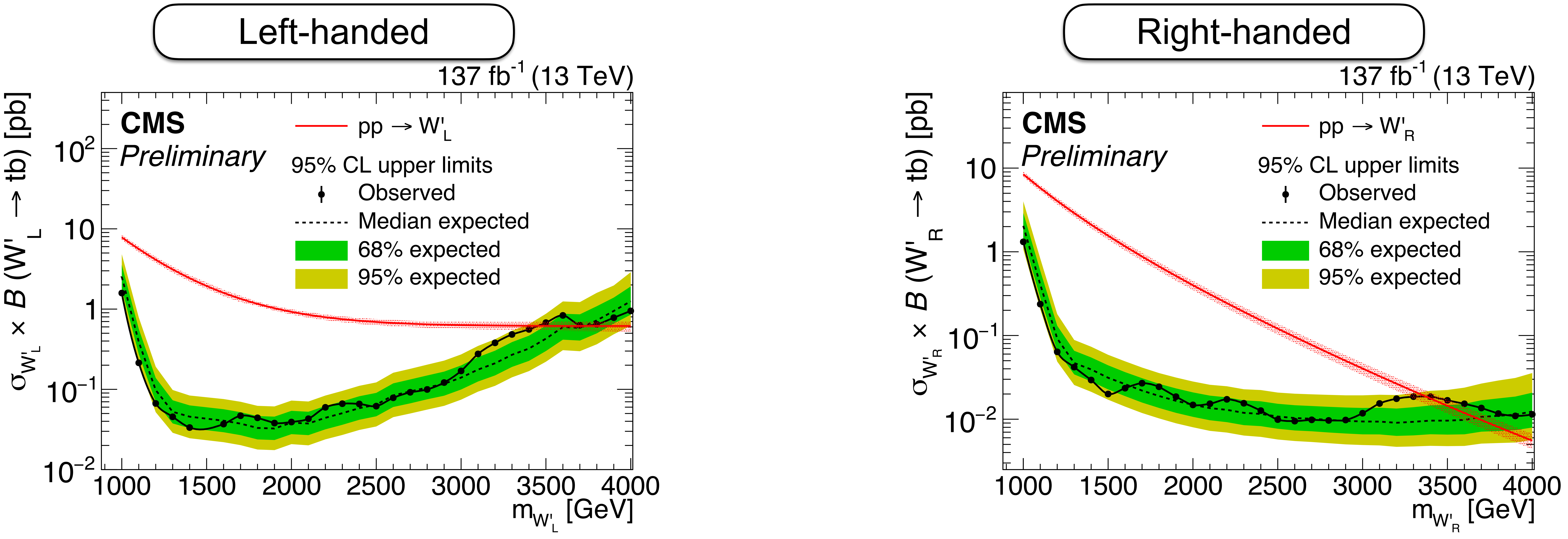
Signal region



Search for W’ ➜ tb

new!

- Set upper limits on the production cross section of a W’ decaying to tb
- W’ can have different chiralities (left- and right-handed)
  - Different chiralities lead to different angular distributions of top quark decay products affecting tagger efficiency
  - Also taking into account interference with standard model



Search for b* ➜ tW

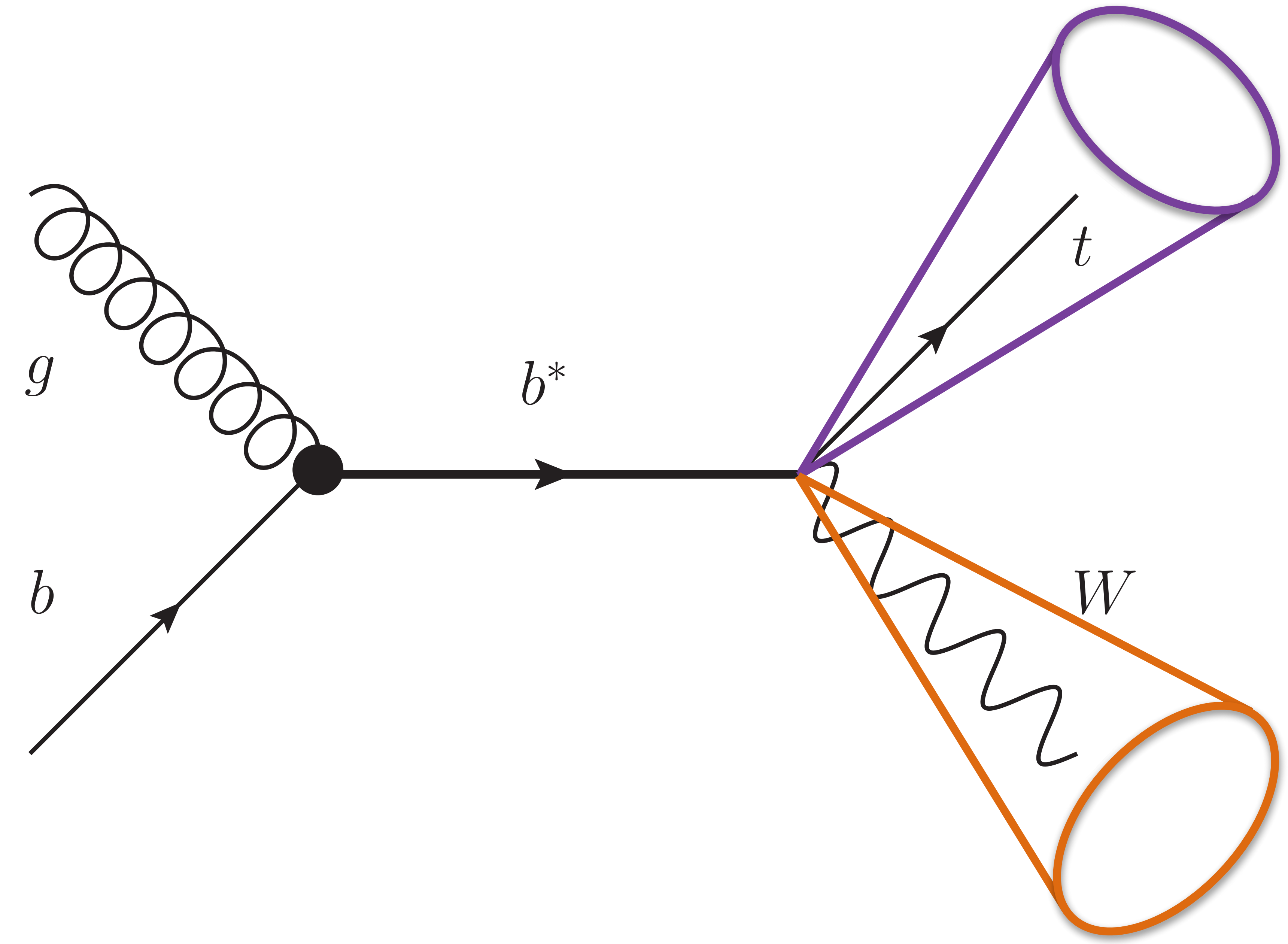
new!

> Topology:

- 1 high-p_T **W-boson jet**
- 1 high-p_T top-quark jet
- both are identified using N-subjettiness ratios (τ_2/τ_1 and τ_3/τ_2), additional subjet b tagging for top quark

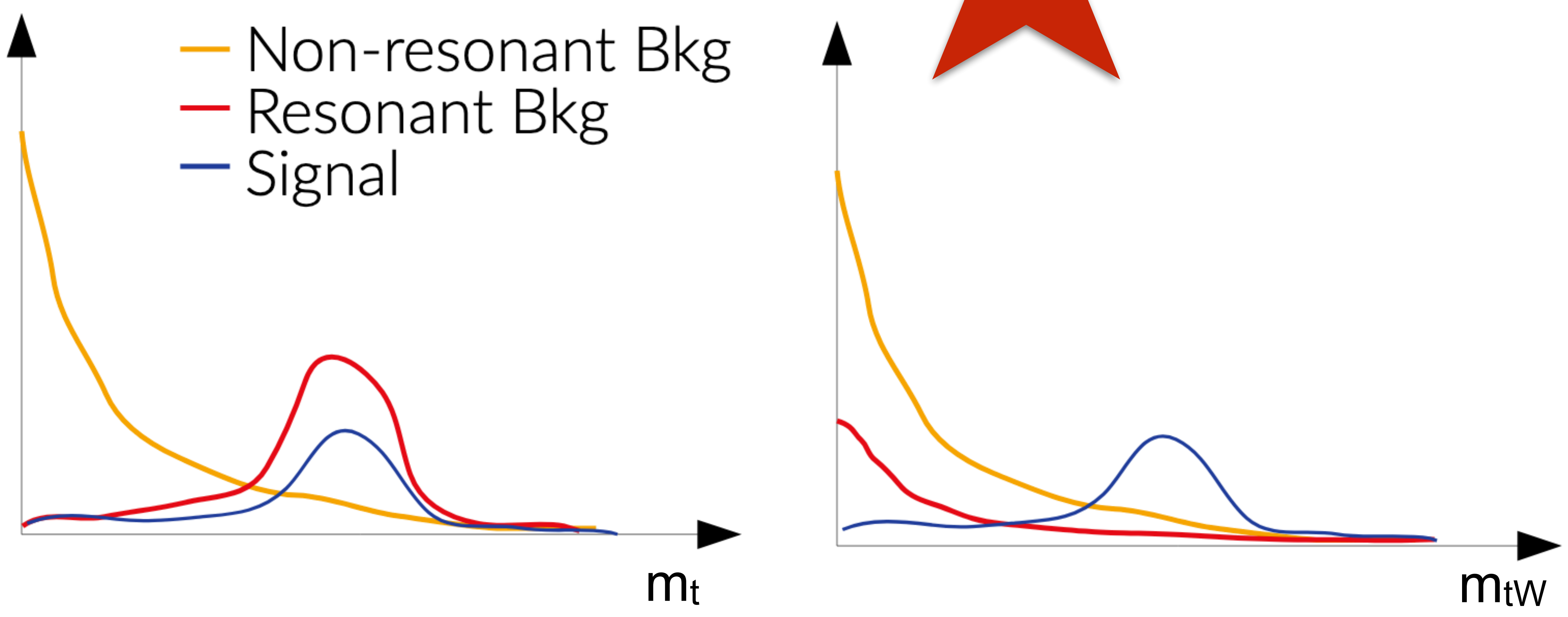
> Selection:

- Two AK8 jets, $p_T > 400$ GeV
- Select W-boson (and top-quark) mass windows 65 (105) < m_{SD} < 105 (210) GeV
- Both well-separated from each other (back-to-back)



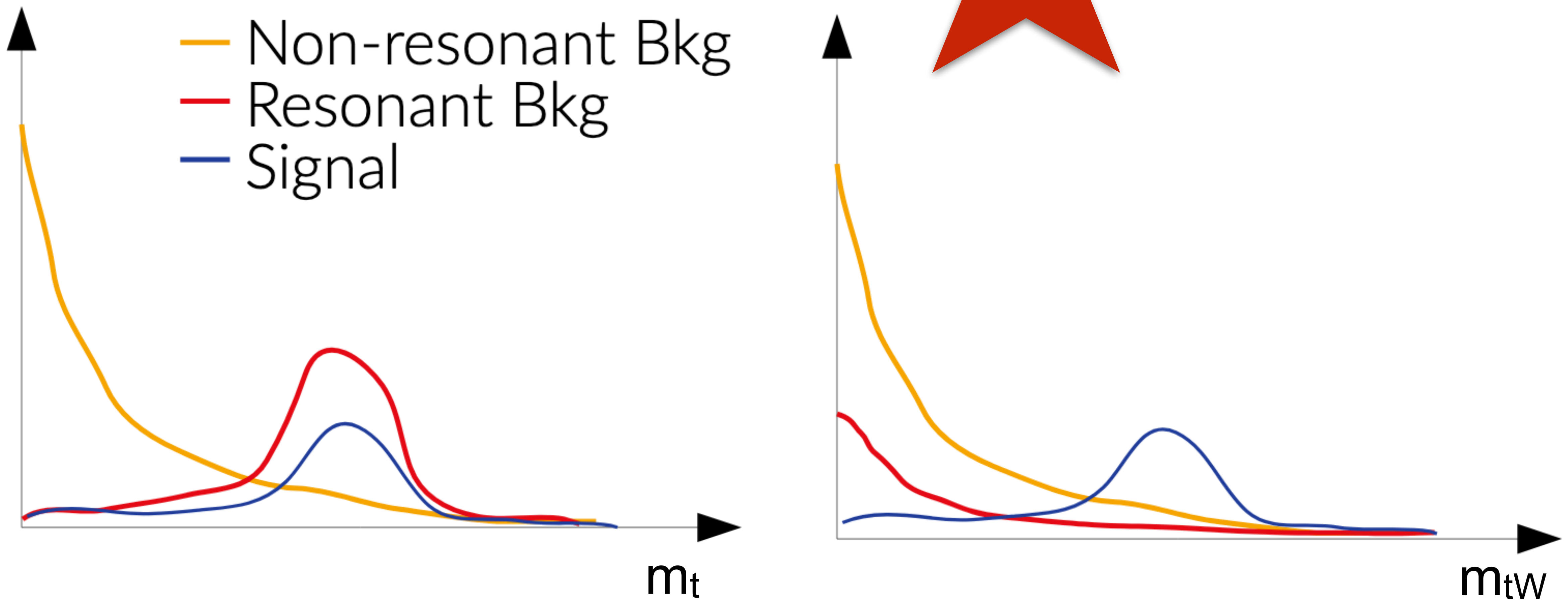
Search for b* ➜ tW

new!



Search for b* → tW

new!



- Parameterize bump hunt in (m_t, m_{tW})
  - Smoothly falling nonresonant background (multijets, W+jets) estimated from data
  - Resonant backgrounds (tt and tW) estimated via template fit from simulation
- Perform a 2D likelihood fit in m_t = [65, 285] GeV and m_{tW} = [1200, 4000] GeV

Search for b* → tW

new!

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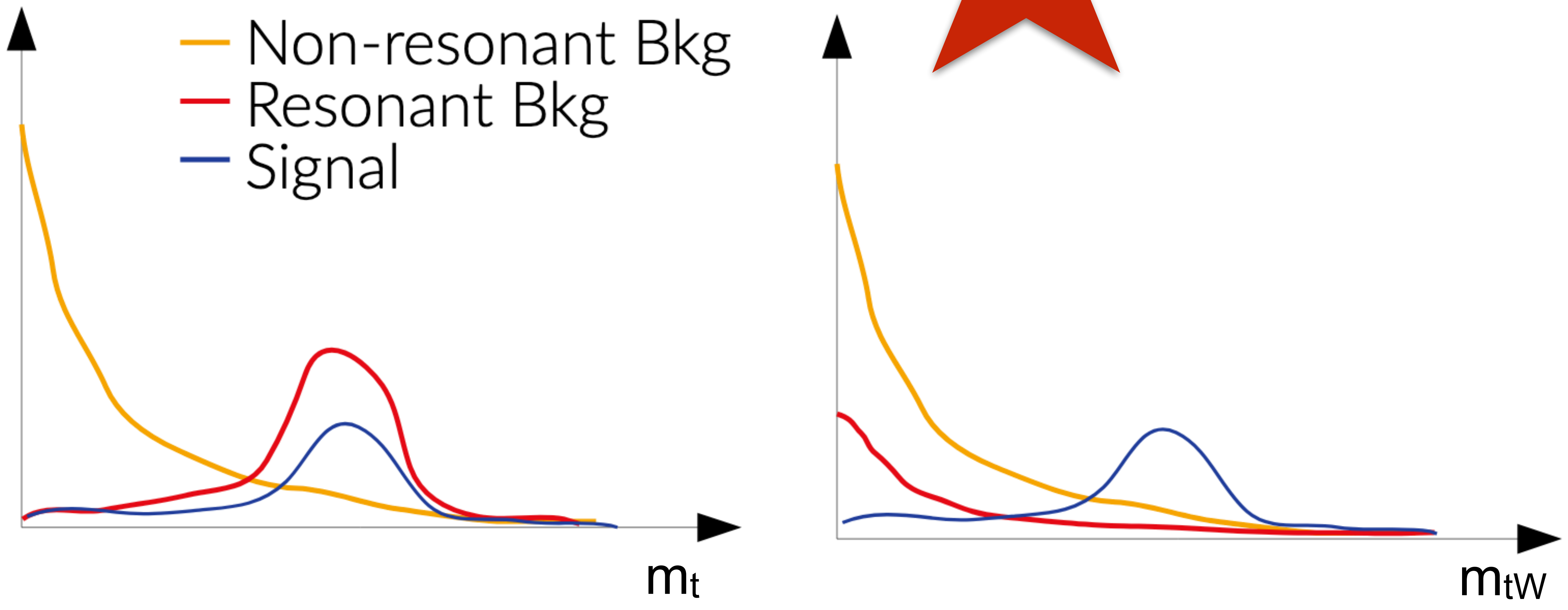
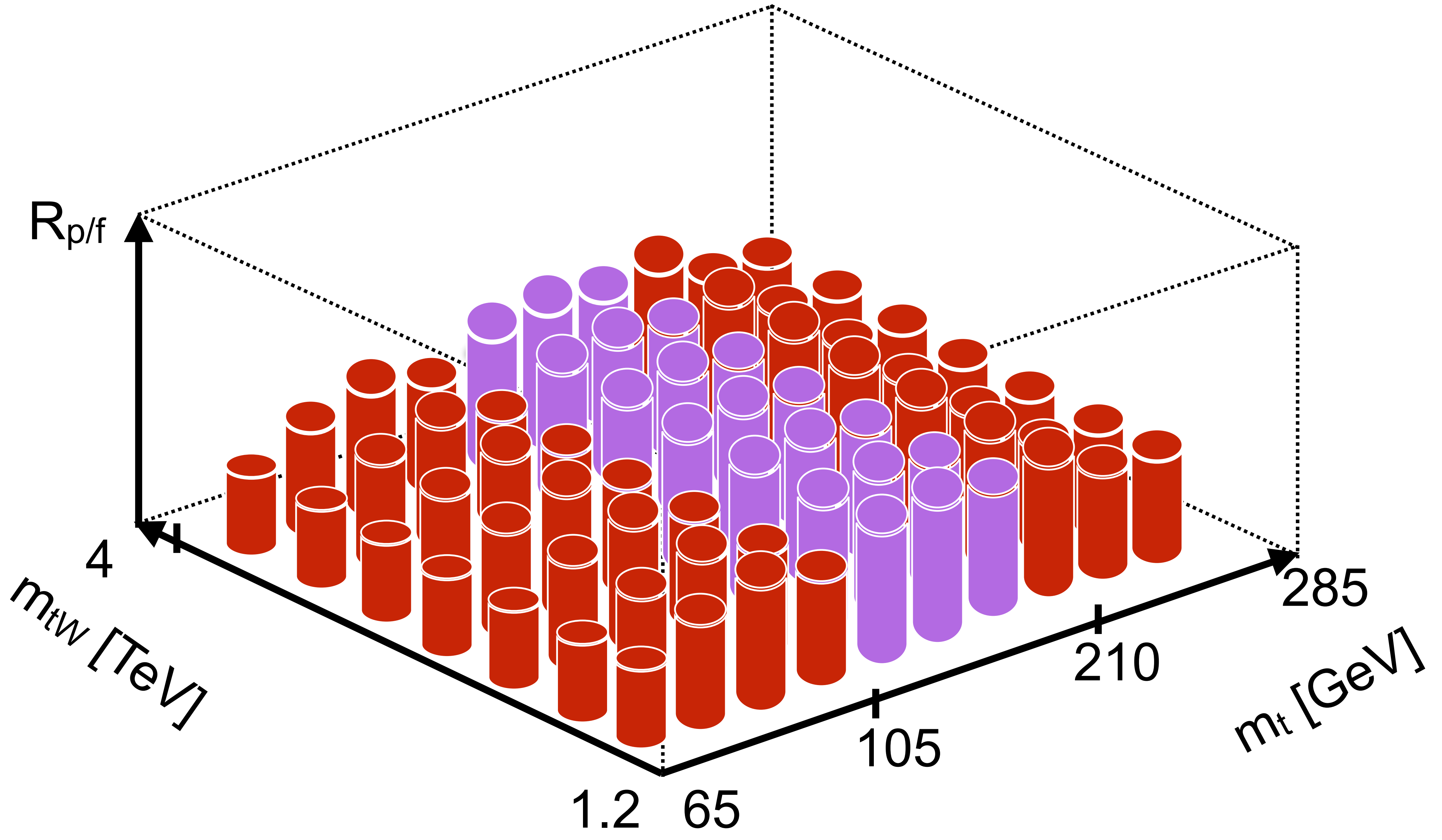
  - Resonant backgrounds (tt and tW) estimated via template fit from simulation
- Perform a 2D likelihood fit in m_t = [65, 285] GeV and m_{tW} = [1200, 4000] GeV
- Nonresonant background: top tag pass/fail ratio
  - Smooth ratio, fit using 2D polynomials



