



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

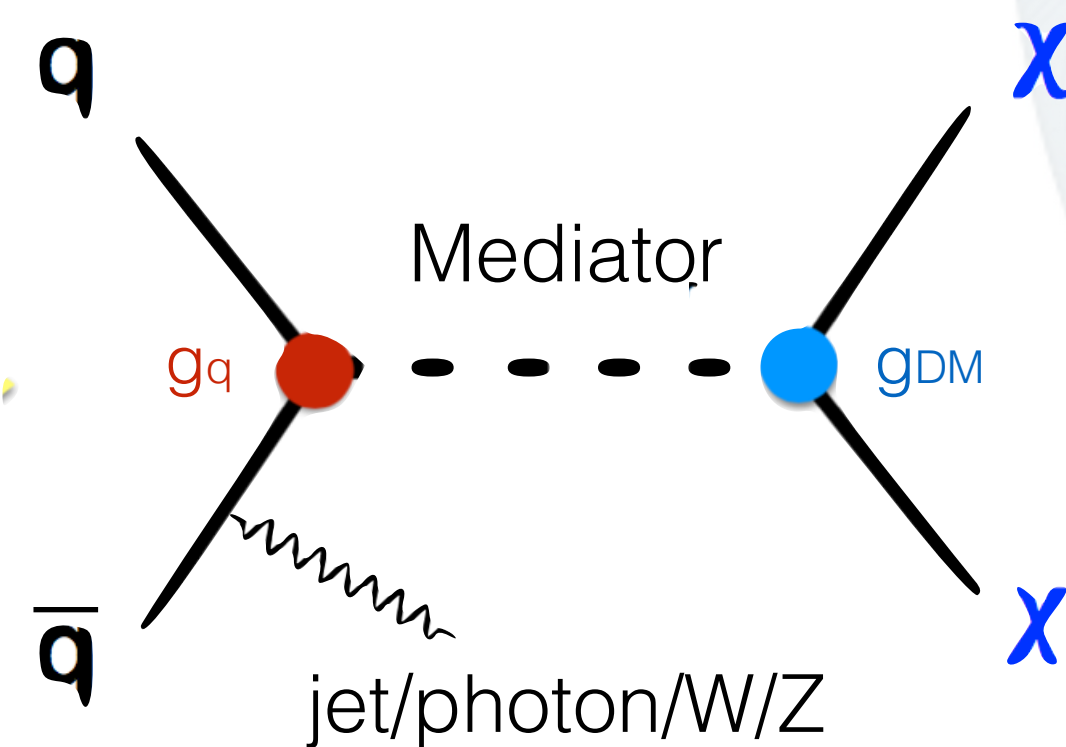
<http://indico.fnal.gov/e/hcpss2022>

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

spin-1
spin-0

vector

$$g_q \sum_q V_\mu \bar{q} \gamma^\mu q$$

axial-vector

$$g_q \sum_q A_\mu \bar{q} \gamma^\mu \gamma^5 q$$

scalar

$$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$$

pseudoscalar

$$g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f} \gamma^5 f$$

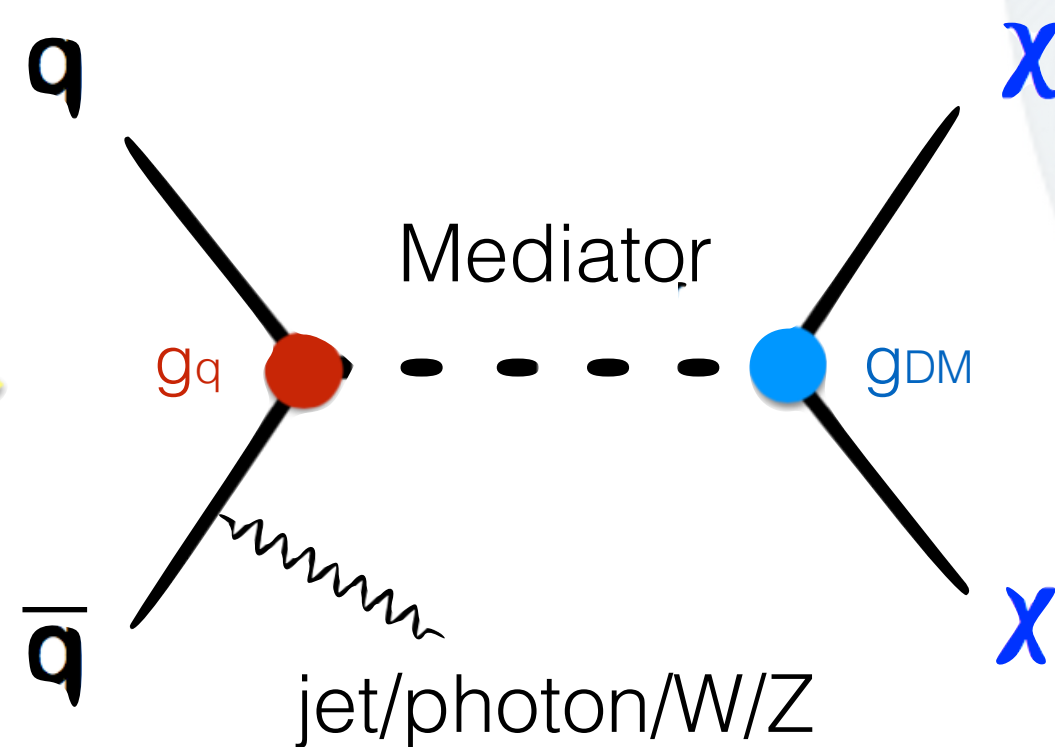
Higgs Portals

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



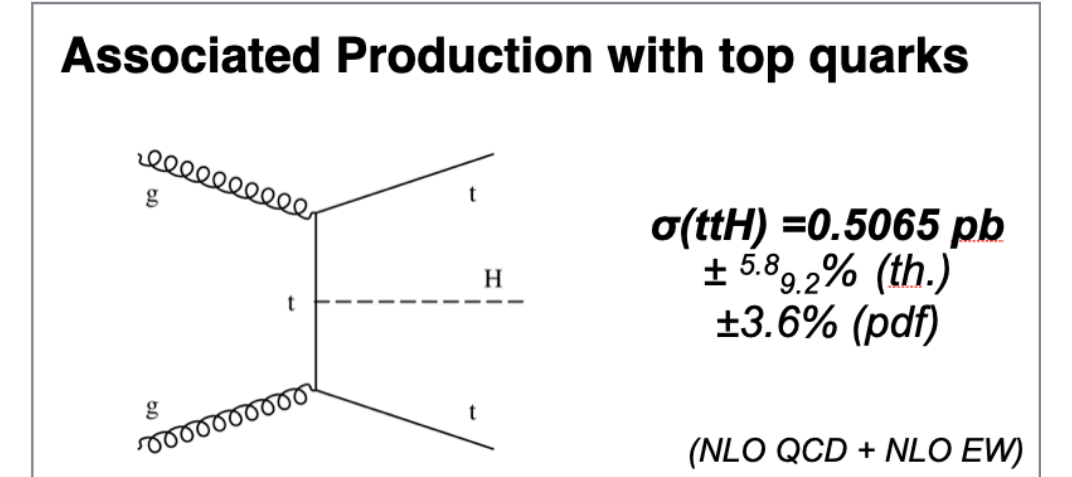
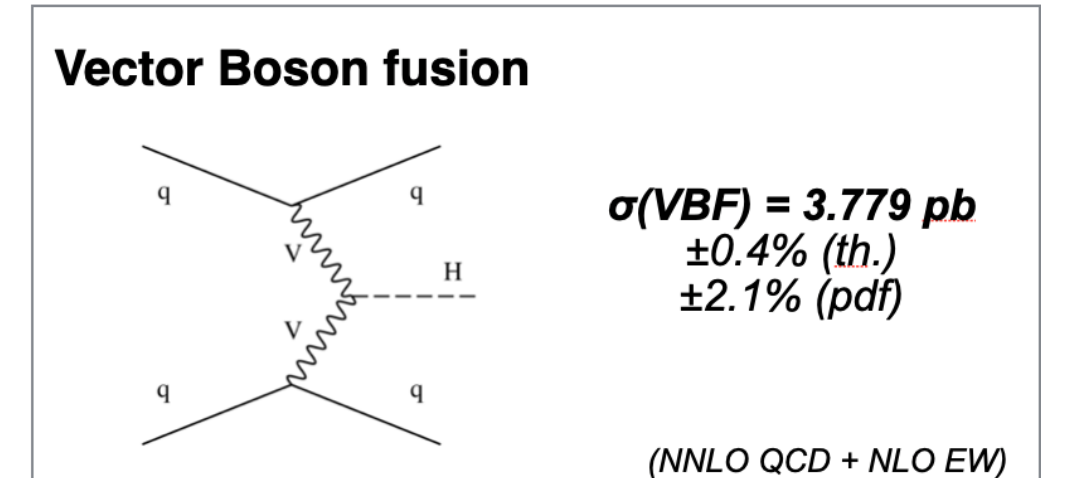
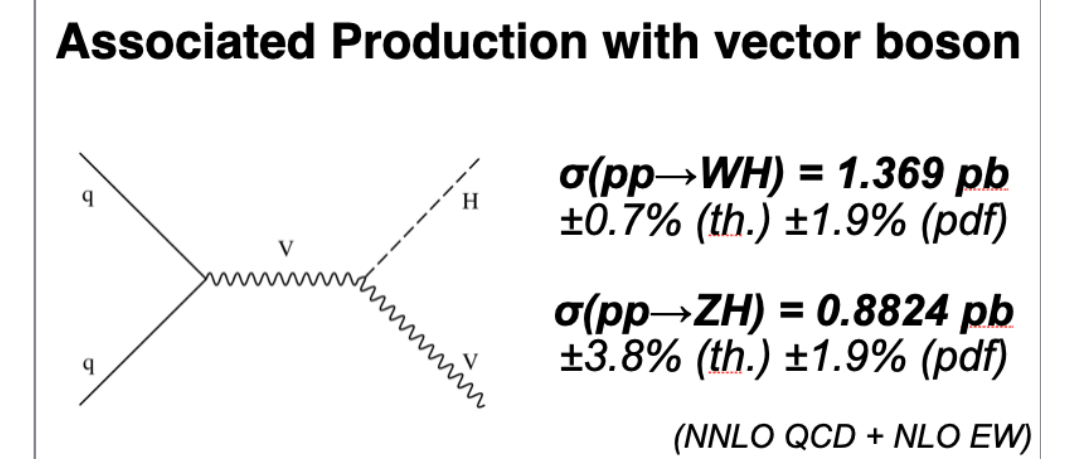
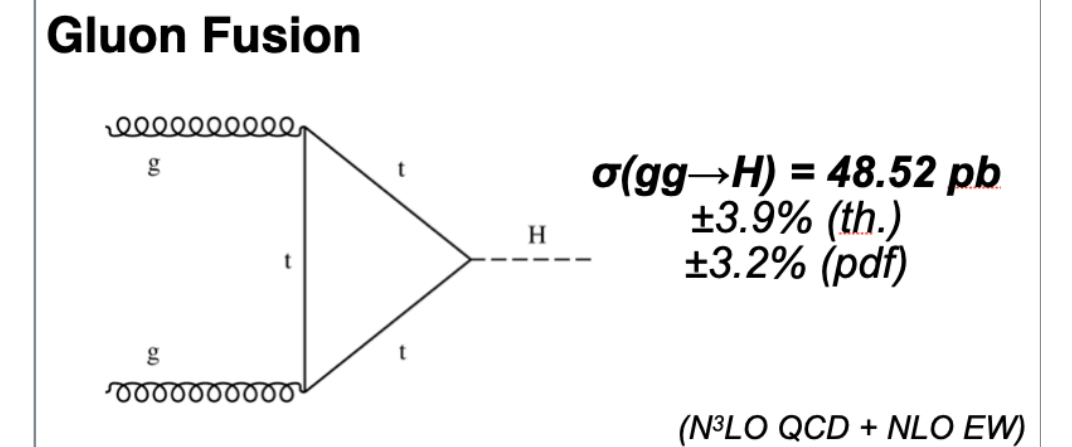
Extended to models with t-channel
mediator and dark sectors

Higgs Portal

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



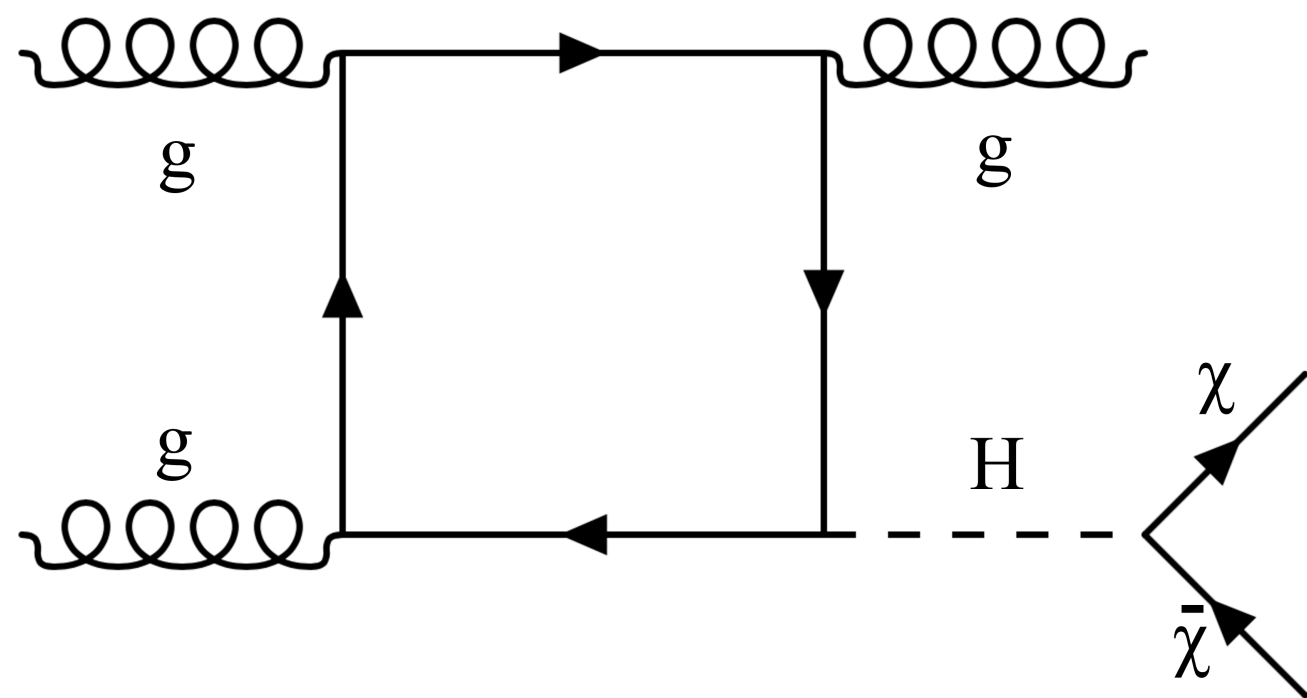
All Higgs production modes
can be studied to tag the event



Higgs Production Modes

Higgs Production modes will determine the signature.

