BOSTON UNIVERSITY

17th annual

Fermilab-CERN Hadron Collider Physics Summer School

August 15 - 25, 2022 Fermilab

BSM Searches: Experiment II

Zeynep Demiragli (Boston University)

FERMILAB-CERN HADRON COLLIDER PHYSICS Summer School

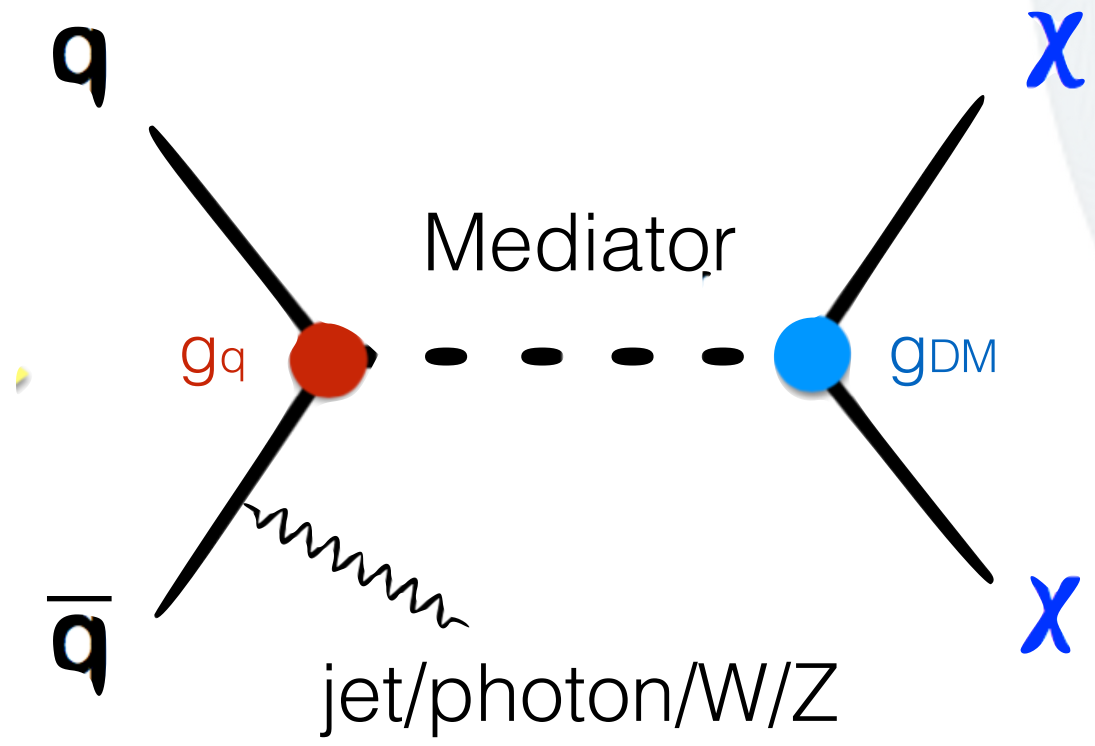
http://indico.fnal.gov/e/hcpss2022

An other look at the Simplified Models

From EFTs to Simplified Models… multiple type of mediators are studied:

Simplified Models

Main parameters of the model: mediator, two vertices, and a DM candidate



Extended to models with t-channel mediator and dark sectors

	vector	*axial-vector*
spin-1	$g_q \sum_q V_\mu \bar{q}\gamma^\mu q$	$g_q \sum_q A_\mu \bar{q}\gamma^\mu \gamma^5 q$
	scalar	*pseudoscalar*
spin-0	$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	$g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$

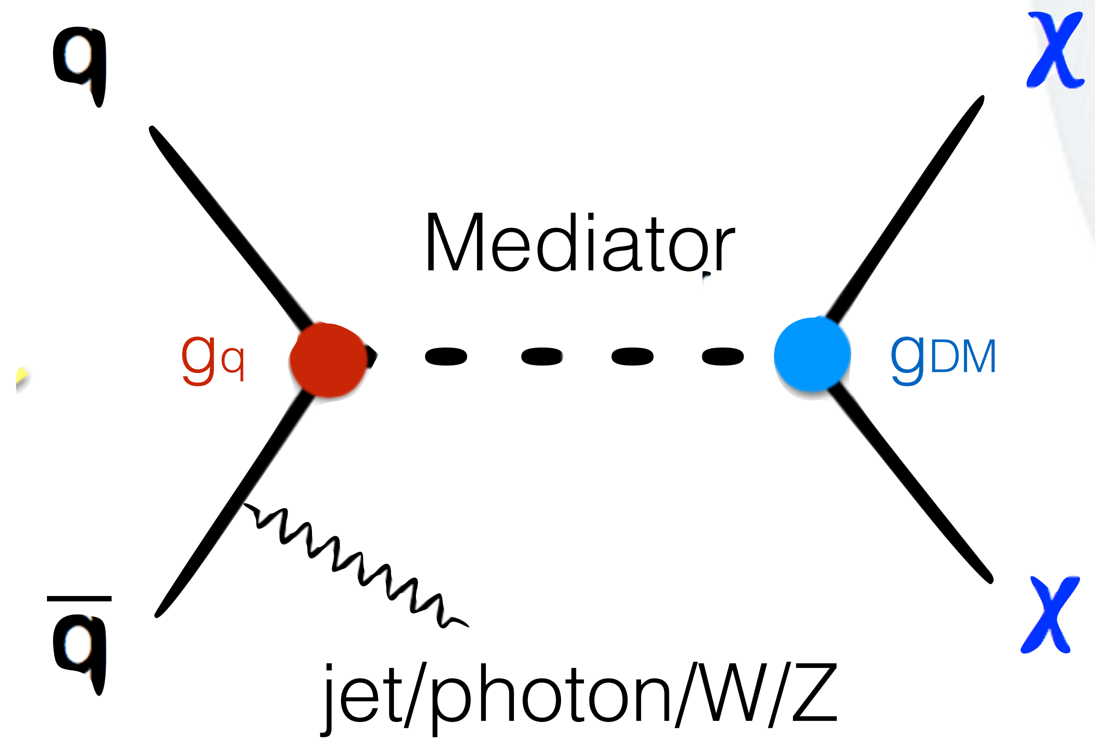
Higgs Portals

From EFTs to Simplified Models… multiple type of mediators are studied

We have a special scalar particle!

Simplified Models

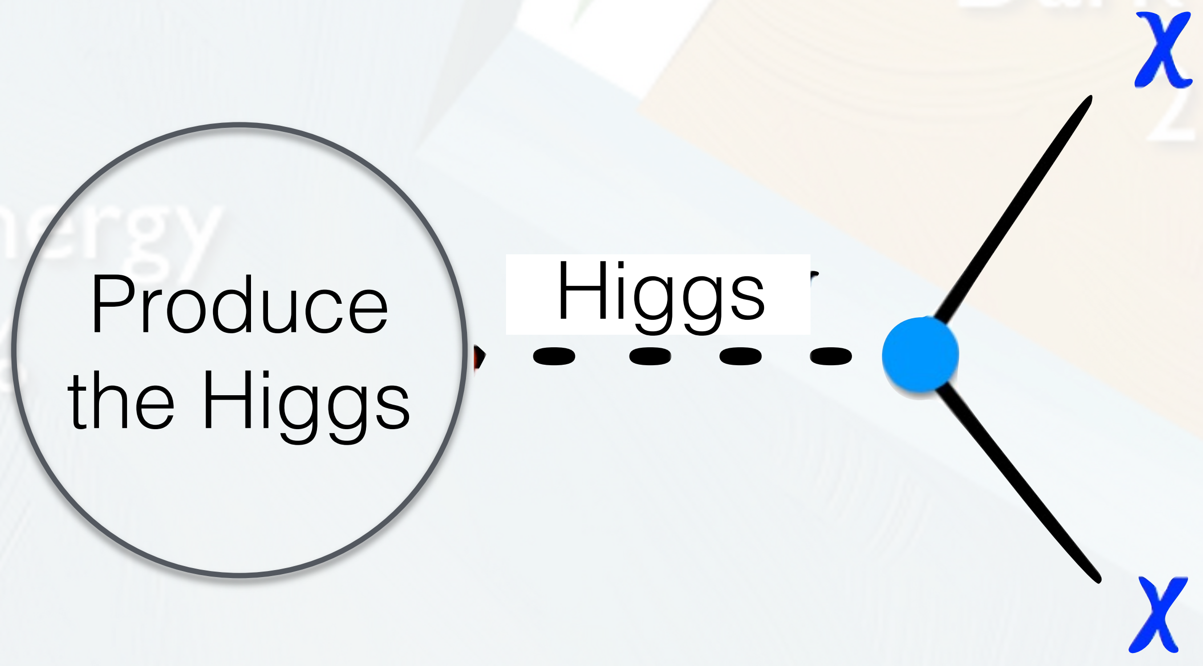
Main parameters of the model: mediator, two vertices, and a DM candidate



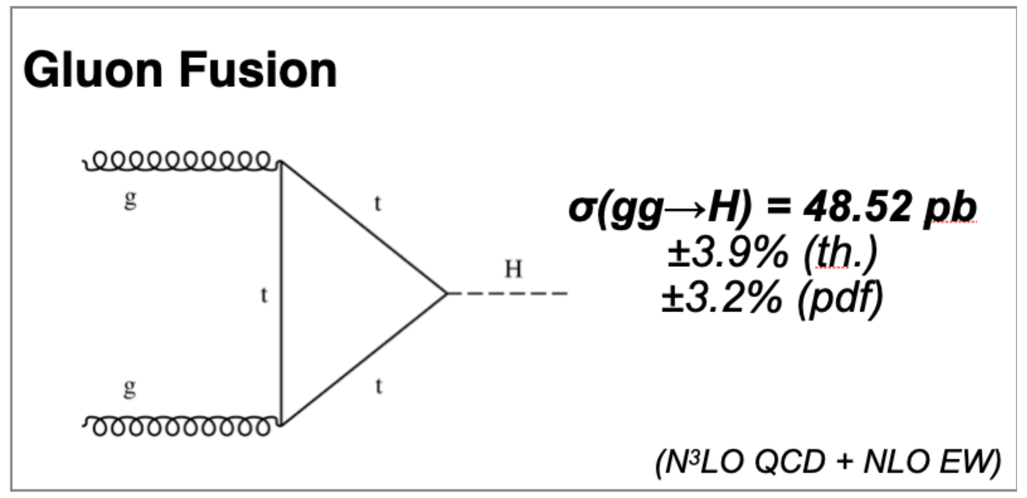
Extended to models with t-channel mediator and dark sectors

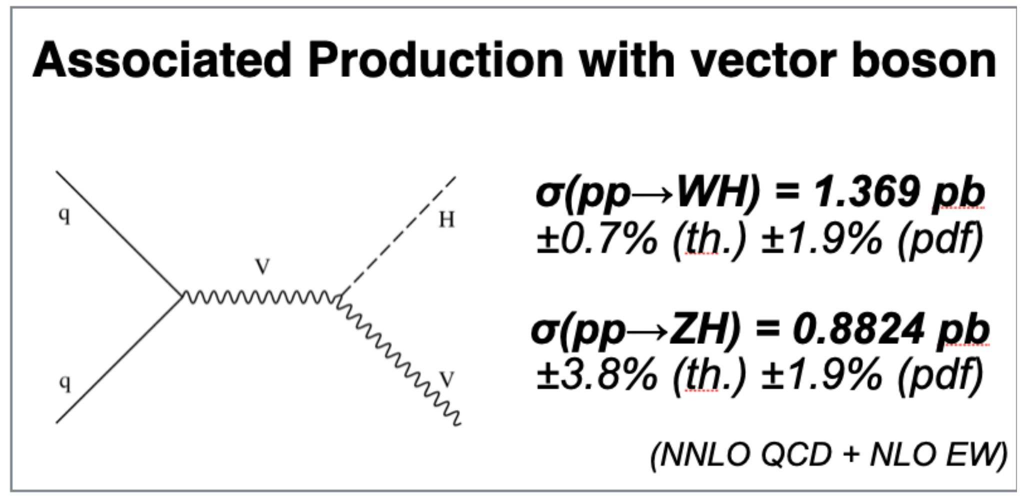
Higgs Portal

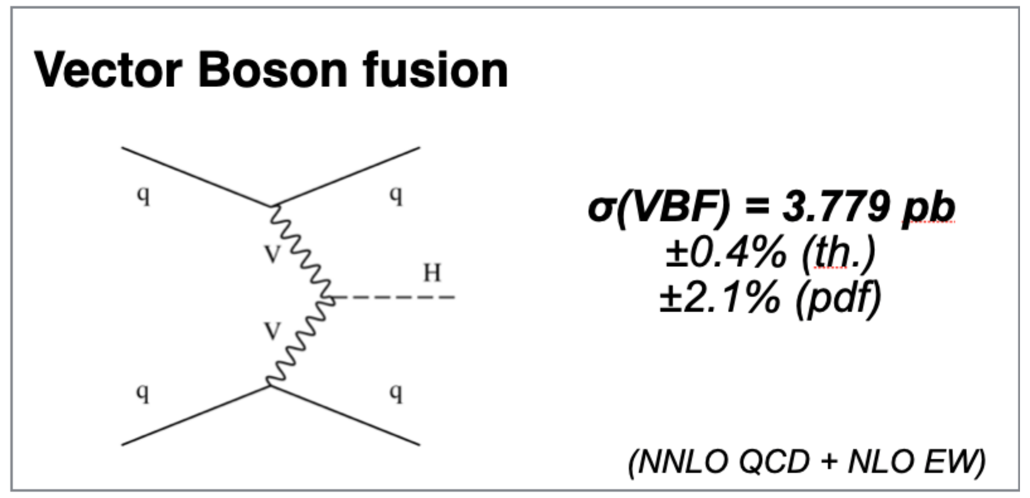
Known Higgs decay branching fractions allow decays to invisible particles ~20%

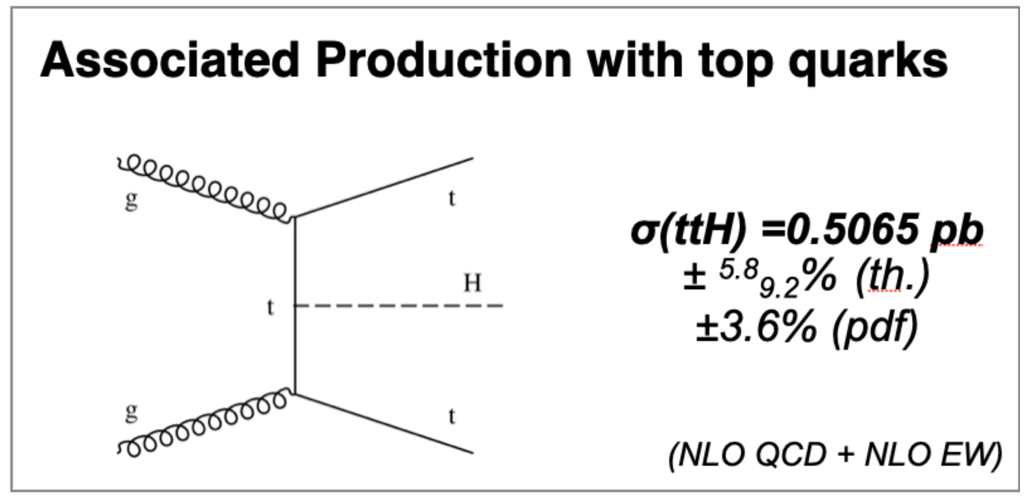


All Higgs production modes can be studied to tag the event





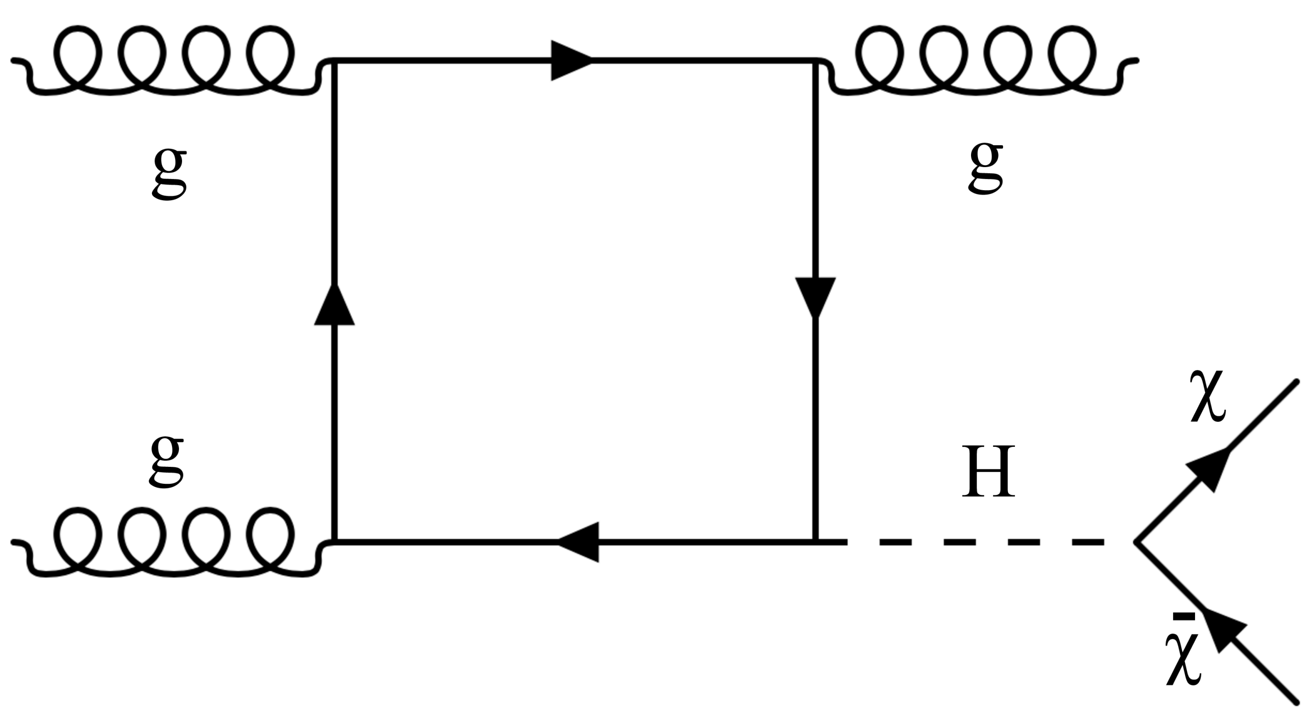




Higgs Production Modes

Higgs Production modes will determine the signature.

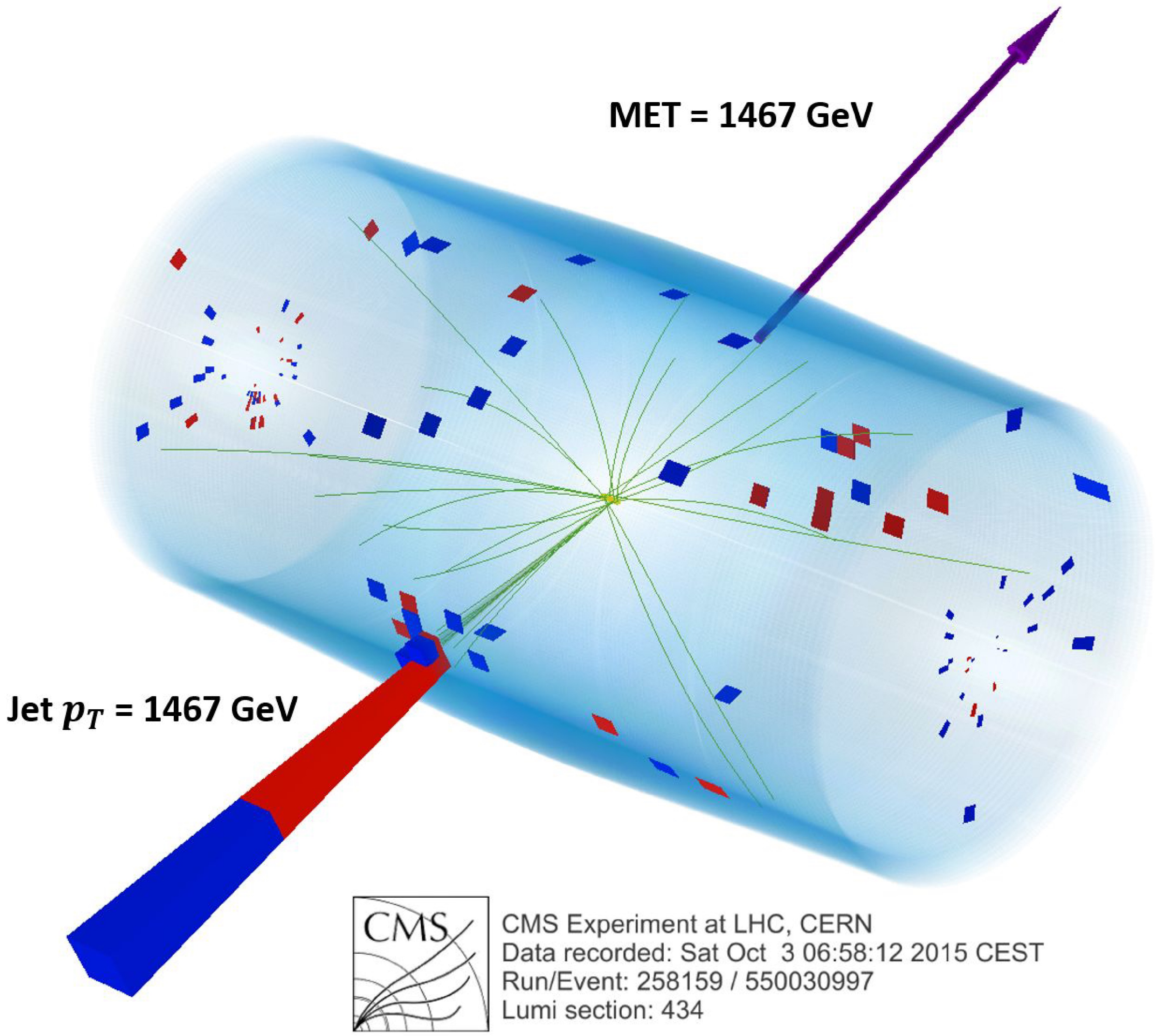
We discussed gluon fusion production mode => That's just monojet!



Gluon fusion

JHEP11(2021)153

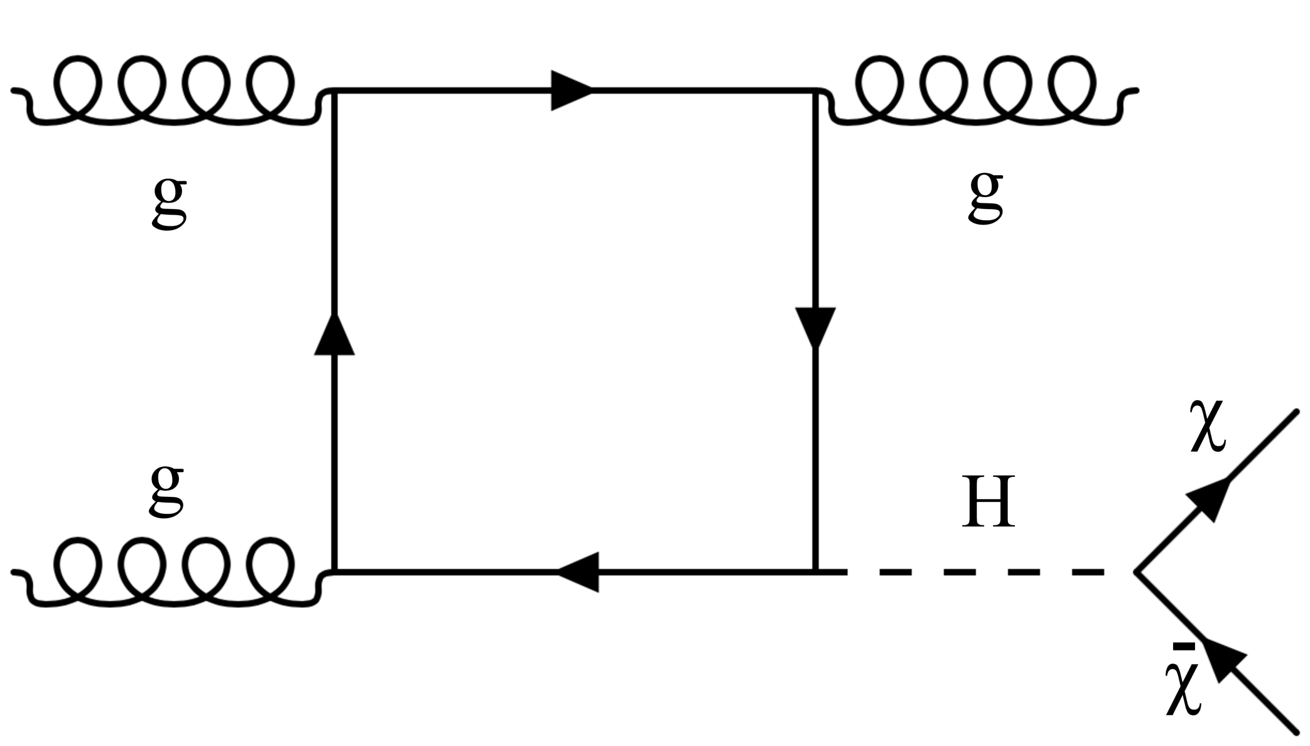
- Largest production production cross section
- Needs to be tagged with a visible object



Higgs Production Modes

Higgs Production modes will determine the signature.

Now lets look at VH production => Let us call it "mono-V"



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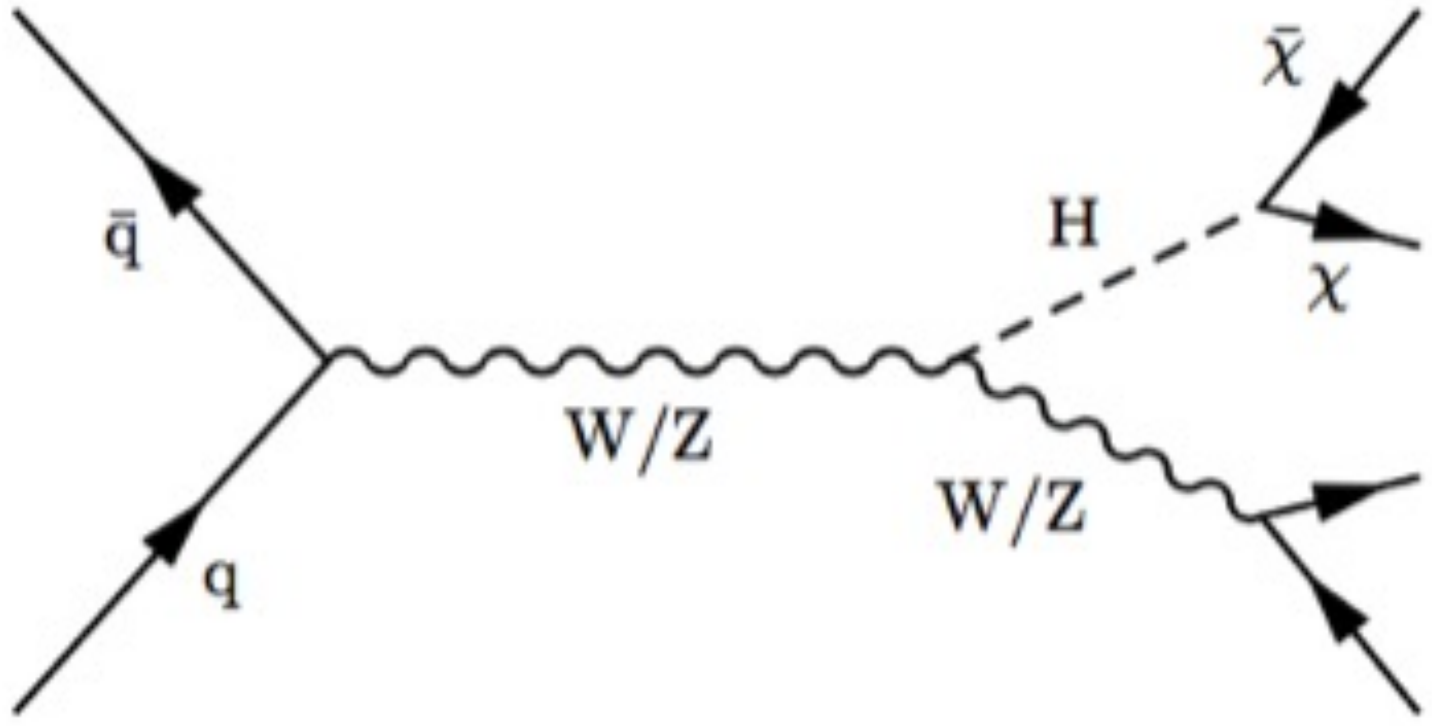


Associated vector boson

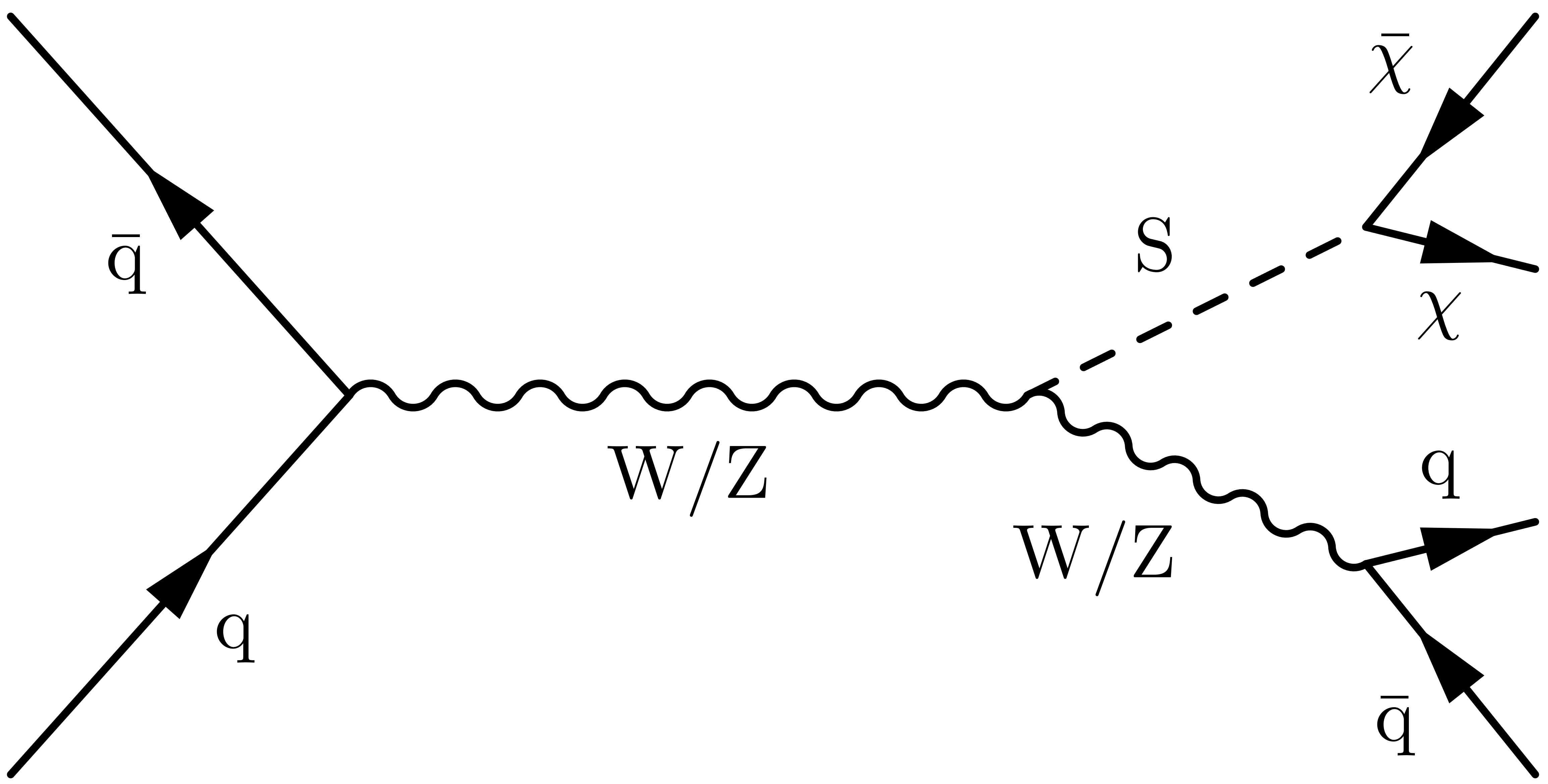
JHEP11(2021)153

- Less cross section: σ(monojet) ~ 30xσ (monoW)
- Boosted topologies & use of substructure - fatter jets

Mono-V Experimental Techniques

… even with state of the art background estimation strategies, we are often overwhelmed by SM

rescue: **boosted topologies** & **substructure.**



σ(ggf) ~ 30 x σ (VH)

… but similar sensitivity in both searches!

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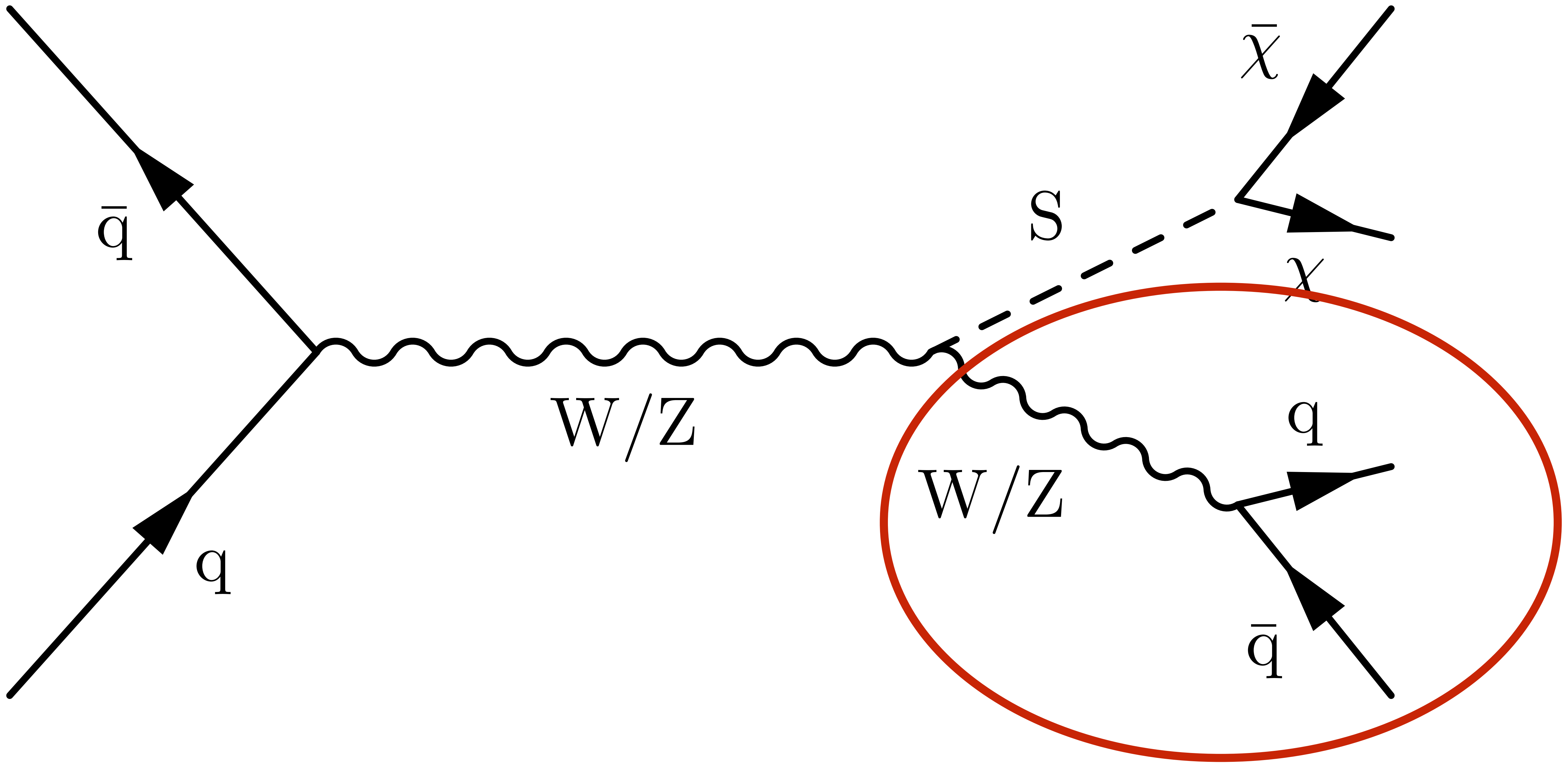

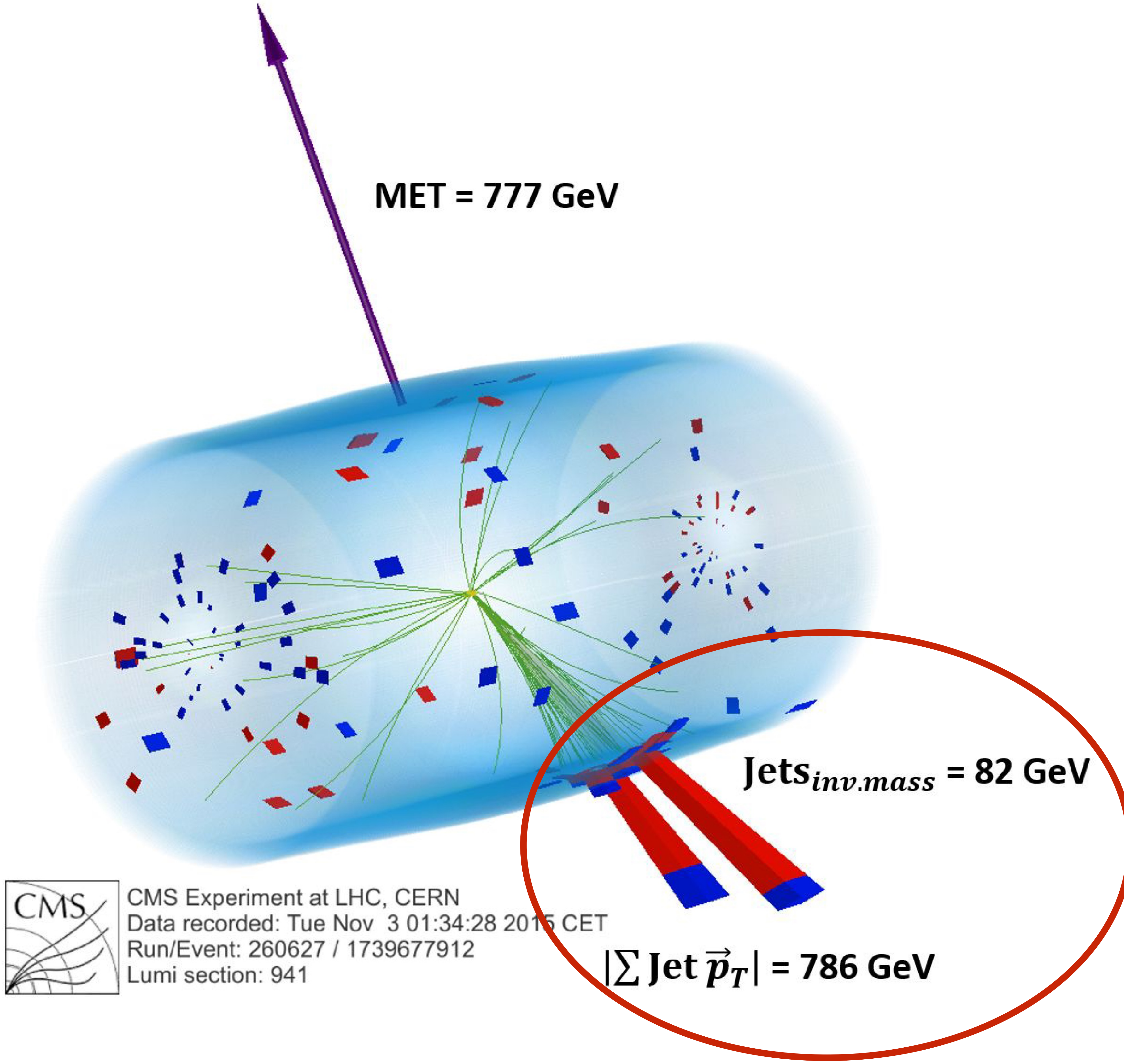

σ(ggf) ~ 30 x σ (VH)

… but better sensitivity with Mono-V!

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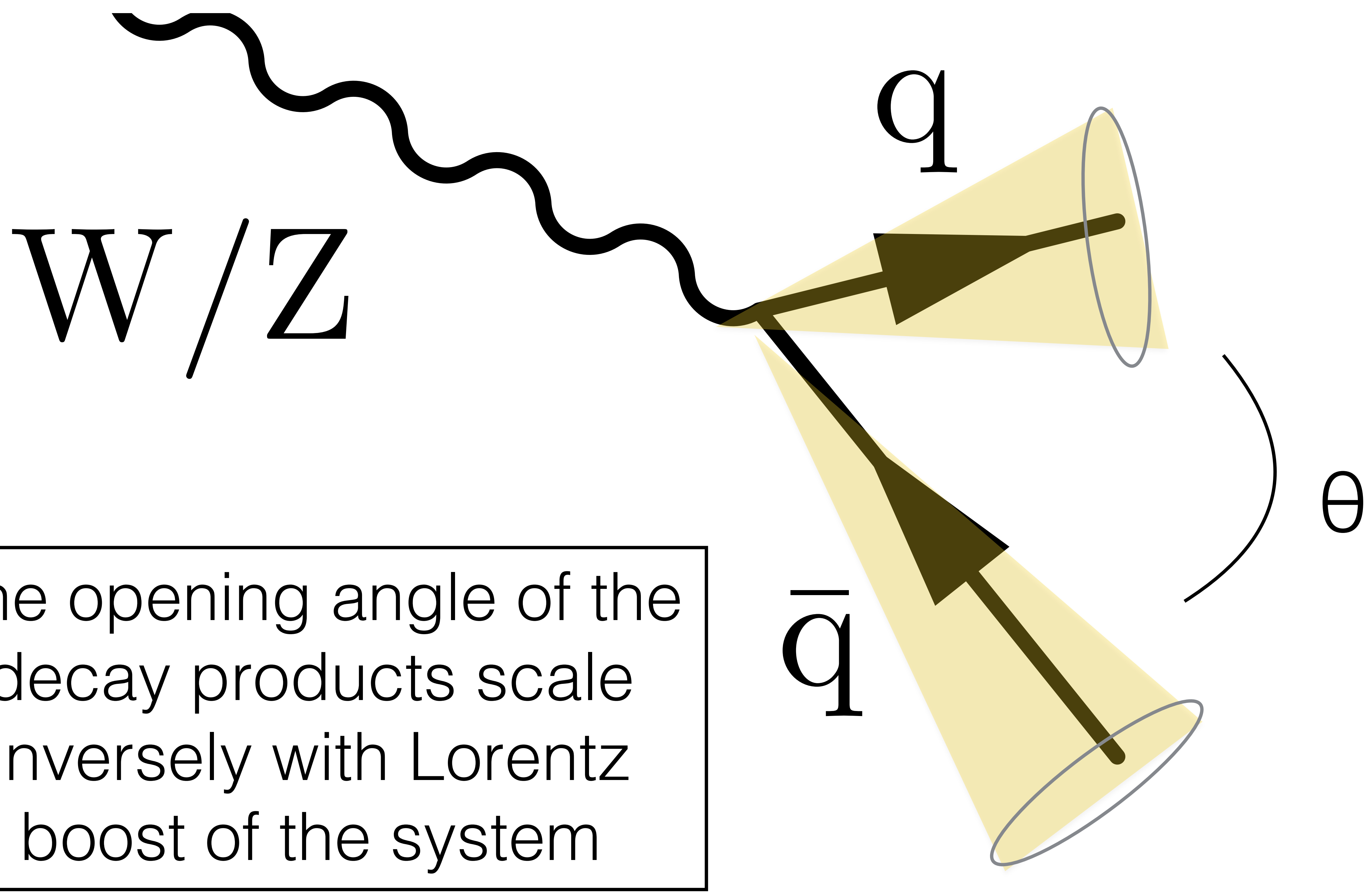
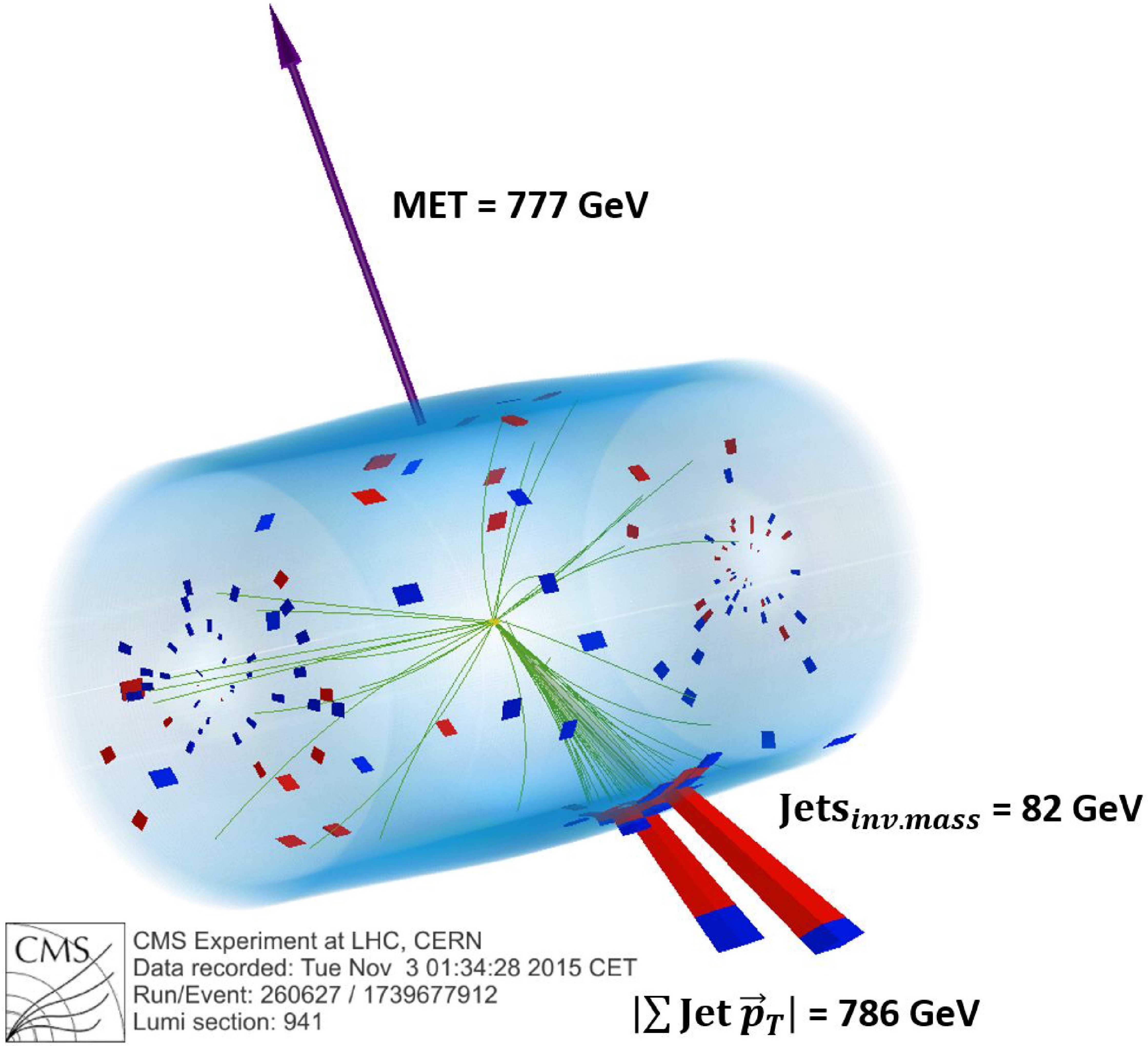


The opening angle of the decay products scale inversely with Lorentz boost of the system