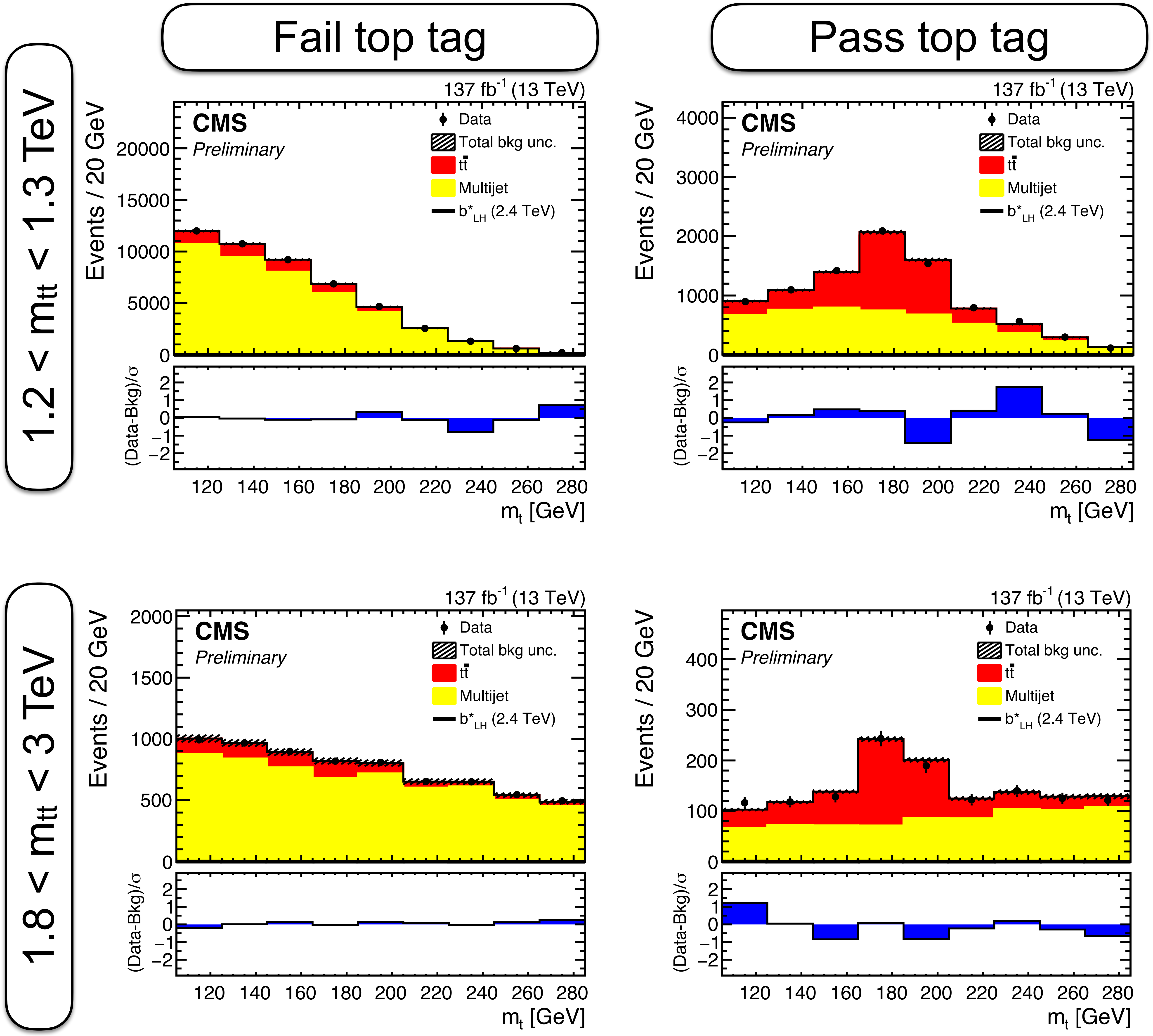
$$N_{\mathrm{p}}^{\mathrm{nonres}}(\mathrm{bin}) = N_{\mathrm{f}}^{\mathrm{nonres}}(\mathrm{bin}) \times f_{\mathrm{p/f}}(m_t, m_{tW})\ ^{\dagger}$$



†actually, $R_{p/f}^{MC}$ ratio is factored out and data/MC $R_{p/f}$ is used

Search for b* ➜ tW

new!



> Resonant tt and tW background:
- Define dedicated measurement region by requiring a second top tag
- Estimate multijet background as for signal

> Constrain top mass scale simultaneously

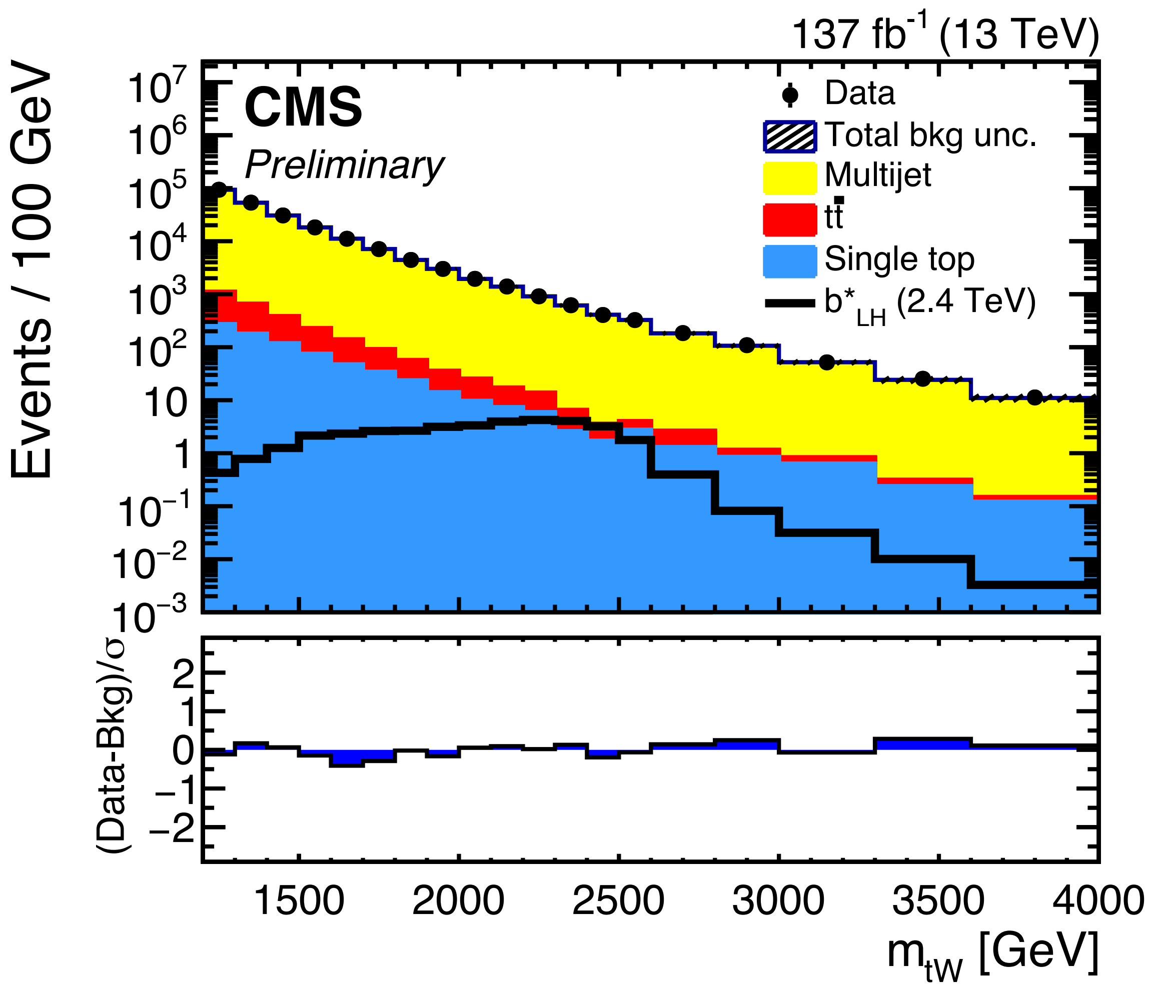
Search for b* ➜ tW

new!

