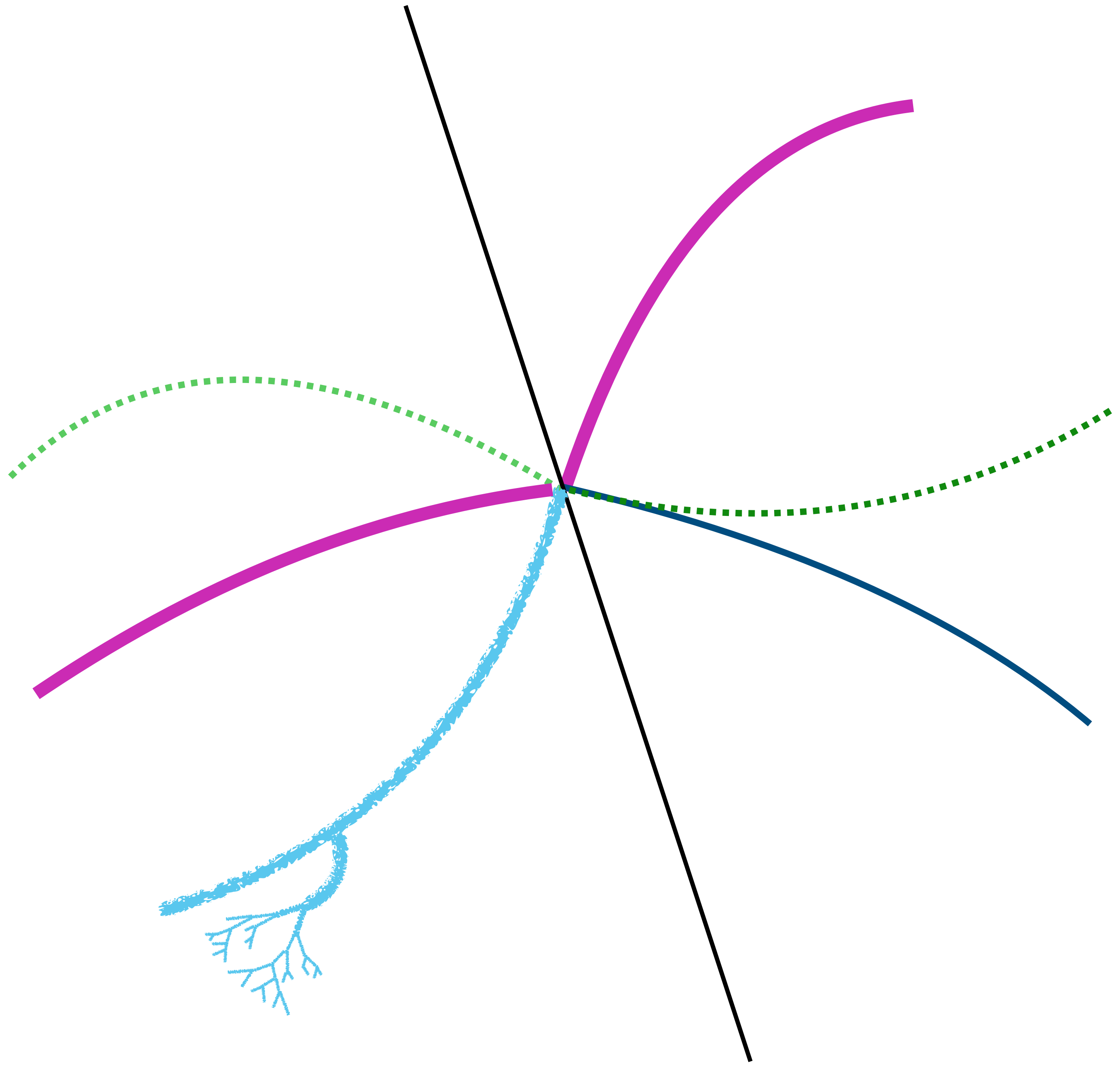
Searching for new physics using W & Z bosons in the ATLAS detector

Dylan van Arneman

Nikhef Jamboree
May 2024



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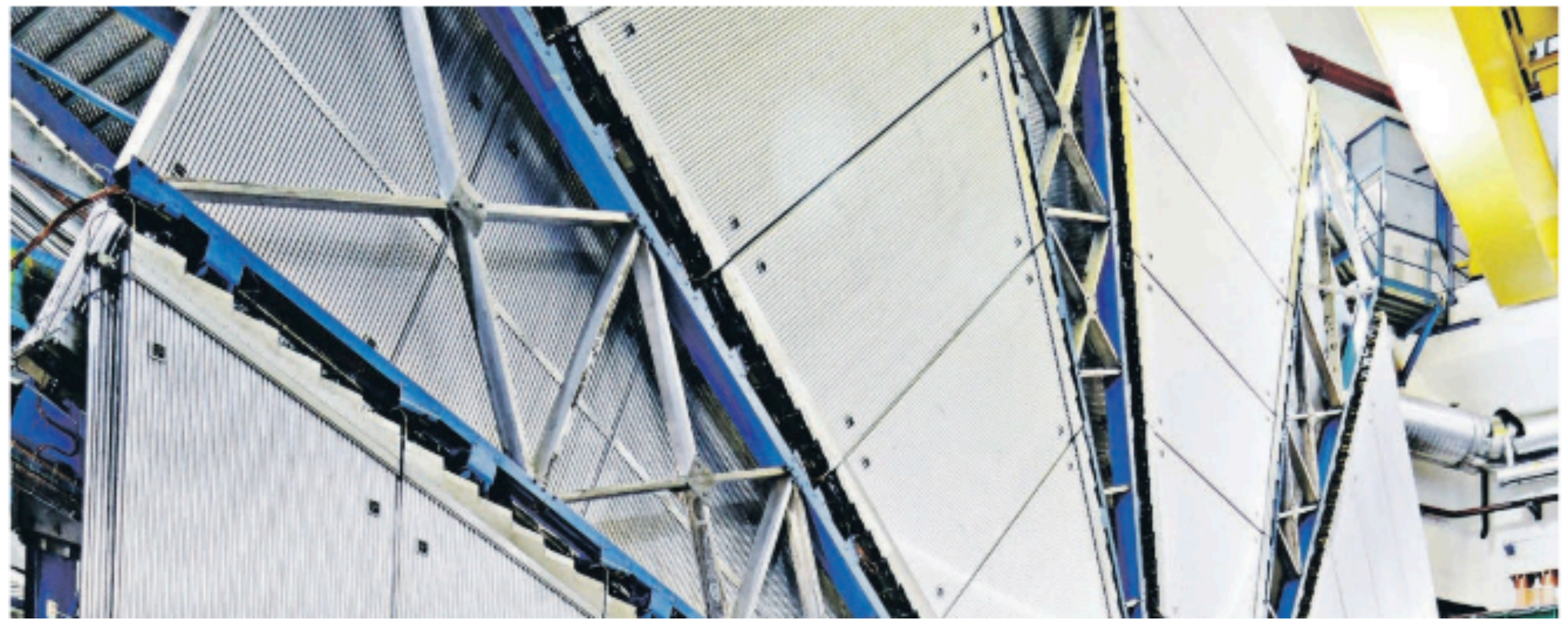
HET PAROOL ZATERDAG 20 APRIL 2024 Het Parool NIEUWS 11

Wetenschap Speuren naar deeltjes in een onbekende dimensie

'Wat ik zoek, bestaat misschien niet eens'

Dylan van Arneman gaat een paar keer per jaar naar de ondergrondse deeltjesversneller van Cern in Genève. Een gesprek over zijn



kunnen snel vervallen naar bekende deeltjes. Daarom heb je een machine nodig die heel snel precies kan meten om te zien wat er nou gebeurd is."

Waar bent u zelf naar op zoek?
"Deeltjes met extra dimensies. Die dimensies zijn de richtingen waarin ze kunnen bewegen. Dus naar voren, naar achteren, links, rechts, boven, onder. Daarnaast is tijd ook een dimensie. Er bestaat een idee dat er misschien meer dimensies zijn en dus meer richtingen waarin ze zouden kunnen bewegen. Als deze dimensies zouden bestaan, zou dat ook kunnen betekenen dat er nieuwe deeltjes aan gerelateerd

Se ... & Z

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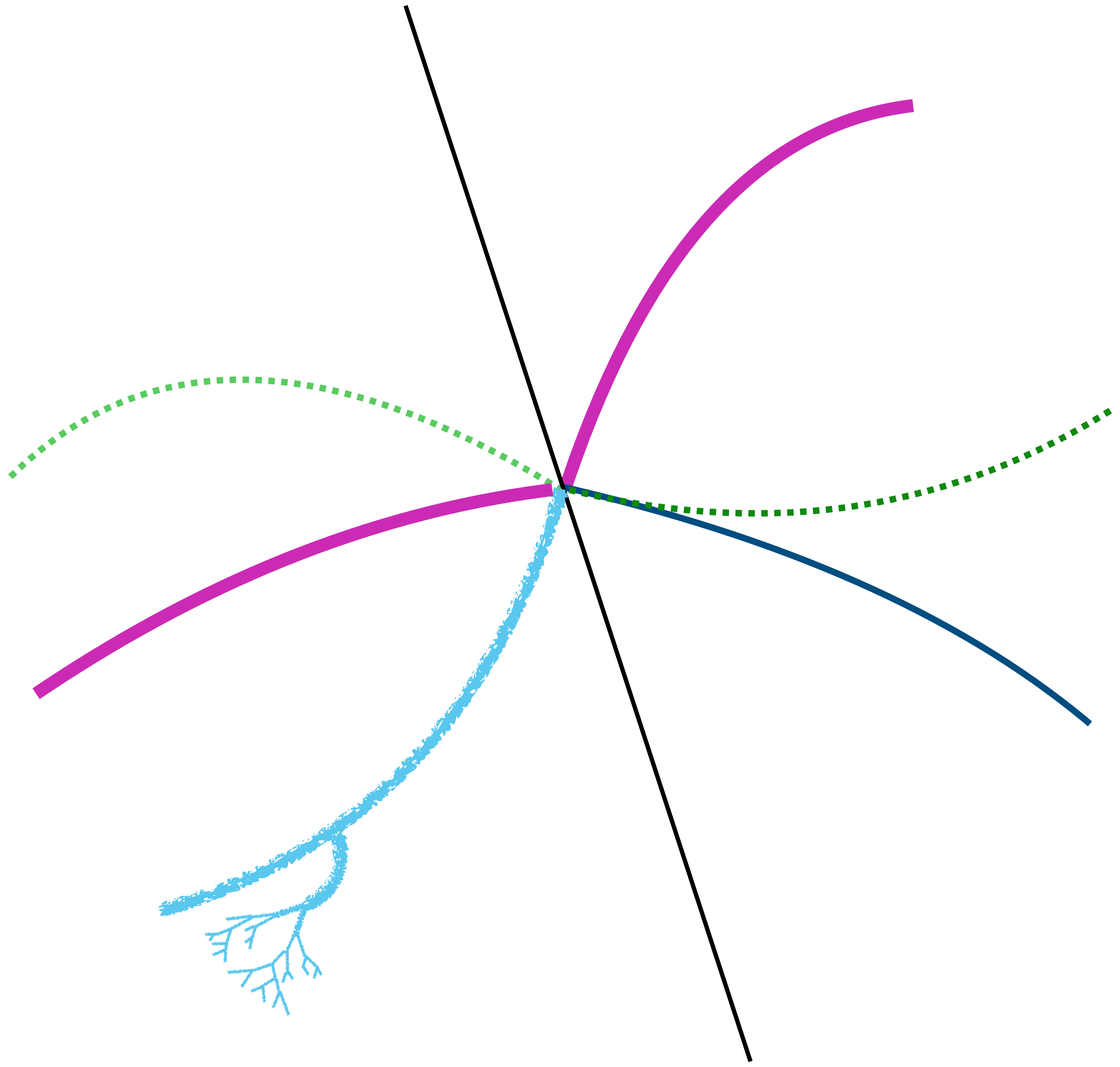

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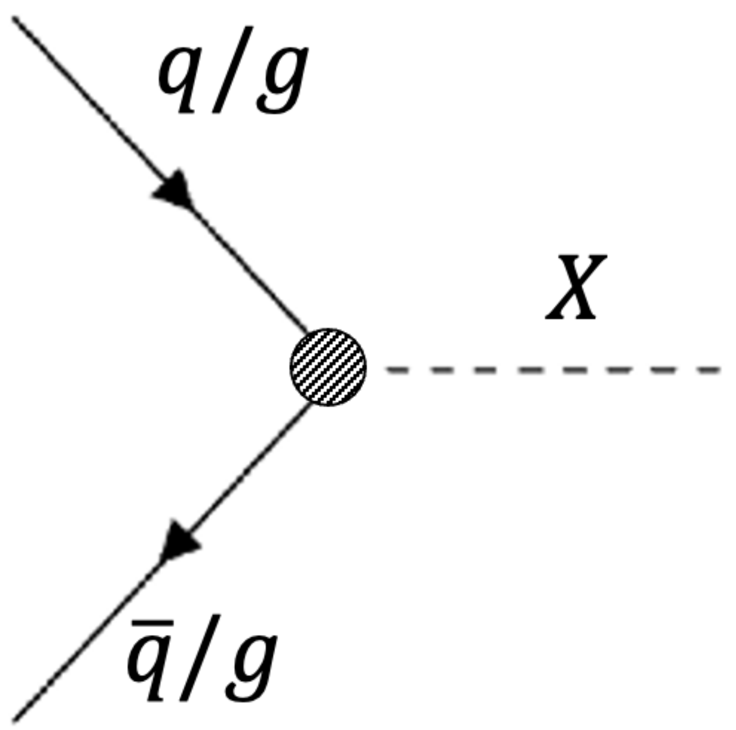
Heavy resonance searches

- Searching for the resonant production of some new heavy (~TeV) particle



Heavy resonance searches

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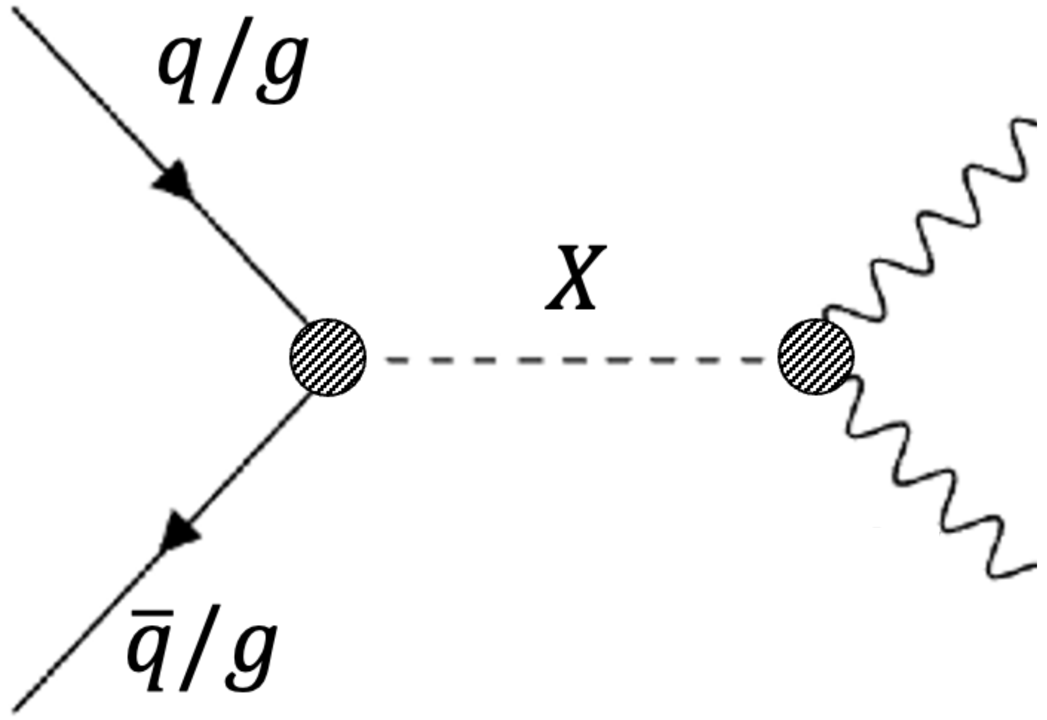
- We don't expect this new particle to live long
  - ➡ Decays into daughter particles quickly



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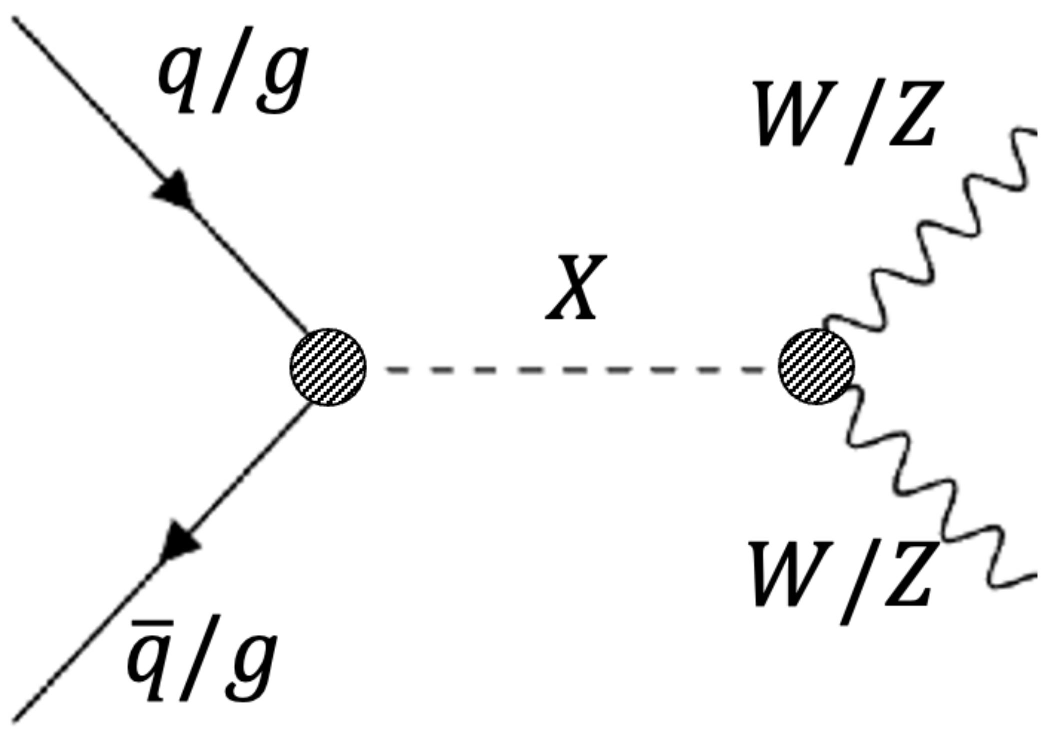

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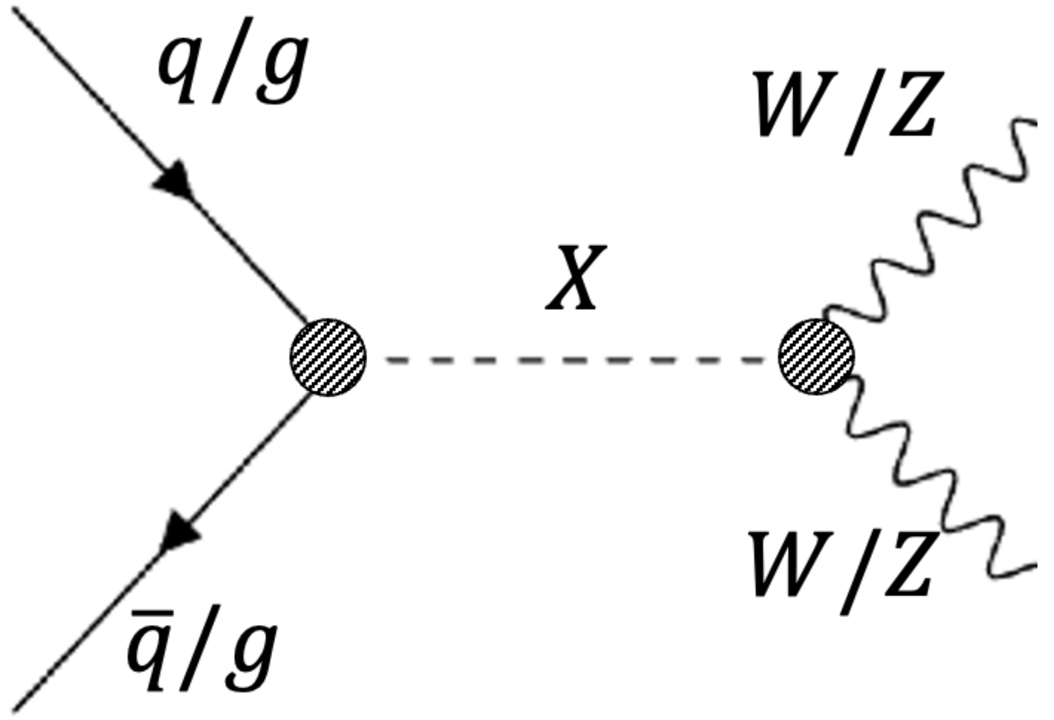

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  - ➡ Choose to focus on decay into a pair of vector bosons (=W or Z)

Why dibosons?

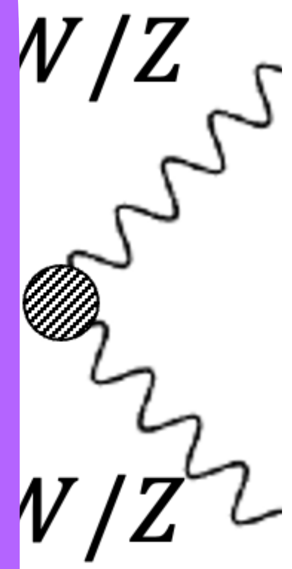
- Pairs of spin-1 EW bosons have a wide range of possible interactions
  - ➡ Pairs of V-bosons can interact with new particle *X* of spin-0 (Radion), spin-1 (Heavy Vector Triplet) or spin-2 (RS Graviton)

Heavy resonance searches

- Searching ... TeV) particle
- We don't t...
  - ➡ Decay...
  - ➡ Choos... or Z)

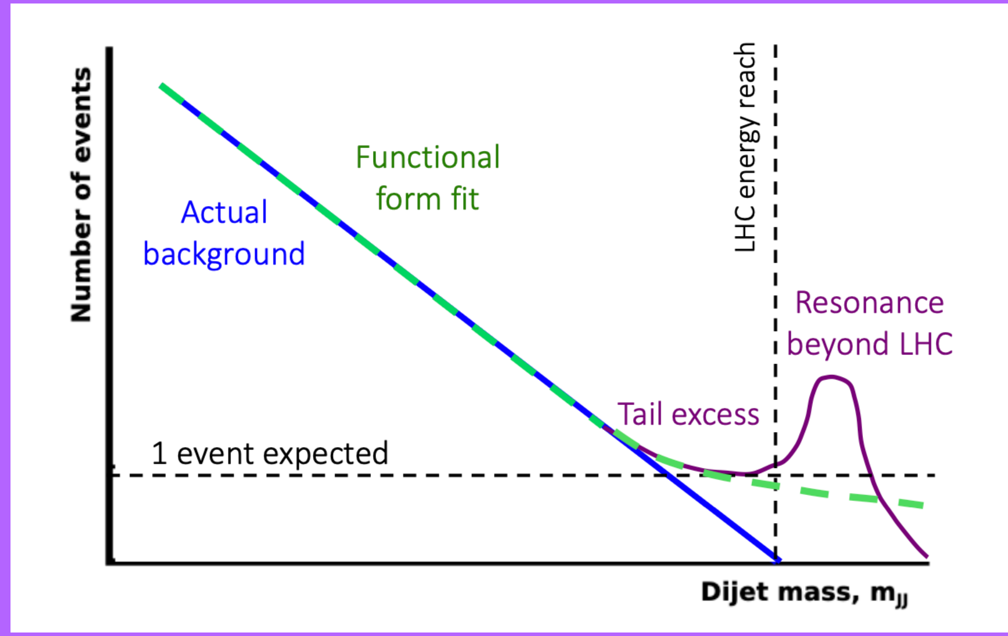
Why diboson...