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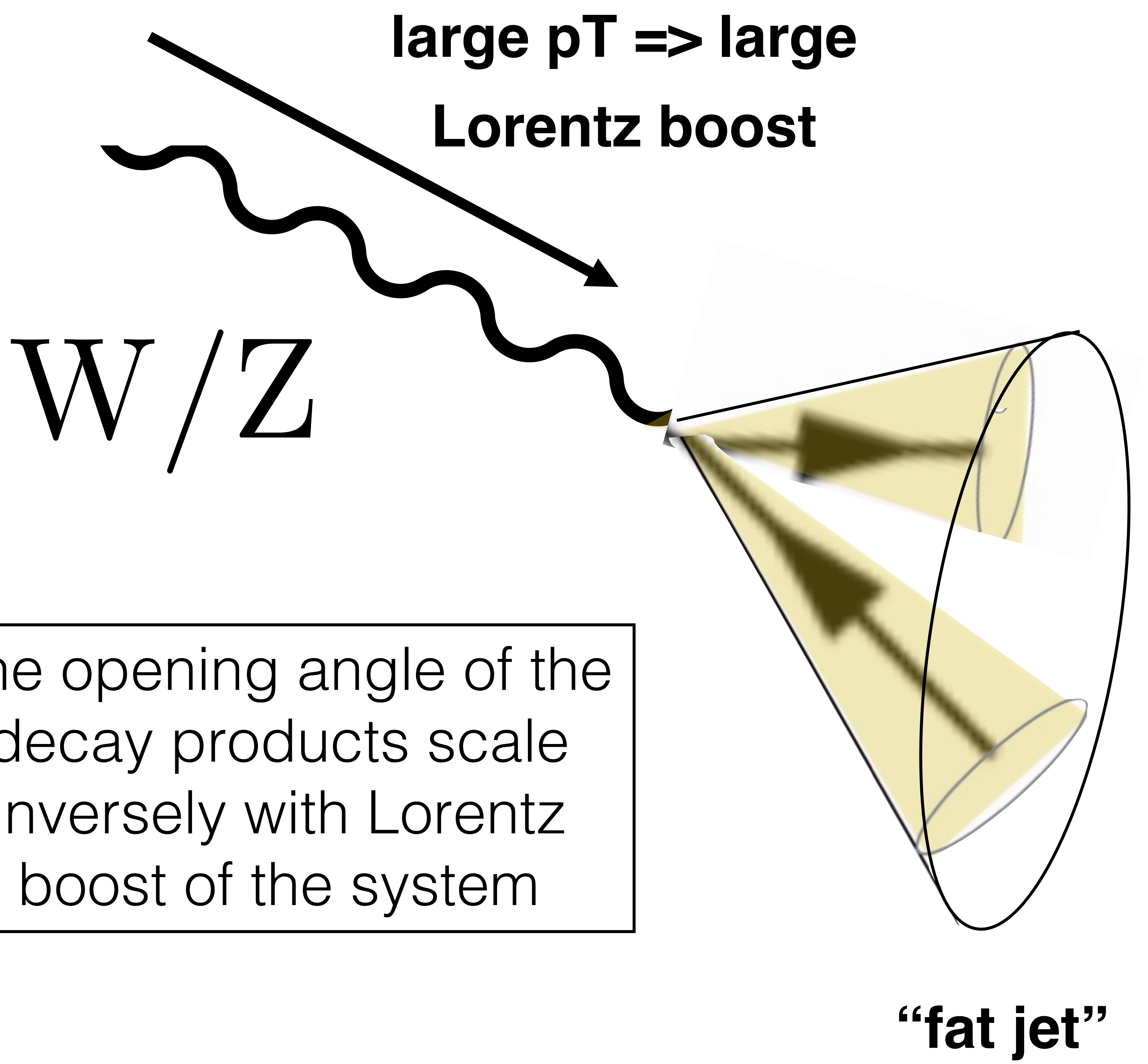

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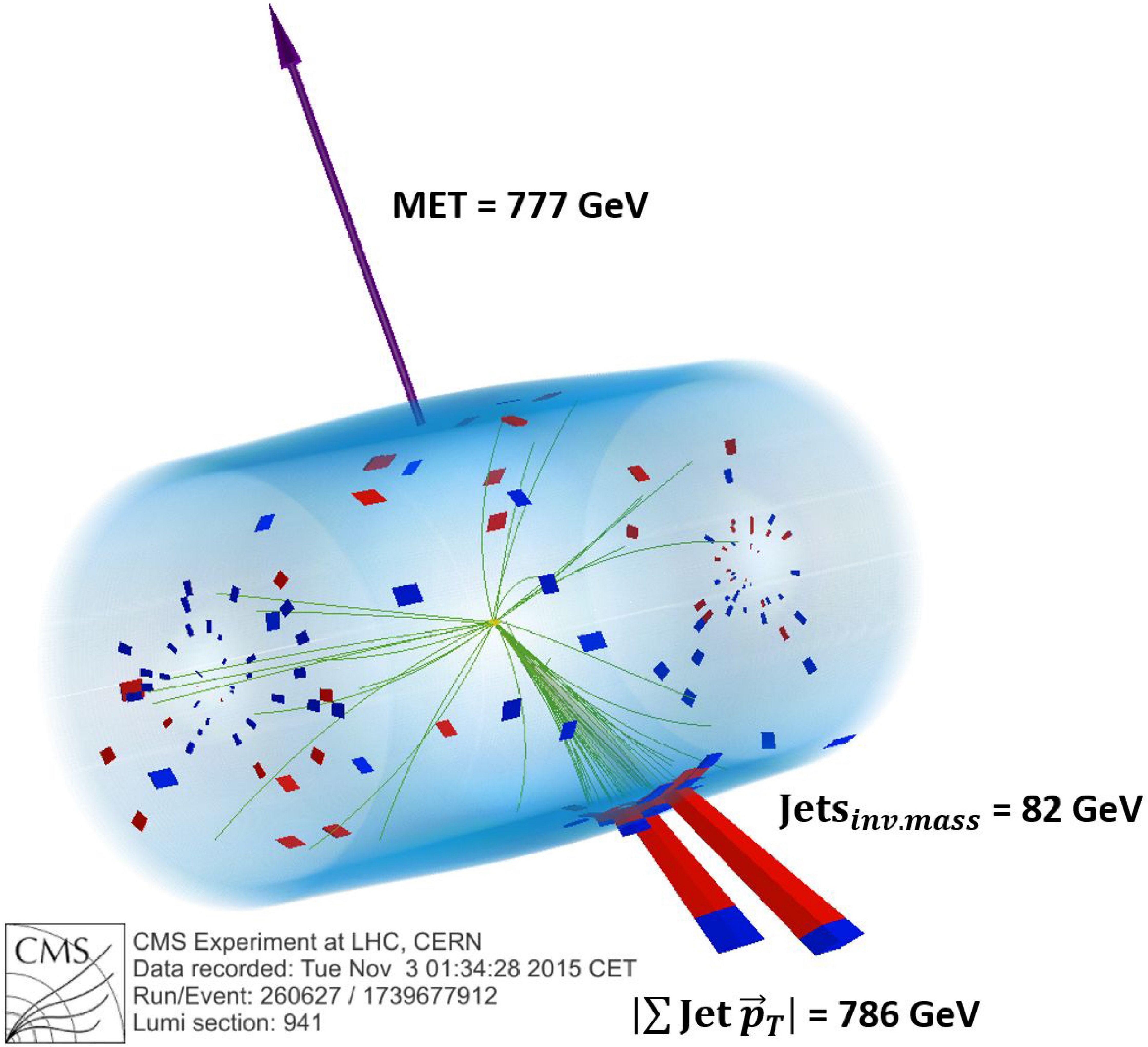

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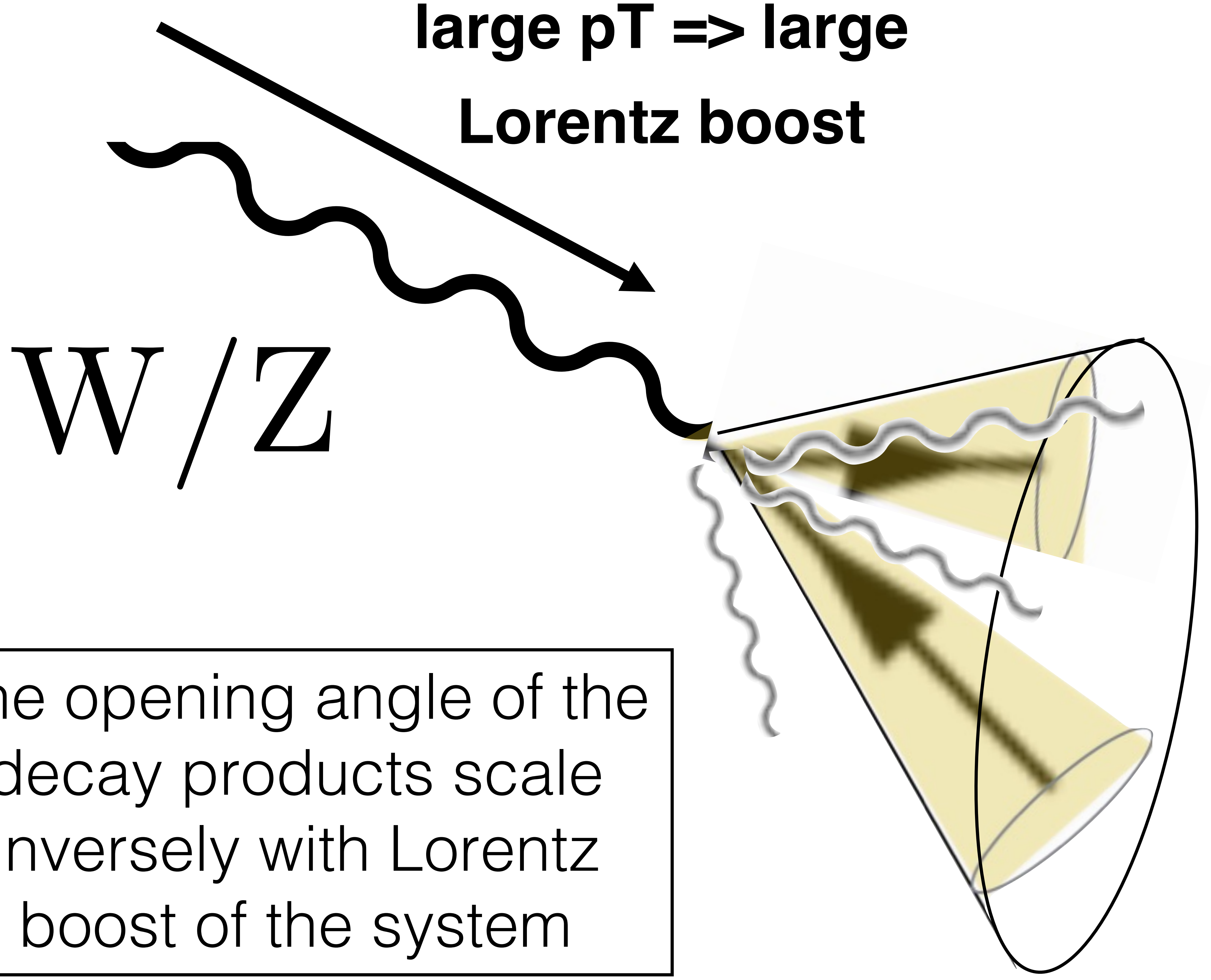
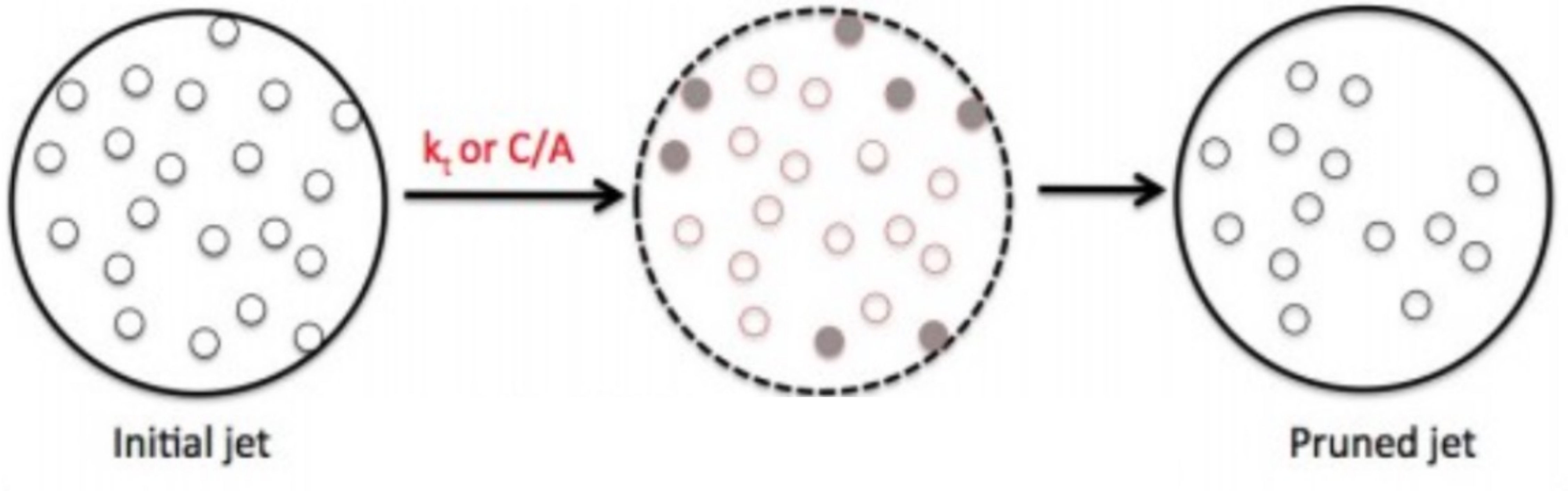
rescue: **boosted topologies** & **substructure.**

large pT => large Lorentz boost

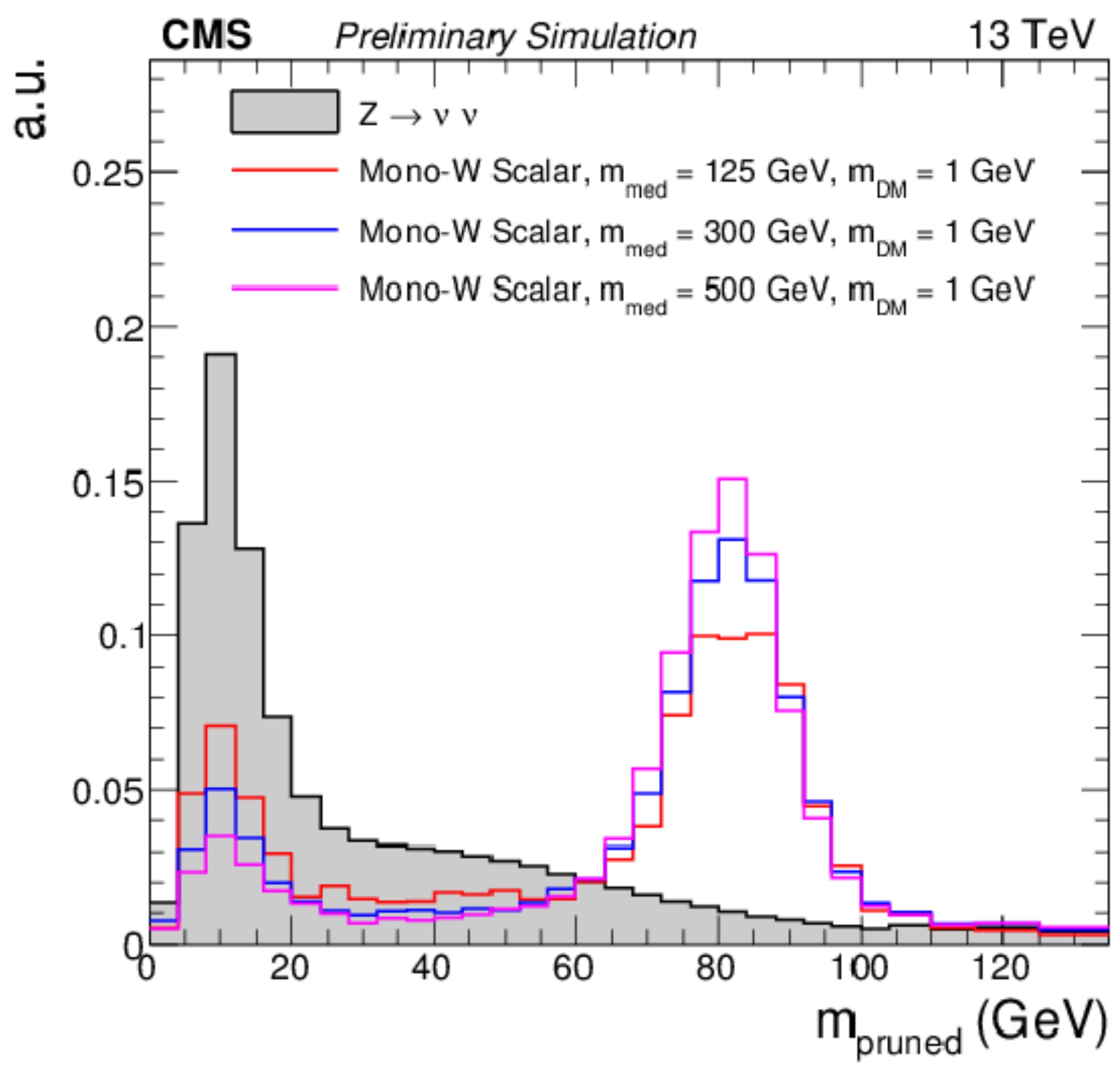


The opening angle of the decay products scale inversely with Lorentz boost of the system

“fat jet”



Pruning



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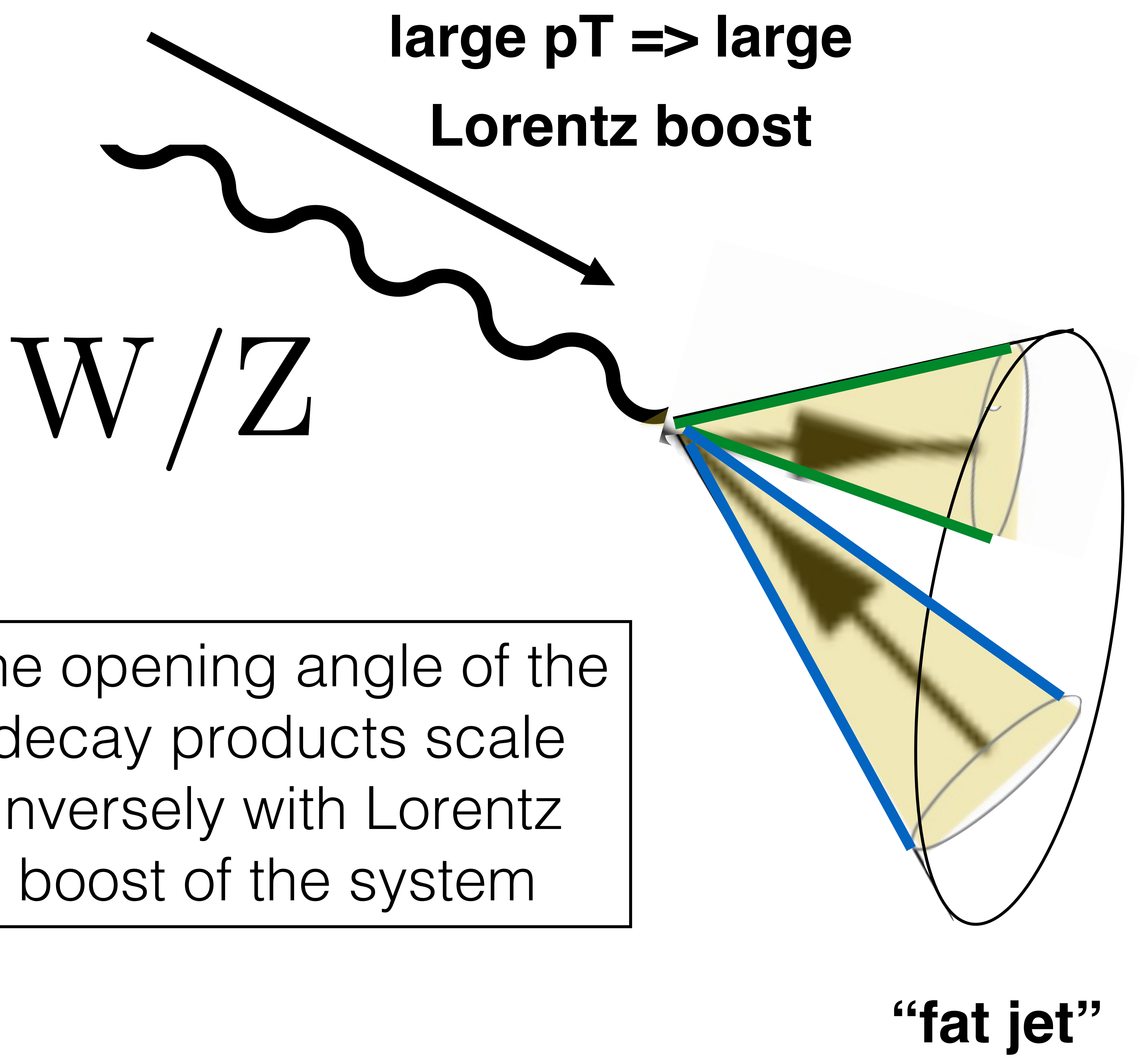

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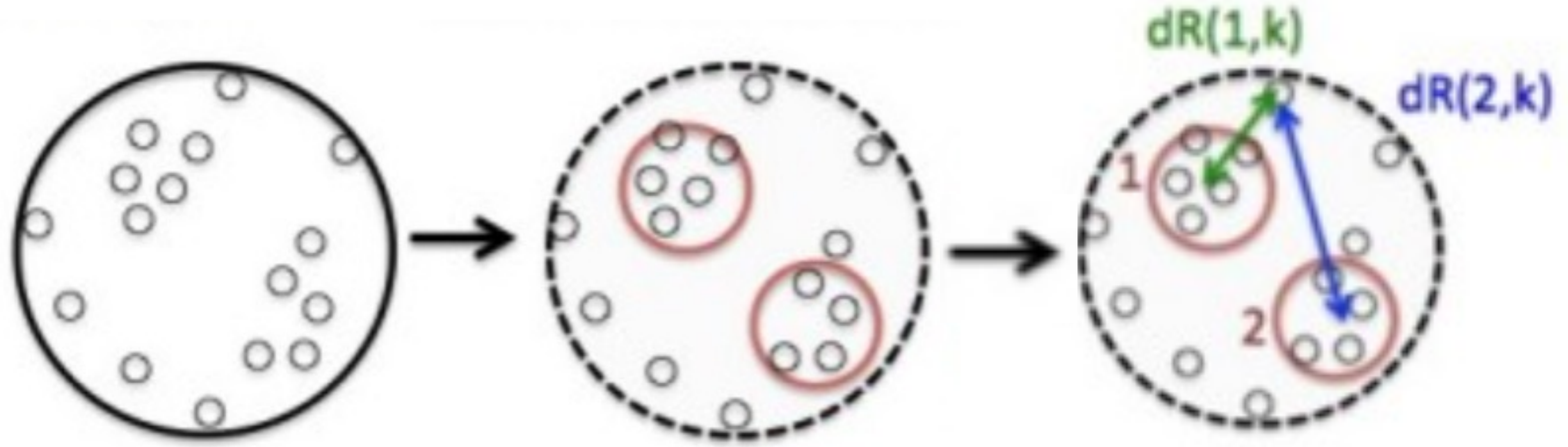

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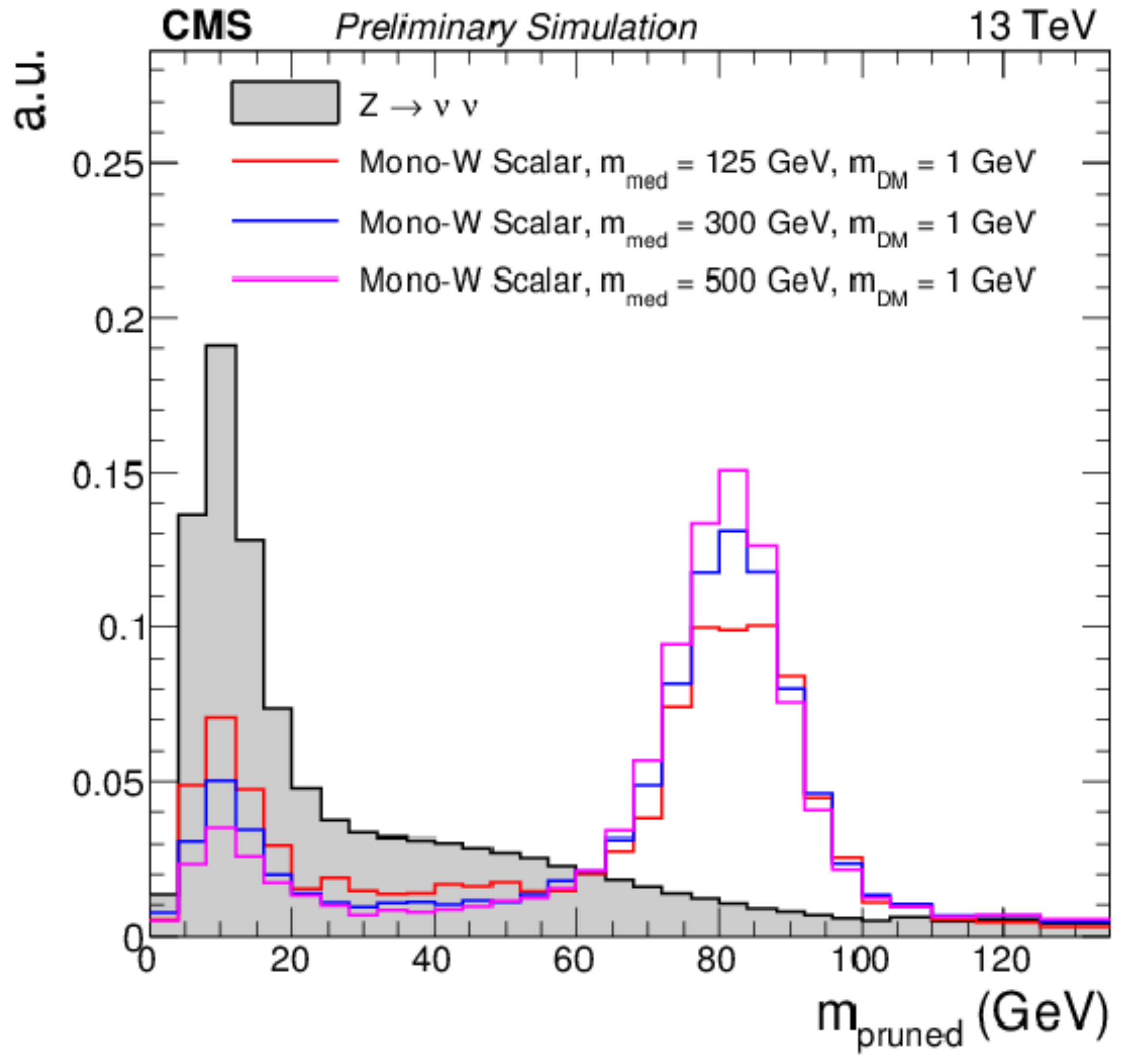
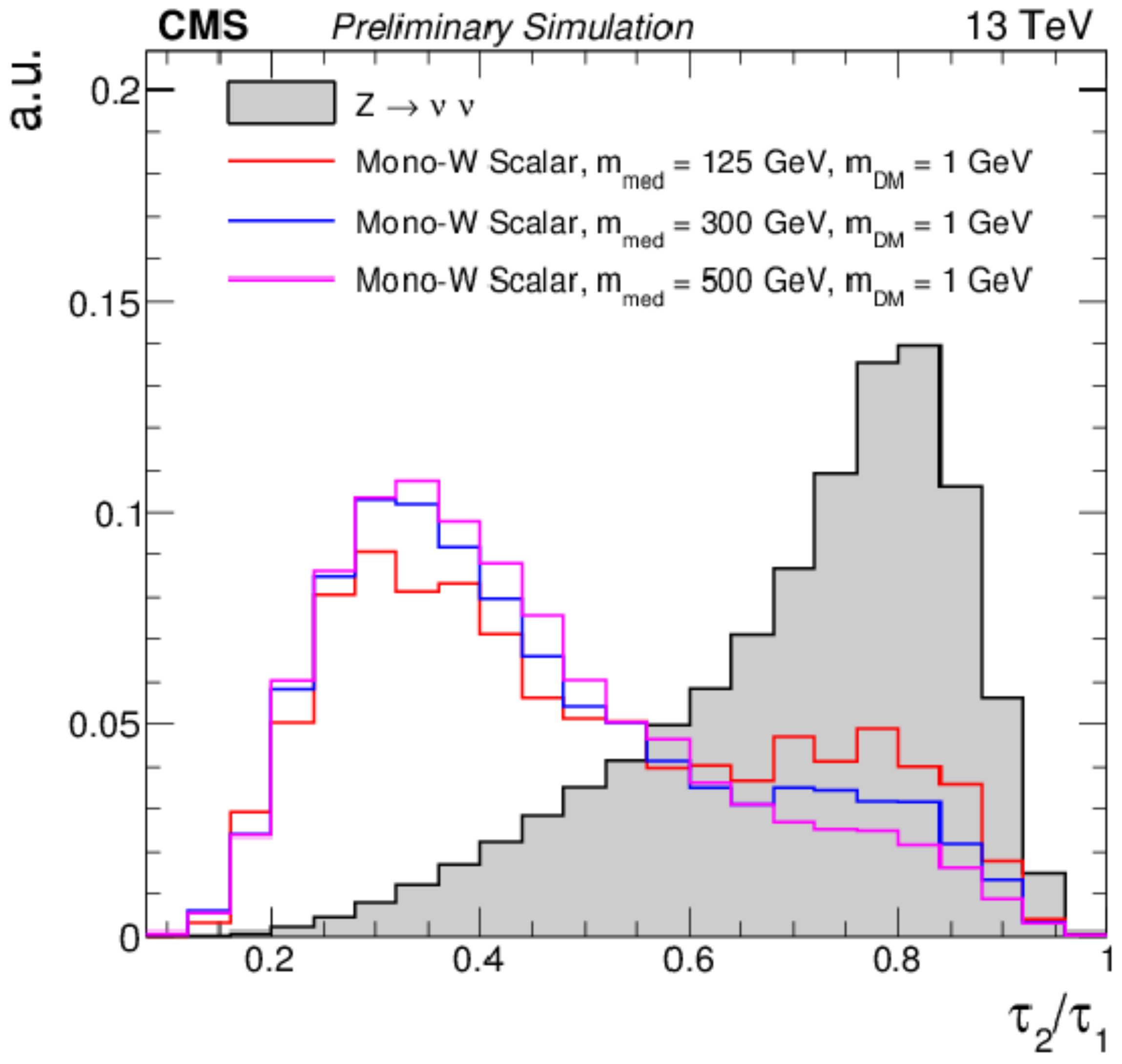


N-subjetiness



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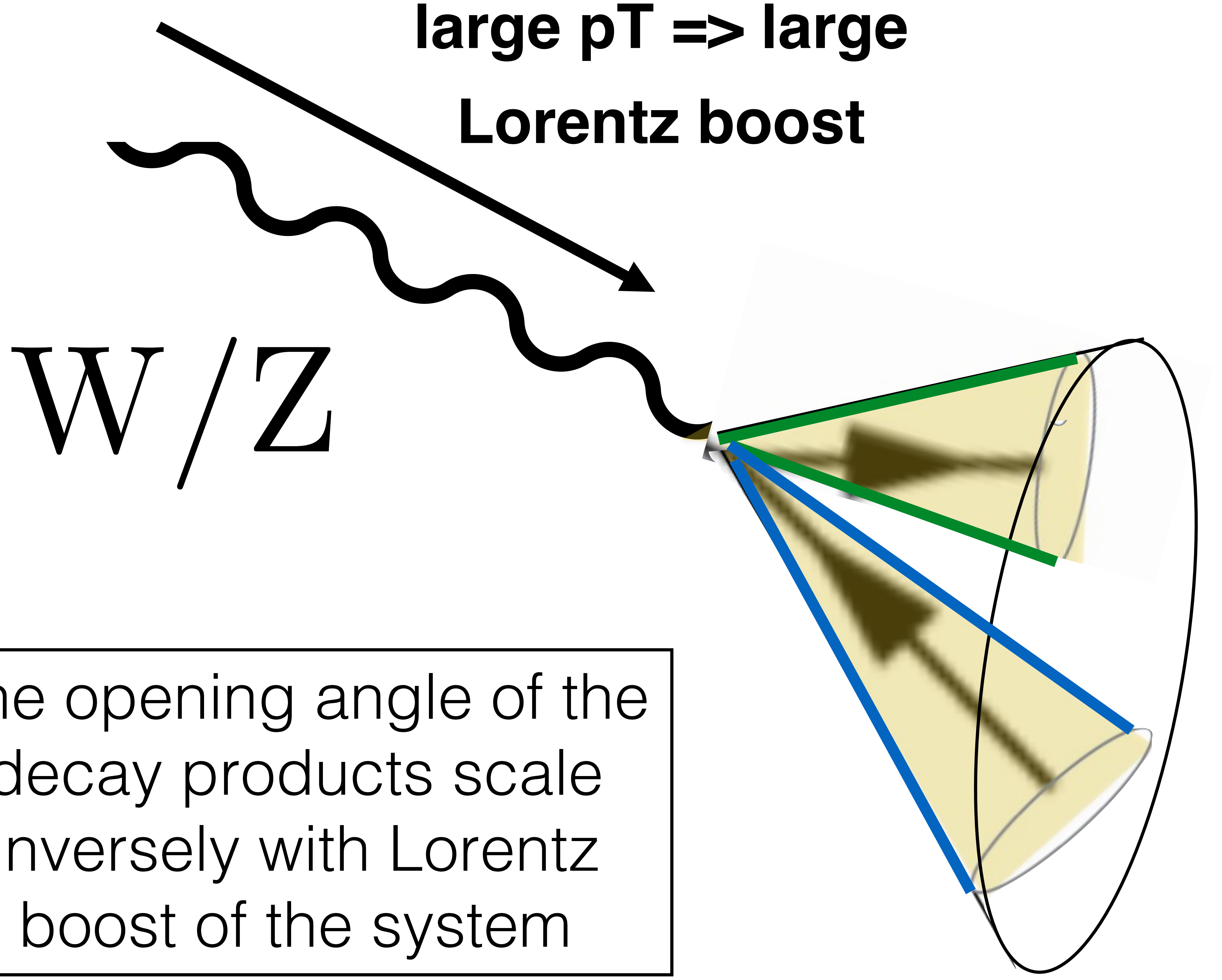

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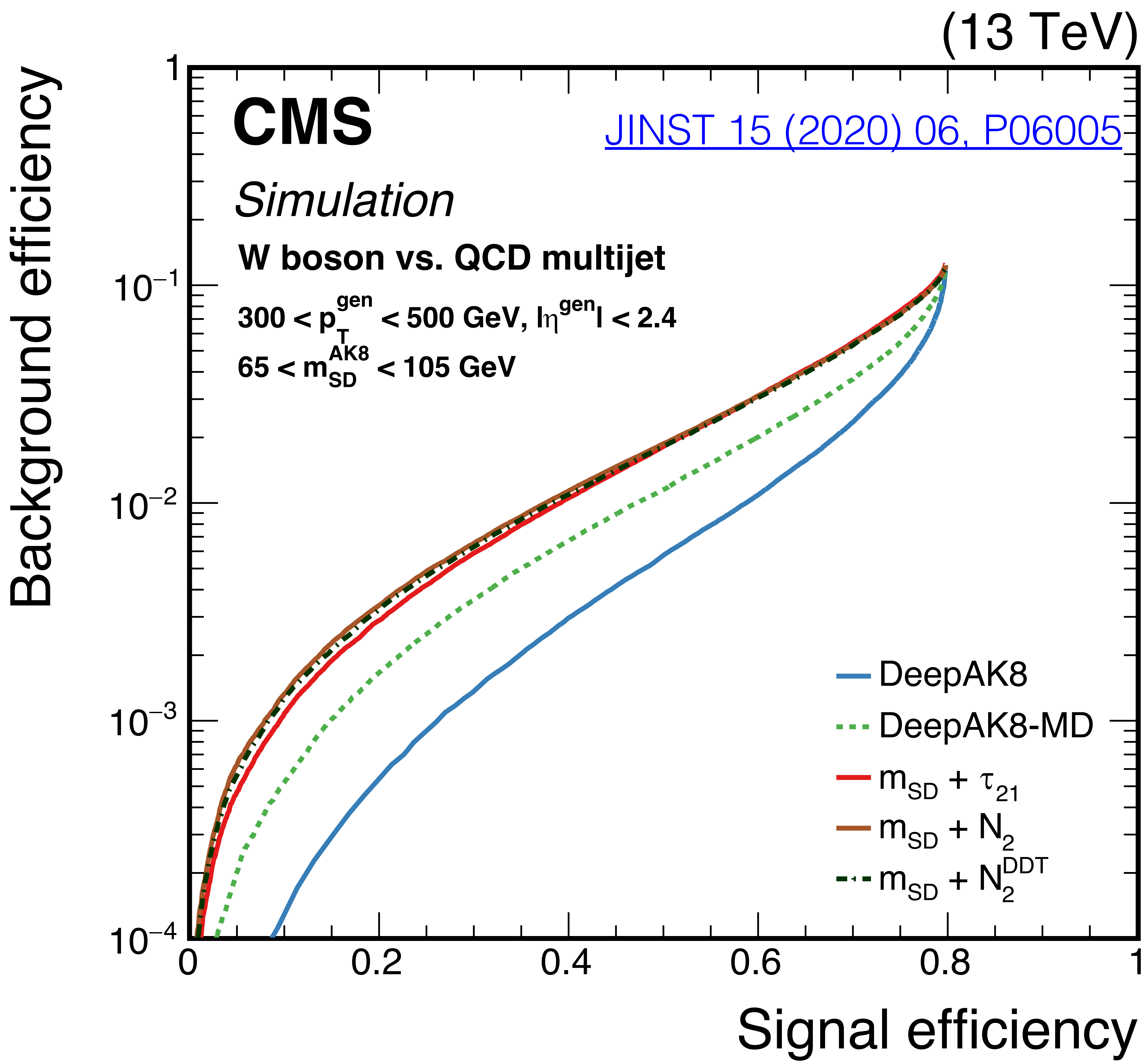

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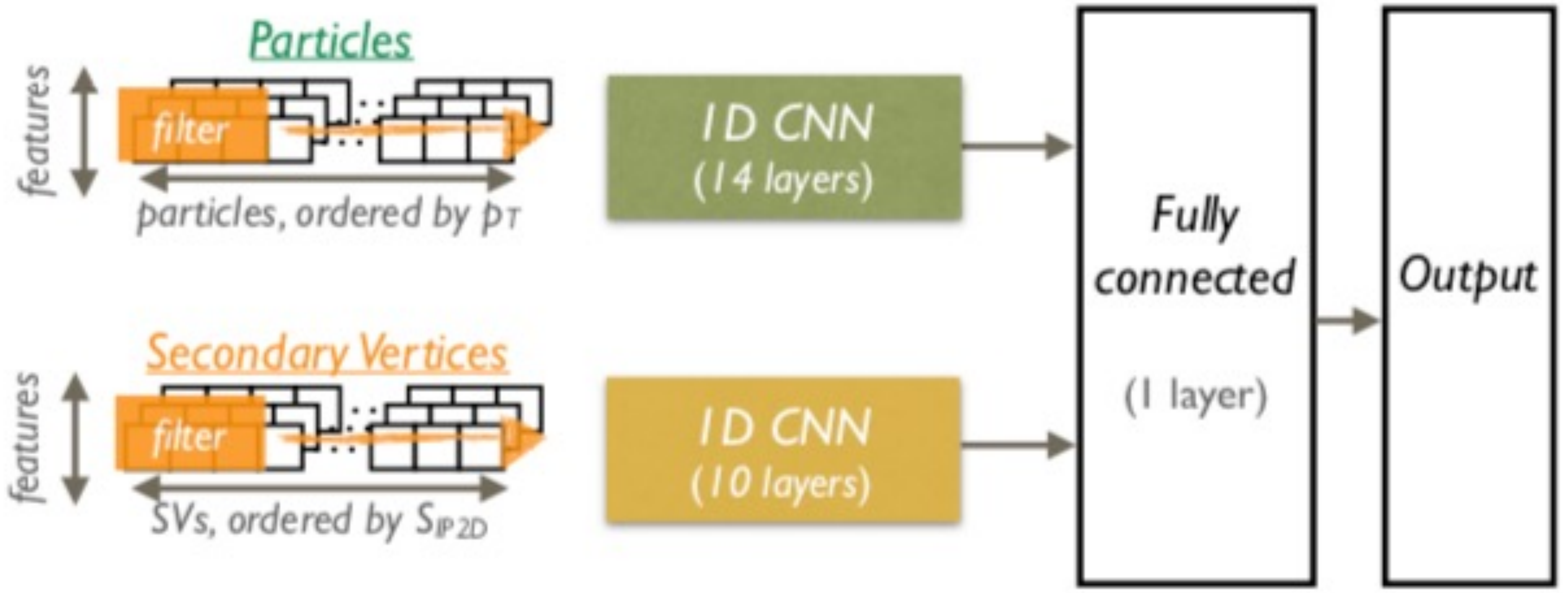
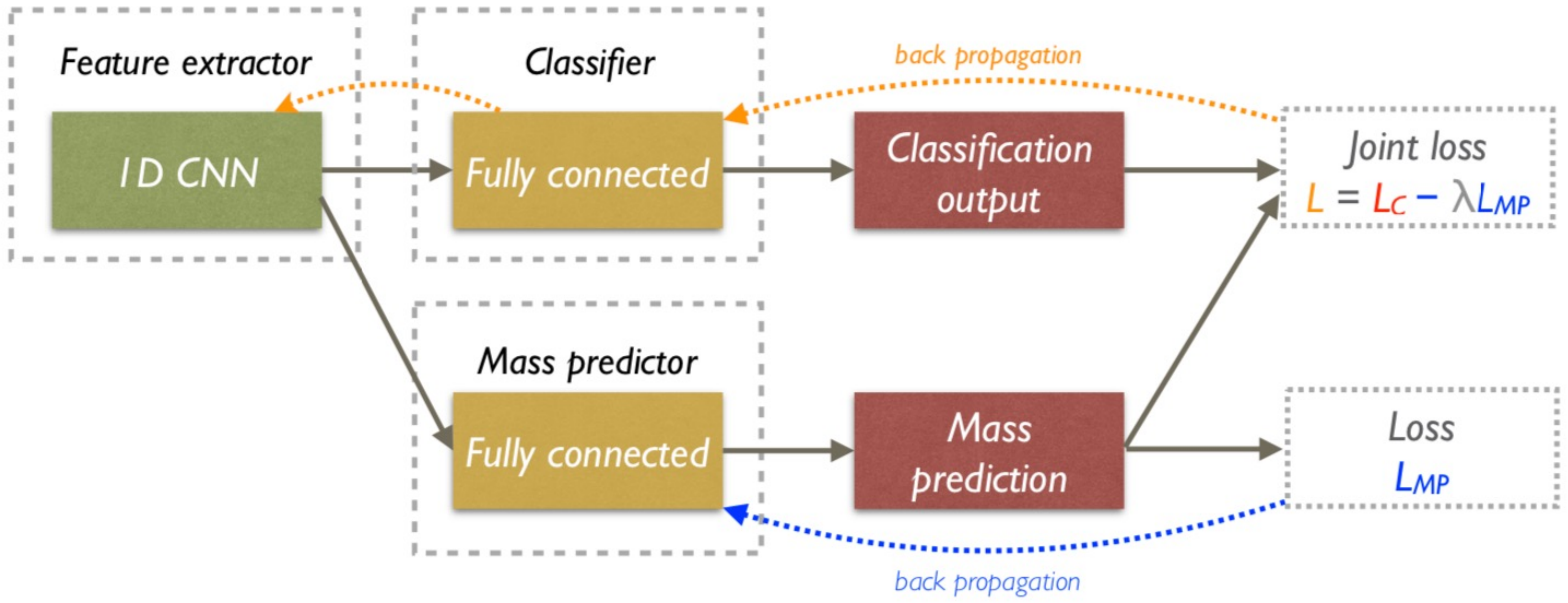
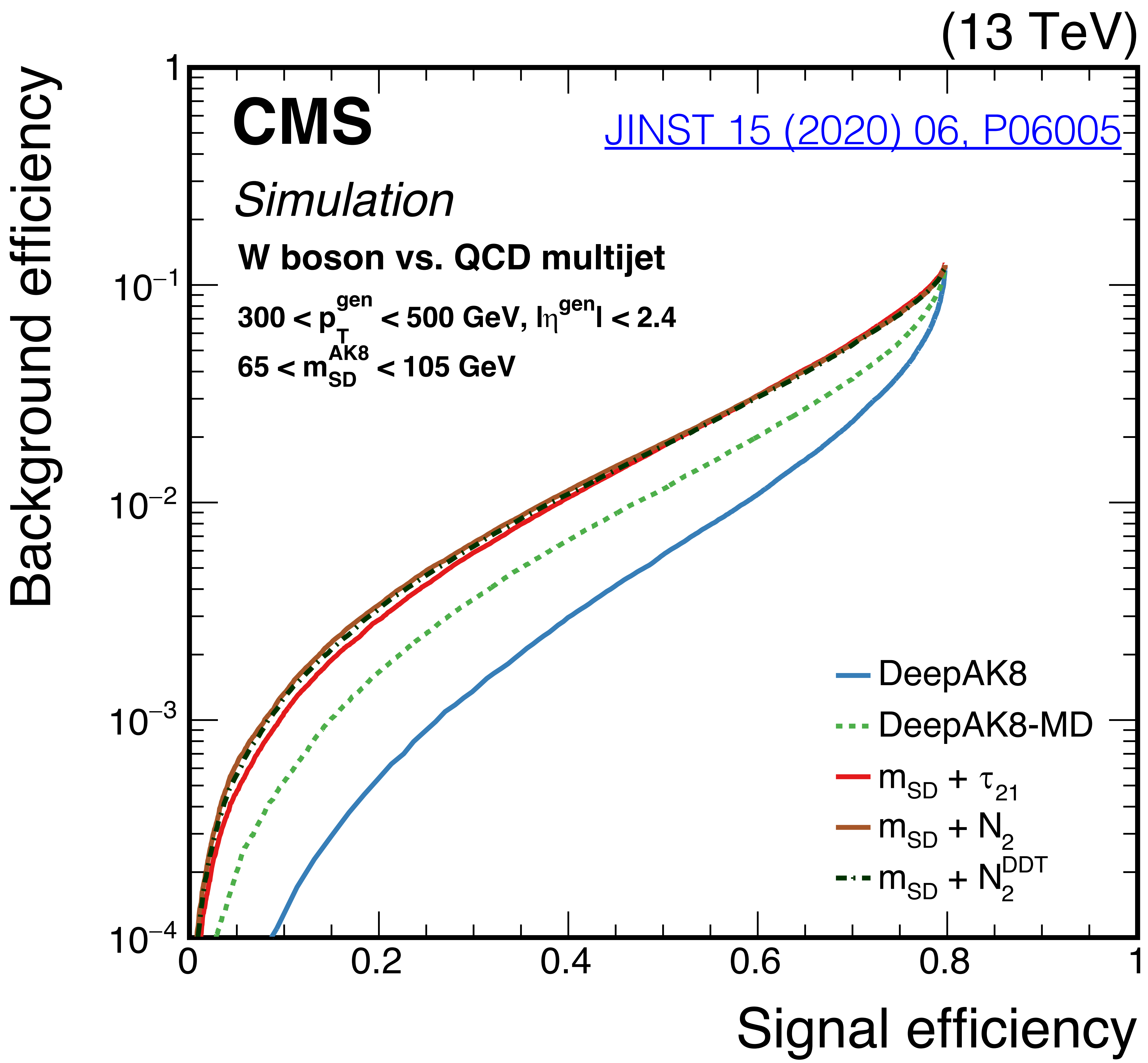


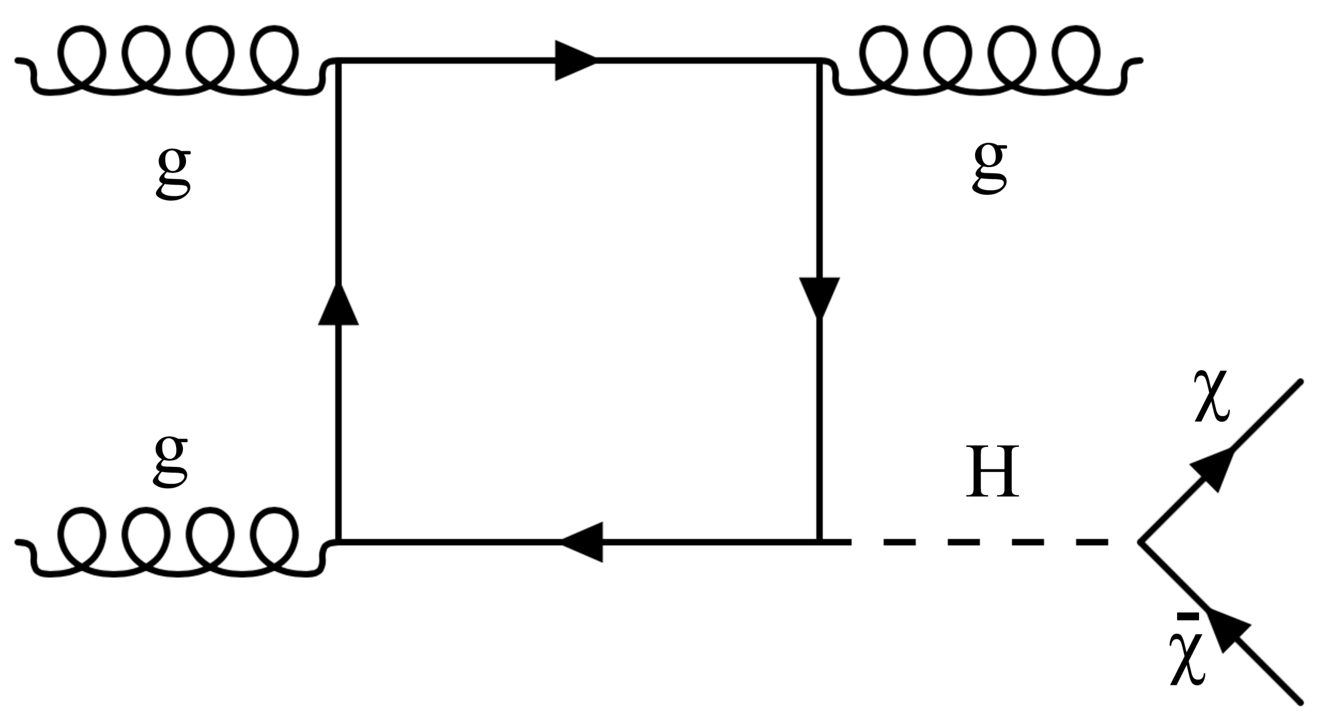




Higgs Production Modes

Higgs Production modes will determine the signature.