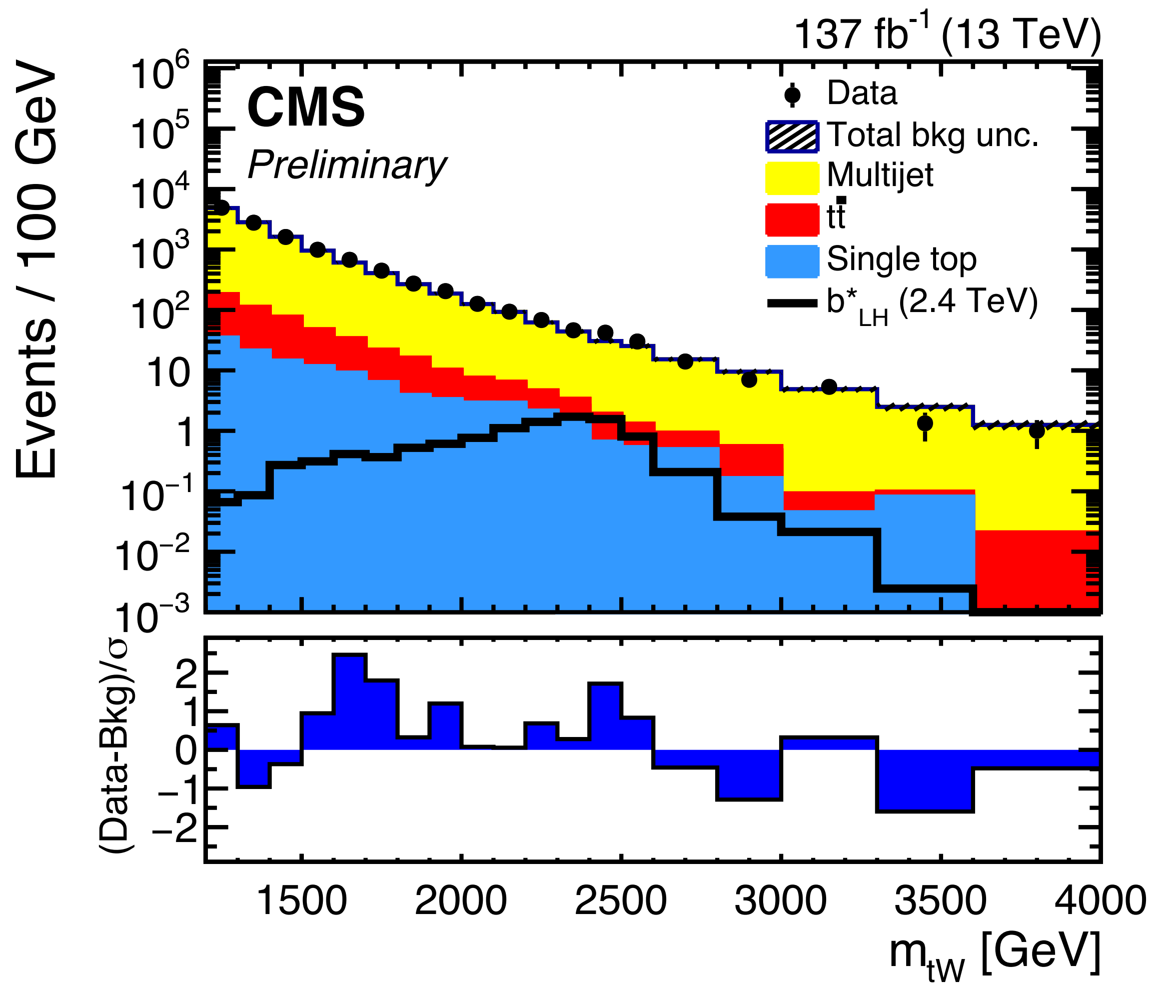
> Signal region post-fit spectra

$65 < m_t < 105$ GeV

Fail top tag

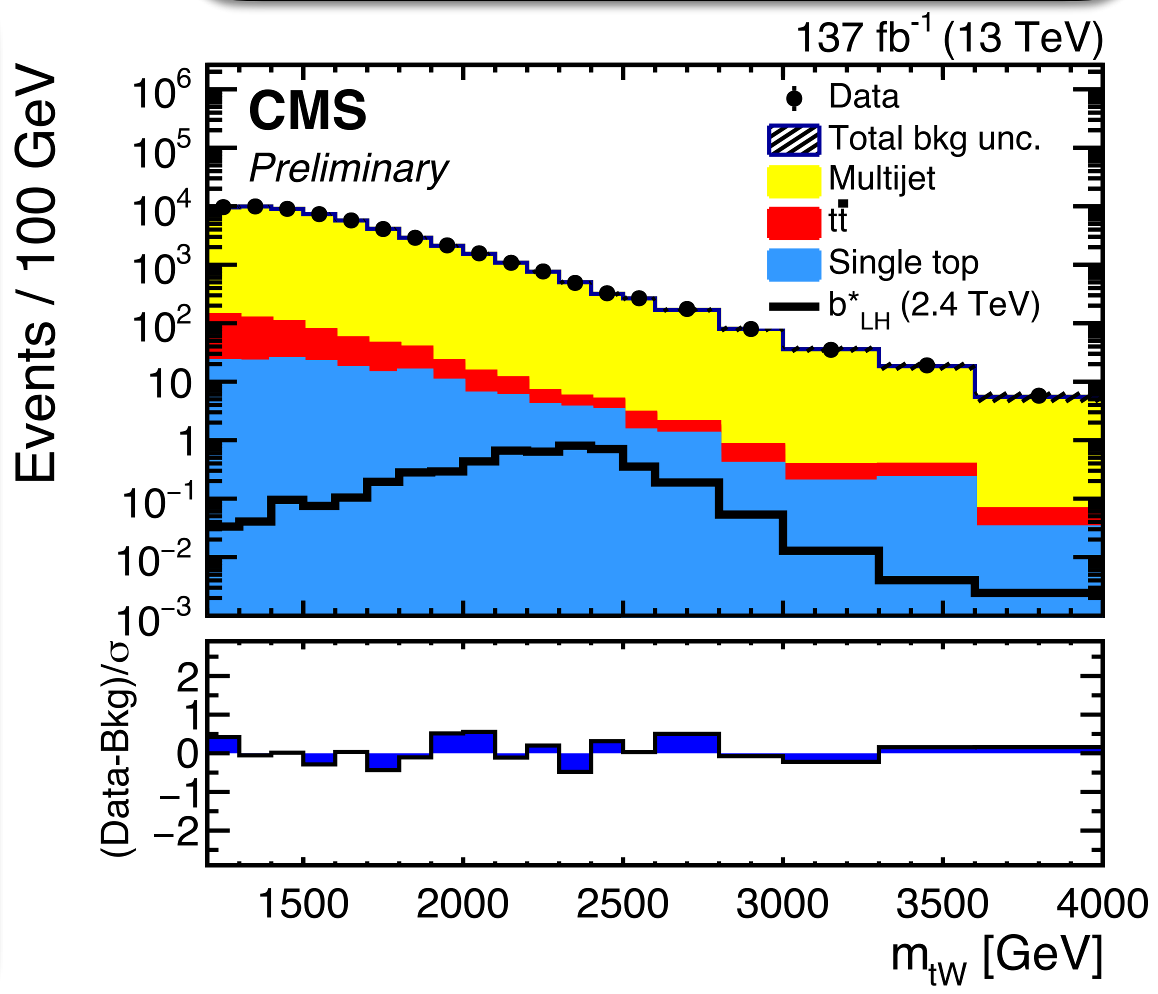


Pass top tag

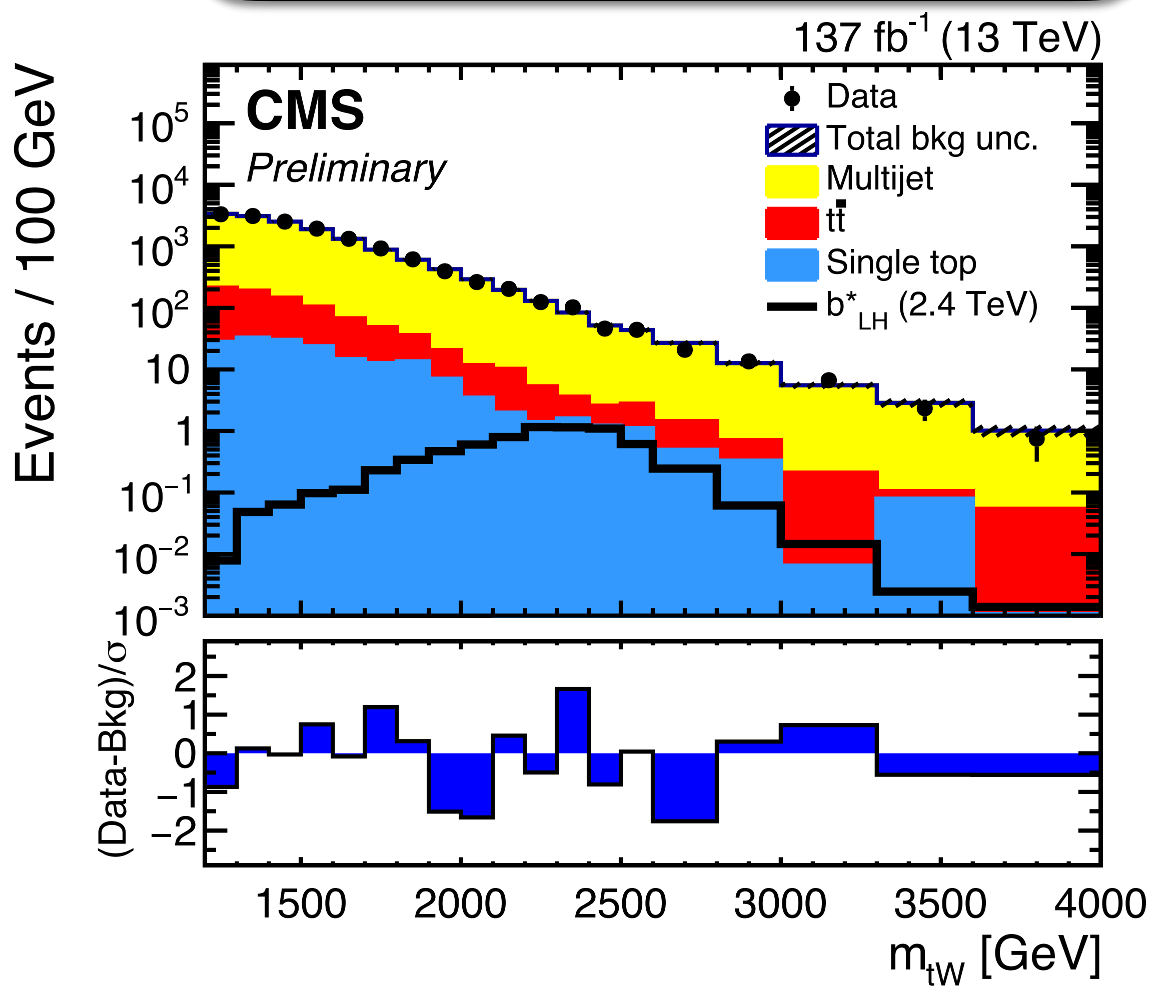


$225 < m_t < 285$ GeV

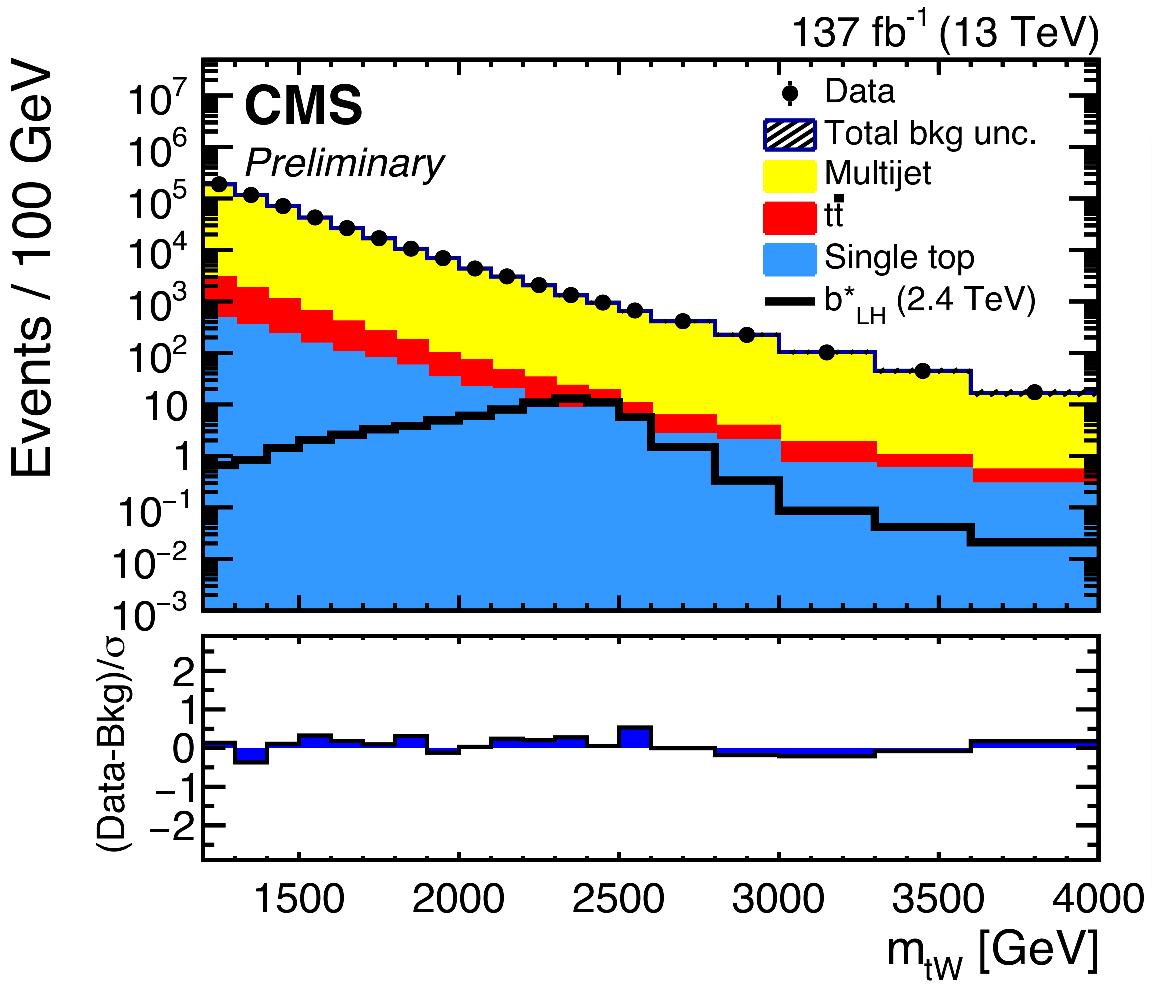
Fail top tag



Pass top tag



$105 < m_t < 225$ GeV



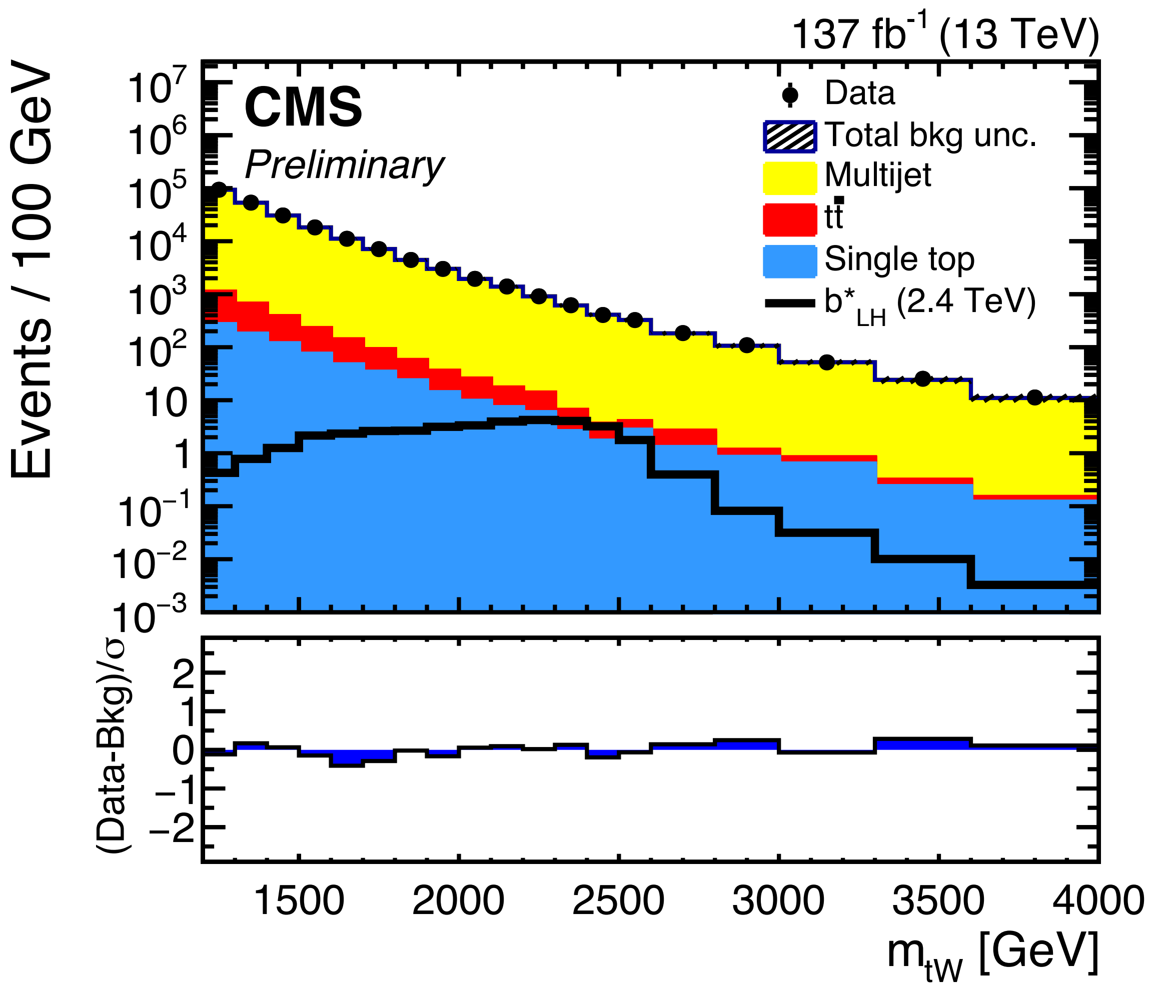
Search for b* ➜ tW

new!

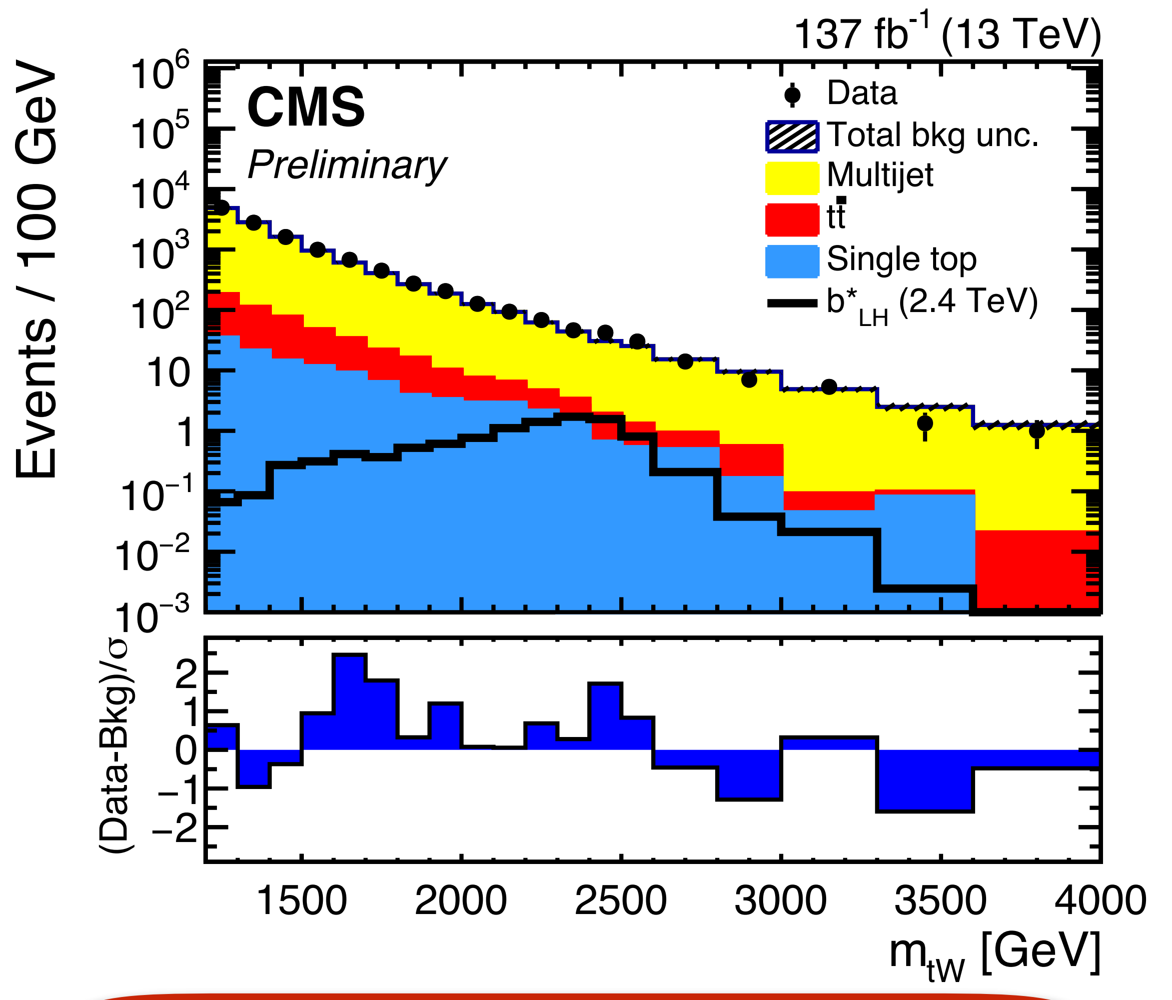
> Signal region post-fit spectra

65 < m_t < 105 GeV

Fail top tag



Pass top tag



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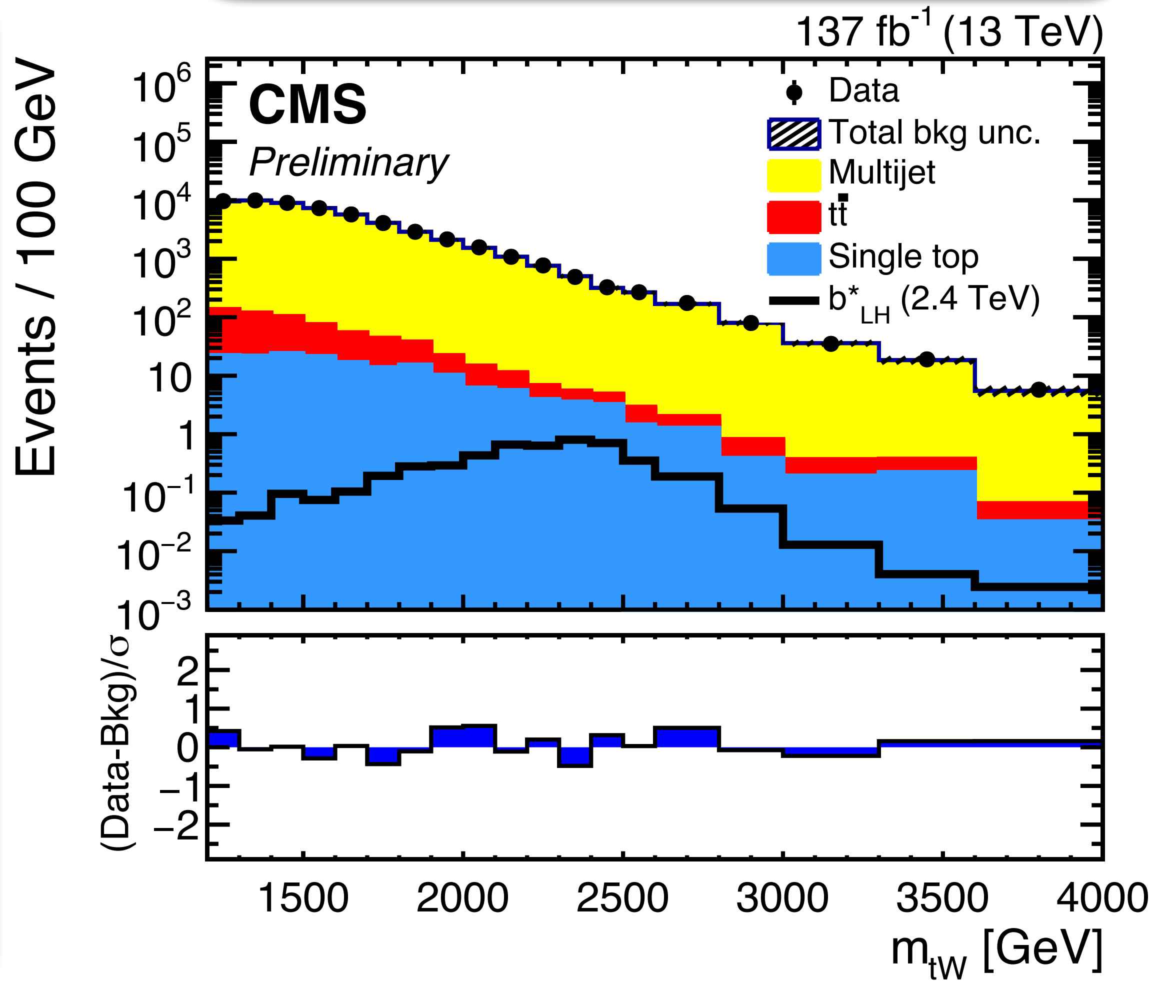
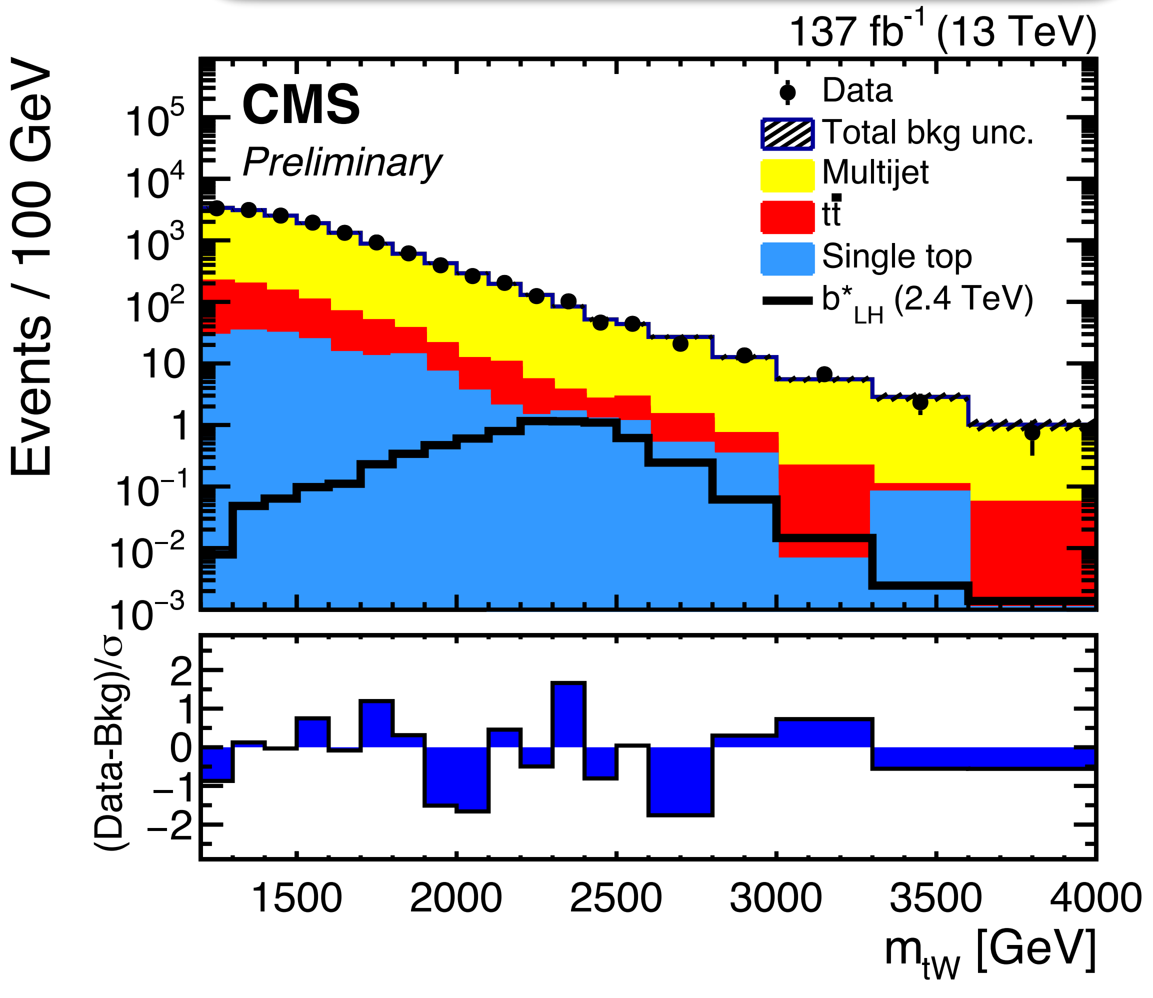
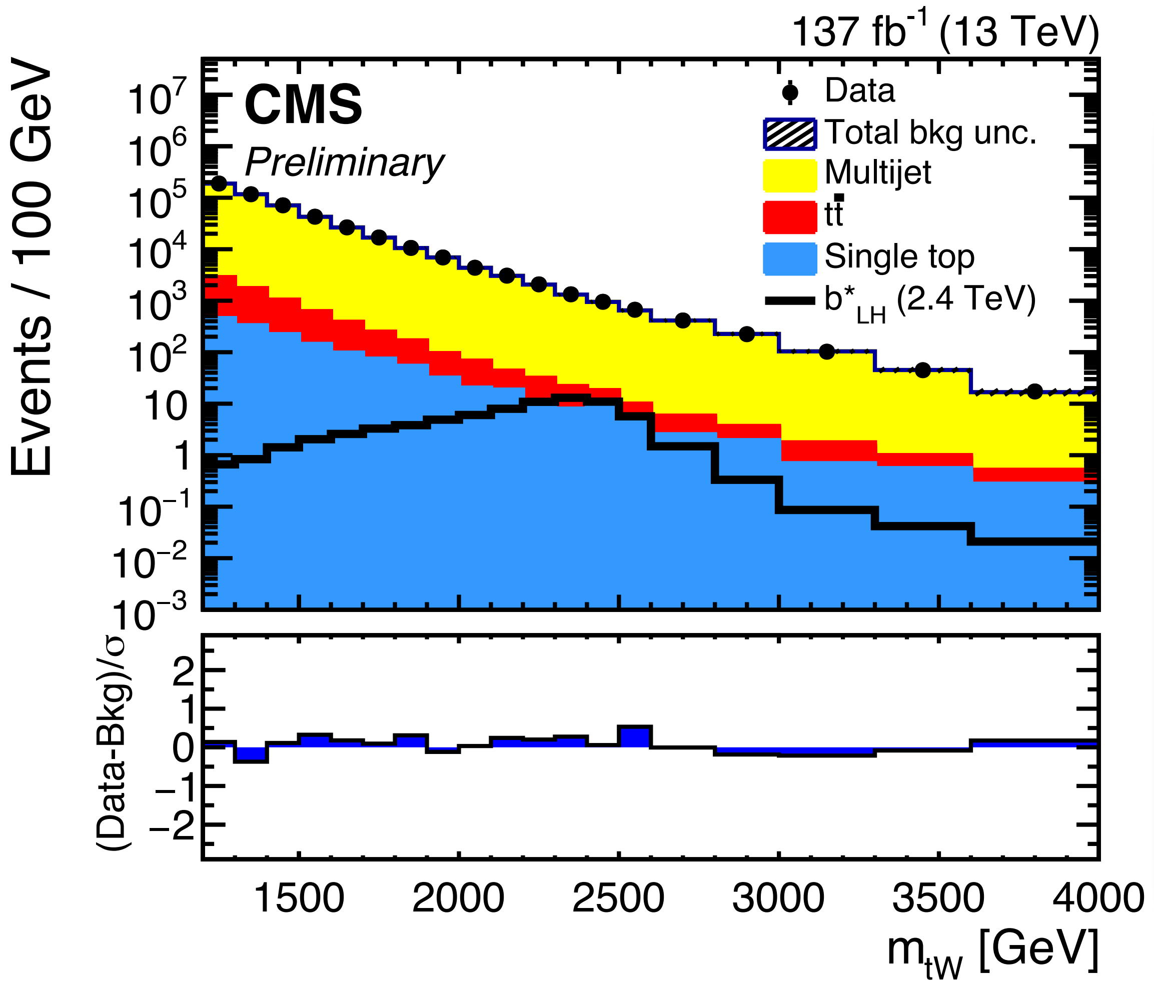
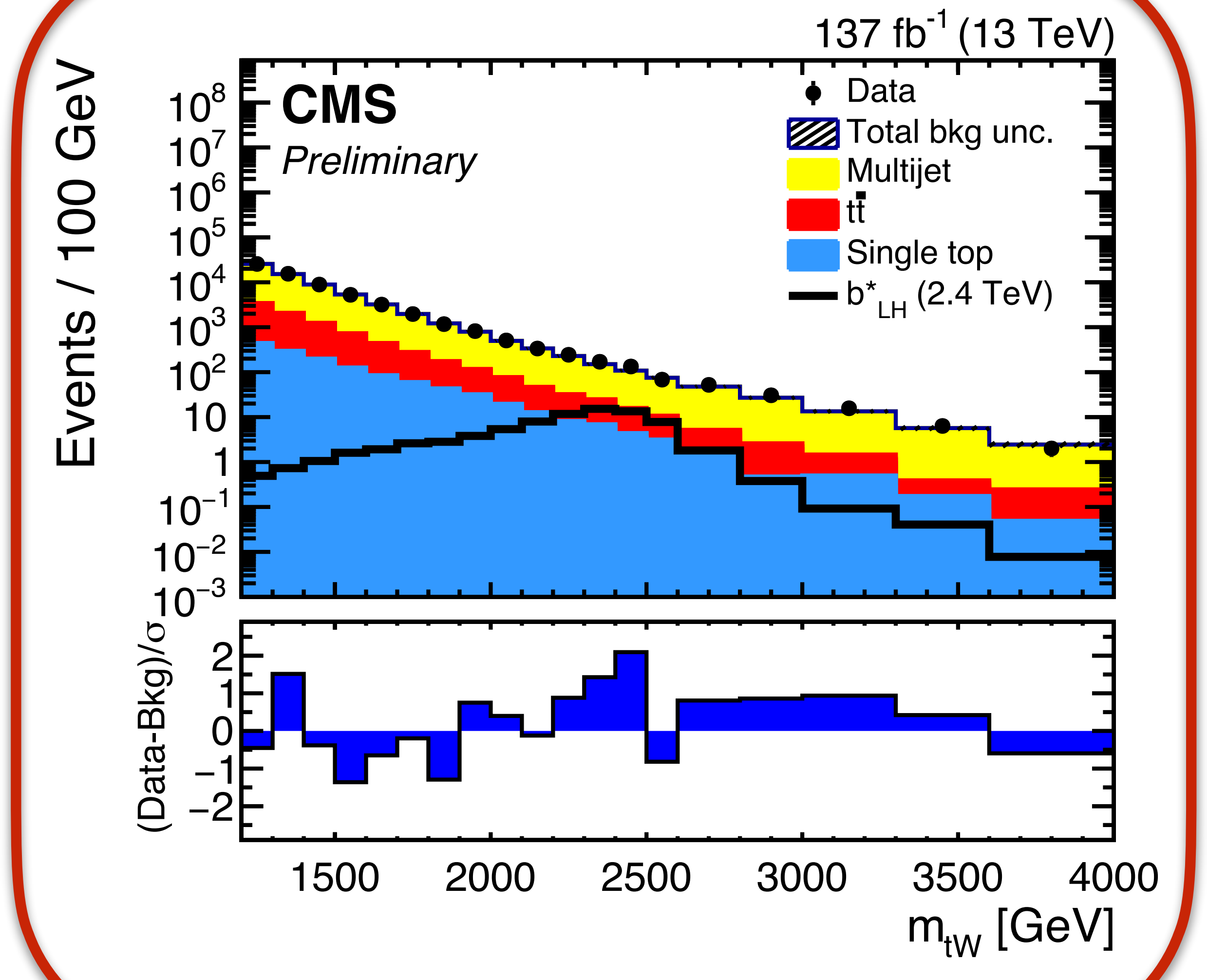