- Pairs of s... actions
  - ➡ Pairs c... (Radion), spin-1 (



Not mentioned in this talk:
Also have some cool work being done on

- EFT



- W/Z boson polarization

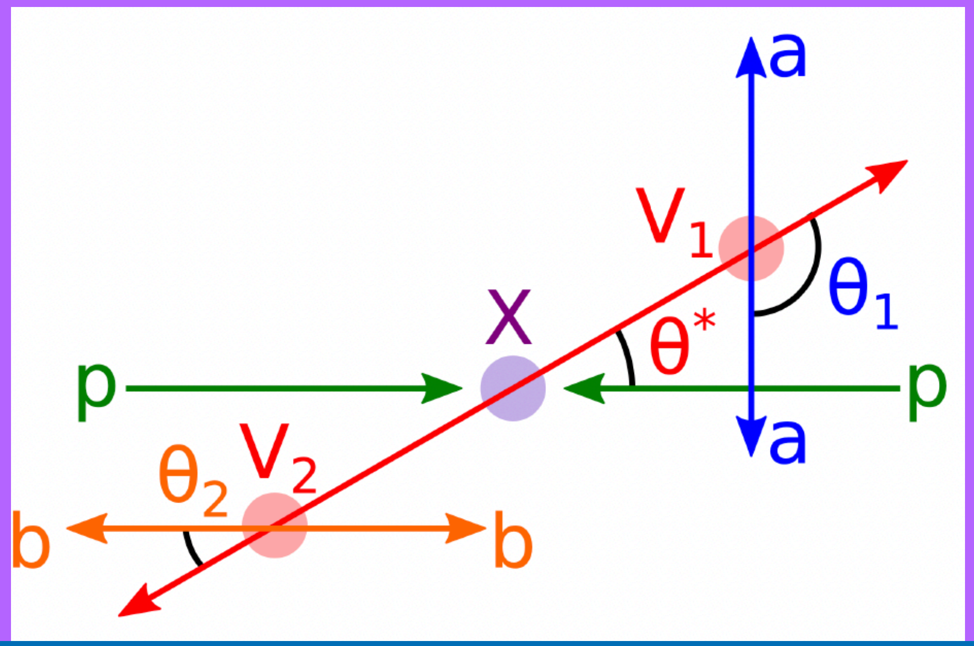


Diagram credit: Sofia Adorni Braccesi Chiassi

Diboson searches

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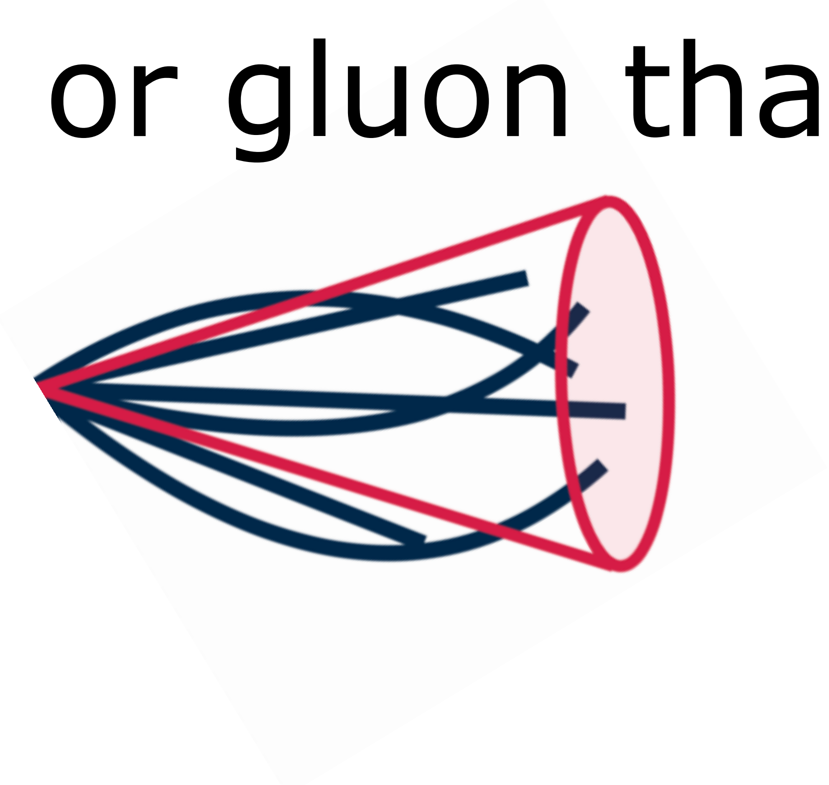
- I study the *fully hadronic* channel
  - ➡ Jargon: "jet" → a quark or gluon that hadronizes into a cone of more hadrons



Diboson searches: fully hadronic

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- Want to study diboson interactions at the highest possible energy scale
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W →
- $q\bar{q}$ 67.6%
- $l\nu$ 7.2%
- $\tau\nu$ 3.6%

Z →
- $q\bar{q}$ 69.2%
- $\nu\nu$ 20.5%
- ll 6.8%
- $\tau\tau$ 3.4%

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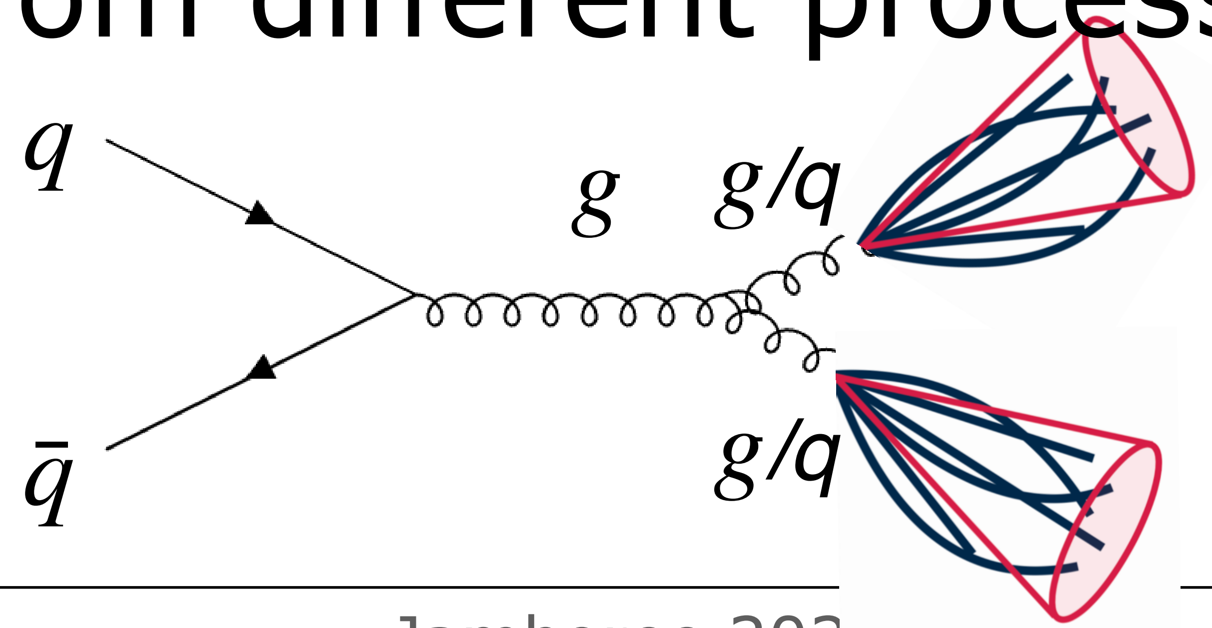
Major challenge:

- Lots of *QCD multijet* background in this channel

→ Jets coming from different processes dominated by strong force



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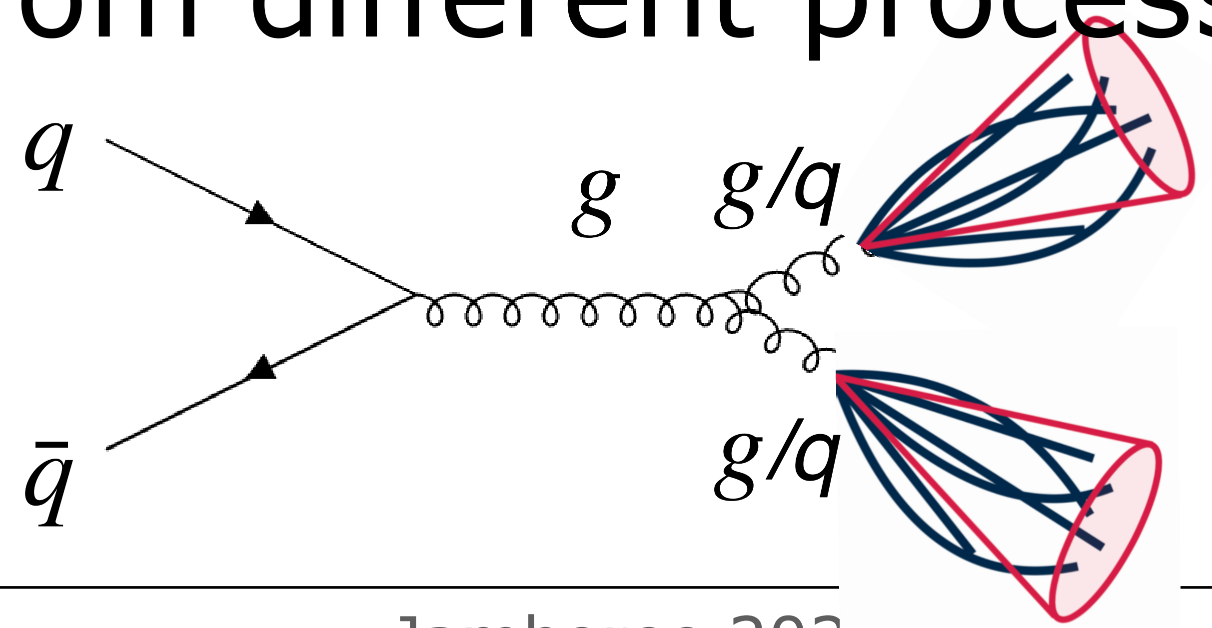
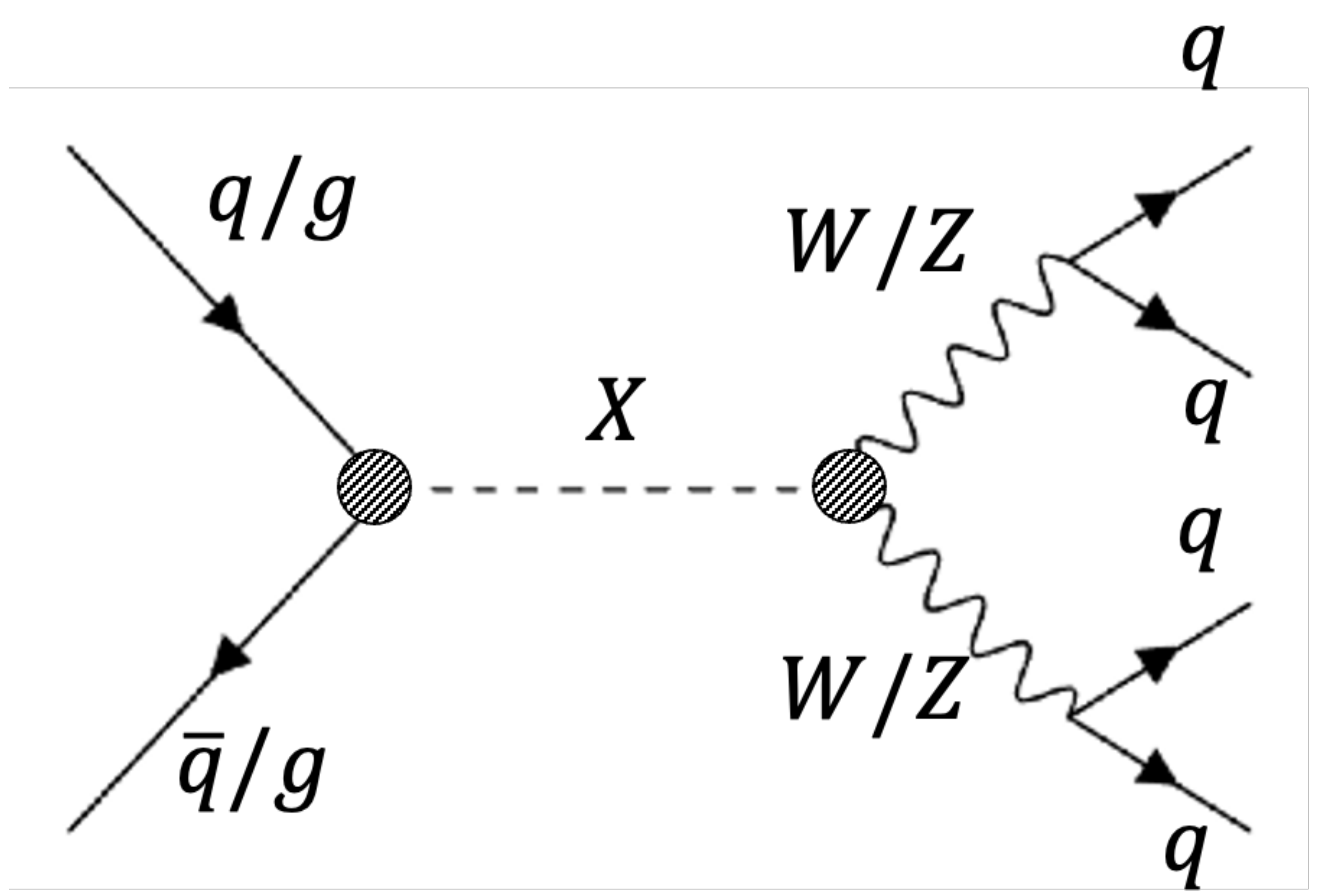


Not our signal!

Diboson searches: fully hadronic

- The signal: $X \rightarrow VV \rightarrow qq\ qq$



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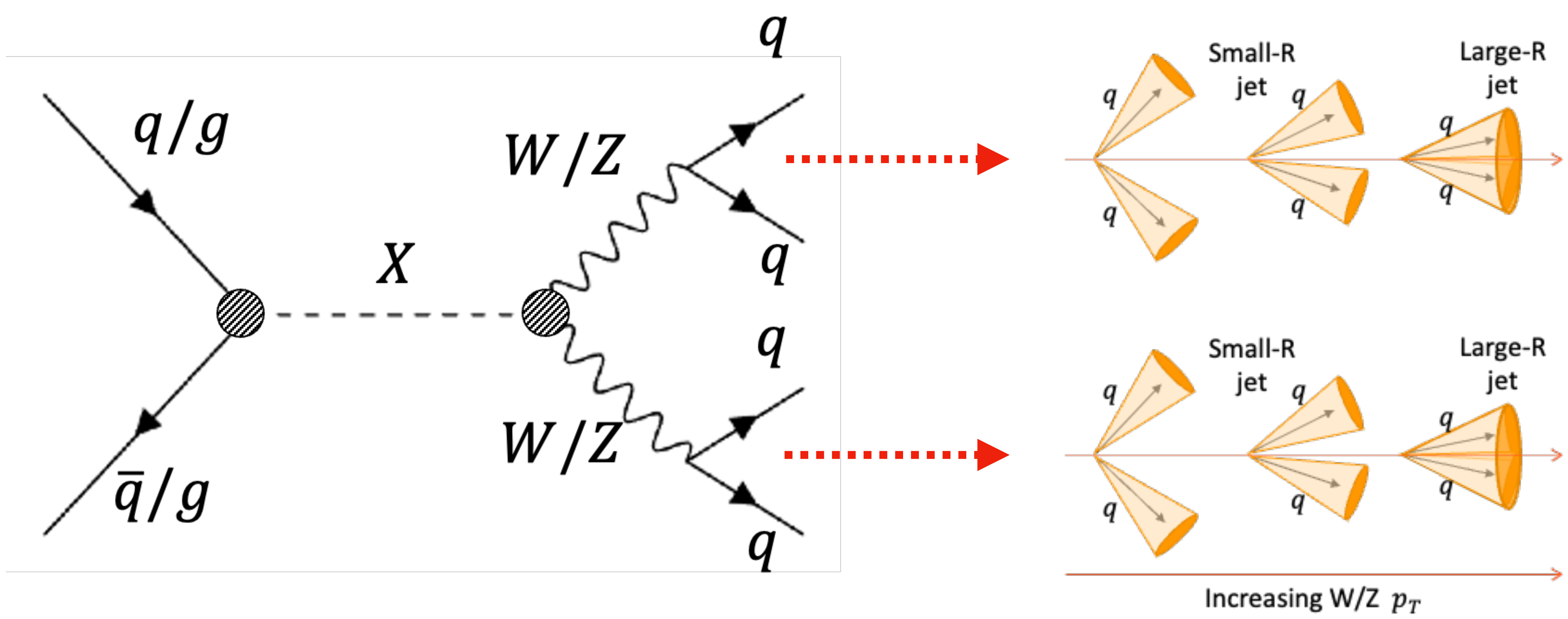
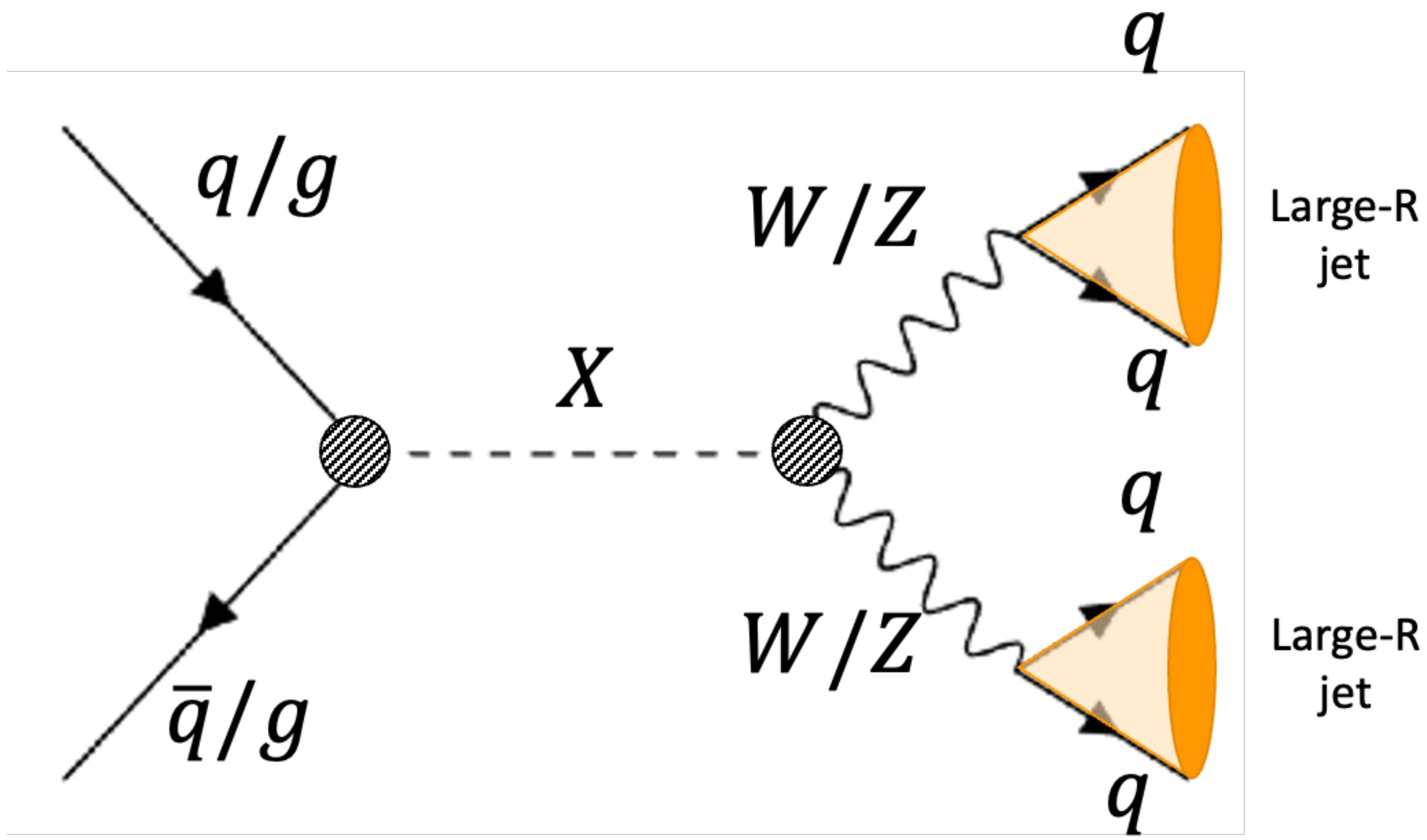


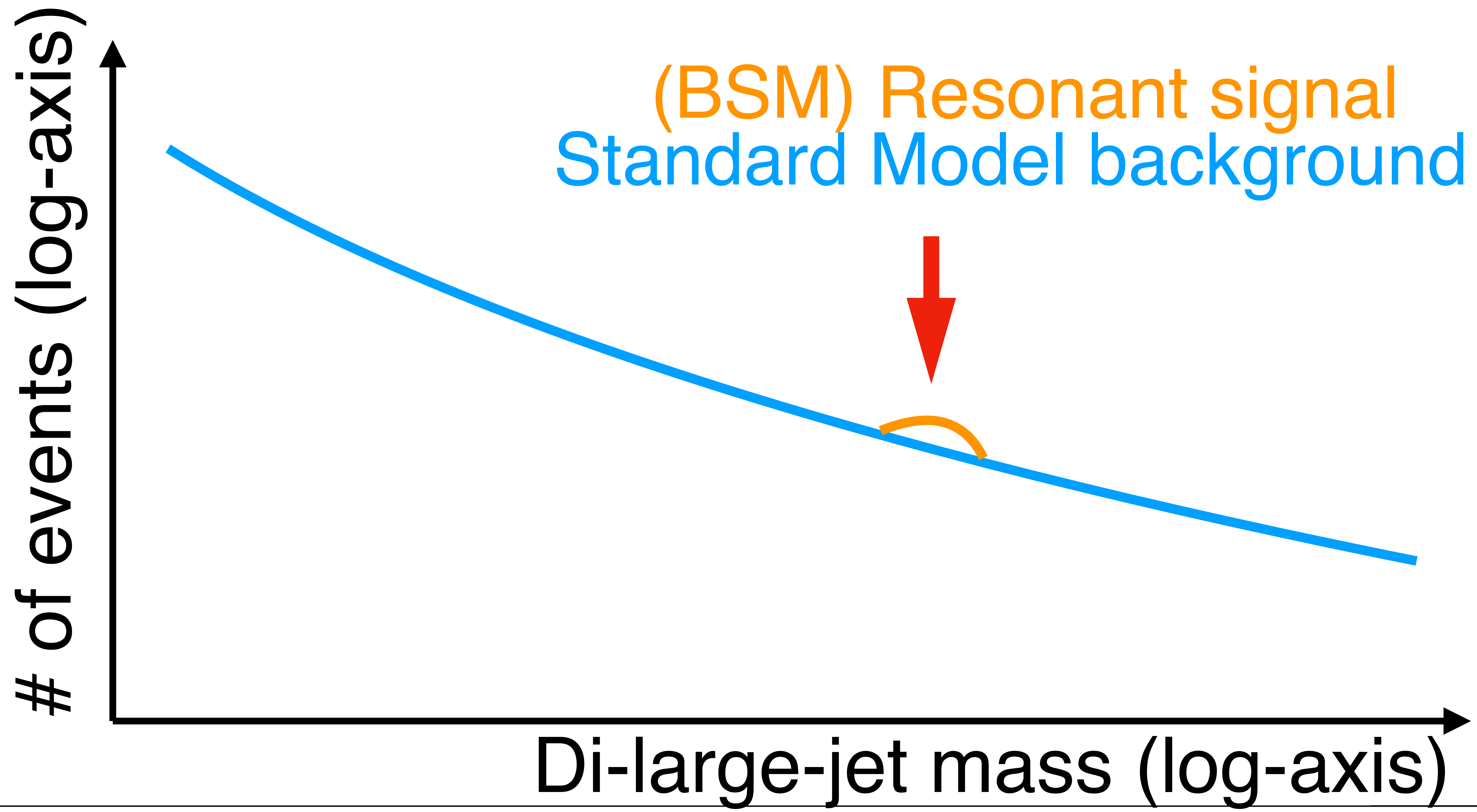
Since X is so heavy, the Vs will have a high momentum (p_T)

➡ Ultimately forming two *large-R jets* in total

Diboson searches: fully hadronic

- The signal: $X \to VV \to$ 2 large-R jets
- What we want to see: two large-R jets with a combined invariant mass 2 - 6 TeV





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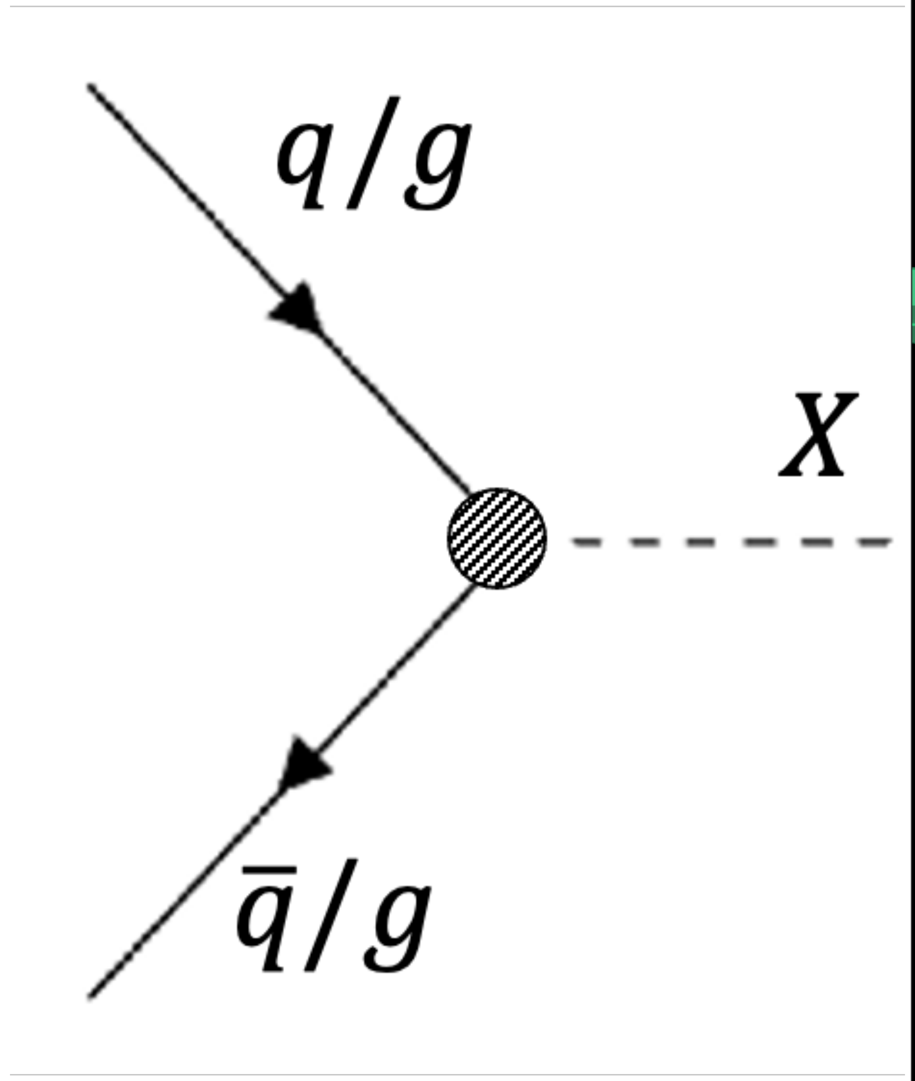