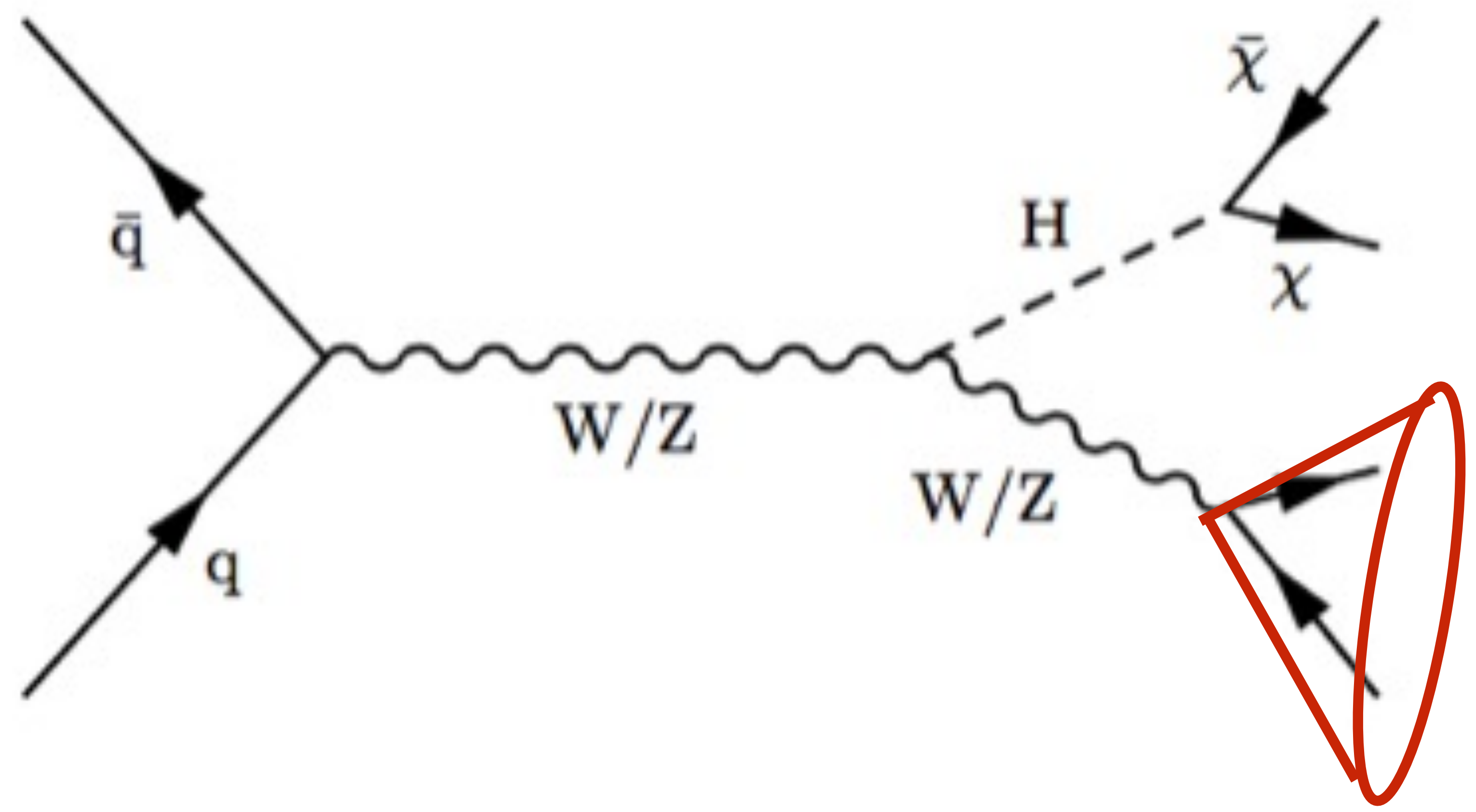
… and vector boson fusion!



Gluon fusion

JHEP11(2021)153

- Largest production production cross section
- Needs to be tagged with a visible object



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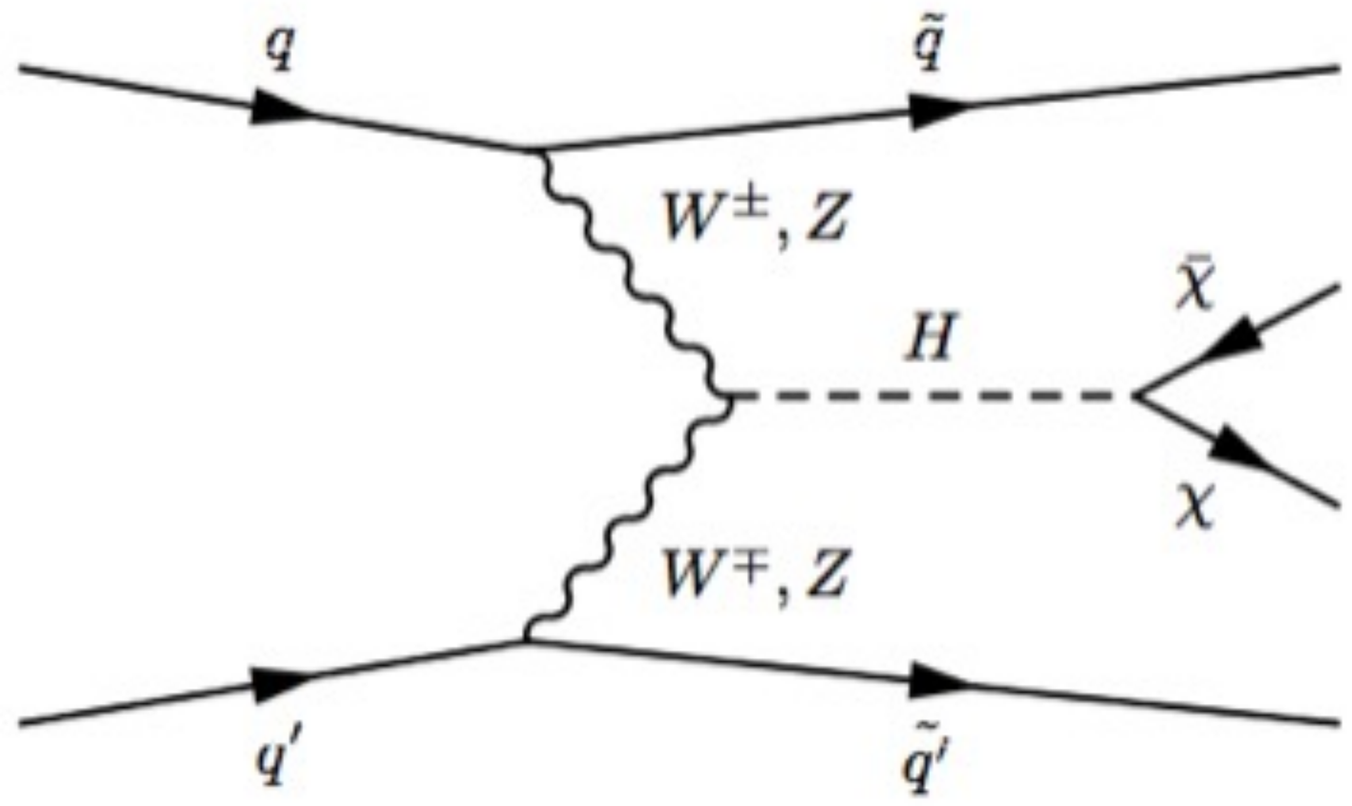


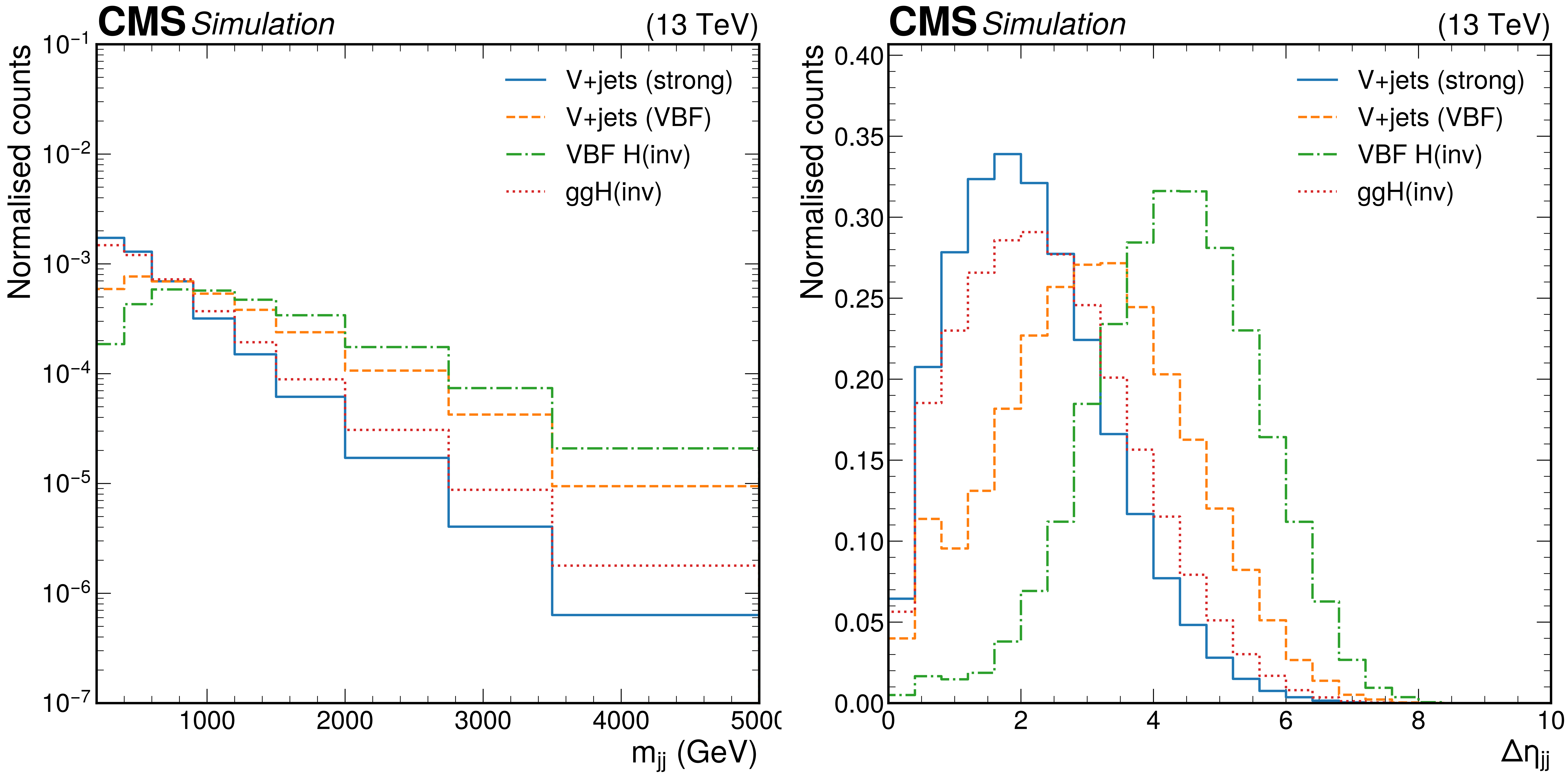
Vector boson fusion

Submitted to Phys. Rev. D

- Largest sensitivity among all approaches!
- Experimentally most challenging with 2 forward jets


CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Tue Aug 16 13:20:56 2016 BST
Run/Event: 278923 / 56352147
Lumi section: 66

VBF: Unique Observables

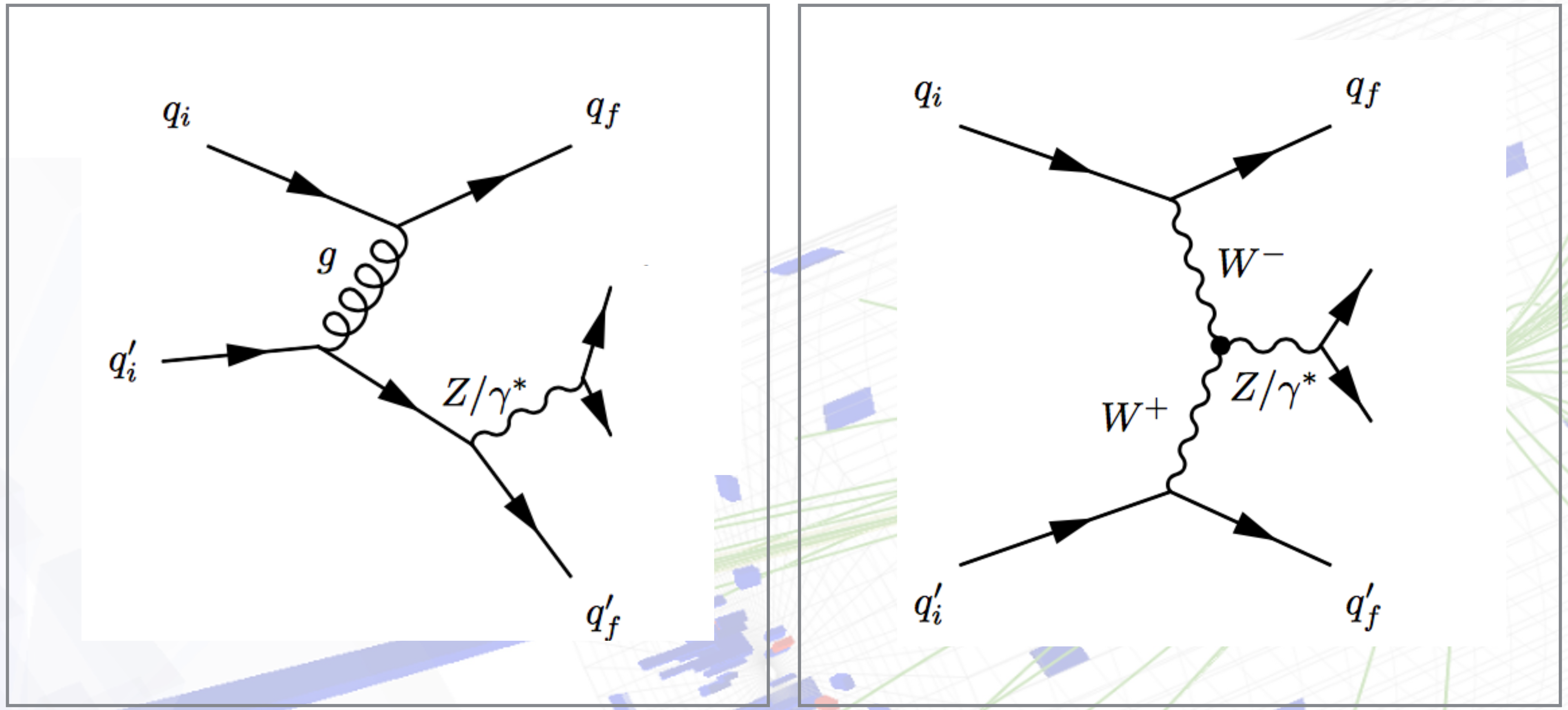


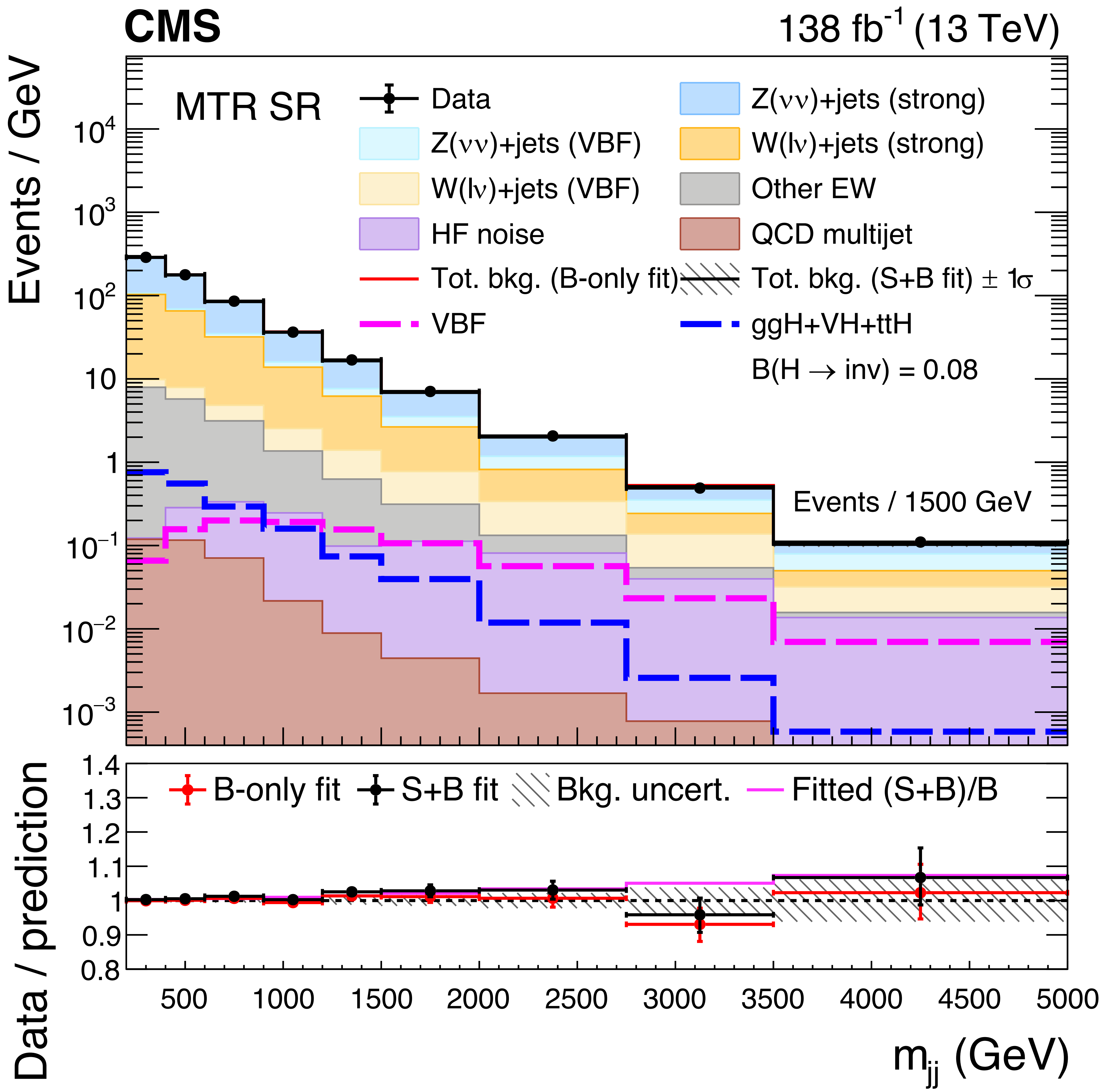
VBF dijet variables: m_{jj}, $\Delta\eta_{jj}$ show separation power

[CMS-HIG-20-003](#) [ATLAS-CONF-2020-008](#)

VBF Higgs Invisible

Background is now a **mixture** of **electroweak** (EW) and **strong processes** of order $\alpha^2_{EW}\alpha^2_S$





VBF production is an "irreducible" background for this search: same signature of two hard forward quarks

VBF Higgs Invisible + Photon

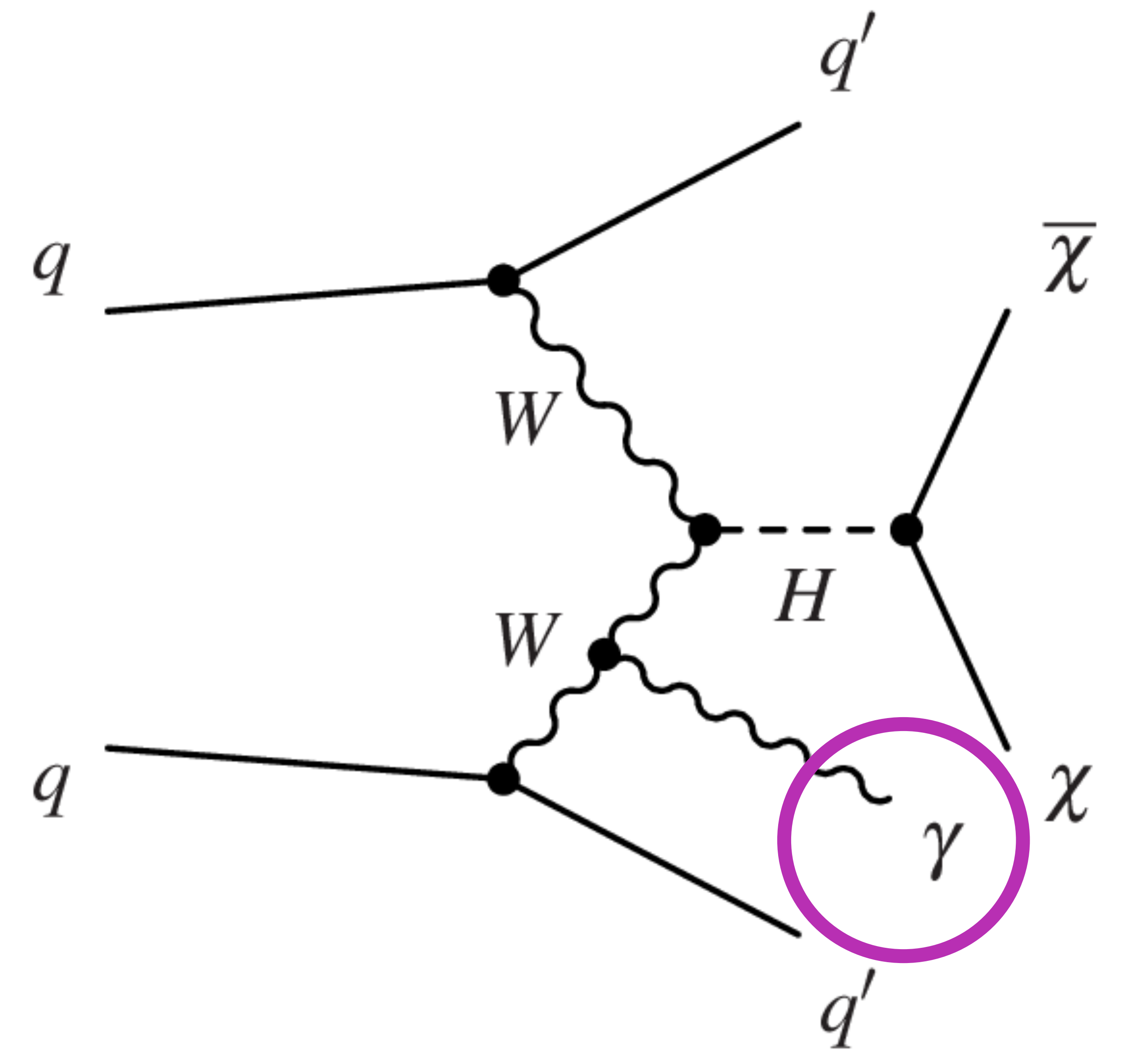
ATLAS EXPERIMENT

Run: 357409
Event: 4893756438
2018-08-04 01:51:53 CEST

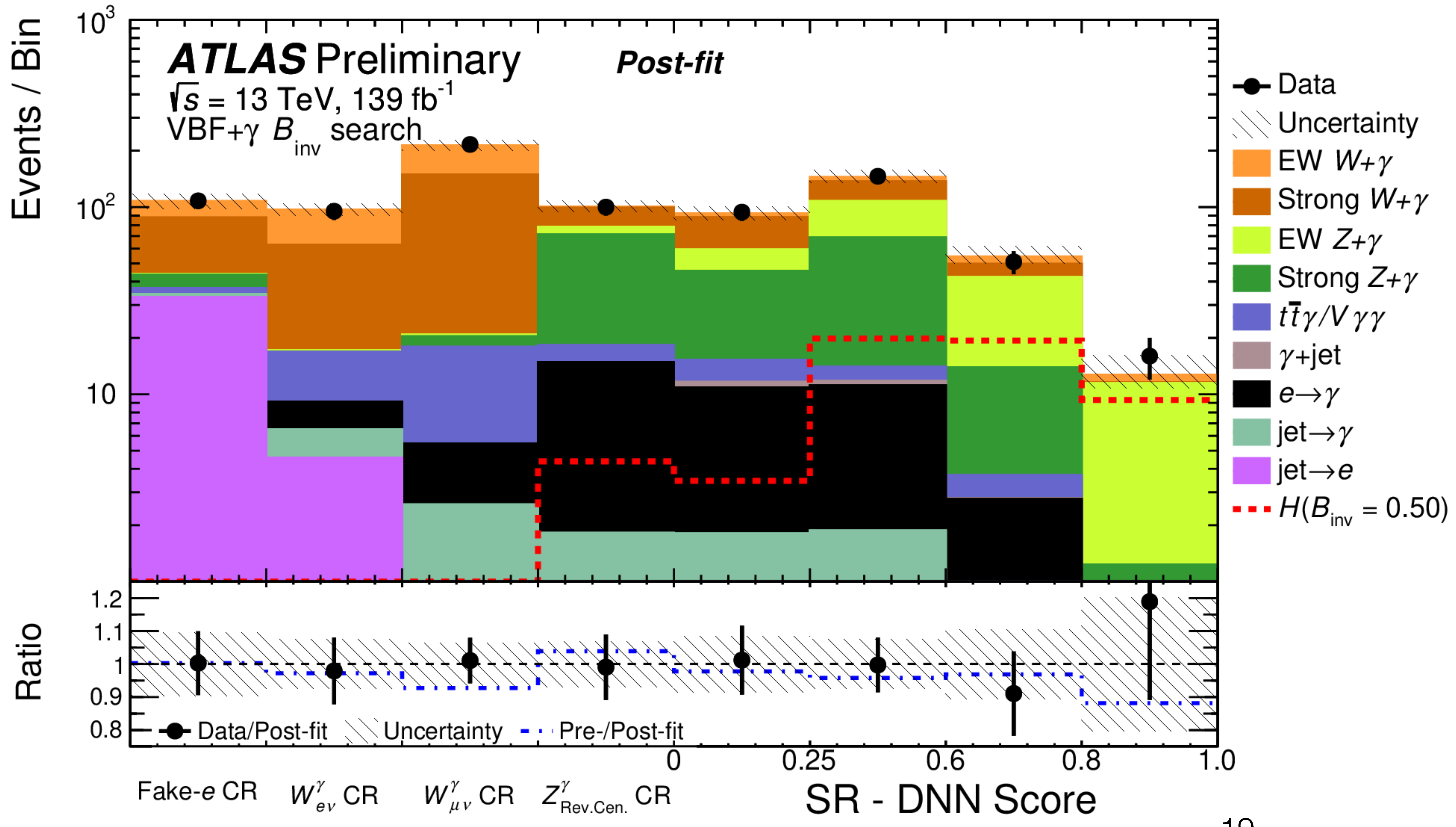
jj mass: 2700 GeV
MET: 198 GeV
mT: 193 GeV
photon pT: 75 GeV

VBF Higgs Invisible + Photon

Similar jet selection to traditional VBF search, with an **addition of low pT photon** (15 - 110 GeV) + centrality requirements on the photon.



Signal discrimination via **deep neutral network training** method **optimizes for H→inv**



ATLAS-CONF-2021-004

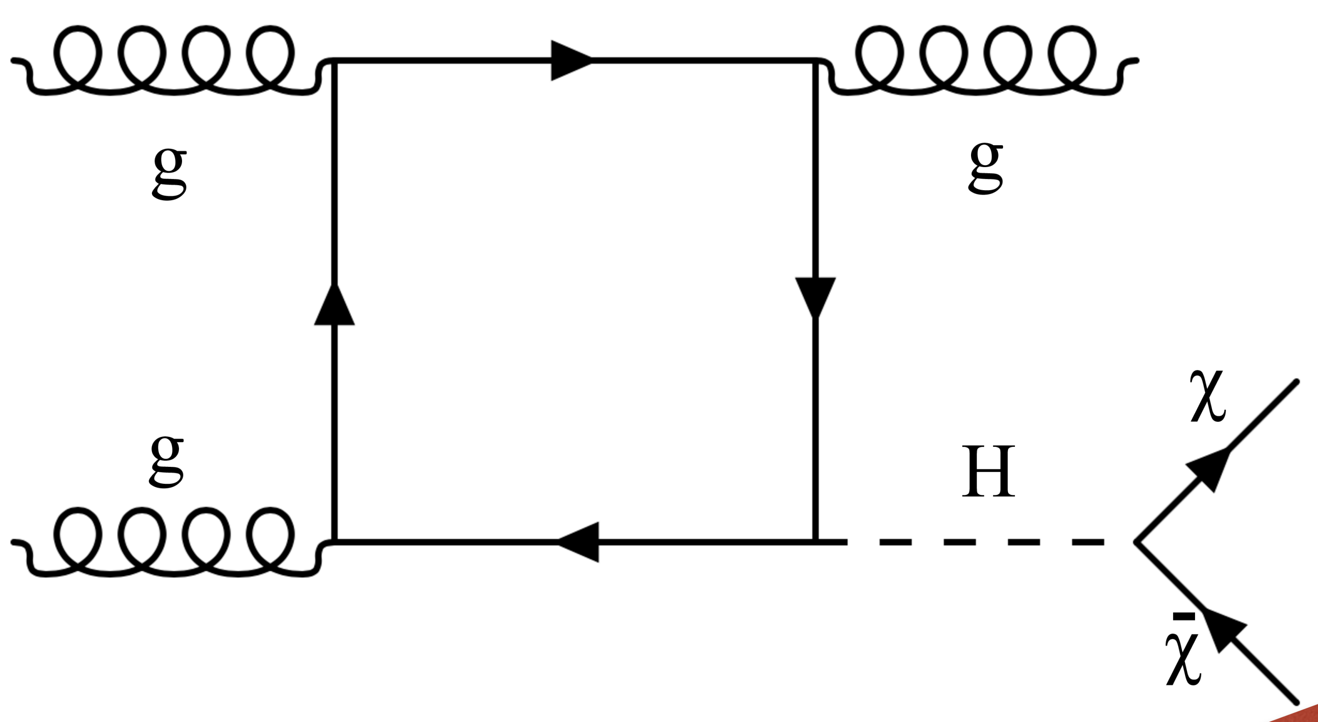
BR(H→ inv) < 37 % (34% exp)

Higgs Production Modes

Higgs Production modes will determine the signature.

… and vector boson fusion!

No Significant Deviation from the Standard Model Prediction



Gluon fusi[illegible]

JHE[illegible]

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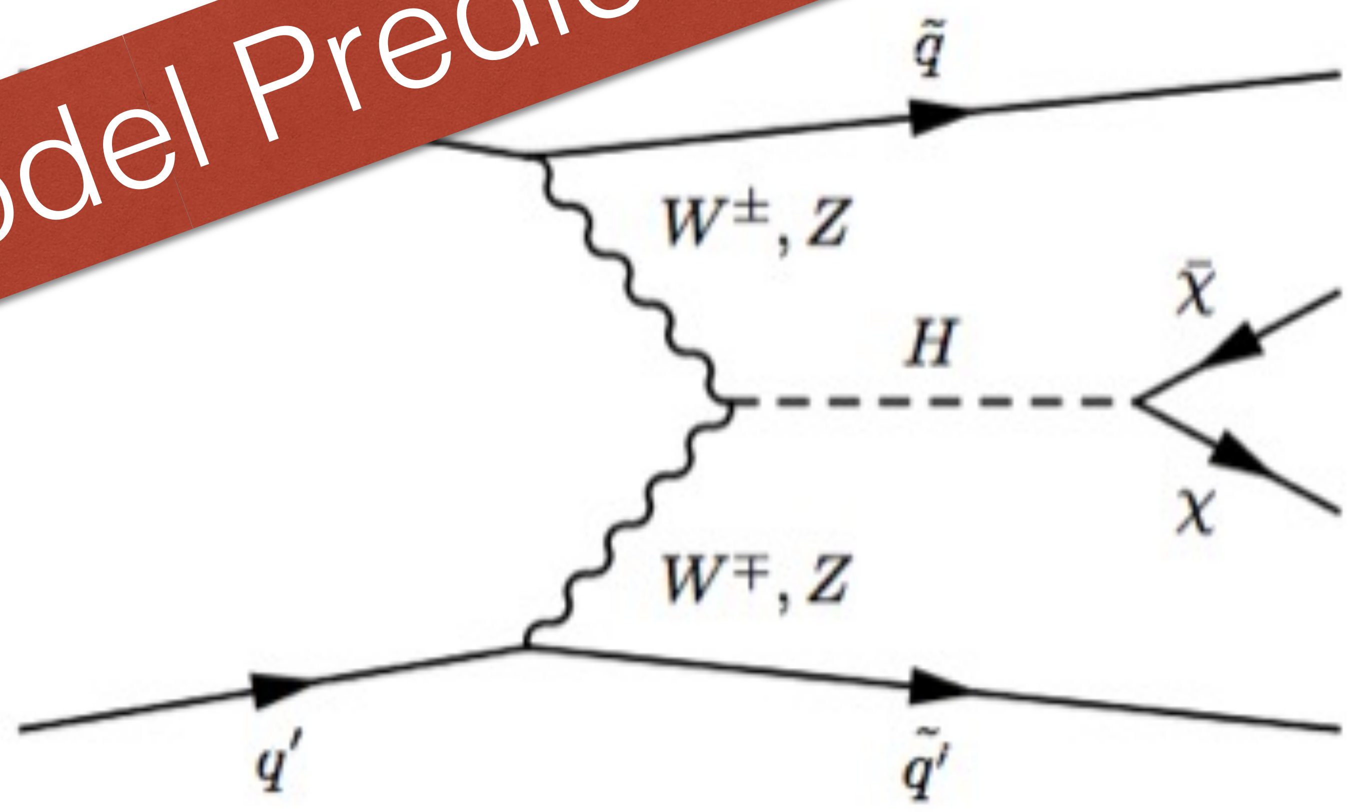


Vector boson fusion

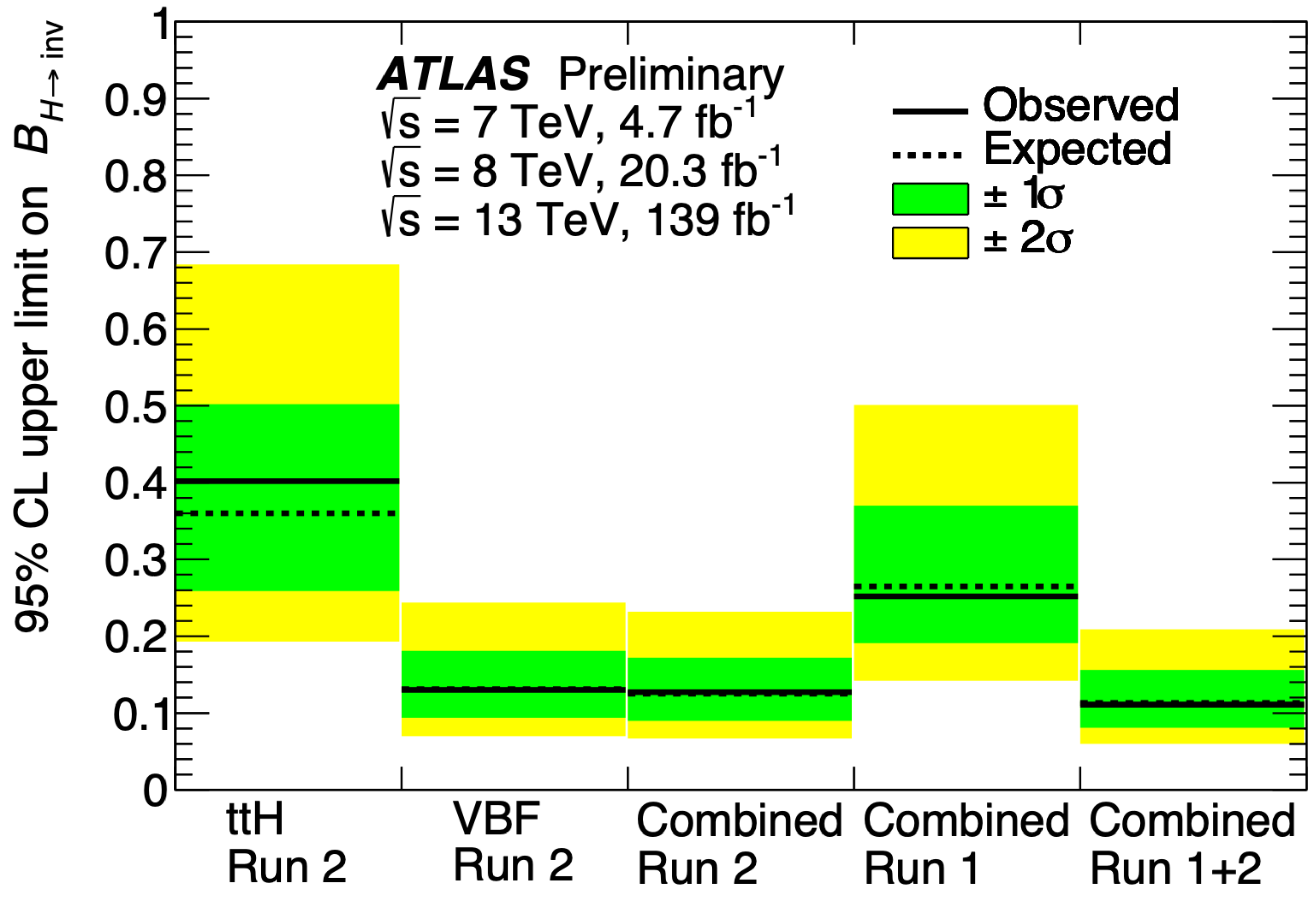
Submitted to Phys. Rev. D

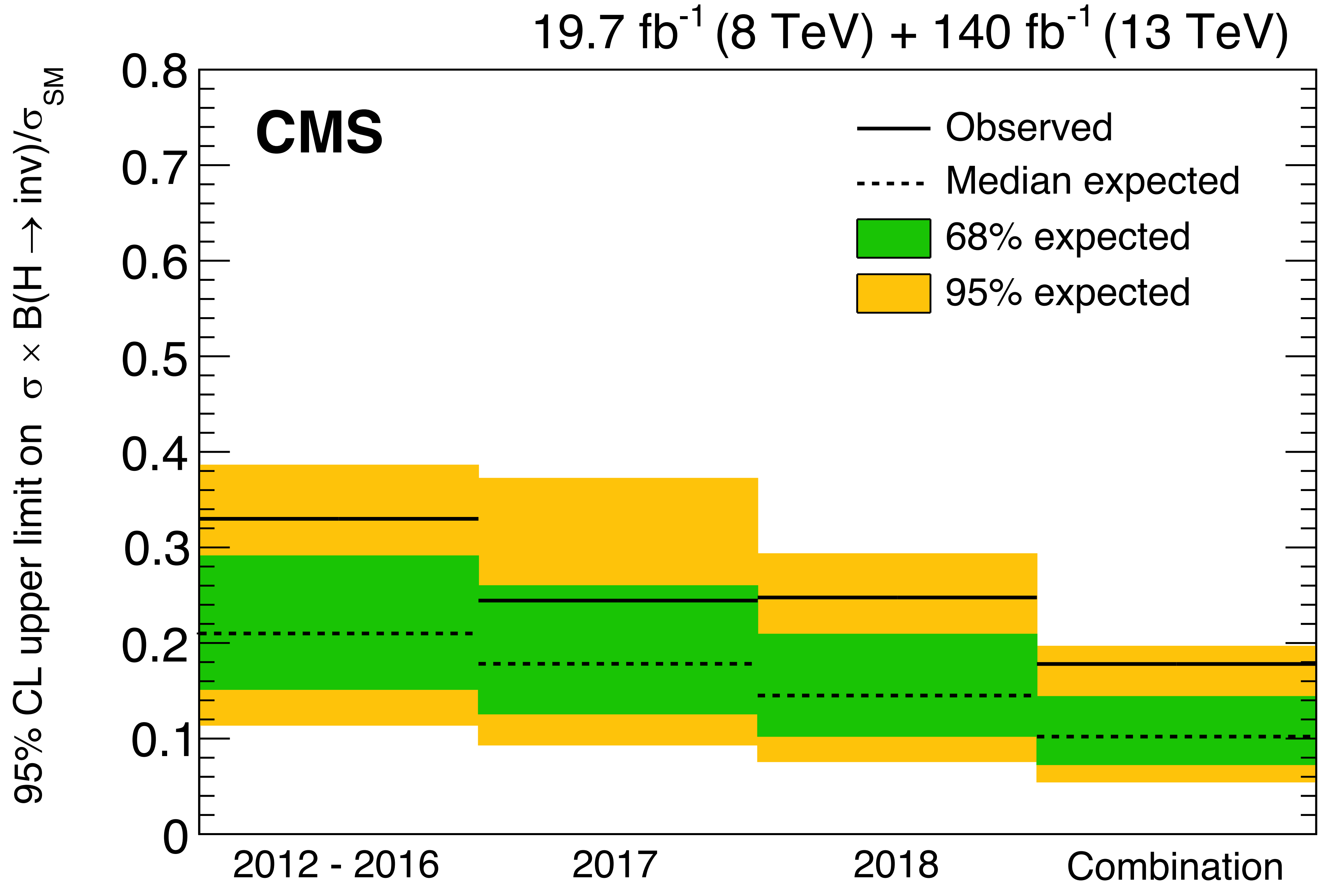
- Largest sensitivity among all approaches!
- Experimentally most challenging with 2 forward jets

Higgs to Invisible Branching Fraction Limits

ATLAS-CONF-2020-052

CMS-HIG-20-003





Current world **best BR(H->inv) < 11%** (11%) obs (exp) from ATLAS

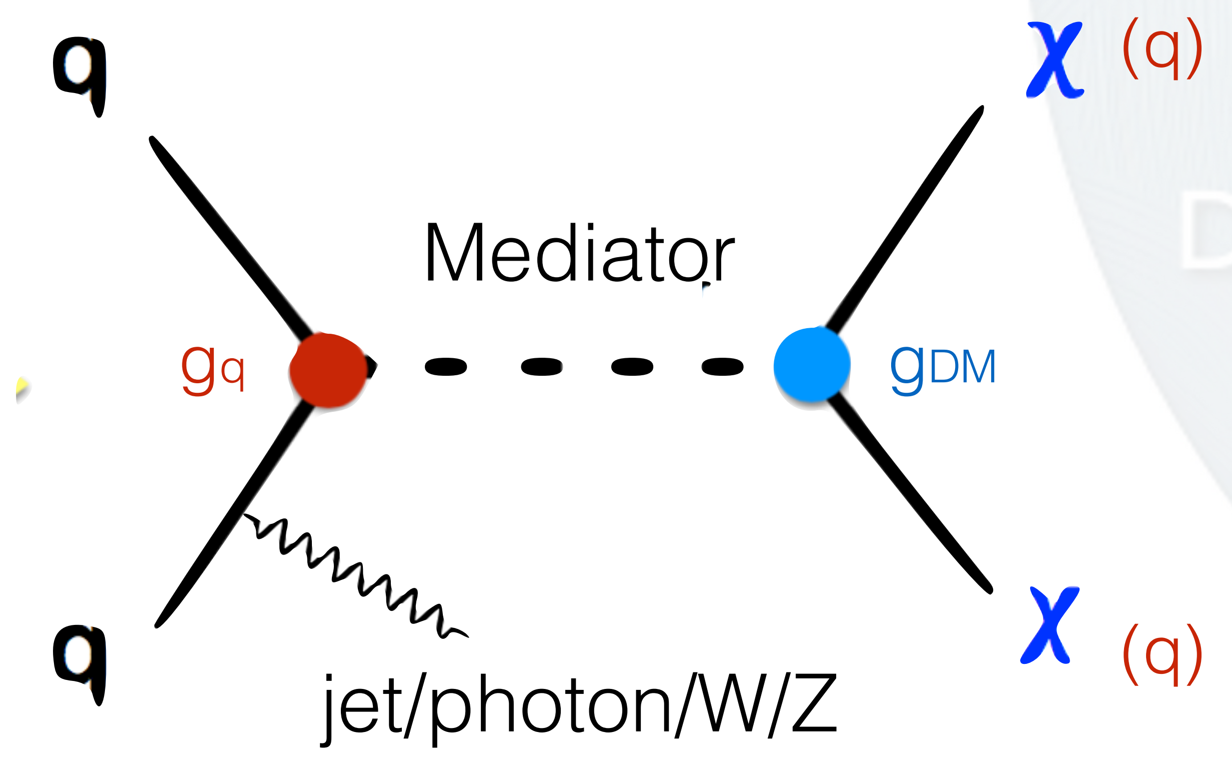
Note: Only a partial combination, more channels to be added.
Updated CMS result is also in preparation

Collider approach to Dark Matter

Strong experimental evidence for DM from astrophysical observations. Most studied class of theories predict DM to be a weakly interacting massive particle.