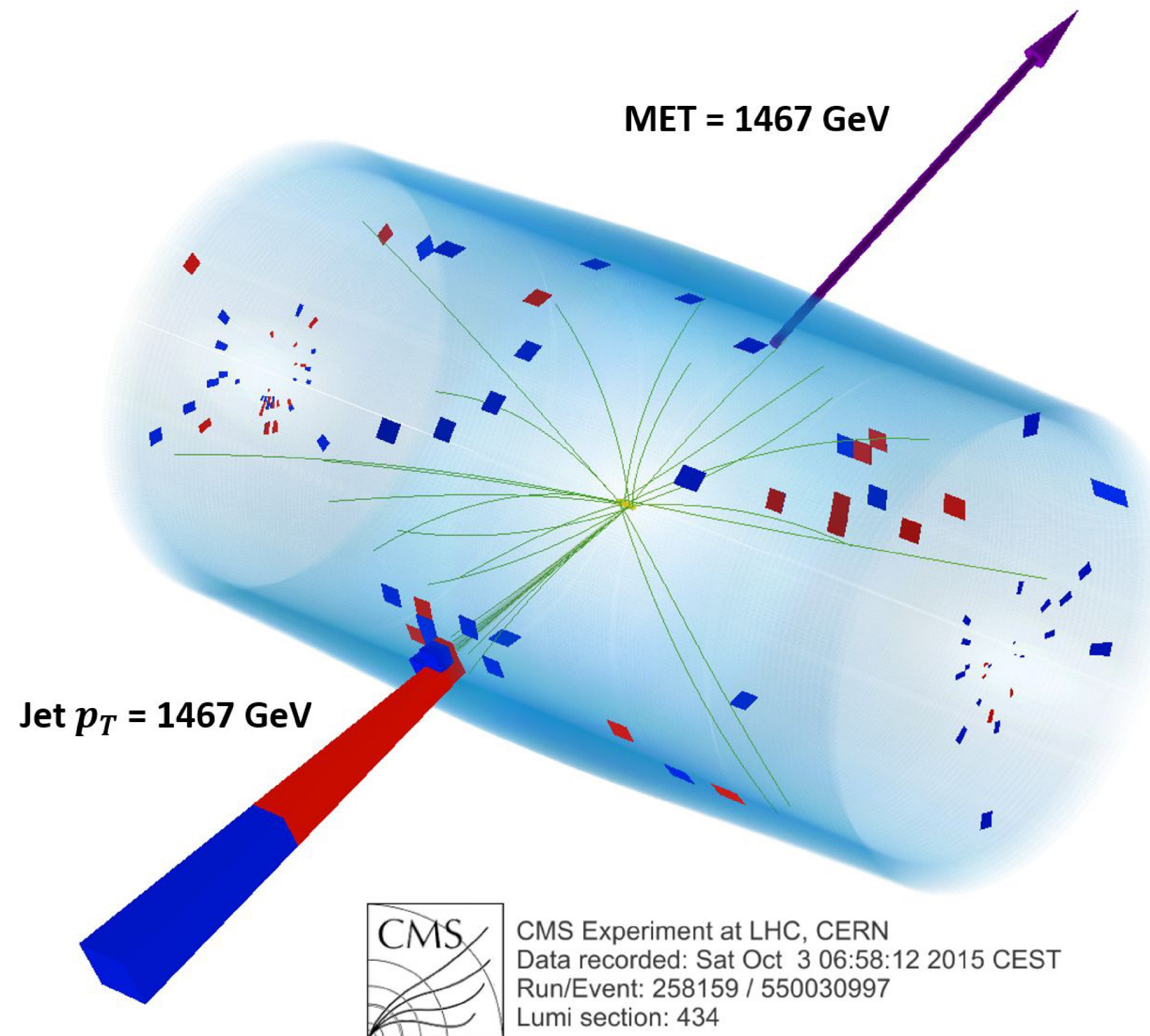
We discussed gluon fusion production mode => That's just monojet!



Gluon fusion

[JHEP11\(2021\)153](https://arxiv.org/abs/1105.3544)

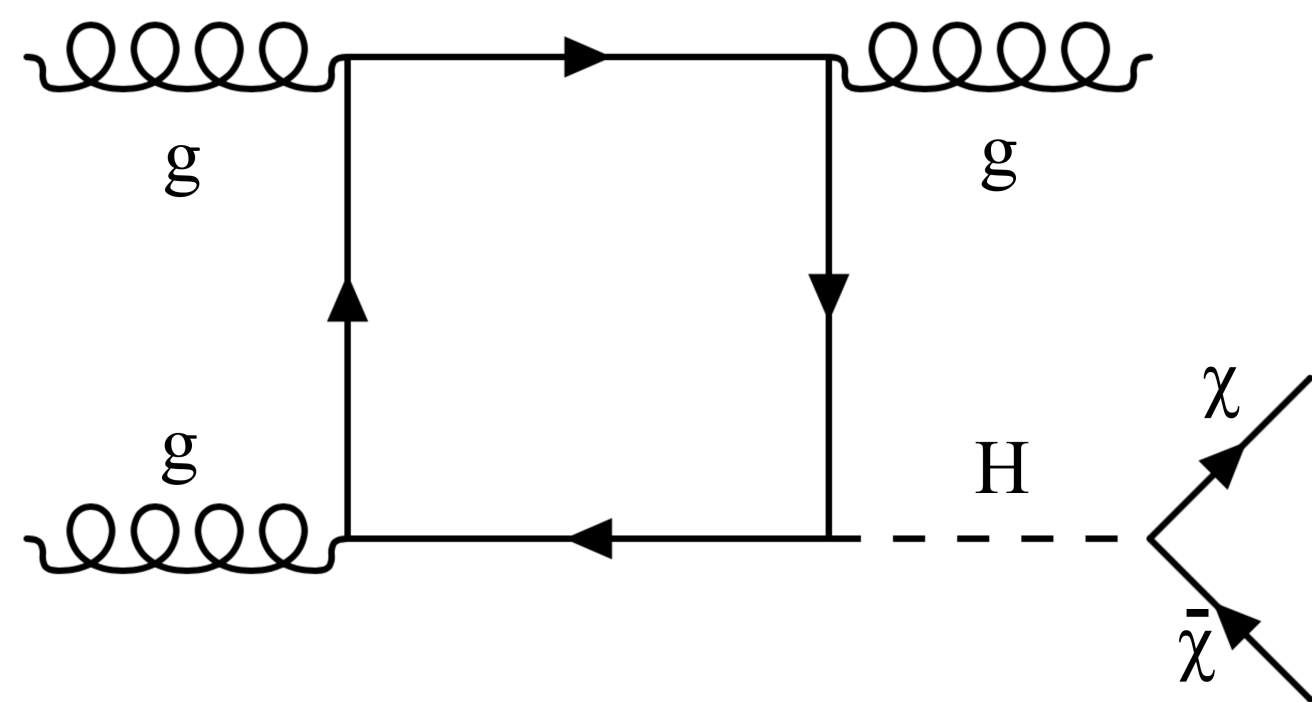
- Largest production production cross section
- Needs to be tagged with a visible object



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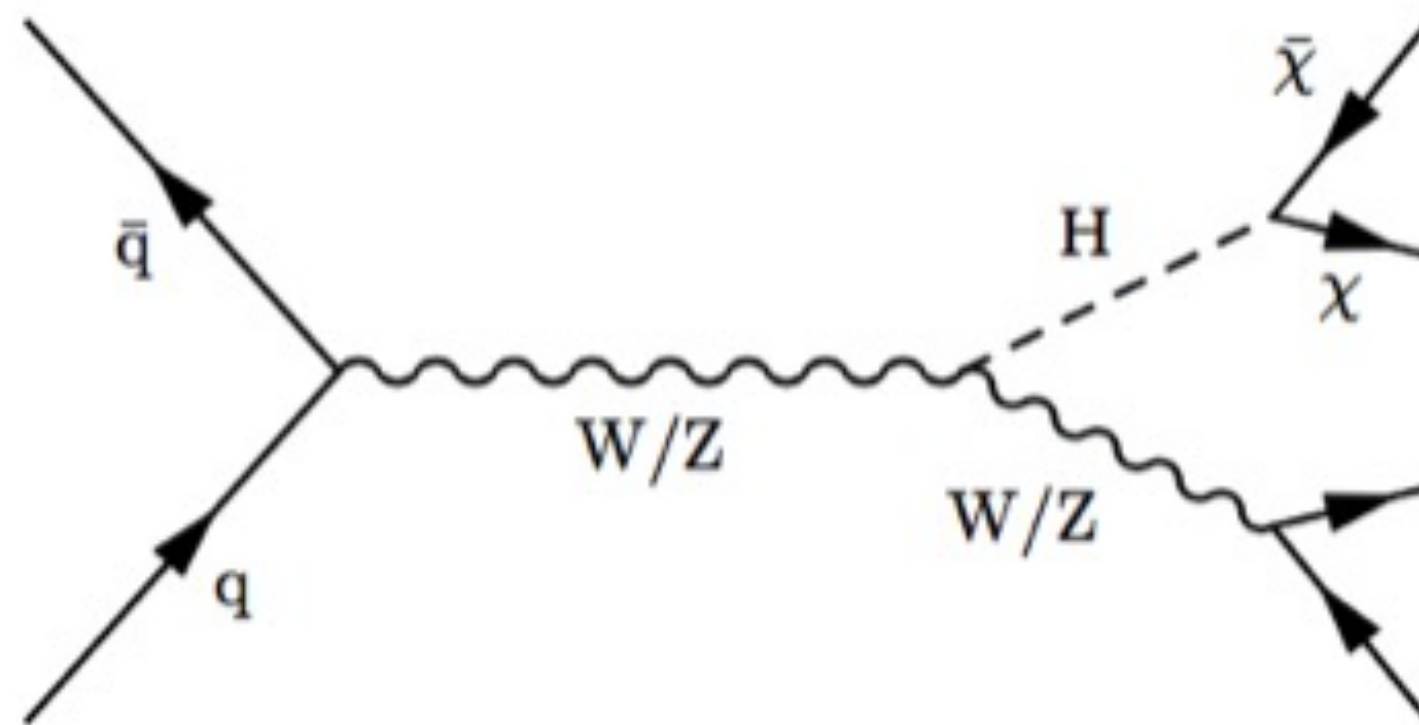
Now lets look at VH production => Let us call it “mono-V”



Gluon fusion

[JHEP11\(2021\)153](#)

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



Associated vector boson

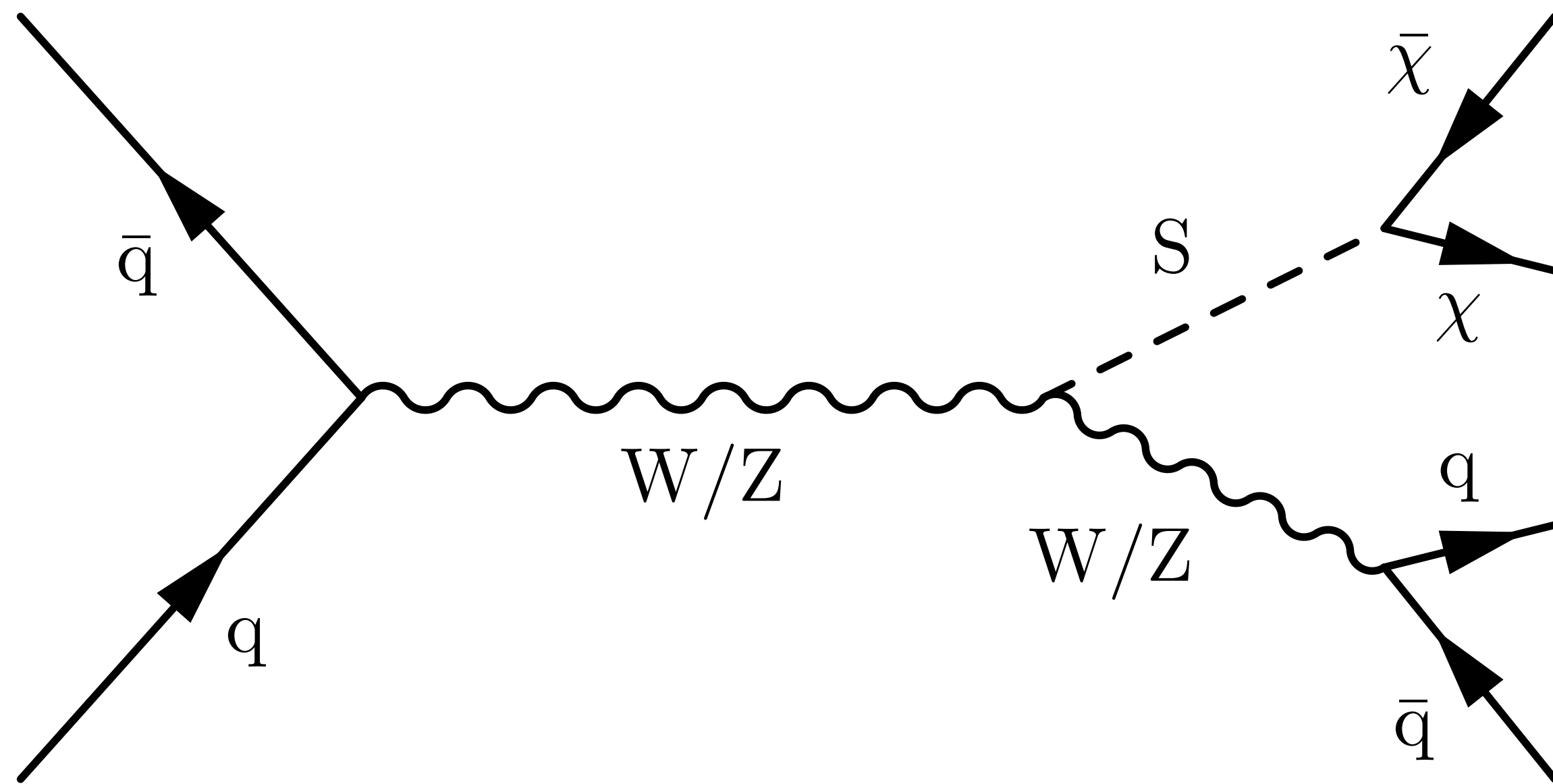
[JHEP11\(2021\)153](#)

- Less cross section:
 $\sigma(\text{monojet}) \sim 30 \times \sigma(\text{monoW})$
- 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**.

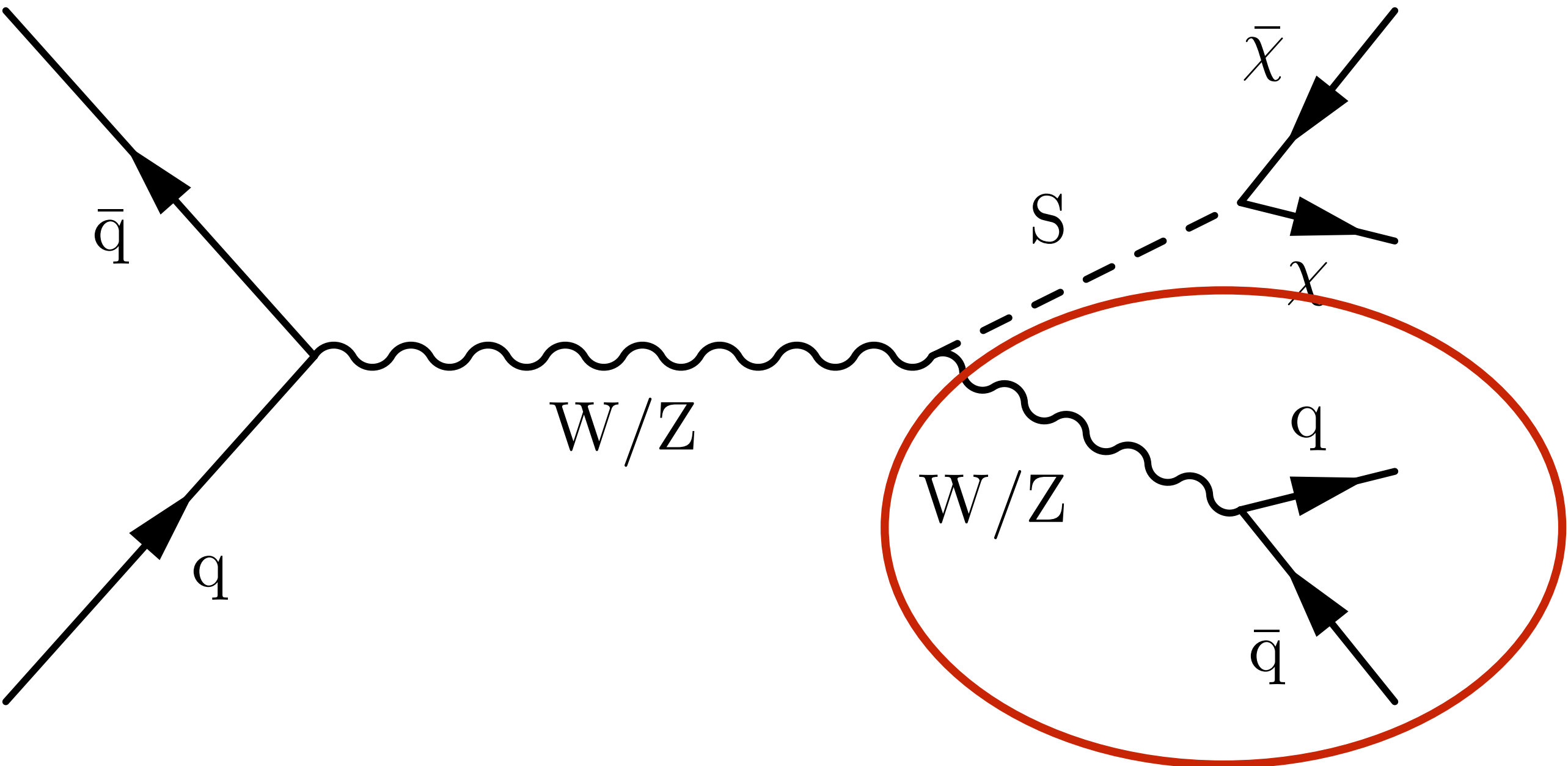


$$\sigma(\text{ggf}) \sim 30 \times \sigma(\text{VH})$$

... but similar sensitivity in both searches!