Pass top tag



105 < m_t < 225 GeV



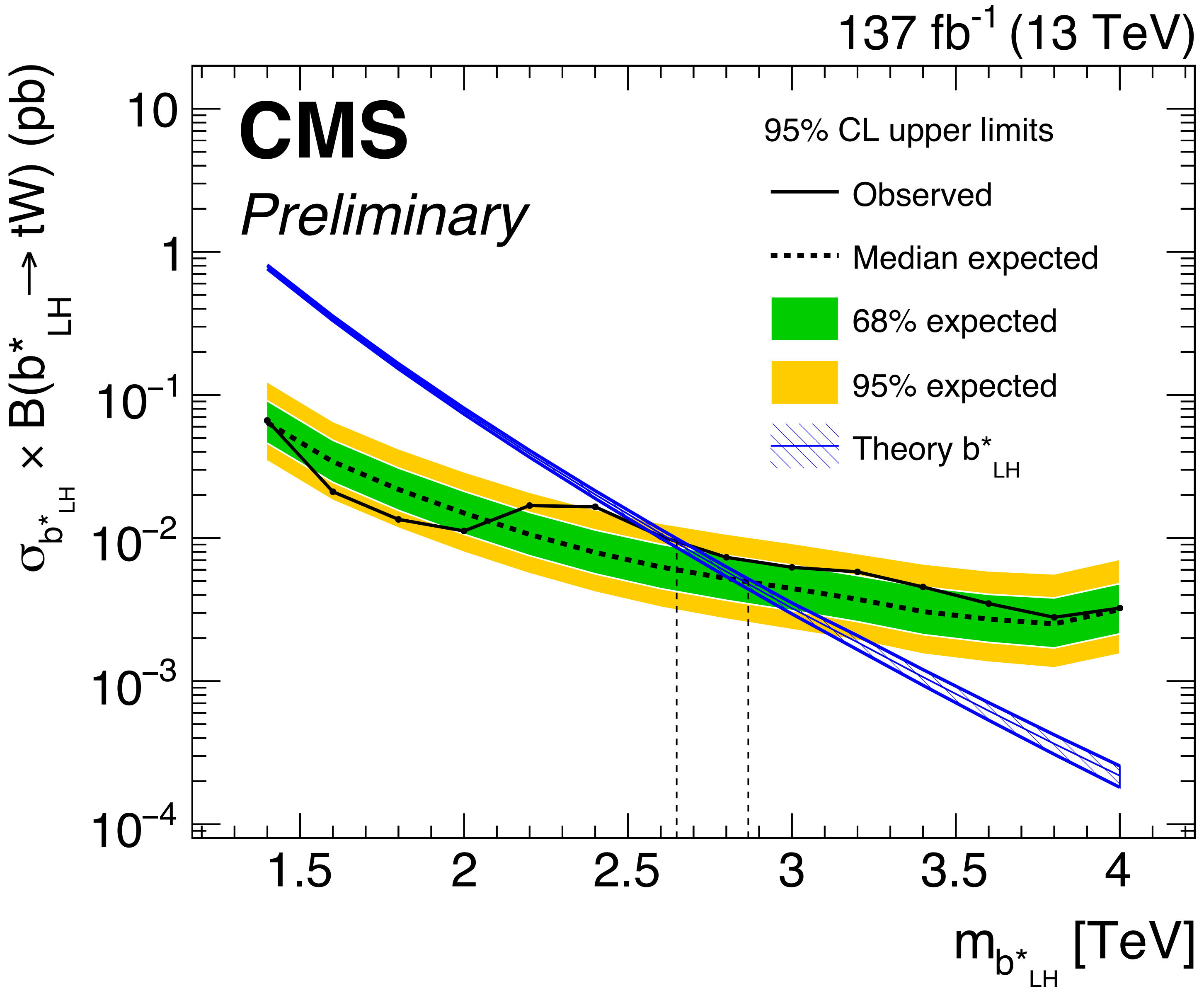


Search for b* ➜ tW

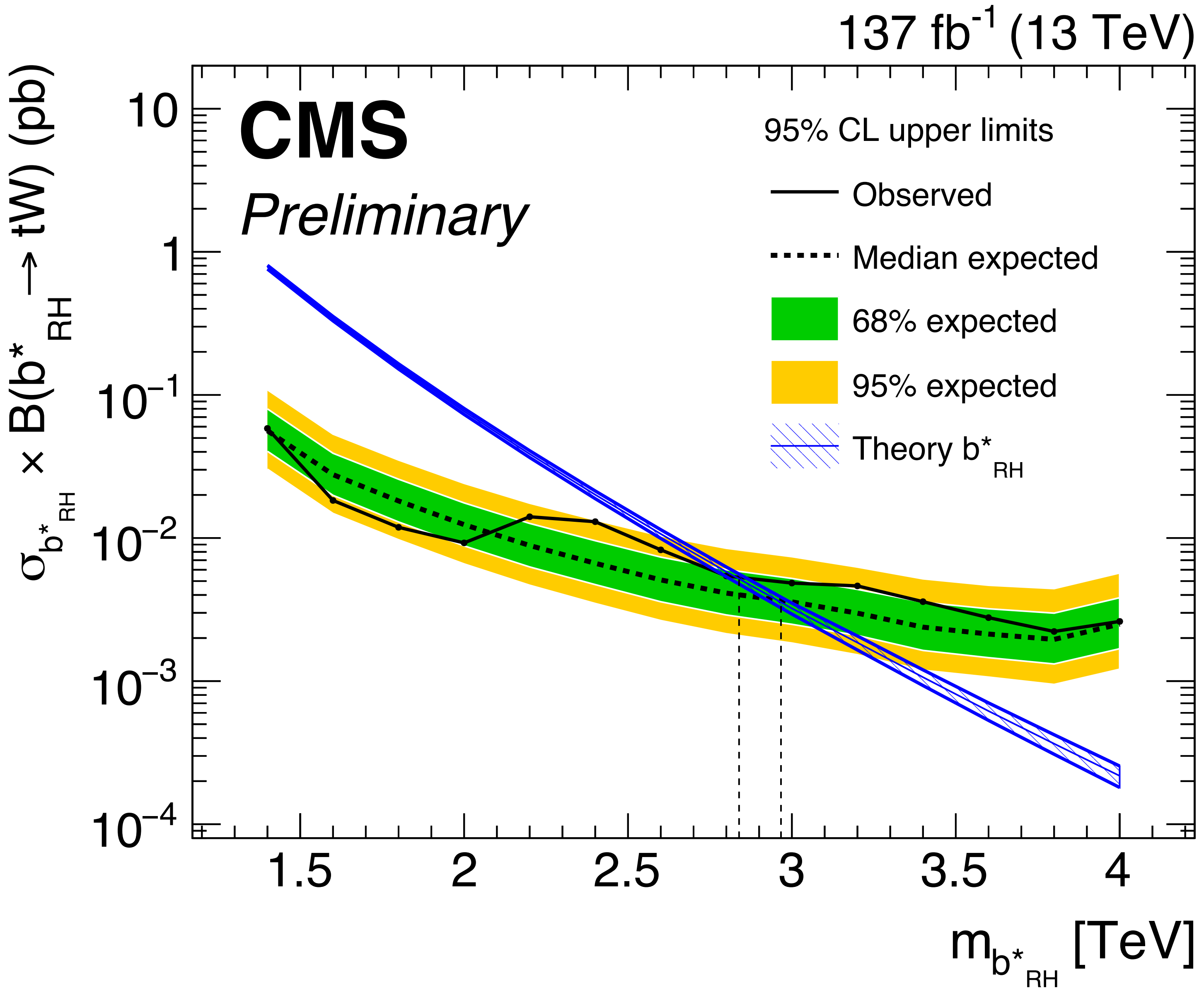
new!

- b* can have different chiralities (left- and right-handed, vector-like)
- Largest excess for left-handed b* at 2.4 TeV (2.3σ local)
- Interpret result in these models

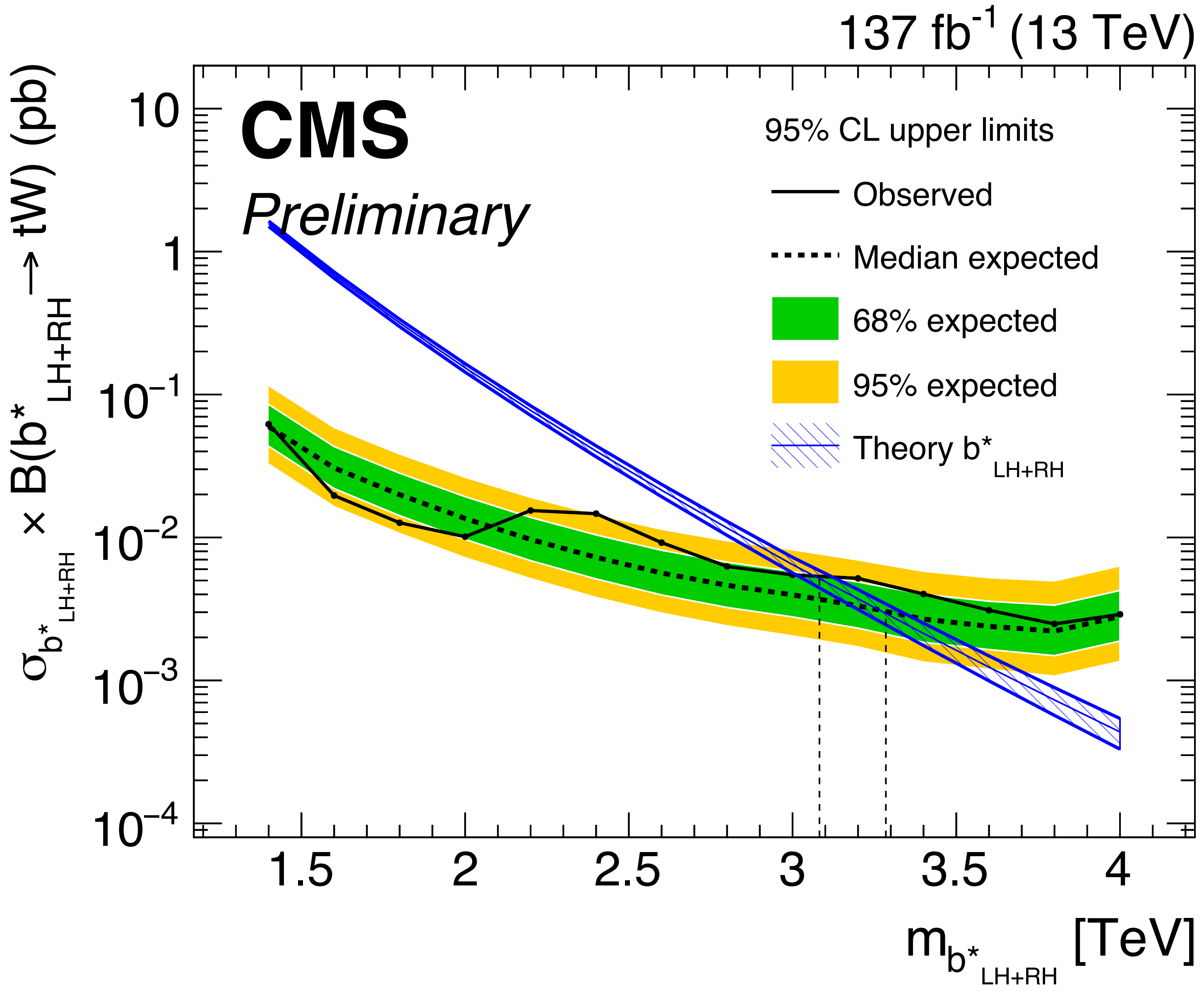
Left-handed



Right-handed



Vector-like



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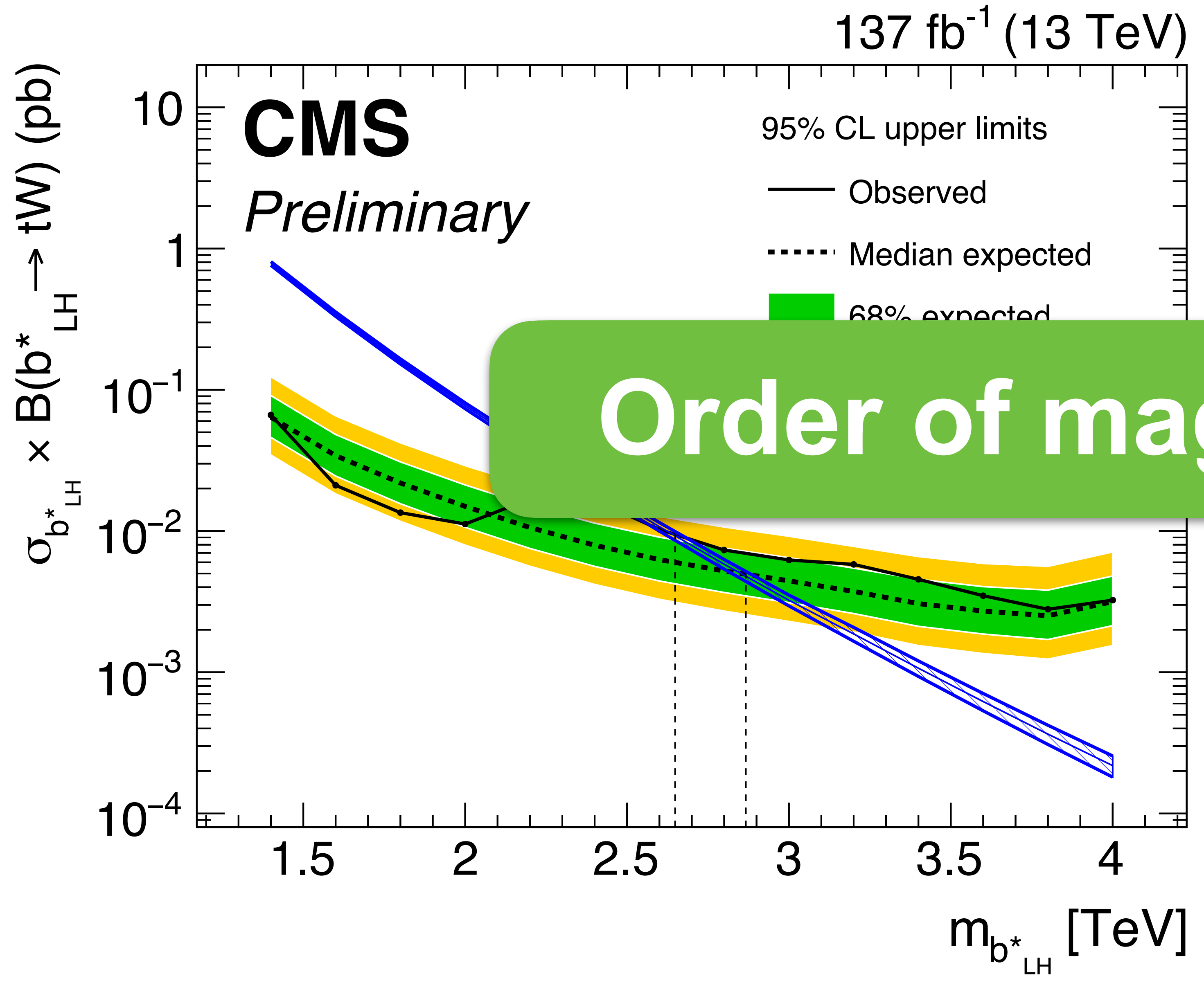

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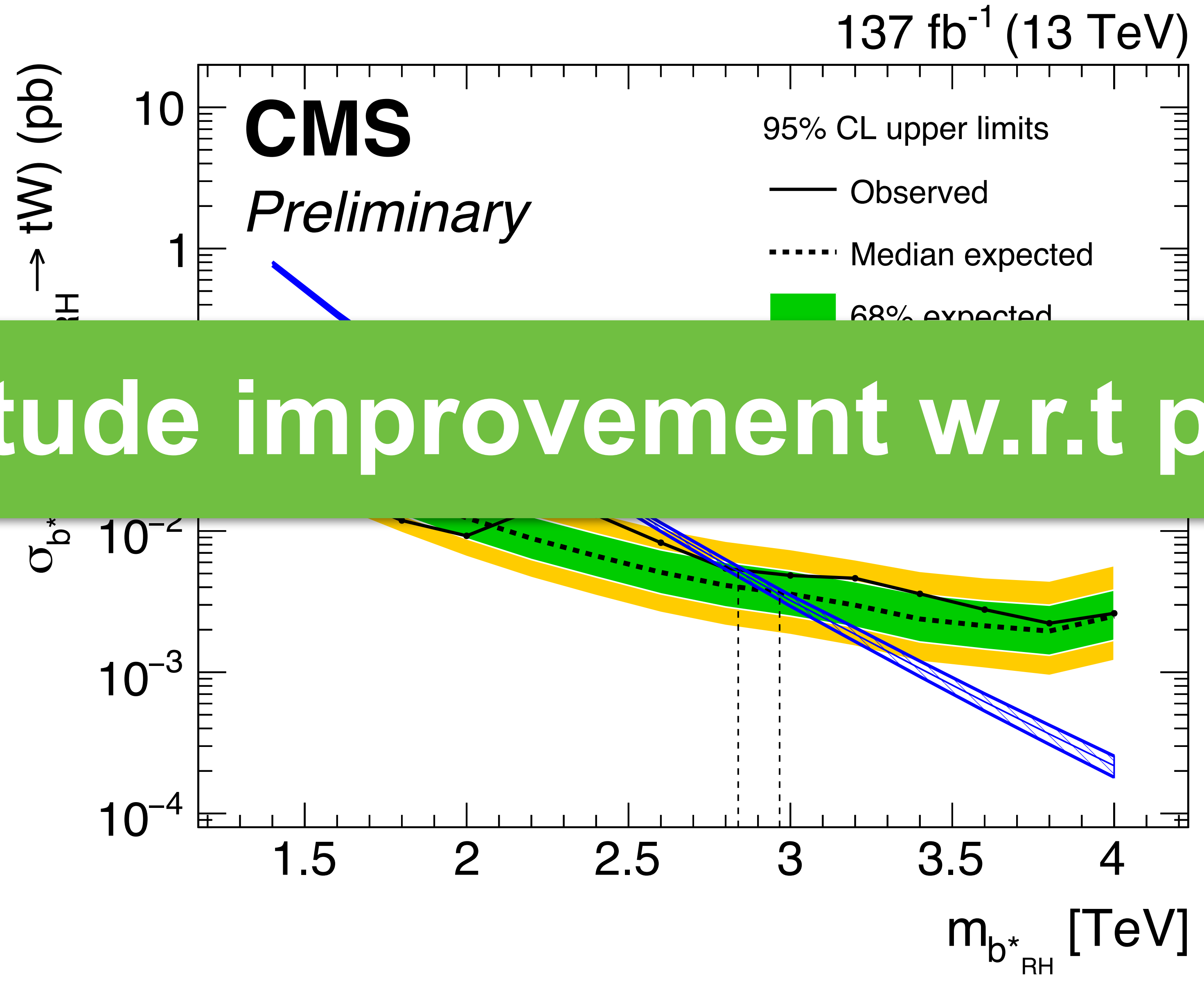
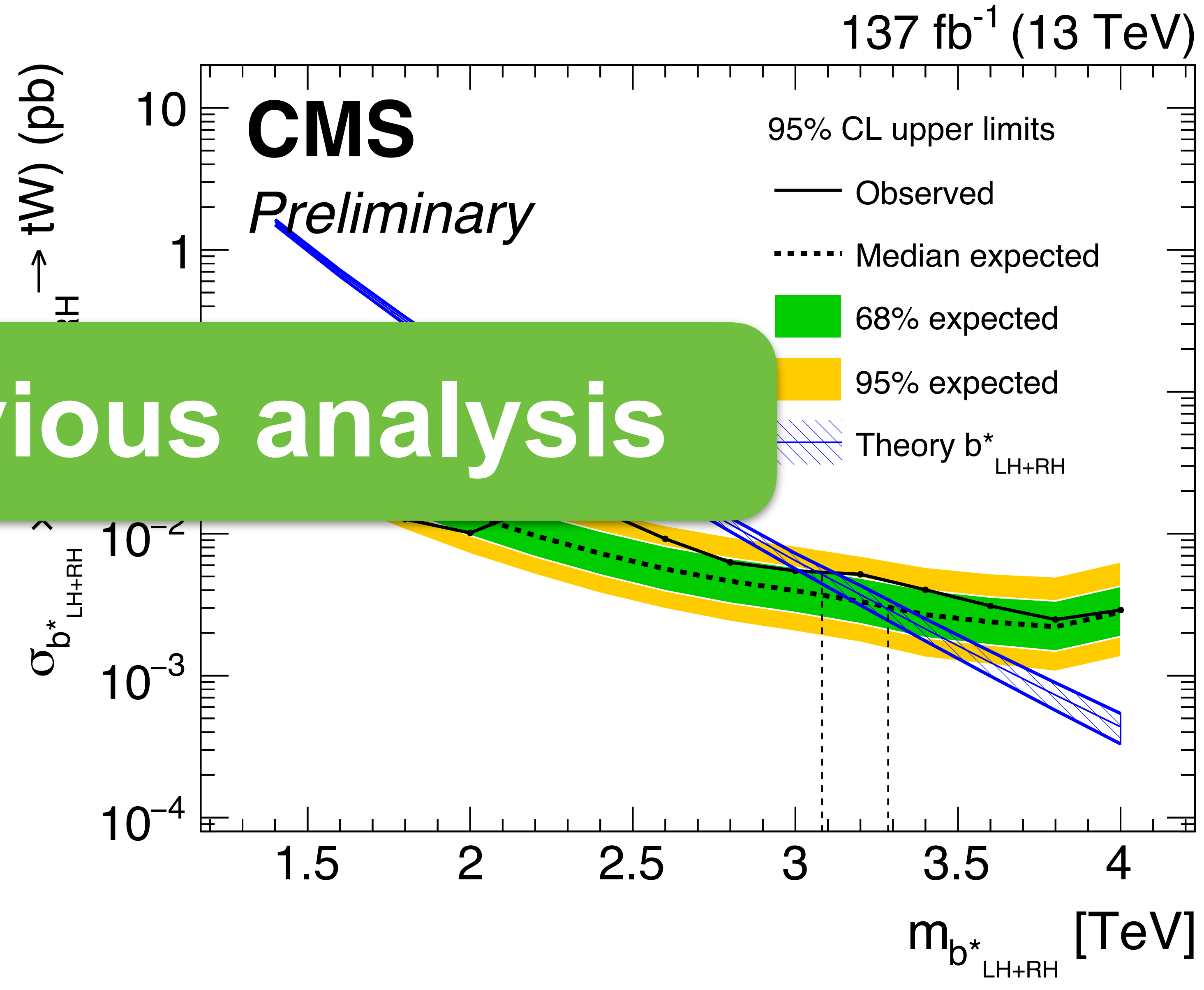