Simplified Models

Main parameters of the model: mediator, two vertices, and a DM candidate



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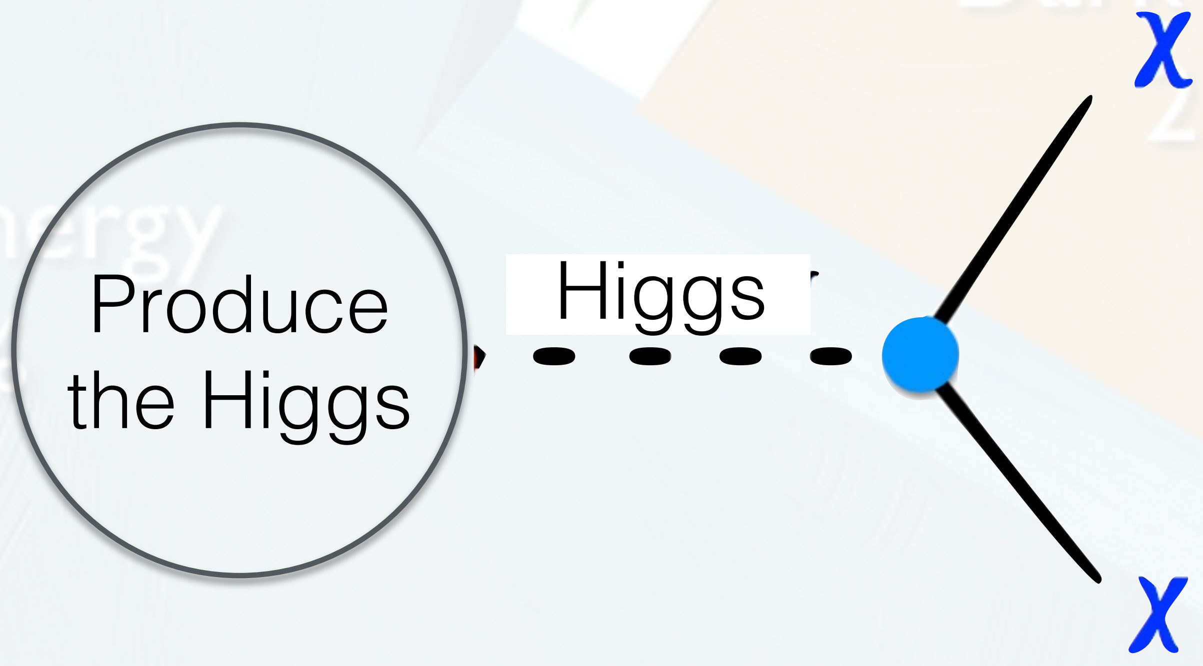
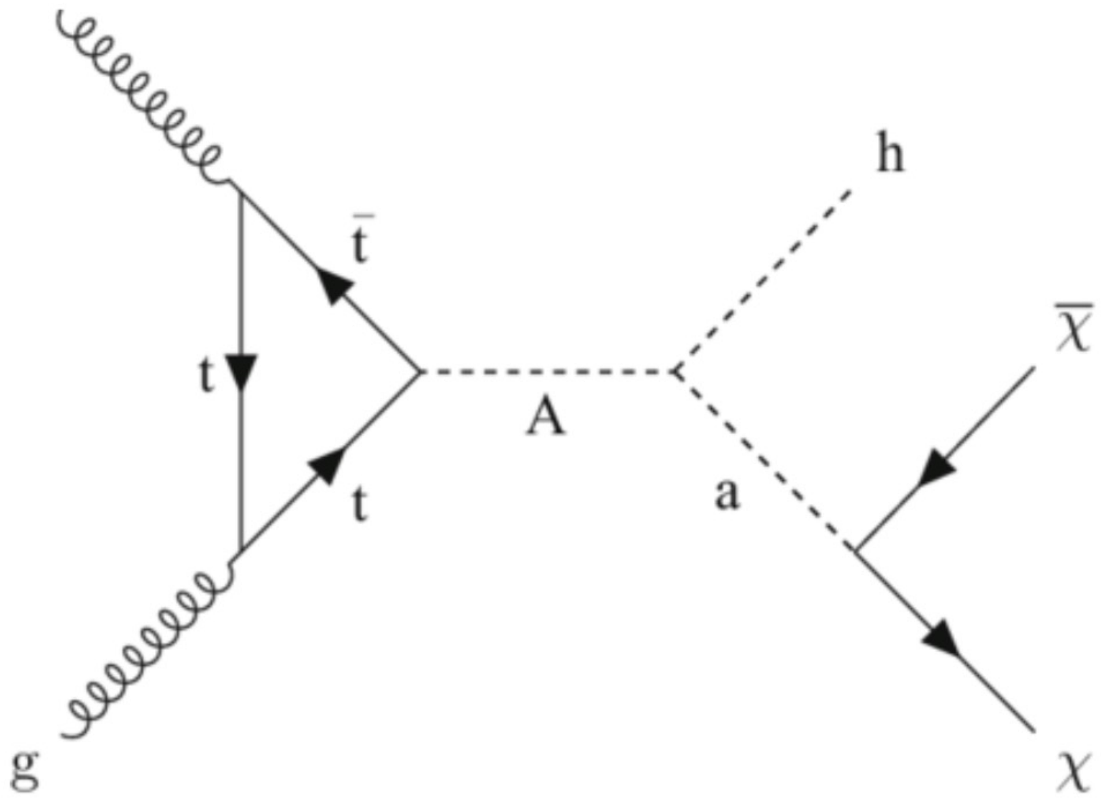


All Higgs production modes can be studied to tag the event

2HDM+a

two-Higgs double model + a pseudo-scalar, can end up with visible and invisible states



A more complete benchmark model with 14 parameters

2HDM+a Models

More complete benchmark model: ultra-violet complete and renormalizable
Assumes SM Higgs boson is part of an **extended Higgs sector** with two complex Higgs doublets

14 independent parameters.. but reduce to **5** free parameters:

- the heavy Higgs mass mA = mH = mH±;
- the pseudoscalar mediator mass ma;
- the DM mass mχ;
- the mixing angle sin θ between the two CP-odd states a and A;
- and VEV ratio tan β .

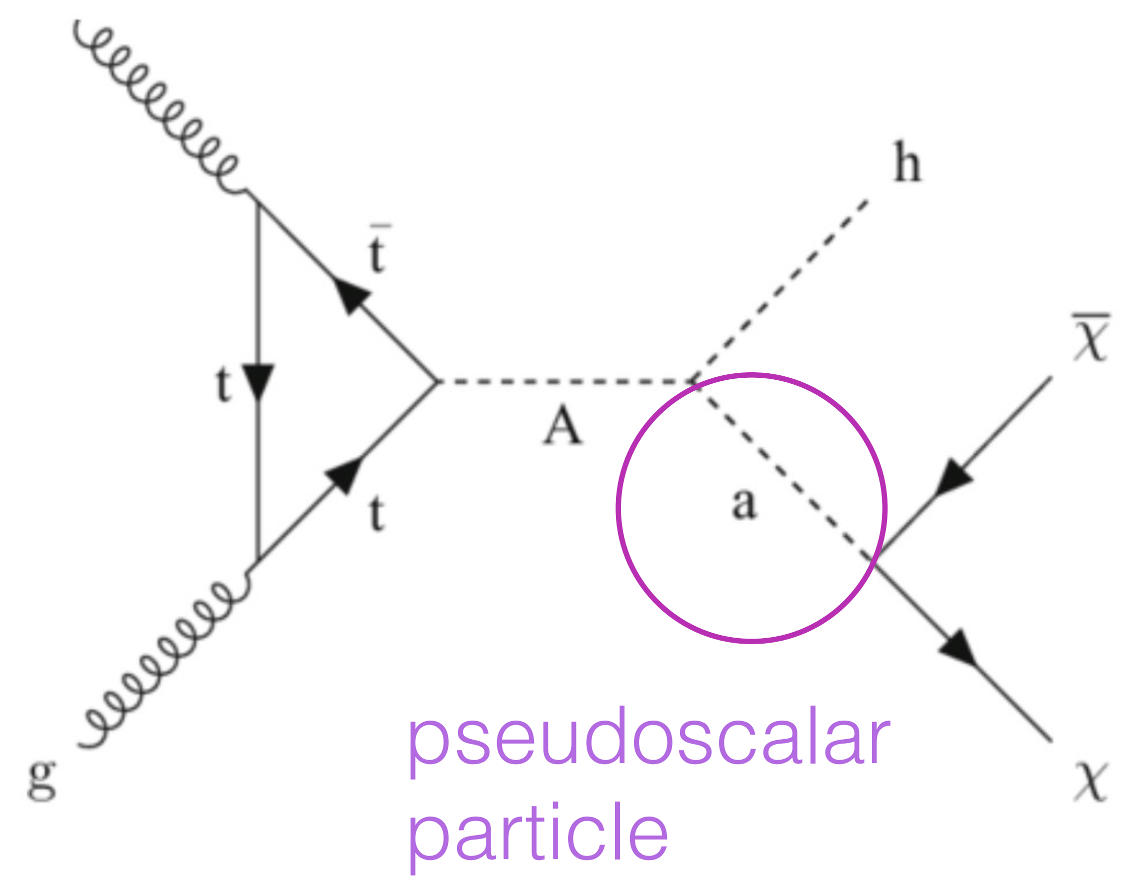
@ **low tanβ** the **ggF** mechanism dominates
@ **higher tanβ** the **bbA** mechanism dominates

Wide variety of detector signatures, DM in association with:

- a Higgs boson (pTmiss+h signatures)
- a Z boson (pTmiss+Z signatures).

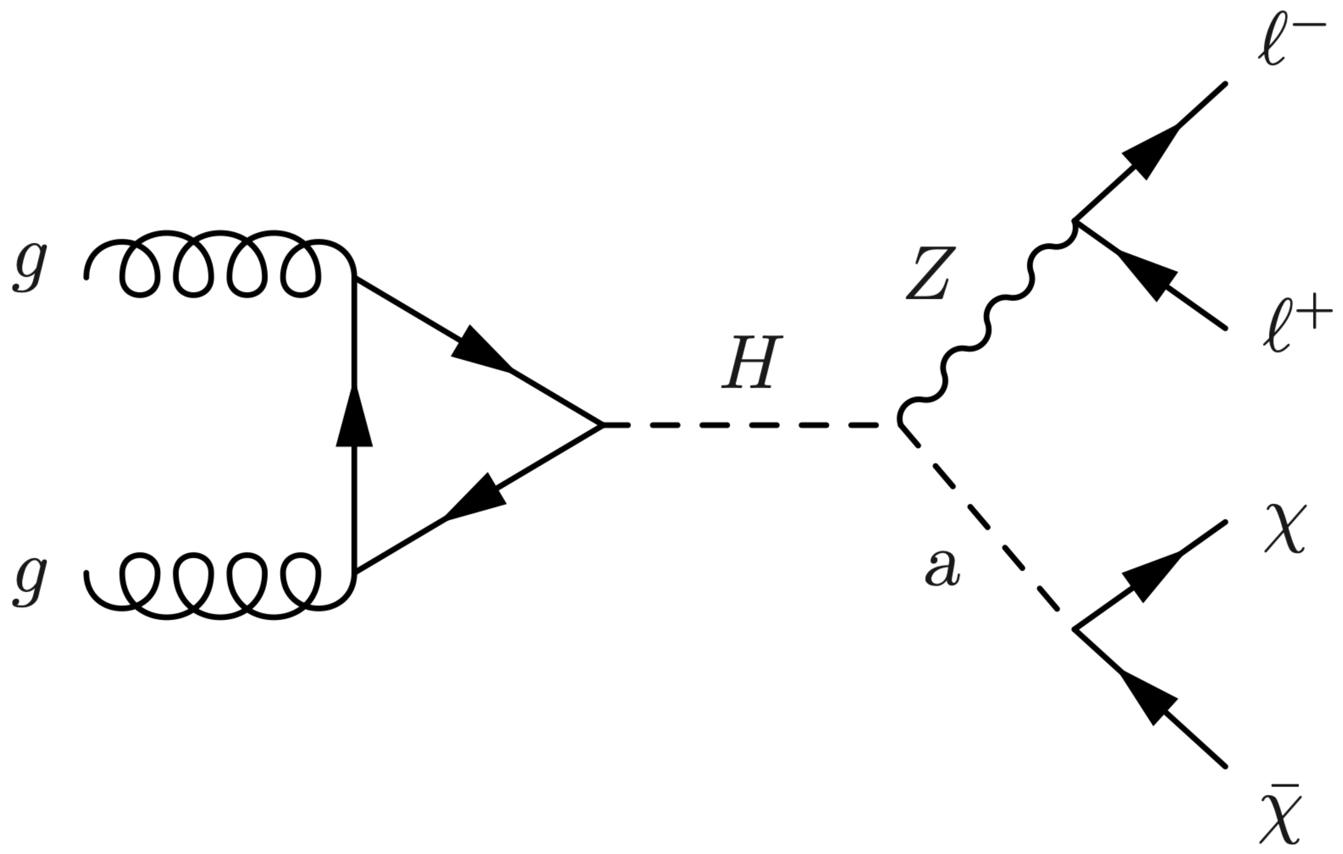
2HDM+a

two-Higgs double model + a pseudo-scalar, can end up with visible and invisible states



A more complete benchmark model with 14 parameters

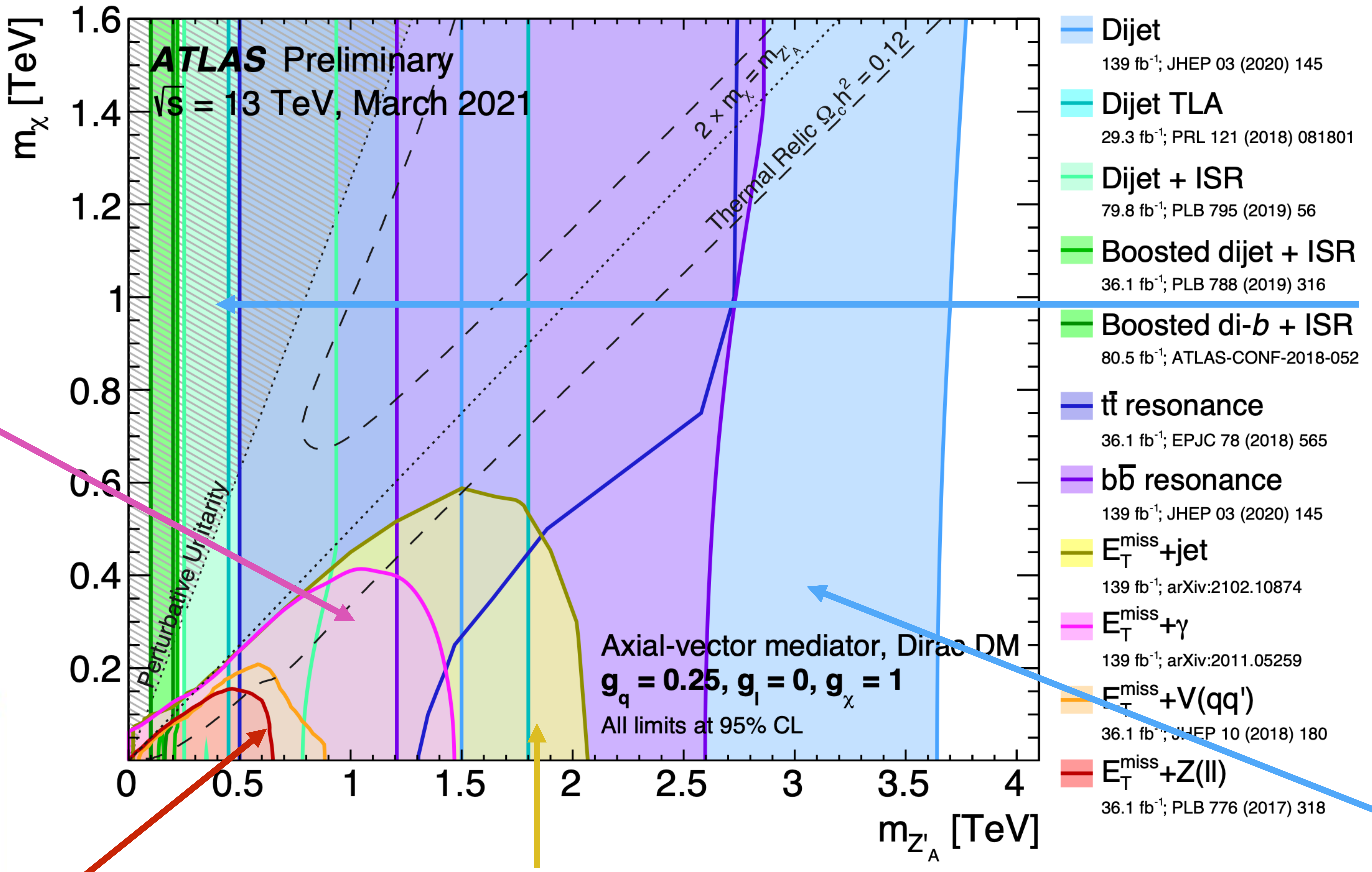
2HDM+a Models: Mono-Z(ll)

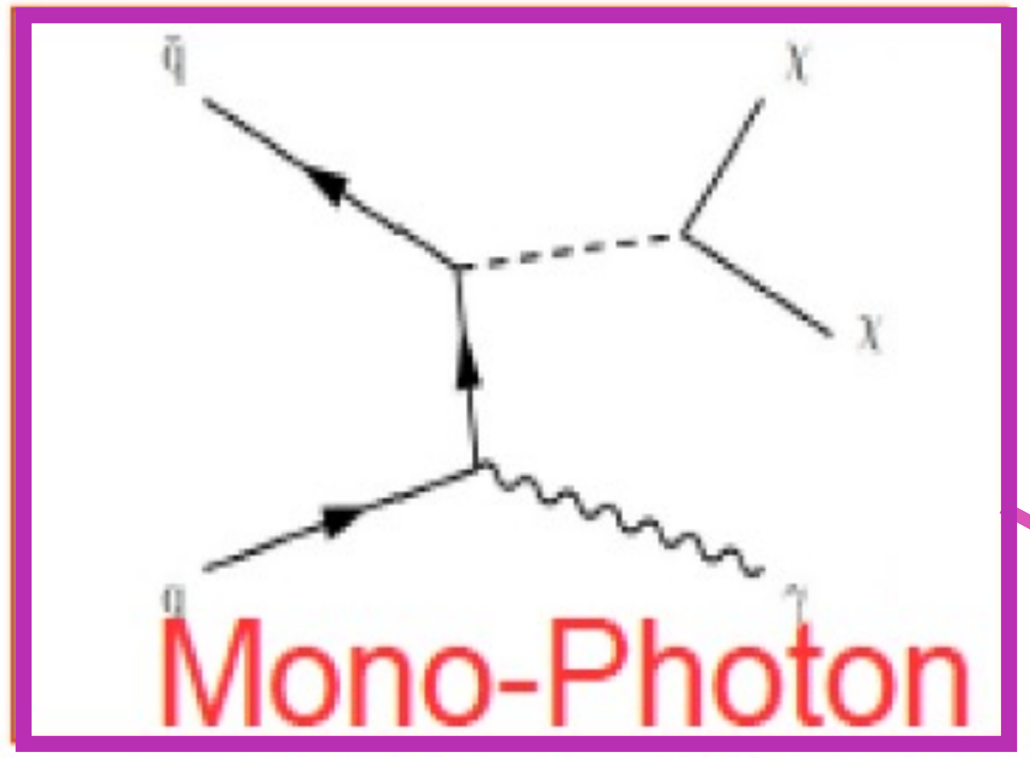


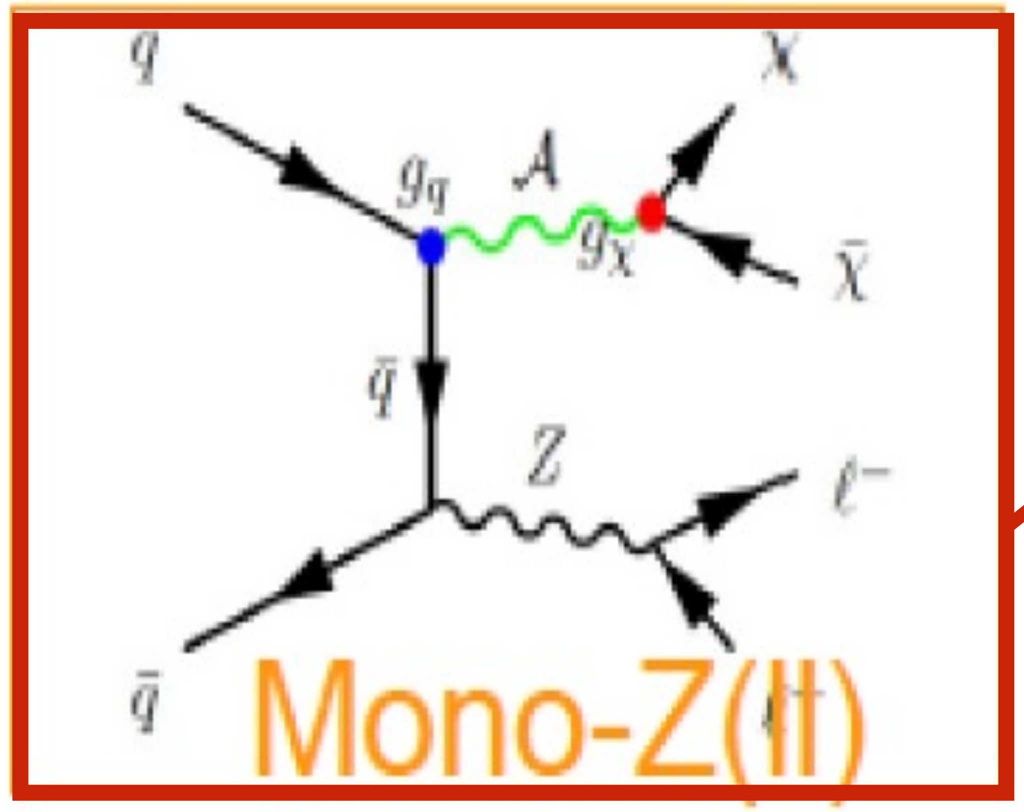
Strategy: look for two leptons (e, μ) compatible with a Z-boson + require large p_T^{miss}. Veto on any additional activity.

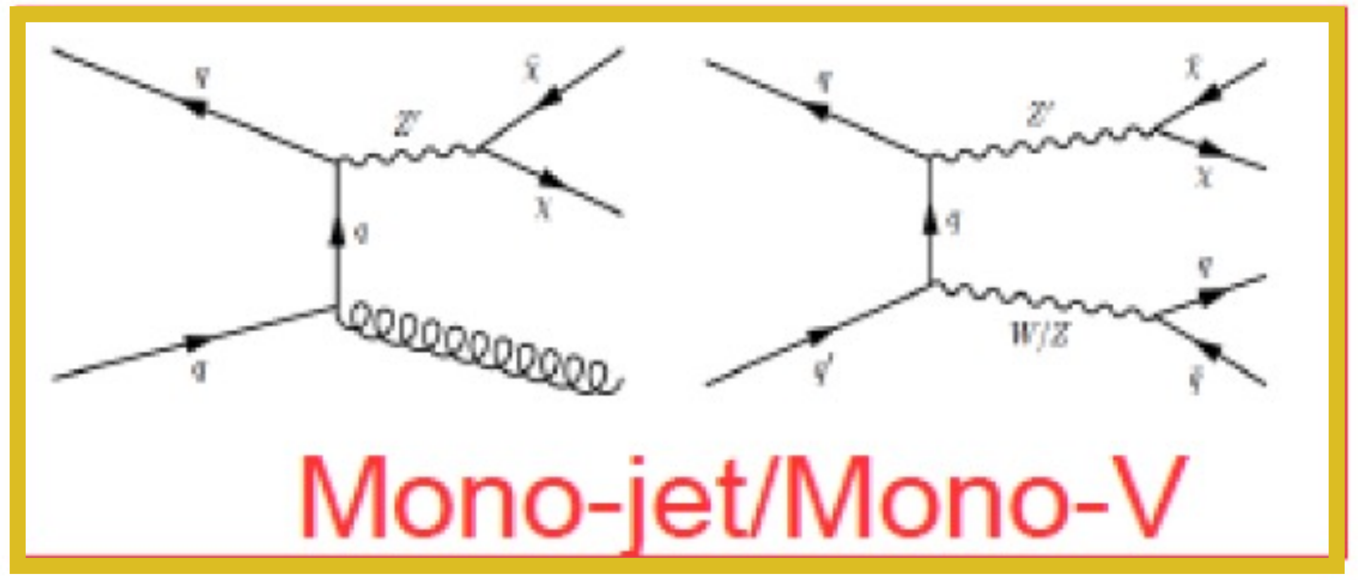
ATL-PHYS-PUB-2021-006

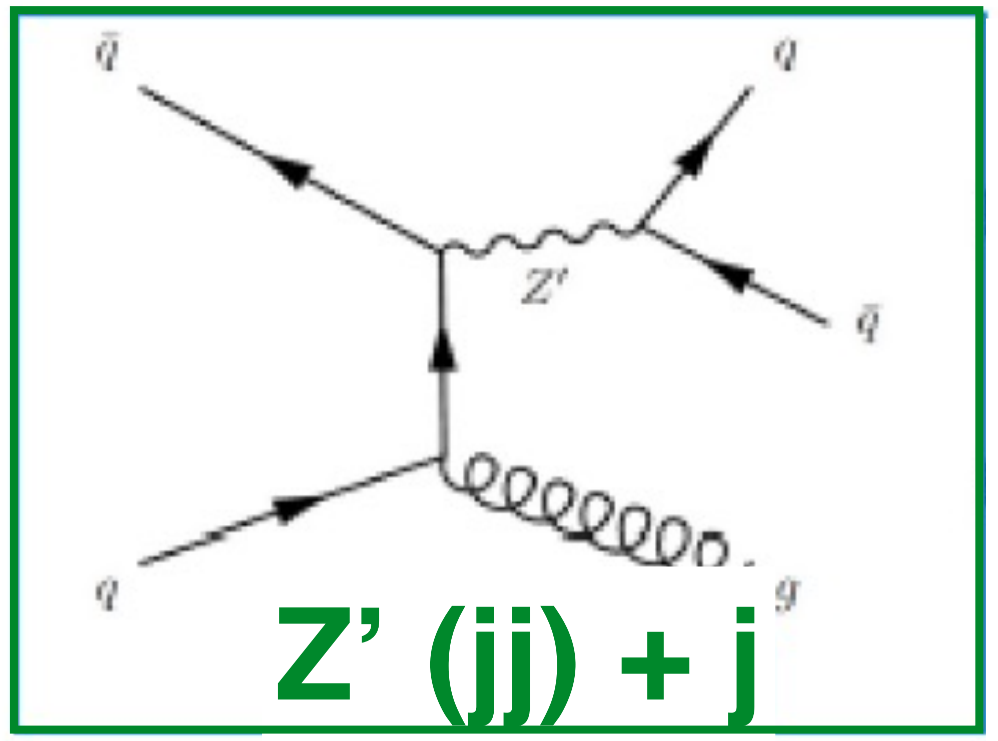
WIMP: It all comes together: Mono-mania

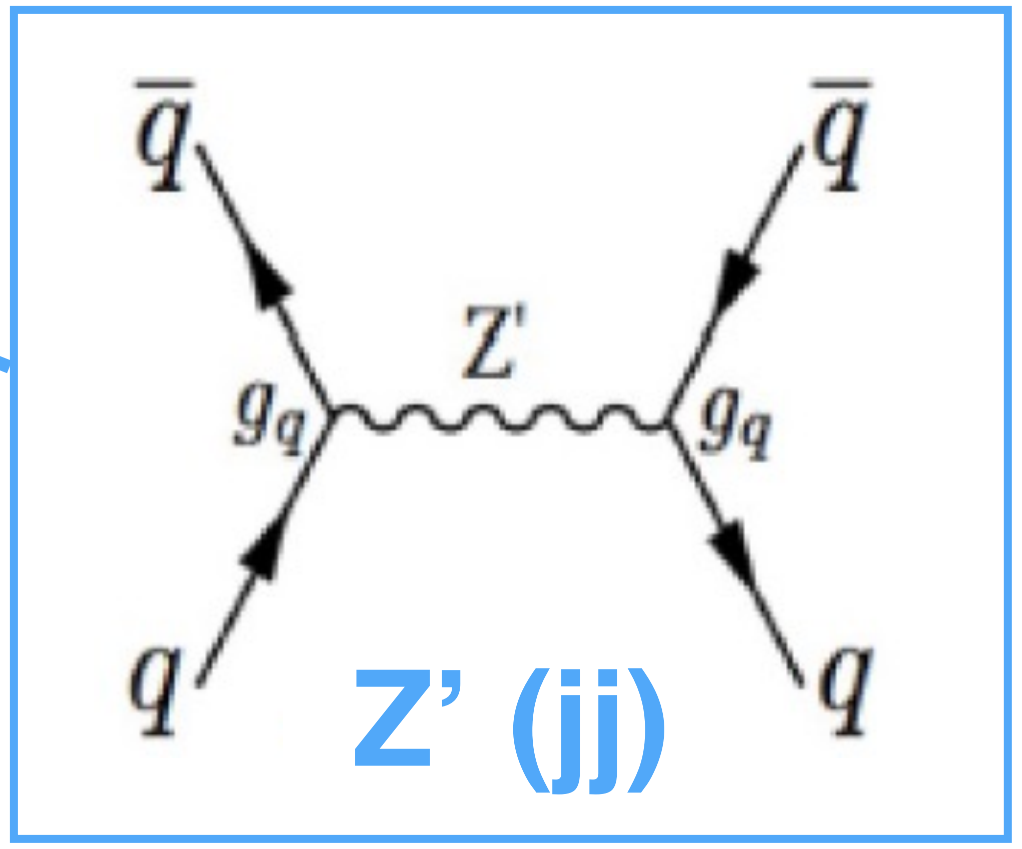












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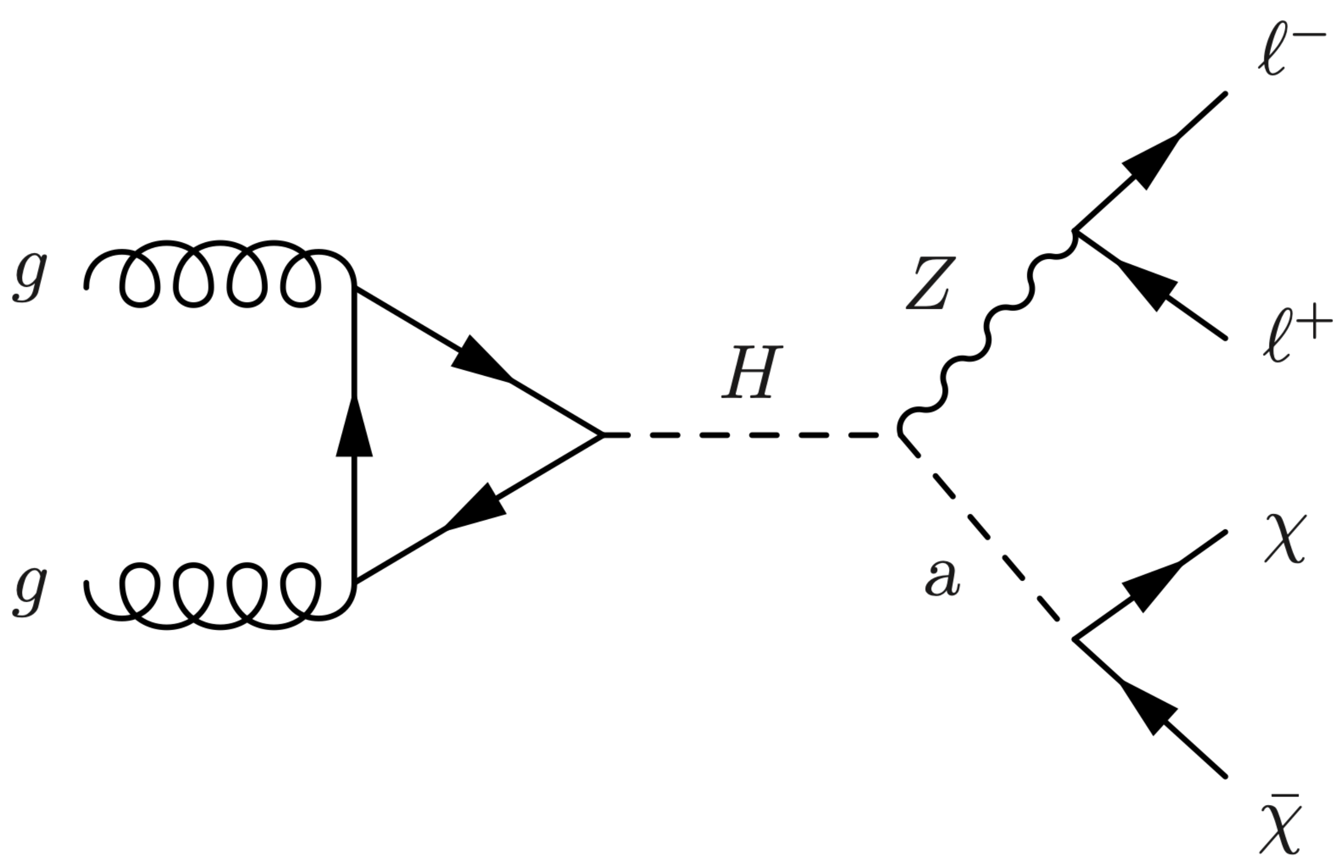

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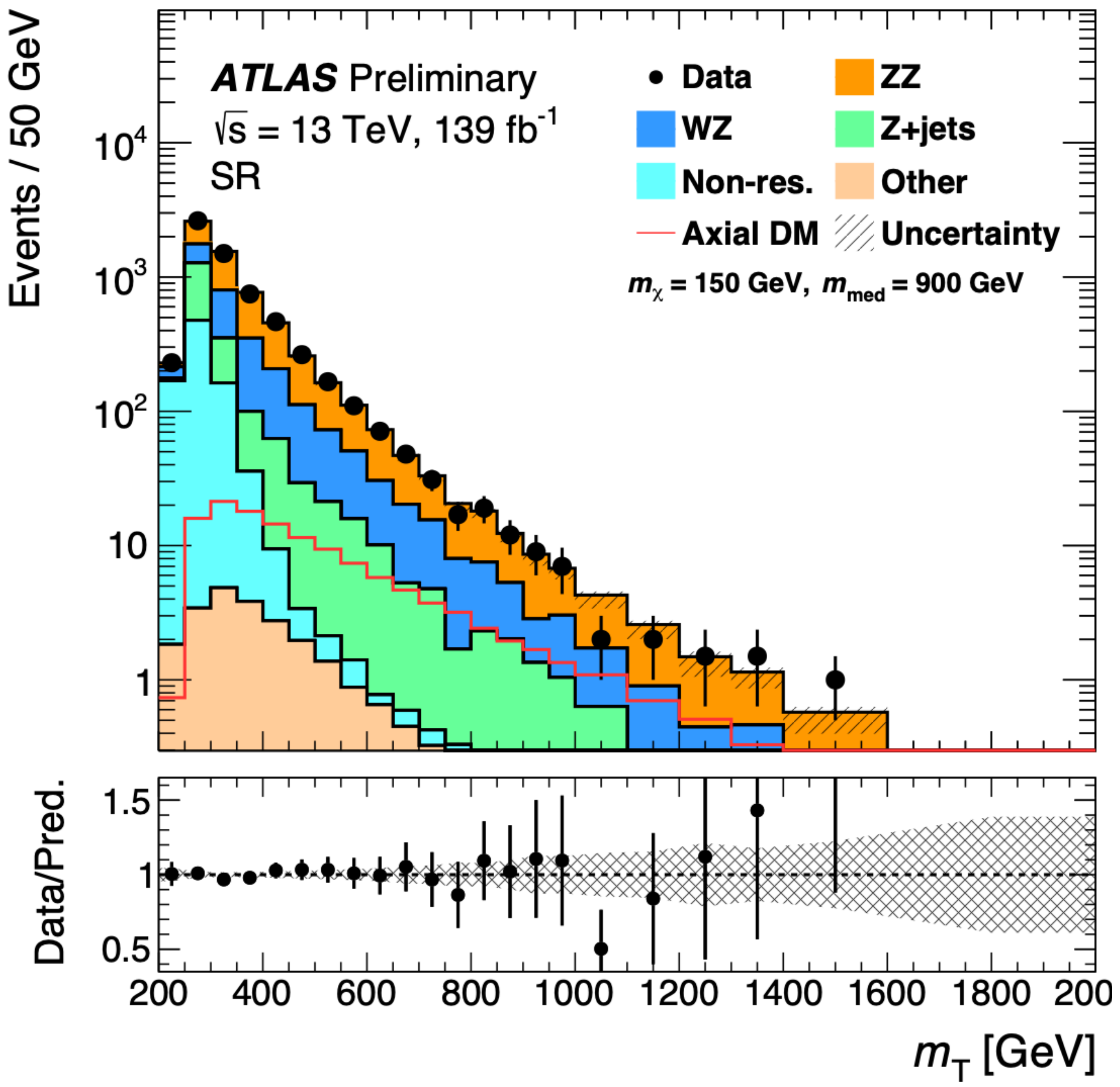
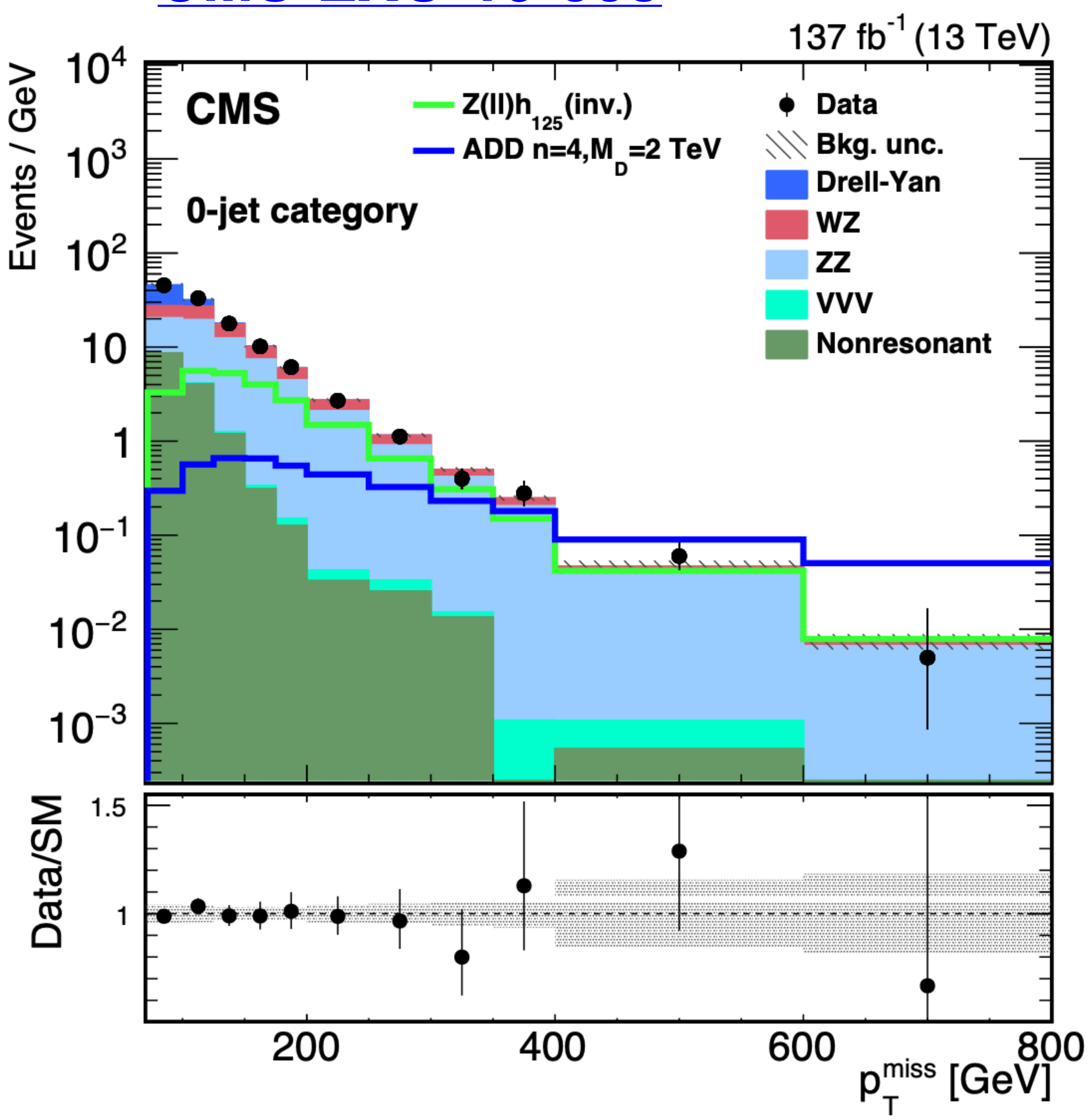
Maximize the **sensitivity** in 2HDM+a parameter space by using the **transverse mass** observable.

[ATLAS-CONF-2021-029]



[CMS-EXO-19-003]

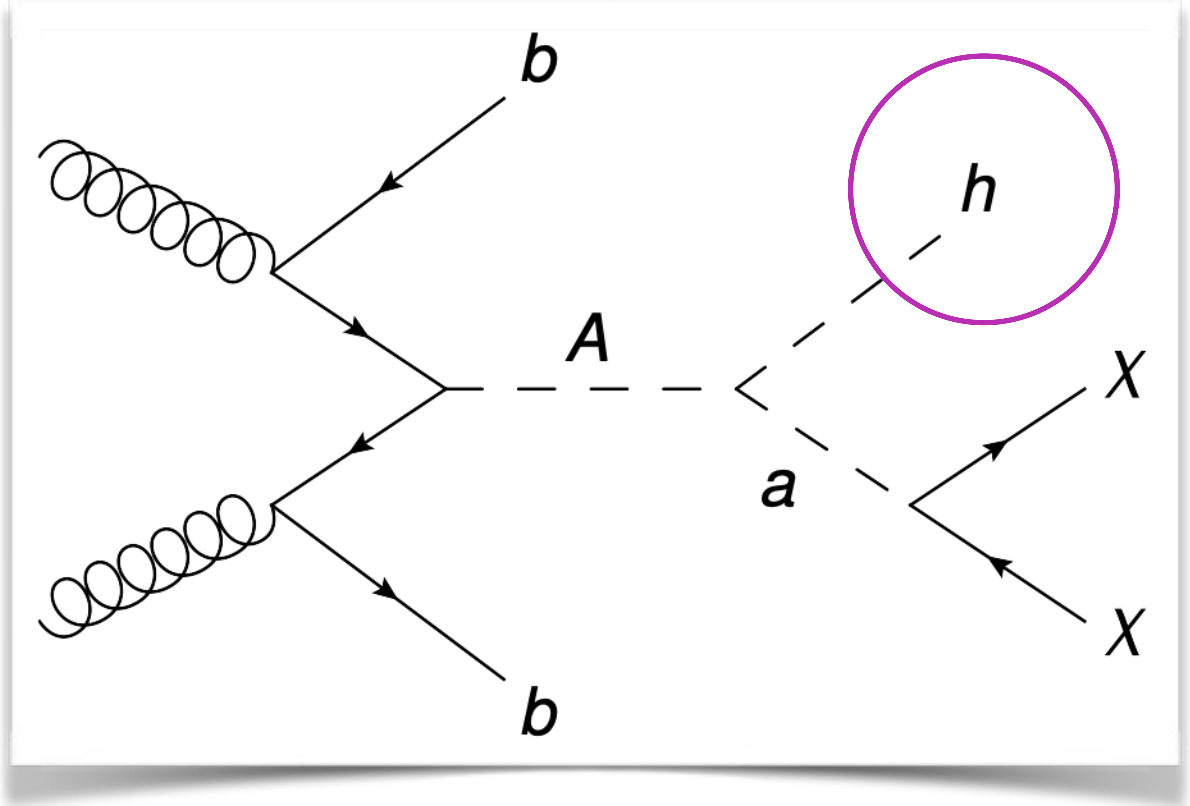


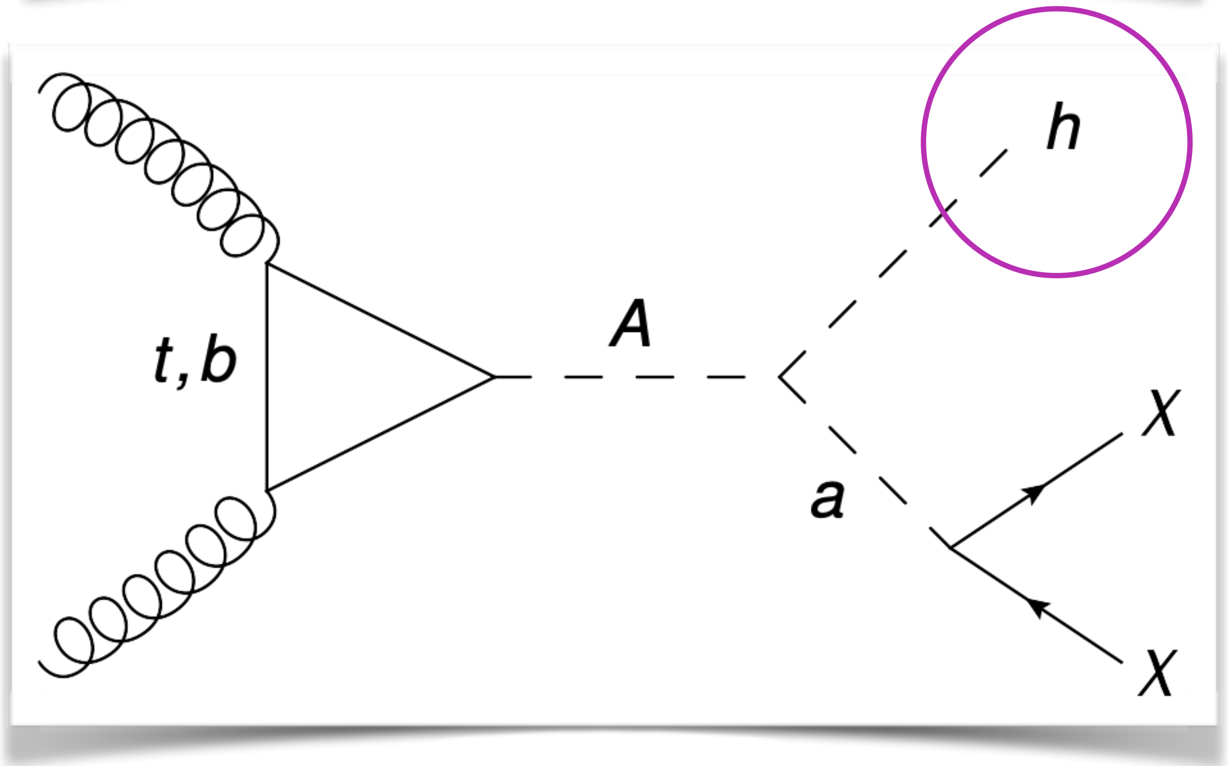
The dominant backgrounds: ZZ, WZ, WW, Z+jets and tt.

Estimated via control regions:

- eμ CR ($t\bar{t}$- and WW- enriched),
- three-lepton CR (WZ-enriched),
- four-lepton CR (ZZ-enriched).