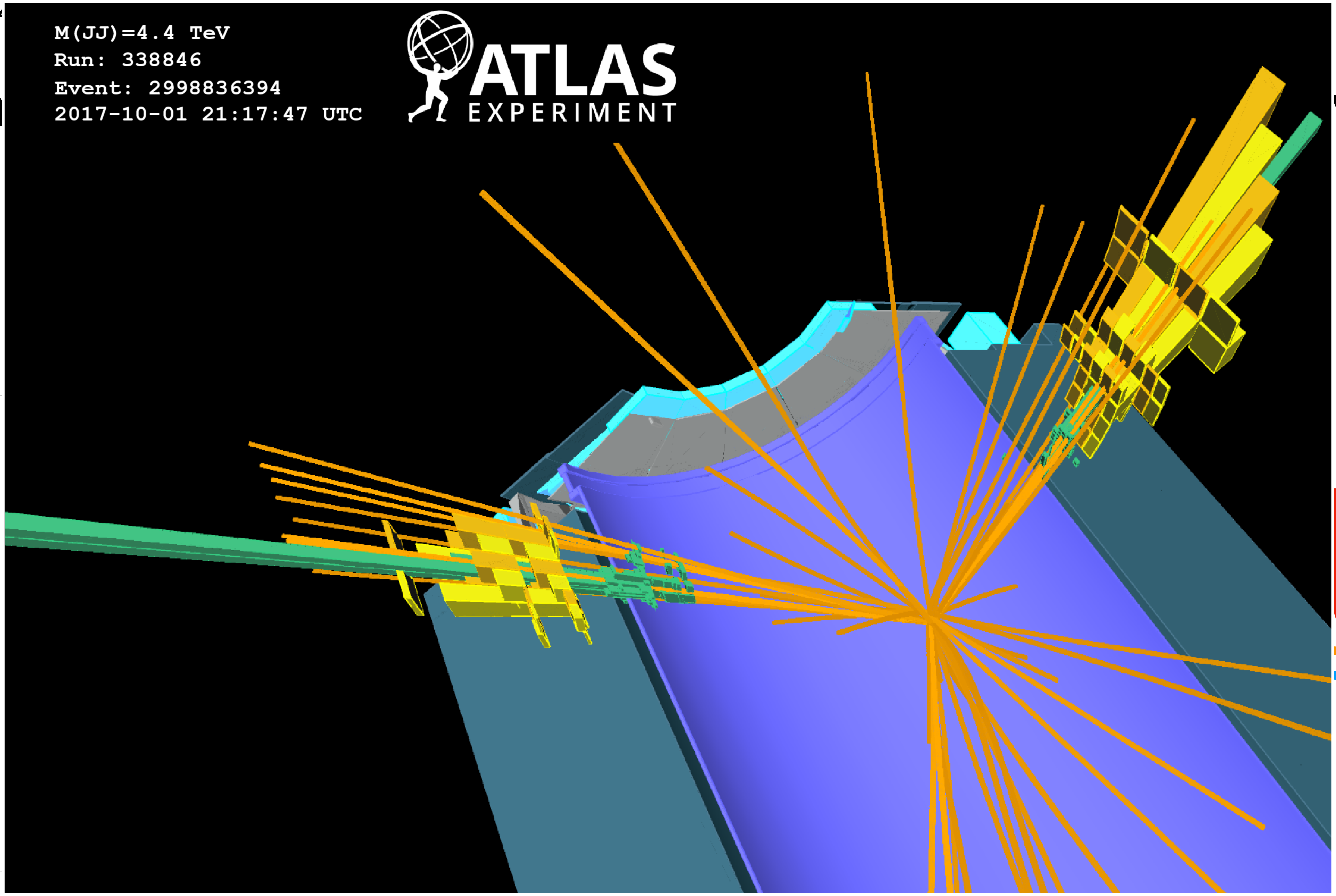

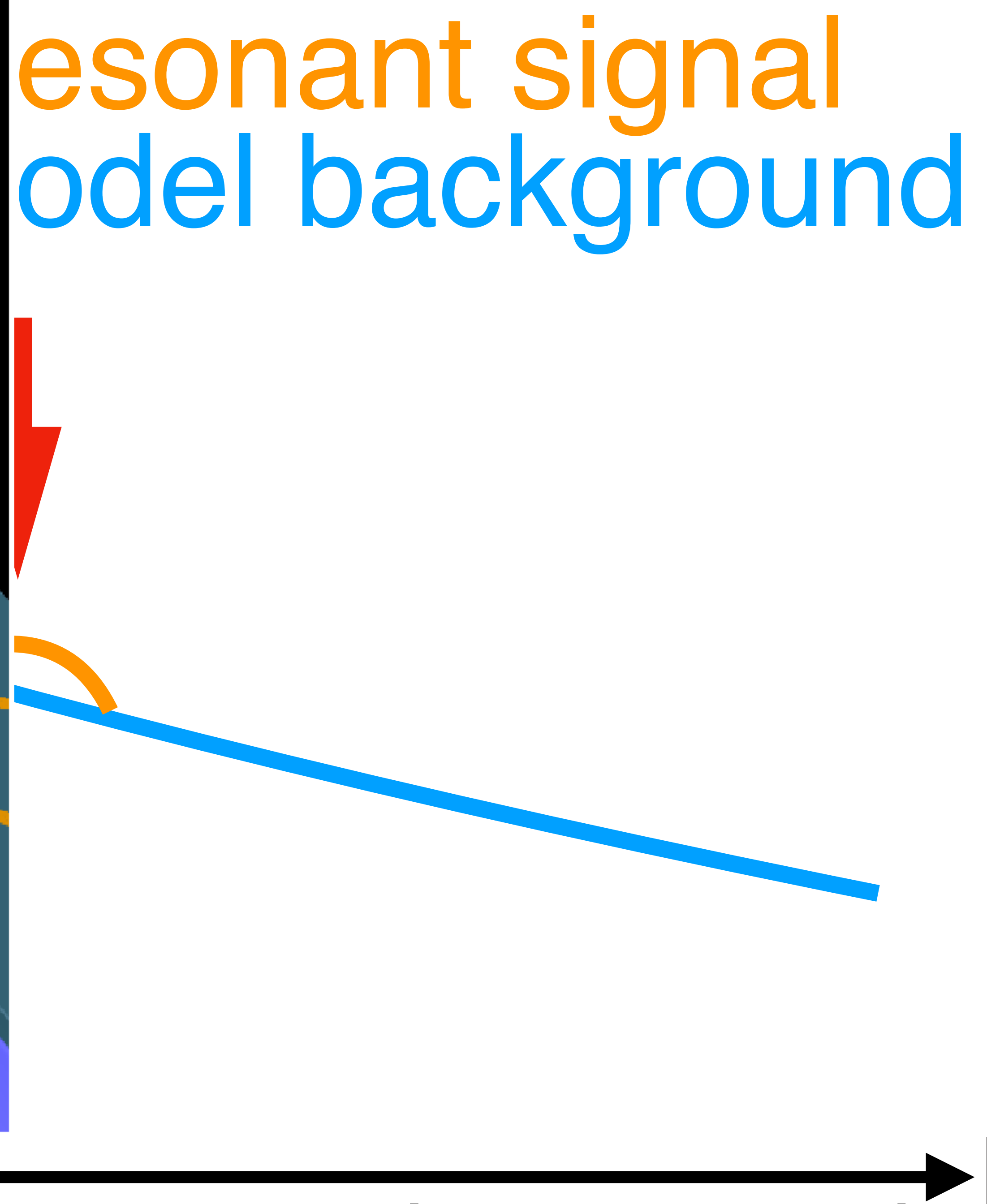

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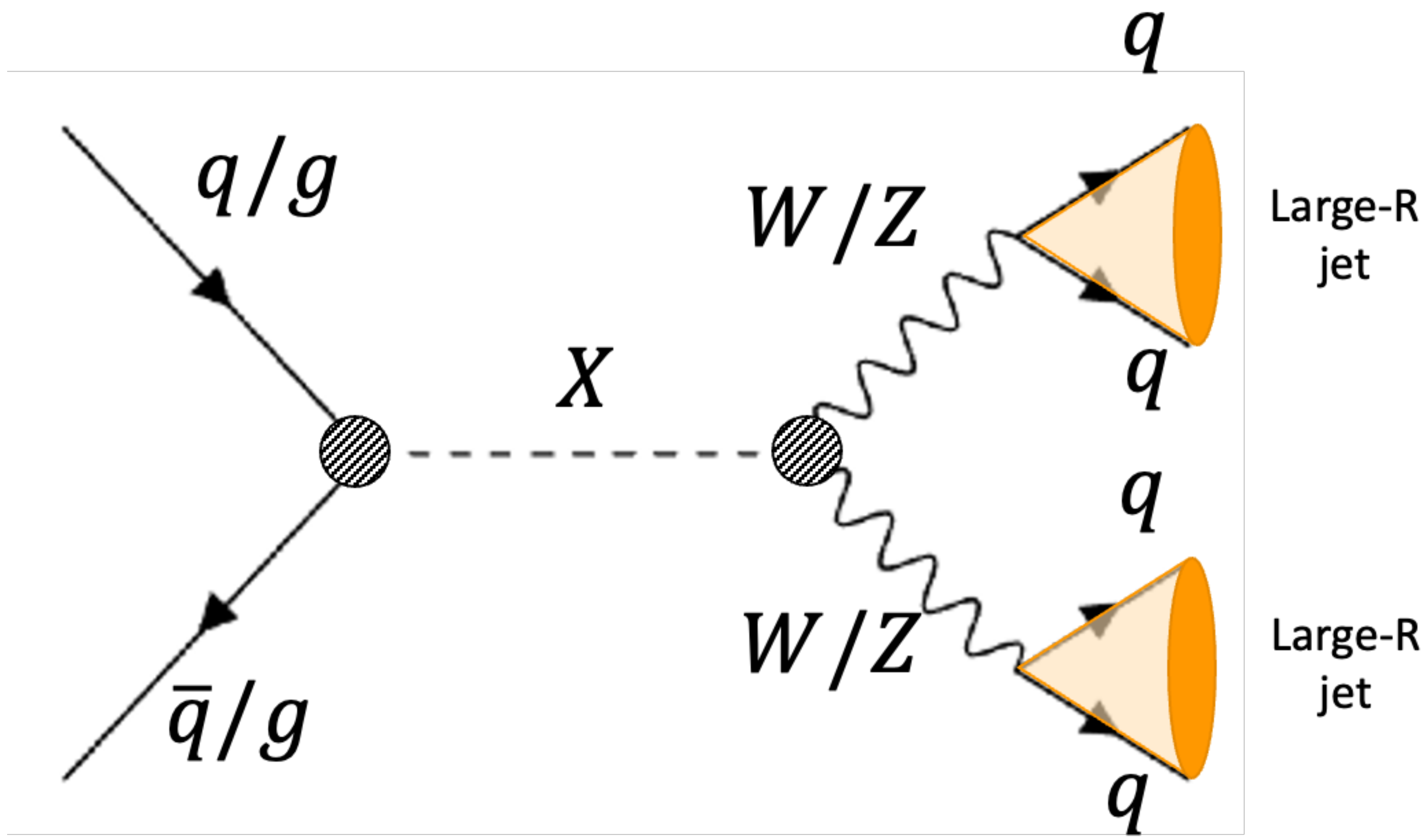

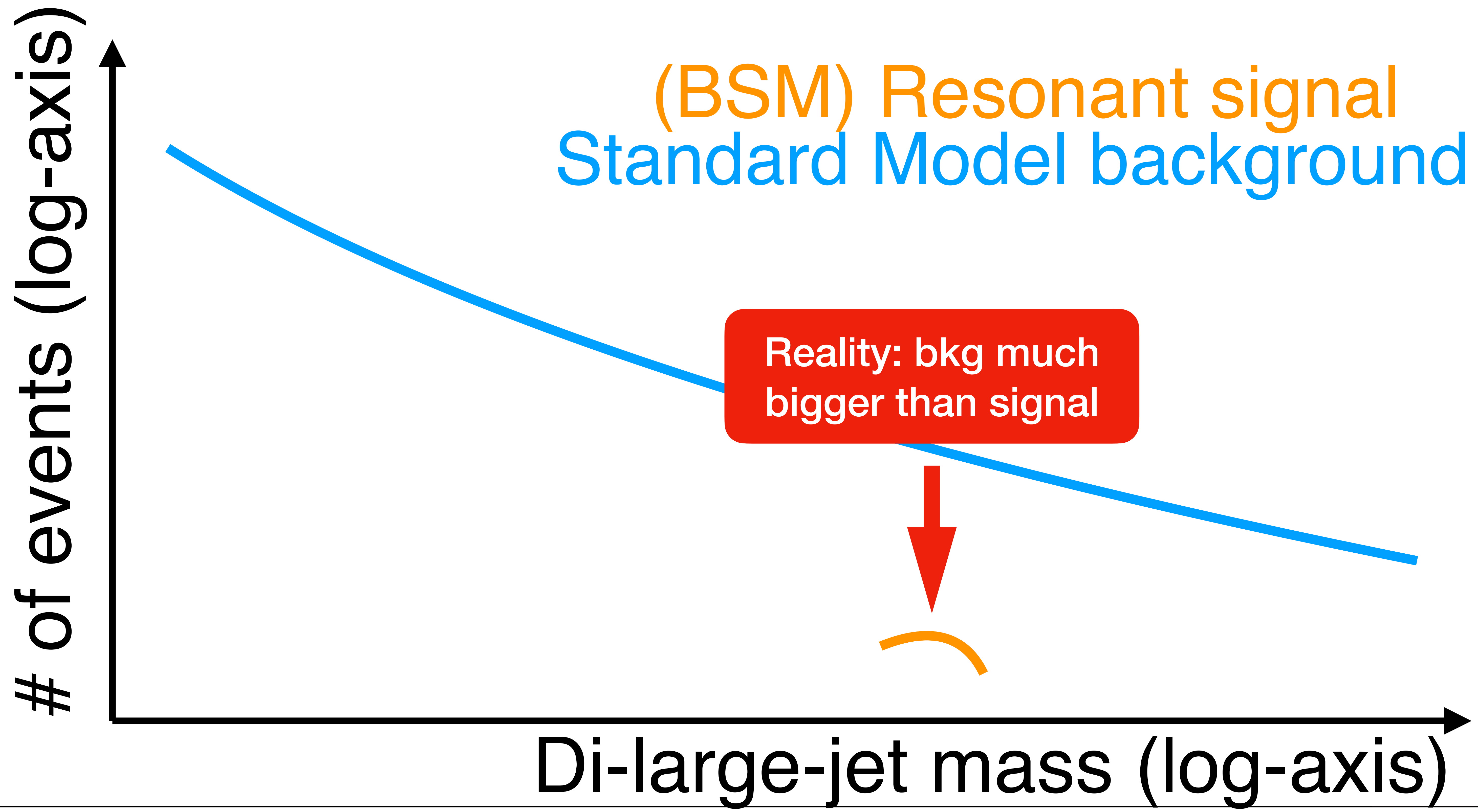

ATLAS EXPERIMENT

Diboson searches: major challenge

- Since we are working with a fully hadronic final state, standard model QCD background is dominant
  - ➡ The cross section of proton-proton → 2 jets is **3 orders of magnitude** bigger than proton-proton → 2 V
    - Means we will have a huge background
  - ➡ Need to find some way to estimate the amount of background events and distinguish it from signal

Background estimation

- Typically there are two options: *MC simulations* or *data driven*
- High-energy QCD is difficult to simulate
  - ➡ MC simulations for QCD not accurate enough for our required level of detail and niche phase space
  - ➡ In this case a data driven method is much more reliable for QCD

Data driven: ABCD Method

- Idea: "estimate background contribution in **signal region** by looking at **control regions**"

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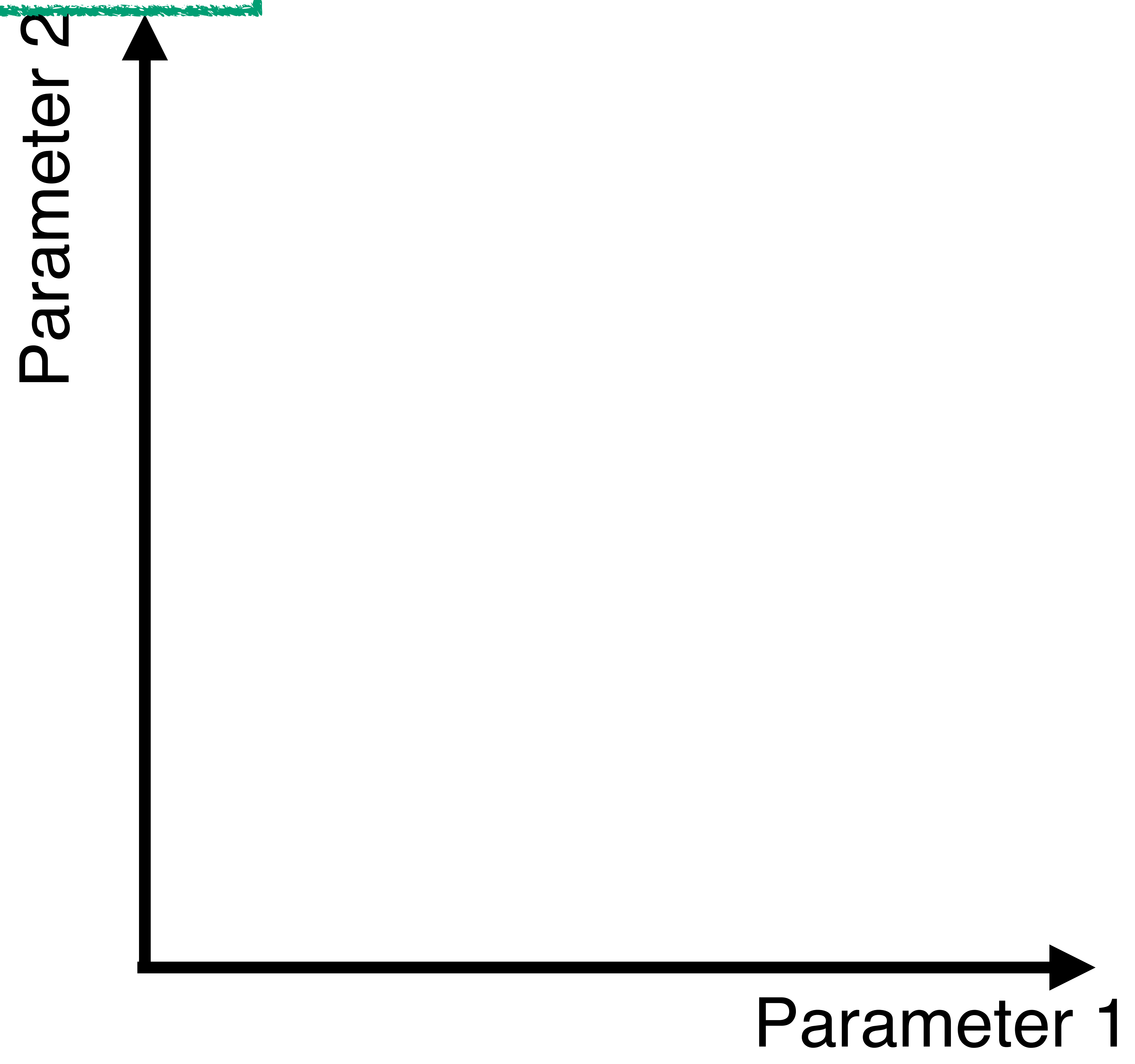
  - ➡ Categorise your data into region(s)

Intermezzo: Signal & Control regions



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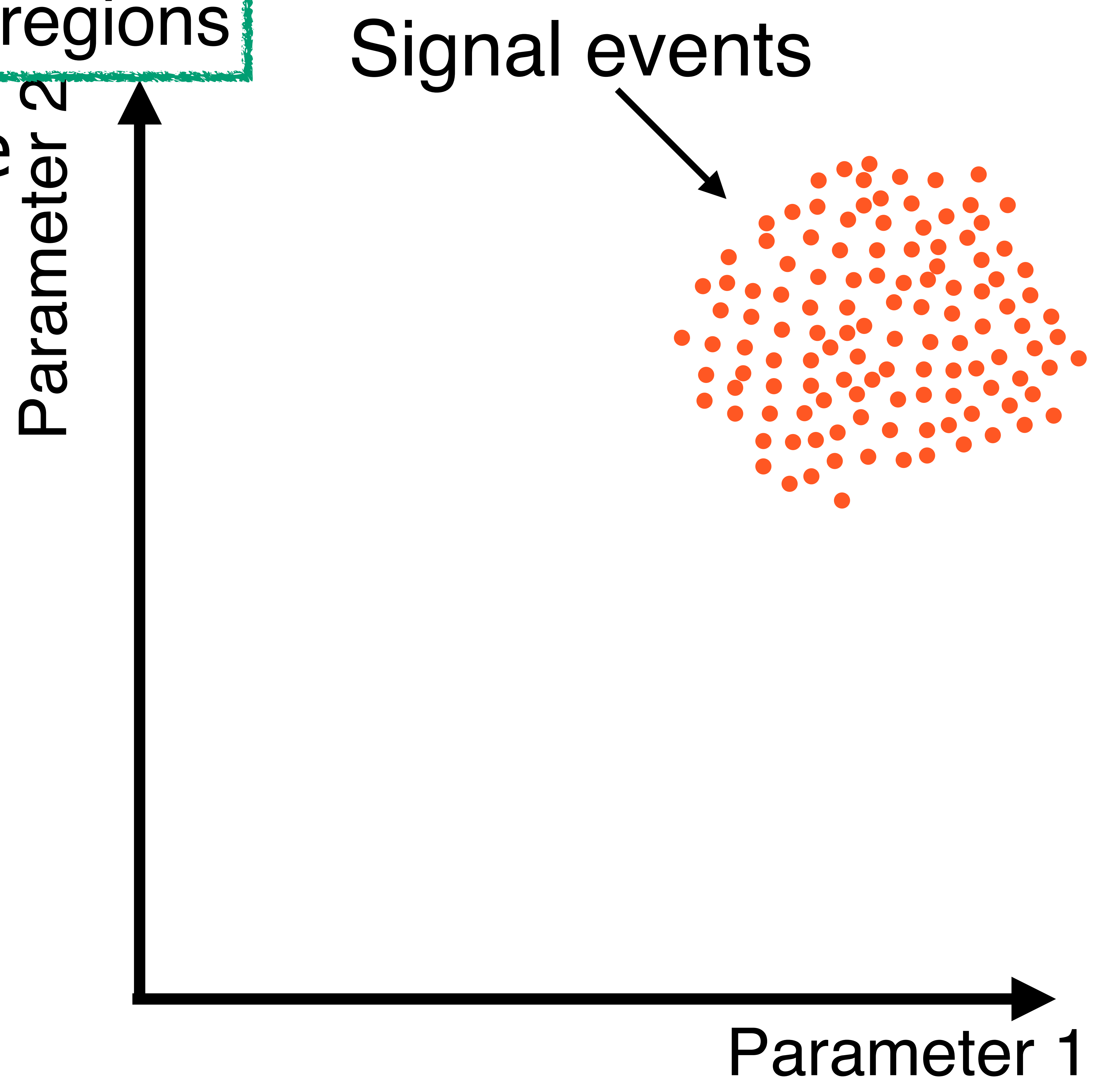

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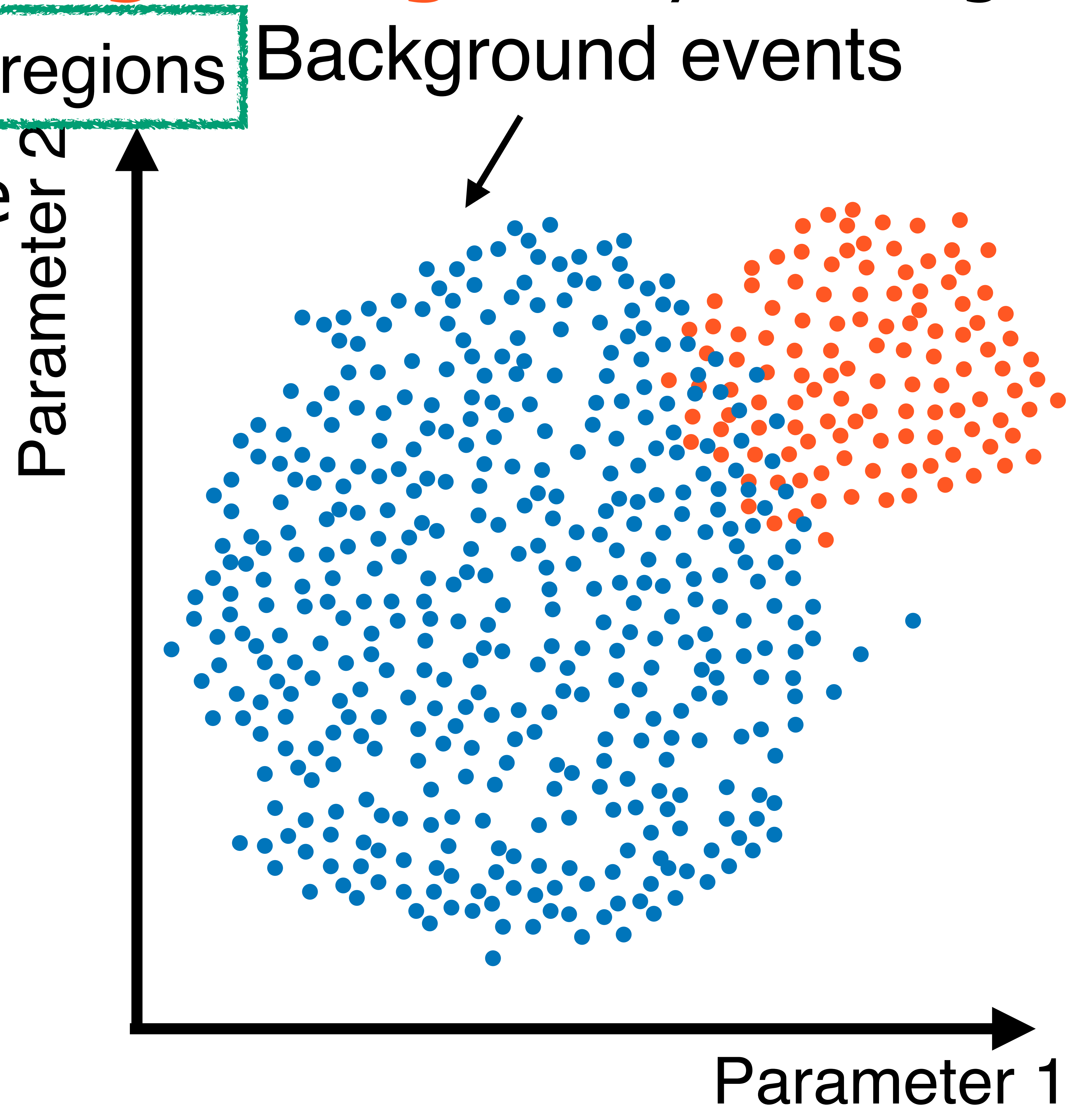

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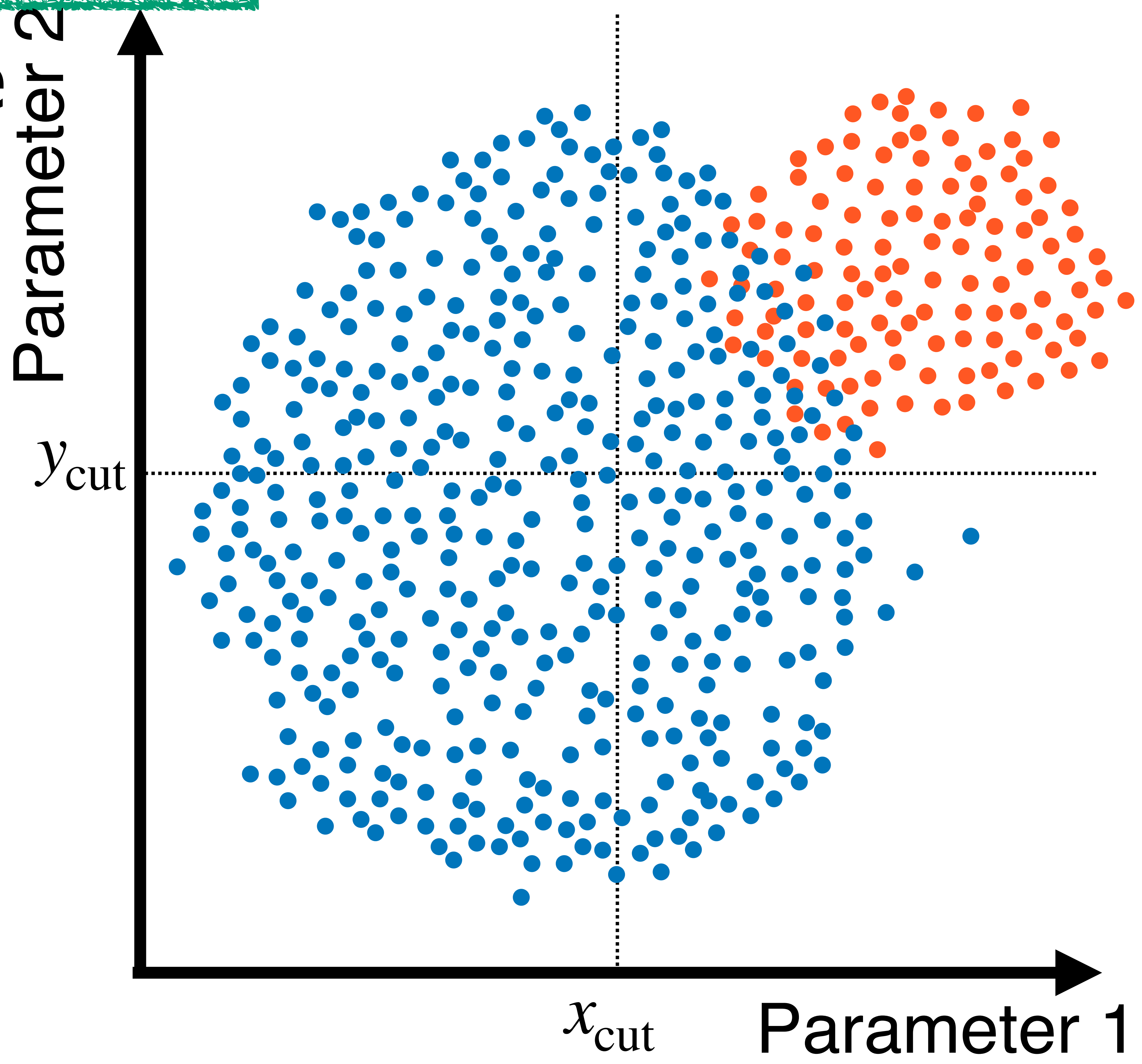