Vector-like



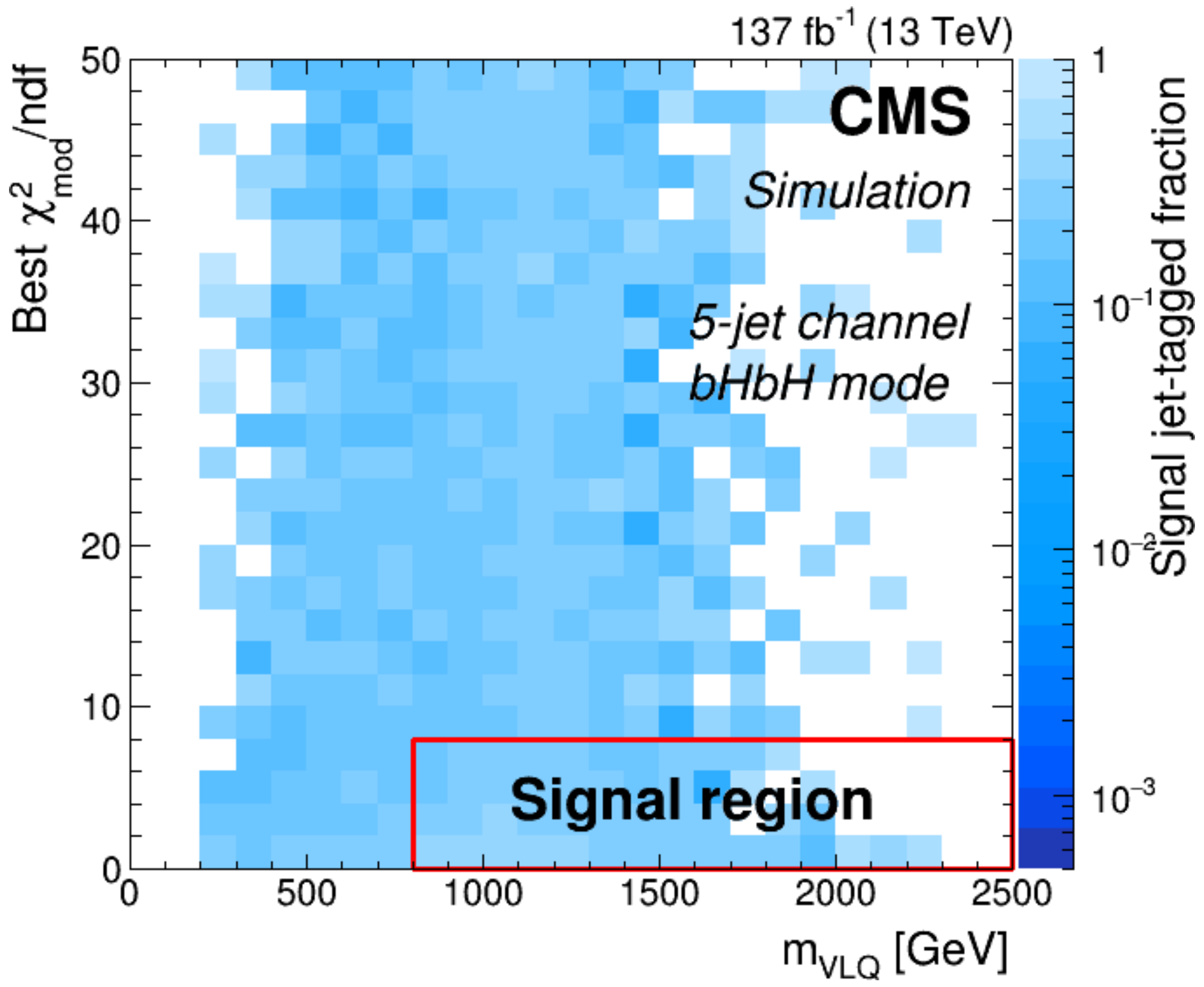
Order of magnitude improvement w.r.t previous analysis

Limits — and now what?

Ensuring analysis long-term impact and collaborating with theory

Phys. Rev. D 102 (2020) 112004

Digitised results?

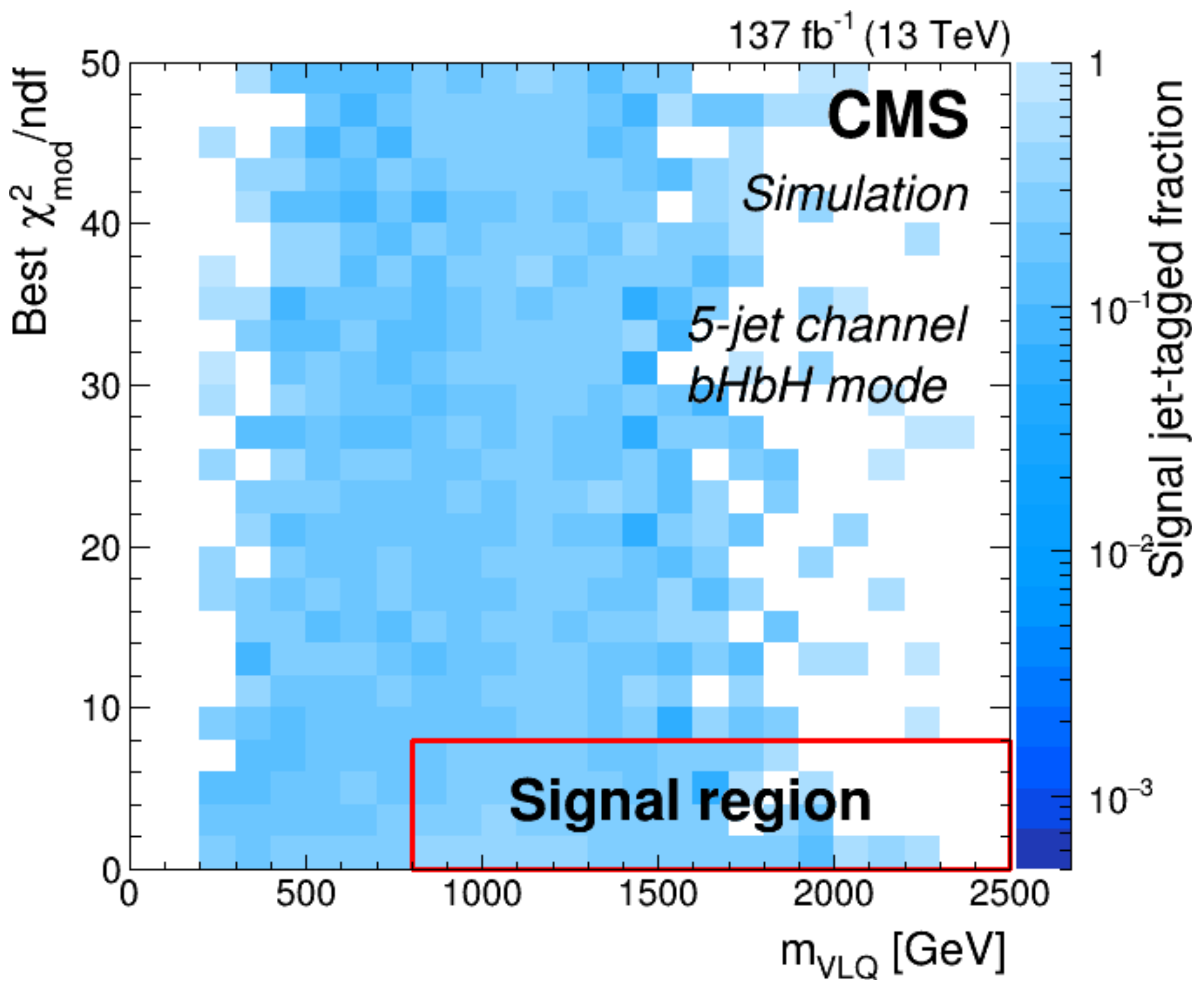


Note: Can also make Rivet analysis available

Phys. Rev. D 102 (2020) 112004

Digitised results?

- The figures that are part of a paper are published as images
- Reading off values can be tedious
  - Note: There are tools such as WebPlotDigitizer that help with that



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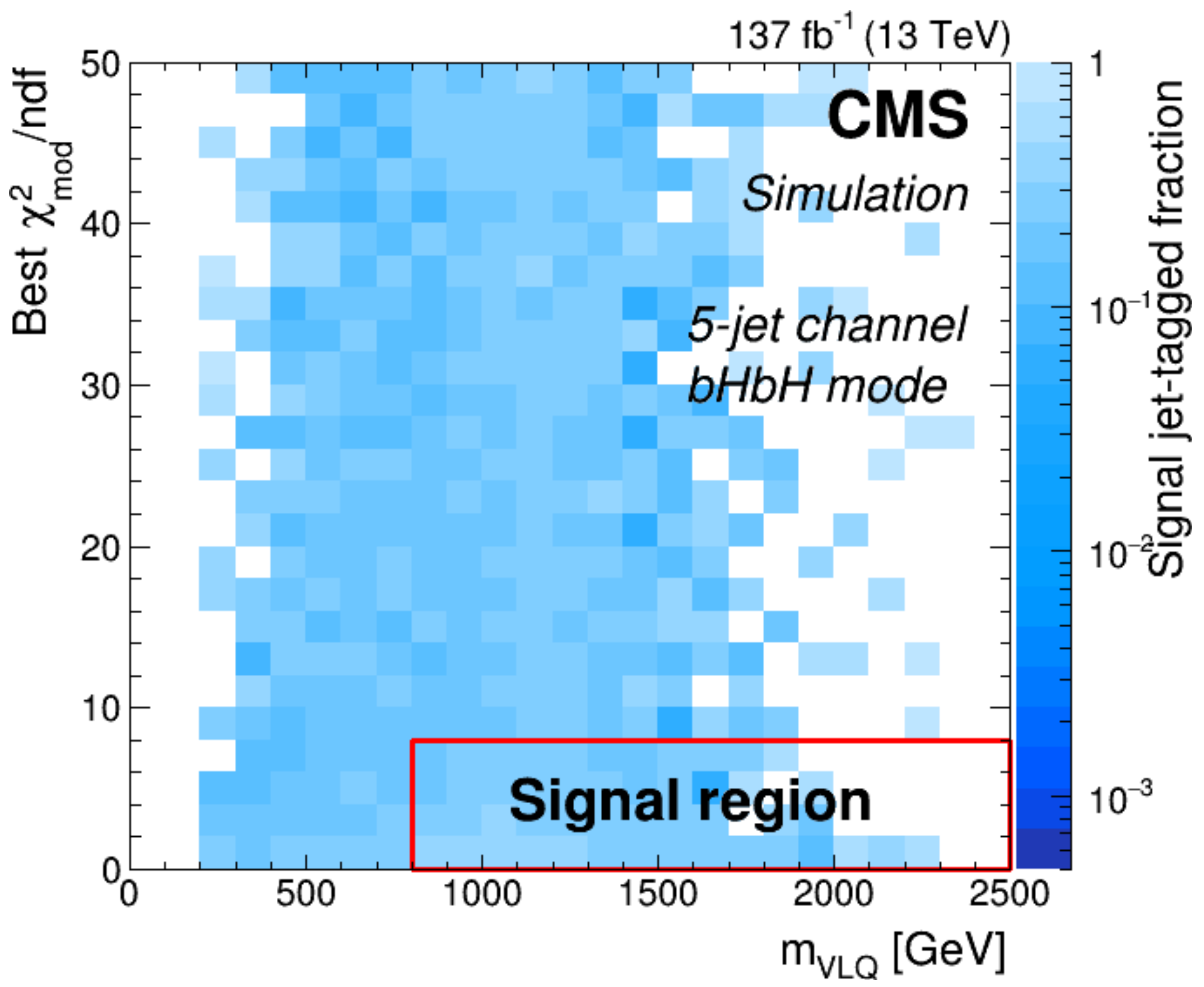
- Better: Provide digitised versions of plots and tables
  - Analyst most likely the only person with those at hand
- For High Energy Physics: HEPData portal
  - Use e.g. hepdata_lib Python library to create a submission

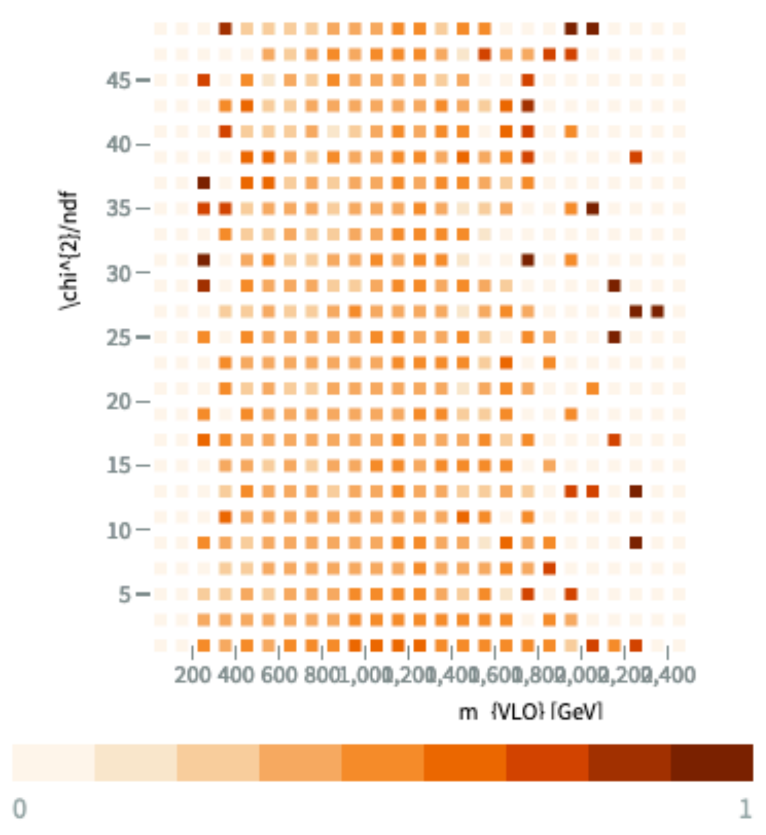


Showing 50 of 625 values

Show All 625 values

SQRT(S)		13 TeV
LUMINOSITY		137 fb^{-1}
m_{VLQ} [GeV]	χ^2/ndf	Jet Tag Efficiency
50.0	1.0	0.0
50.0	3.0	0.0
50.0	5.0	0.0
50.0	7.0	0.0
50.0	9.0	0.0
50.0	11.0	0.0
50.0	13.0	0.0

Visualize



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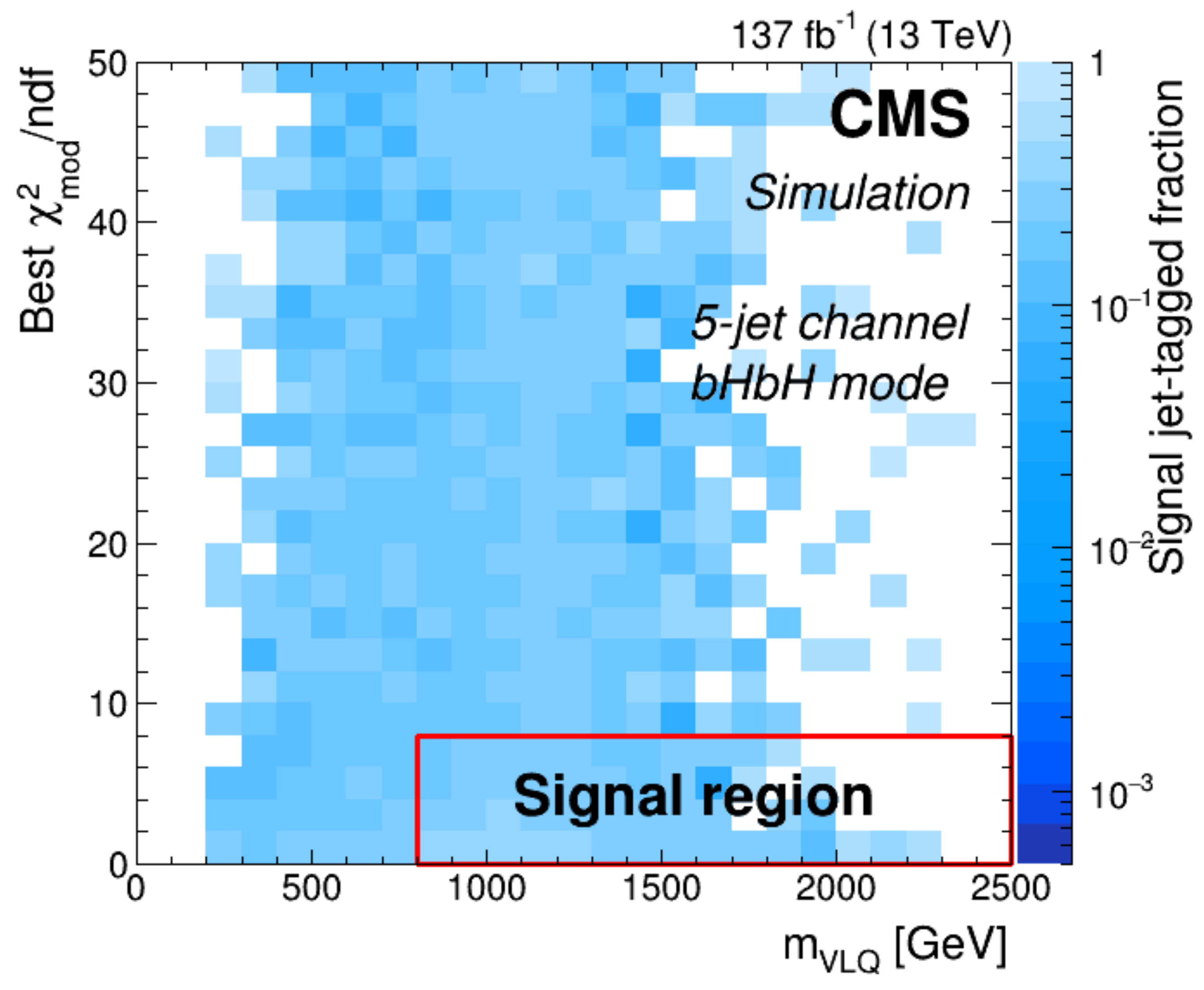
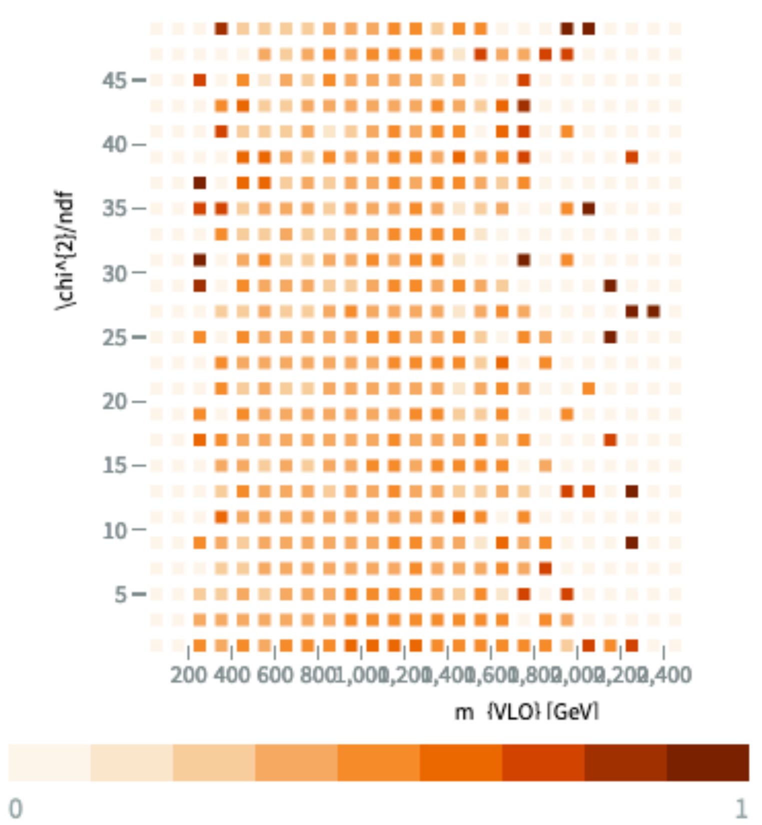