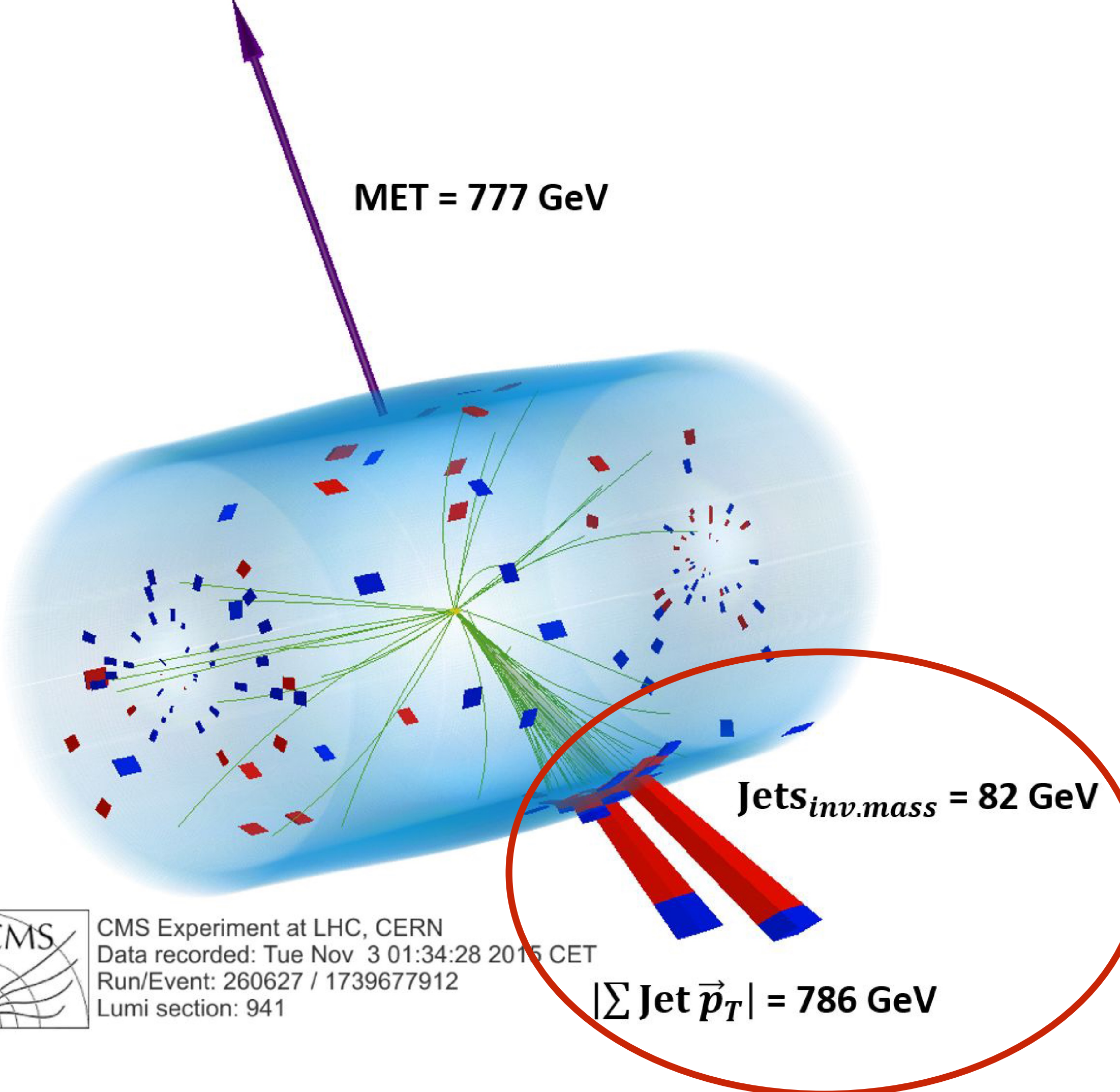
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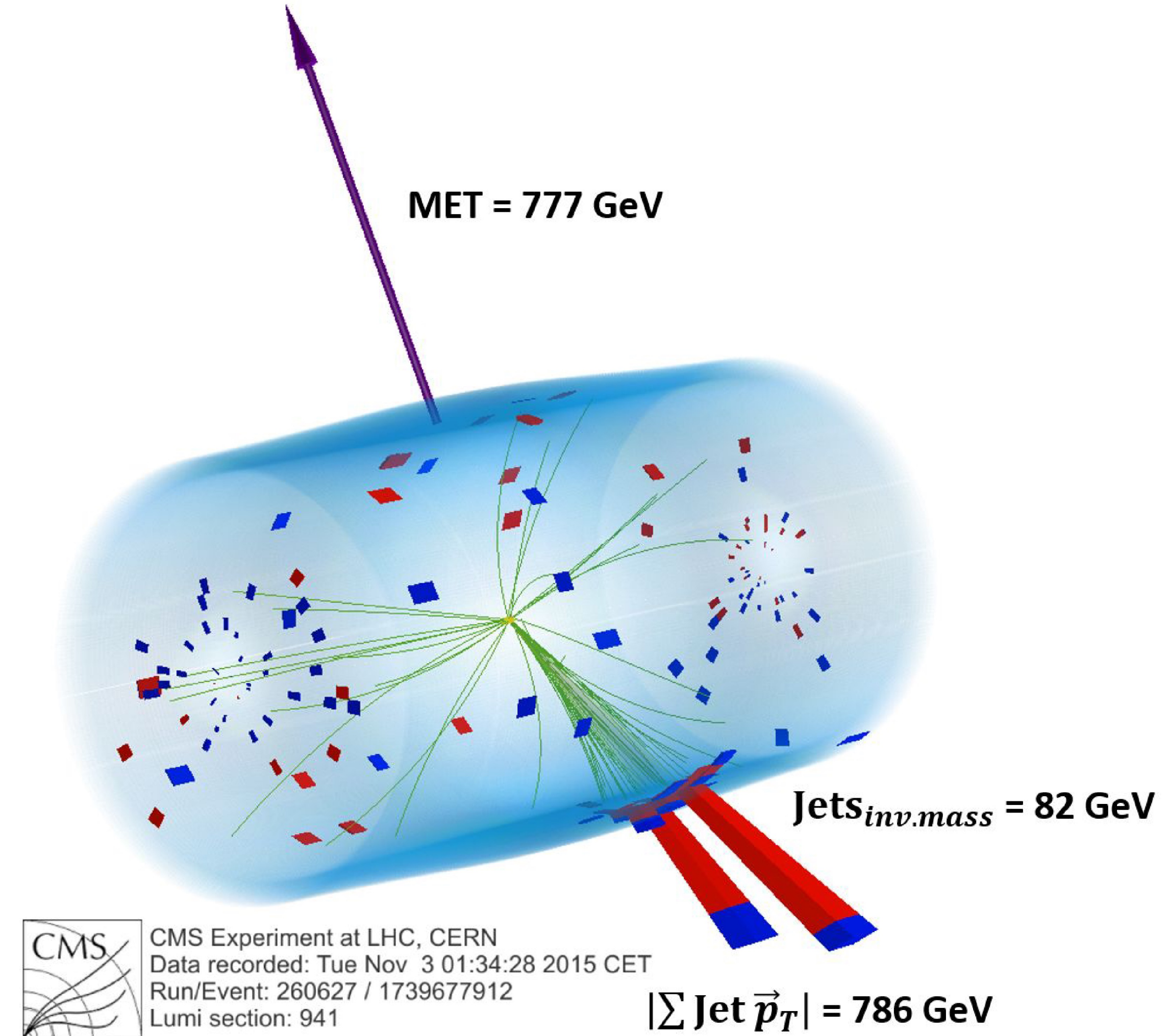
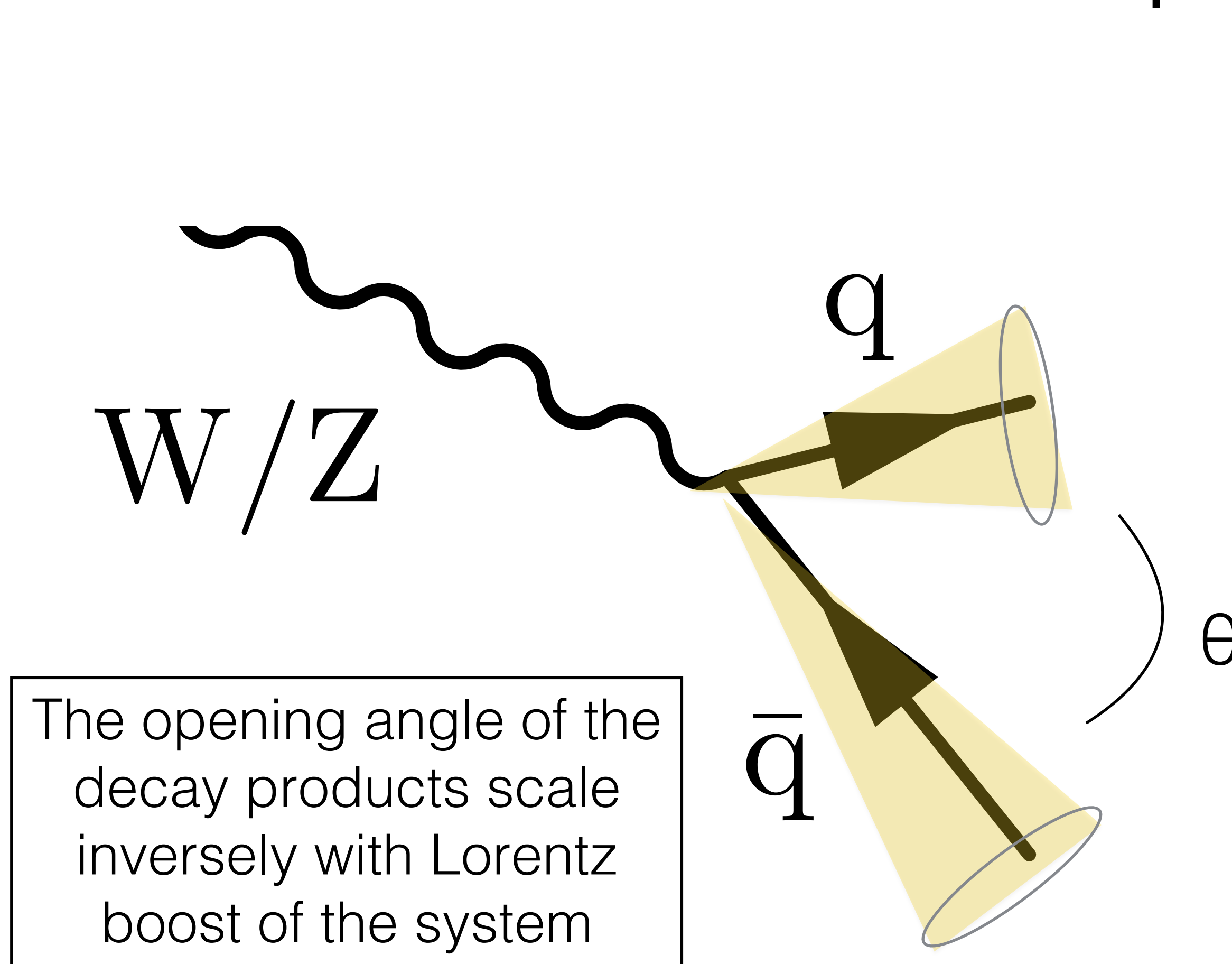
... but better sensitivity with Mono-V!



CMS
 CMS Experiment at LHC, CERN
 Data recorded: Tue Nov 3 01:34:28 2015 CET
 Run/Event: 260627 / 1739677912
 Lumi section: 941