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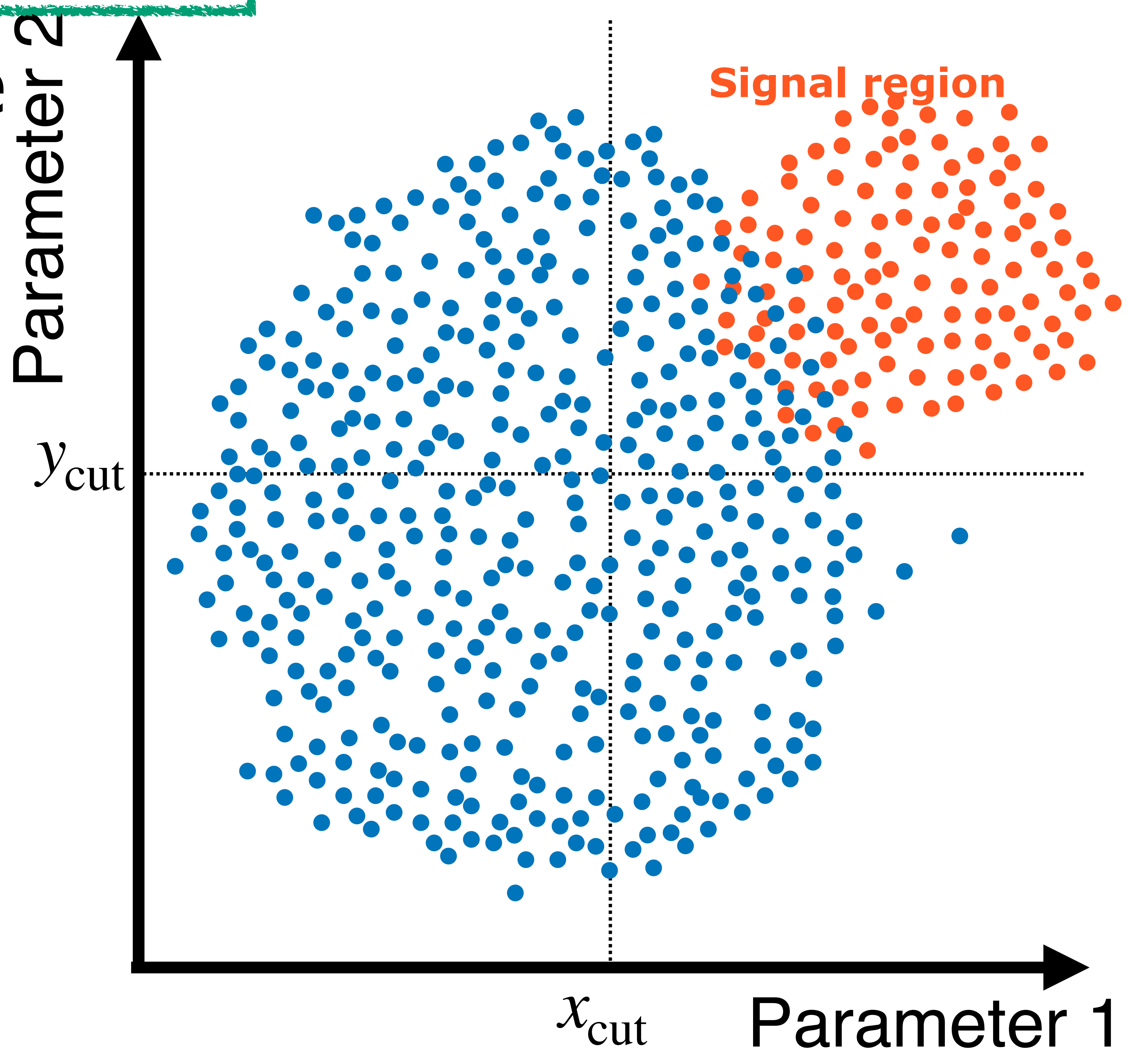

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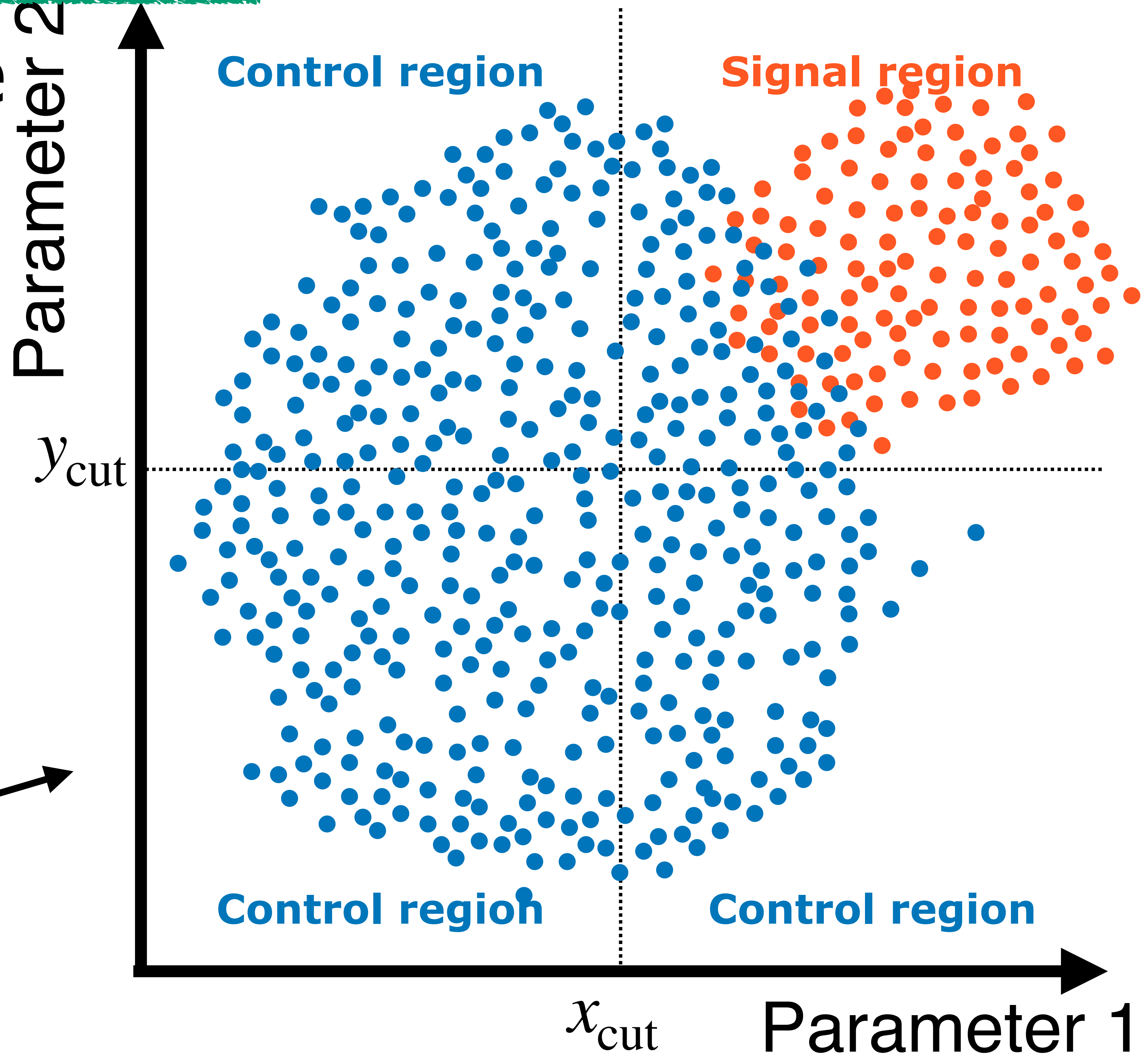

Ideal scenario where you know exactly what each event is beforehand

Data driven: ABCD Method

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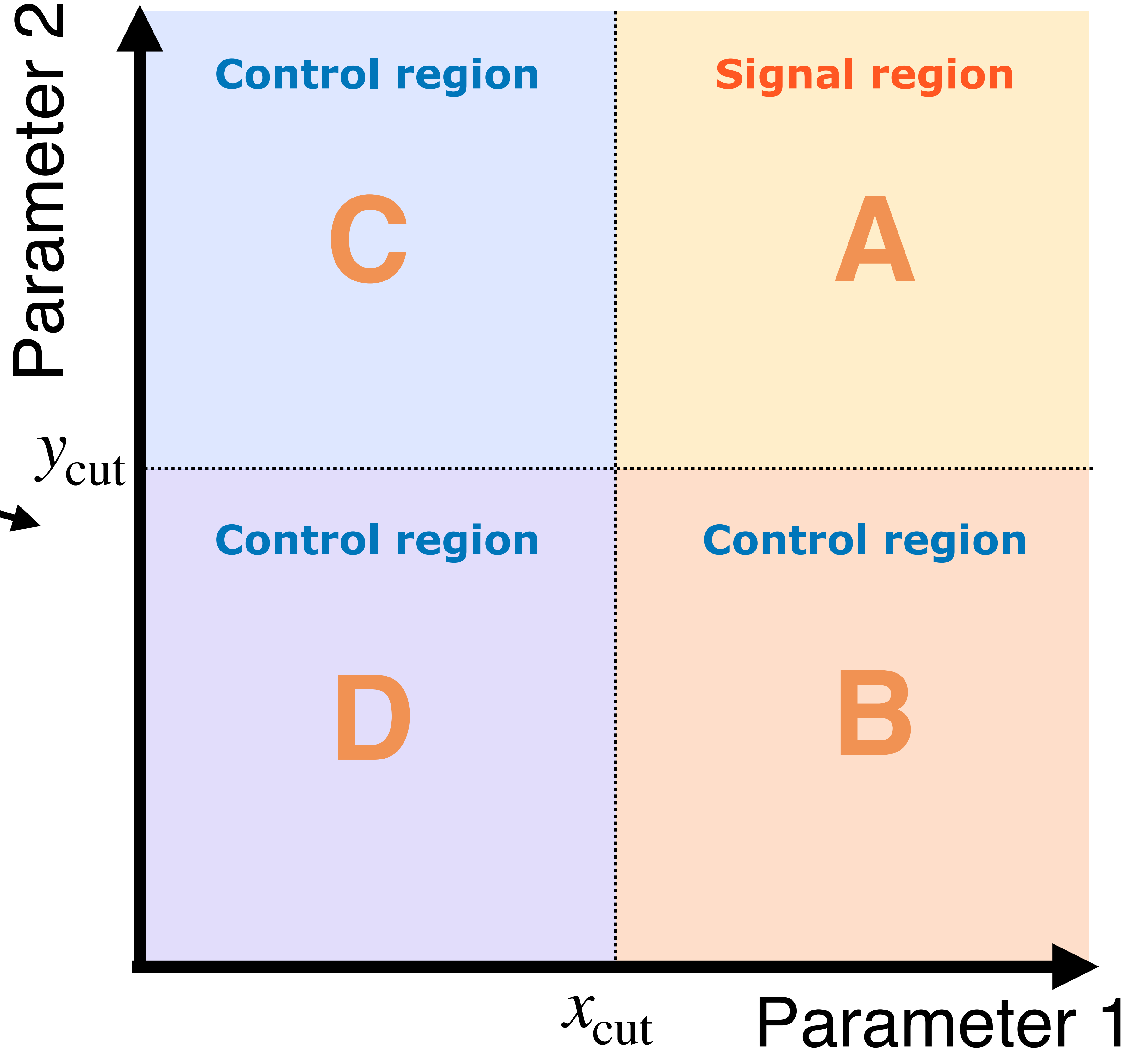
What do you do if you don't know whether an event is signal or background?



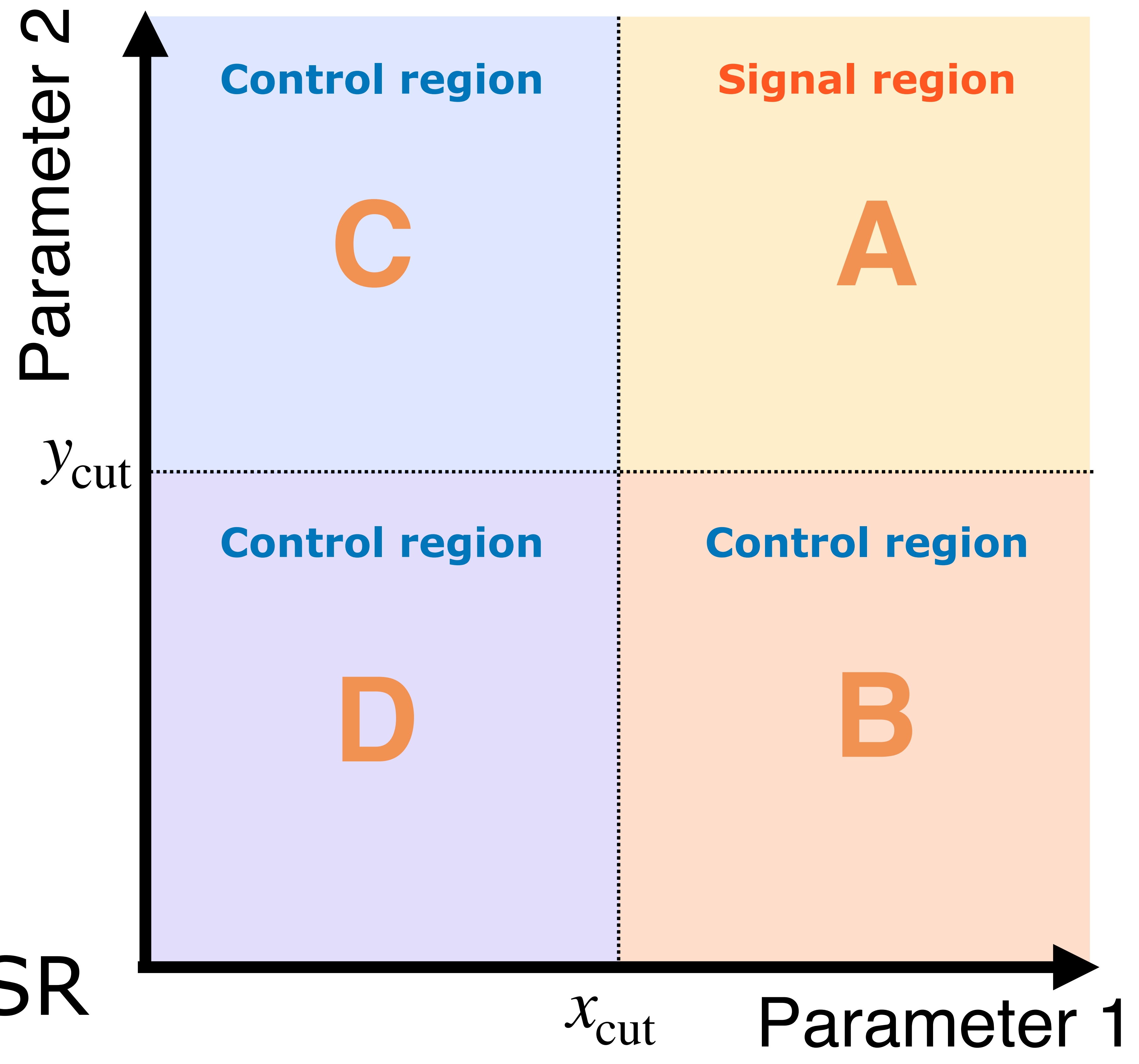
Data driven: ABCD Method

- Idea: "estimate background contribution in **signal region** by looking at **control regions**"
- If the parameters chosen for the x- & y-axis are **not correlated**, *and* if your **signal region is well defined** You can say:

➡ $\frac{A}{B} = \frac{C}{D}$ (For # background events)

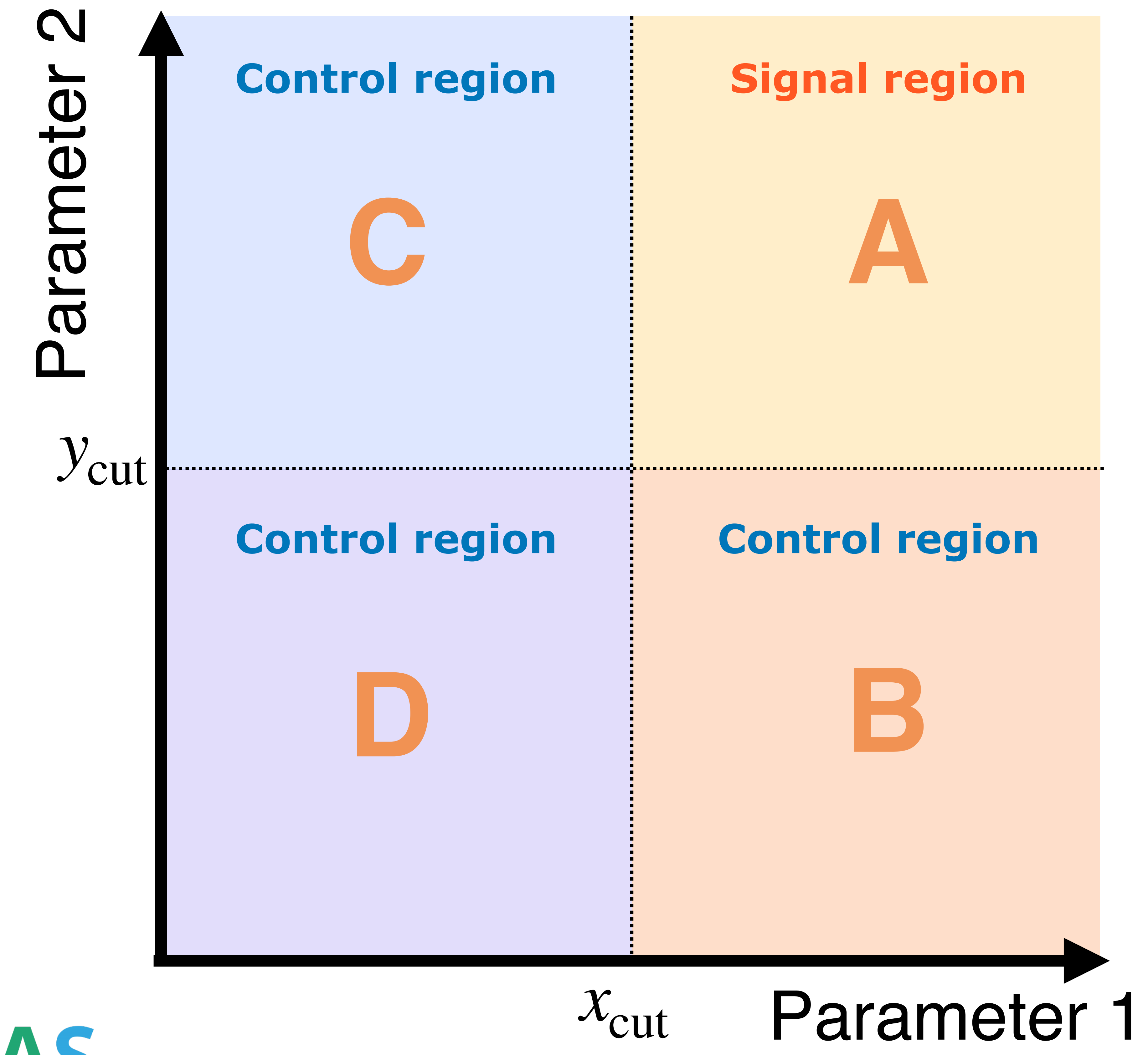
➡ $A = B \times \frac{C}{D}$

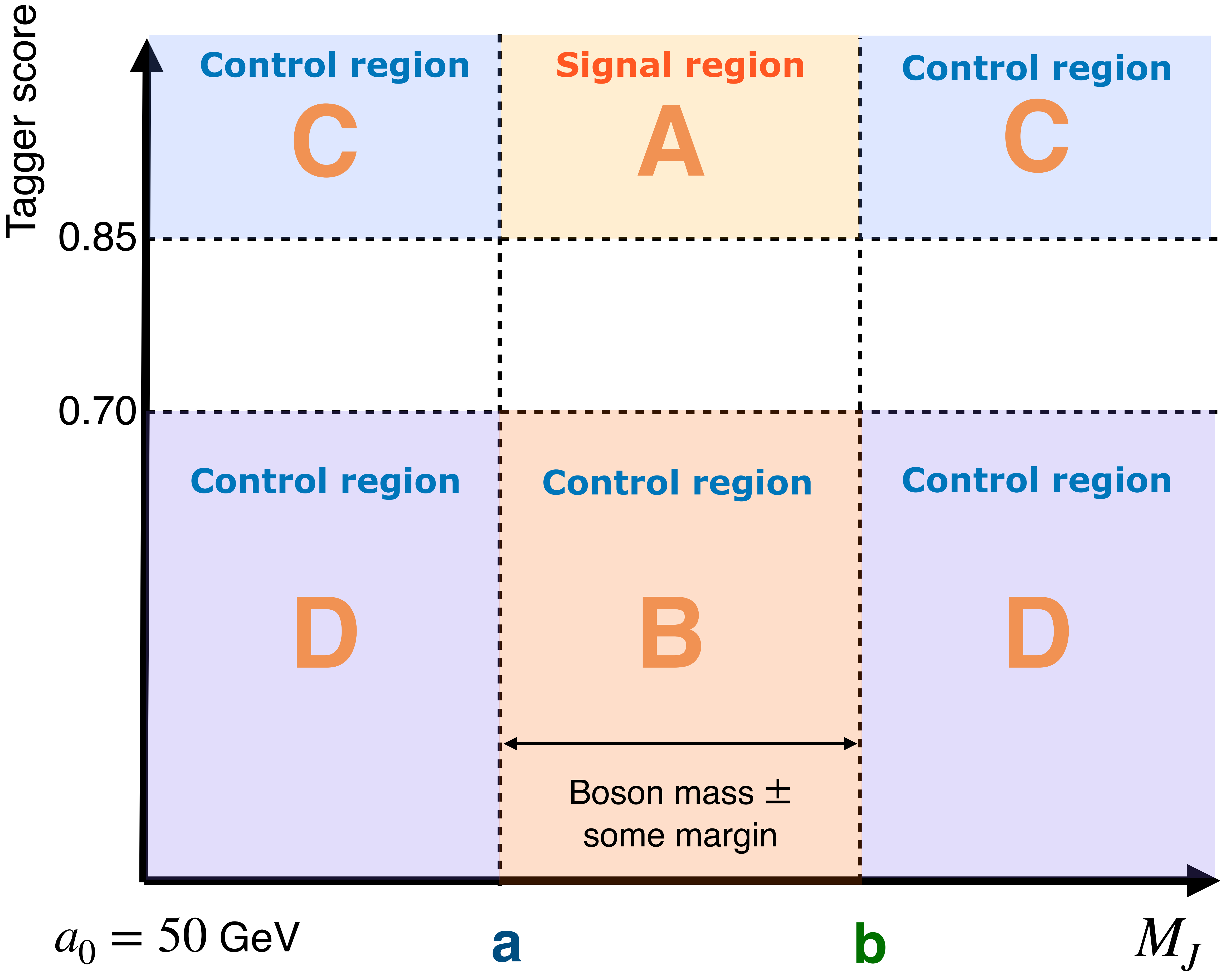
➡ Now you can estimate # bkg events in SR by only looking at control regions



ABCD Method: Our Case

- $A = B \times \frac{C}{D}$, where A, B, C & D are the #bkg events within the specific regions