Anyone can reproduce the plot!

values

50.0	1.0	0.0
50.0	3.0	0.0
50.0	5.0	0.0
50.0	7.0	0.0
50.0	9.0	0.0
50.0	11.0	0.0
50.0	13.0	0.0

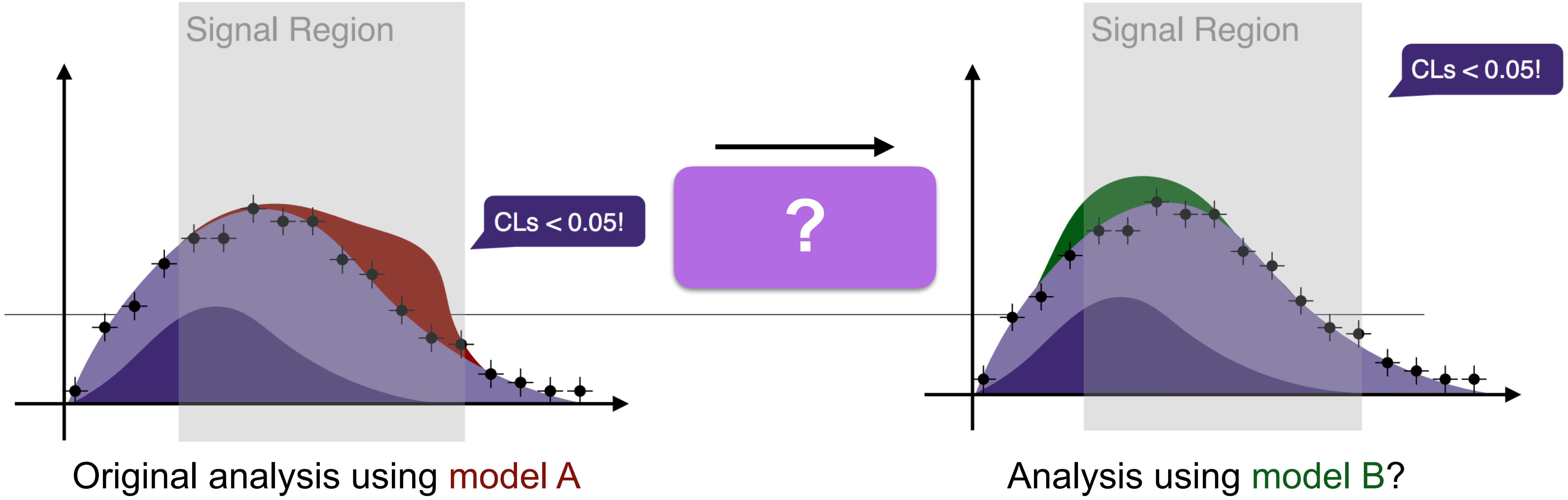
Visualize



Note: Can also make Rivet analysis available

Reinterpretation

- We try to interpret our experimental results in a breadth of theoretical models and frameworks
- However:
  - New models are continuously being developed and could be quite different
  - There can be surprises in the data that “motivate” to take another look (remember the 2015 ɣɣ excess?)



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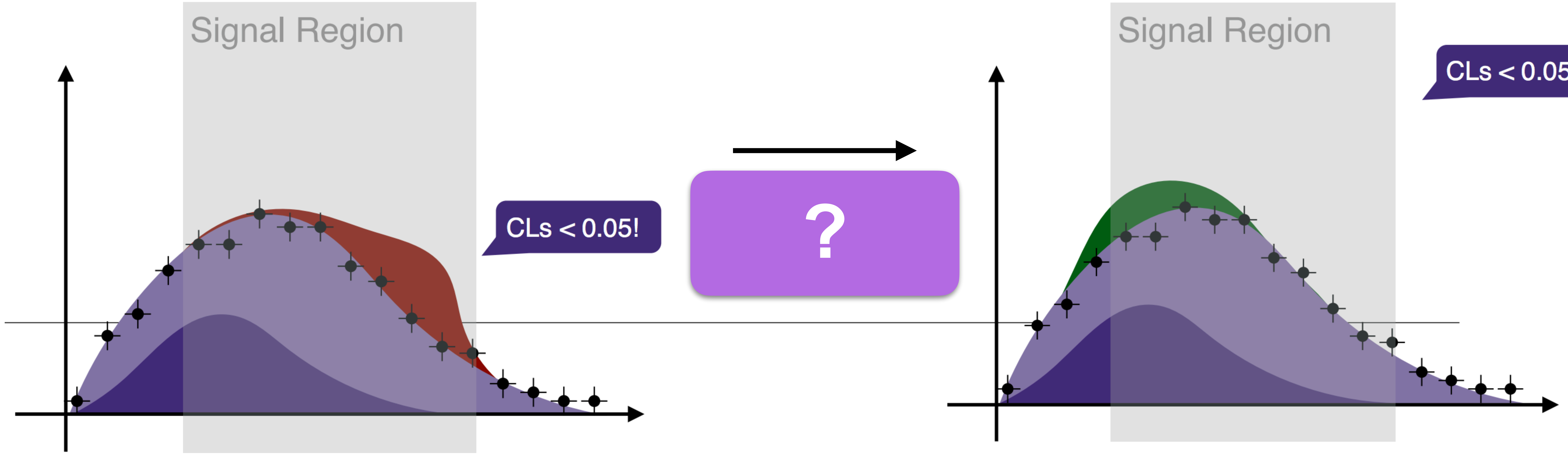


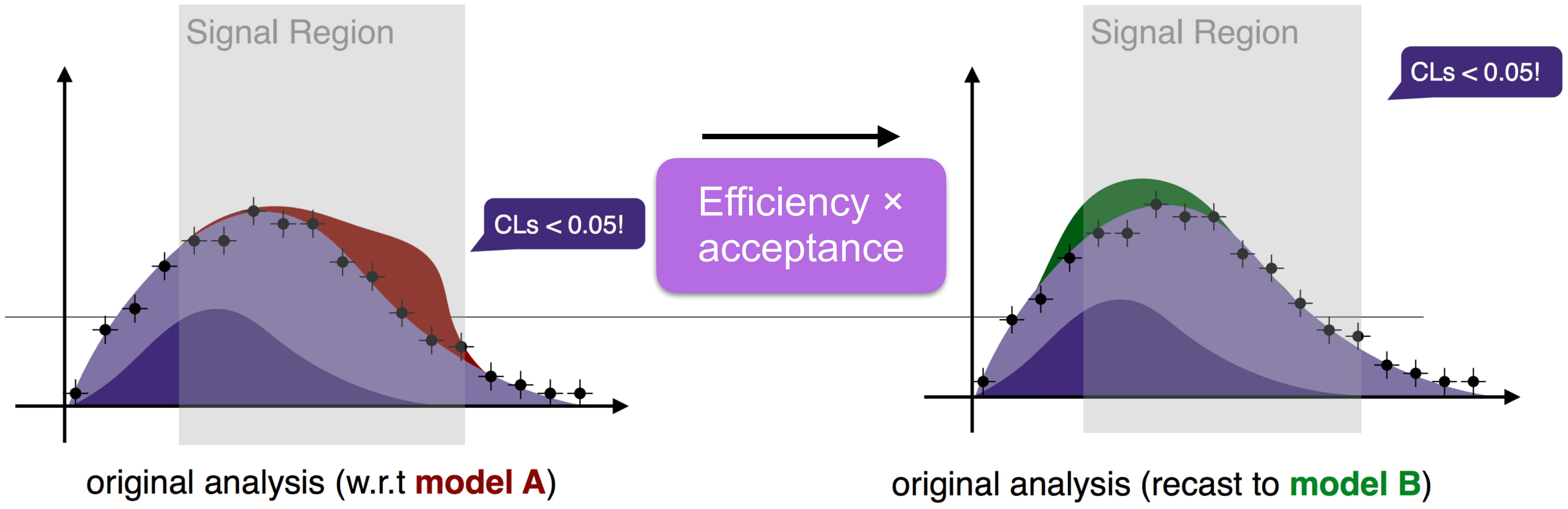
Original analysis using model A

Analysis using model B?

How to make sure a reinterpretation is possible?

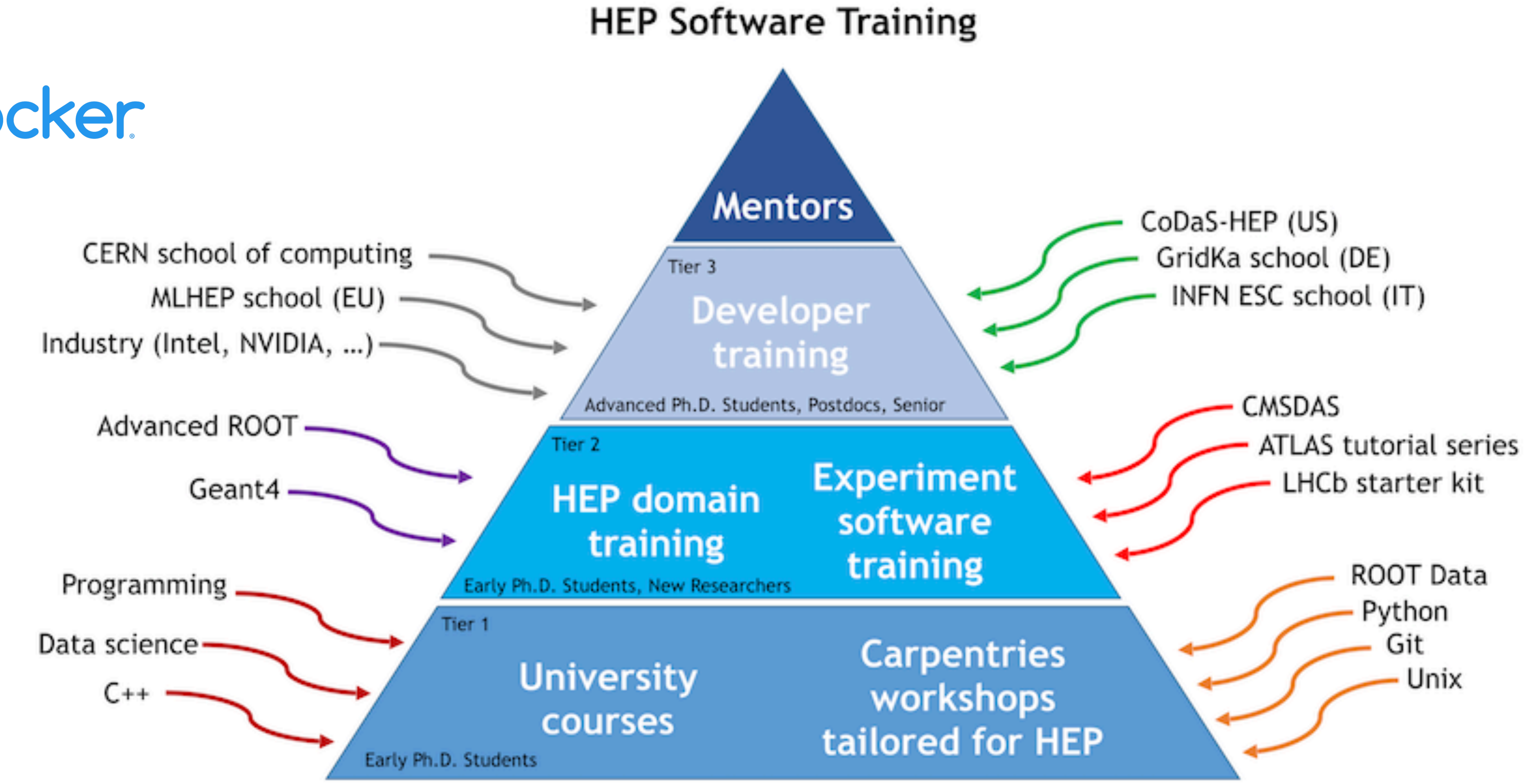
Preparing for reinterpretation

- A new theory model only changes the posited signal, less often the background processes
  - Do not need to process the data and backgrounds again
  - Probably background model won't have to be changed either
- Need to estimate new signal's selection efficiency × acceptance
  - Does the paper publication contain enough information to do that?
- Optimal approach: preserve overall analysis setup



Tools for preservation and reusability

- Tools for preservation/reusability:
  - Version-controlled software (Git) including automated checks
  - Containerised software images (Docker)
  - Automated workflows
- Training available via HEP Software Foundation, LPC hands-on training sessions (HATS), experiment-specific trainings
- Tools being developed at CERN:
  - CERN Analysis Preservation Portal
  - REANA (Reusable analysis platform)



Performing a reinterpretation

Theory model/LHE file

CMS event generation + simulation step

CMS digitisation step

CMS reconstruction step

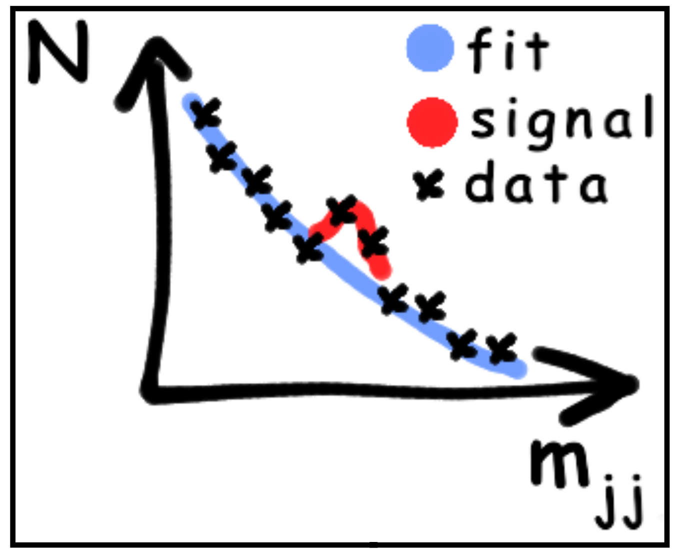
ntuplisation/selection

Statistical analysis

detector geometry/ conditions database

CMS specific

Analysis specific



See also ATLAS Analysis Preservation efforts

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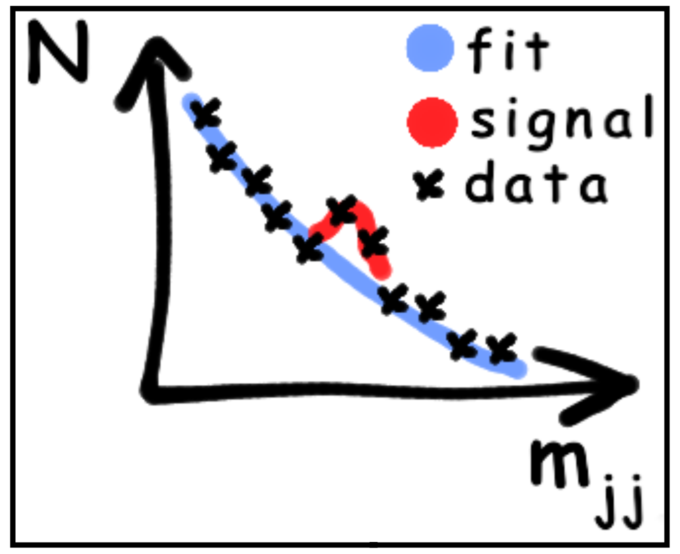
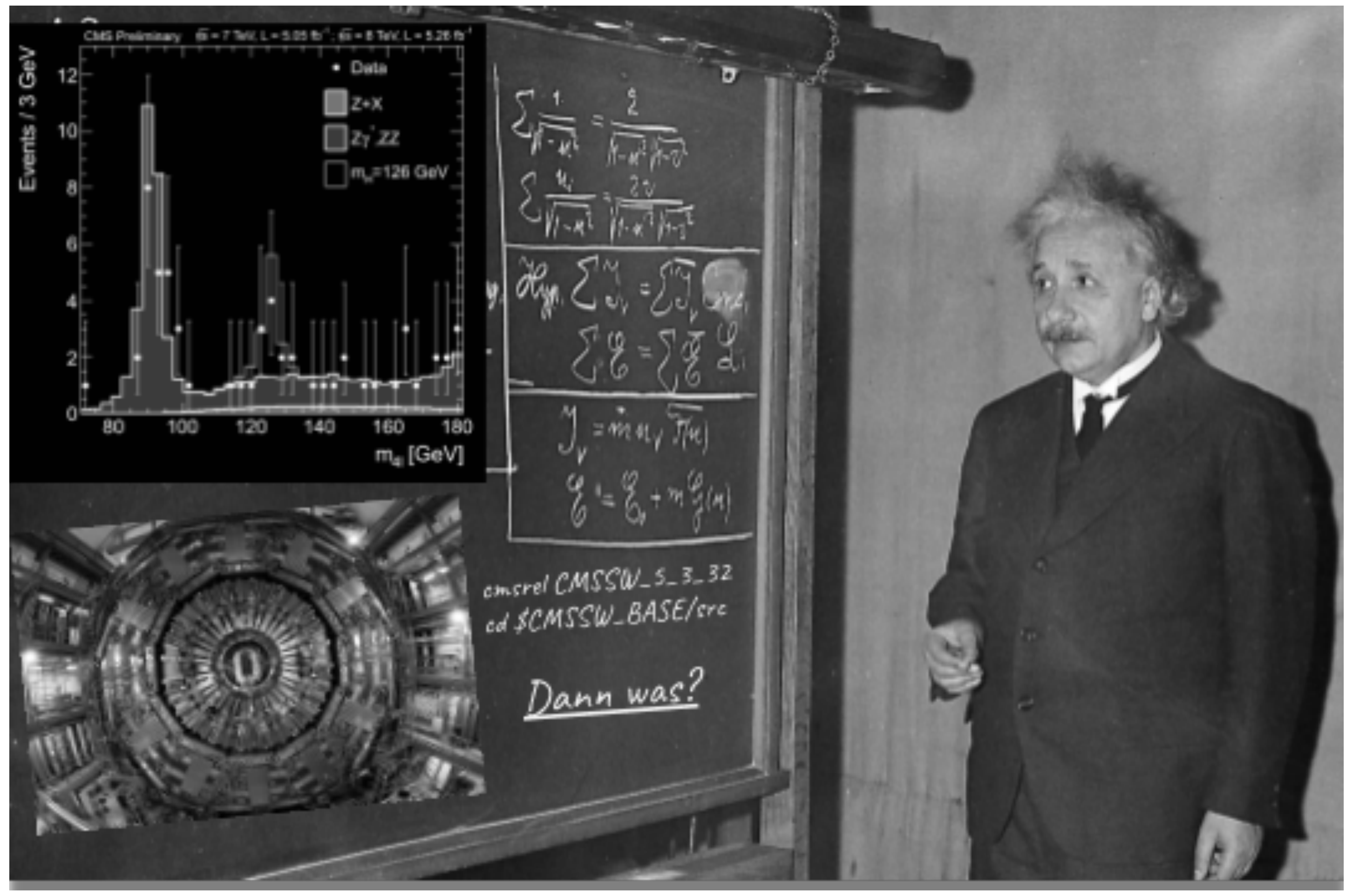


Theorists are welcome to send us models to test on existing analyses!