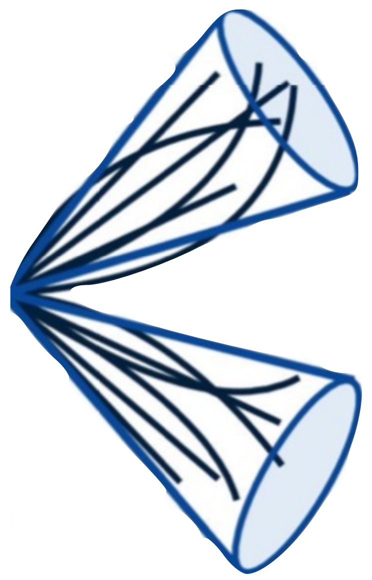
2HDM+a Models: Mono-H(bb)



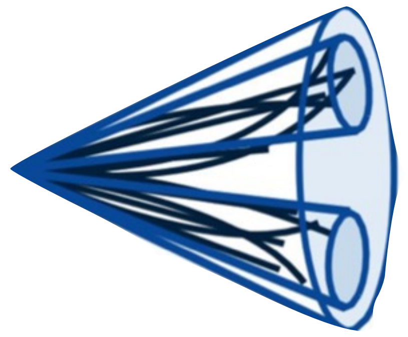


The analysis is split into:

- resolved



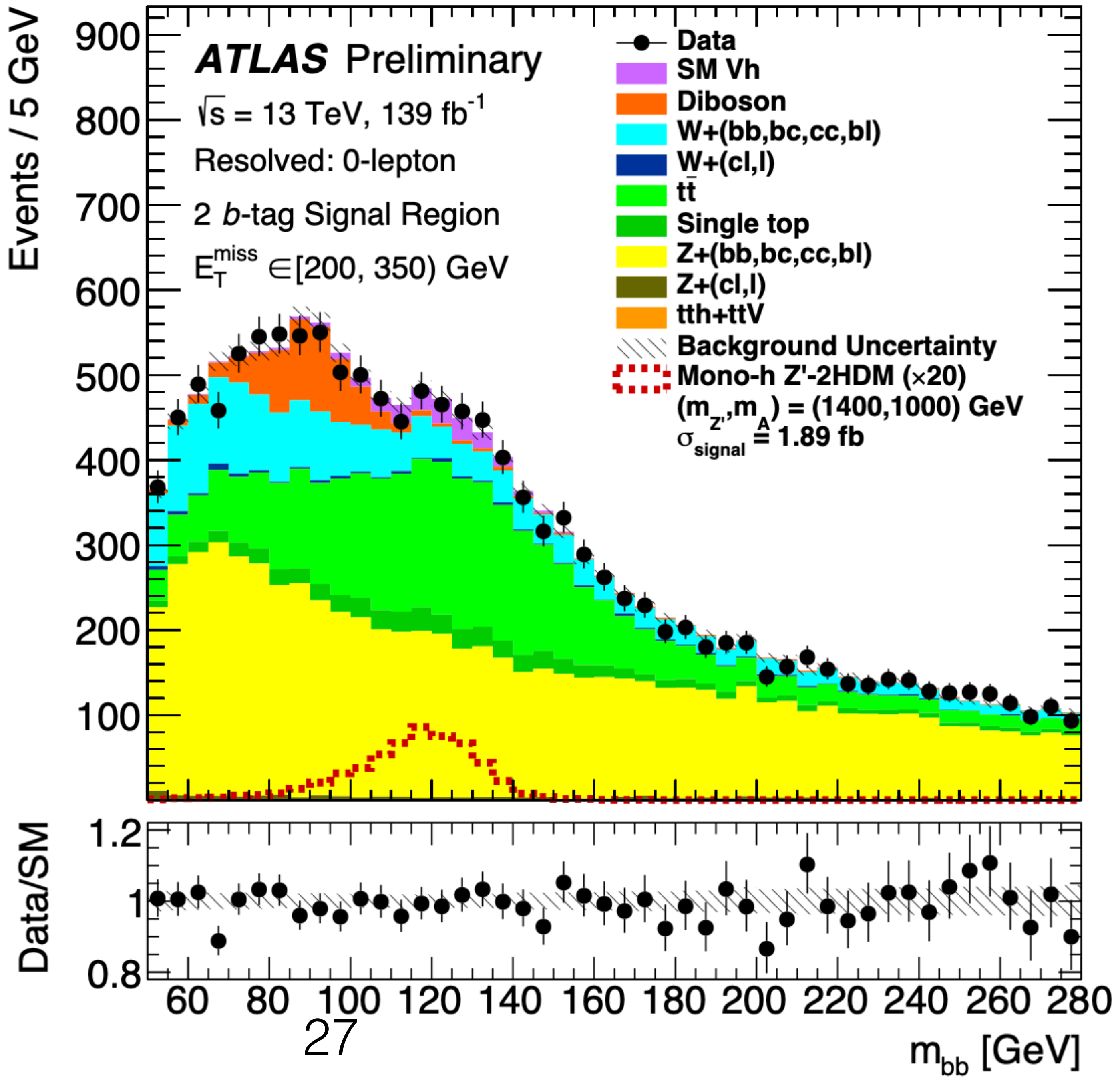
- merged signal regions

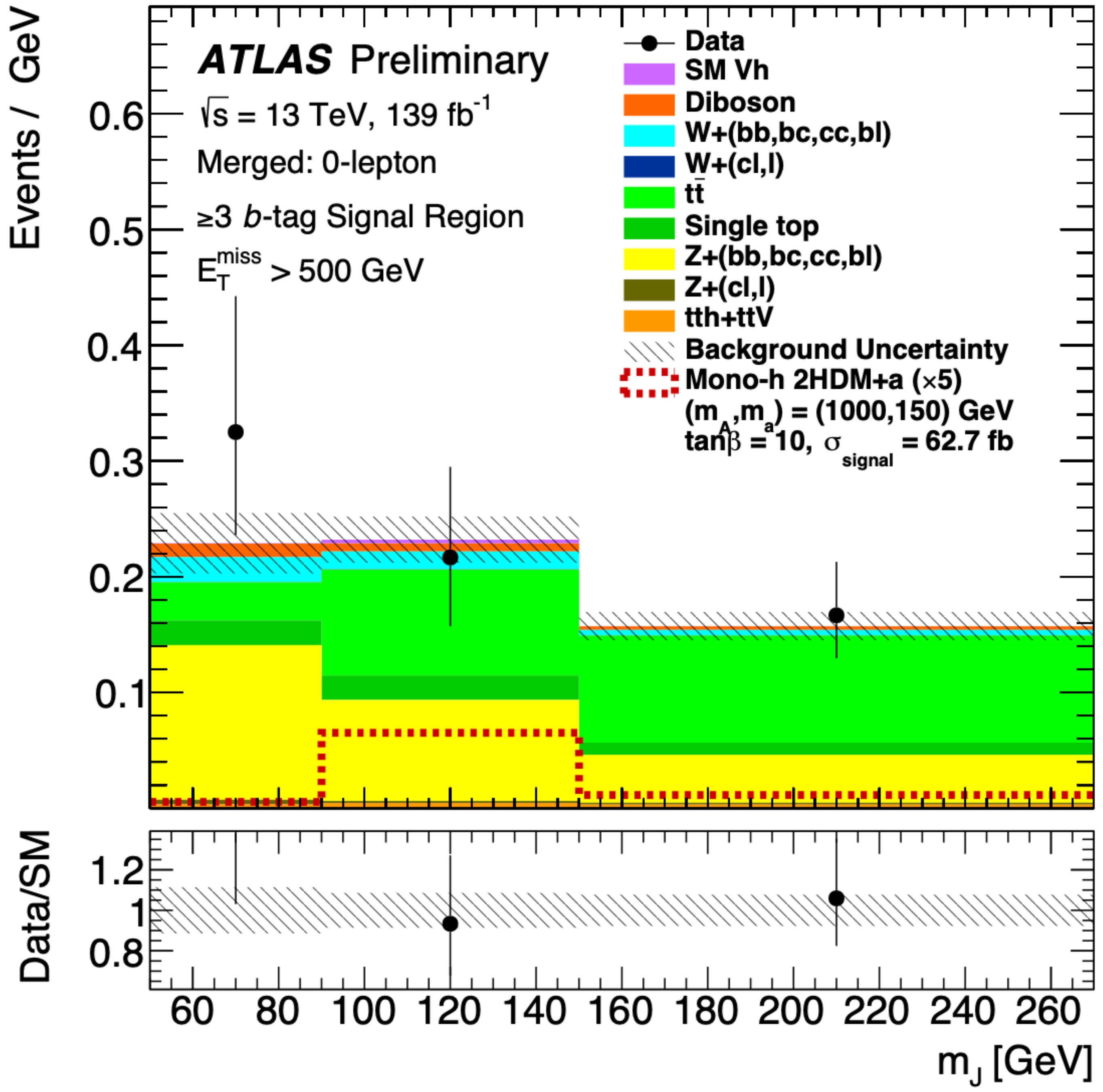


\+ split further into 2 b-tagged jets and at least 3 b-tagged jets and in pTmiss bins.

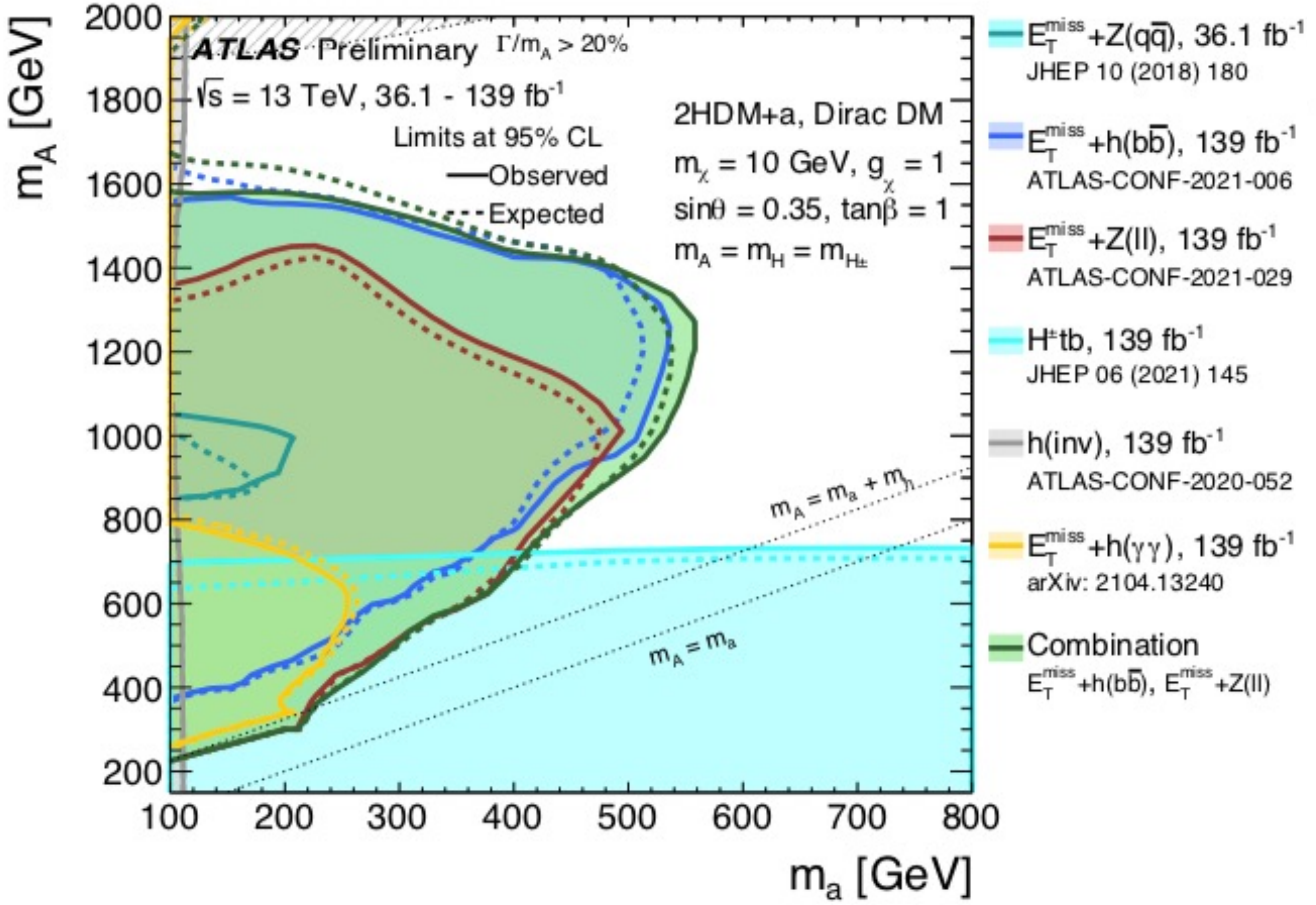
The $t\bar{t}$, W+HF and Z+HF contributions are **modeled using simulations** and **normalization corrected** from **control region** data

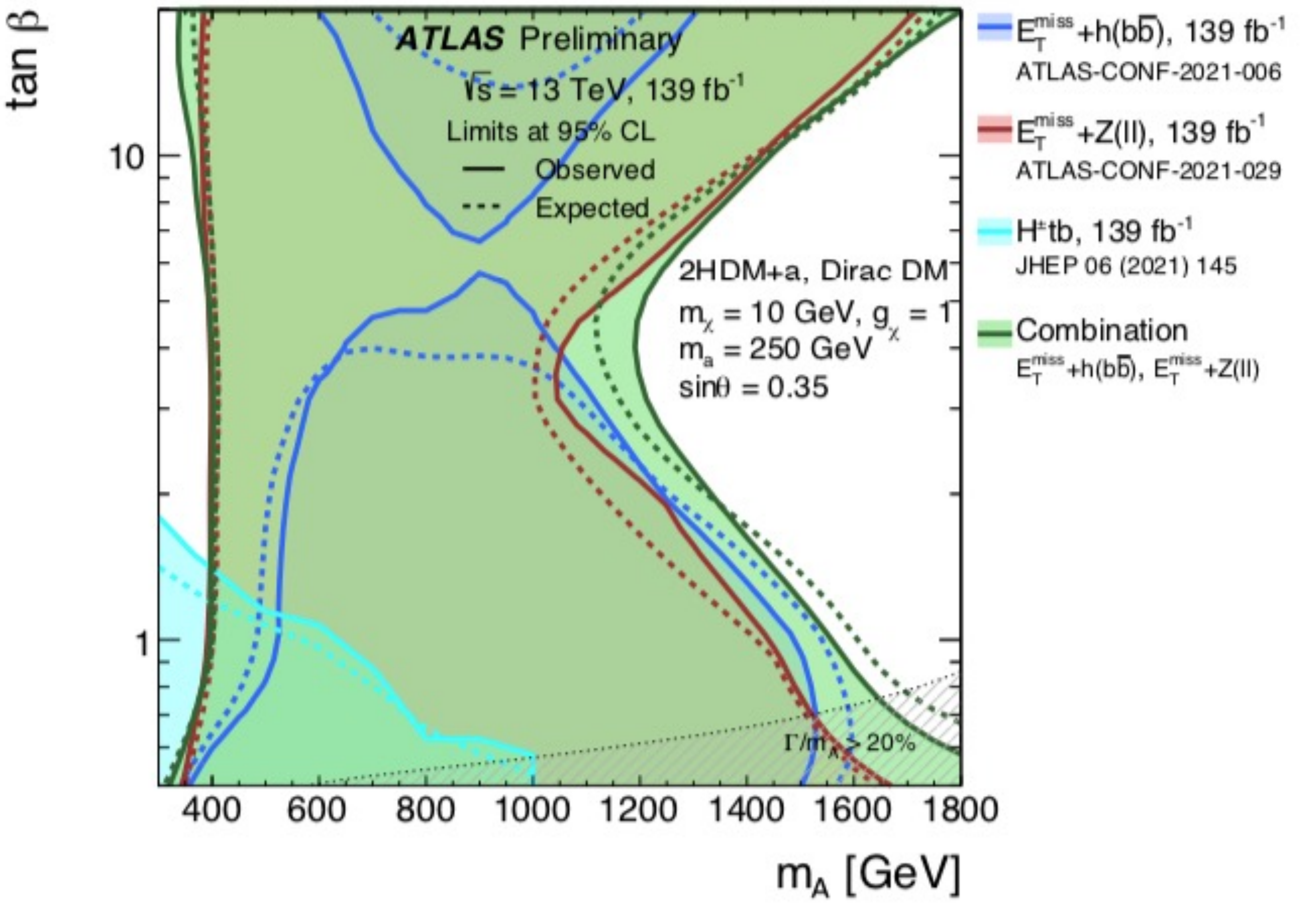
ATLAS-CONF-2021-006





2HDM+a Models - Putting it all together





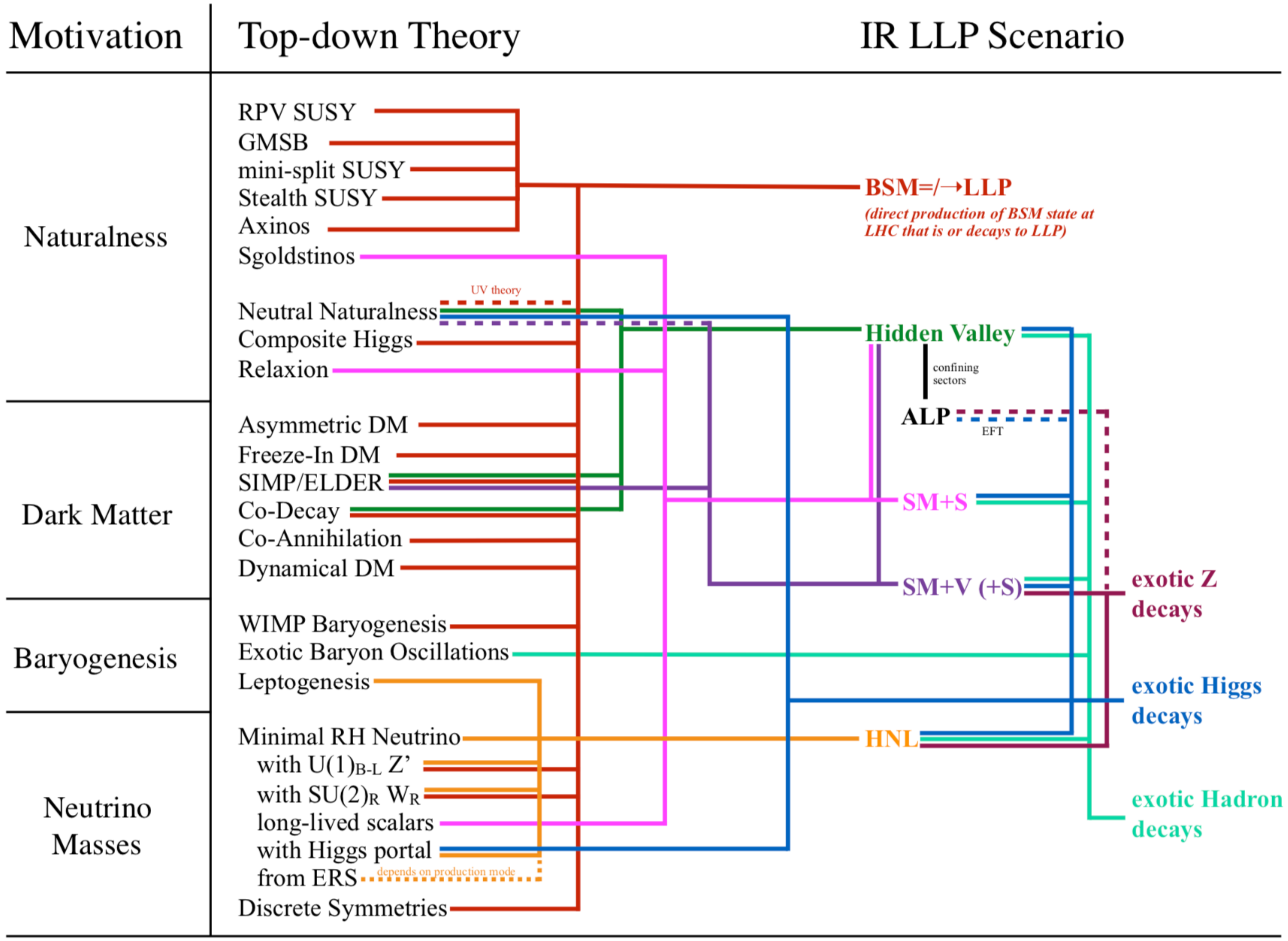
Combination only with Mono-H(bb) and Mono-Z(ll) channels.

ATLAS-CONF-2021-036

CMS-EXO-18-011 targeting Z' 2HDM

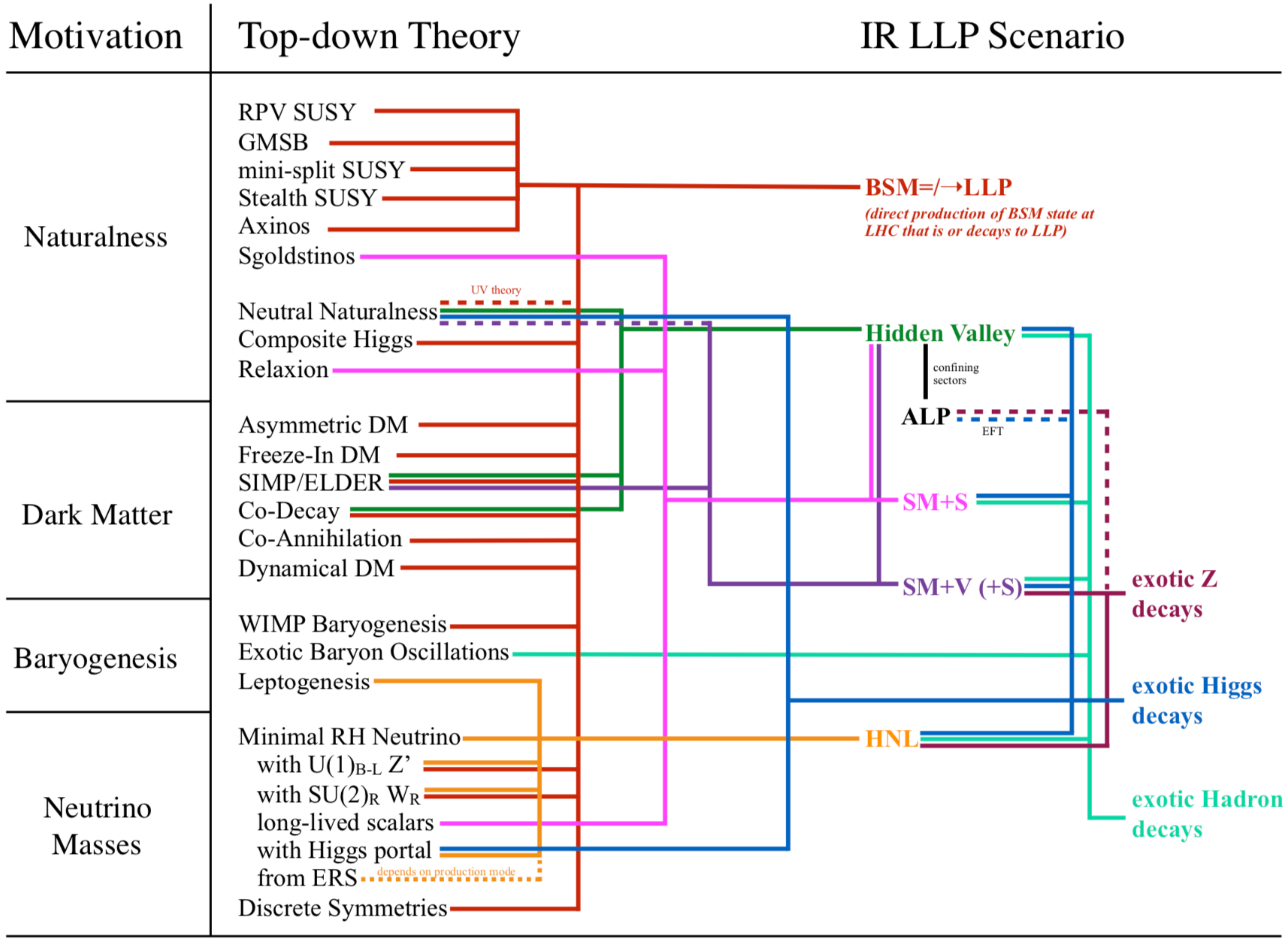
Long-lived signatures

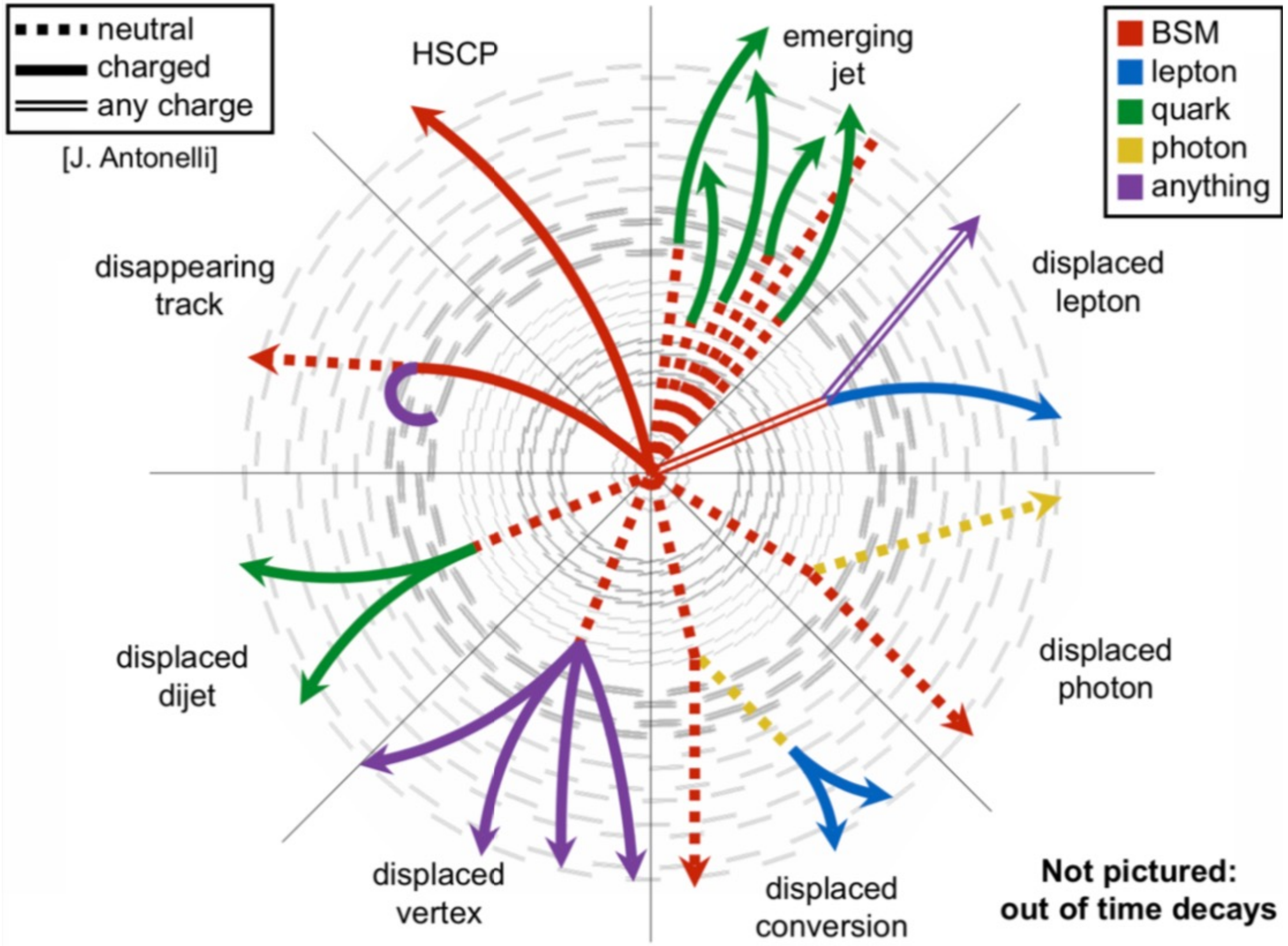
[1806.07396](1806.07396)



Long-lived signatures

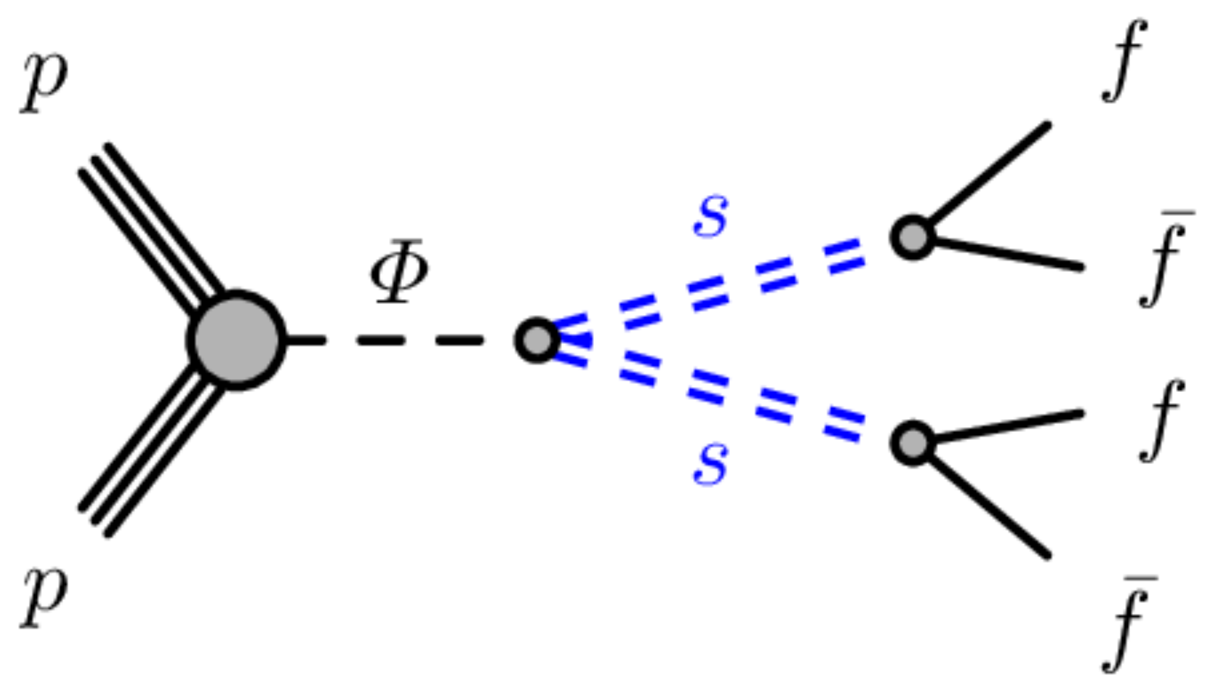
[1806.07396](1806.07396)

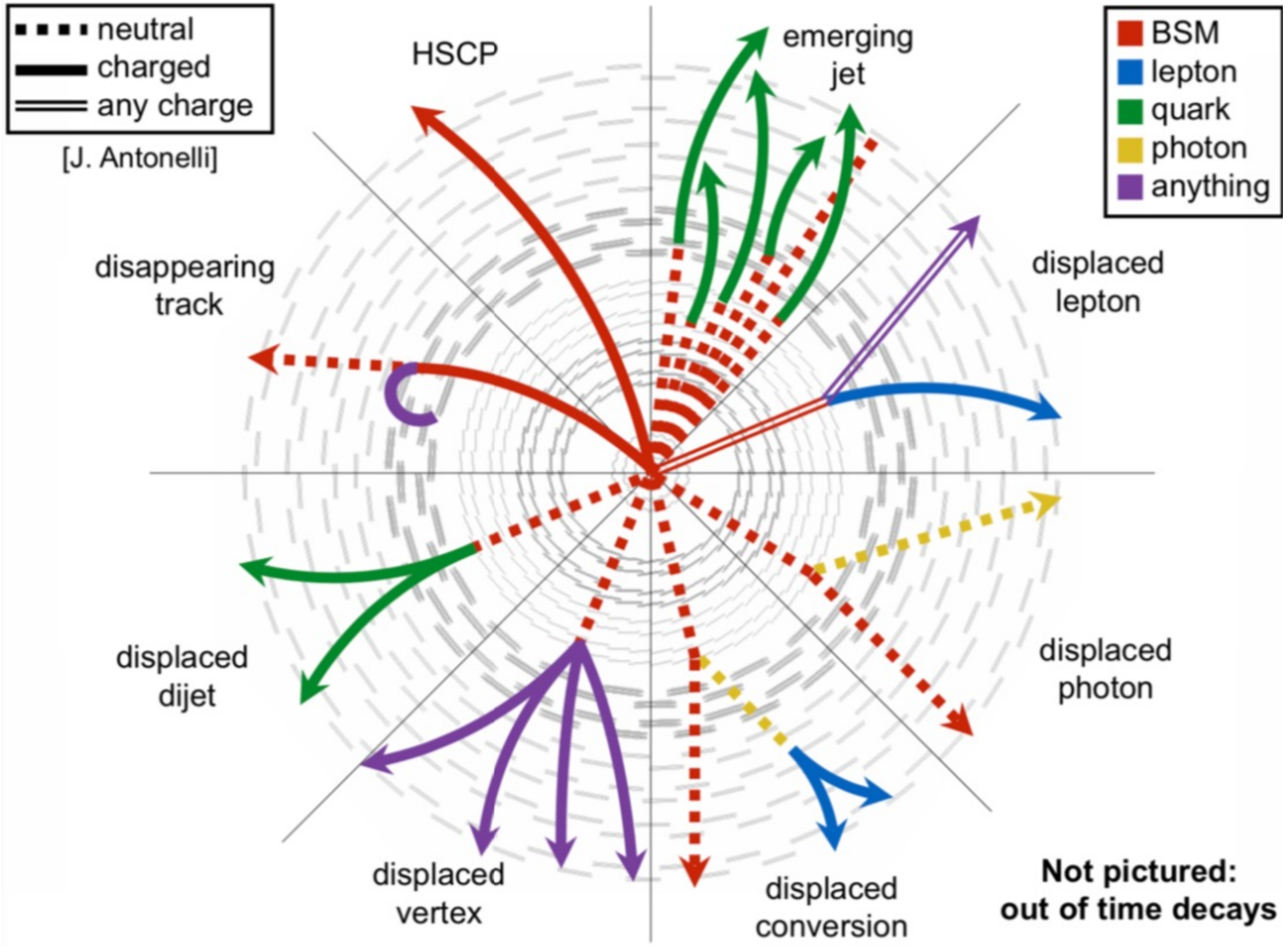




Long-lived signatures and Exotic Higgs decays

Sufficient freedom for exotic couplings
BR(H→Non-SM) could be up to $\mathcal{O}(10)$ %





Long-lived signatures and Exotic Higgs decays

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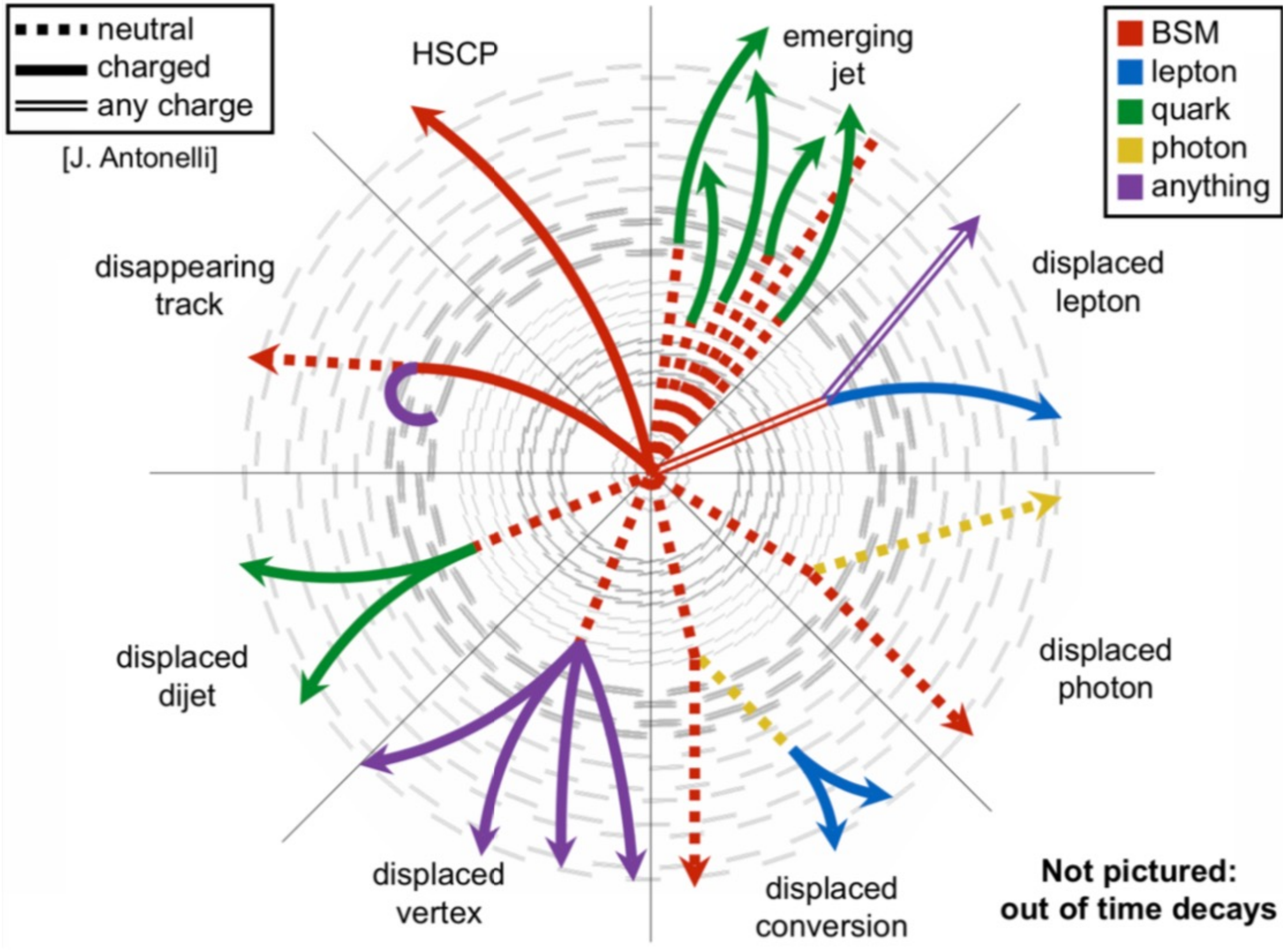
If the decay product is **light**, and/or couple with **small couplings → long lived particle**



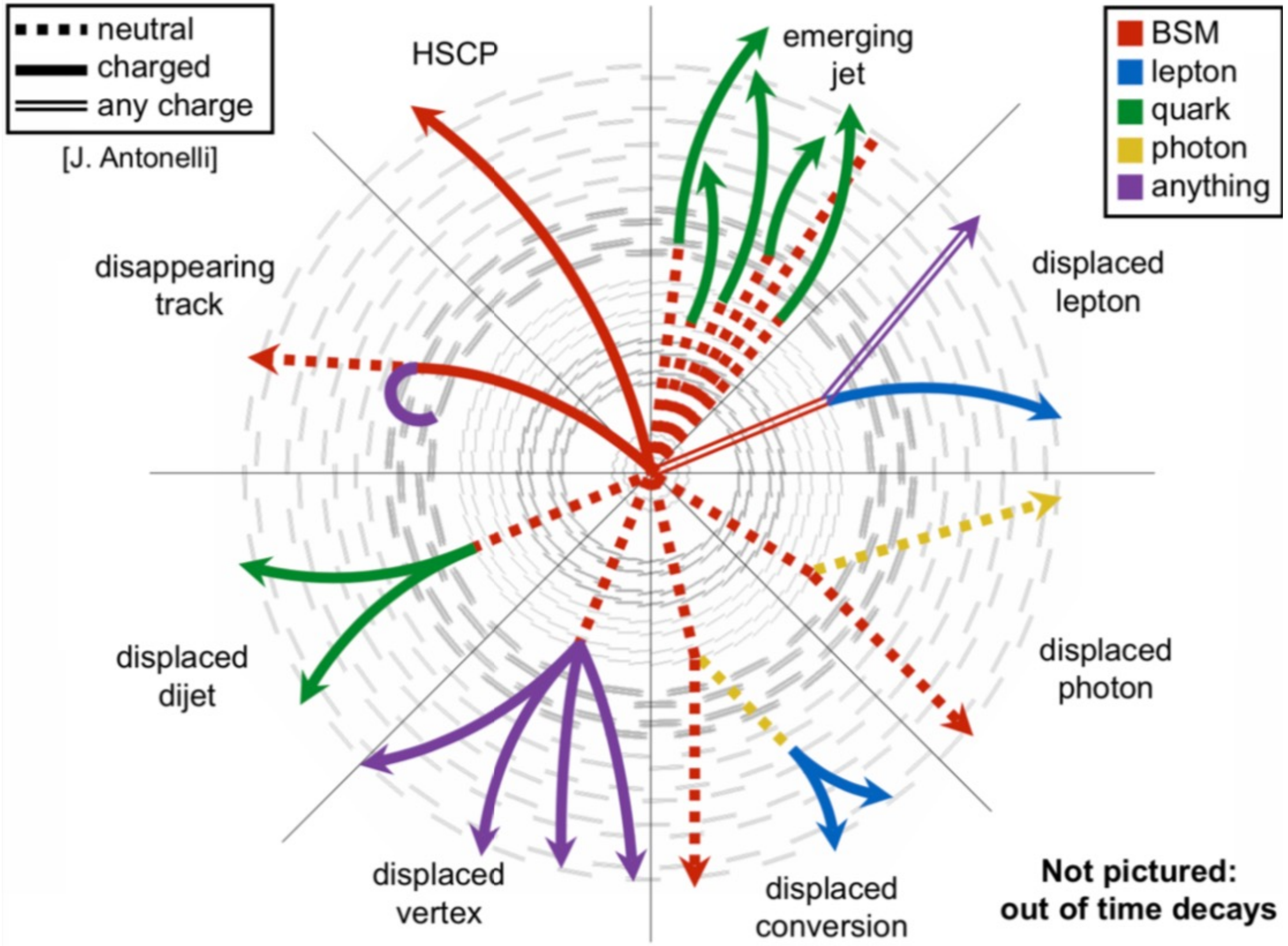
Long-lived signatures and Exotic Higgs decays

Sufficient freedom for exotic couplings BR(H→Non-SM) could be up to $\mathcal{O}(10)$ %

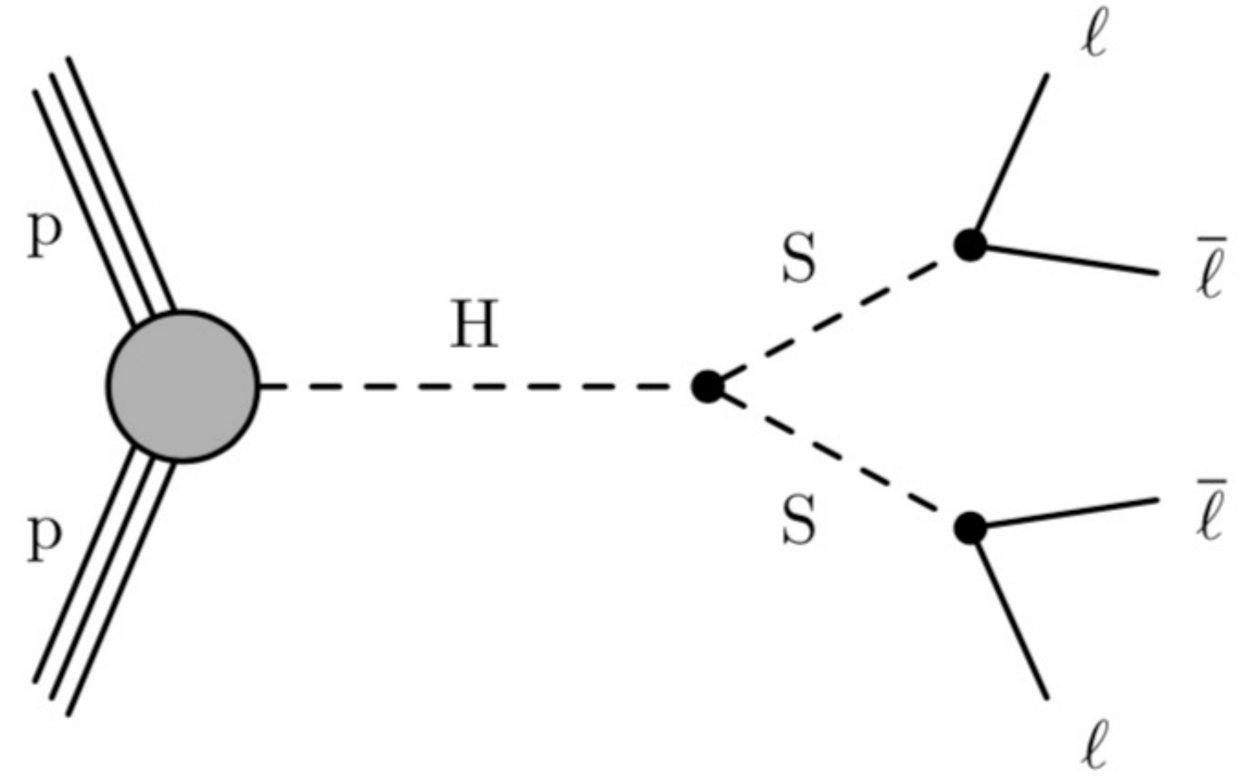
If the decay product is **light**, and/or couple with **small couplings** → **long lived particle**

CMS & ATLAS is designed (mostly) for prompt decays, which makes LLP searches notoriously difficult!