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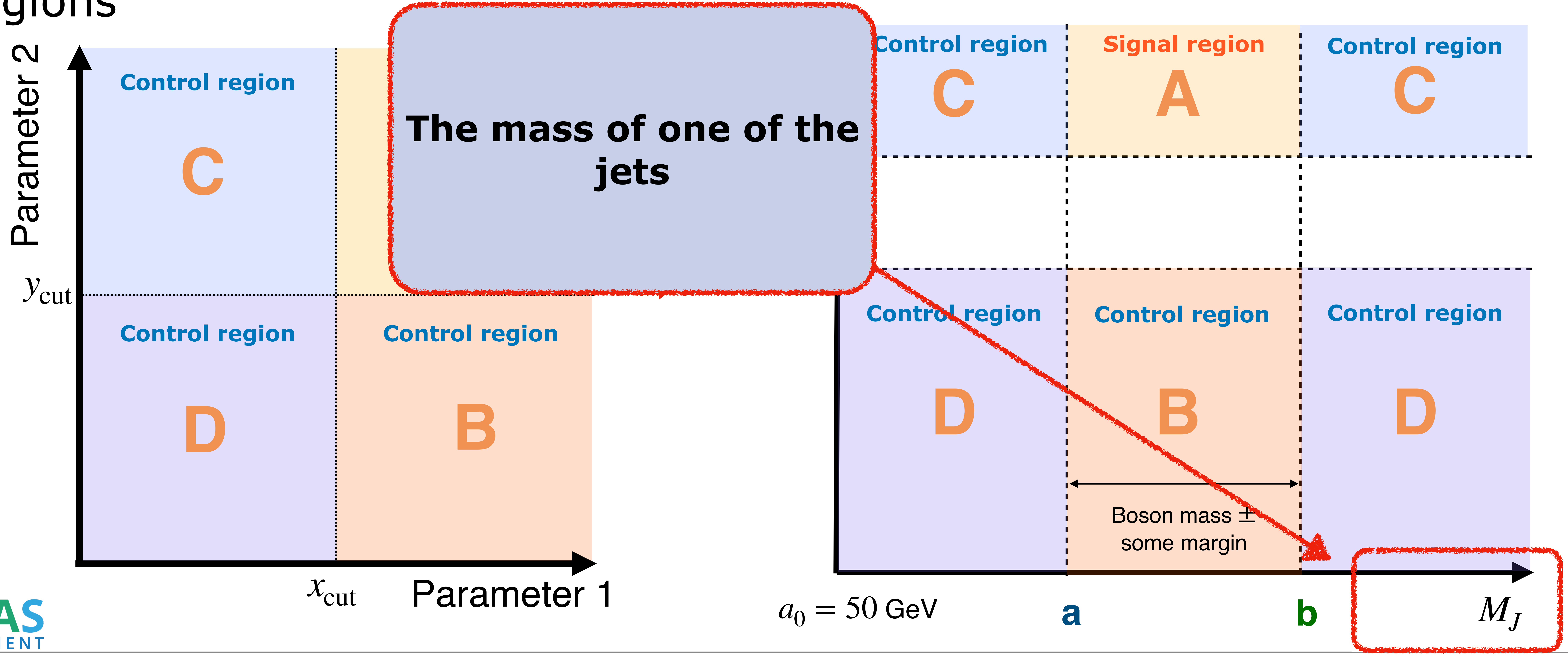
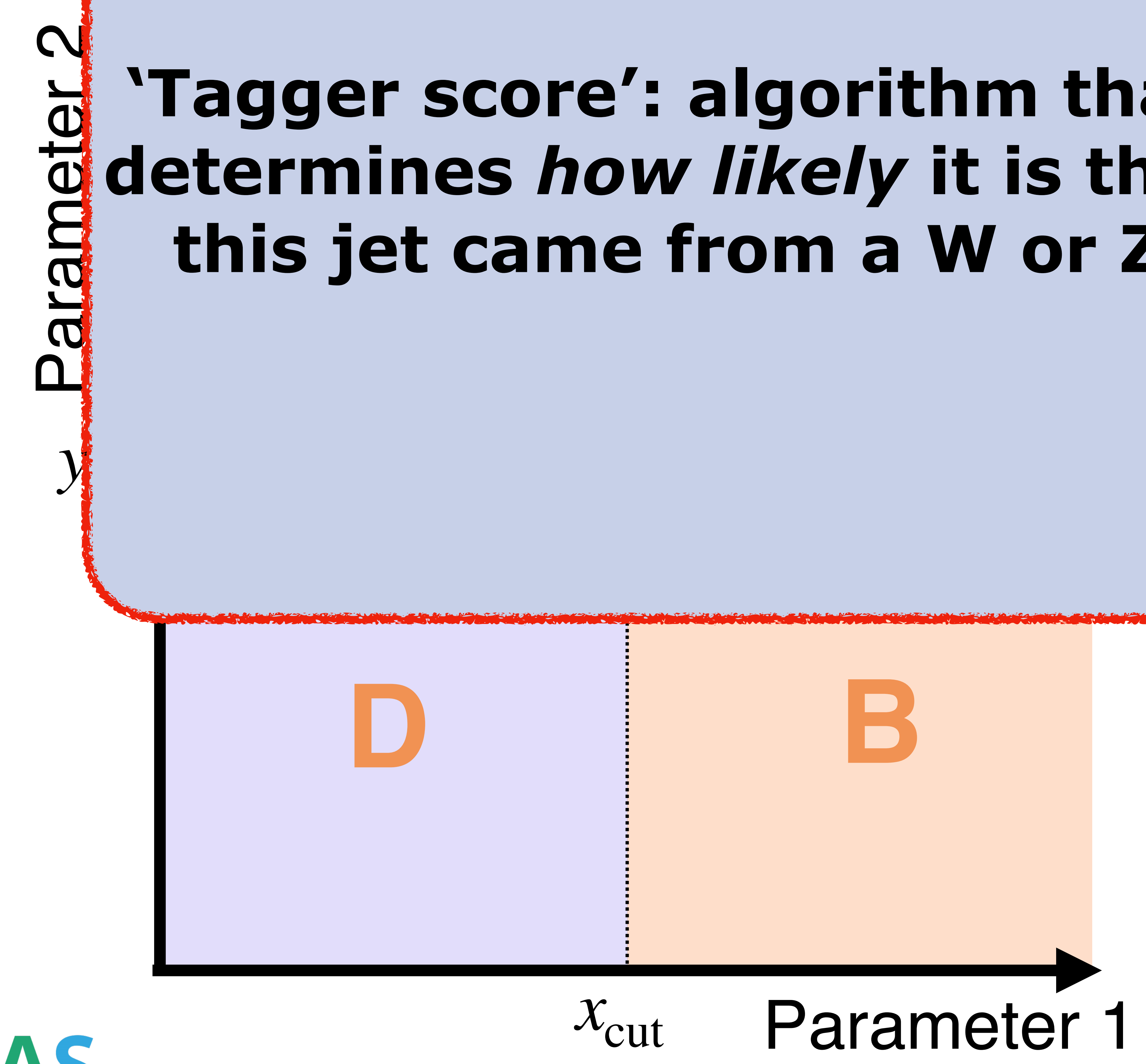
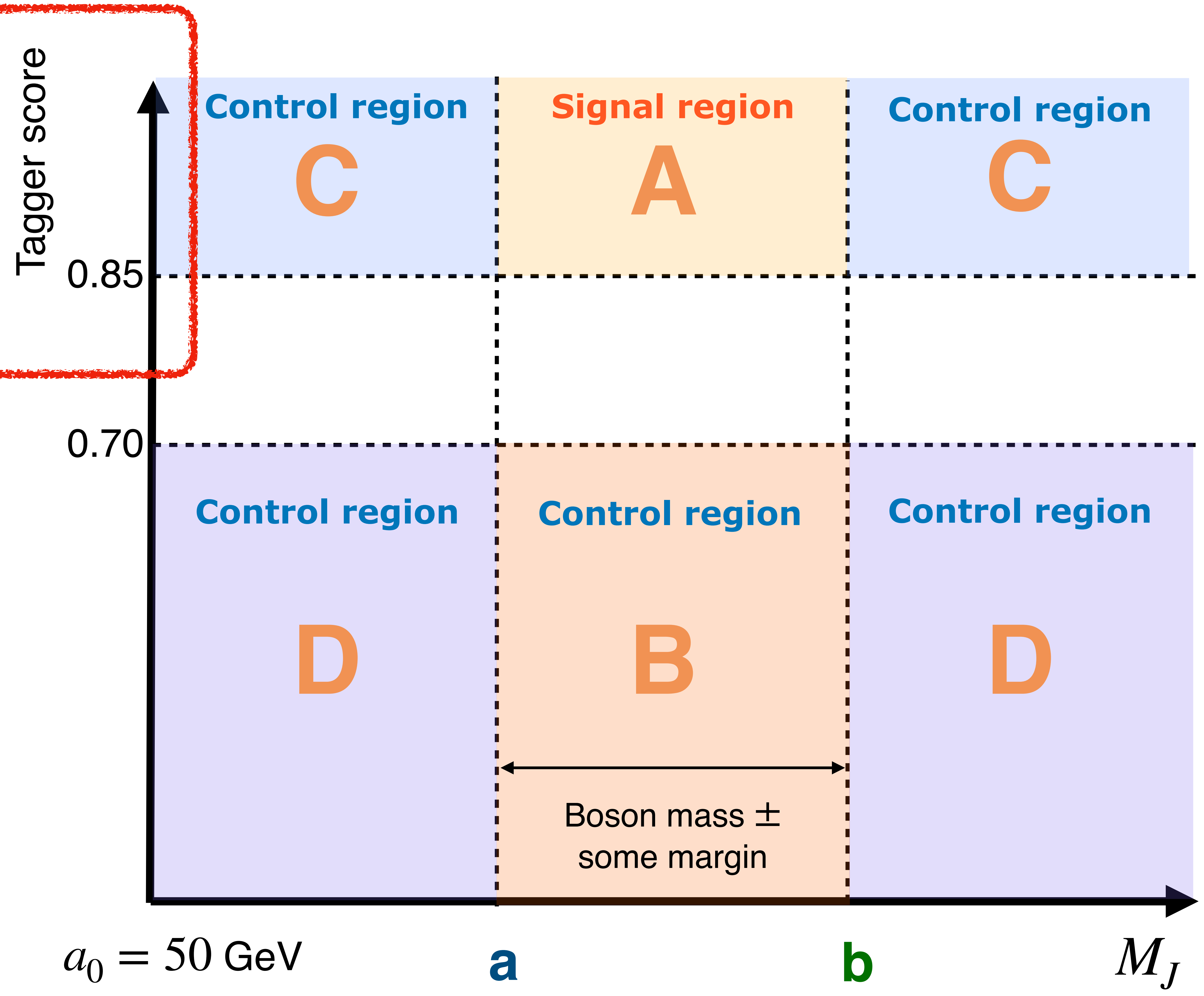


ABCD Method: Our Case

- $A = B$ ... the #bkg events within the specific regi...

'Tagger score': algorithm that determines *how likely* it is that this jet came from a W or Z





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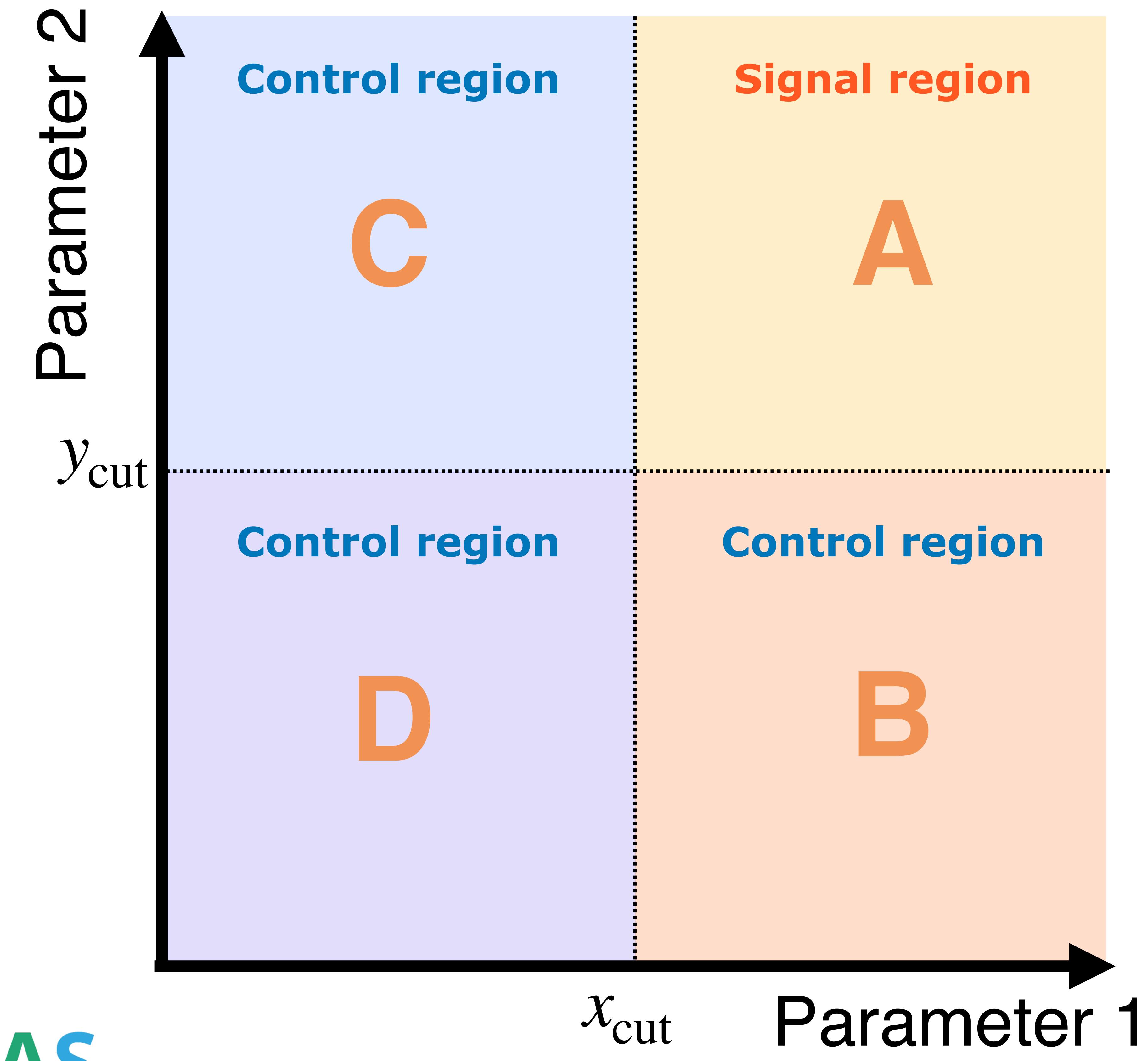

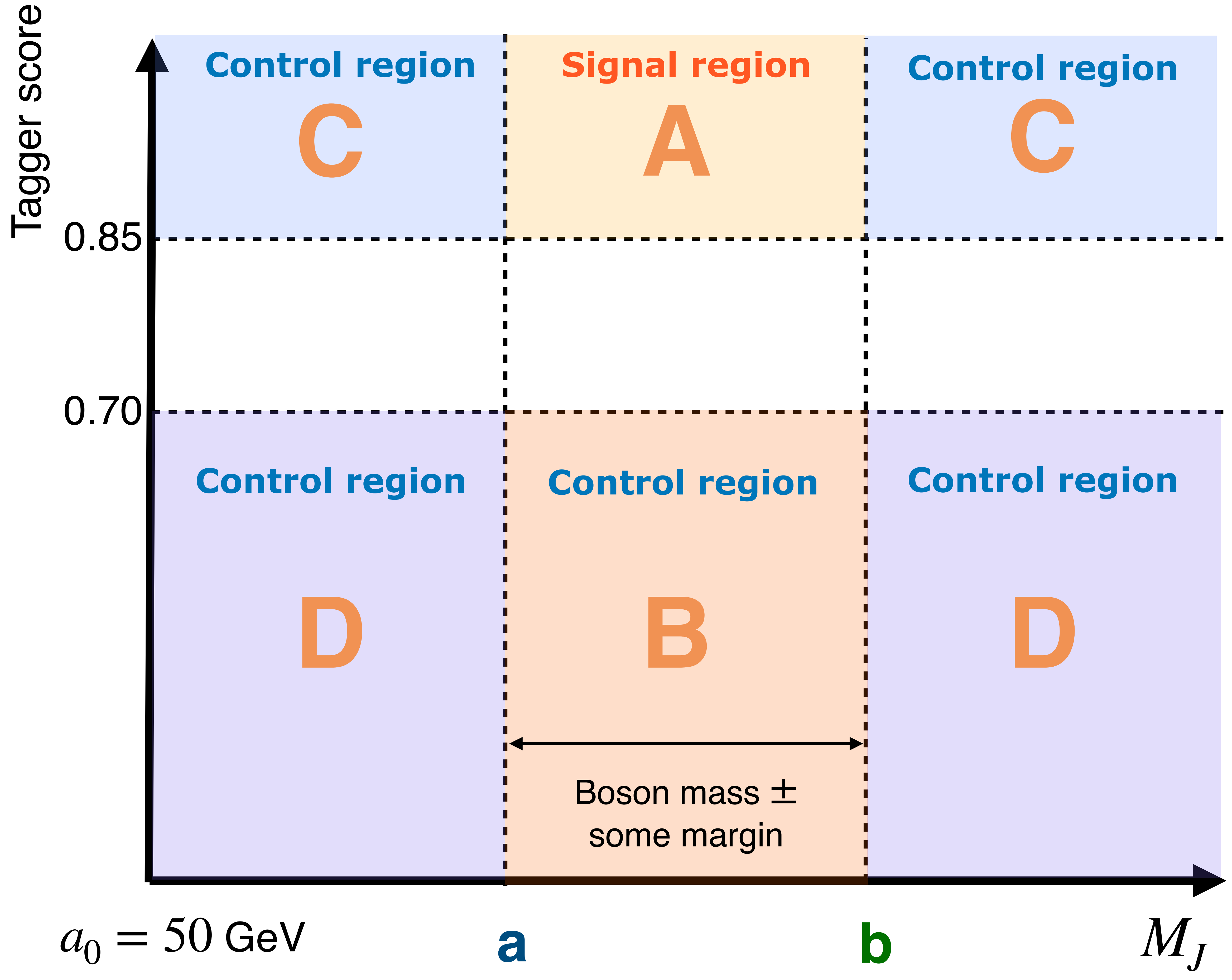

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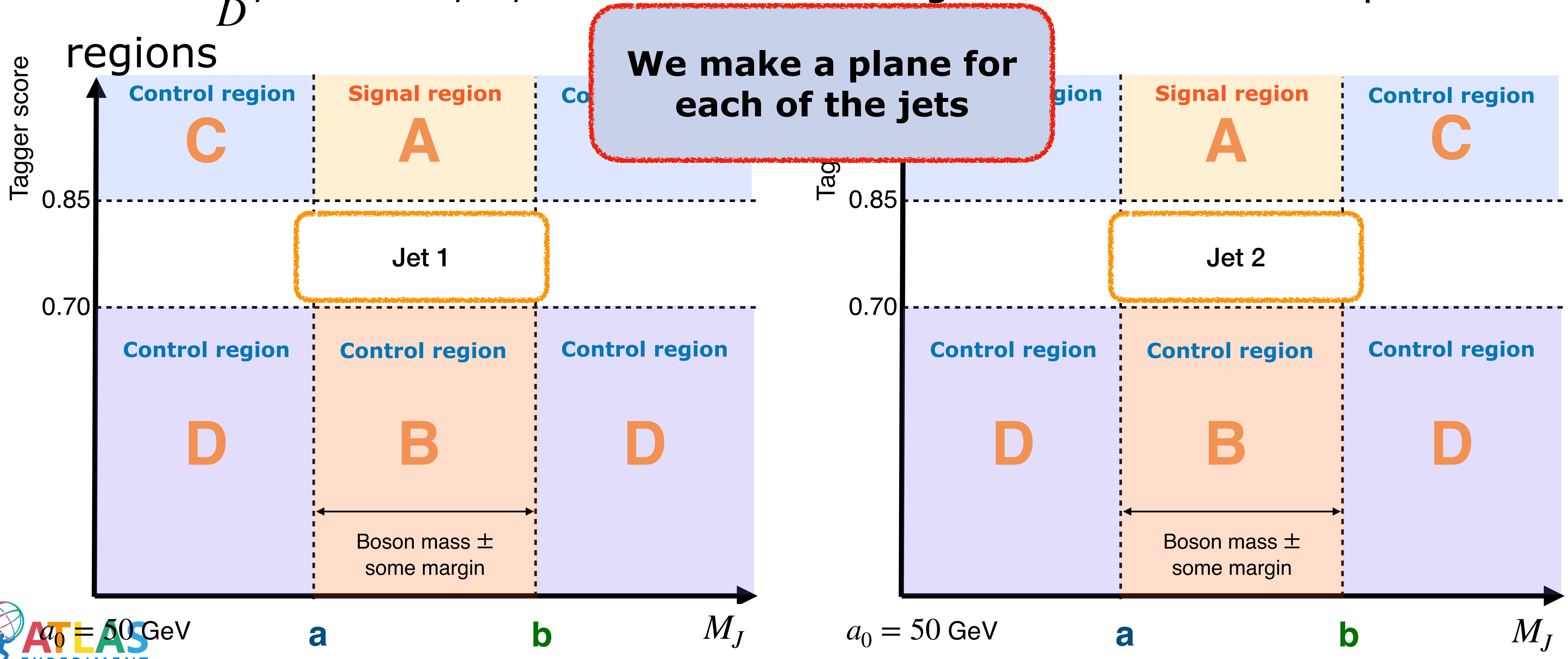

Final QCD Estimate

- After several validation checks, we applied this method to real data

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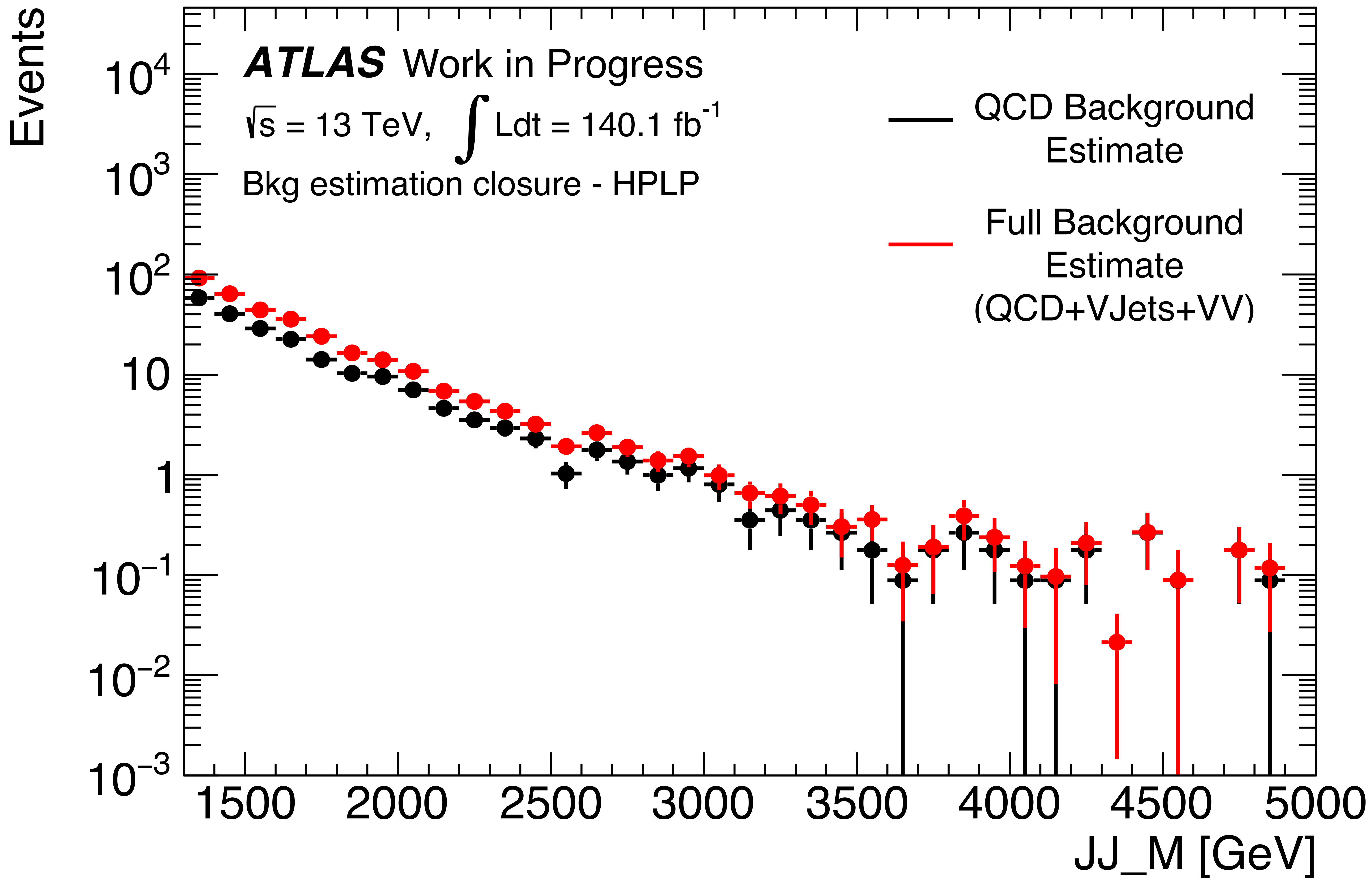
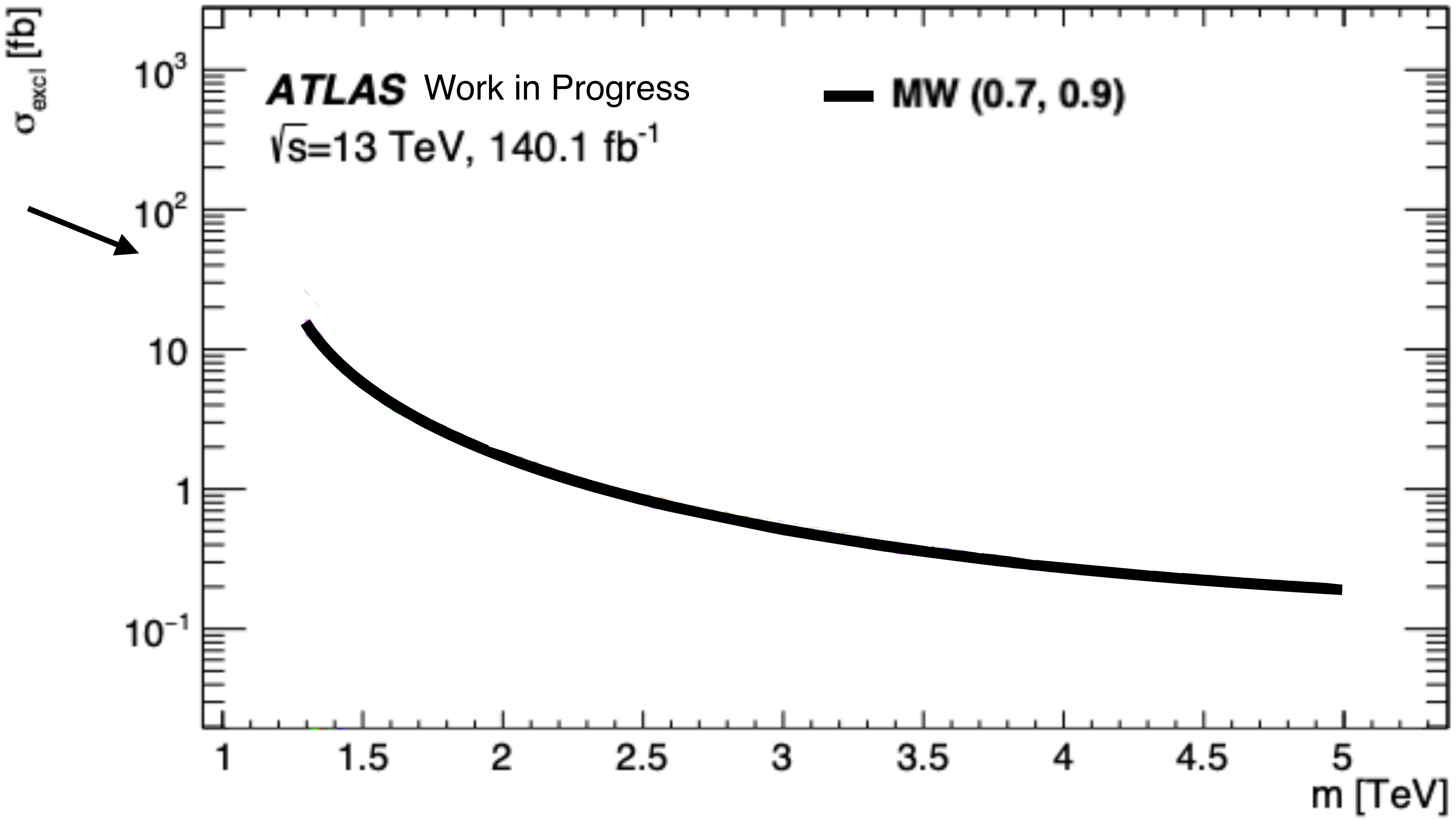