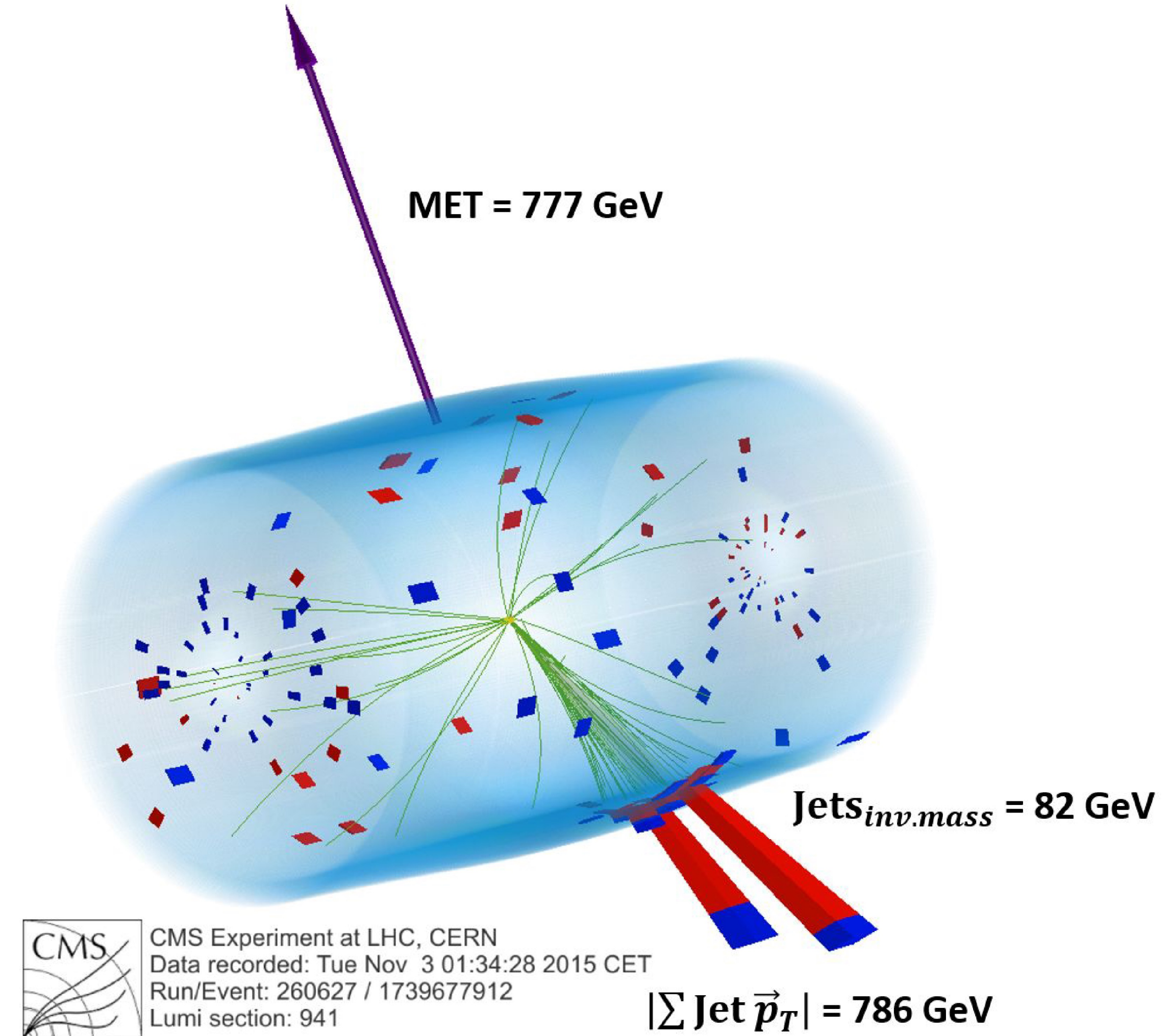
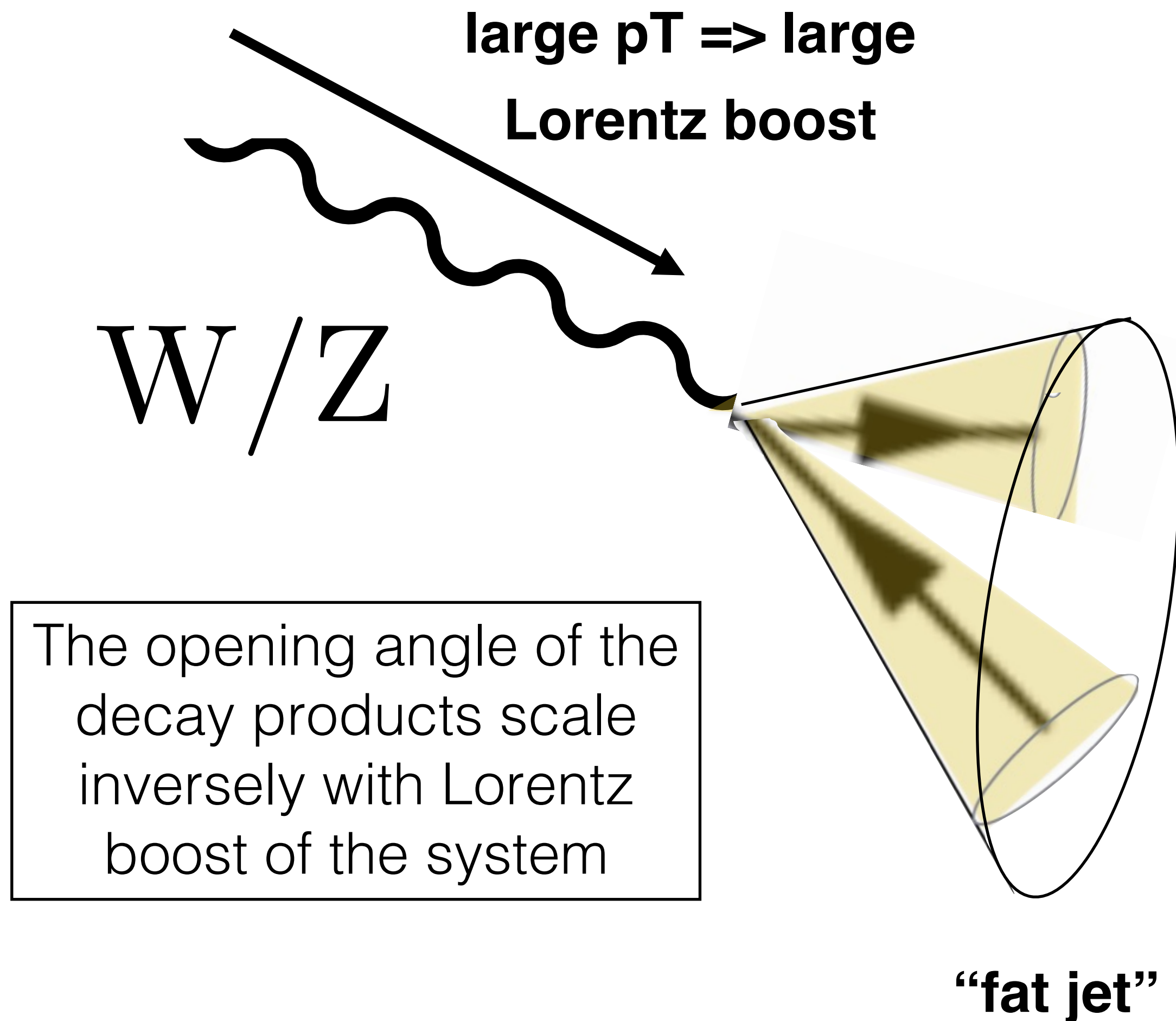
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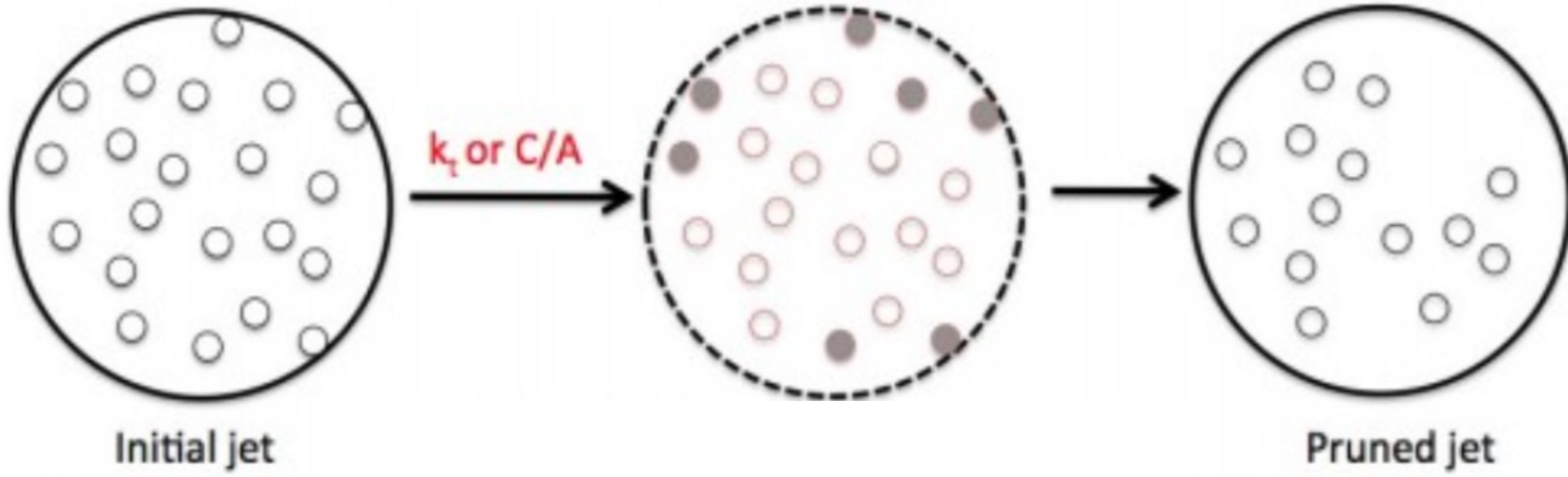
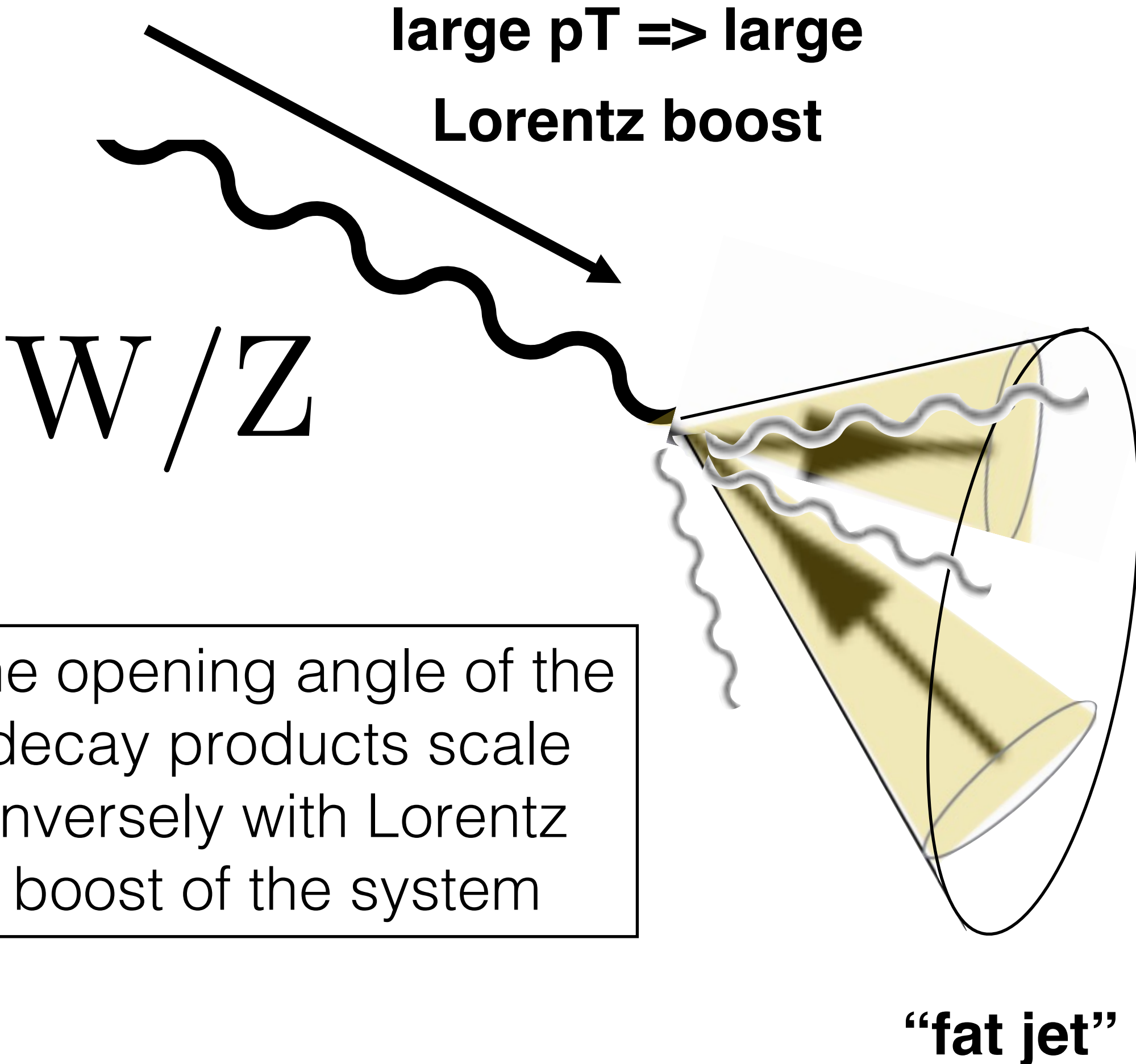
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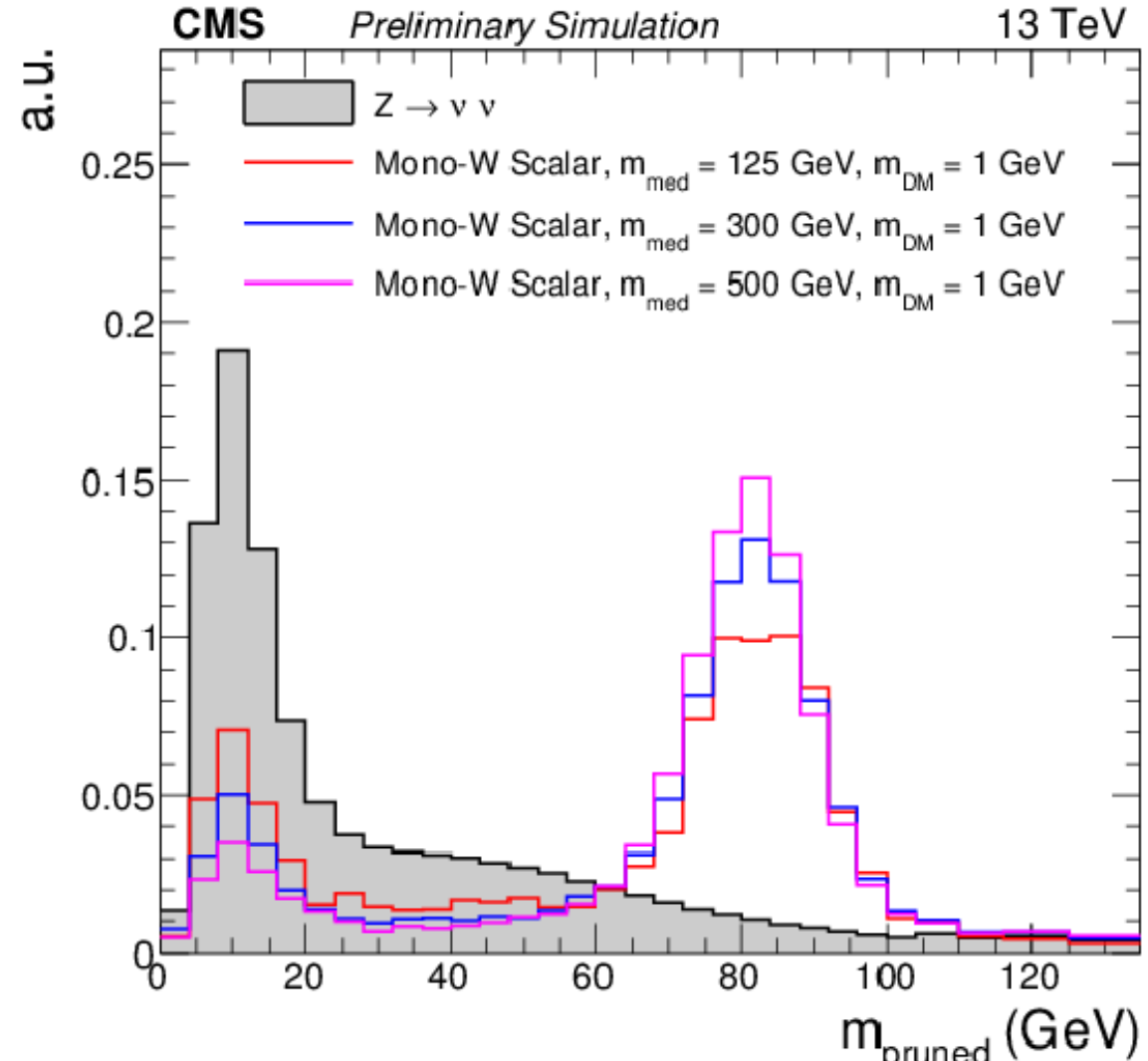