Challenges in triggers, reconstruction and simulation. Backgrounds are generally from non-collision sources: electronic noise, material interactions satellite bunches, beam halo and cosmic

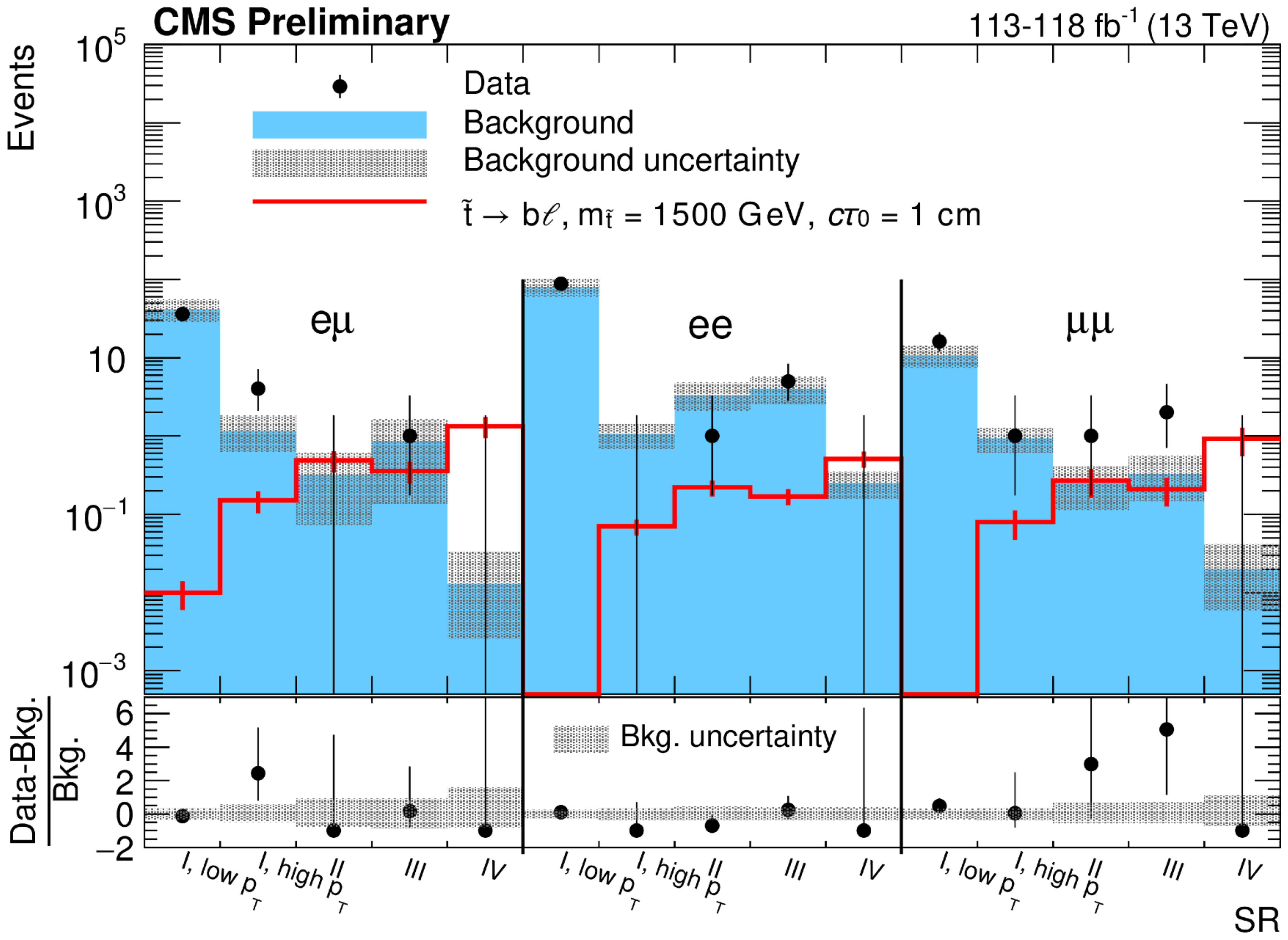


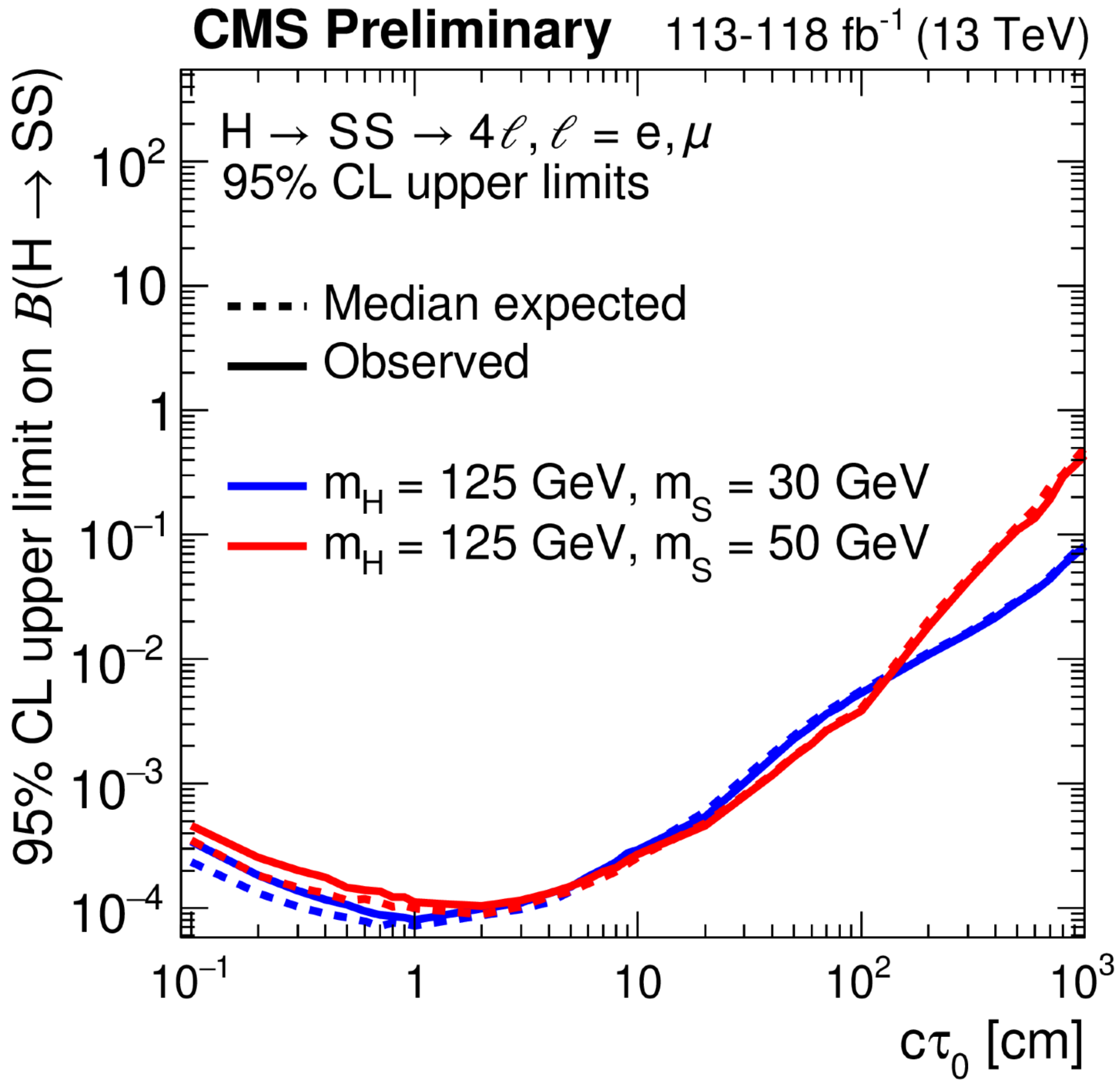
H → SS → 4l



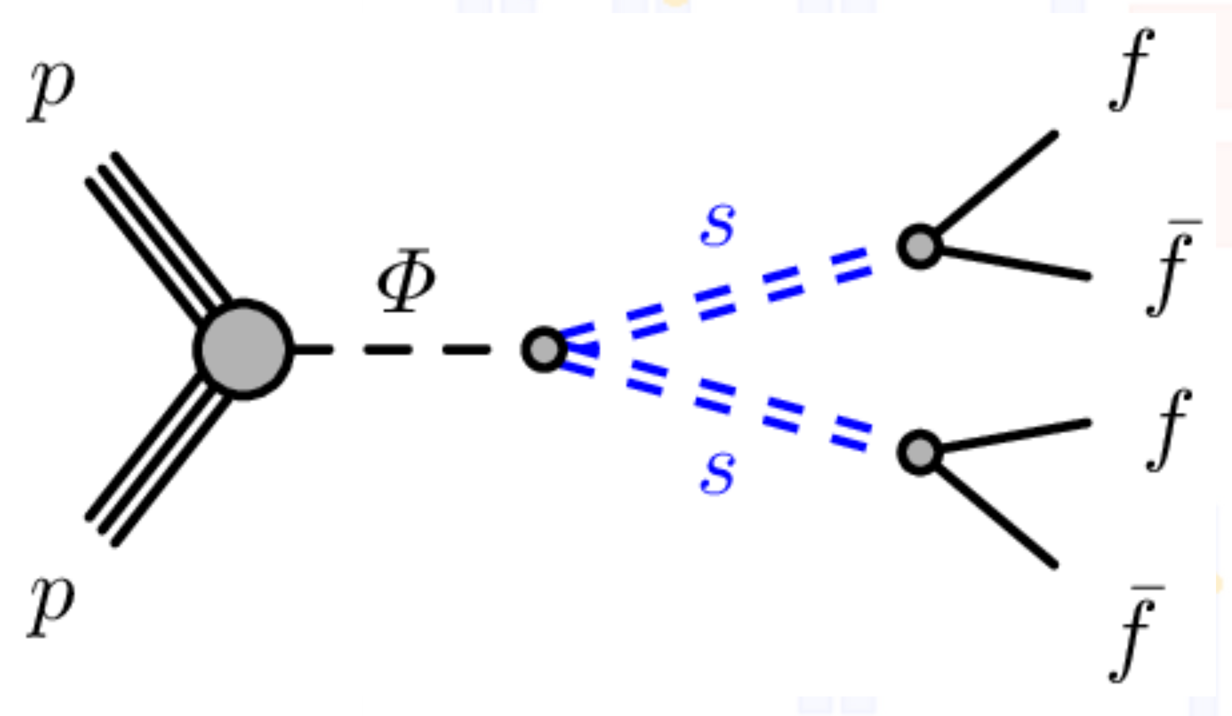
Strategy: Perform a very inclusive search for displaced leptons, without requiring a common vertex and look for eμ, ee, μμ final states where both leptons have large transverse impact parameter

CMS-EXO-18-003



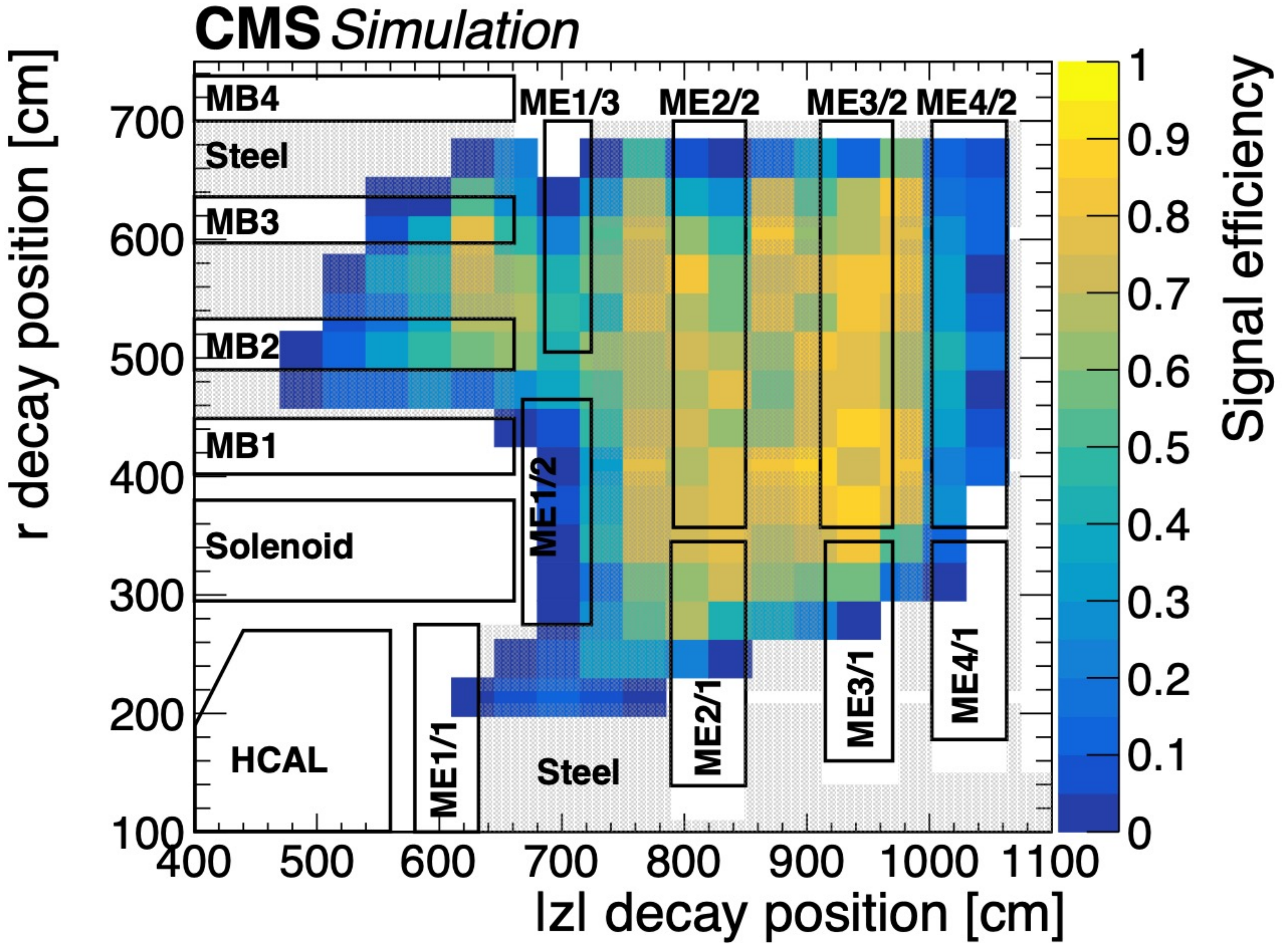


H → SS → 4j



Strategy: Reconstruct decays of LLPs in the muon detectors. No tracks, no jets. Instead clusters in the muon system! Using the muon system like a "sampling calorimeter"

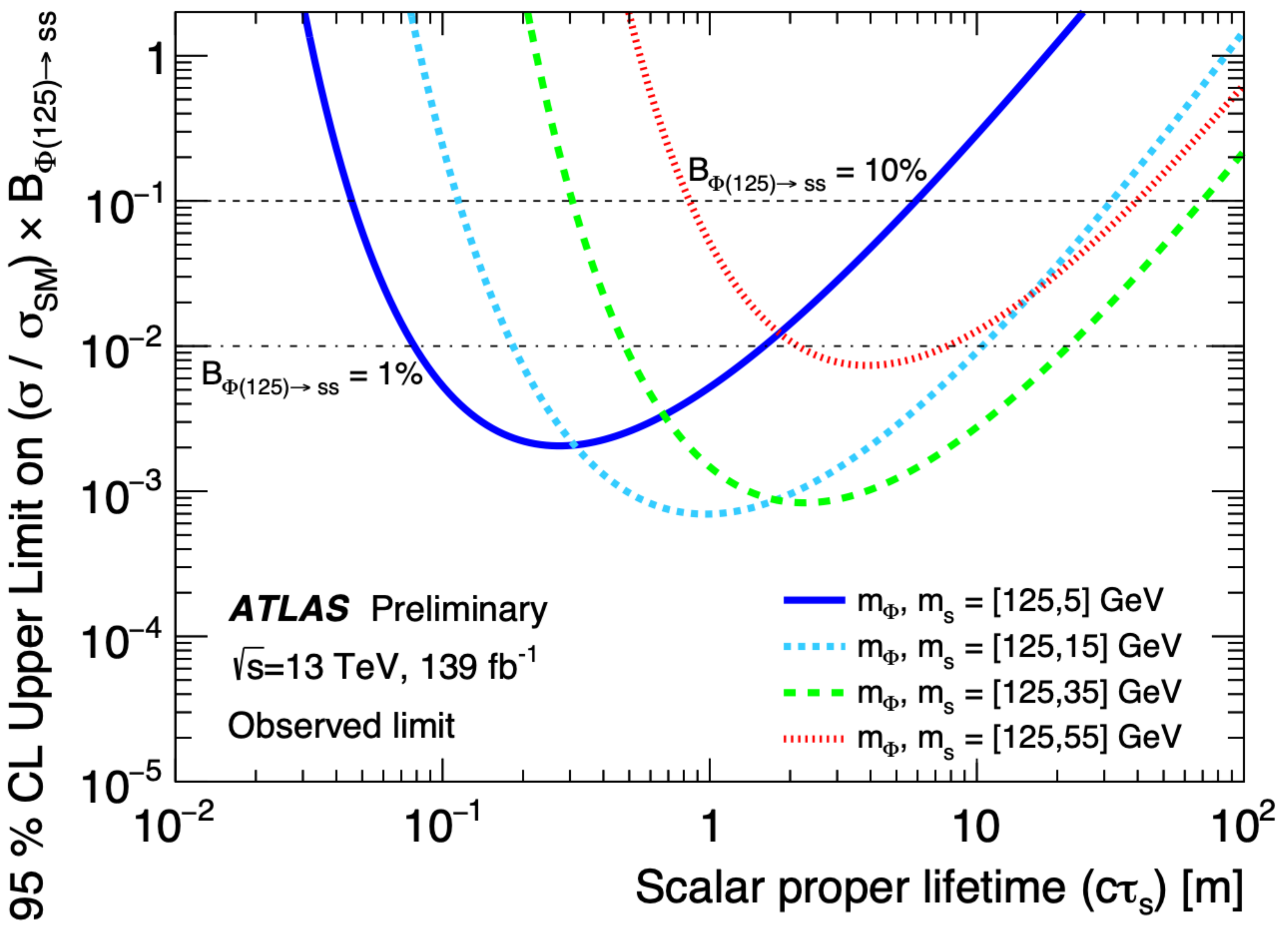
@ATLAS: additional stand alone vertex finding in the ATLAS spectrometer



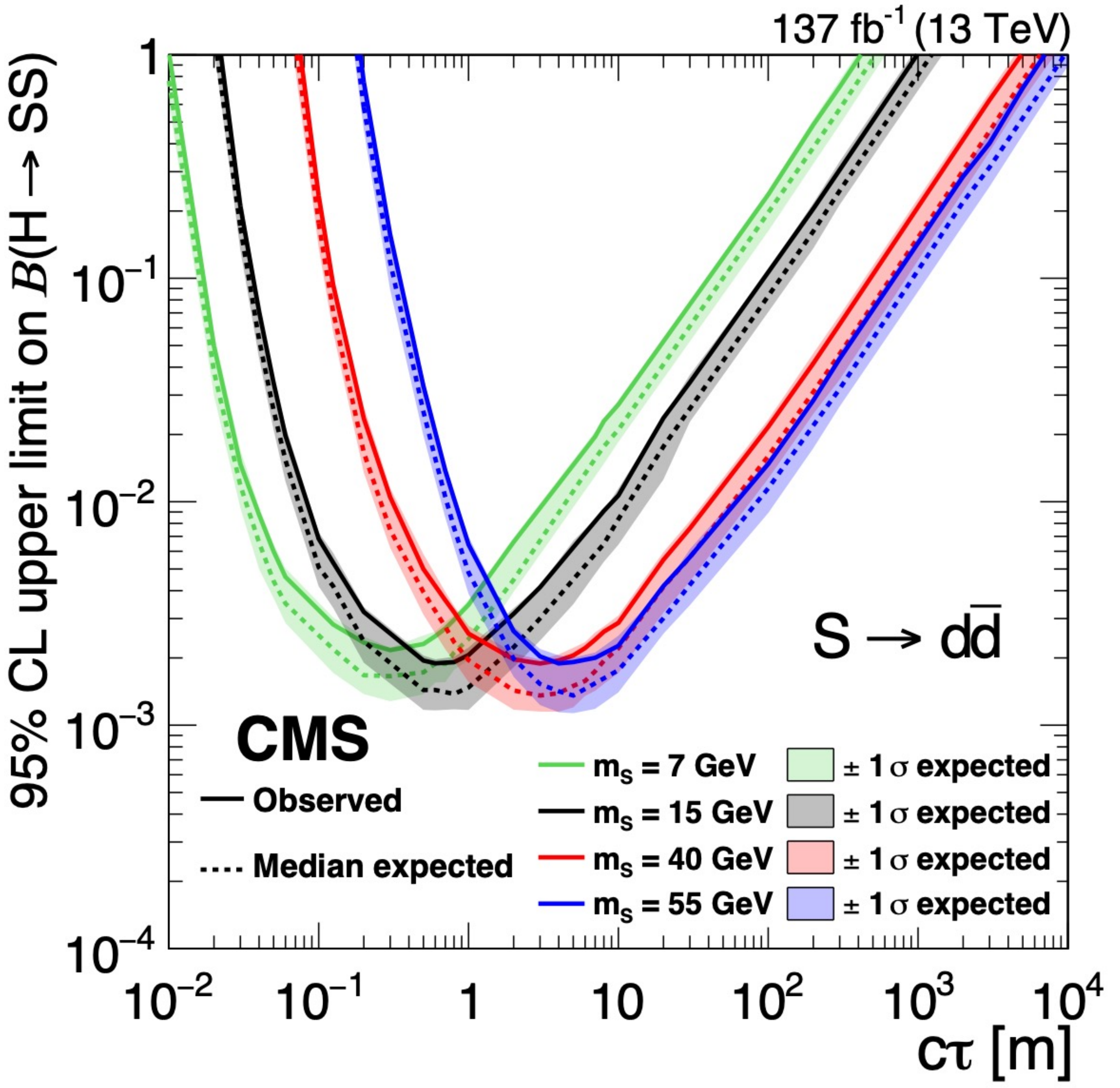
CMS triggers: MET based triggers (MET induced from an ISR jet requirement).

ATLAS triggers: dedicated muon region-of-interest trigger that is signature driven.

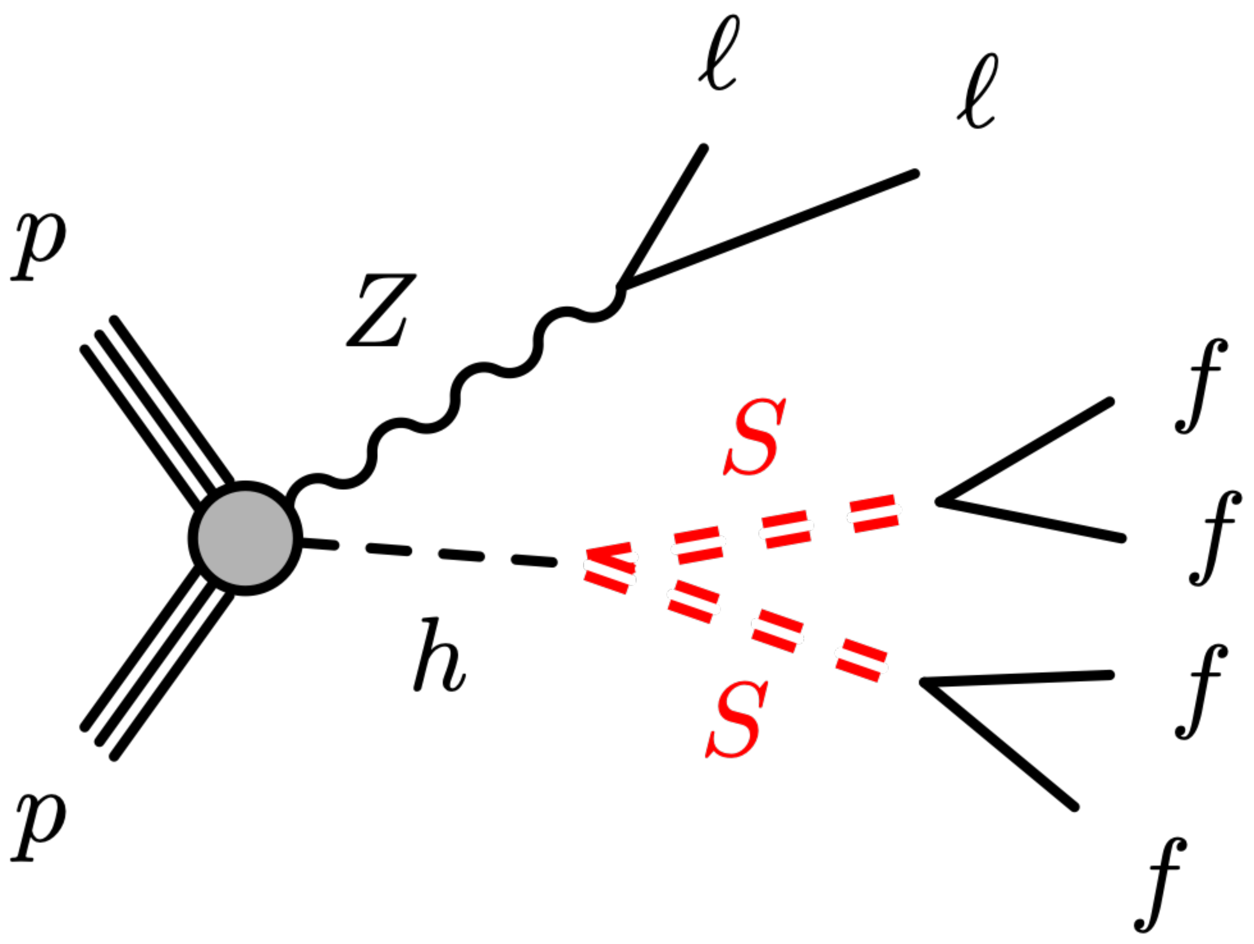
ATLAS-CONF-2021-032



CMS-EXO-20-015

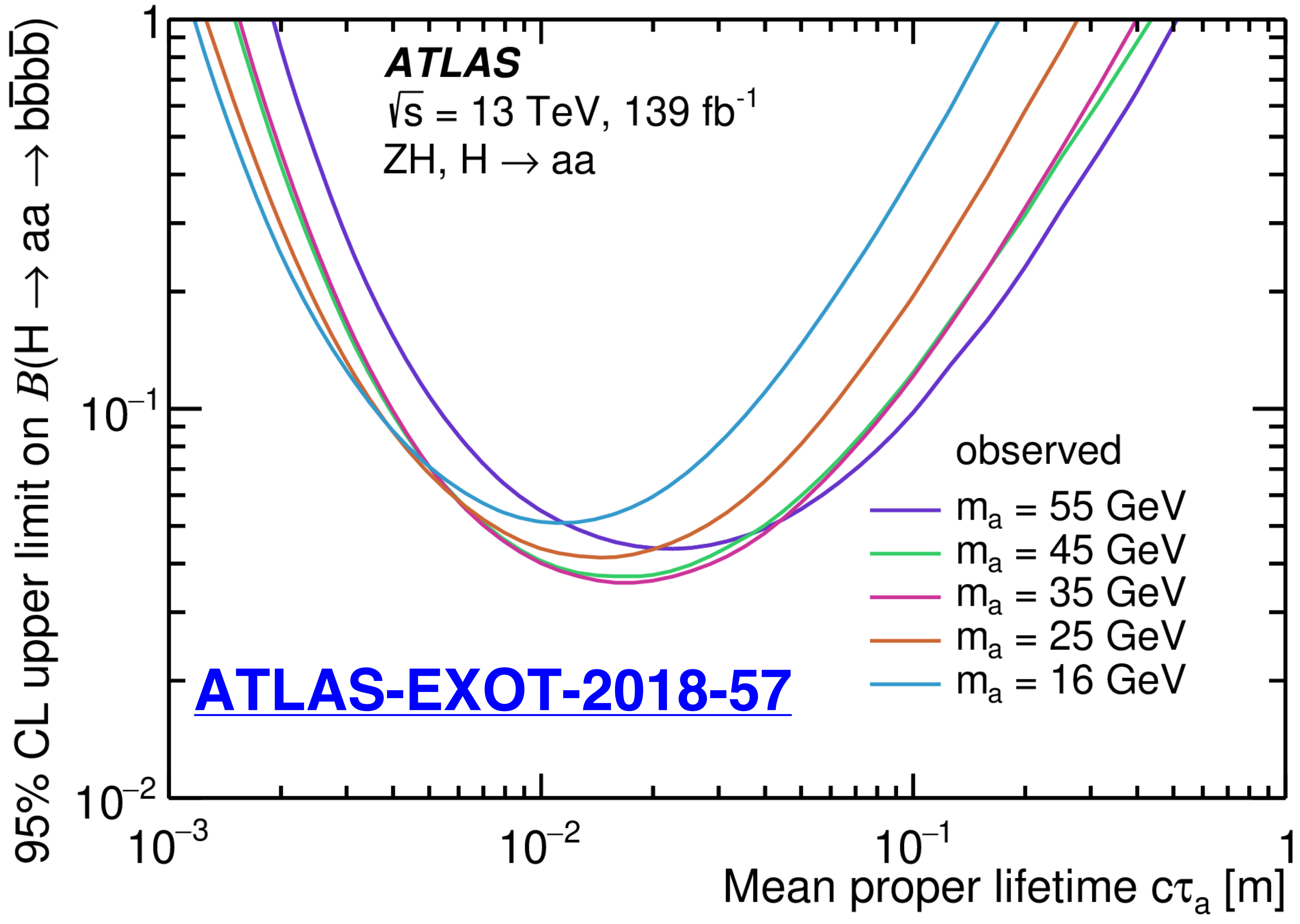


ZH → ZSS → 2l4b

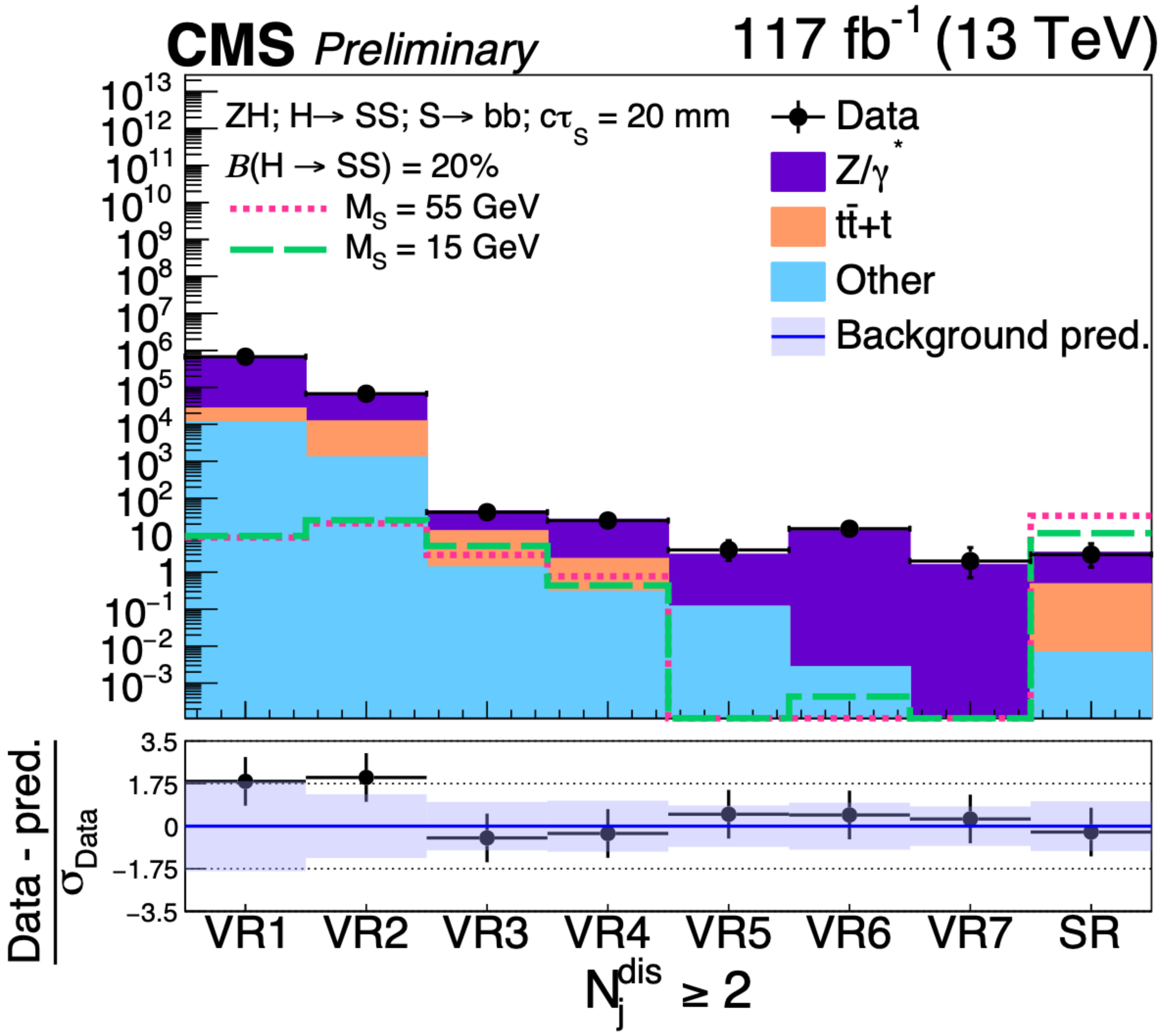


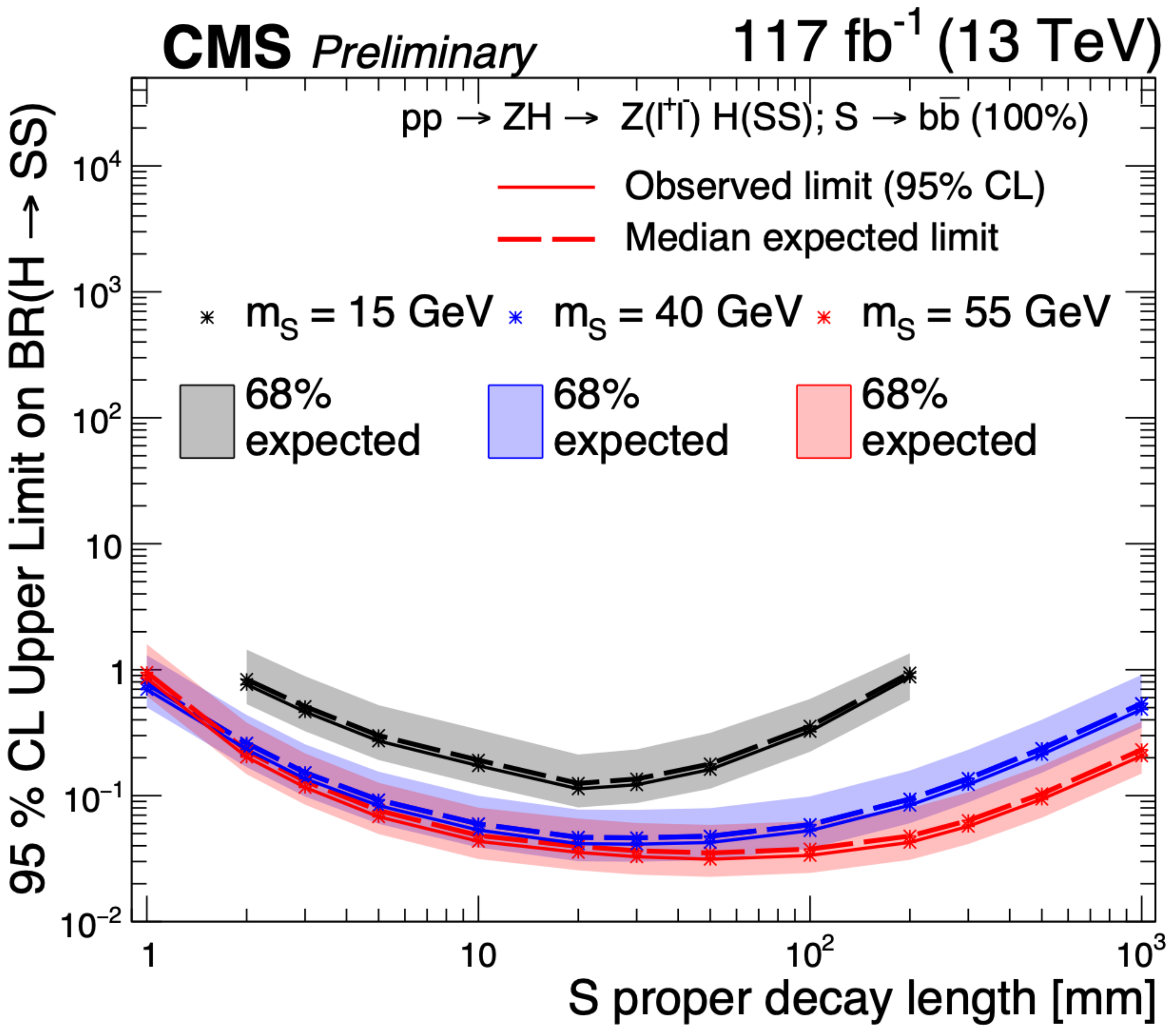
Prompt dilepton (used to trigger) and displaced jet final state associated production is **efficient** to access low pT LLP's jets!

Displaced jet tagging relying on tracks' IP, transverse angle, PV-association



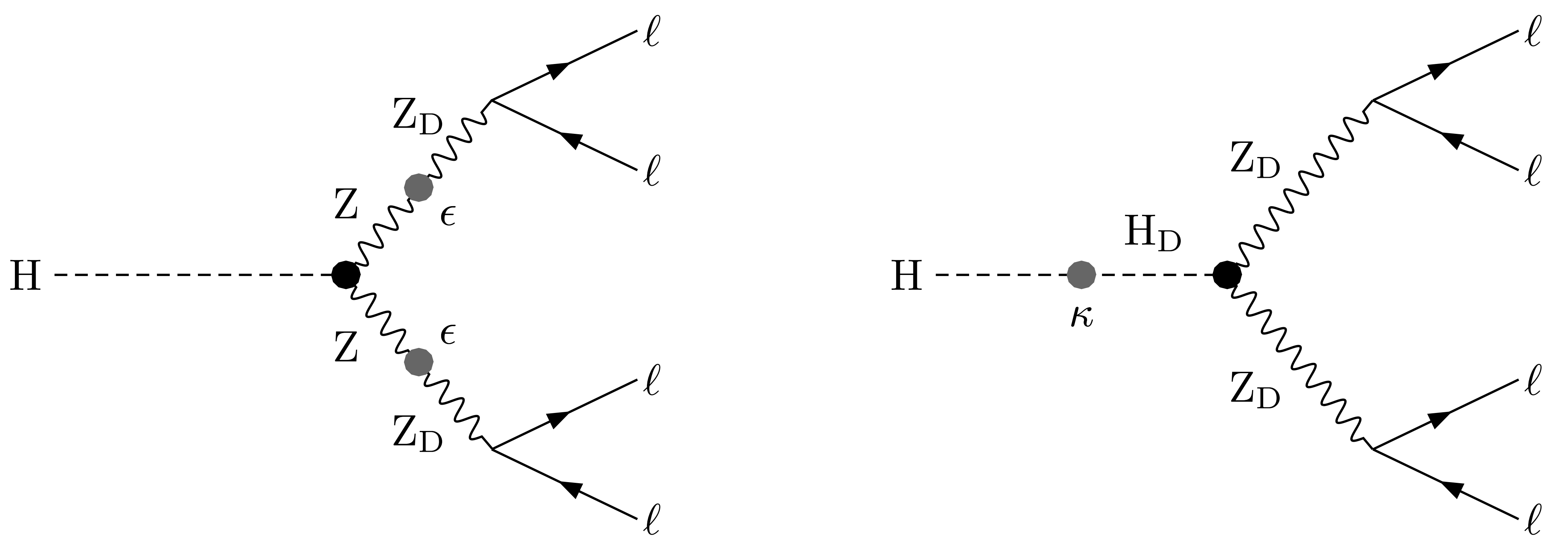
CMS-EXO-20-003

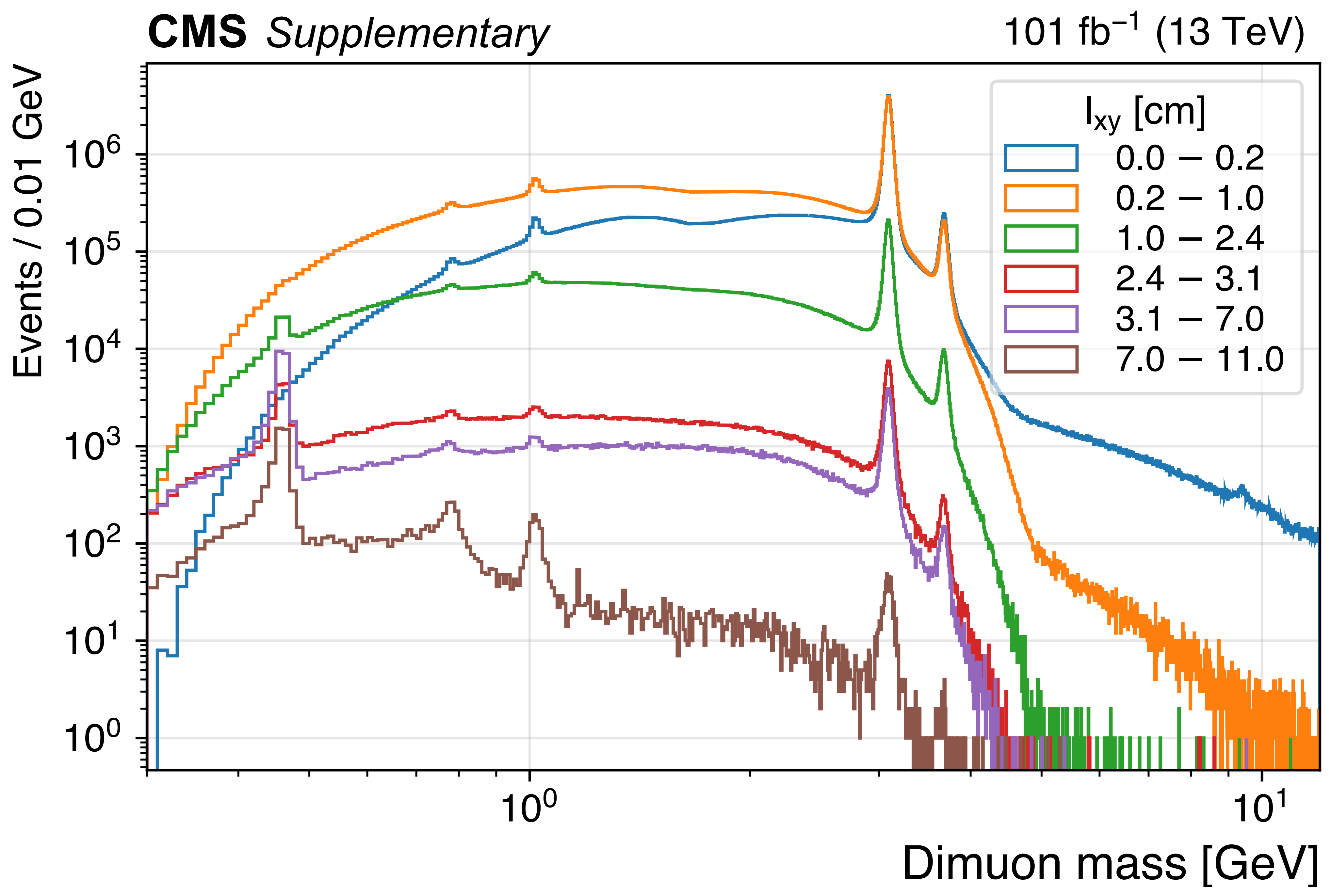




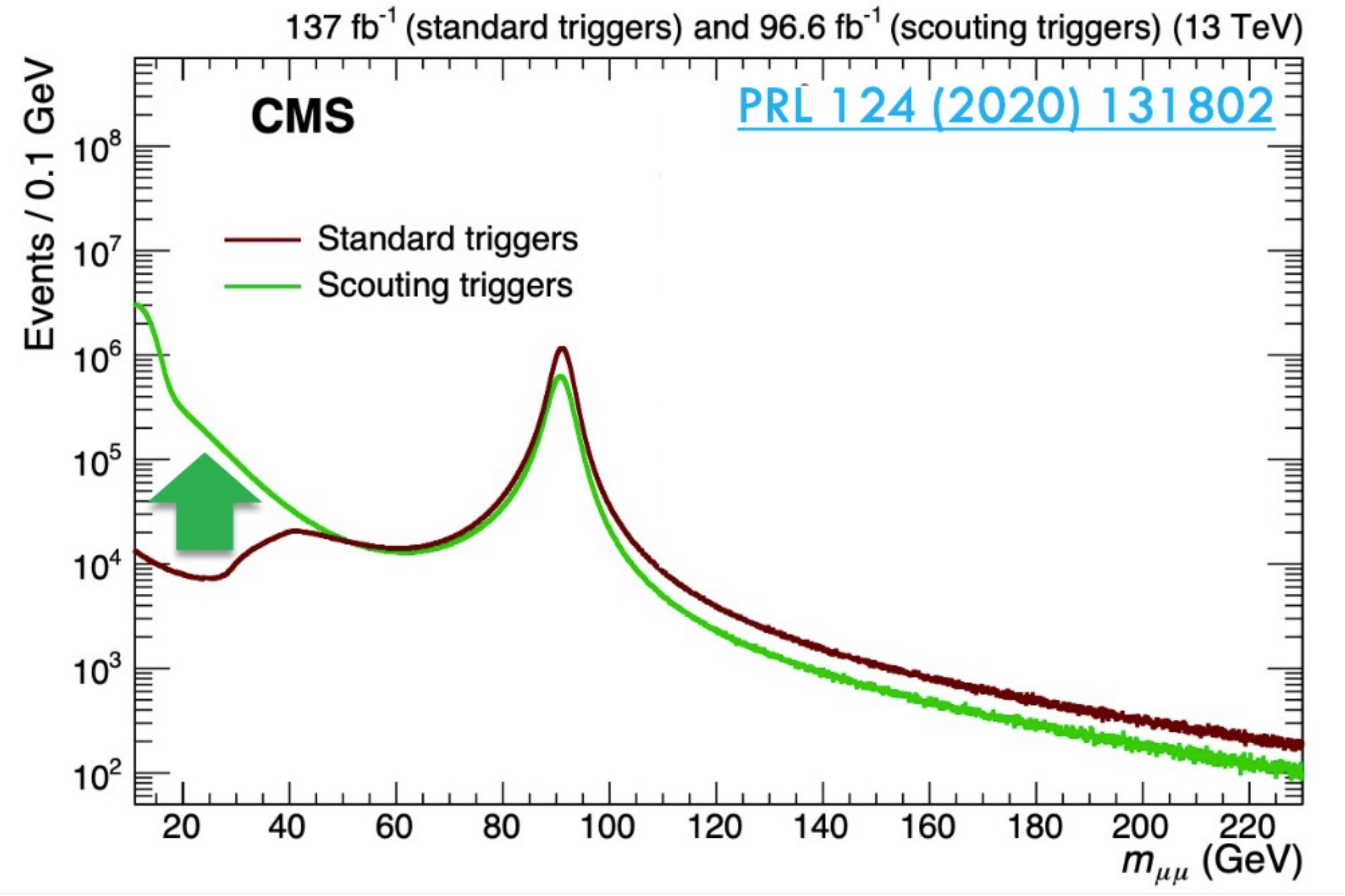
Displaced dimuons with scouting

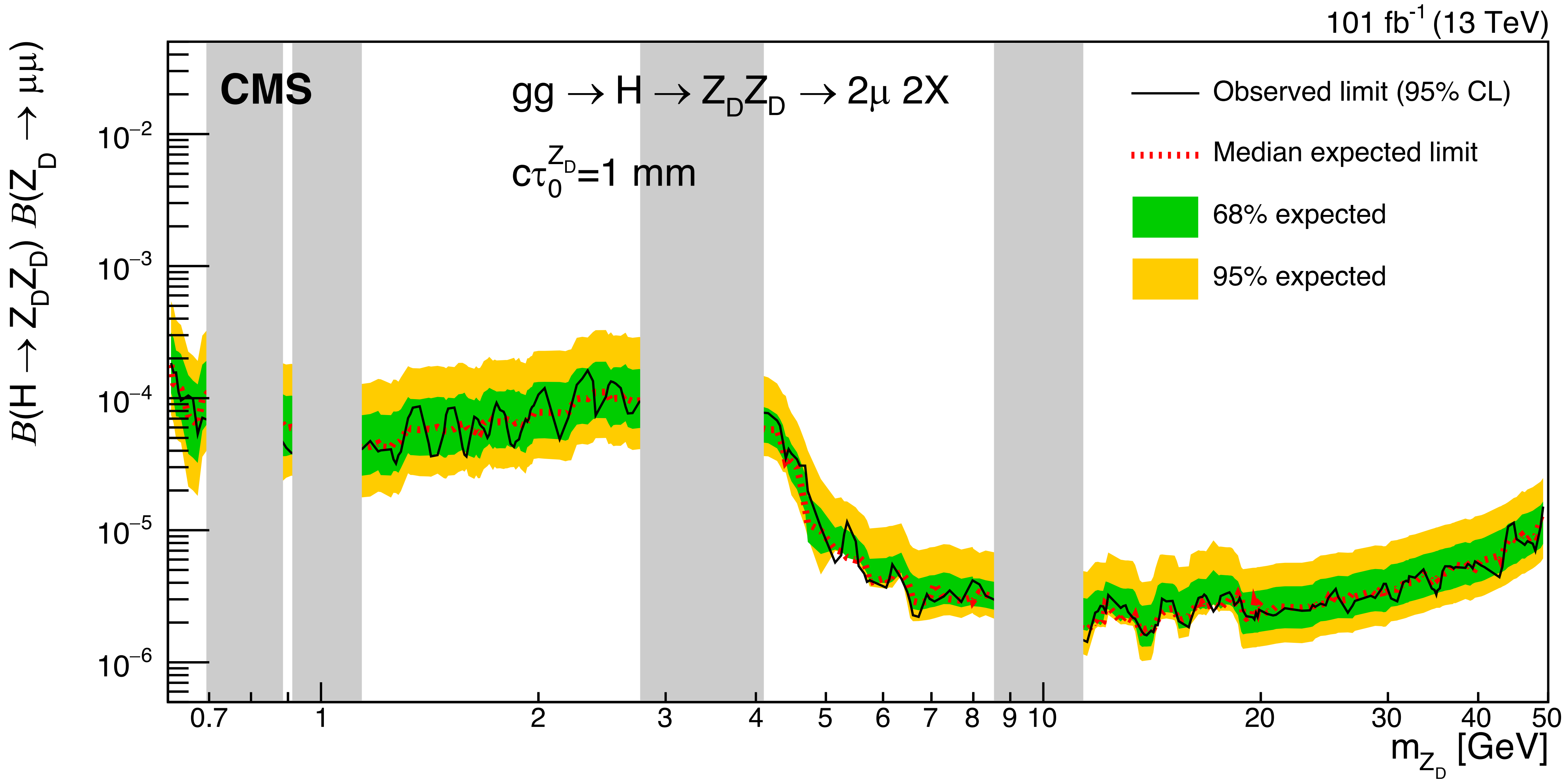
CMS-EXO-20-014



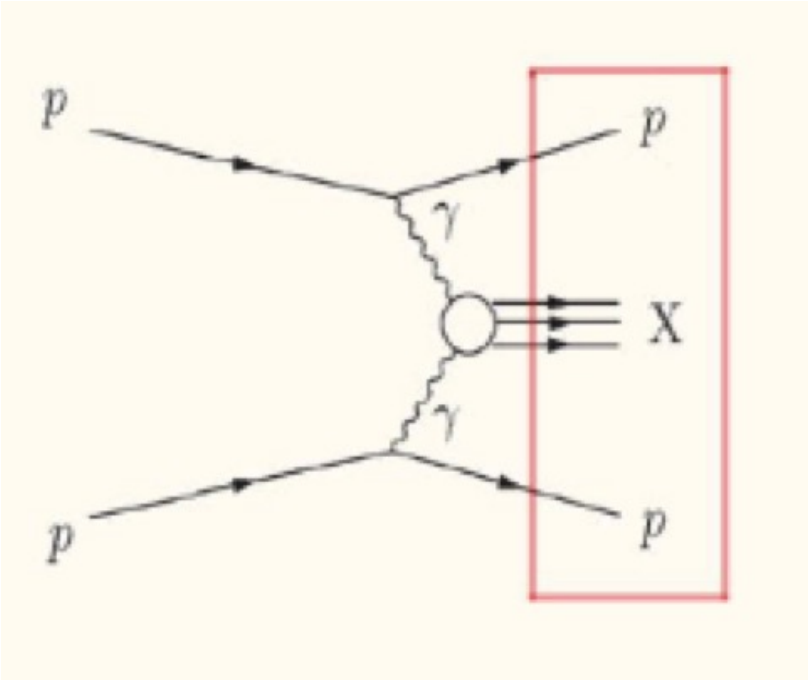


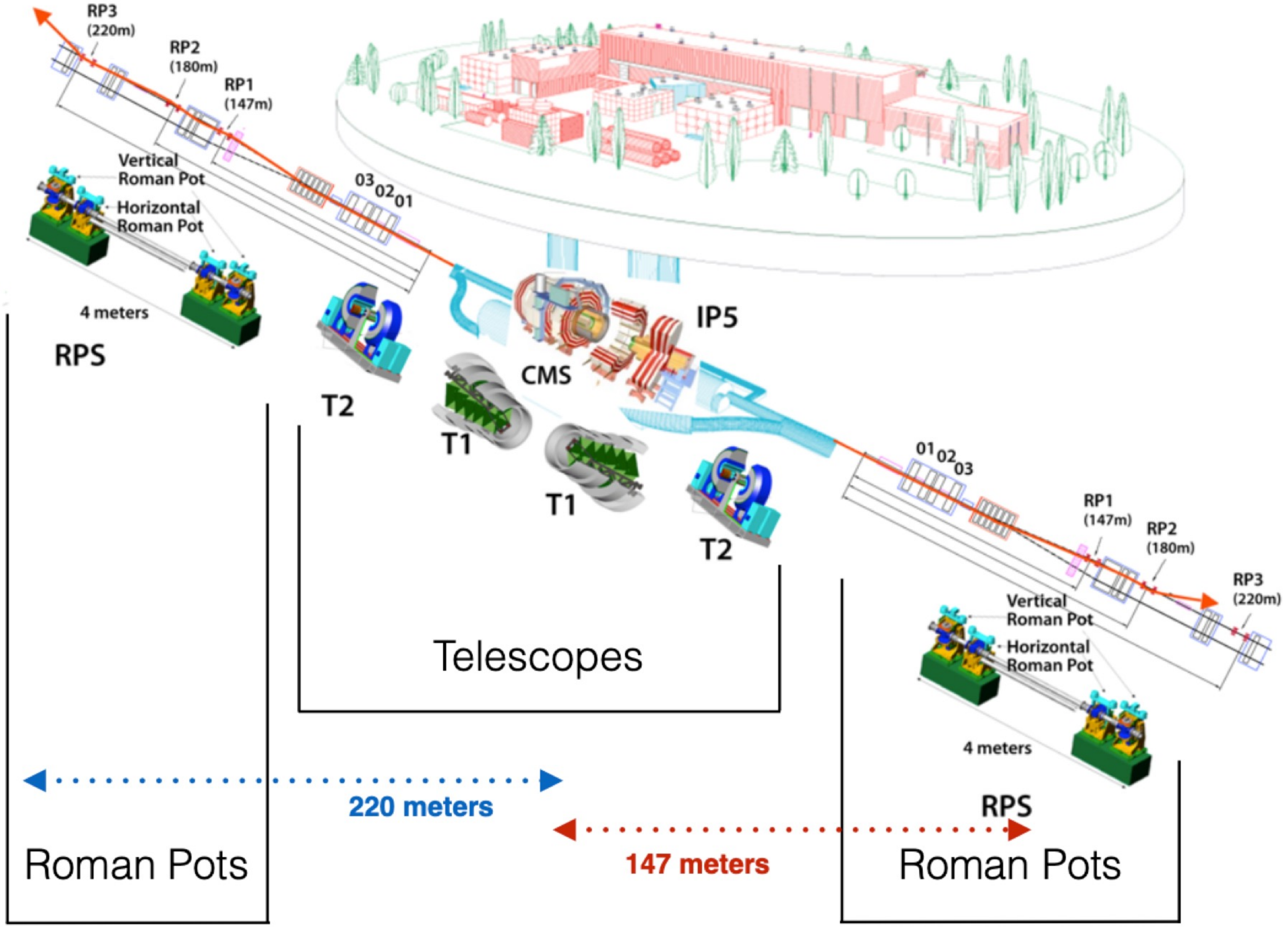
Search for a narrow long-lived dimuon resonance with $m_{LLP} > 2m_{muon}$ and lifetime > 0