See also ATLAS Analysis Preservation efforts

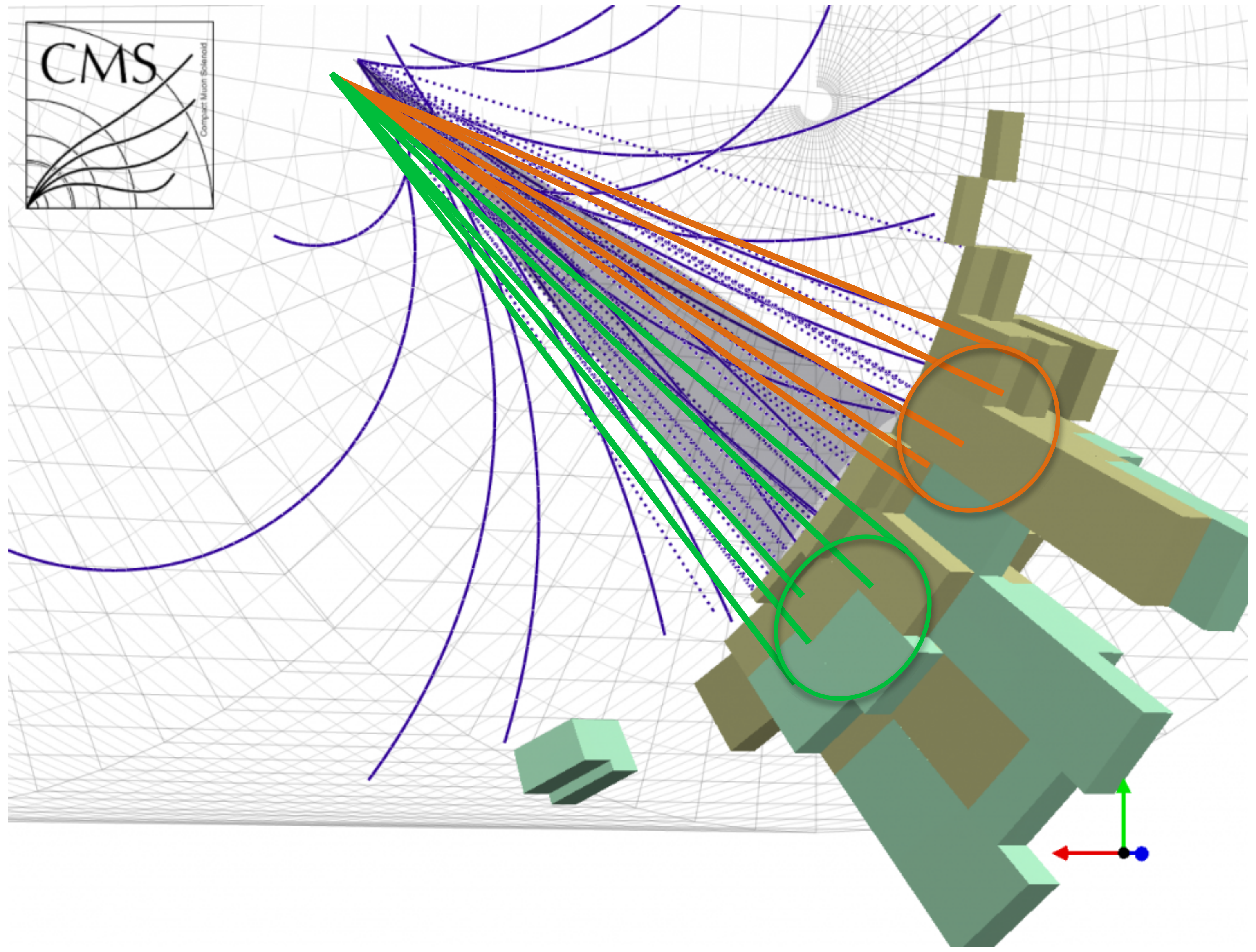
Reinterpretation with Open Data

- Theorists (and anyone else) can also use CMS data
- More than 2 PB available (mostly Run-1) from the CERN Open Data Portal
- Using the data can be a challenge
  - Training available through CMS Open Data Workshop for Theorists (Sep/Oct 2020)
  - Includes using public cloud offerings for large-scale data analysis



- More good news: New Open Data policy by the LHC experiments
  - All experiments will make data for scientific use available starting five years after data taking

Summary and conclusions



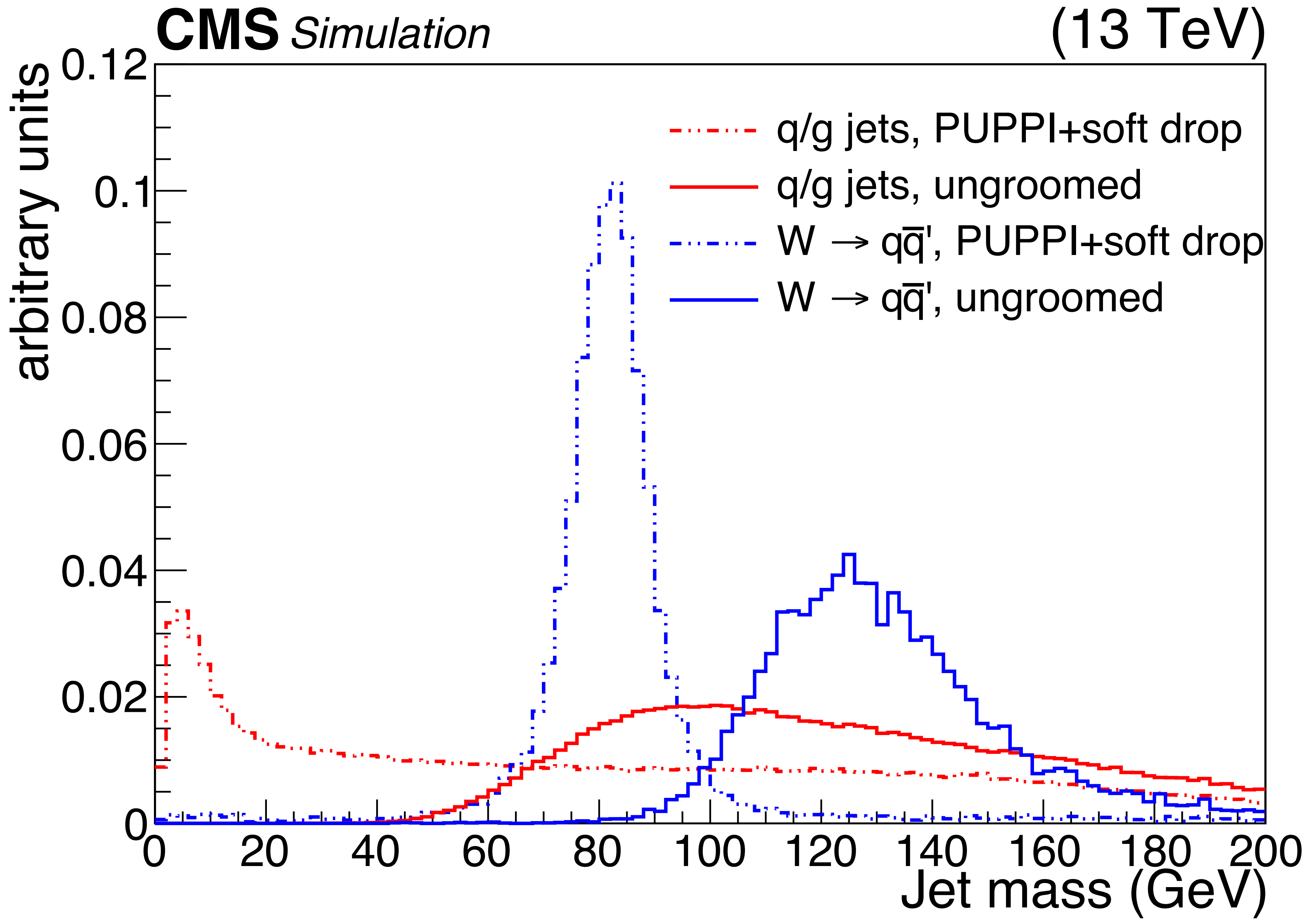
- Jet substructure enables the search for extremely rare and heavy resonances
- Several new CMS analyses using 2016-18 data becoming public pushing the boundaries
  - Only presented the latest two results
- Performing reusable analyses has a long-term impact on the field

Example: “modified mass-drop tagger”

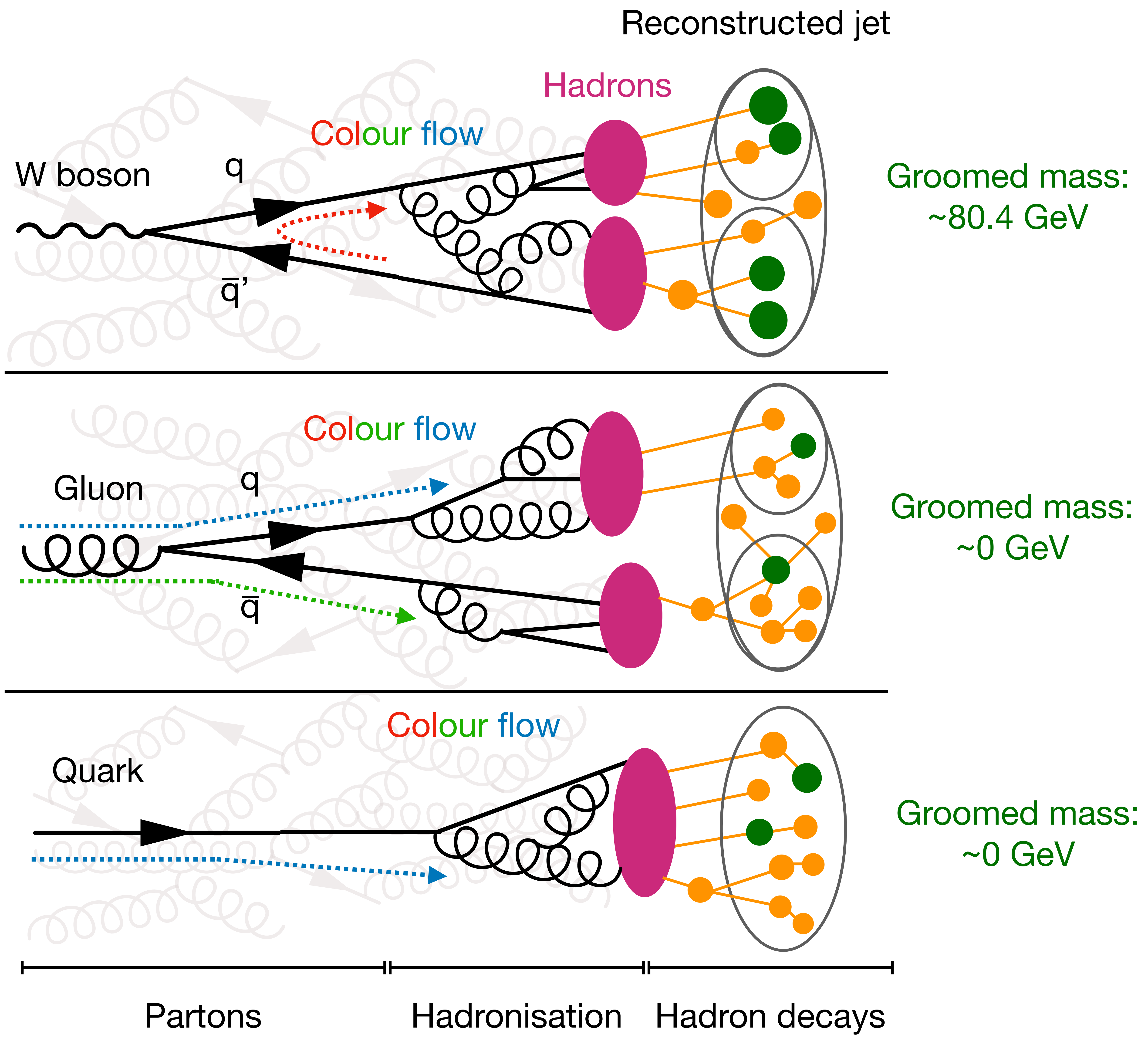
- Recluster jet constituents using Cambridge-Aachen jet algorithm (based on **spatial separation** only)
- Iteratively break into two subjets
- Remove softer contribution (and continue with harder one) if:

$$\frac{\min(p_{T_1}, p_{T_2})}{p_{T_1} + p_{T_2}} < 0.1 \text{ (CMS choice)}$$

- Stop otherwise



Undoing hadronisation



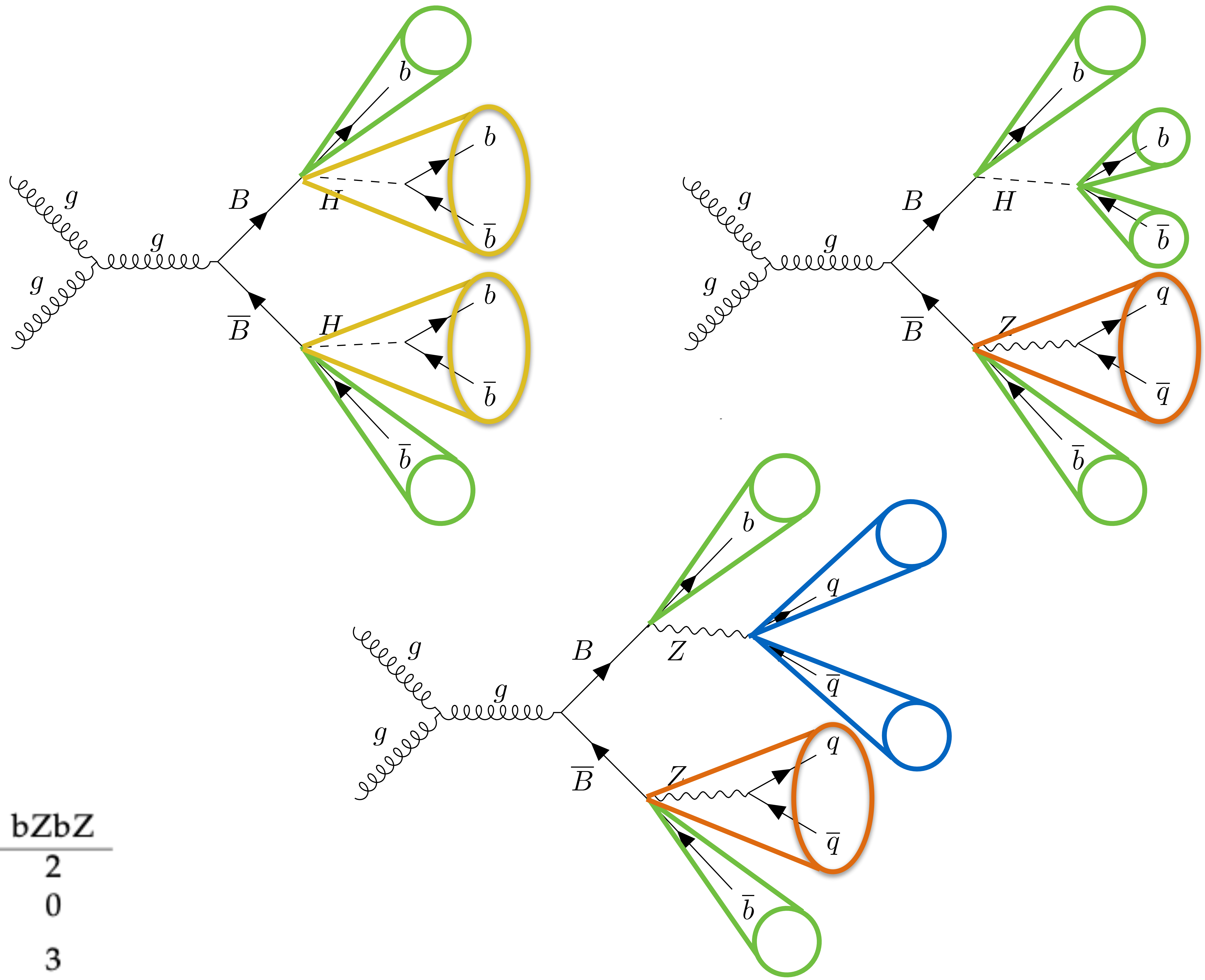
Search for bottom-type, vector-like quark pair production

> Topology:

- Each B decays to a b quark and a Z or Higgs boson
- Investigate H ➜ bb and Z ➜ qq (incl. bb)

> Selection:

- Select at least 4 AK4 jets, p_T > 30 GeV
- If AK8 jet (pT > 200 GeV) exists close to AK4 jet (ΔR < 0.3) and sufficiently far from a second AK4 jet AK4 jet (ΔR > 0.6), use AK8 jet instead
- Use DeepJet b tag algorithm for AK4 jets
- Double-b tagger (incl. substructure info) for AK8 jets

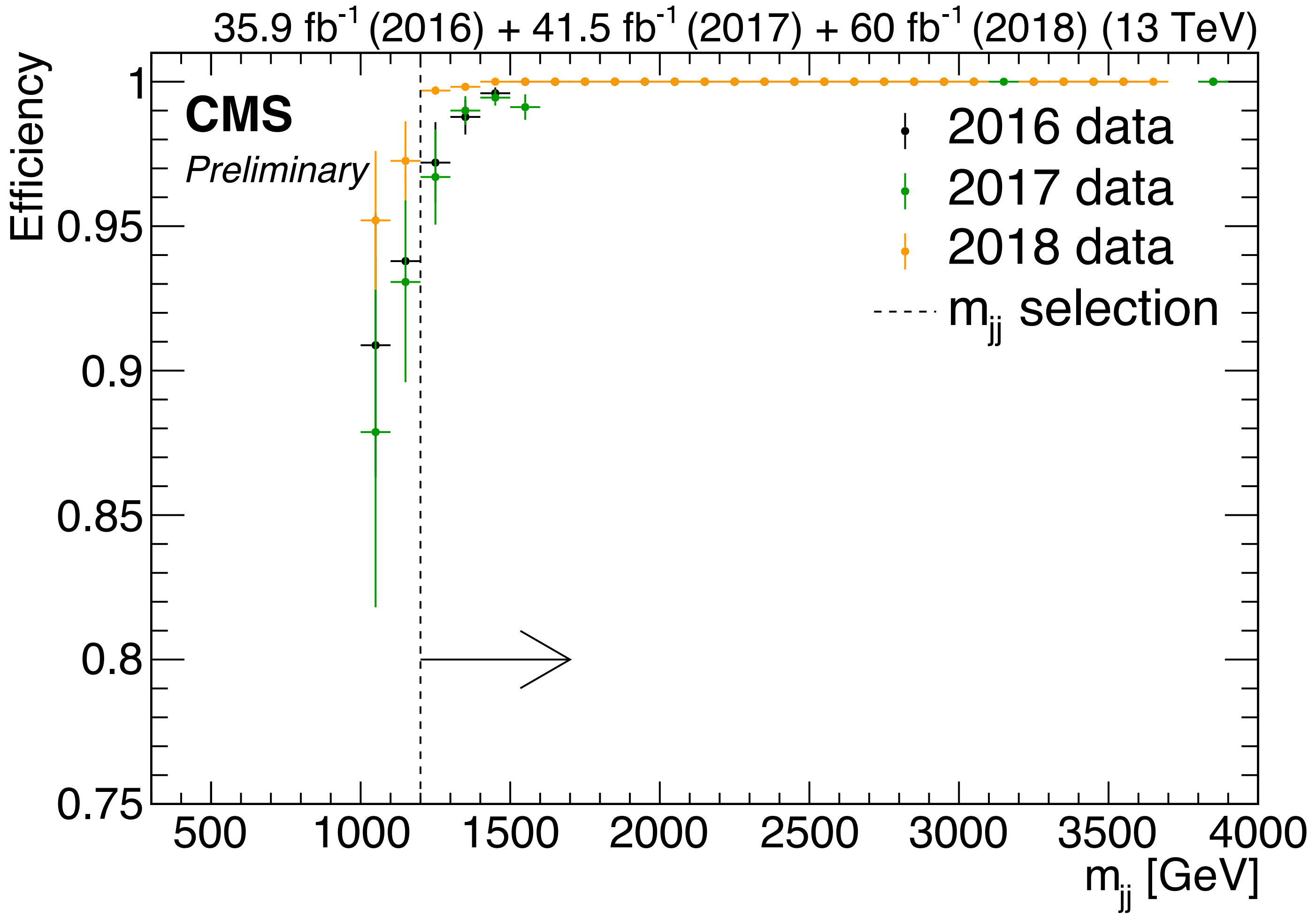


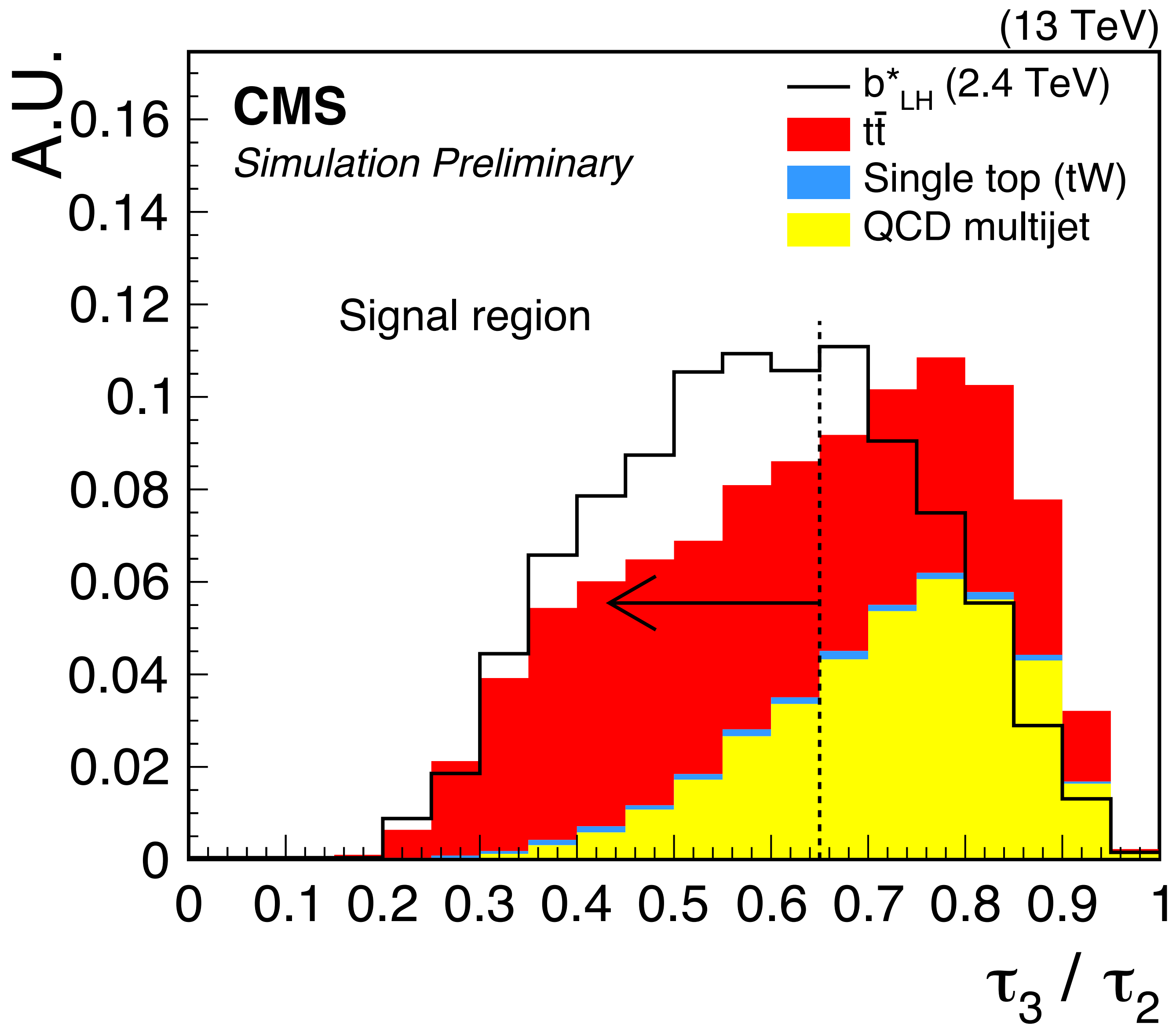
Jet multiplicity	Tag	bHbH	bHbZ	bZbZ
4 jets	Single b	2	2	2
	Double b	1	1	0
5 jets	Single b	3	3	3
	Double b	0	0	0
6 jets	Single b	4	4	3