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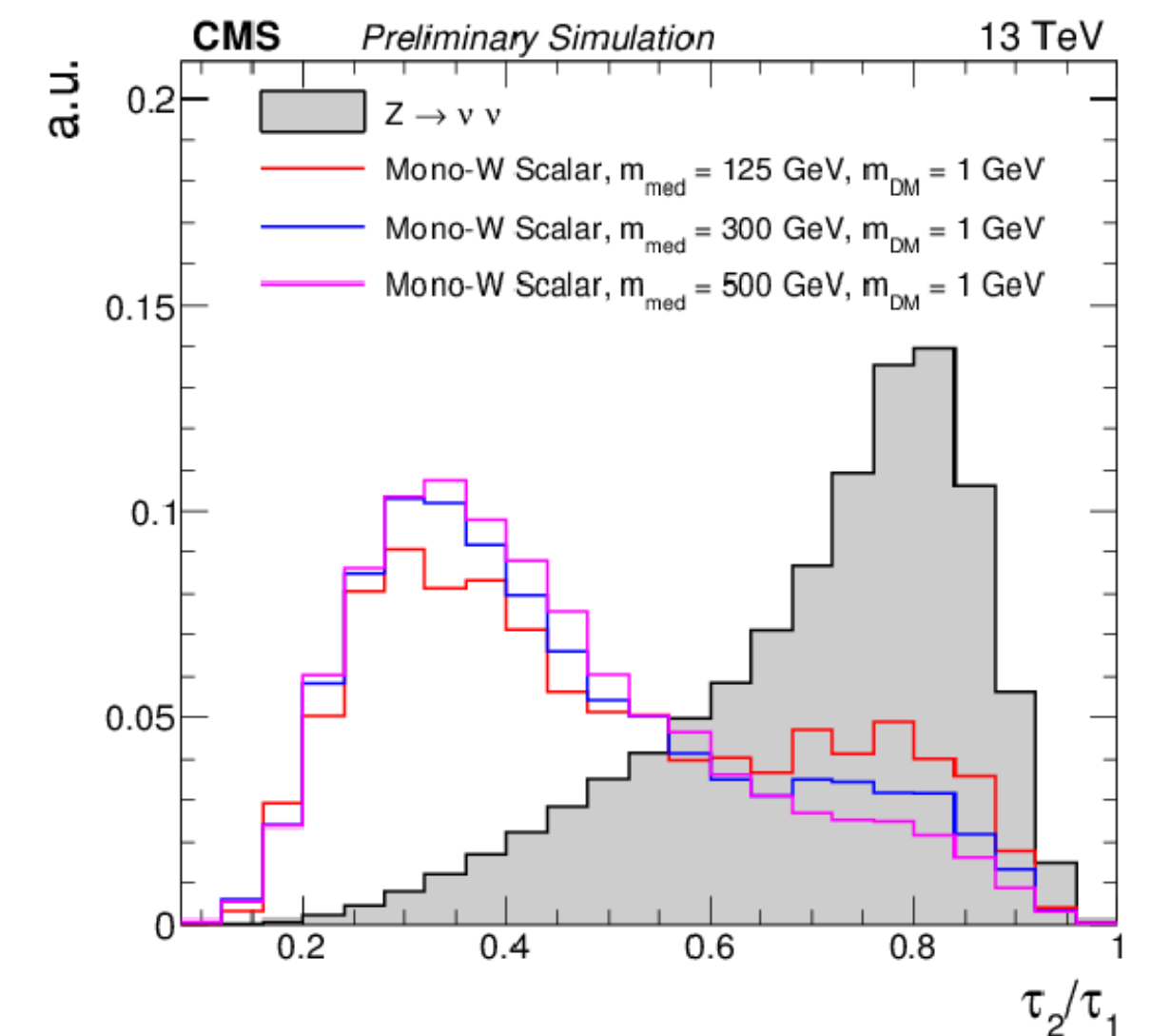
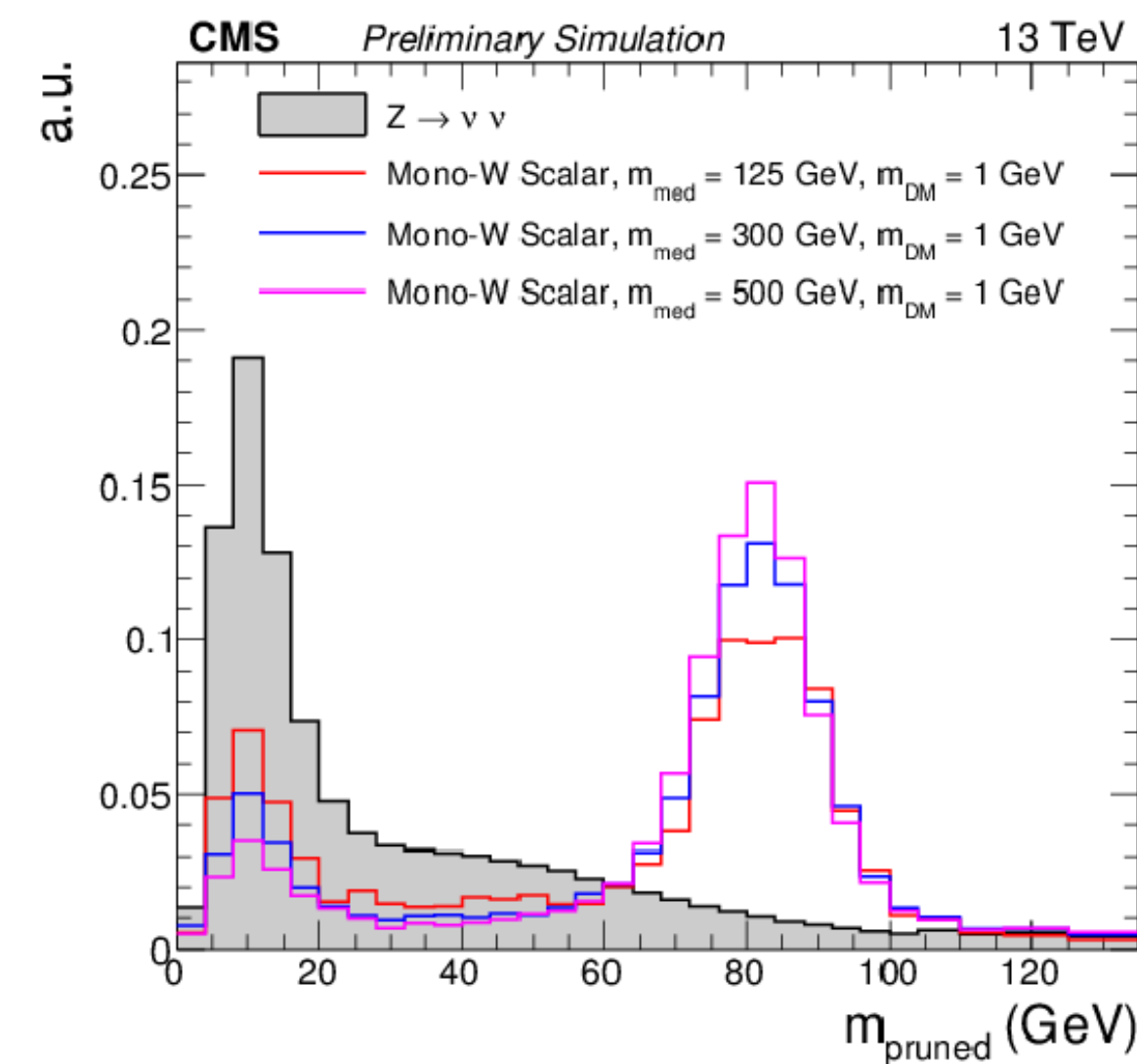
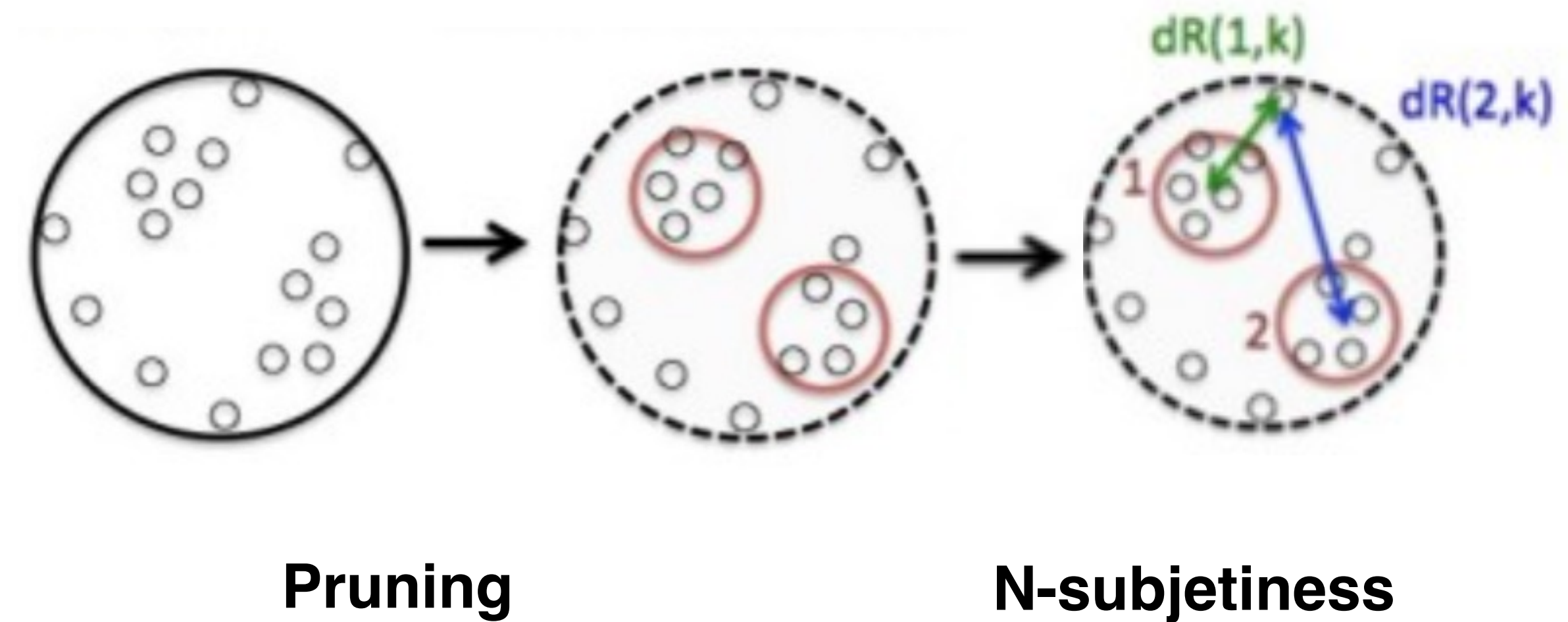
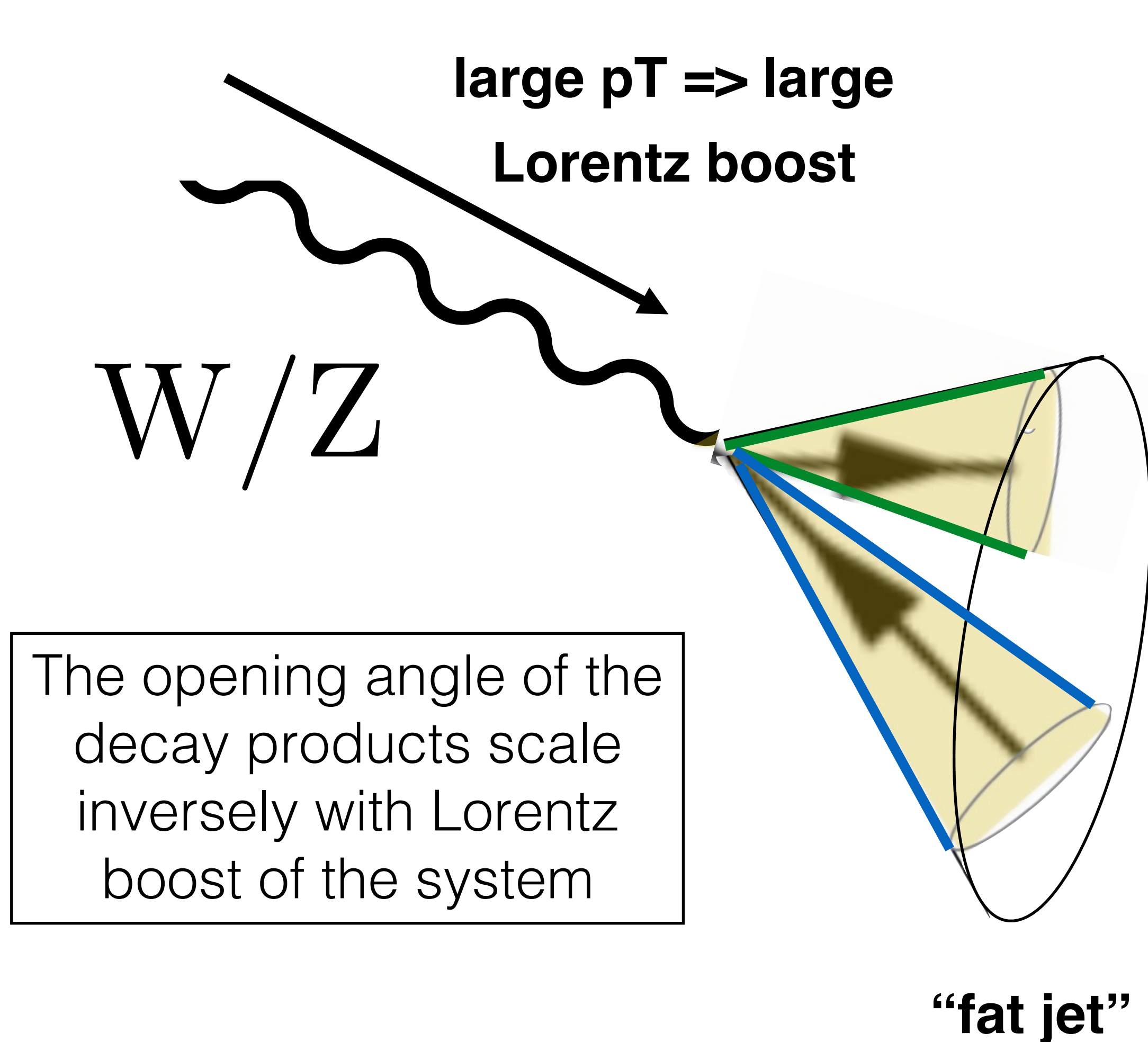