Precision Proton Spectrometer





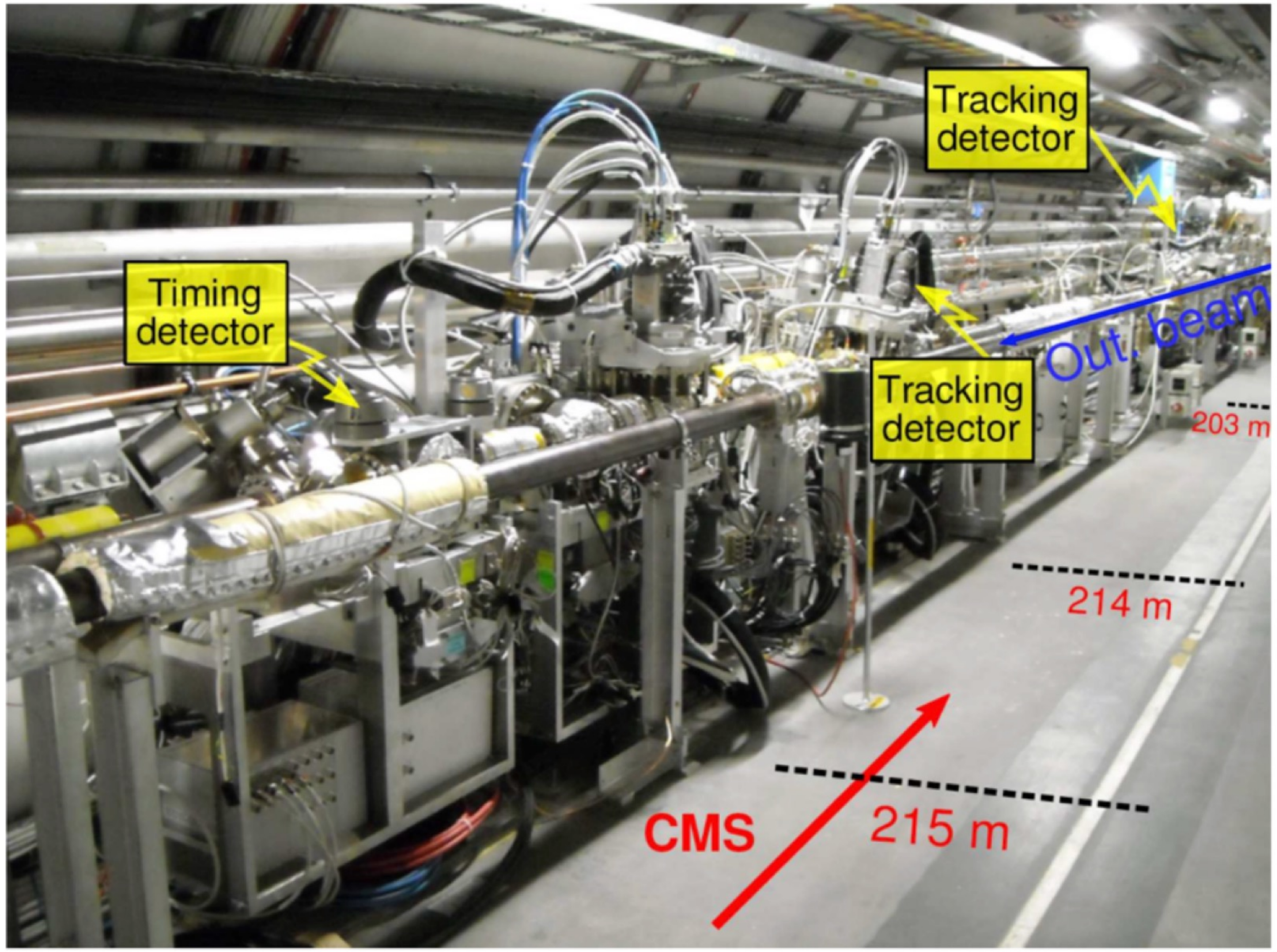
TOTEM experiment is designed to take **precise measurements** of protons as they emerge from collisions **at small angles.**

This region is known as the '**forward**' direction and is **inaccessible**

TOTEM and CMS collaborations have coordinated the use of their detectors to **perform combined measurements**

Precision Proton Spectrometer

CT-PPS is a magnetic spectrometer that uses the LHC magnets and detector stations, to bend protons to measure their trajectories. **It is fully integrated into CMS DAQ + Reconstruction Software**



Proton tag advantages:

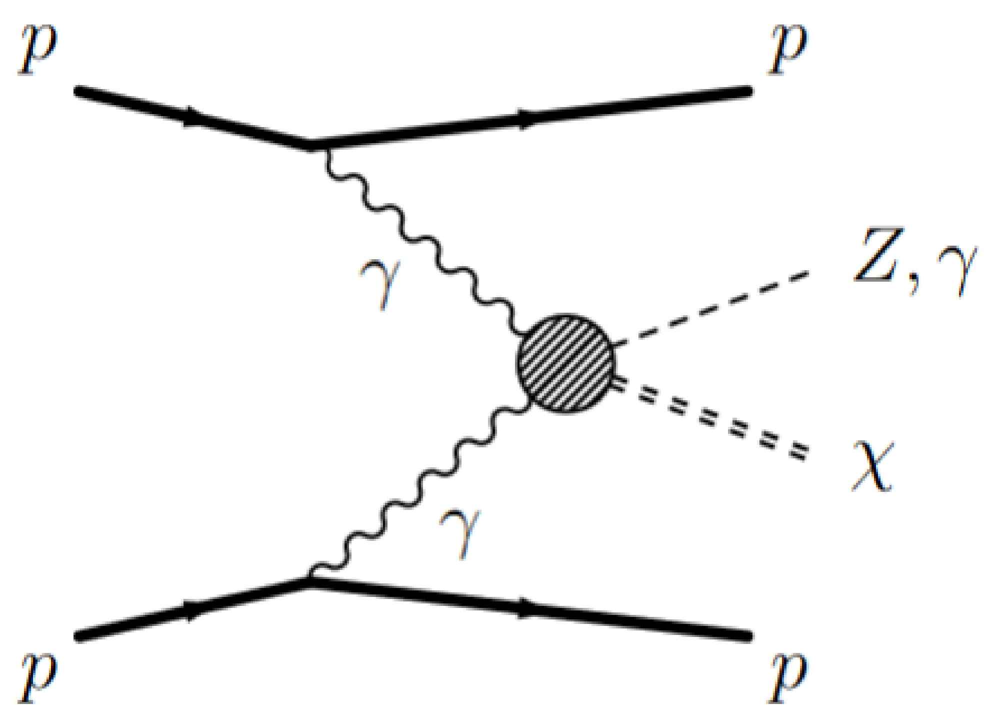
- closure of event kinematics (full 13 TeV energy reconstructed)
- effective background rejection

Opportunity to access a variety of topics:

- anomalous couplings with high sensitivity
- new resonances in very clean final state
- rare SM processes

Precision Proton Spectrometer

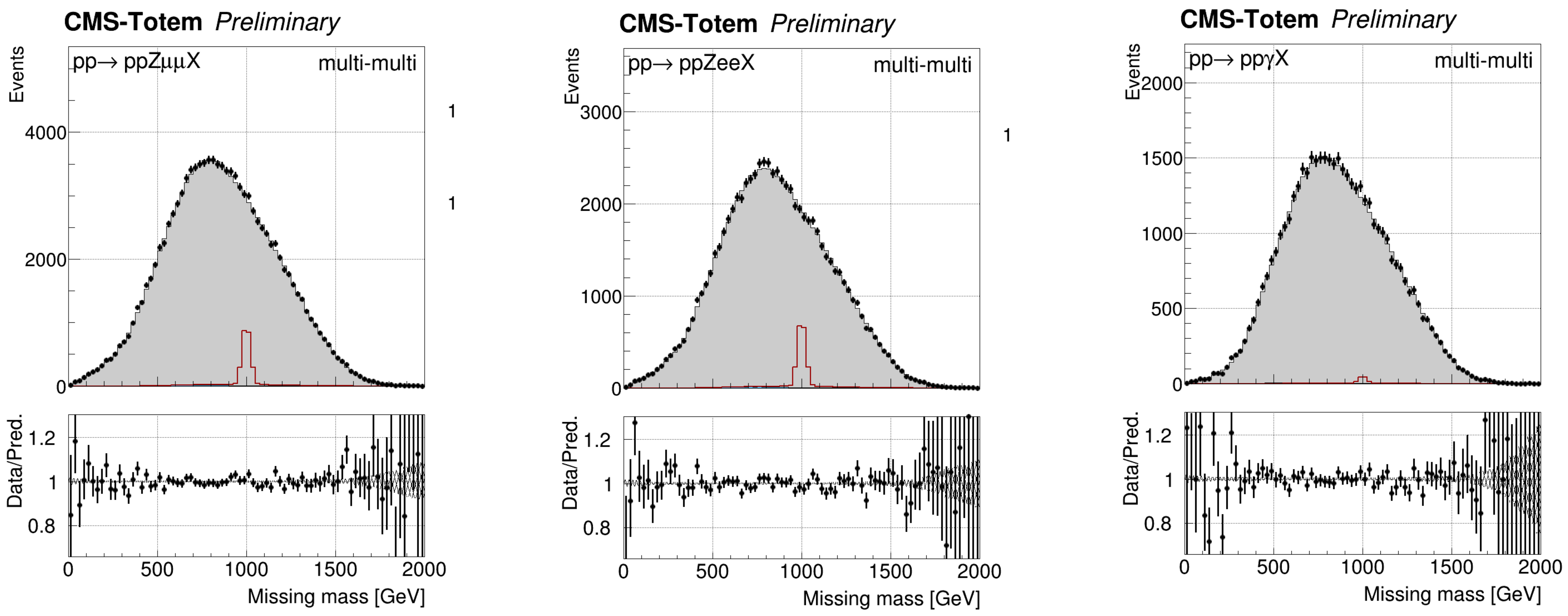
A search for new physics in central exclusive production using the missing mass technique with the CMS-TOTEM precision proton spectrometer EXO-19-009



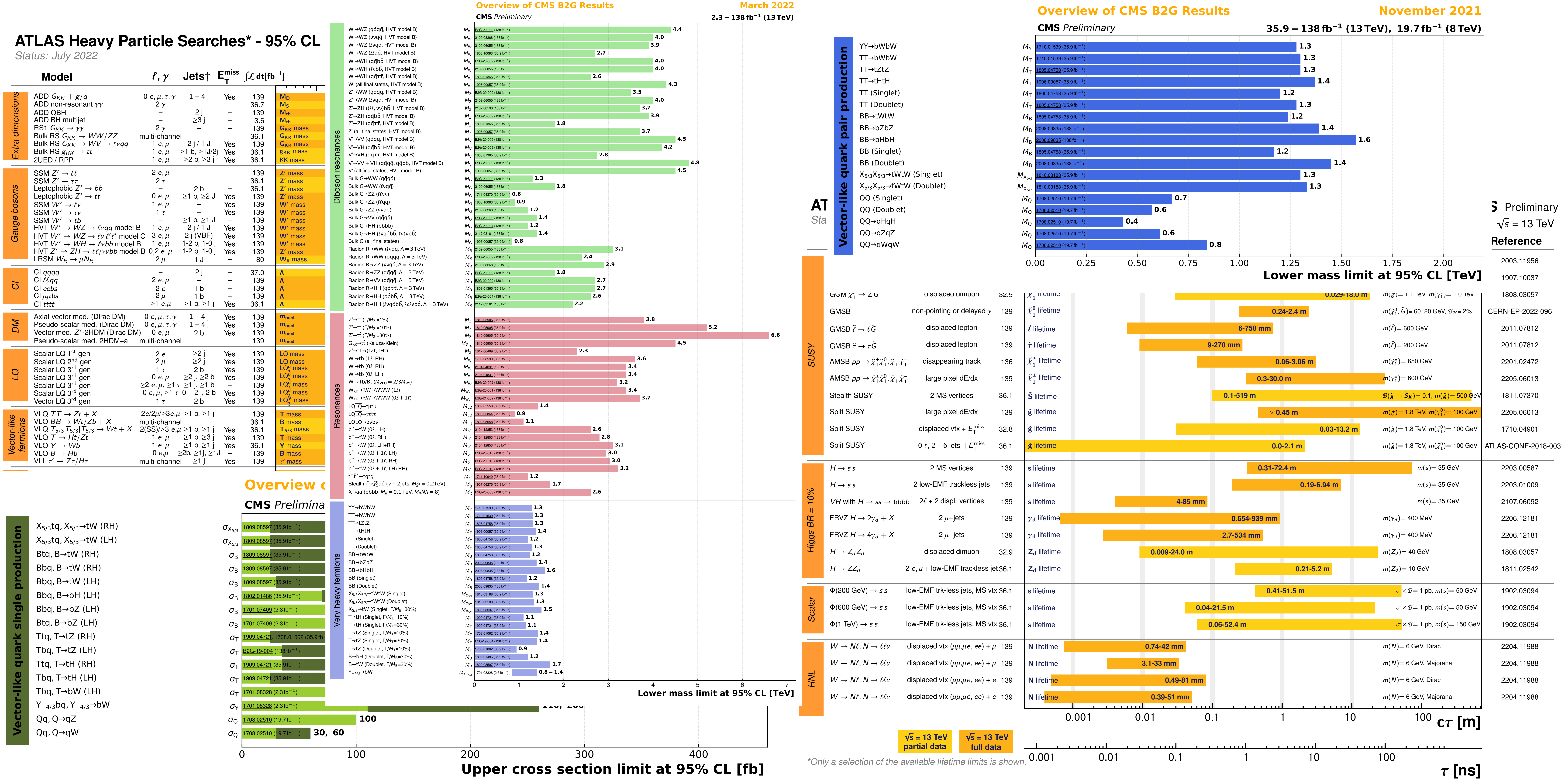
Main variable of interest is the so-called **missing mass**: first use of this technique at the LHC.

$$m^2_{\text{miss}} = \left[(P^{\text{in}}_{p_1} + P^{\text{in}}_{p_2}) - (P_V + P^{\text{out}}_{p_1} + P^{\text{out}}_{p_2}) \right]^2$$

Excellent proton momentum reconstruction of PPS allows to search for missing mass signatures at high invariant mass



That was just looking at one question… We have many…

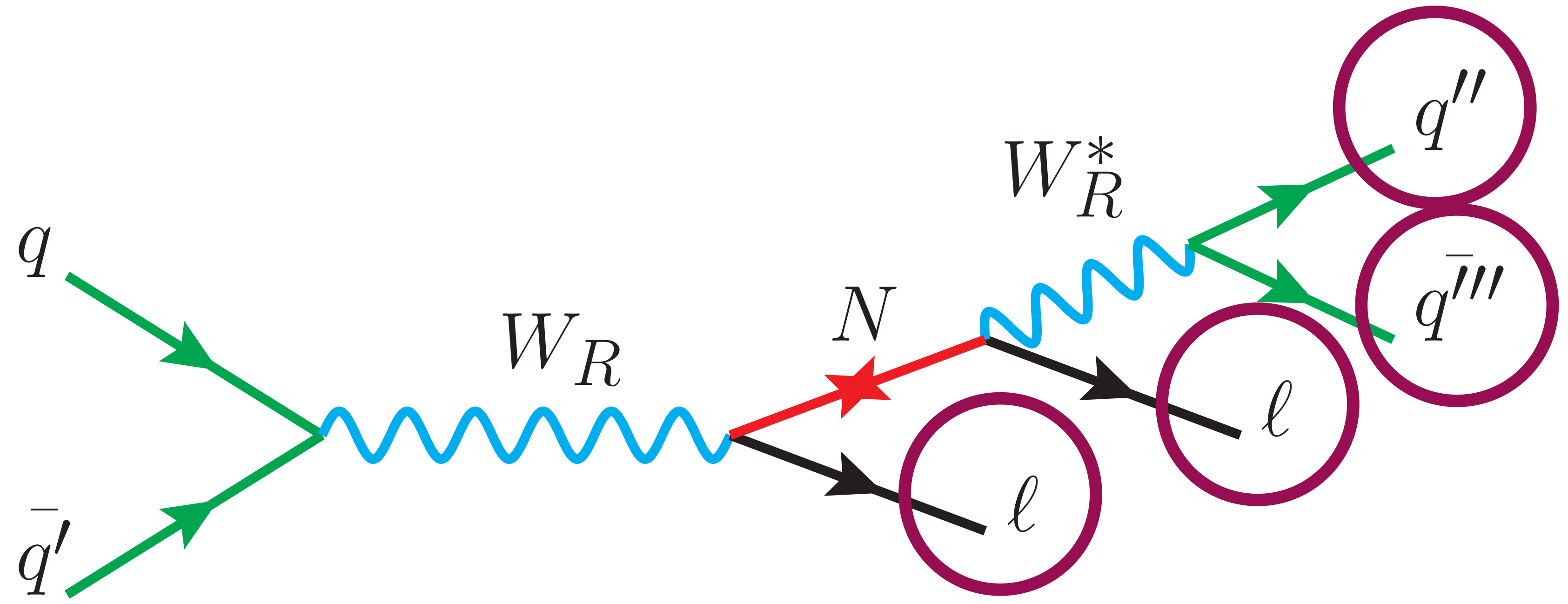


Some highlights with excesses from Run2

CMS-EXO-20-002

Search for W_R boson and a N: Strategy

The **dominant production** process for the $\mathbf{W_R}$ boson at the LHC is the **Drell–Yan mechanism**
Assuming: no mixing between lepton flavors and left-right-handed weak gauge couplings are equivalent (gL = gR).



Resolved Category

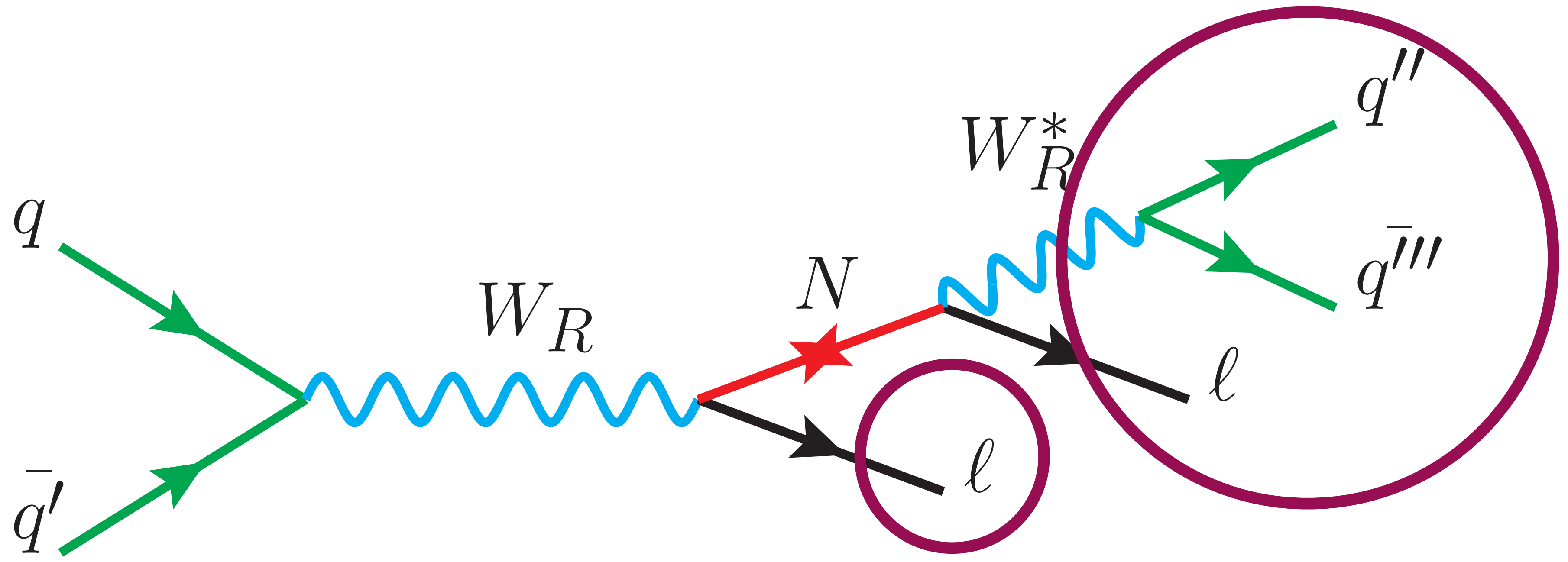
Trigger on single lepton, then …

- require 2 leptons (no charge requirements)
- reject events with additional leptons
- require at least 2 AK4 Jets

Considering only ee and μμ lepton pairs

Boosted Category (New)**

W_R is heavy compared to the N ($mW_R/mN > 10$).



Require 1 lepton and 1 wide jet (with a lepton inside)

The lepton subjet fraction algorithm: checking the consistency of the jet with three subjets, where one subjet is dominated by the four-momentum of a lepton.

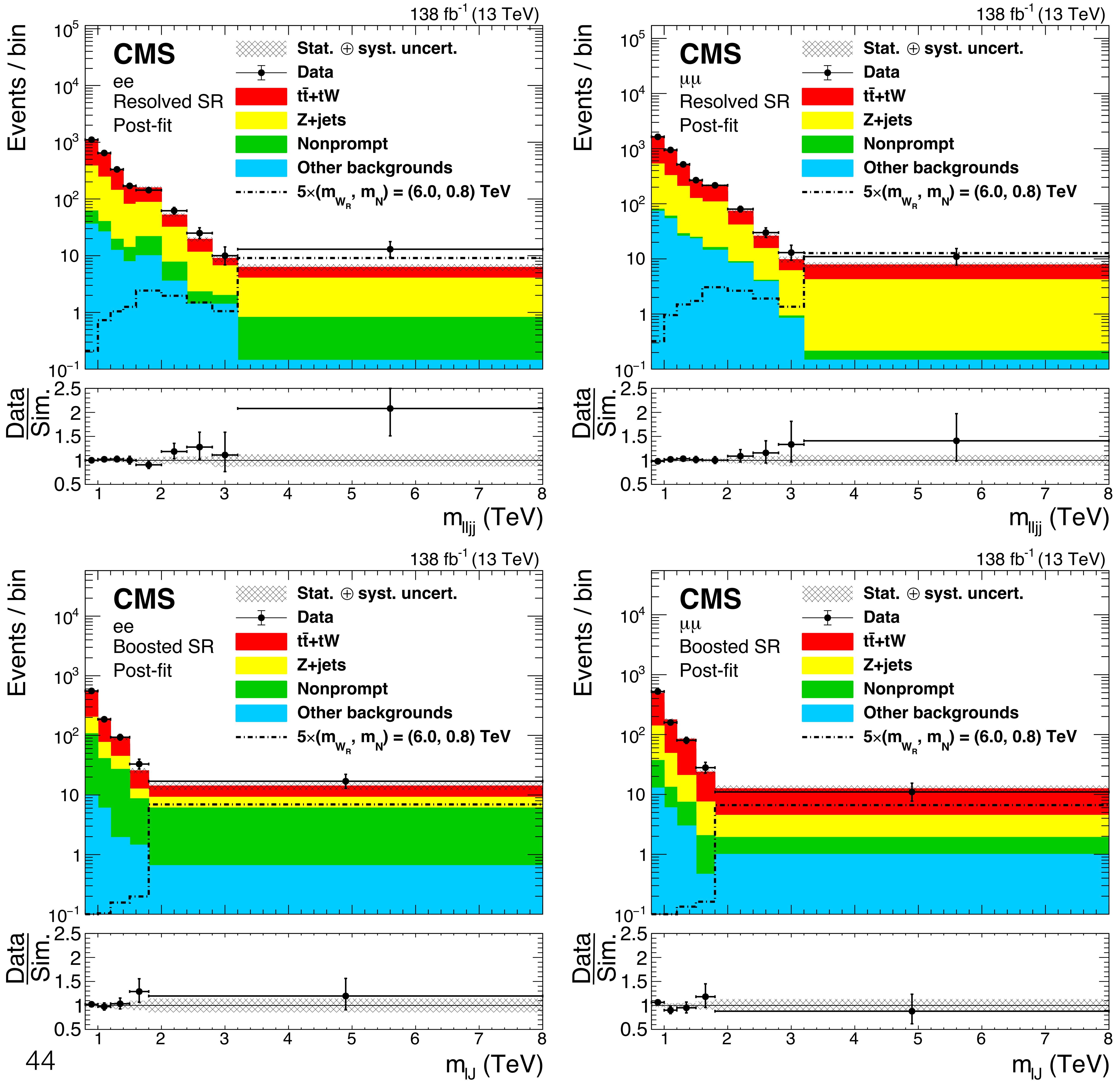
CMS-EXO-20-002

Search for W_R boson and a N: Results

A maximum-likelihood fit is performed on the mlljj (mlJ) distributions in the resolved (boosted) SRs and CRs, with the systematic uncertainties as nuisance parameters.

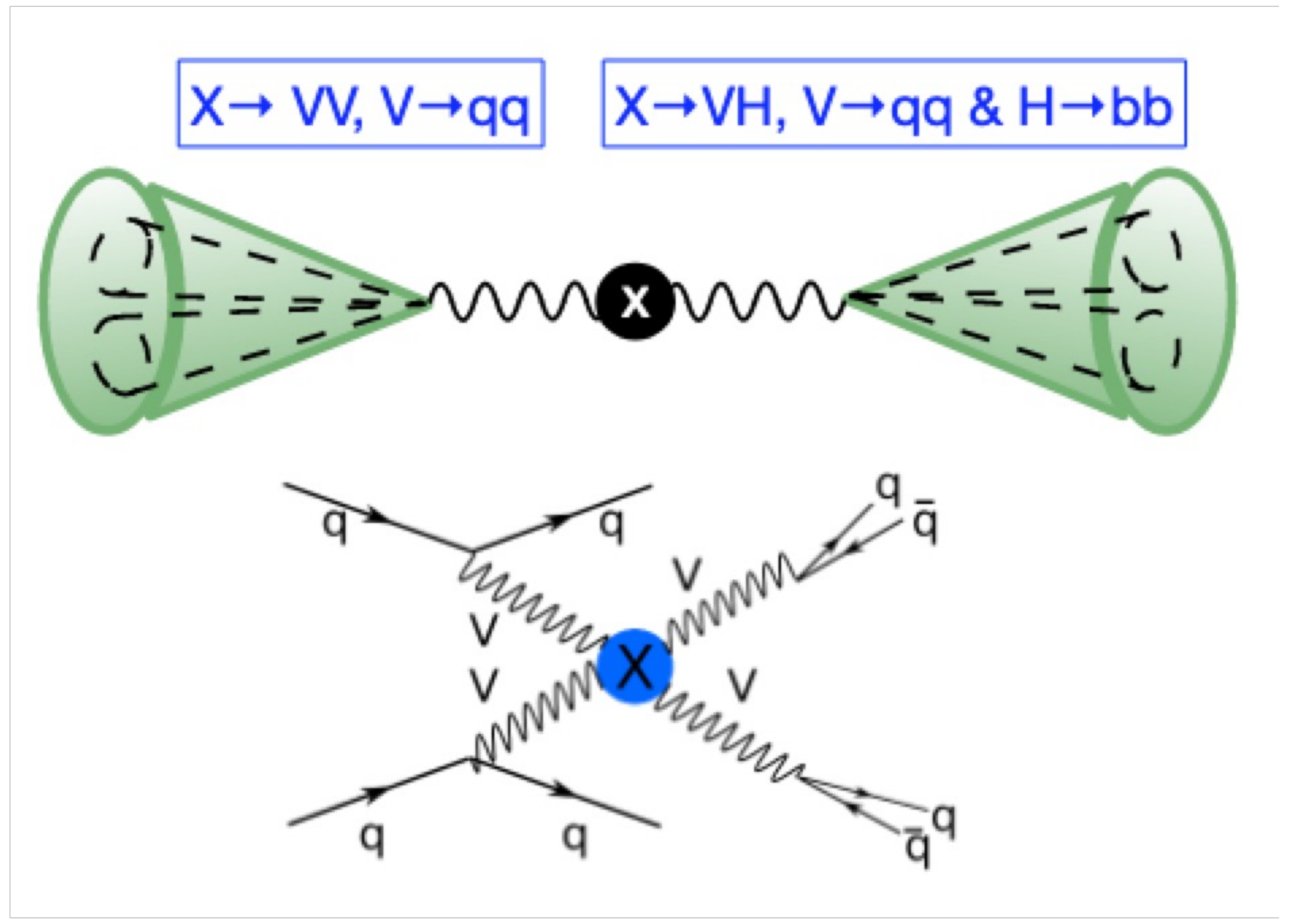
The most extreme **p-value** in the electron channel:

(mW_R,mN) = (6.0,0.8)TeV mass point corresponding to a **local (global) significance of 2.95σ (2.78σ)**.

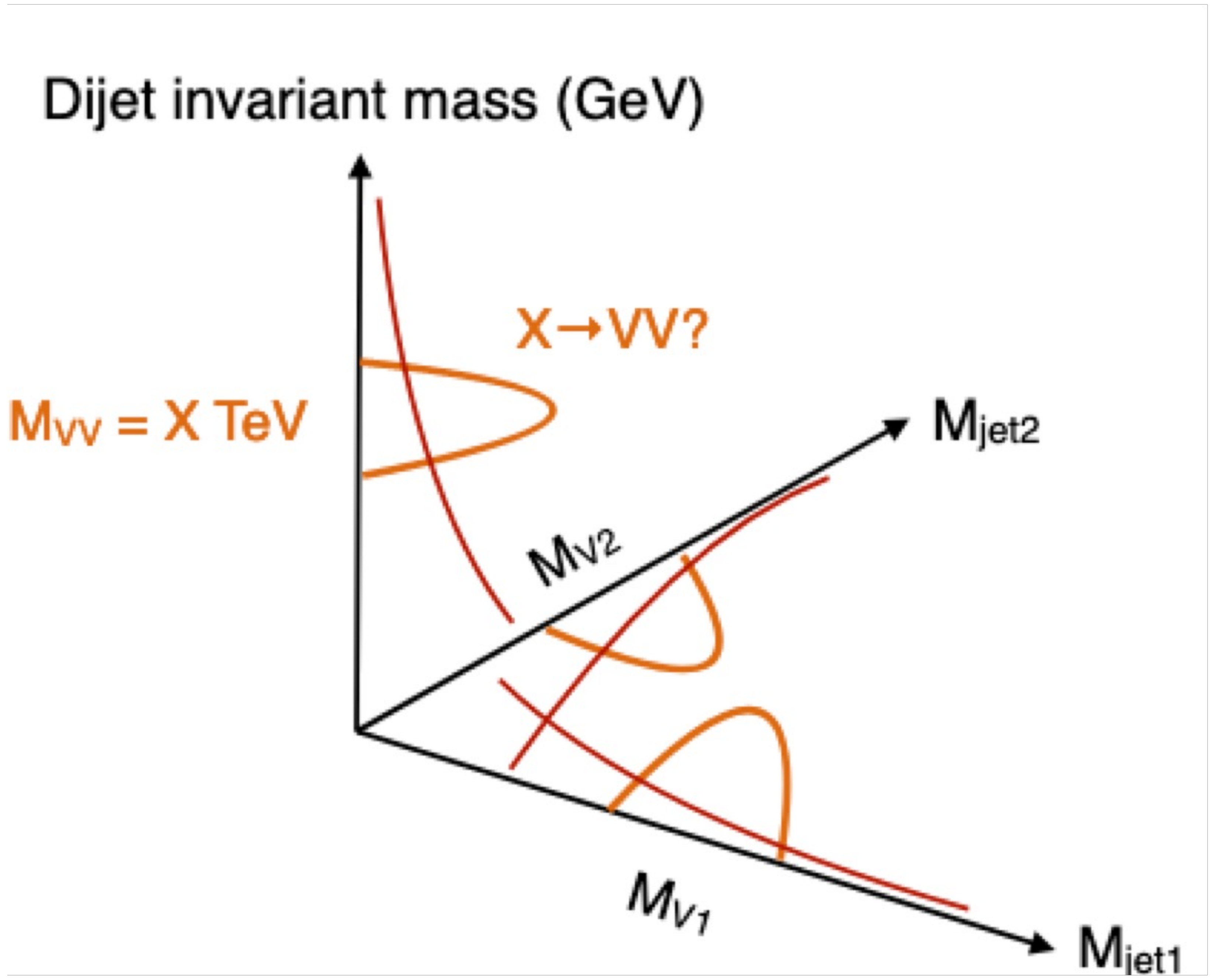


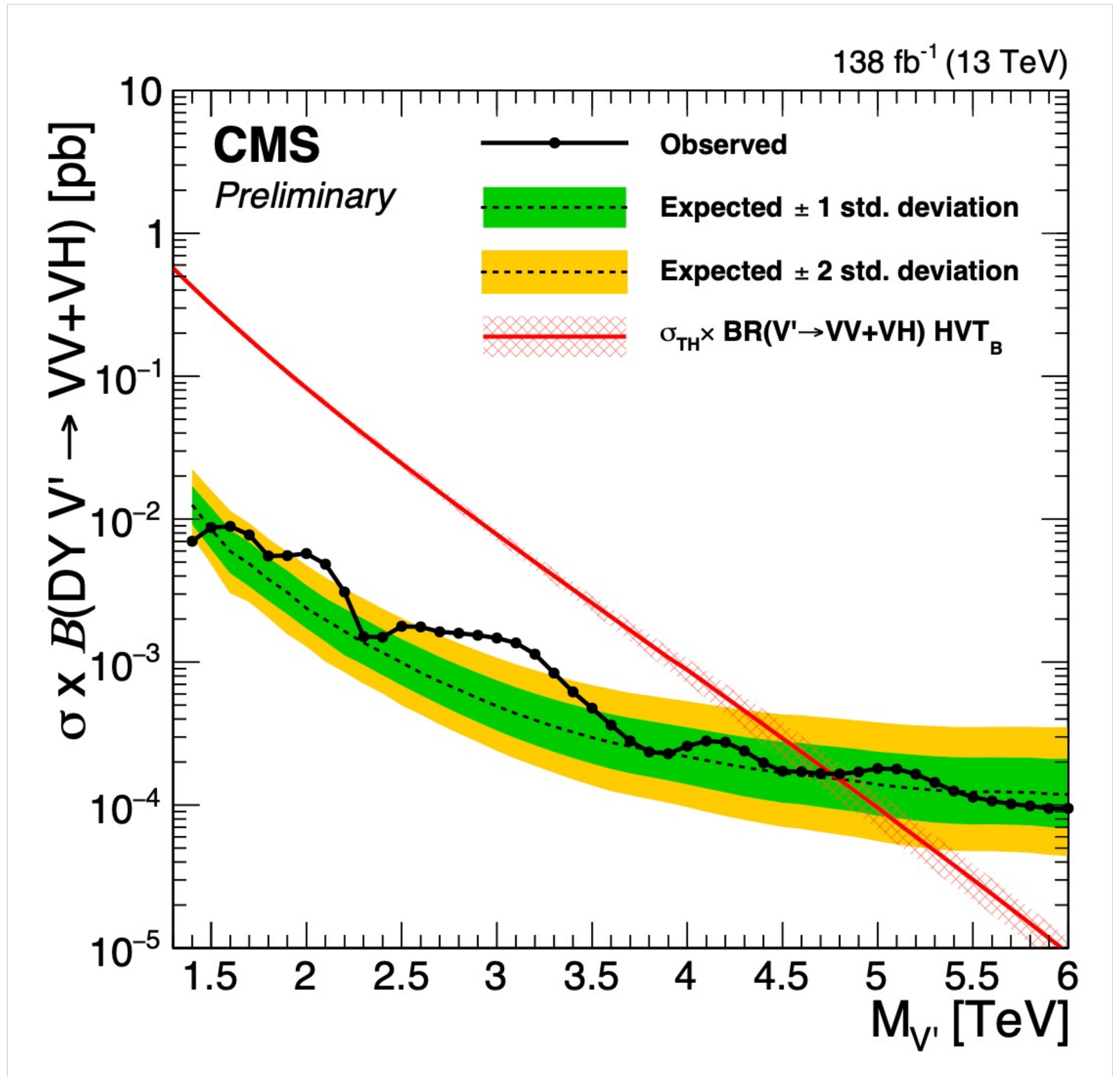
Detour: Bump hunt with an excess

Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state B2G-20-009



- Using 2 large cone jets (resonance decay products), and 2 small cone jets (VBF tags)
- Tag the jets with ML algorithms to distinguish from QCD



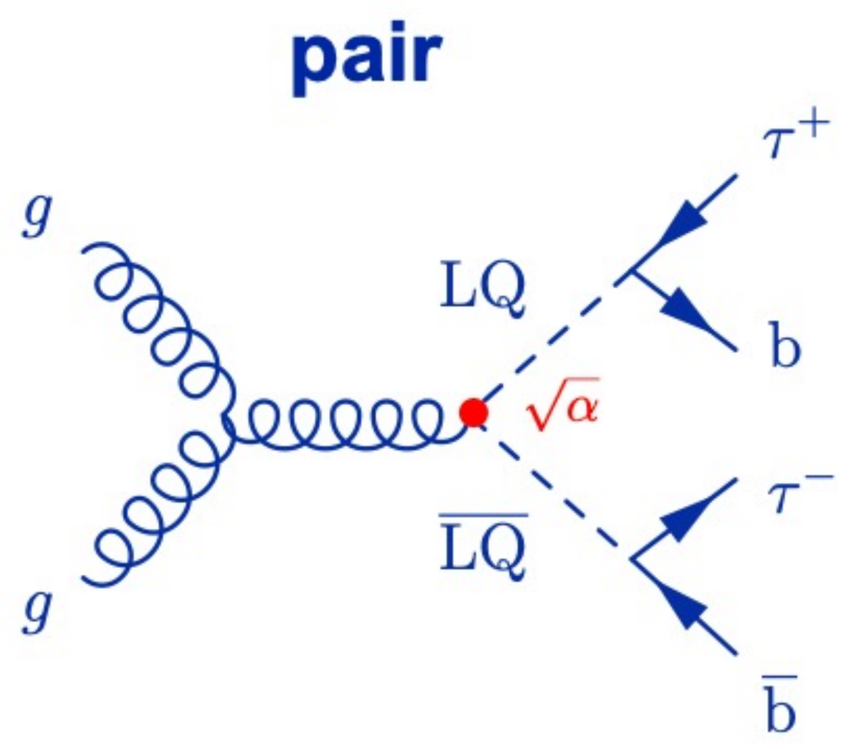


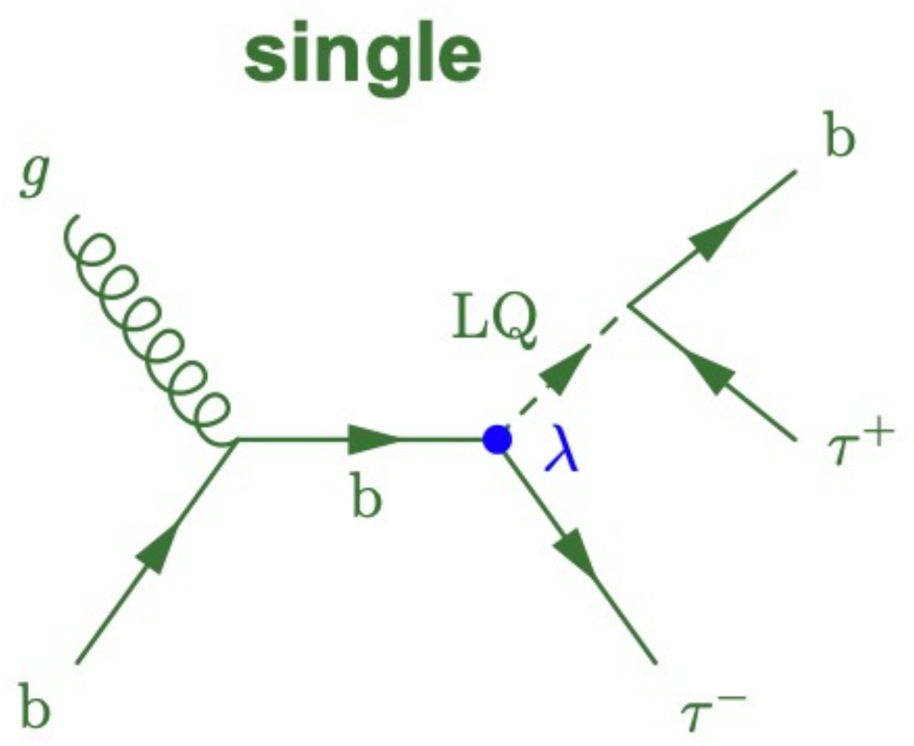
2 excesses in VV decay modes only:

Local significant: 3.6 σ
Global significance: 2.3 σ

Third-generation Leptoquark

CMS-EXO-19-016

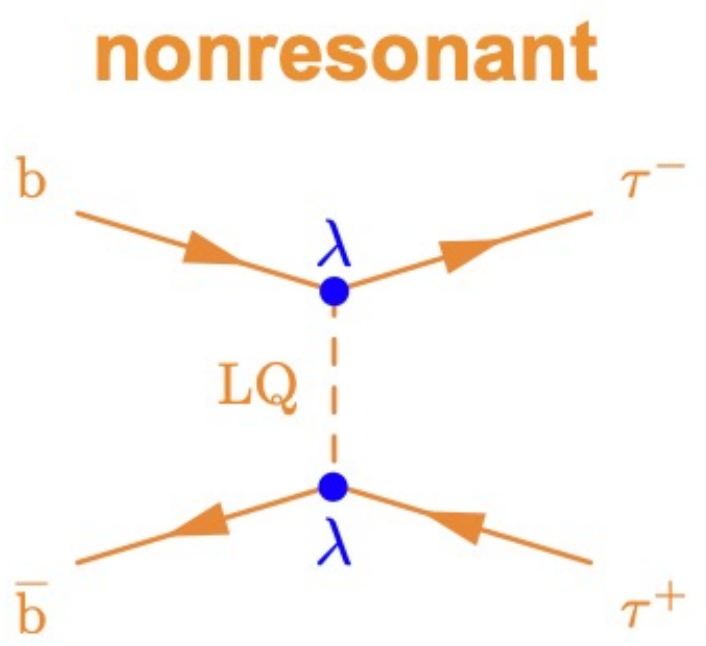




For a representative LQ mass of 2 TeV and a coupling strength of 2.5, an excess with a significance of **3.4 sigma** above the SM expectation is observed in the data.