Expected sensitivity

- Given this background estimate, these are the cross sections we can probe



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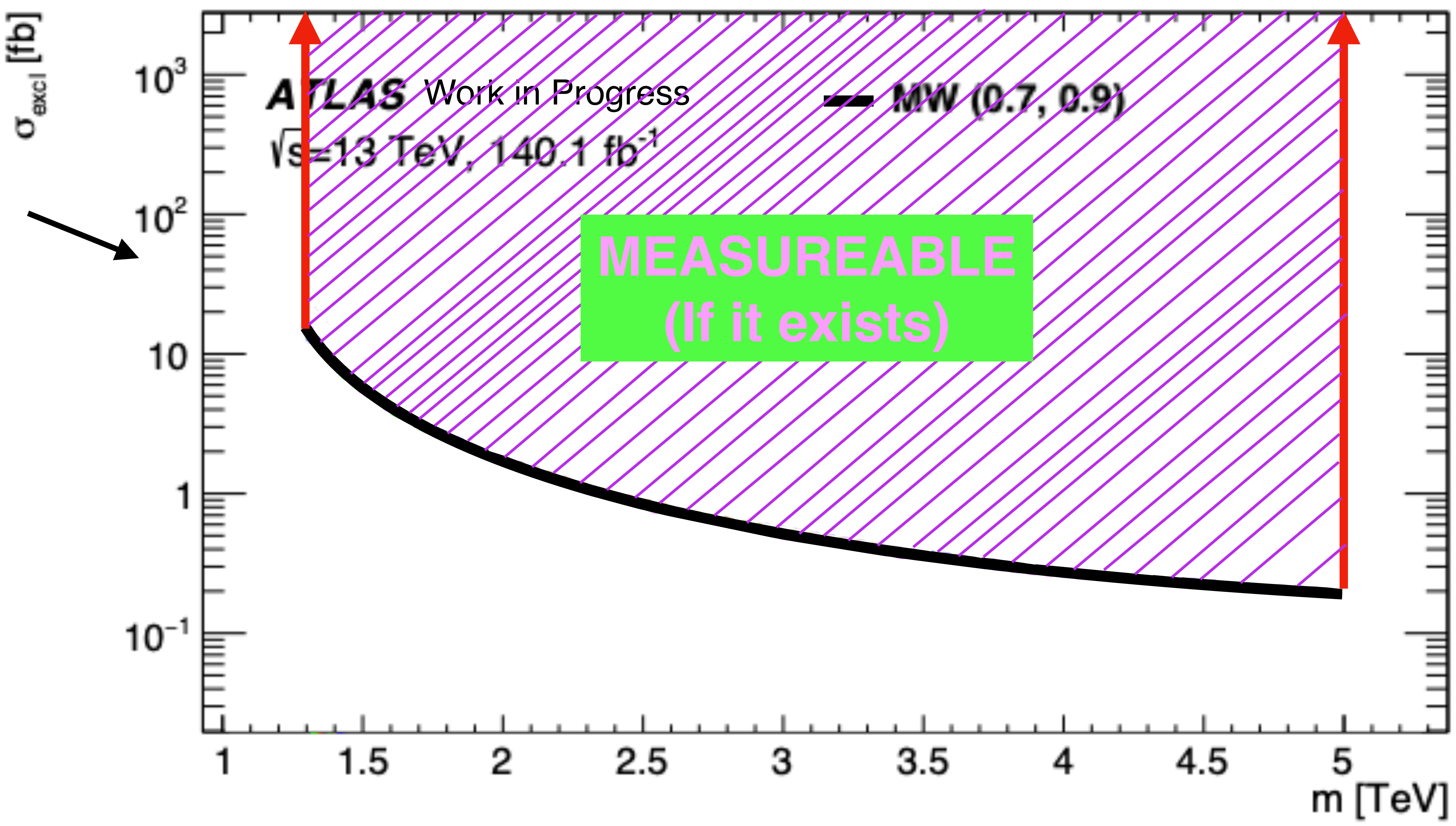

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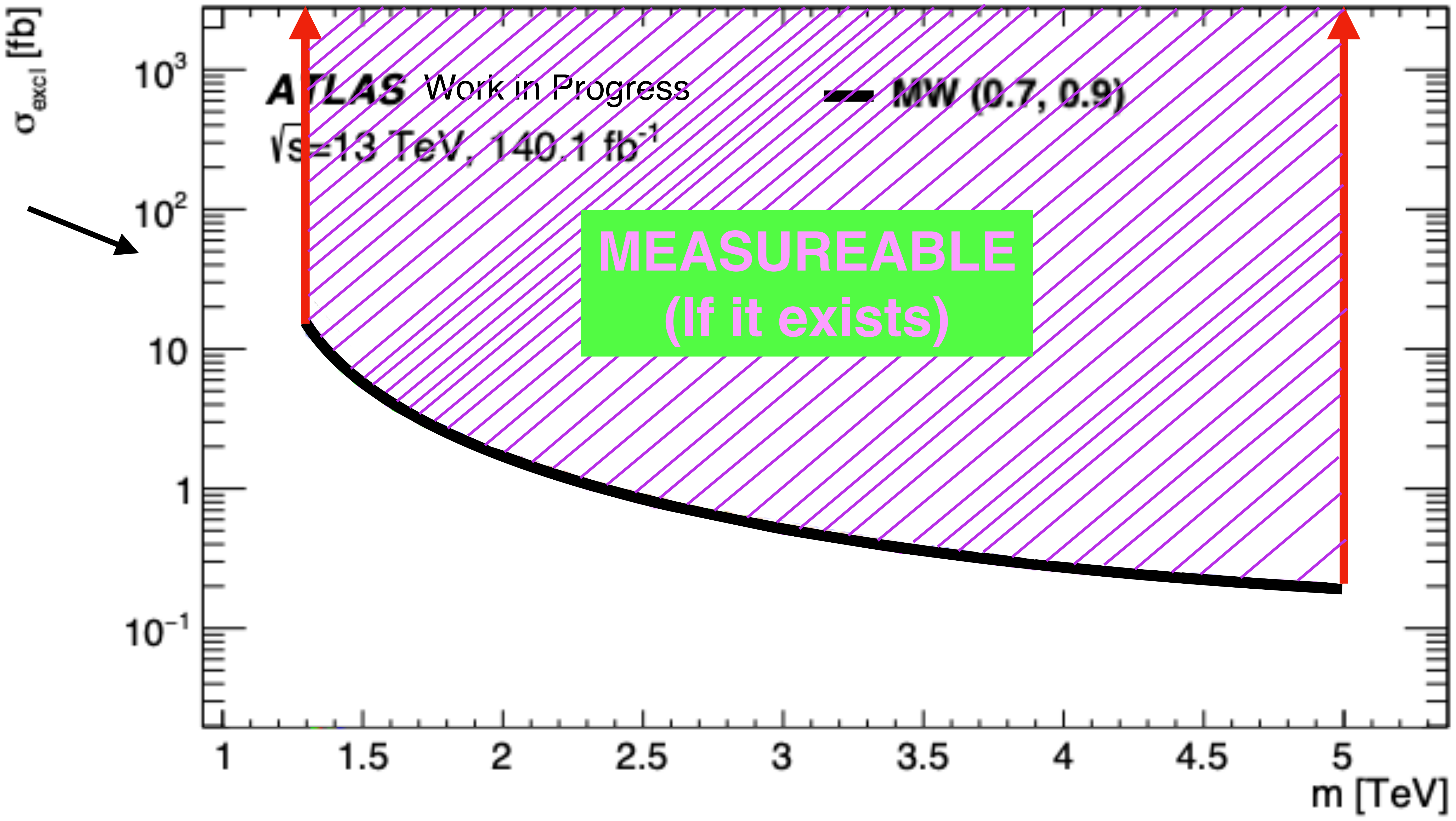
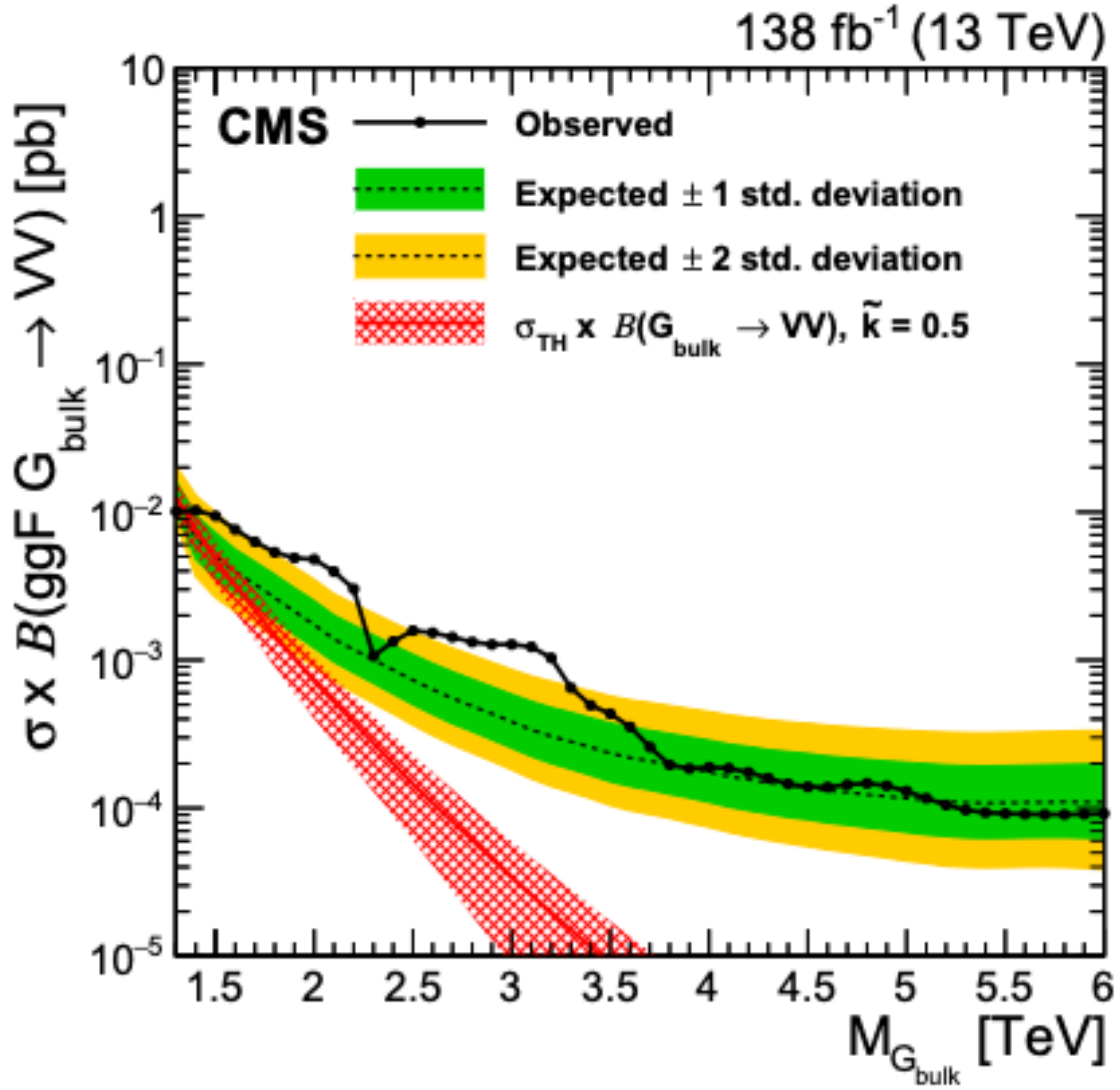


CMS result

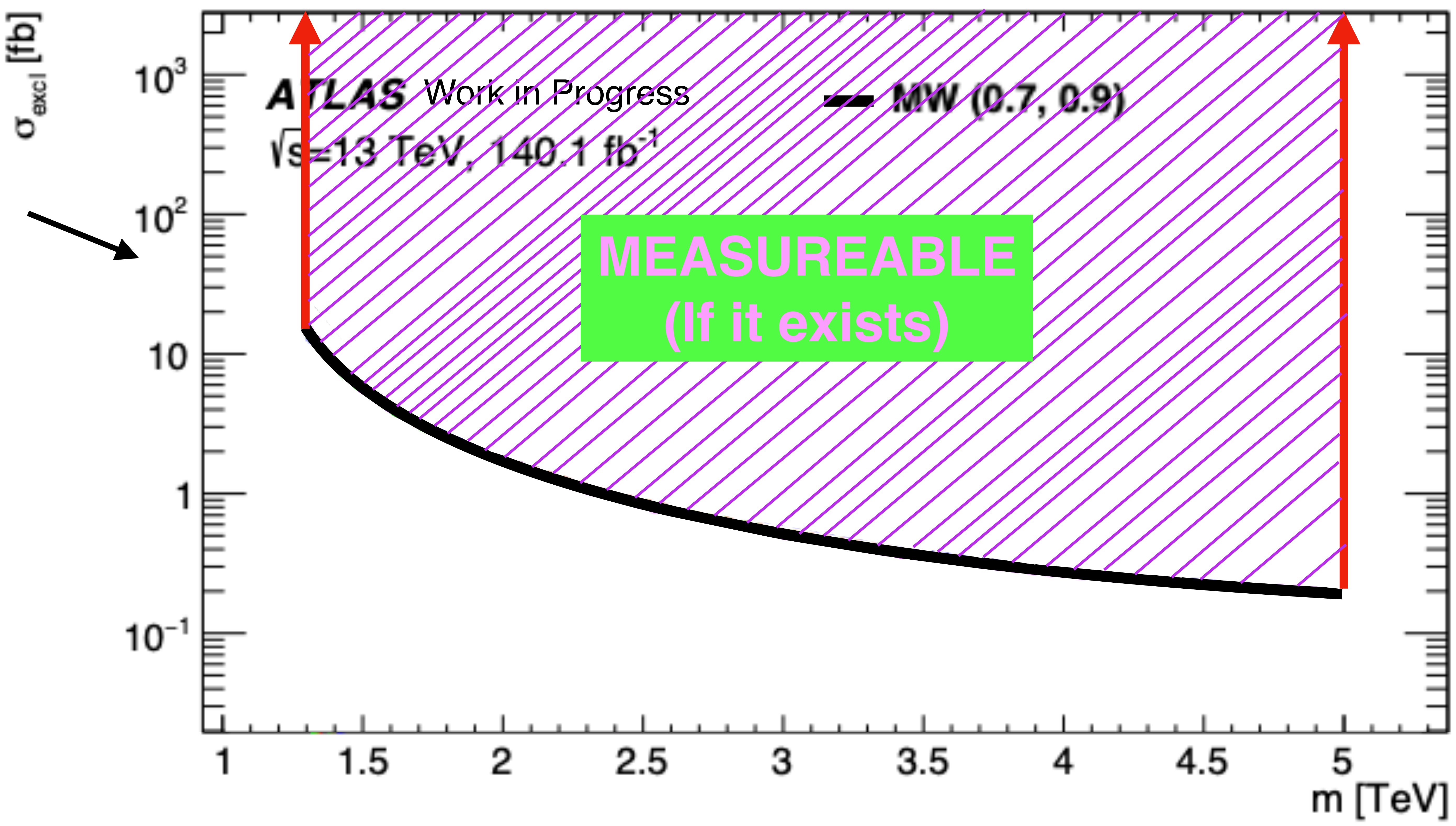
2210.00043

- We are still in the process of waiting for approval…
- Our results are not public yet, but CMS has released theirs
  - ➡ They find a 3.6σ local excess at 2.1 TeV and 2.9 TeV (2.3σ global)



Expected sensitivity

- Given this background estimate, these are the cross sections we can probe
  - ➡ Might be sensitive to BSM signal?
  - ➡ Have to look at data!
    - We are sensitive enough to confirm or refute CMS' observation



Summary & Conclusion

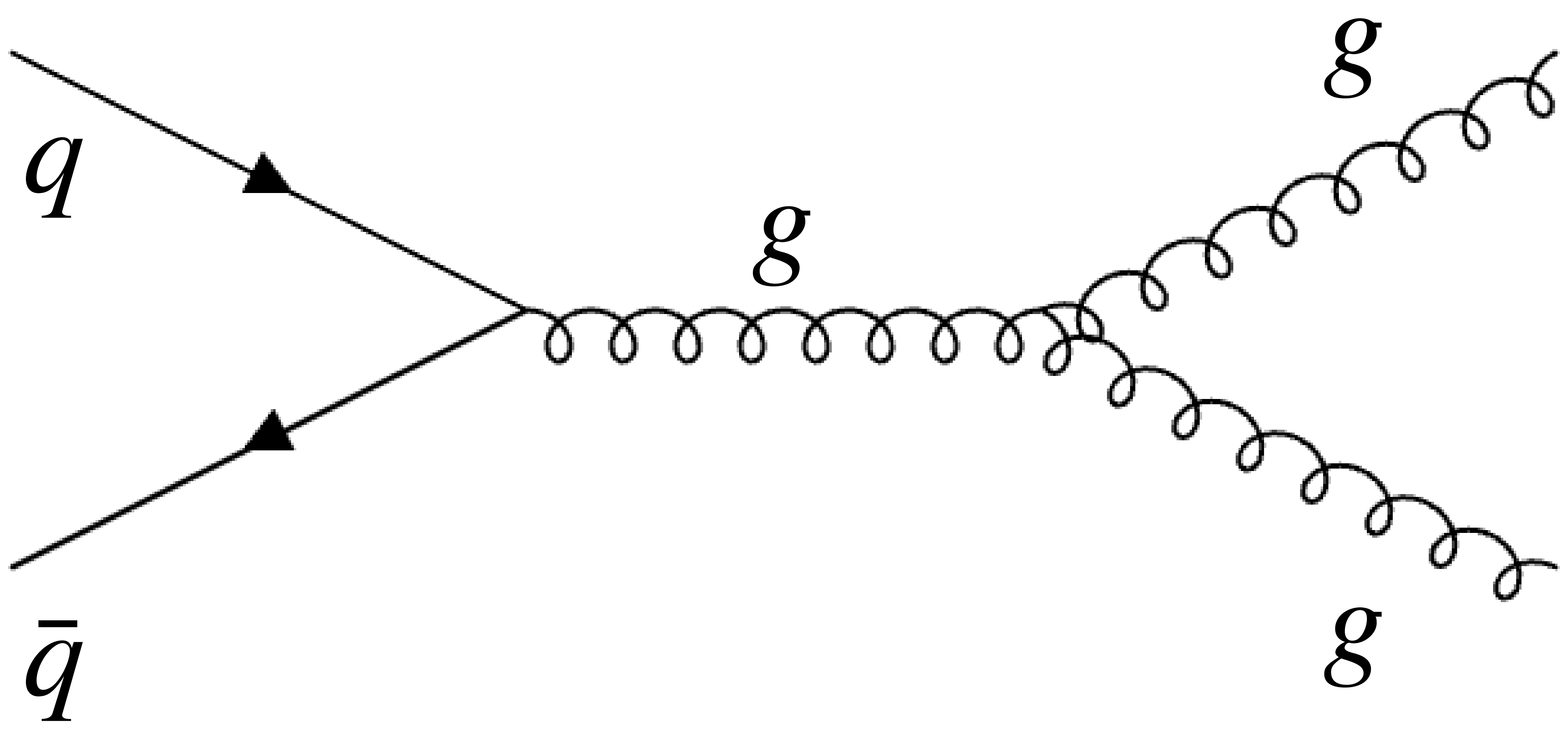
- W/Z bosons good probe for new physics
- Overcome QCD hurdle by using ABCD method
- Now that we have our background fully under control we can move onto the next steps
  - ➡ Look at full data set and compare with bkg estimation to see if there is any new physics

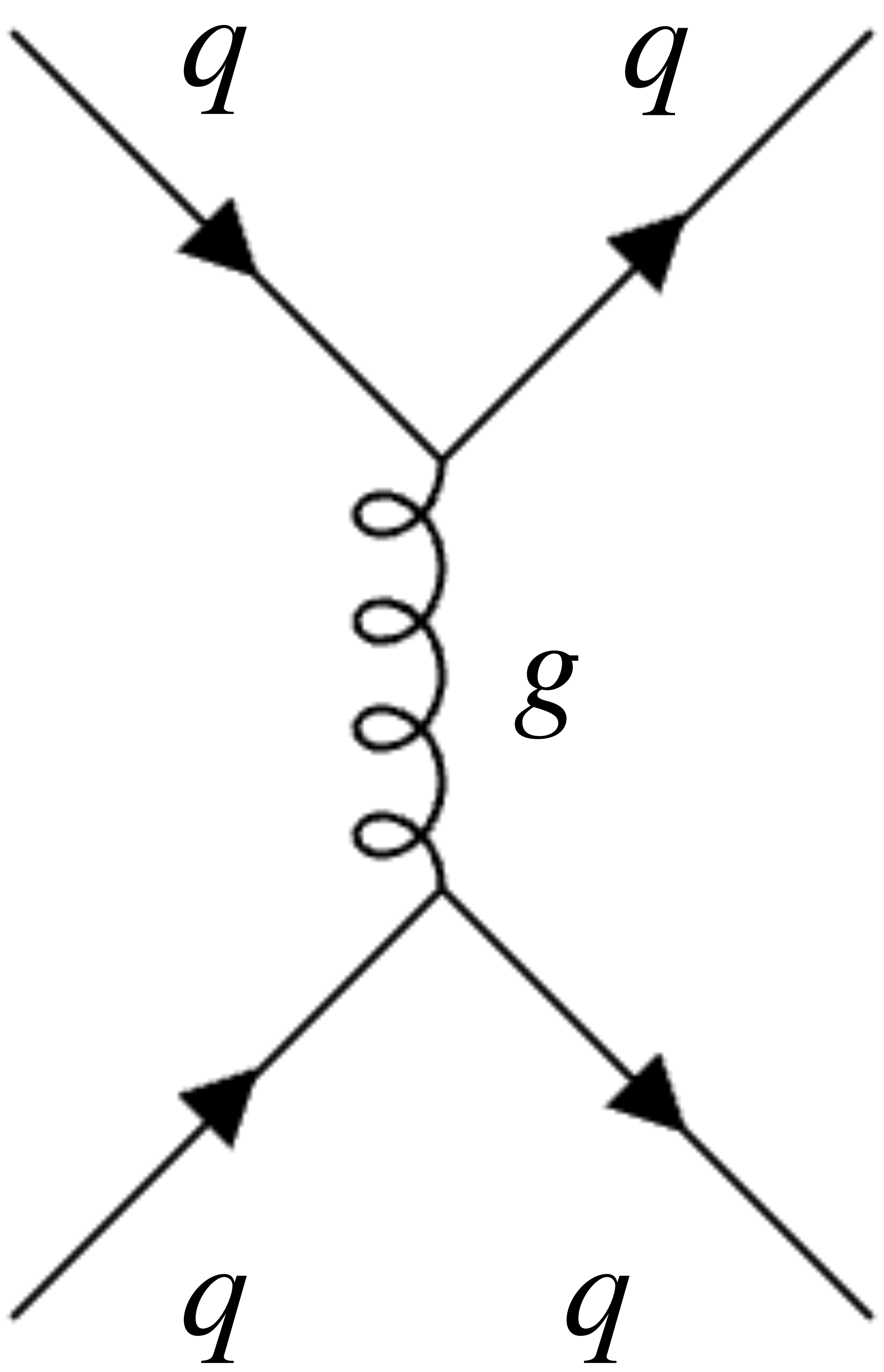
Backup

Diboson searches: fully hadronic

- Lots of *QCD multijet* background in this channel
  → Jets coming from different processes

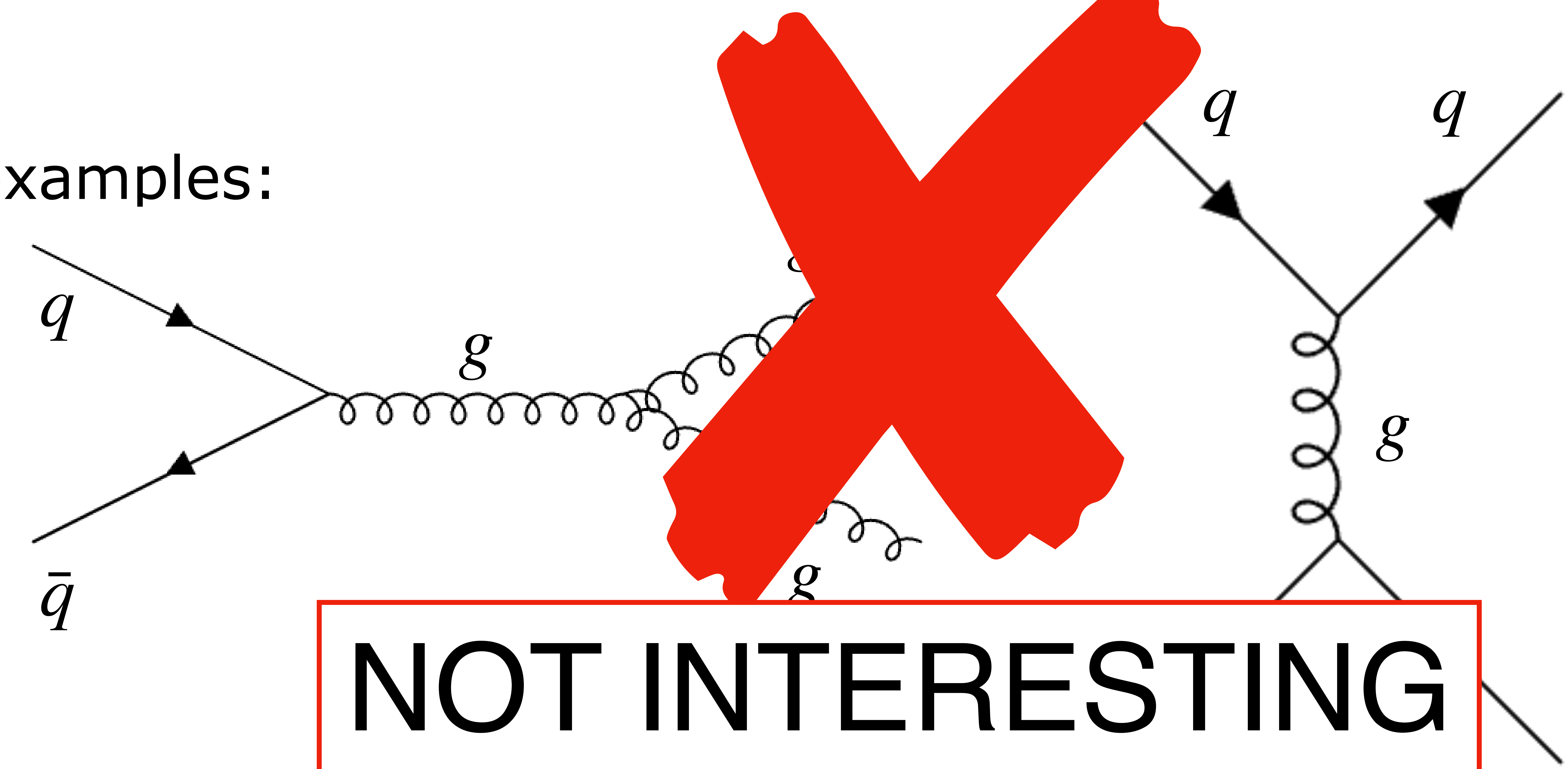
- Two examples:





Diboson searches: fully hadronic

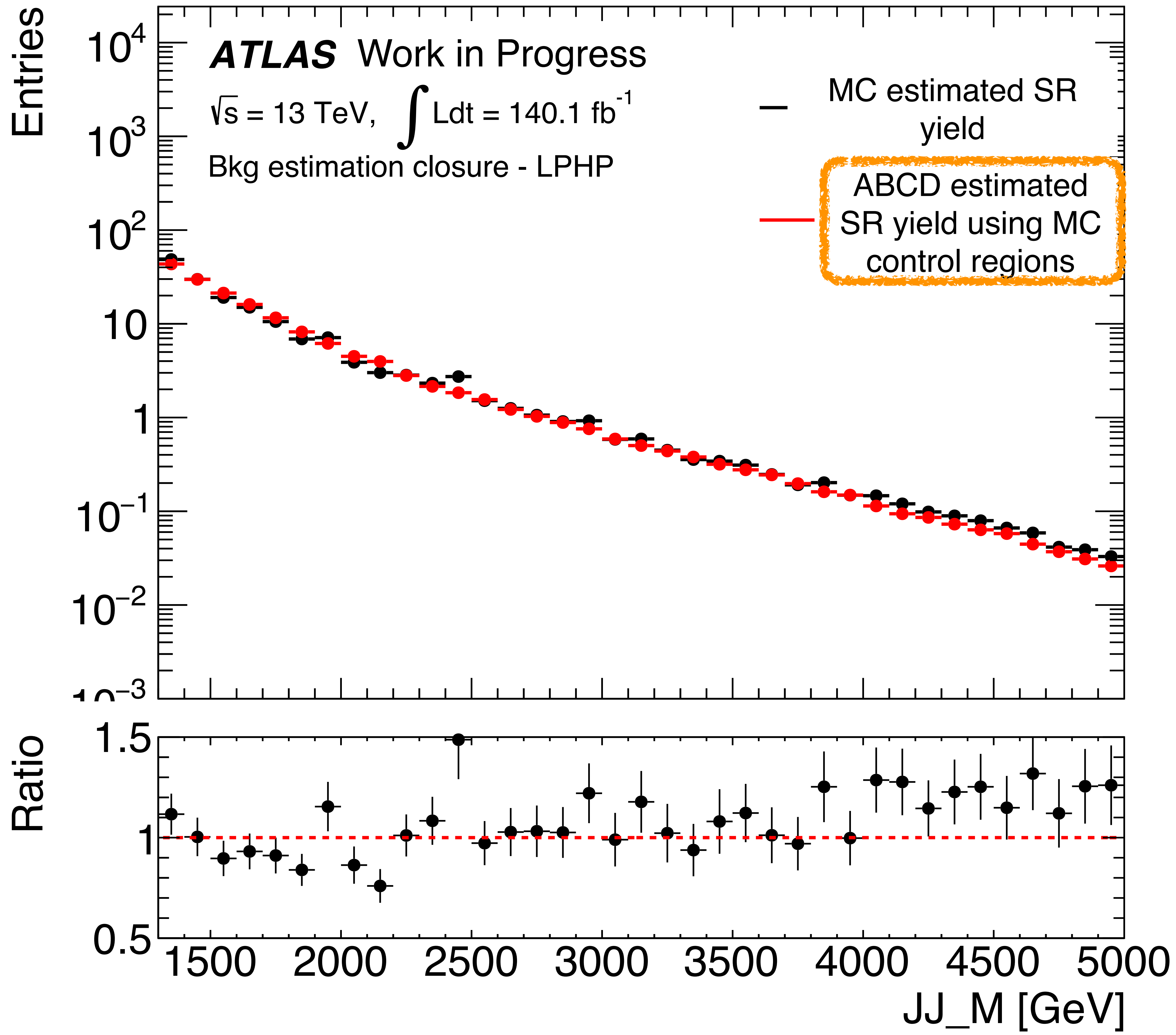
- Lots of *QCD multijet* background in this channel
  → Jets coming from different processes
- Two examples:



NOT INTERESTING
(to us 😊)

Final QCD Estimate

- We have the setup and machinery ready, now need to see if it works properly (= validation)
- First try out the method on MC simulations to see if it delivers consistent results:
  - ➡ Use MC control regions as input for ABCD (and see if it returns the same SR output as 'raw' MC)
  - ➡ Consistency check



Final QCD Estimate

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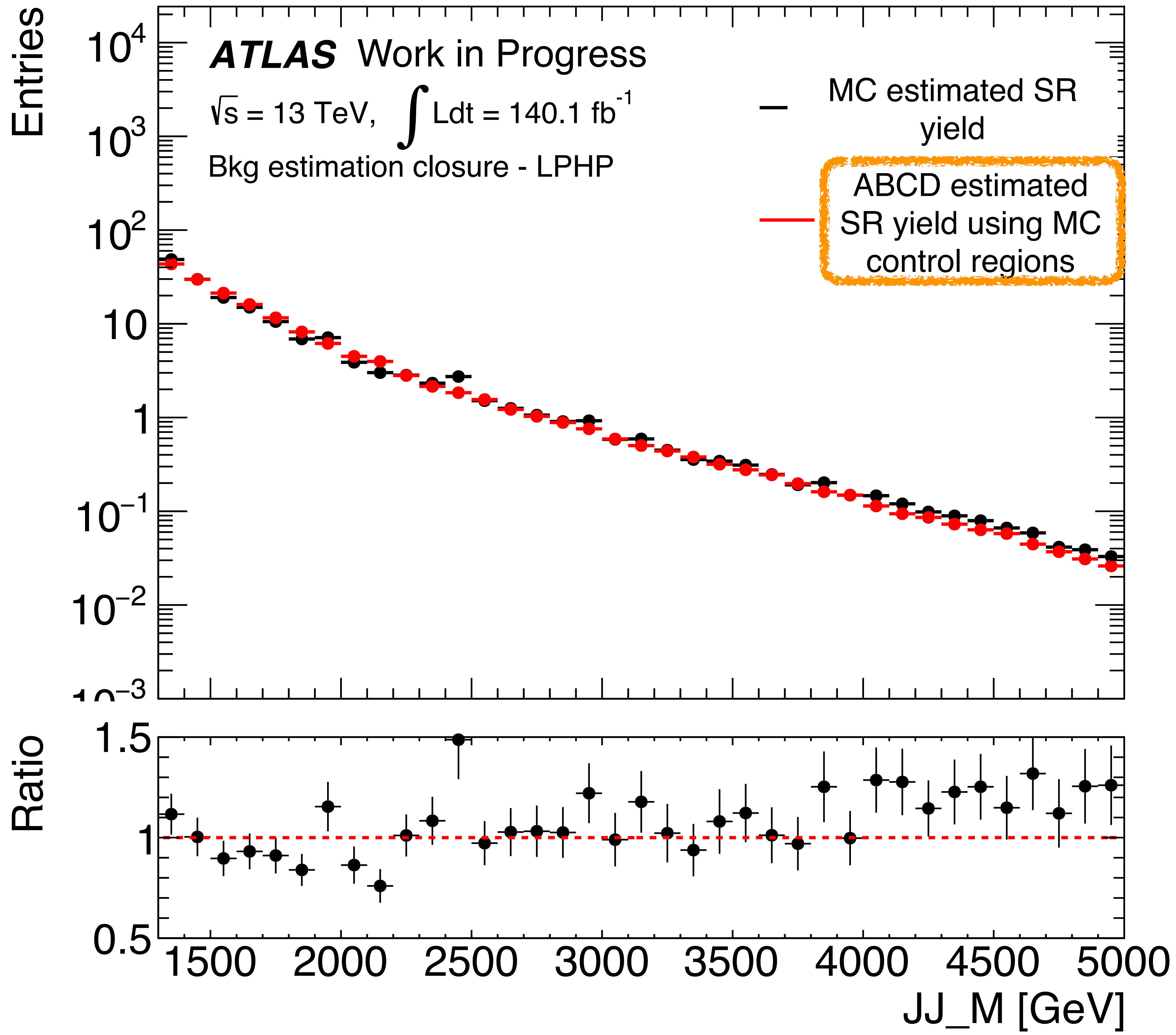
- First try out the method on MC simulations to see if it delivers consistent results:
  - ➡ Use MC control regions as input for ABCD (and see if it returns the same SR output as 'raw' MC)
  - ➡ Consistency check
- We find good agreement between MC and ABCD ✓



ABCD Method: Our Case

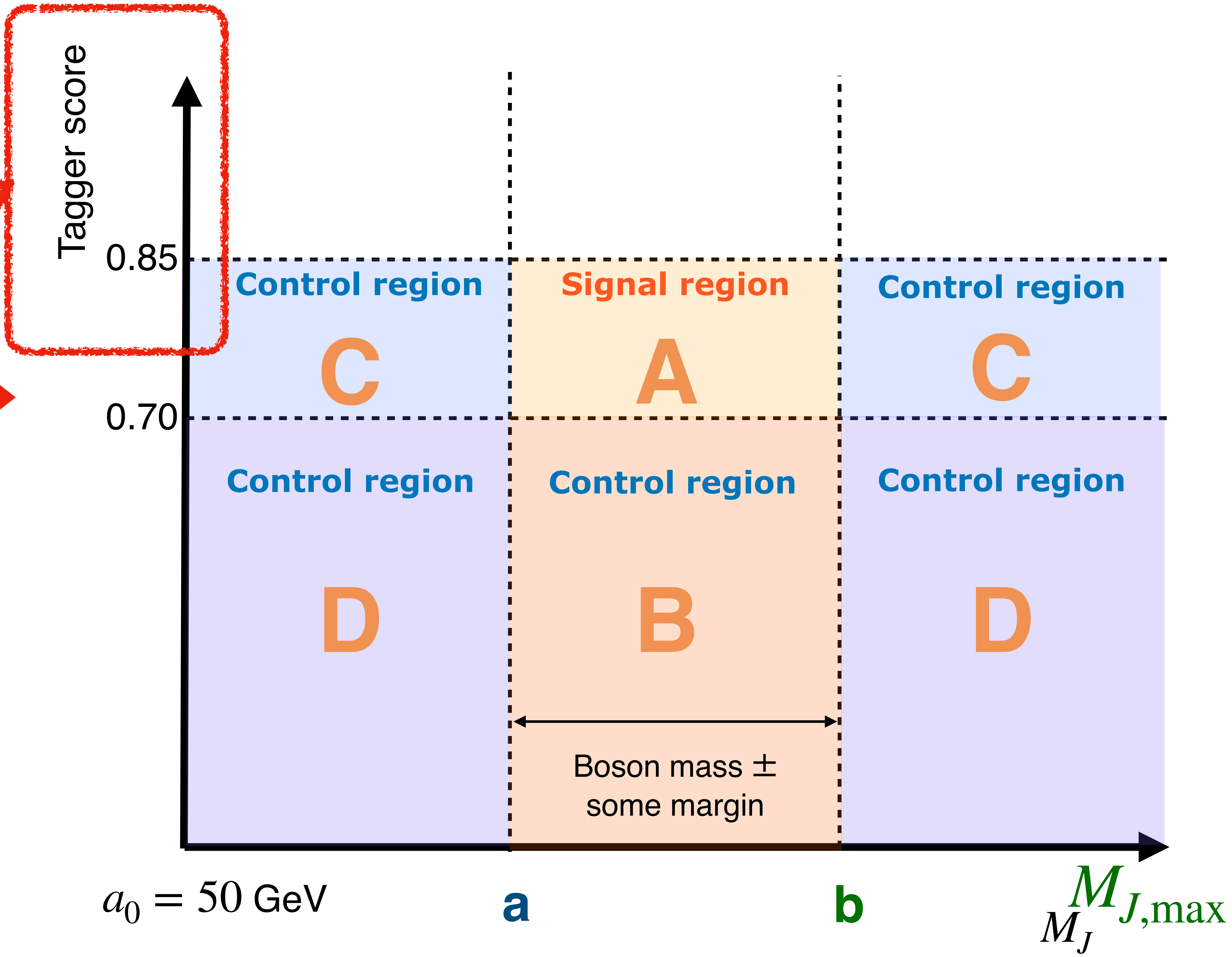
- $A = B \frac{C}{}$ … the #bkg events within the specific regi…

Parameter 2

y

x_{cut} Parameter 1

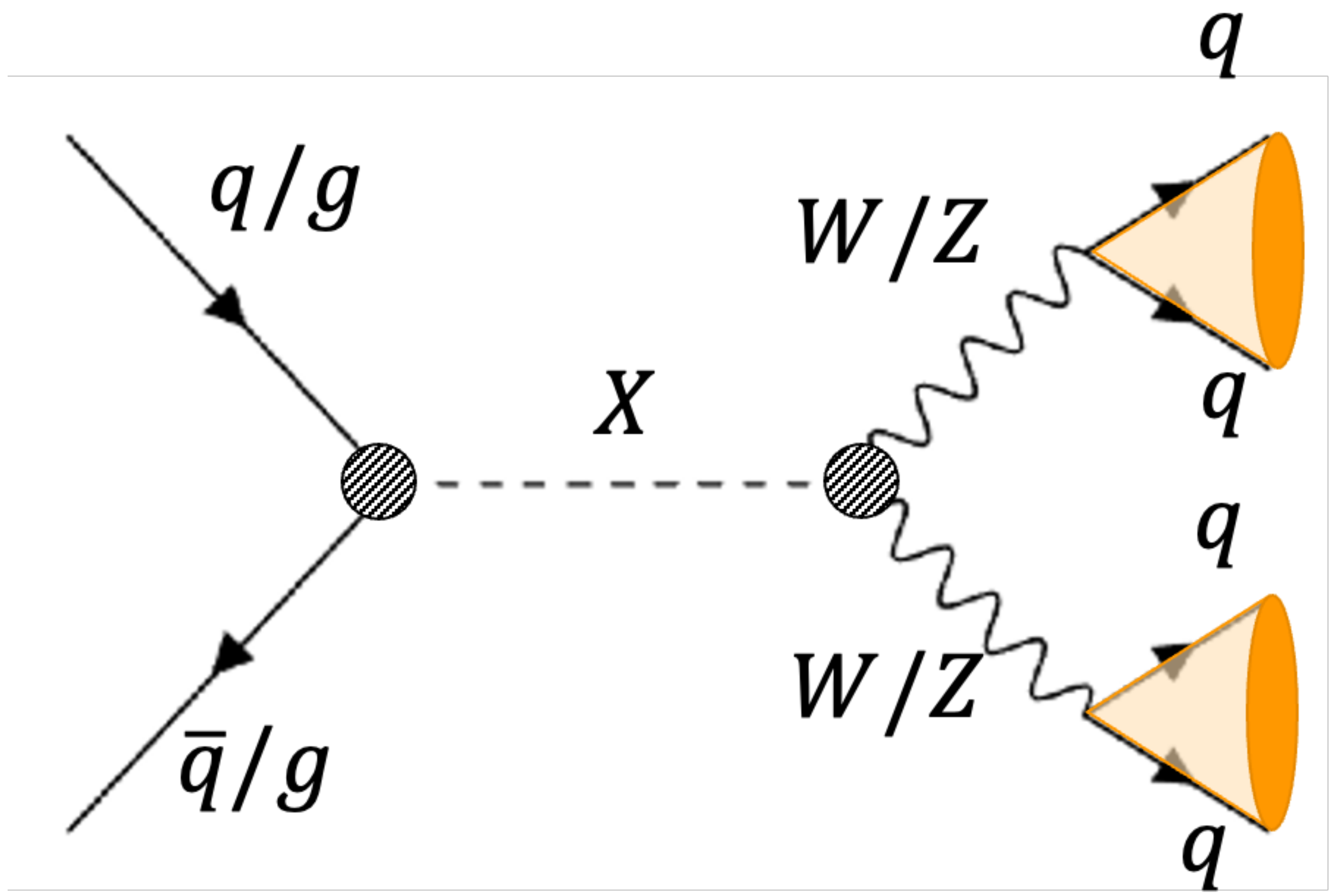
Also have a less strict scenario, we require a lower tagger score -> “Low Purity” (LP)

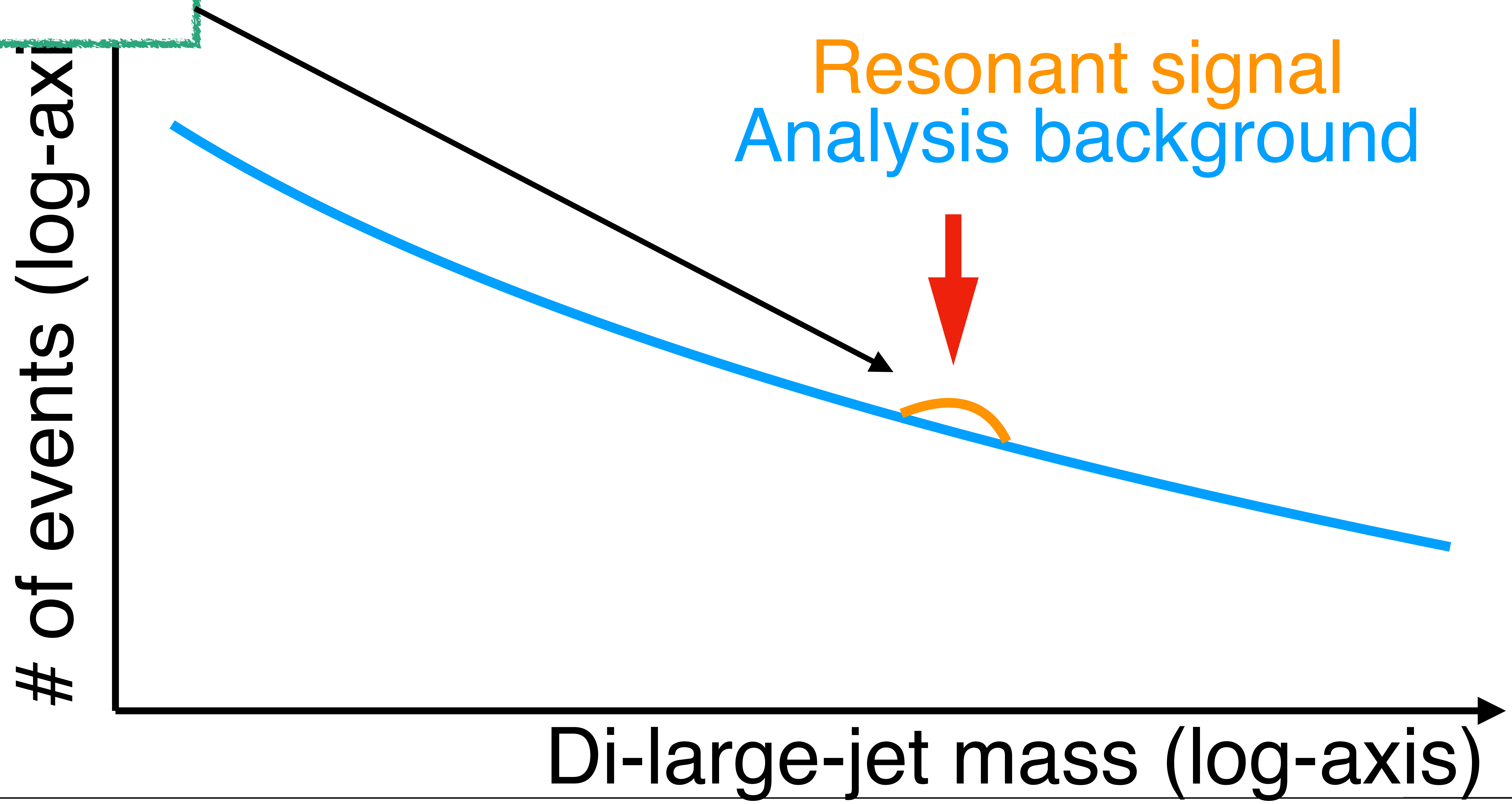


Diboson searches: fully hadronic

- The signal: some heavy particle *X* decays into *two V-bosons* which decay into **two of large-R jets (=dibosons)**
- What we wa[nt] ... [j]ets with a combined invariant mass 2 - 6 TeV

Expect the signal to look like a resonance peak

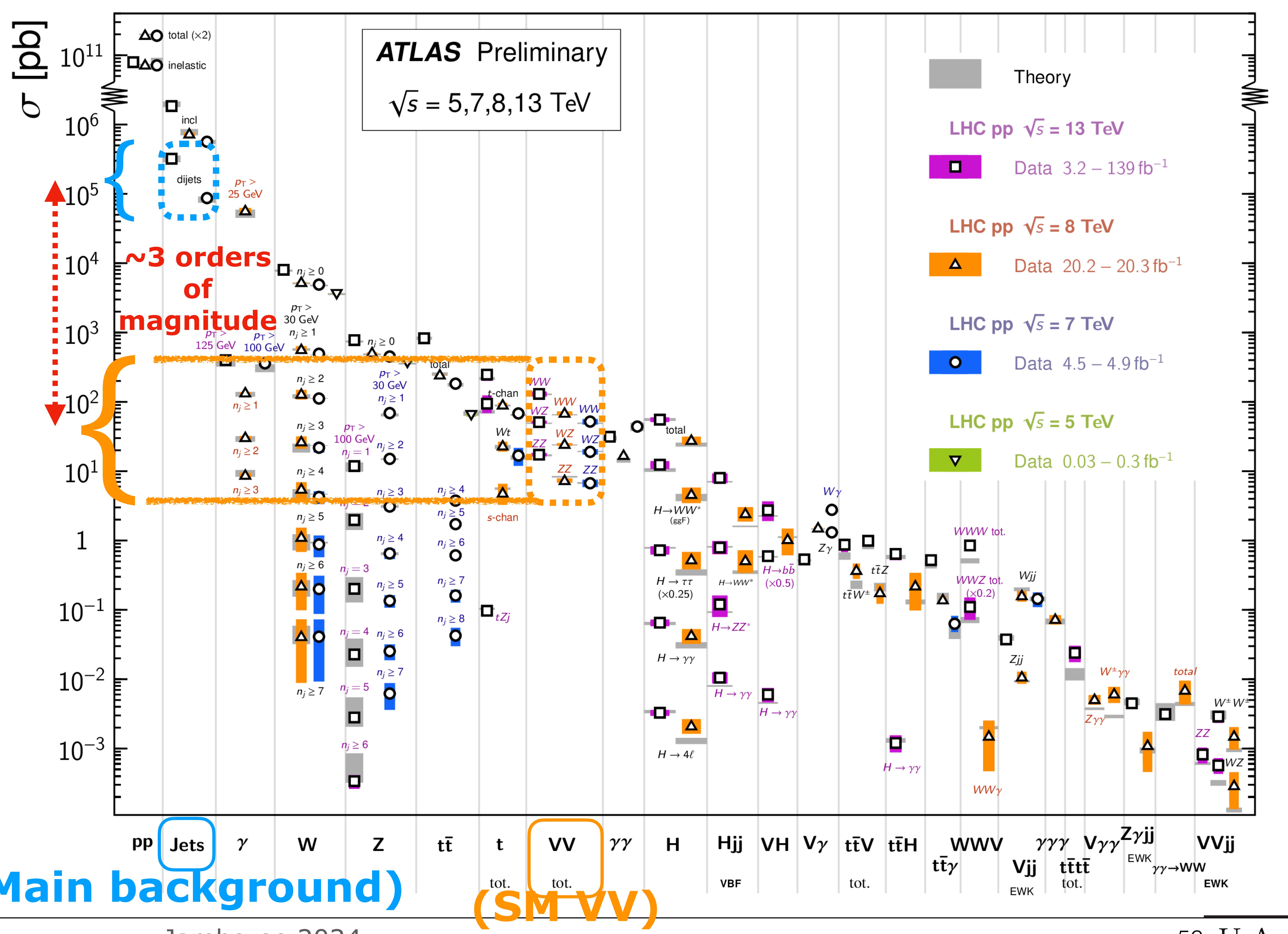




Diboson searches: major challenge

Plot: PUB-2021-03

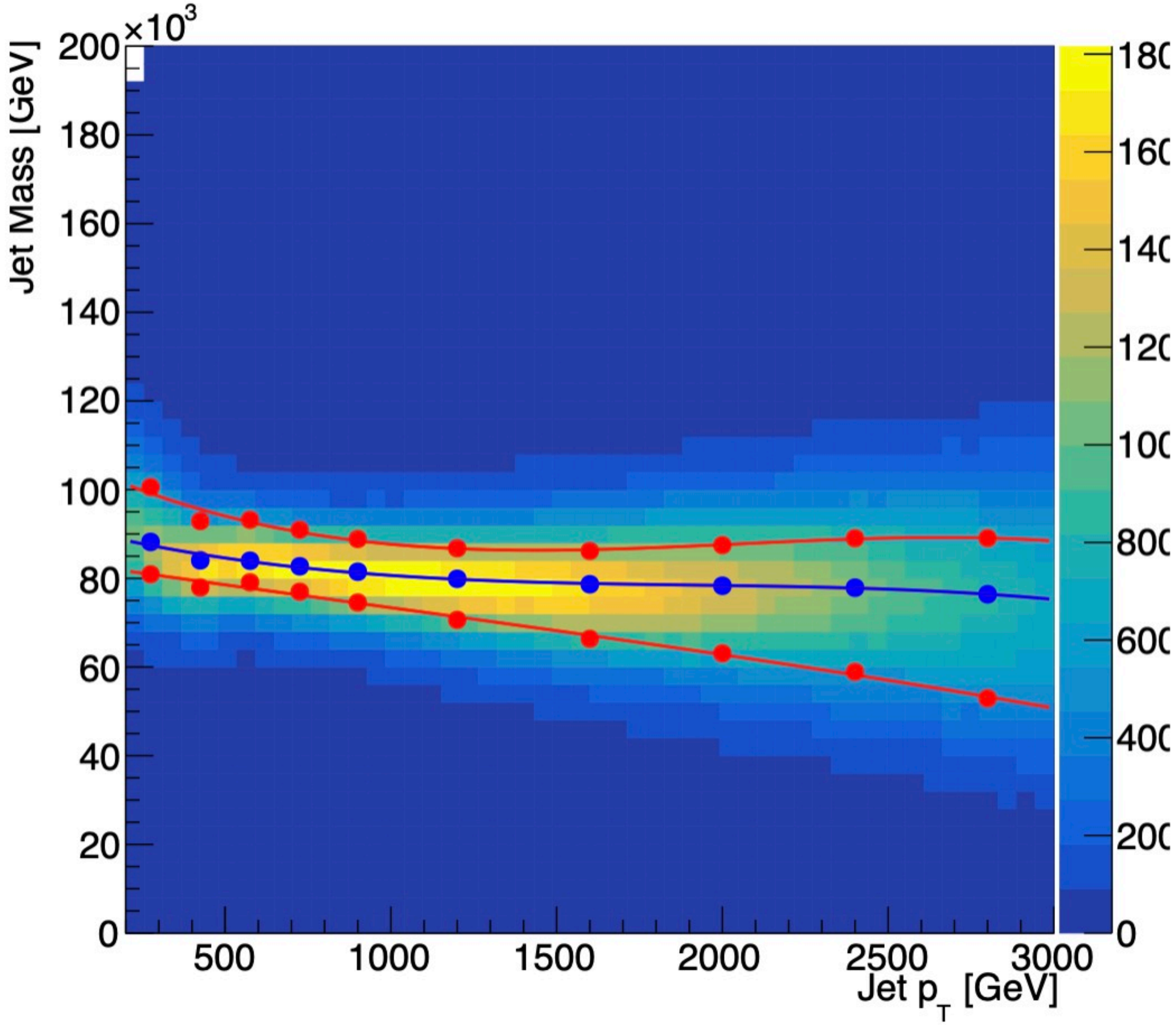
- Since we are working with a fully hadronic final state, QCD background is dominant
  - ➡ Need to find some way to keep our bkg under control