Pruning



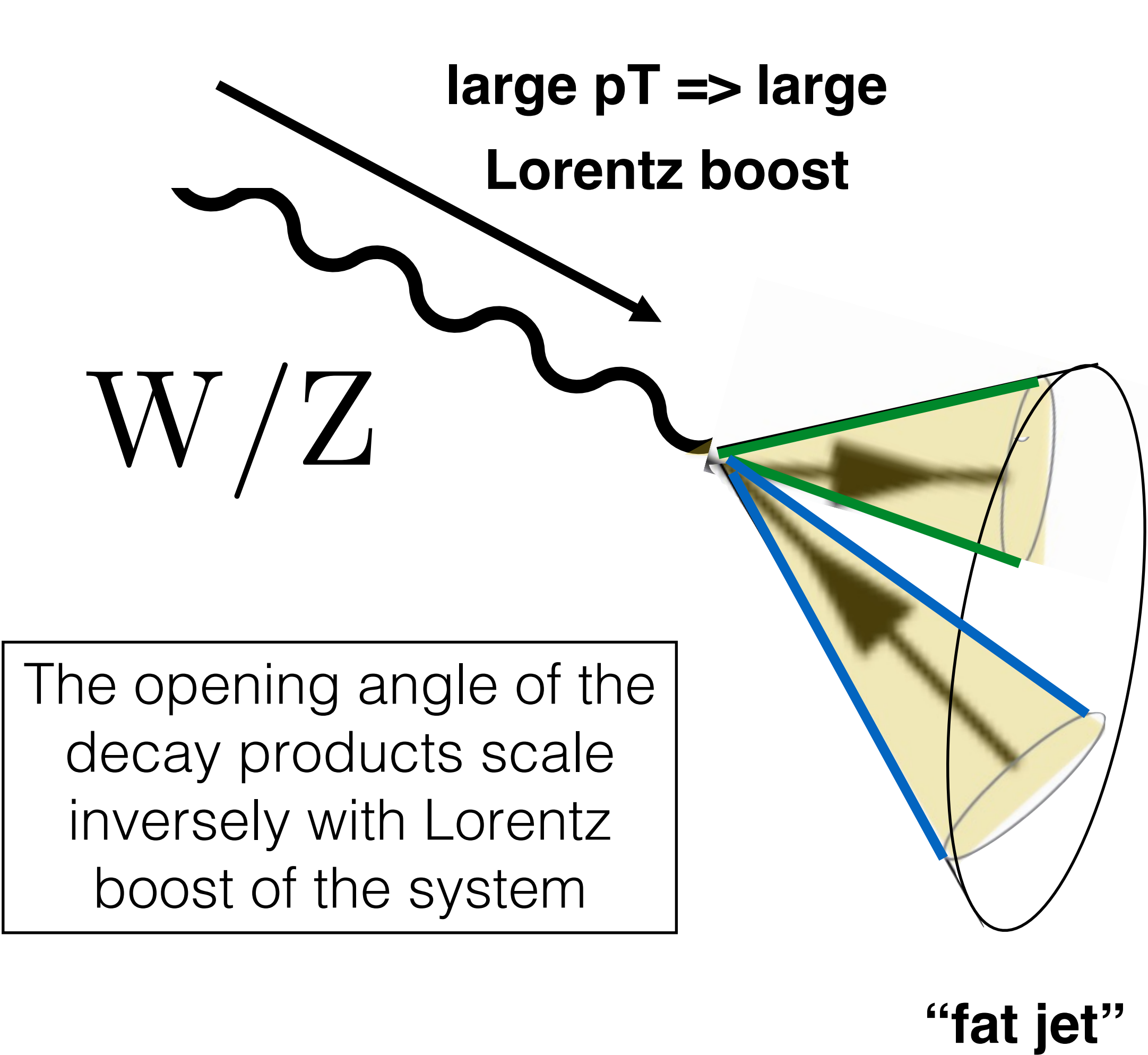
Mono-V Experimental Techniques

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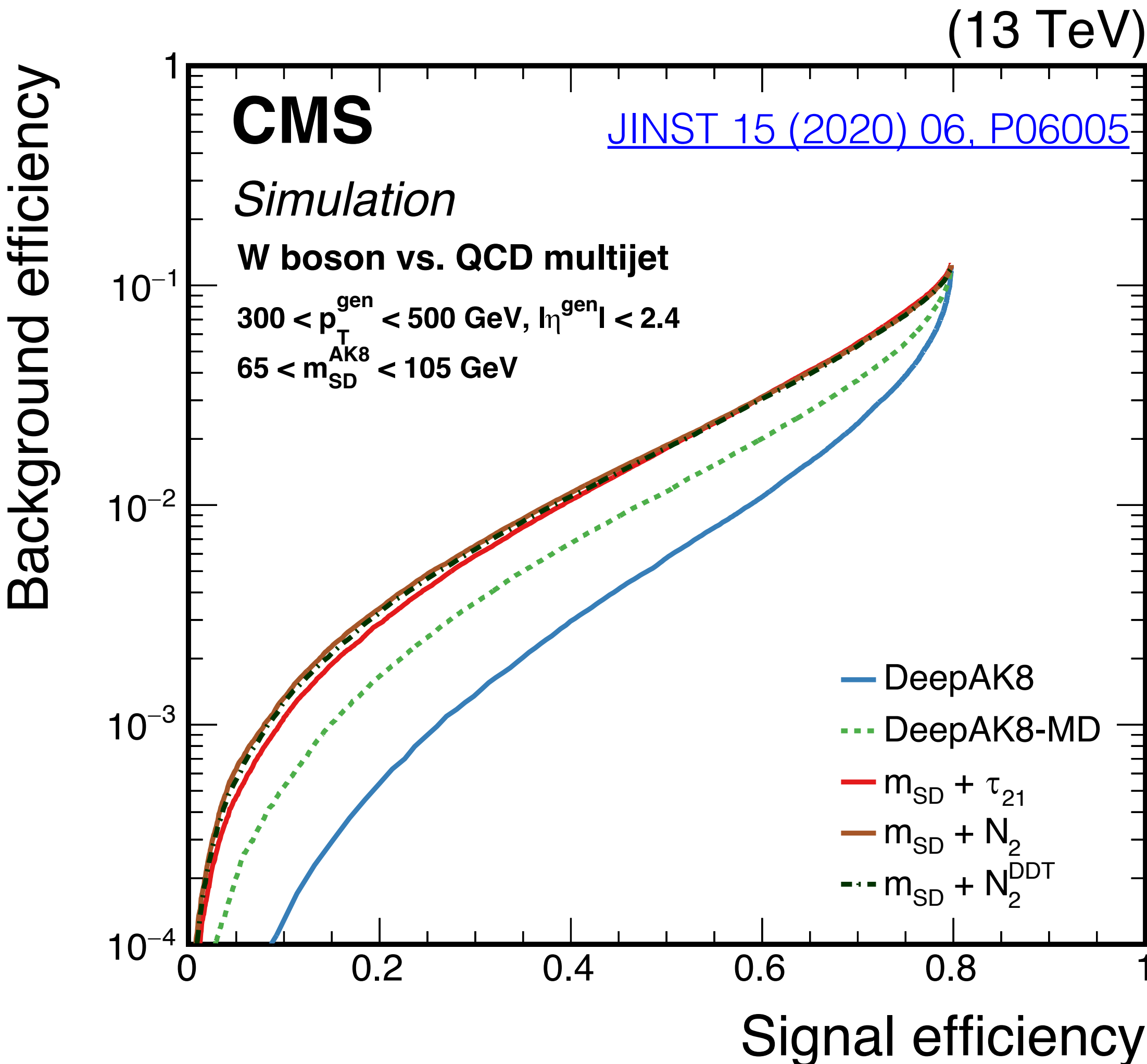


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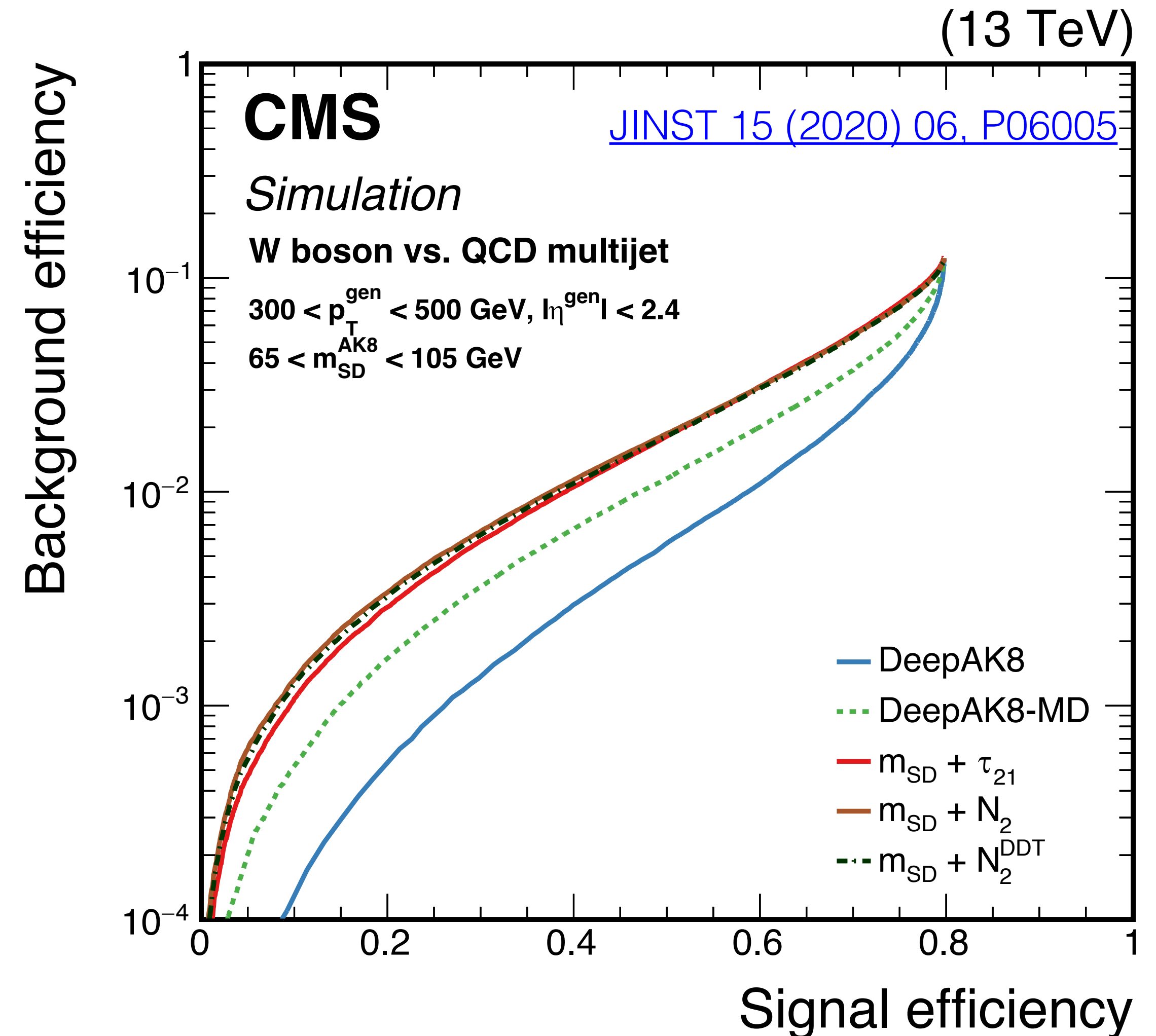
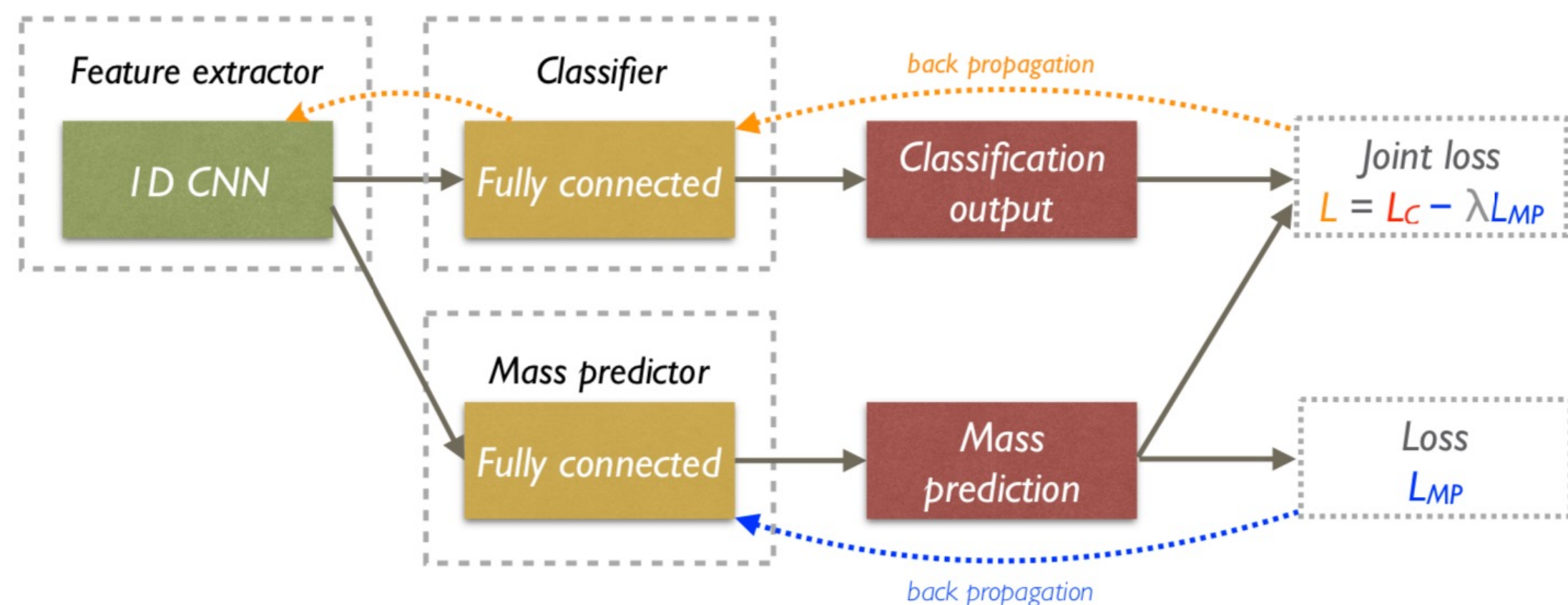
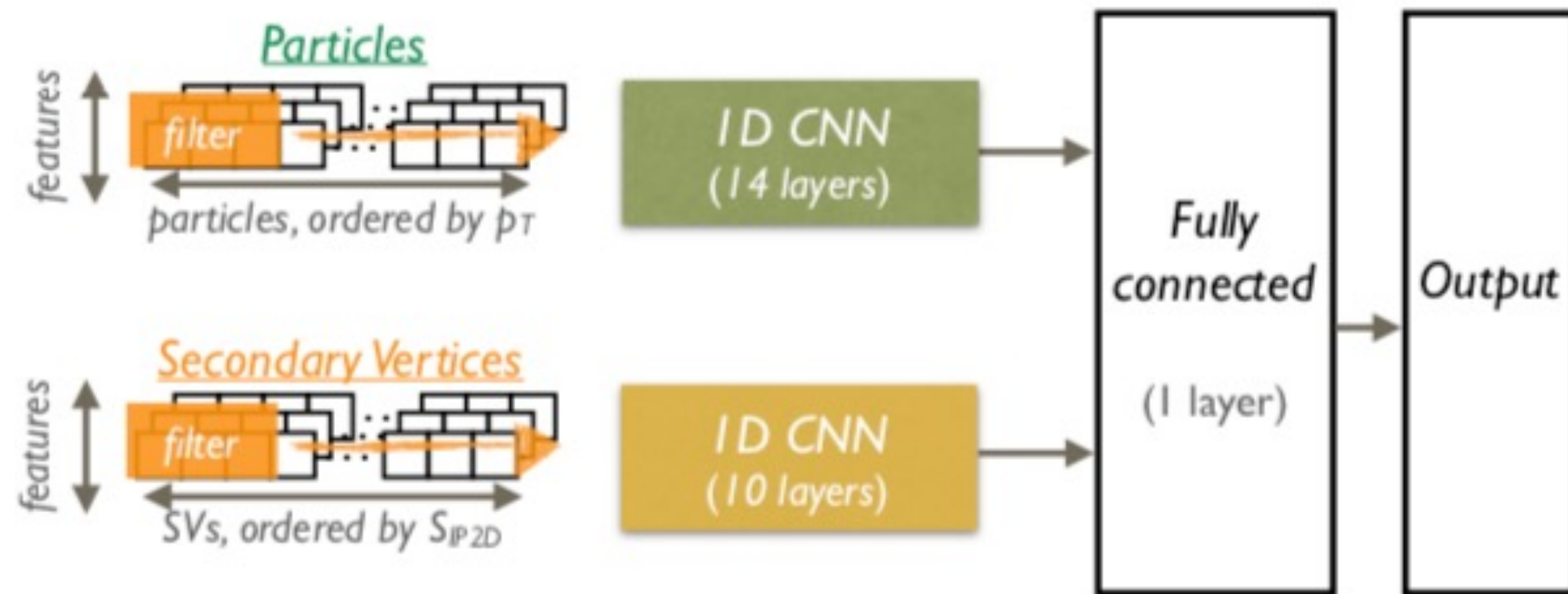
The opening angle of the decay products scale inversely with Lorentz boost of the system



Mono-V Experimental Techniques

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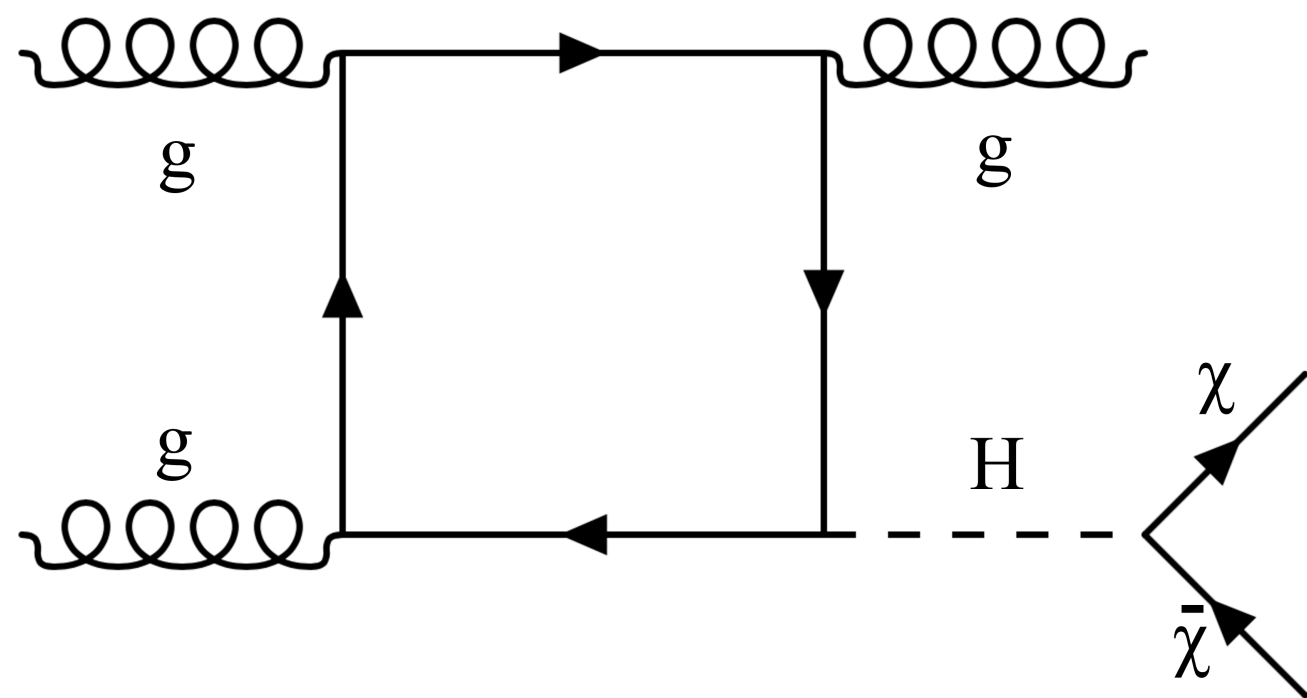
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Higgs Production Modes

Higgs Production modes will determine the signature.