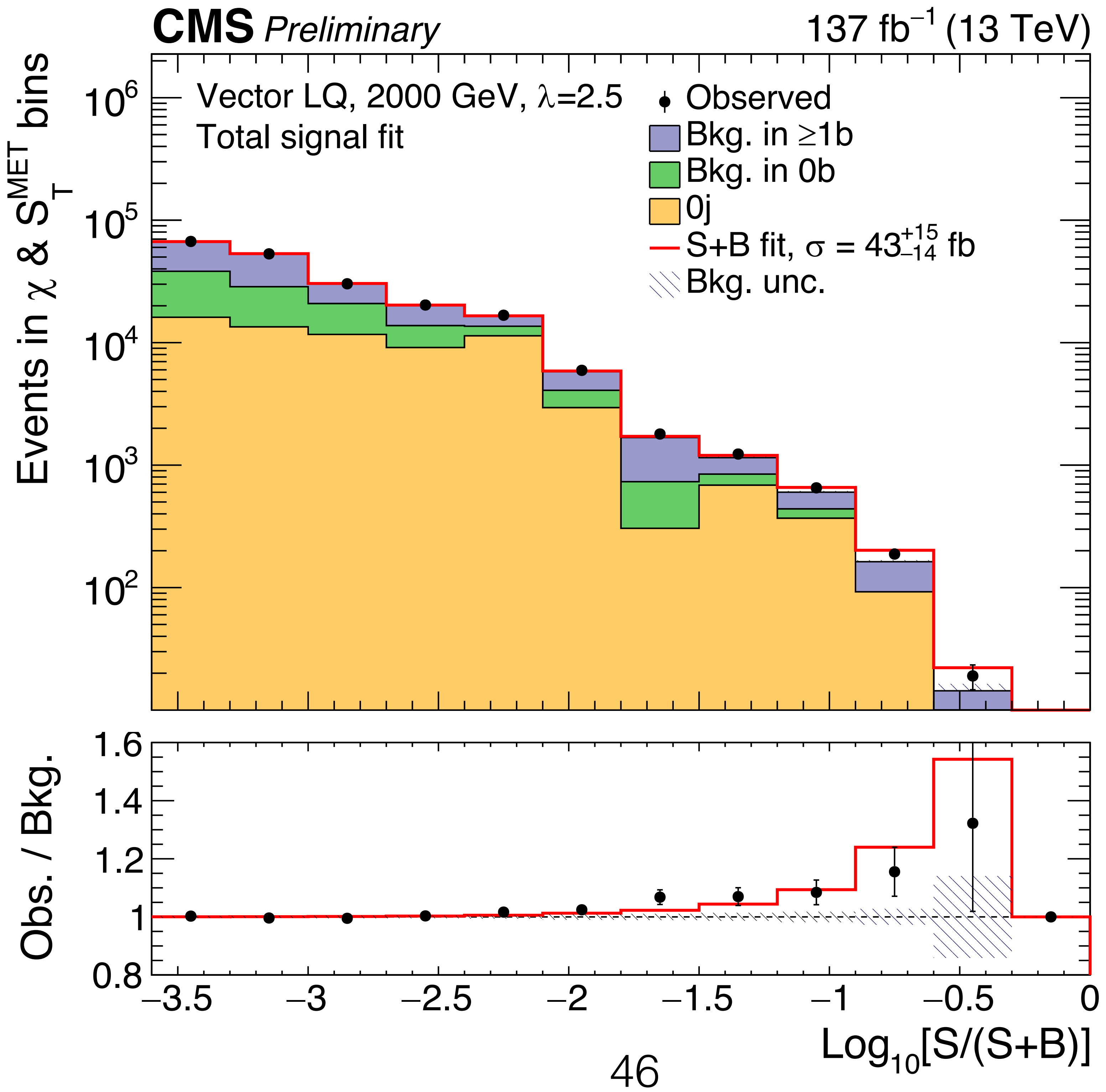
discriminating variable:

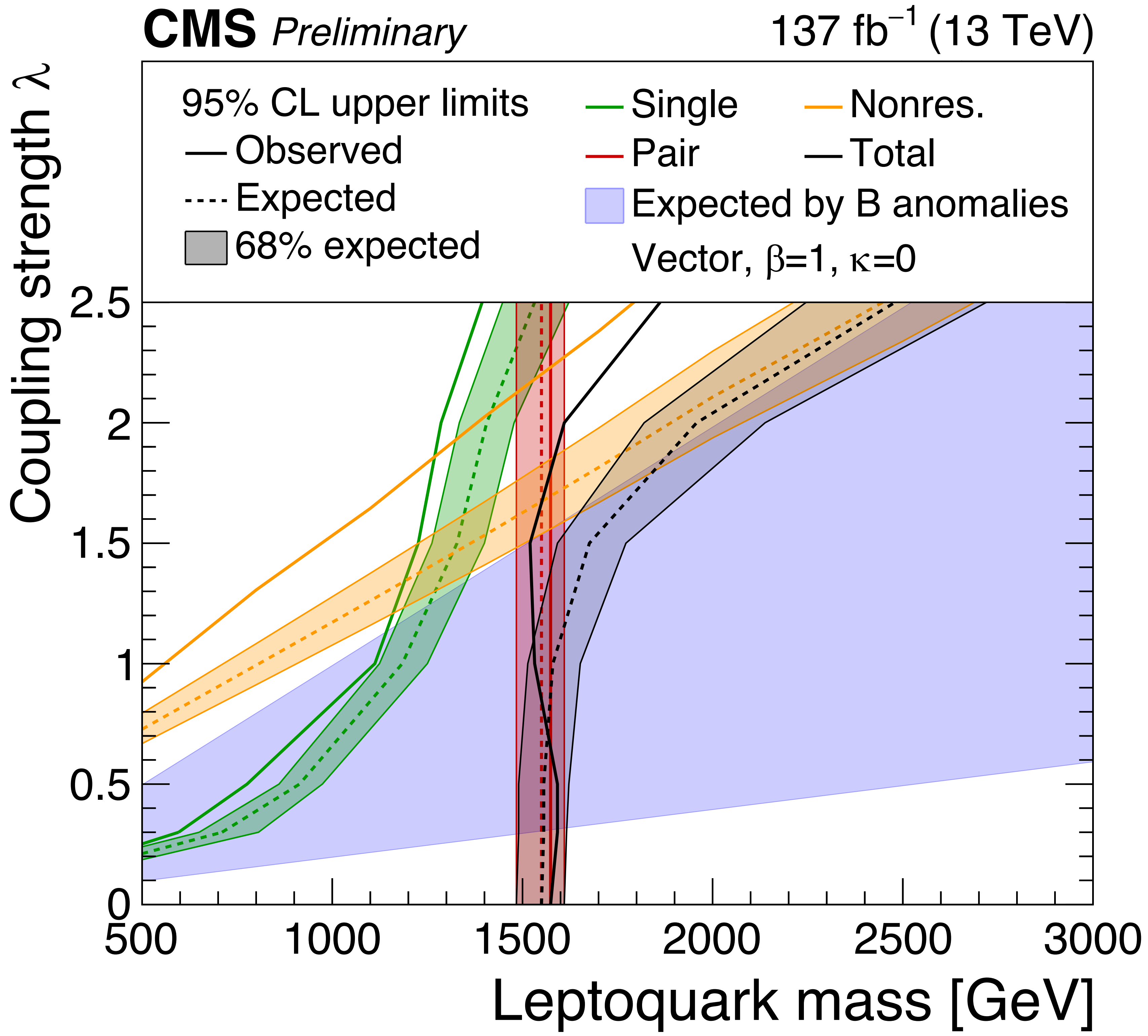
$$S_T^{\text{MET}} = p_T^{\tau_1} + p_T^{\tau_2} + p_T^{j} + \text{MET}$$



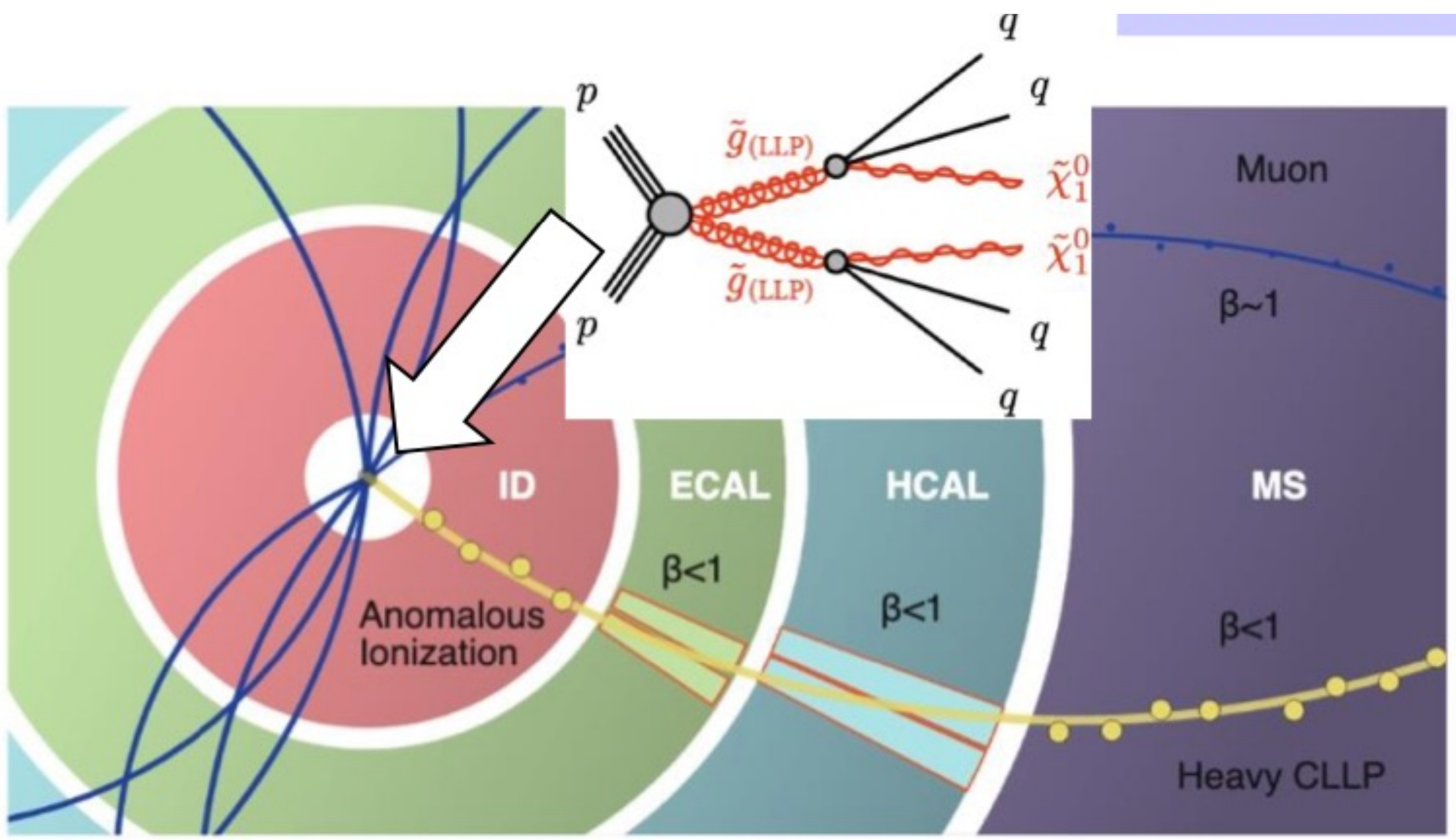
discriminating variable:

$$\chi = e^{\Delta\eta}$$





Heavy, long-lived, charged particles

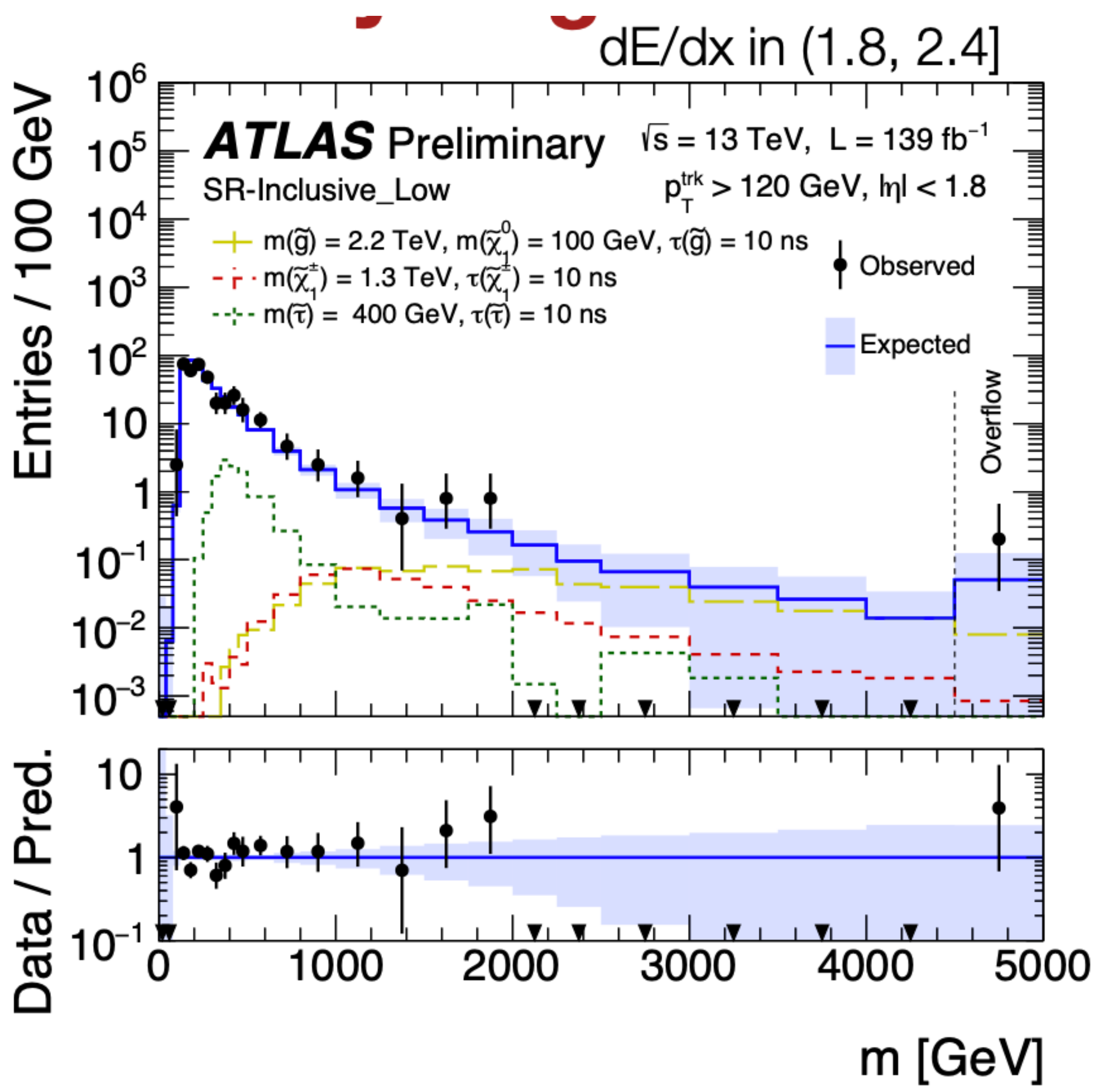


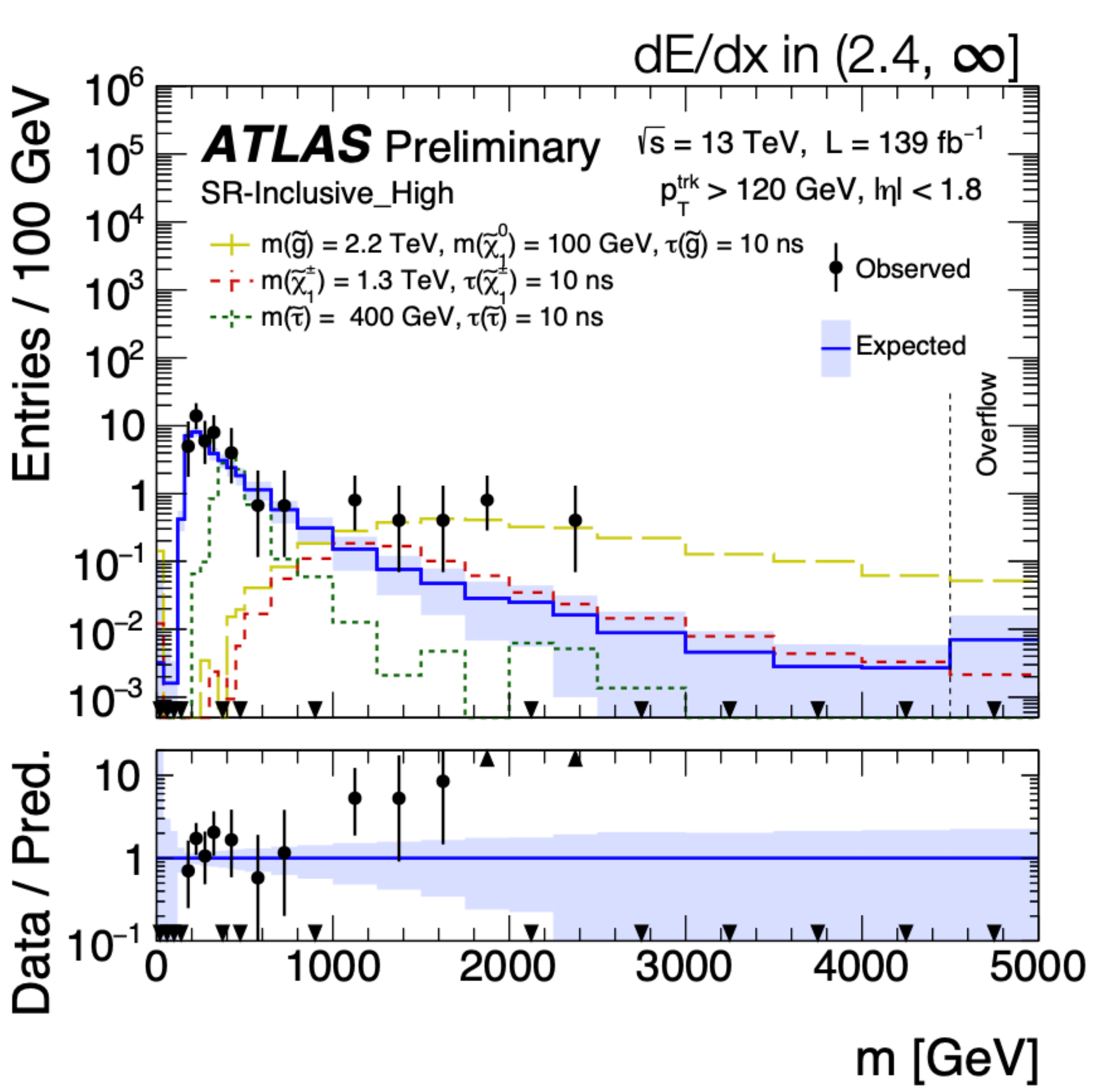
Signature: high-pT track with anomalously high dE/dx in the pixel detector

Sensitive to: gluinos, charginos, and staus with m = 200-2500 GeV and $\tau > O(0.1\ ns)$

Strategy:

- extract and parameterize relation between <dE/dx> and βγ using low- pileup runs
- compute $\langle dE/dx \rangle_{trunc;}$ evaluate m = p/(βγ)

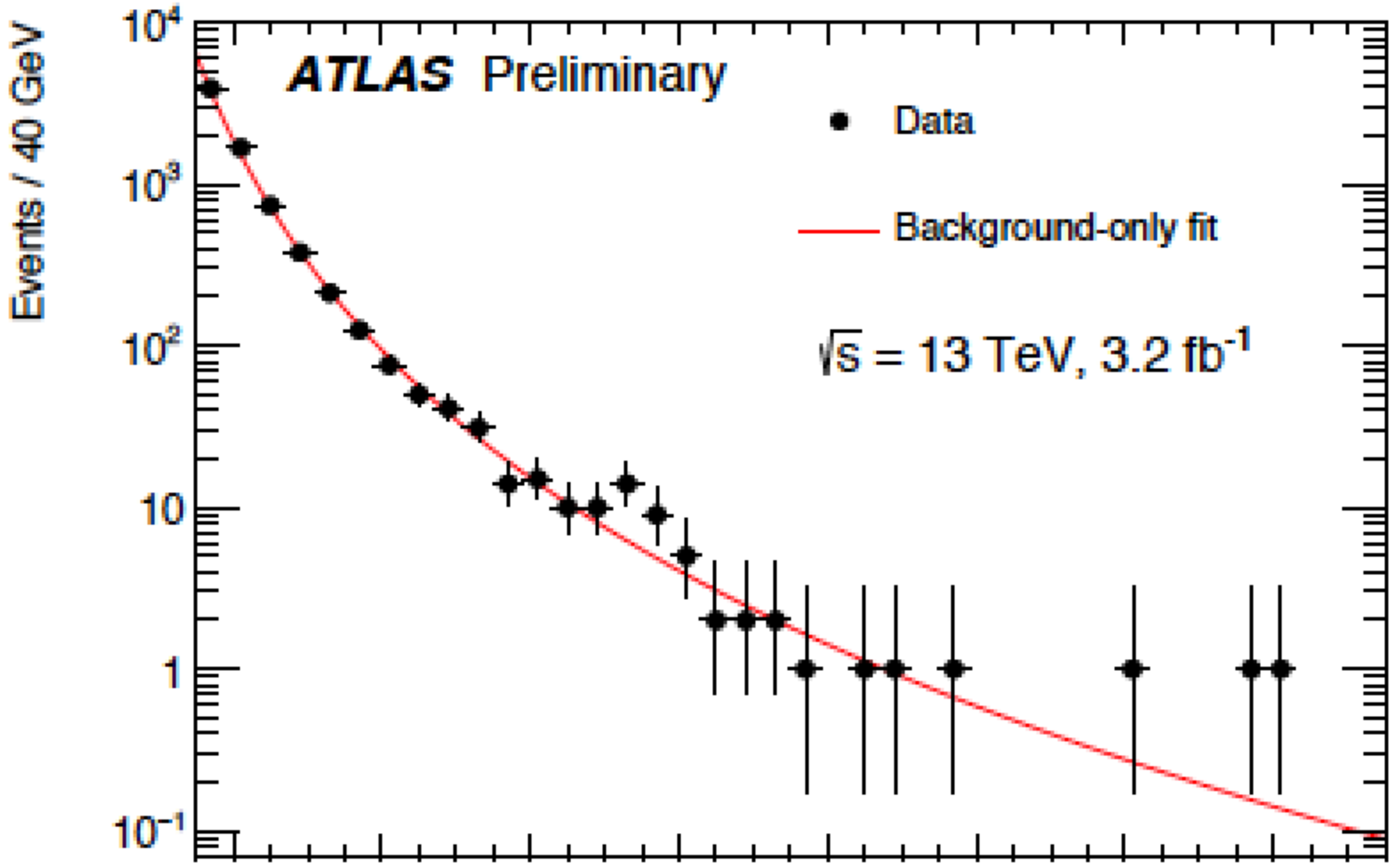


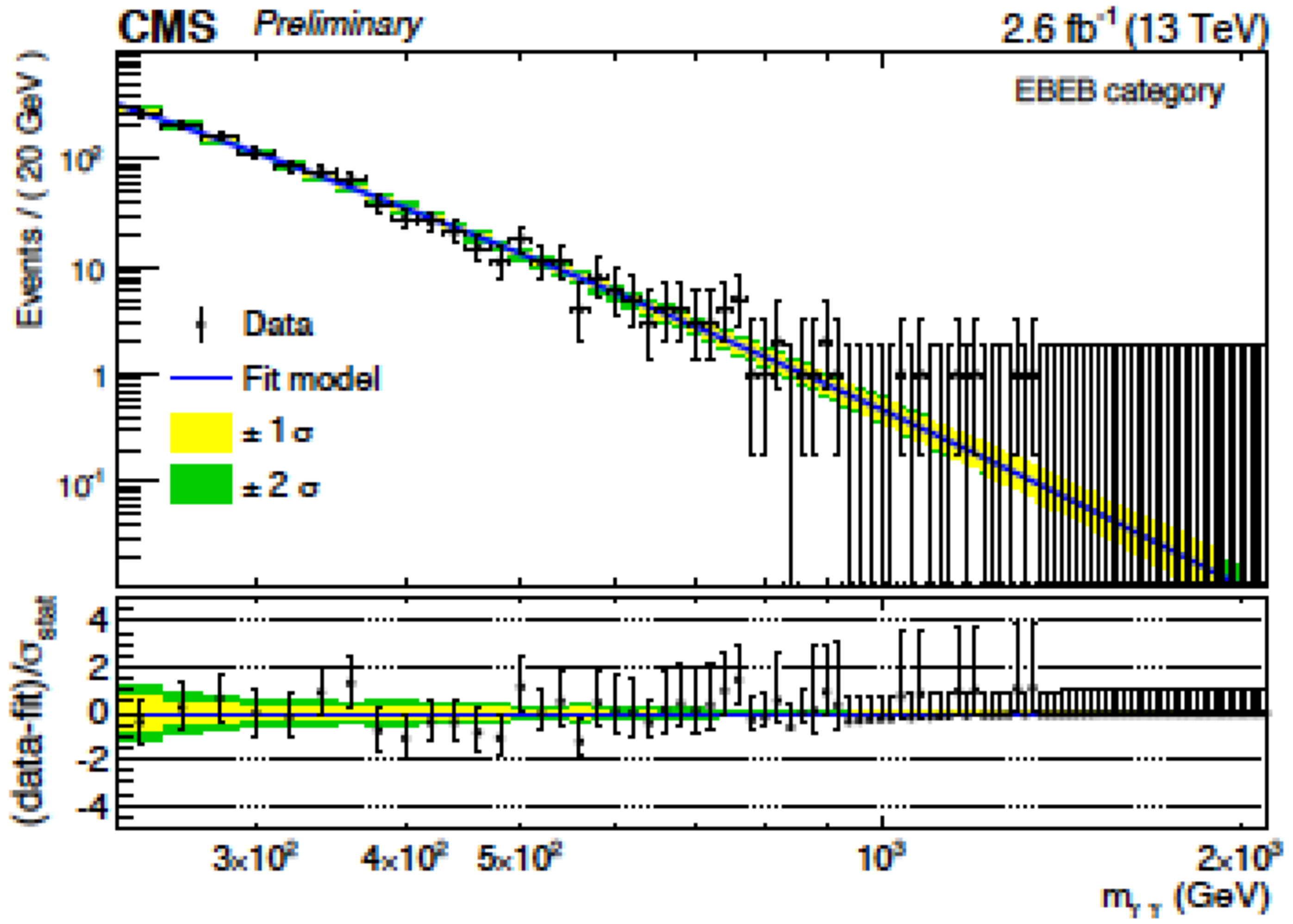


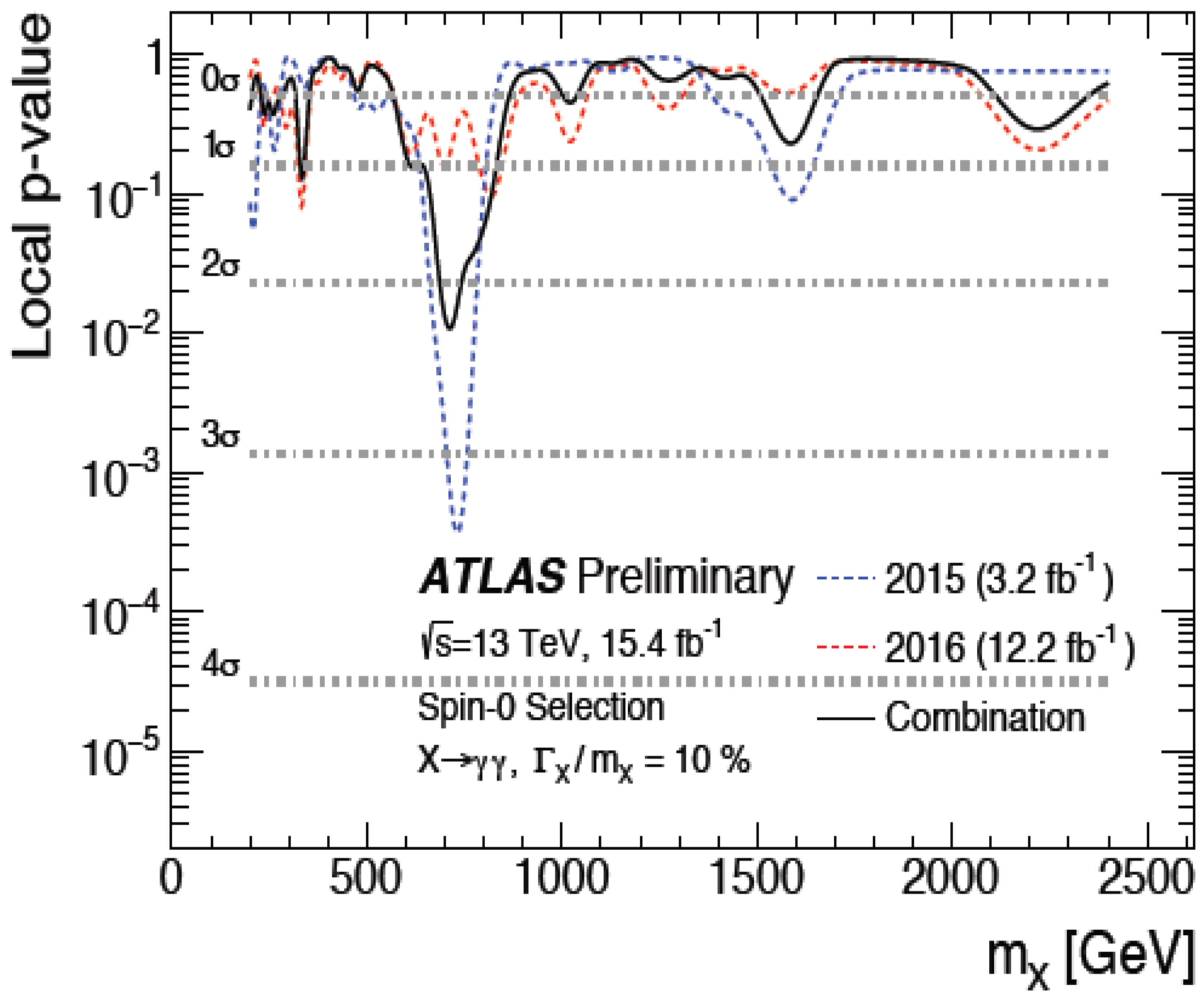
Excess in the high dE/dx signal region at m>1 TeV. It is 3.3 sigma global for a particle mass hypothesis of 1.4 TeV

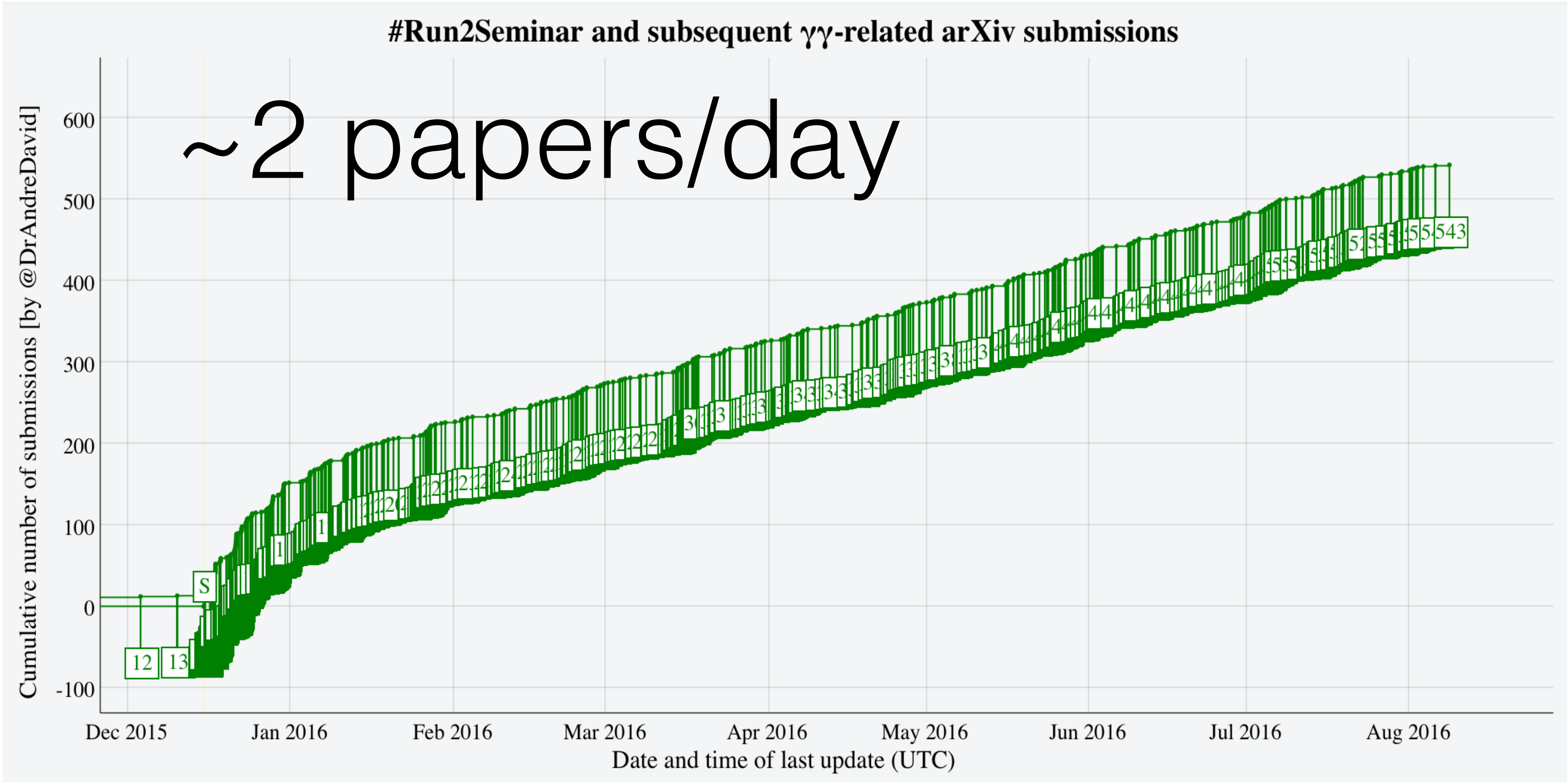
Timing of the 7 tracks responsible for an excess in the calorimeters and in the muon spectrometer but the time of flight was consistent with β~1. Not LLP?

Careful with “Discoveries”: Remember 750 GeV bump?



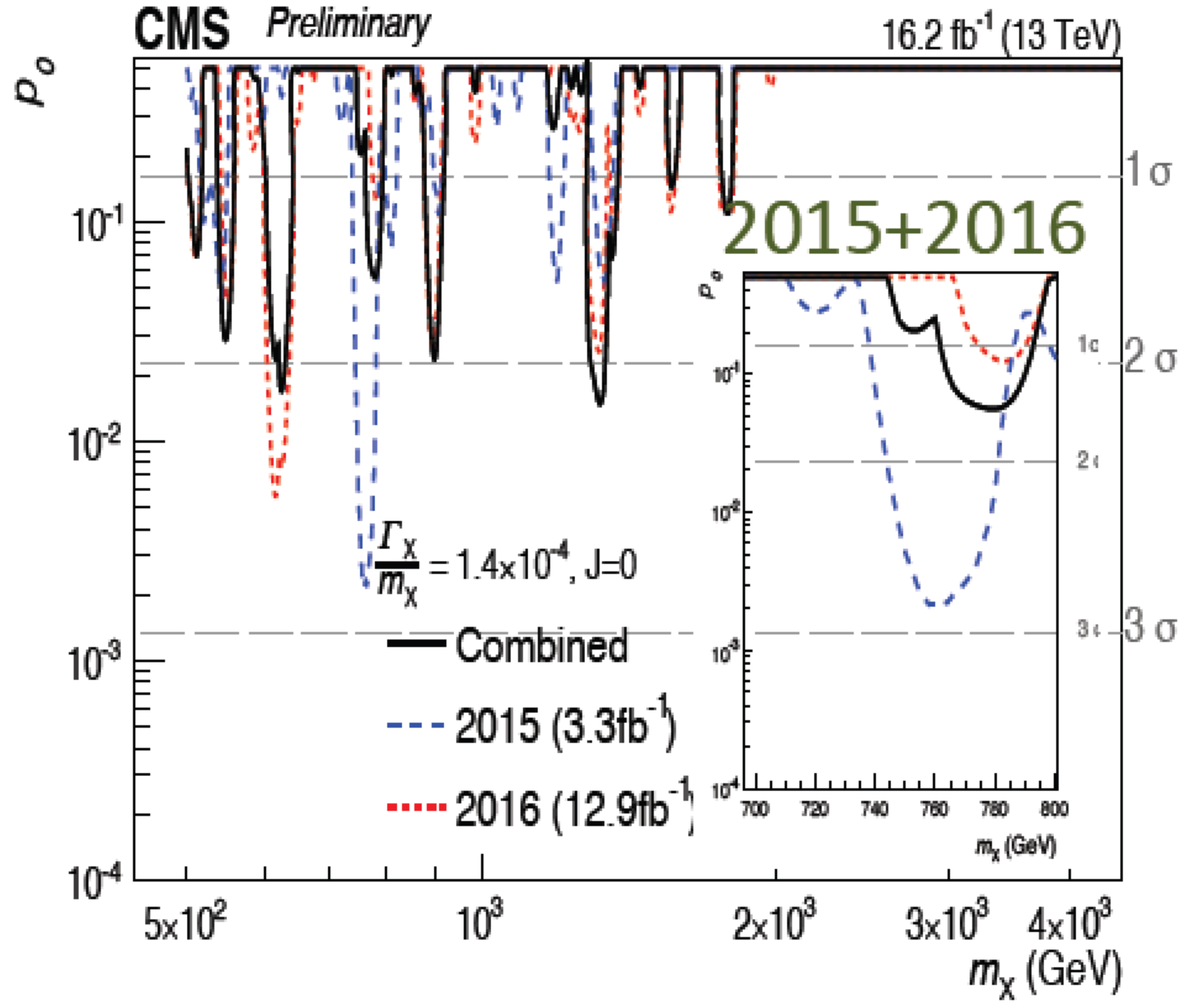






Atlas had 3.9 sigma,
CMS had 3.4 sigma
using 2015 dataset

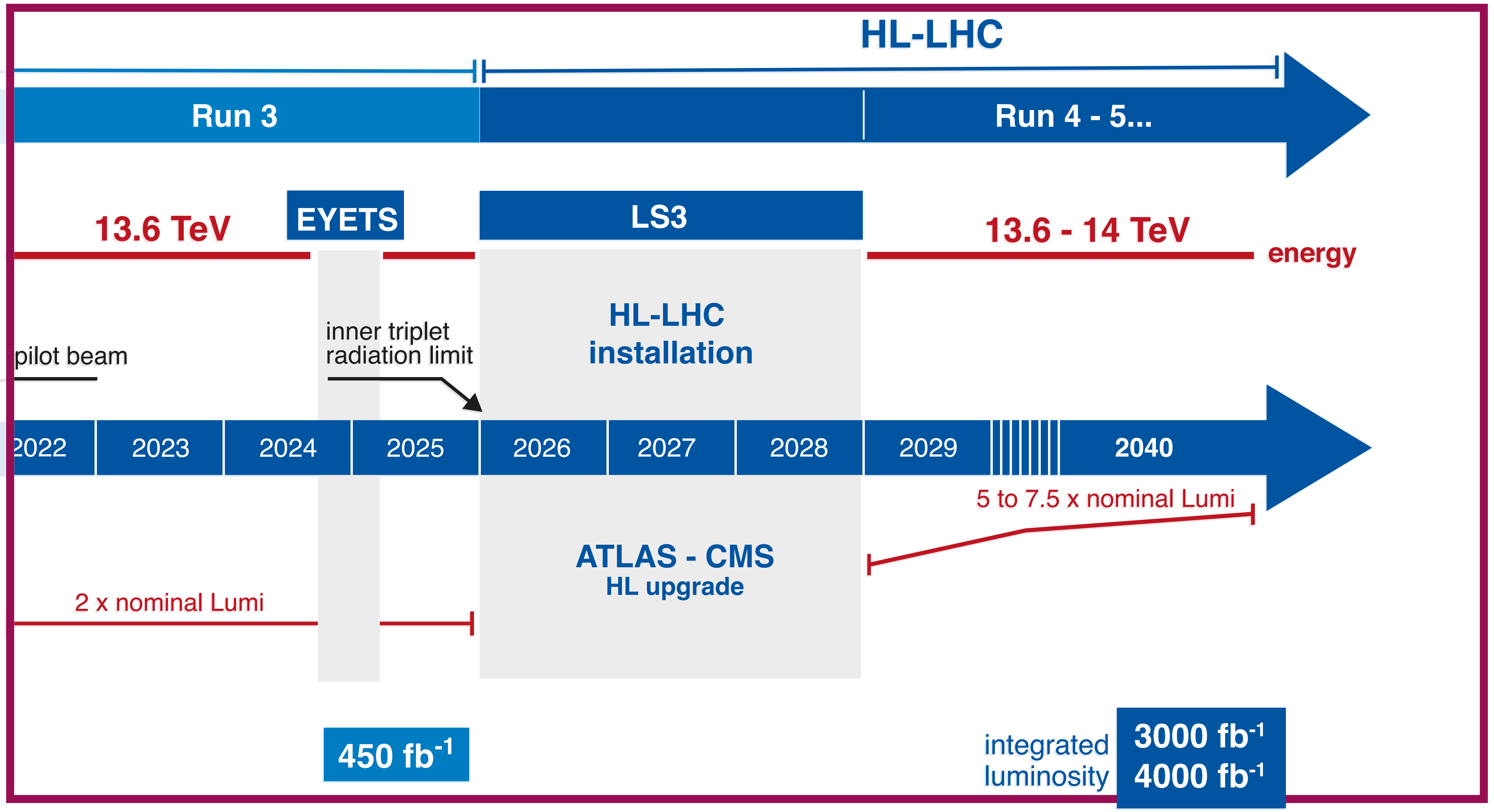
But nothing in 2016…



Data Taking

Run 3 : COM Energies of 13.6 TeV and luminosities of ~300 fb^{-1} and pu of ~30-40

HL-LHC : COM Energy of 13.6-14 TeV and luminosities of ~3000 fb^{-1} and pu of ~200



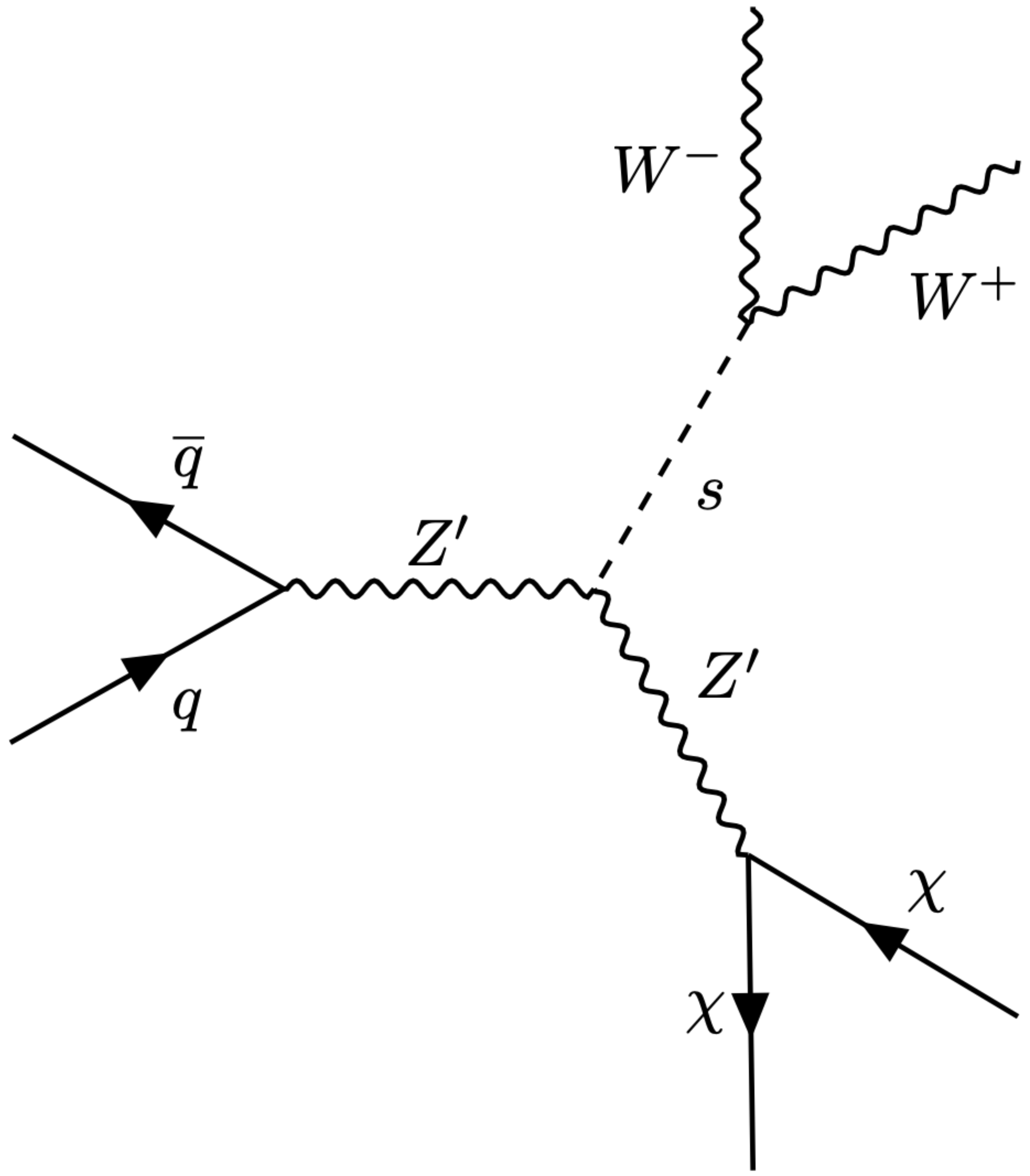
Major ATLAS and CMS upgrades:

- Tracker upgrade with larger pseudo rapidity coverage (also hardware level triggering)
- Readout upgrades in all detectors.
- New timing detectors with LGAD silicons: 30-40 ps

DON'T GIVE UP.
GREAT THINGS TAKE TIME.

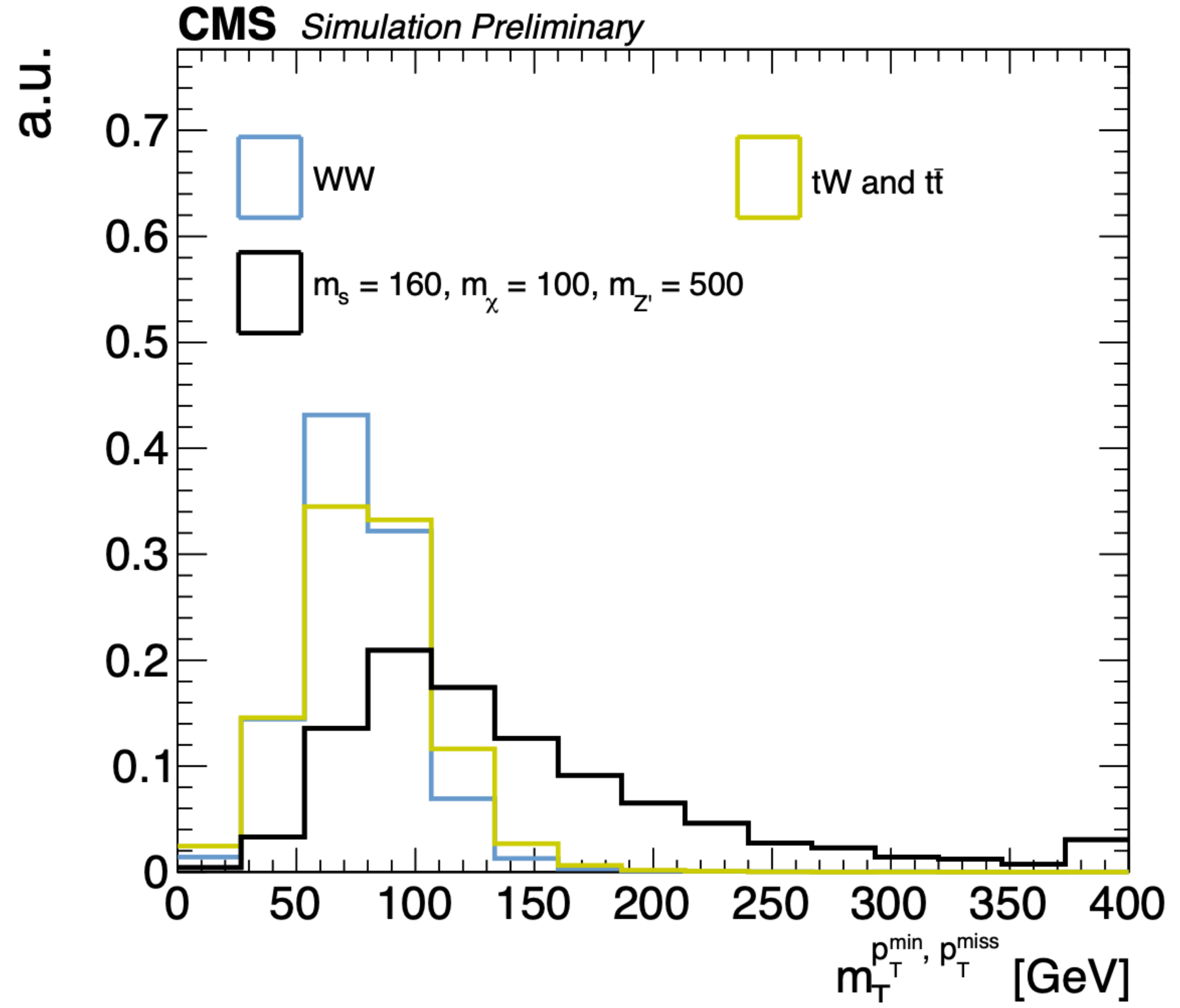
[CMS-EXO-20-013]

Dark Higgs (WW)



DM particles acquire their mass through their interactions with a Dark Higgs boson.

Signal extraction: 3D ML fit to ΔR(ll), mll, mT(lmin + pT)



Model parameters are:

- DM mass: mχ,
- Z′ mass: mZ′,
- dark Higgs mass: ms,
- Z′ couplings to quarks (gq)
- Z′ couplings to DM (gχ),
- the mixing angle between SM and the dark Higgs bosons (sin θ).

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