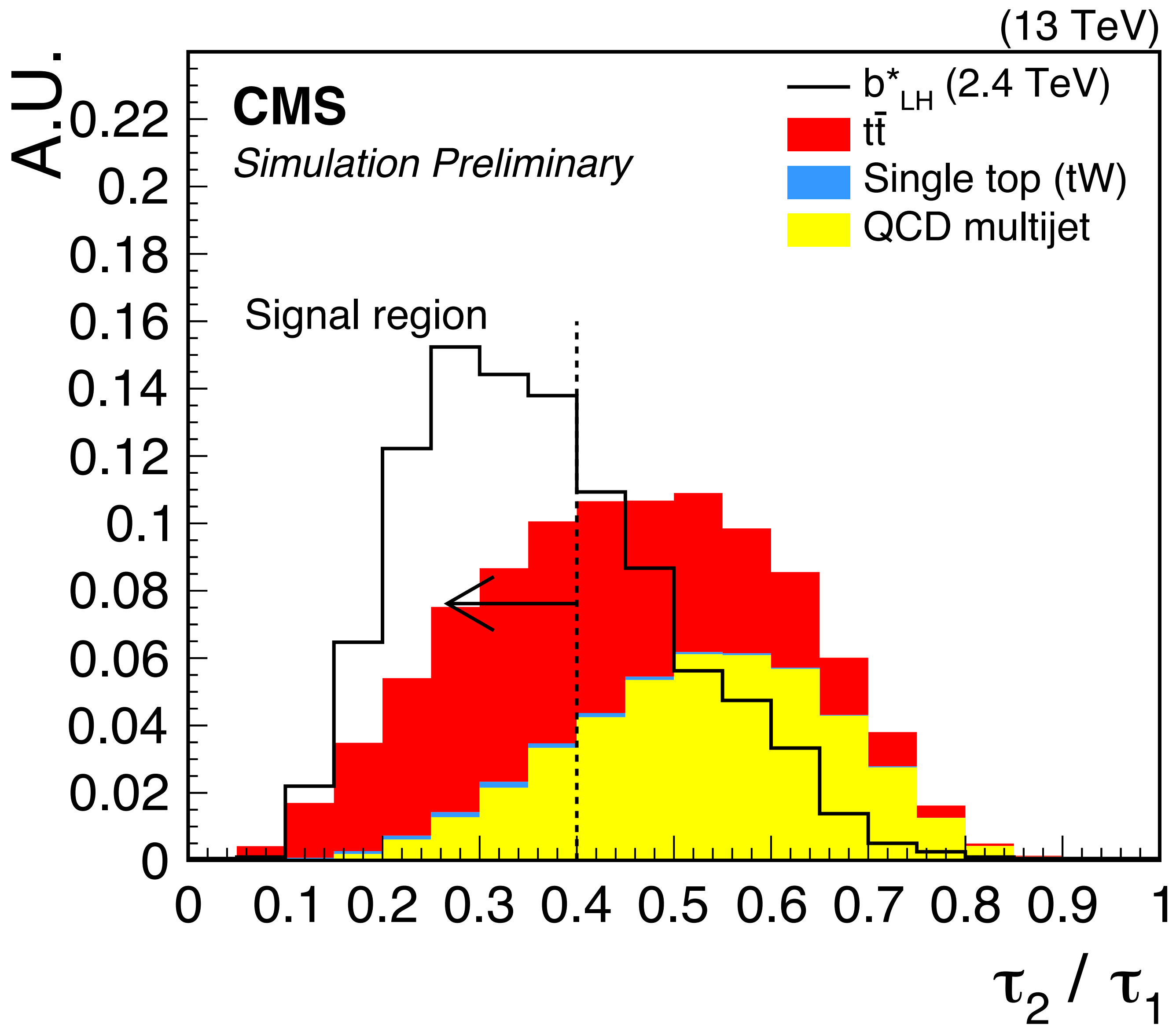
Search for W' ➜ tb: uncertainties

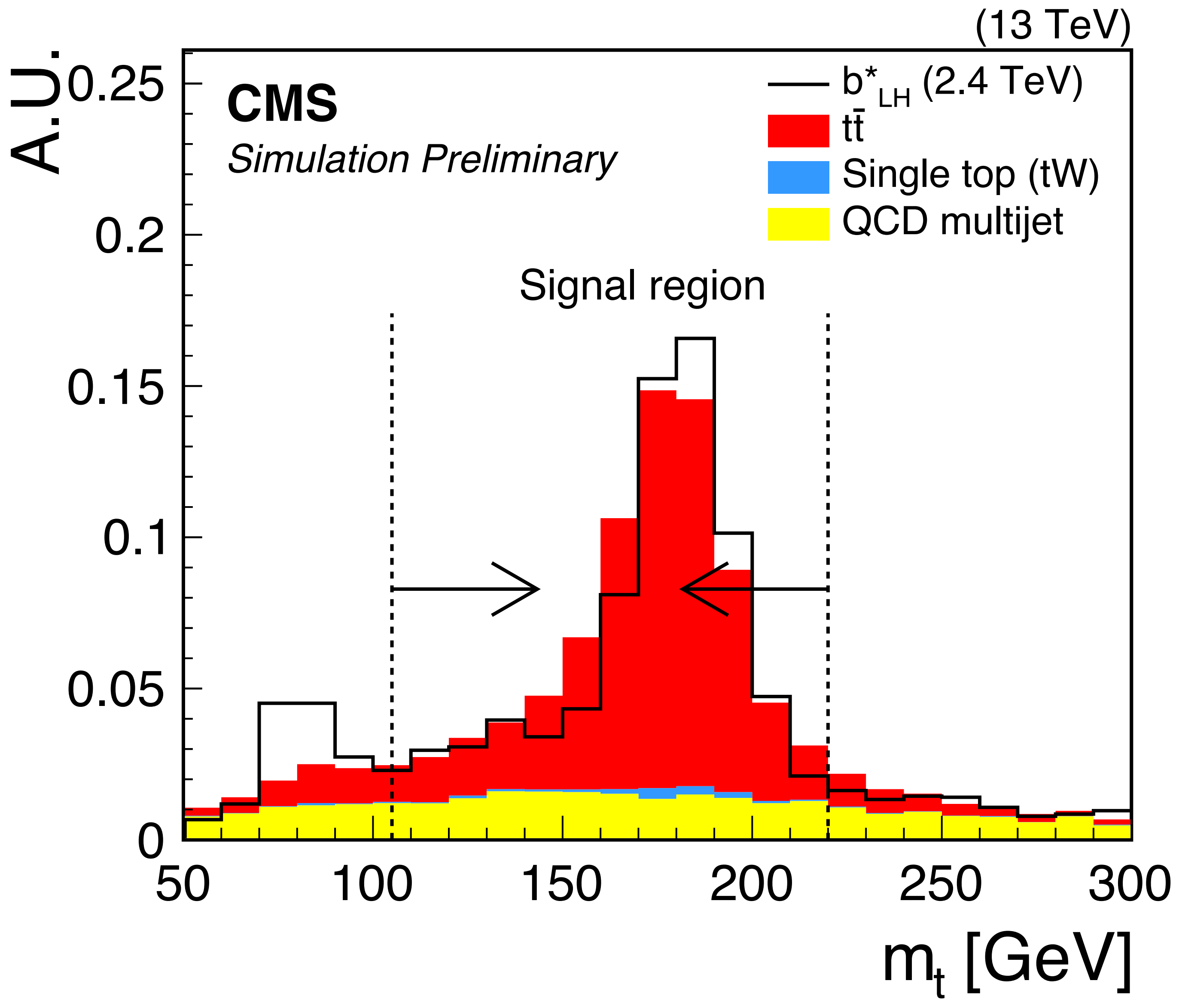
Systematic source	Correlation between different years	Impact
Luminosity	No correlation	0.5%
$t\bar{t}$ cross section	Full correlation	0.1%
Single top cross section	Full correlation	0.2%
JES	No correlation	0.8%
JER	No correlation	$< 0.1\%$
B tagging scale factor	No correlation	$< 0.1\%$
top quark tagging scale factor	No correlation	0.2%
Pileup	Full correlation	$< 0.1\%$
Prefire correction	No correlation	$< 0.1\%$
$\mathrm{t\bar{t}}$ normalization and slope	No correlation	0.2%
Scale (μ_R and μ_F)	Full correlation	0.3%
PDF	Full correlation	$< 0.1\%$
Pass-to-fail ratio	No correlation	0.2%
Alternative function of pass-to-fail ratio	No correlation	0.1%
Non-closure uncertainty	No correlation	0.3%
B candidate m_{SD} correction	No correlation	0.9%

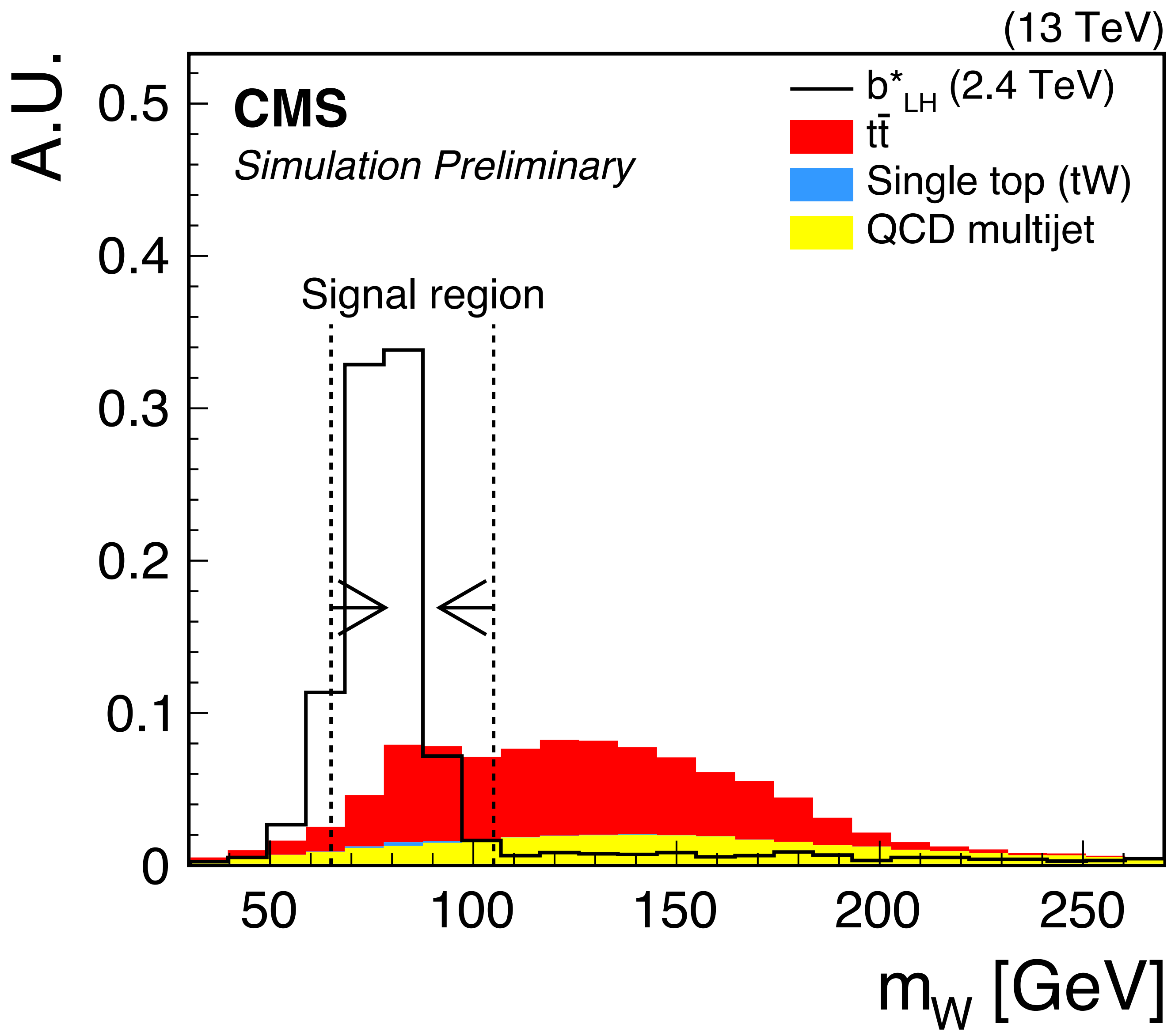
Search for b* ➜ tW: additional plots

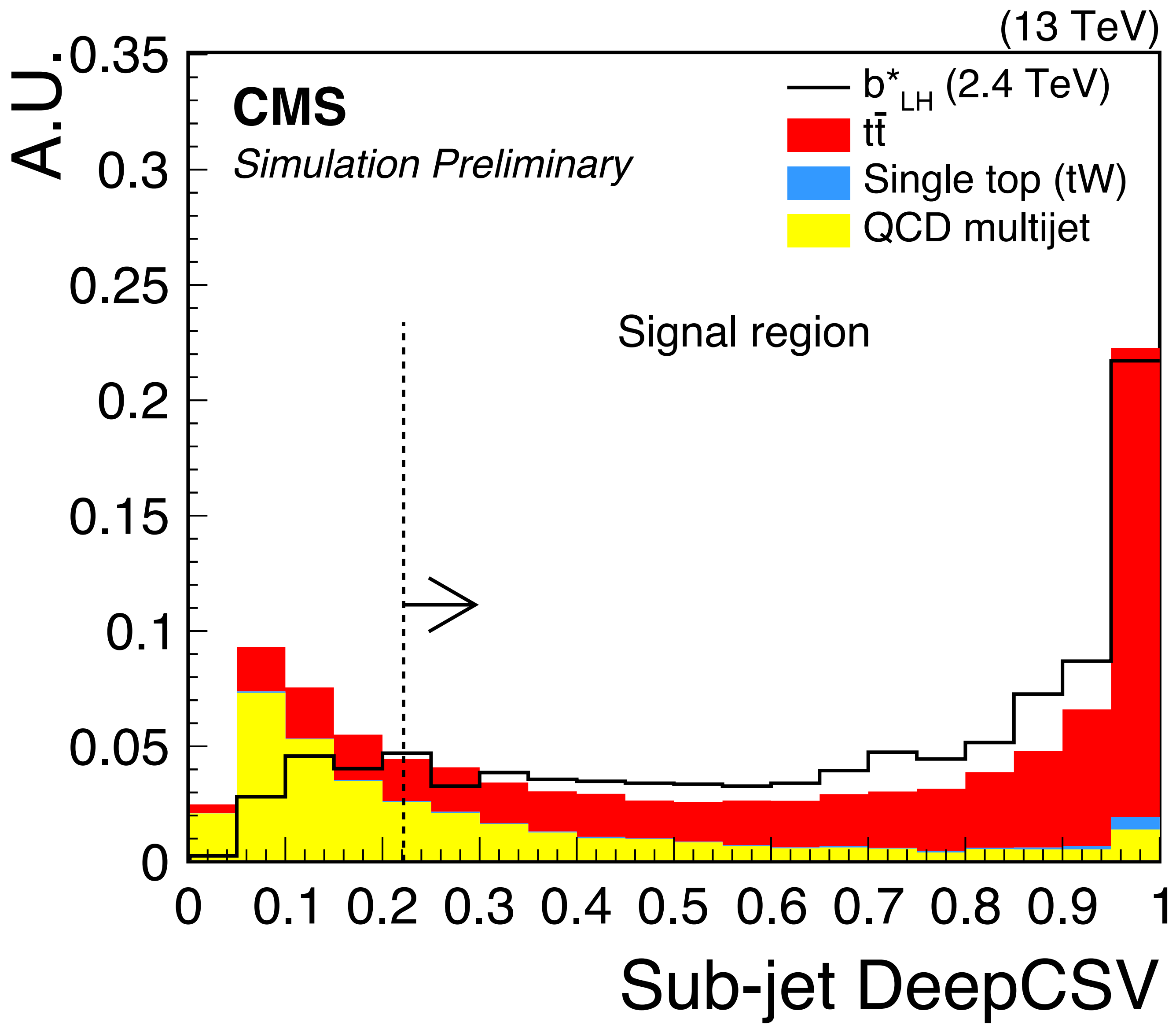












Search for b* ➜ tW: uncertainties

Source	Uncertainty	Samples	Impact (up/down)
$t\bar{t}$ cross section	±20%	$t\bar{t}$	−4.6/ +4.4%
Single top cross section	±30%	single top	+1.2/ −1.4%
Integrated Luminosity	±1.8%	$t\bar{t}$, single top, signal	+1.6/ −1.1%
Pileup	Shape (σ_{mb})	$t\bar{t}$, signal, single top	+0.3/ −0.2%
Prefire	Shape (p_T, η)	$t\bar{t}$, signal, single top	+0.0/ +0.1%
Jet energy scale	Shape (p_T)	$t\bar{t}$, signal, single top	+0.3/ −0.6%
Jet energy resolution	Shape (p_T, η)	$t\bar{t}$, signal, single top	−0.4/ −0.5%
Jet mass scale	Shape (m_W)	$t\bar{t}$, signal, single top	−0.1/ −0.0%
Jet mass resolution	Shape (m_W)	$t\bar{t}$, signal, single top	+0.0/ +0.9%
W tagging	Shape (p_T)	signal, single top	+0.9/ −0.9%
W tagging: p_T extrapolation	Shape (p_T)	signal, single top	+4.9/ −4.9%
Top tagging, merged	Shape (p_T)	$t\bar{t}$, signal, single top	+0.2/ −0.2%
Top tagging, semimerged	Shape (p_T)	$t\bar{t}$, signal, single top	+1.1/ −0.9%
Top tagging, not merged	Shape (p_T)	$t\bar{t}$, signal, single top	−0.1/ +0.1%
Trigger	Shape (H_T)	$t\bar{t}$, signal, single top	+0.3/ −0.4%
Top quark p_T correction - α	Shape (p_T)	$t\bar{t}$	−0.3/ +0.3%
Top quark p_T correction - β	Shape (p_T)	$t\bar{t}$	−3.9/ +3.5%
PDF	Shape (m_t, m_{tW})	signal	+0.1/ −0.1%
KDE bandwidth	Shape (m_t, m_{tW})	multijet (from simulation)	−1.2/ +0.2%
$R_{ratio}(m_t, m_{tW})^{SR} p_0$	Shape (m_t, m_{tW})	multijet (from data)	−4.4/ +0.0%
$R_{ratio}(m_t, m_{tW})^{SR} p_1$	Shape (m_t, m_{tW})	multijet (from data)	−2.0/ +2.2%
$R_{ratio}(m_t, m_{tW})^{SR} p_2$	Shape (m_t, m_{tW})	multijet (from data)	+0.9/ −0.8%
$R_{ratio}(m_t, m_{tW})^{SR} p_3$	Shape (m_t, m_{tW})	multijet (from data)	+18.6/ −18.8%
$R_{ratio}(m_t, m_{tW})^{t\bar{t}} p_0$	Shape (m_t, m_{tW})	multijet (from data)	−0.4/ +0.6%
$R_{ratio}(m_t, m_{tW})^{t\bar{t}} p_1$	Shape (m_t, m_{tW})	multijet (from data)	−0.4/ +0.6%
$R_{ratio}(m_t, m_{tW})^{t\bar{t}} p_2$	Shape (m_t, m_{tW})	multijet (from data)	+0.5/ −0.6%
$R_{ratio}(m_t, m_{tW})^{t\bar{t}} p_3$	Shape (m_t, m_{tW})	multijet (from data)	−0.6/ +0.6%