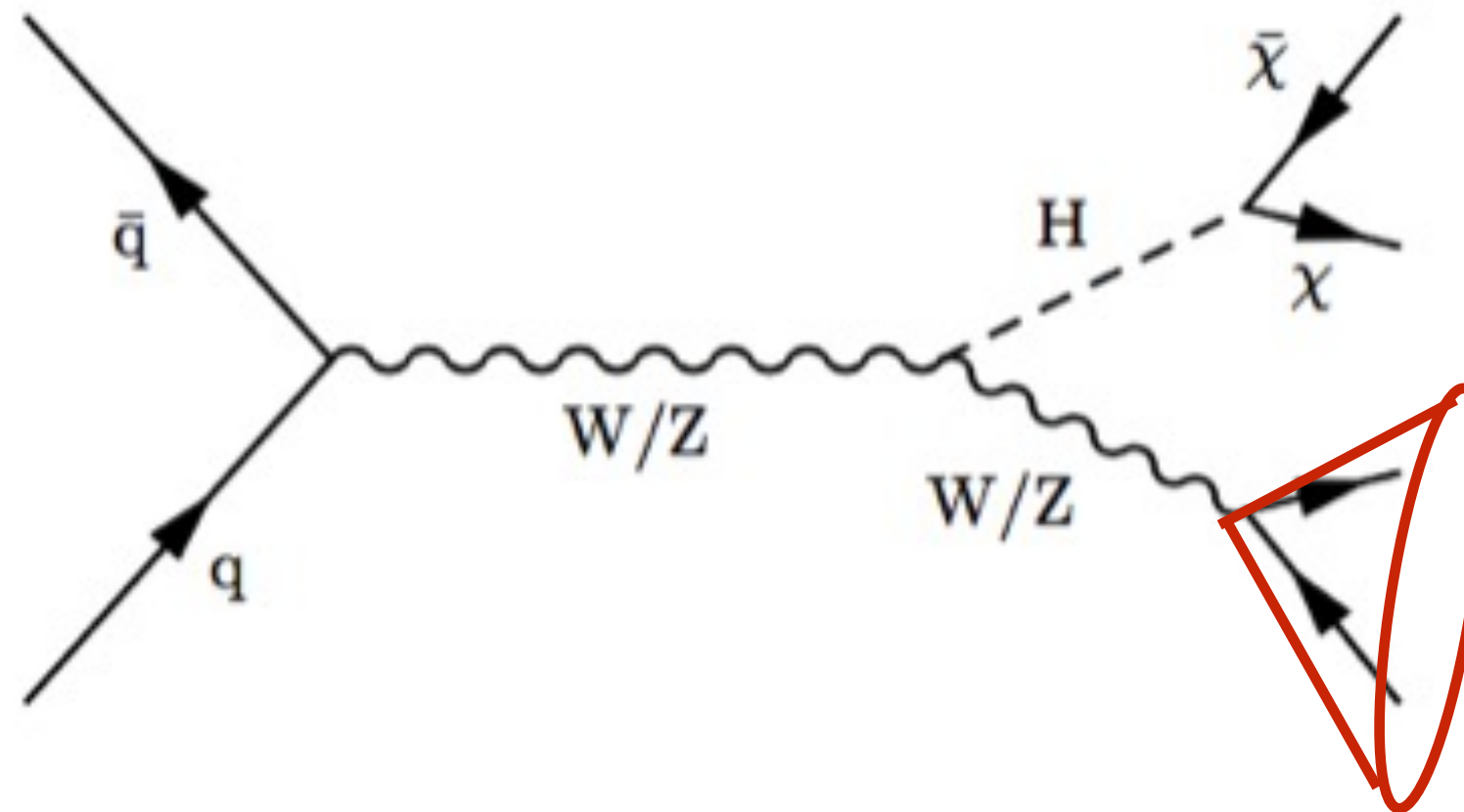
... and vector boson fusion!



Gluon fusion

[JHEP11\(2021\)153](#)

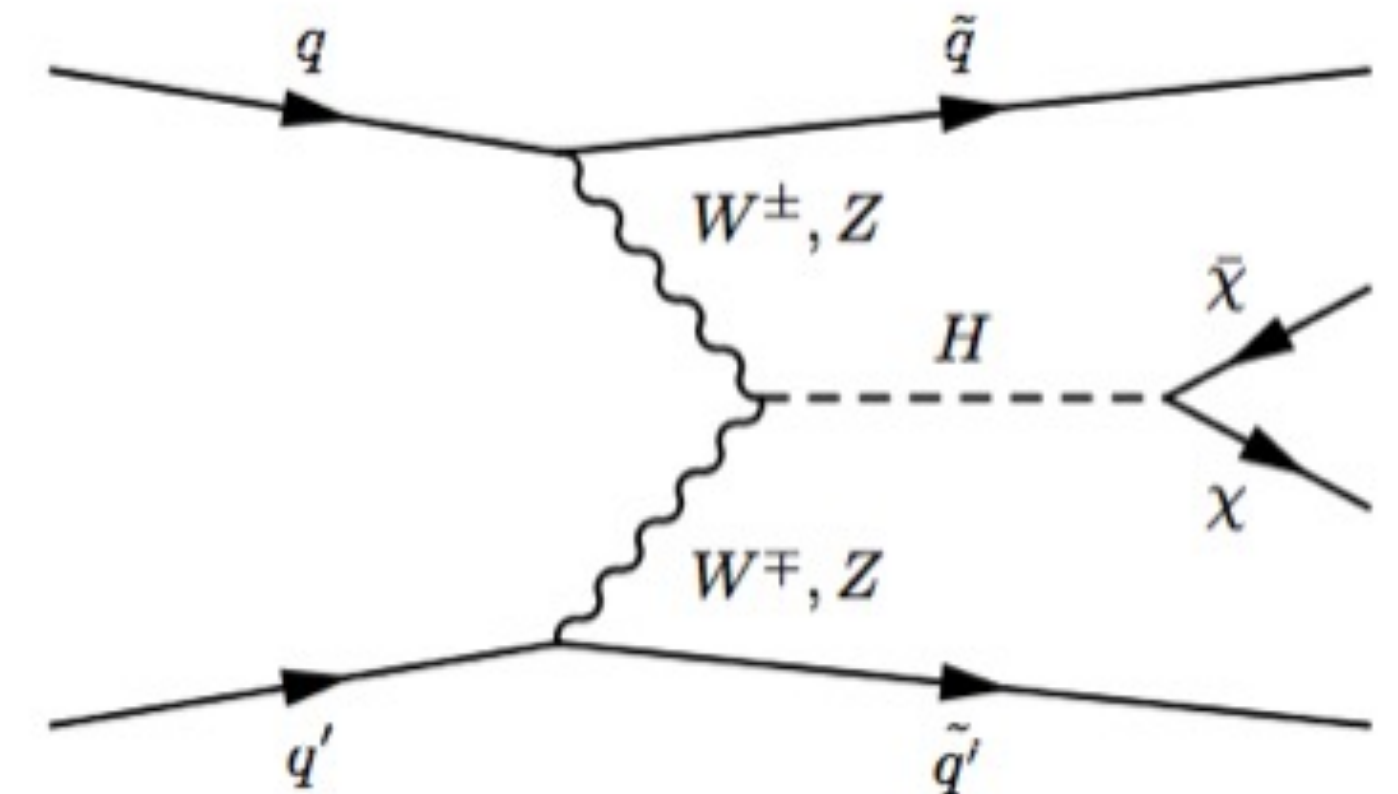
- Largest production production cross section
- Needs to be tagged with a visible object



Associated vector boson

[JHEP11\(2021\)153](#)

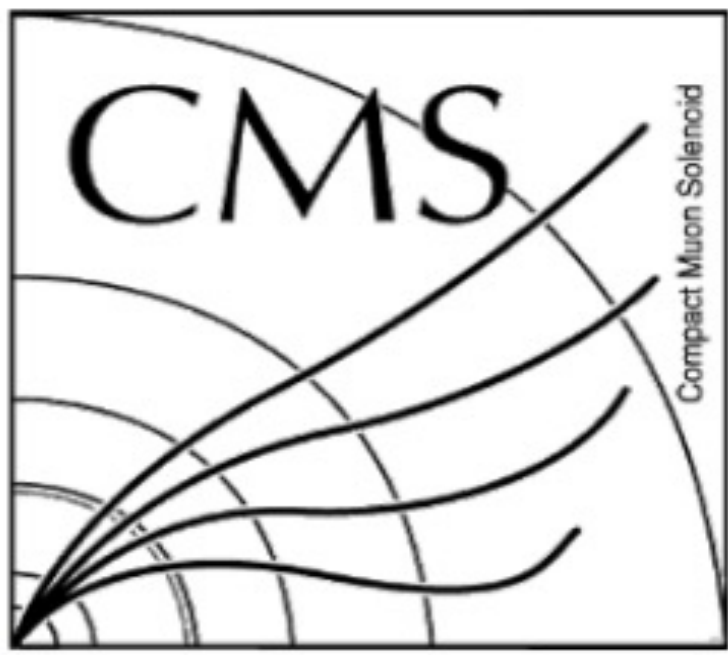
- Less cross section: $\sigma(\text{monojet}) \sim 30 \times \sigma(\text{mono}W)$
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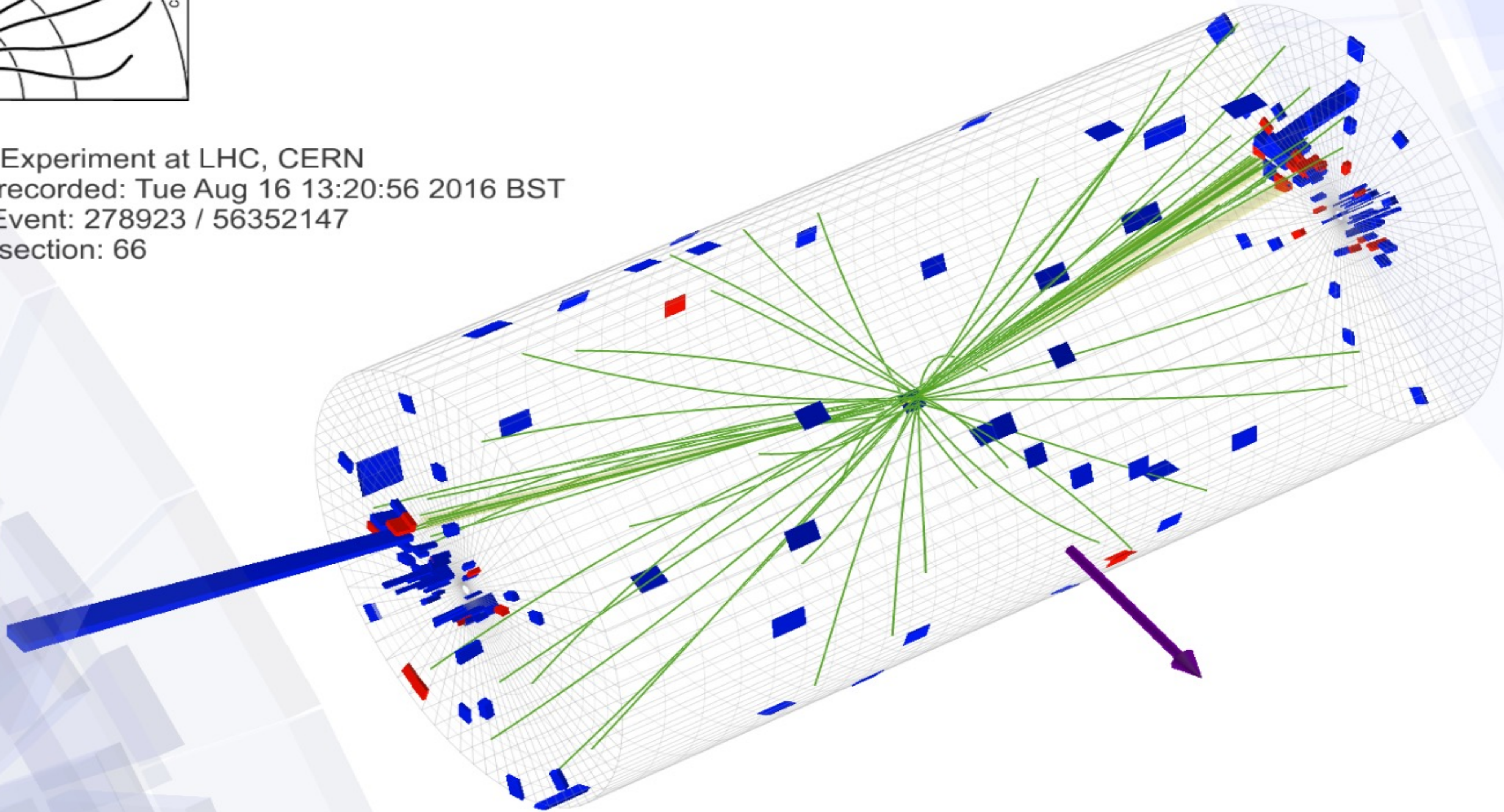
Vector boson fusion

[Submitted to Phys. Rev. D](#)