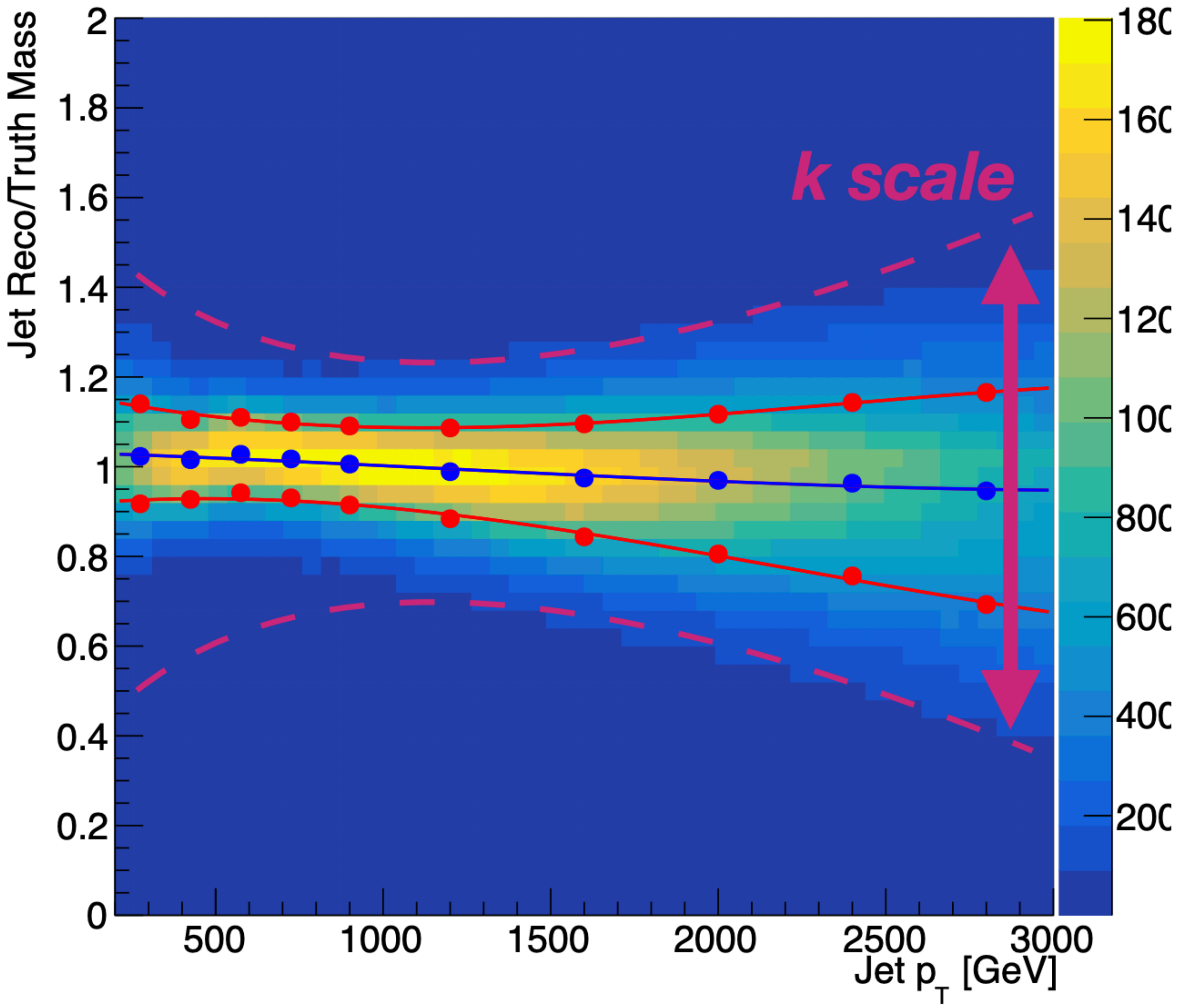


Background ABCD setup

Strategy 1006		Jet 1	Jet 2
HPHP			
	A	HP, MW	HP, MW
	B	QCD, MW	HP, MW
	C	HP, LSB || HP, HSB	HP, MW
	D	QCD, LSB || QCD, HSB	HP, MW
HPLP			
	A	HP, MW	LP, MW
	B	HP, MW	QCD, MW
	C	HP, MW	LP, LSB || LP, HSB
	D	HP, MW	QCD, LSB || QCD, HSB
LPHP			
	A	LP, MW	HP, MW
	B	QCD, MW	HP, MW
	C	LP, LSB || LP, HSB	HP, MW
	D	QCD, LSB || QCD, HSB	HP, MW

Mass Window


×10^3
Jet Mass [GeV]
Jet p_T [GeV]
0
20
40
60
80
100
120
140
160
180
200
500
1000
1500
2000
2500
3000

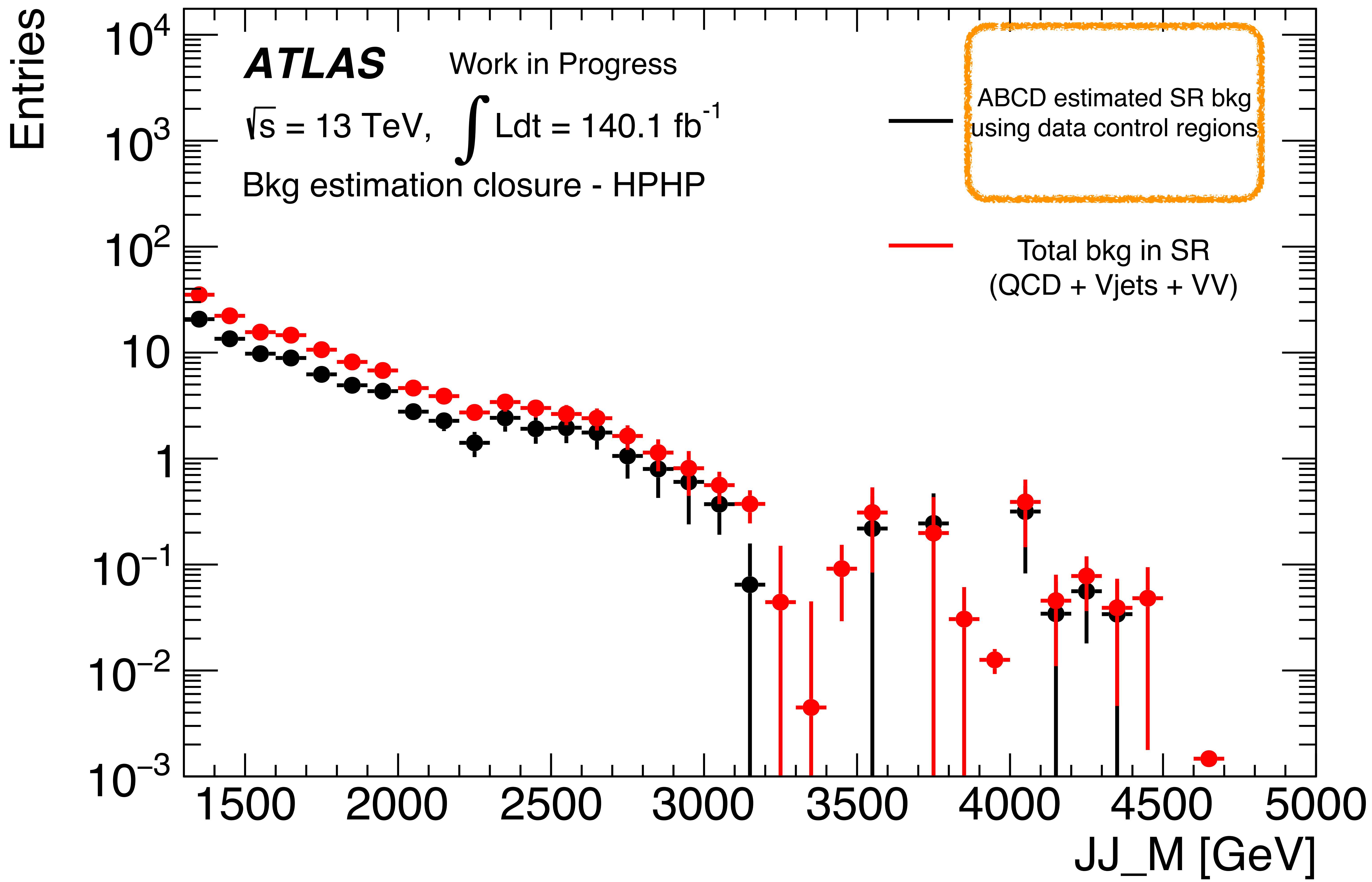

Jet Reco/Truth Mass
Jet p_T [GeV]
k scale
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
500
1000
1500
2000
2500
3000

Input for tagger algorithm

- Low-level: jet constituents
- High-level: jet variables (ntracks, energy distribution within the jet, other jet substructure variables)
- Jet mass
- Output: mass decorrelated score

Final QCD Estimate

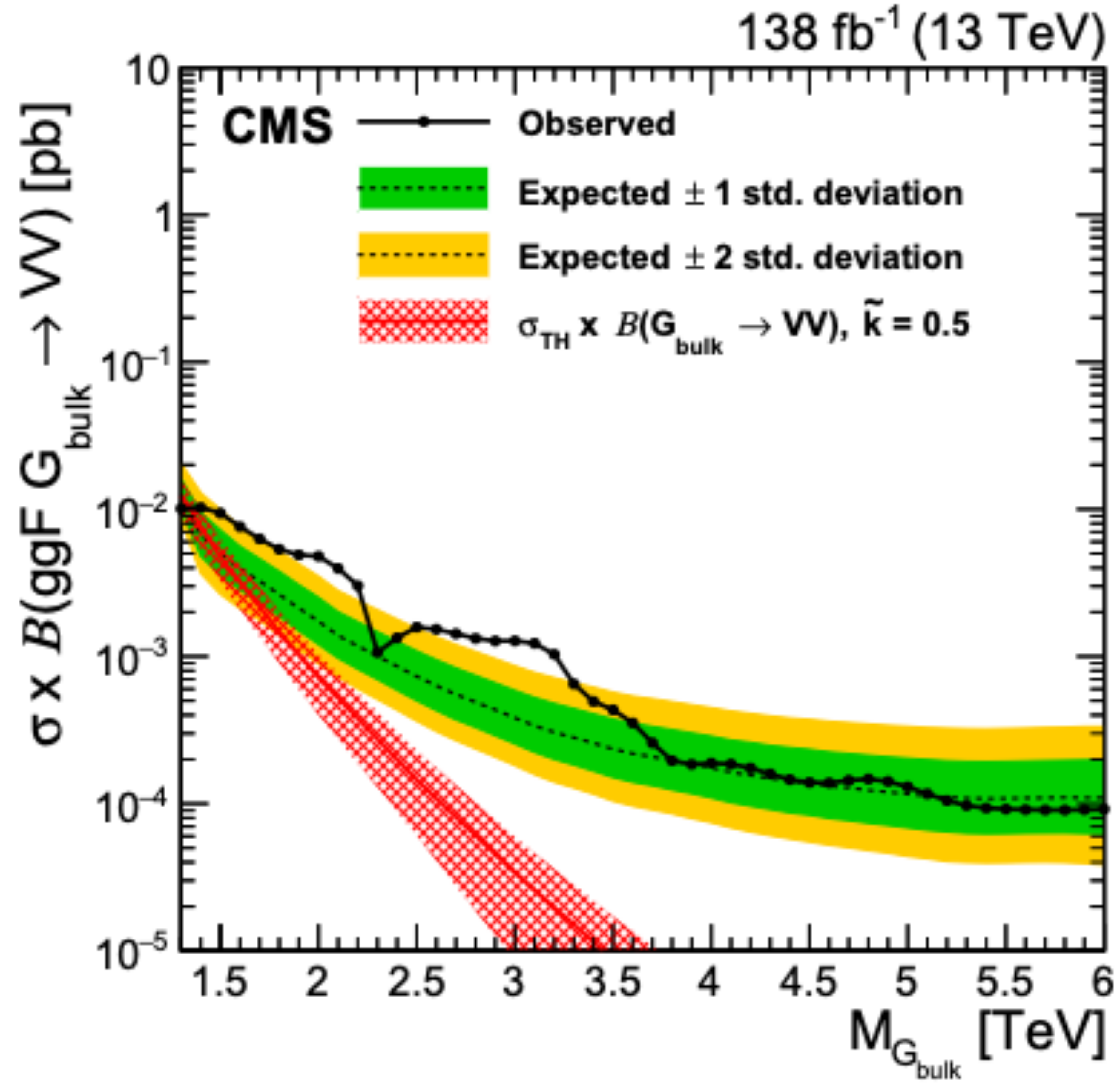
- After several validation checks, we applied this method to real data



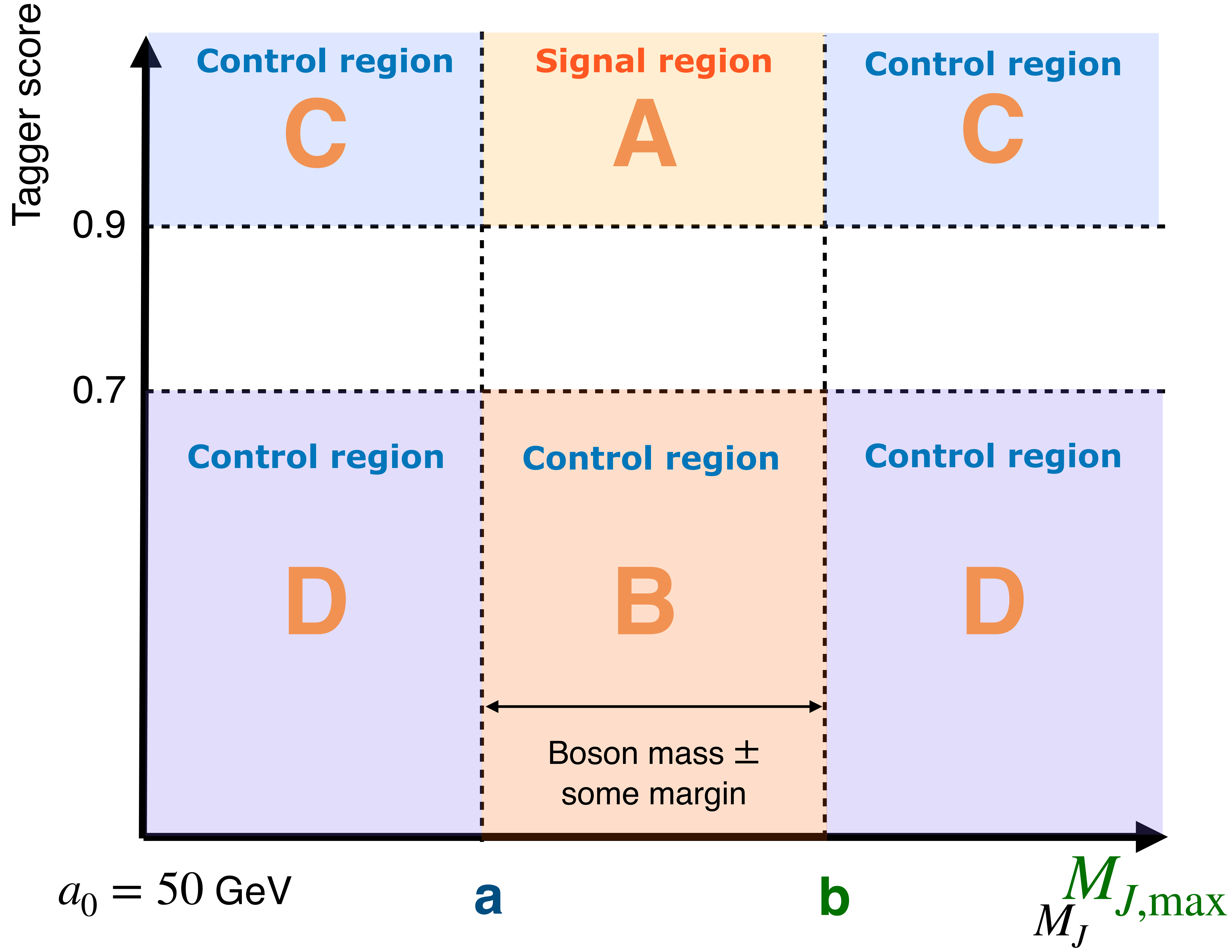
CMS result

2210.00043

- Our results are not public yet, but CMS has released theirs
  - ➡ They find a 3.6σ local excess at 2.1 TeV and 2.9 TeV (2.3σ global)
  - ➡ Good motivation to keep looking at this channel!

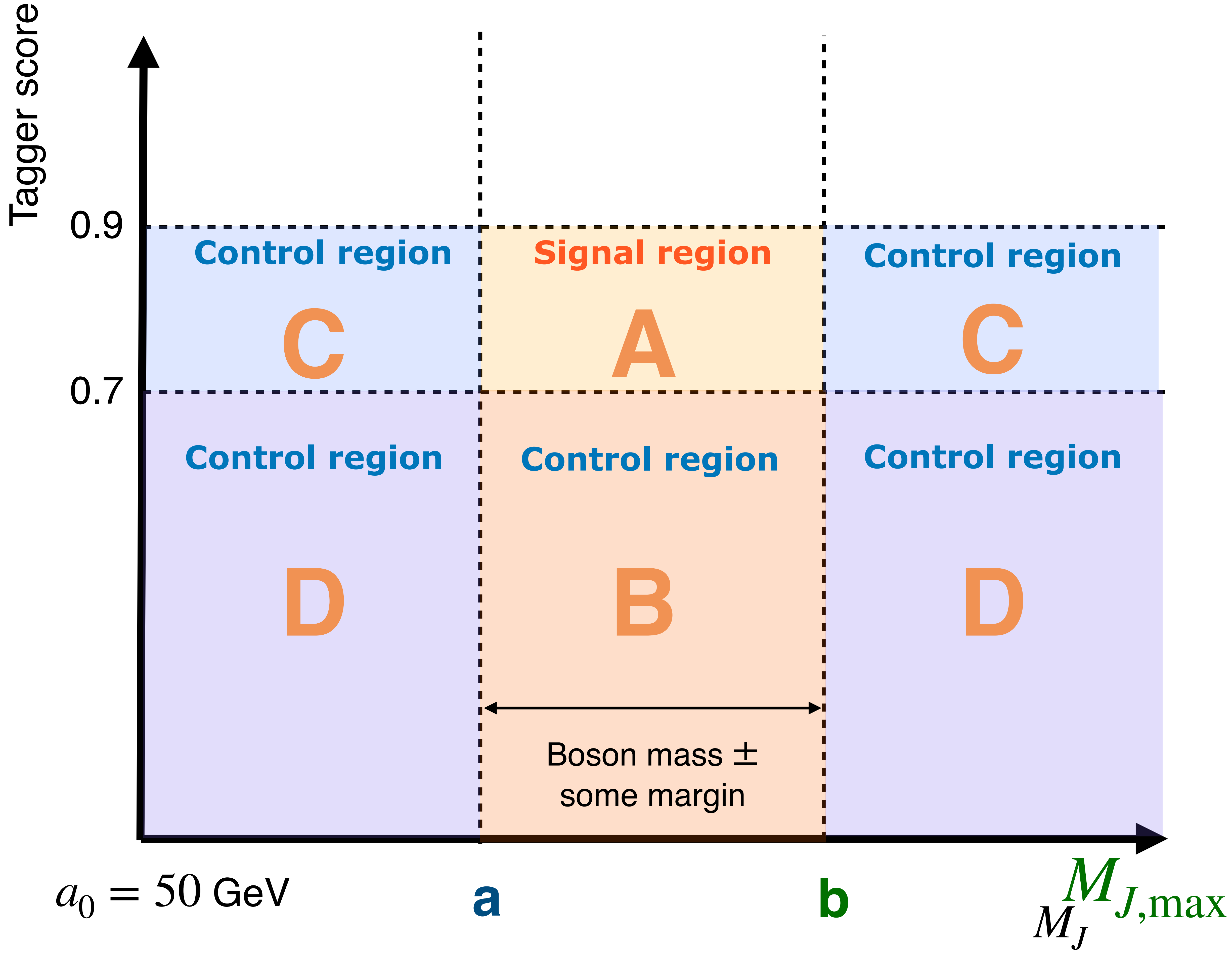


ABCD Method: Our Case



ATLAS EXPERIMENT

ABCD Method: Our Case



Overview

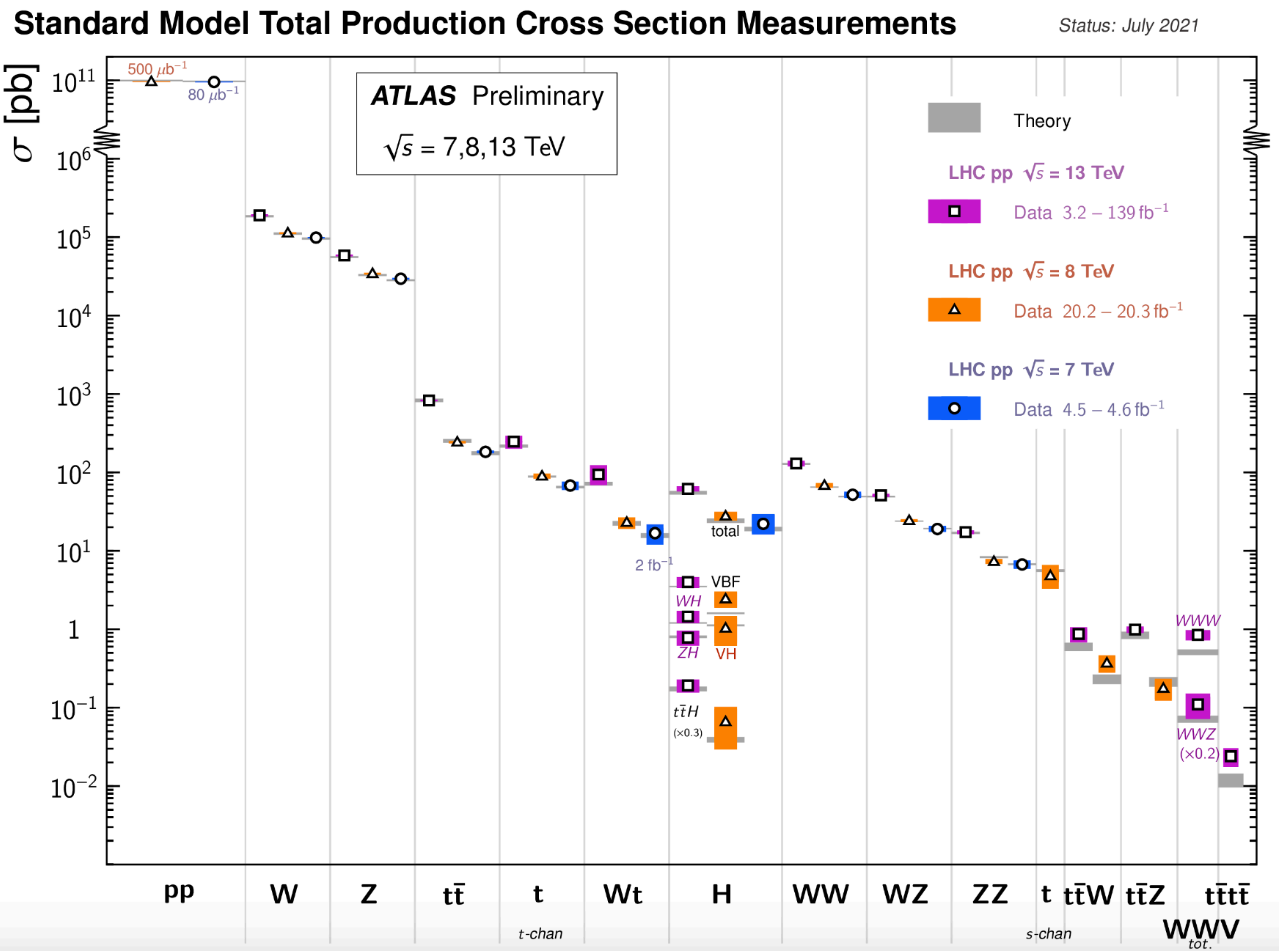
Two main parts:

- General introduction and overview of the analysis
- My main contribution: the background estimation

Diboson searches: major challenge

Plot: PUB-2021-03

- Since we are working with a fully hadronic final state, standard model QCD background is dominant
  - ➡ The cross section of proton-proton → 2 jets is **3 orders of magnitude** bigger than proton-proton → 2 V
    - Means we will have a huge background



Plot: PUB-2021-03

- Since we ... odel
  QCD bac
  - ➡ The c
    mag
    - Me

Diboson searches: major challenge

Plot: PUB-2021-03

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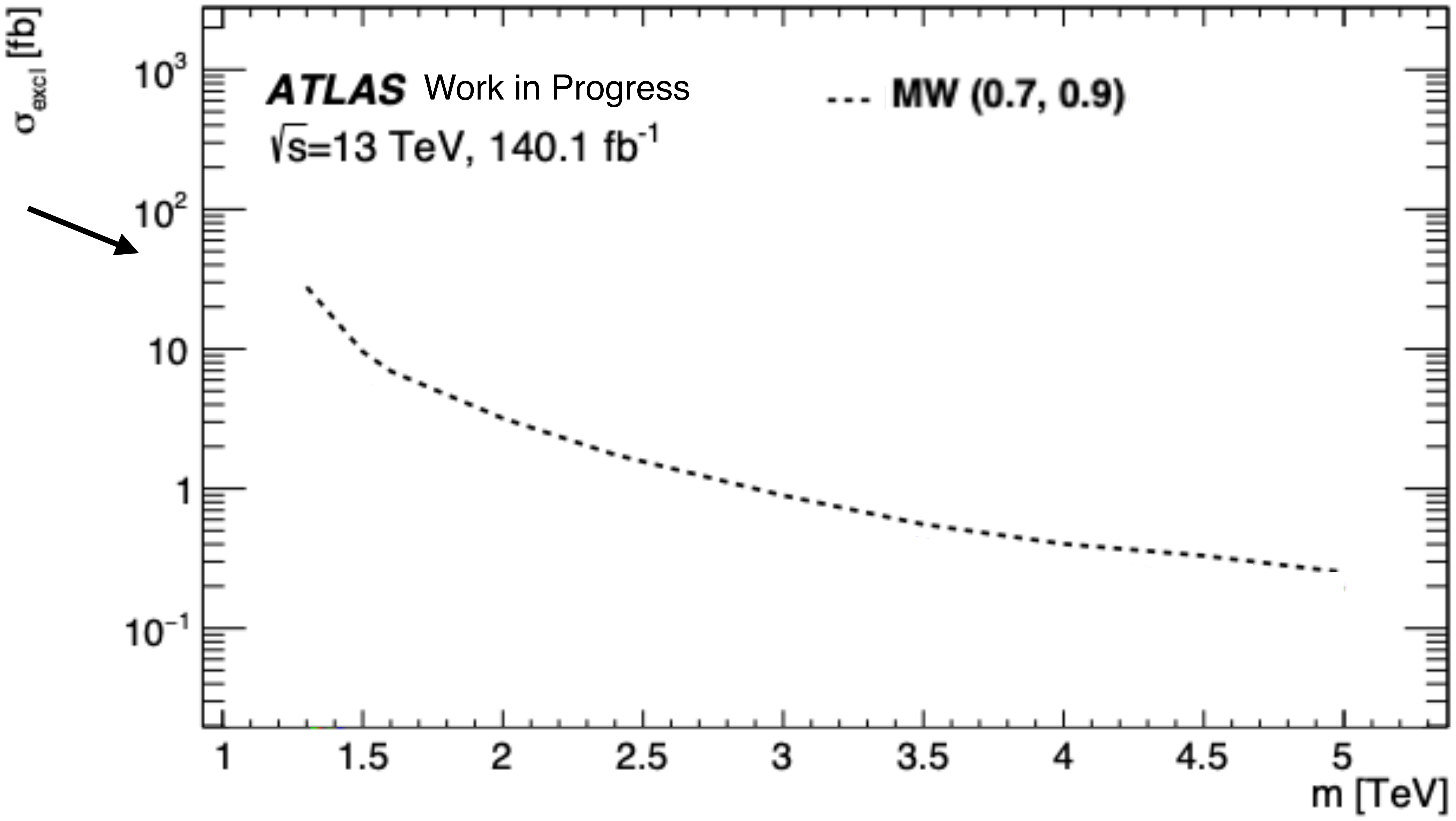
  - ➡ Need to find some way to keep our bkg under control

Expected sensitivity

- Given this background estimate, these are the cross sections we can probe
  - ➡ Might be sensitive to BSM signal?
  - ➡ Have to look at data!



Final QCD Estimate (old)

- After several validation checks, we applied this method to real data