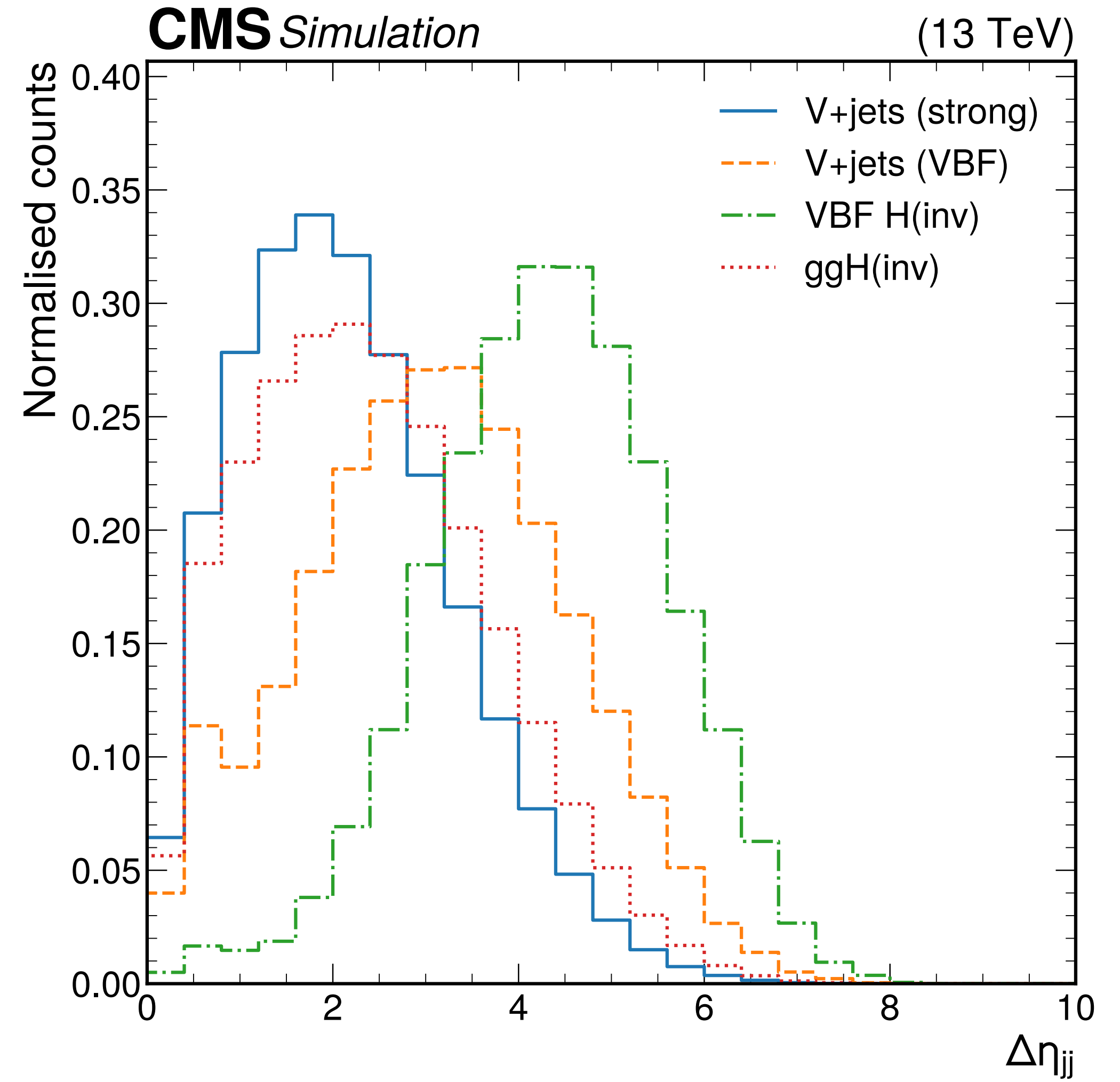
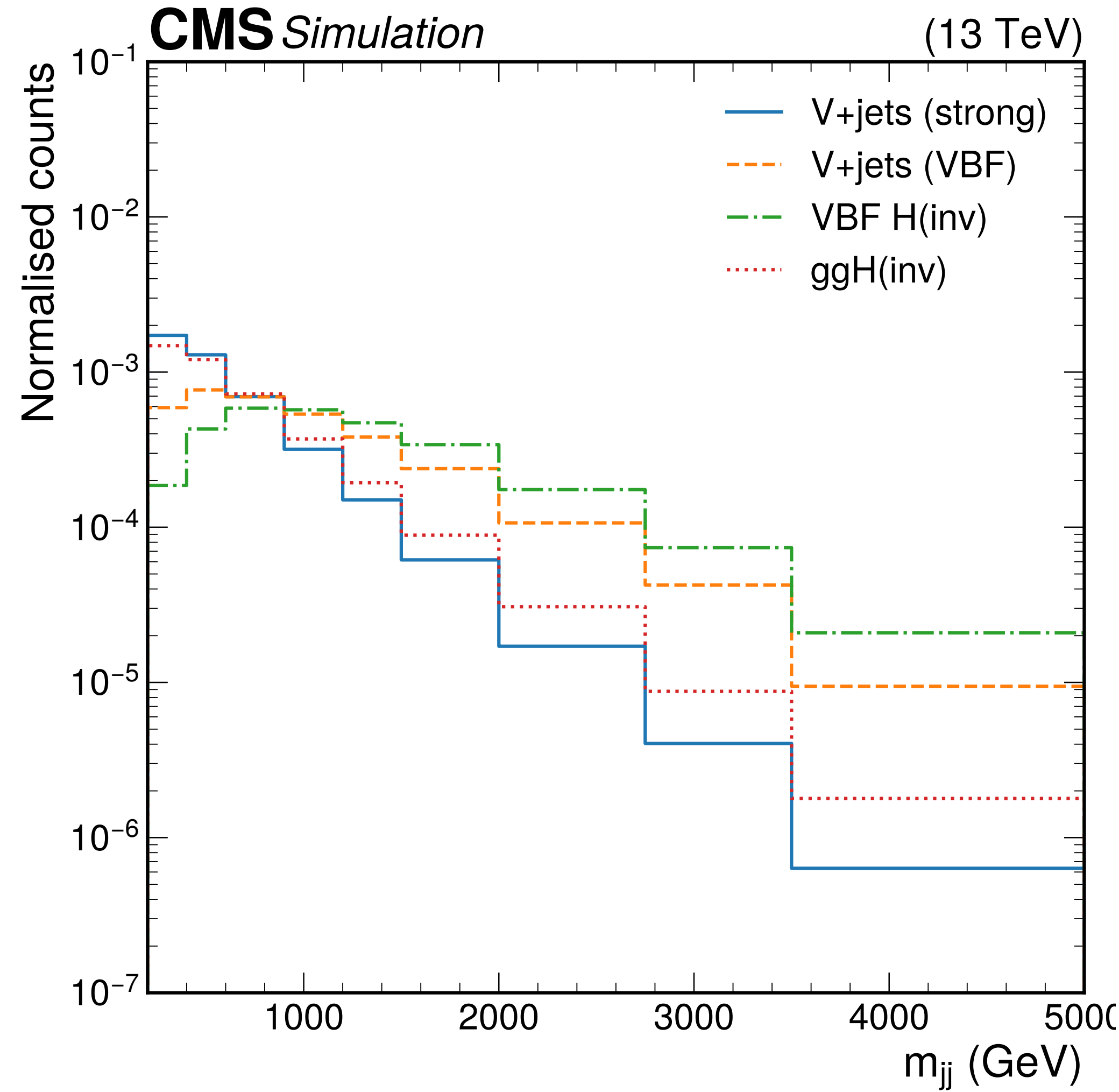
- Largest sensitivity among all approaches!
- Experimentally most challenging with 2 forward jets



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



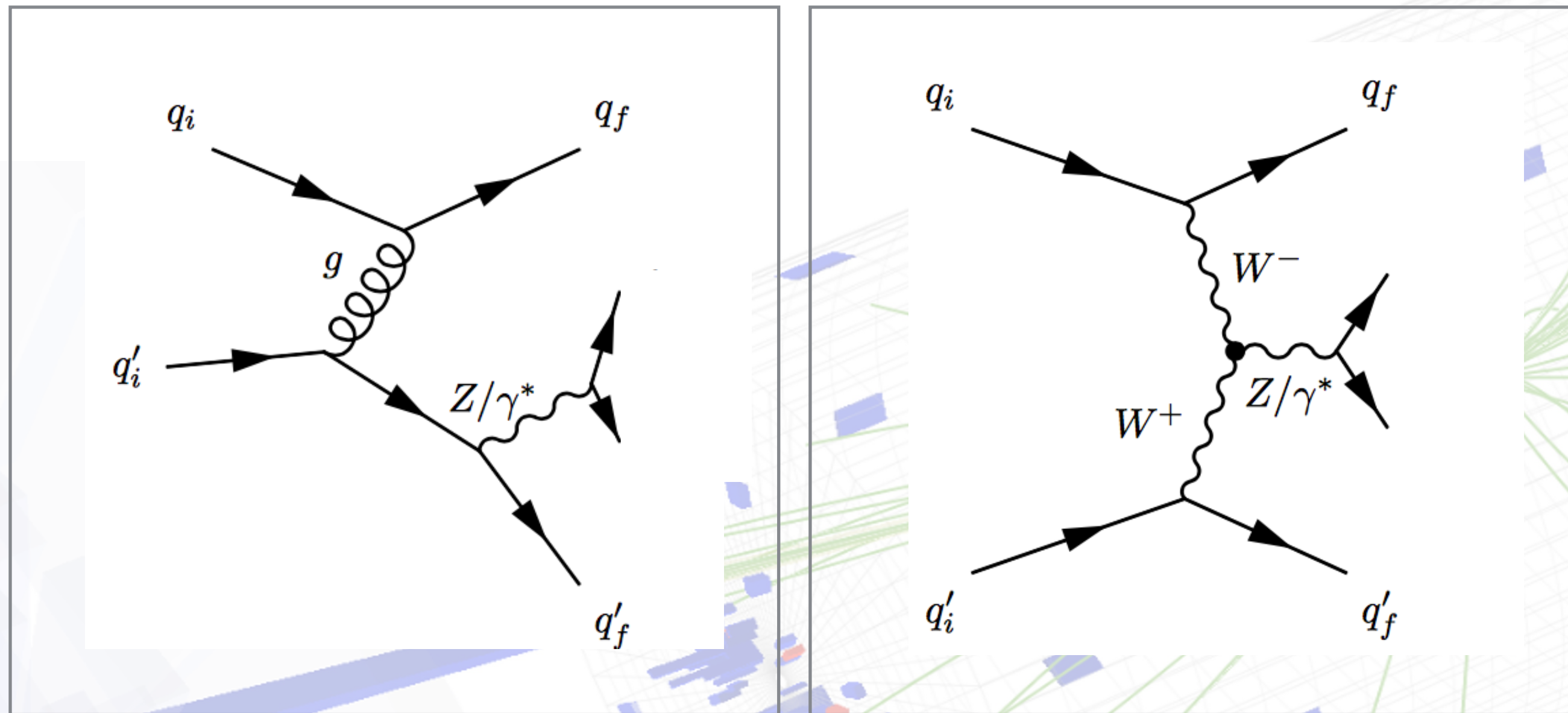
VBF: Unique Observables



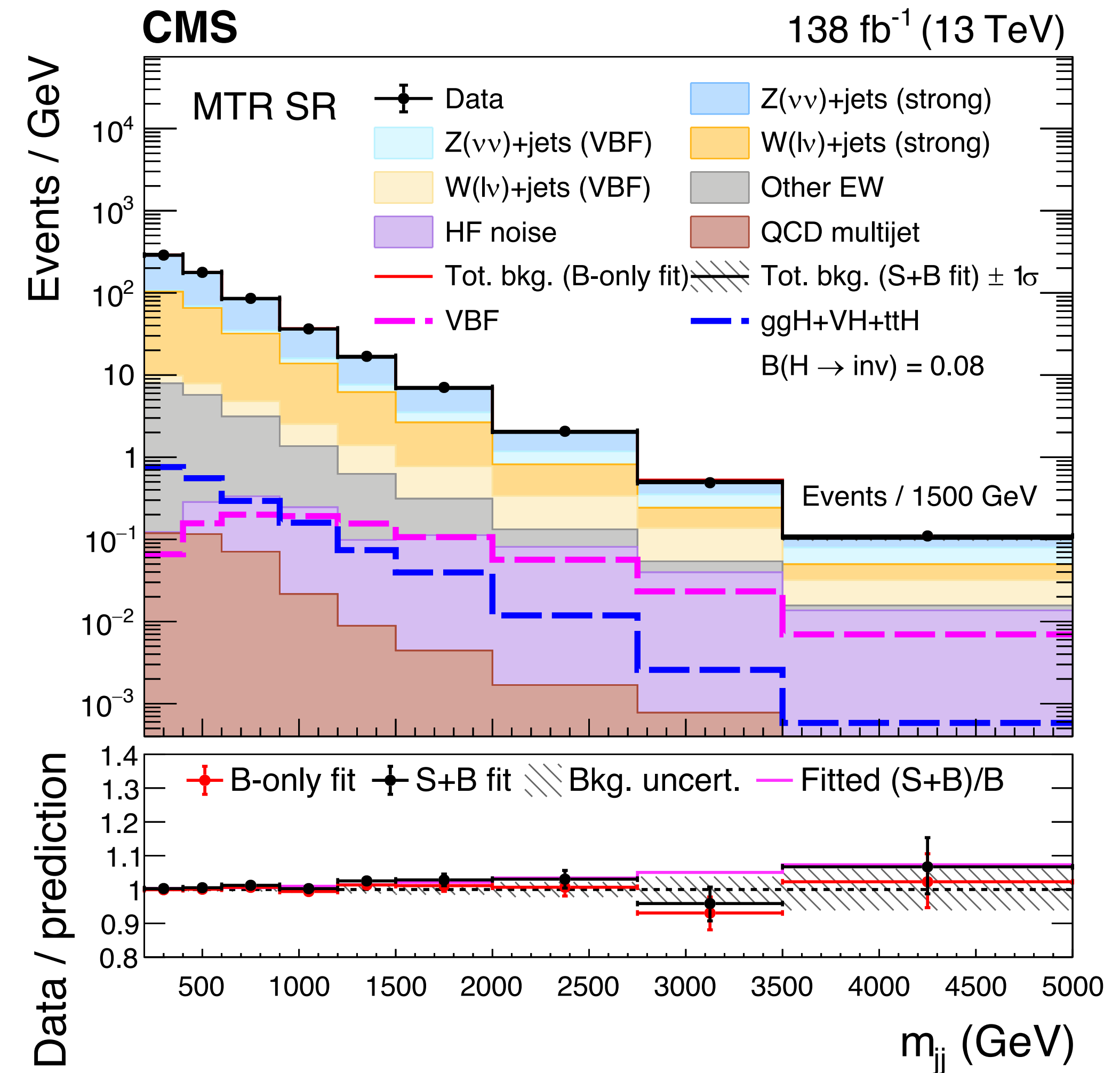
VBF dijet variables: m_{jj} , $\Delta\eta_{jj}$ show separation power

VBF Higgs Invisible

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



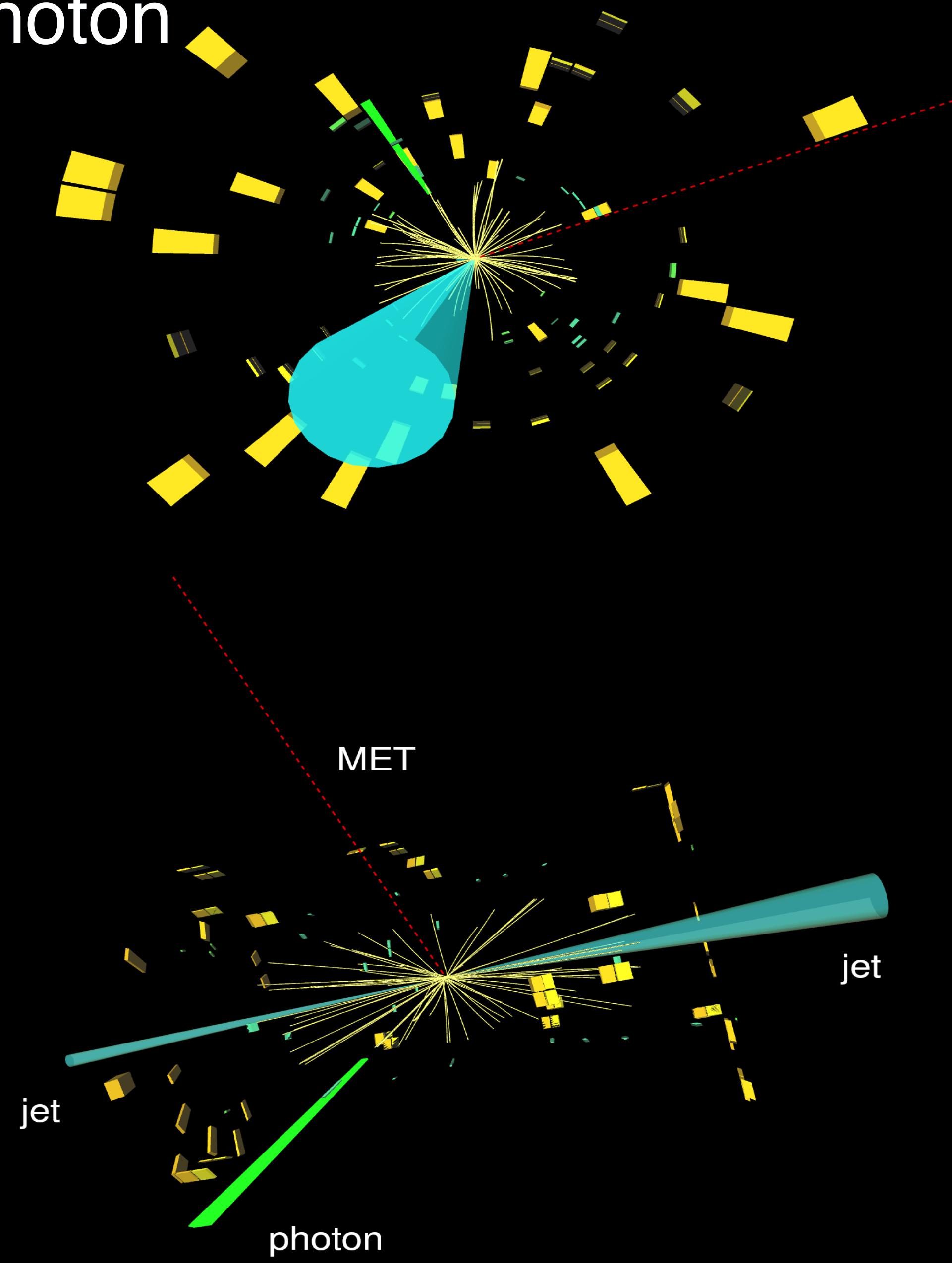
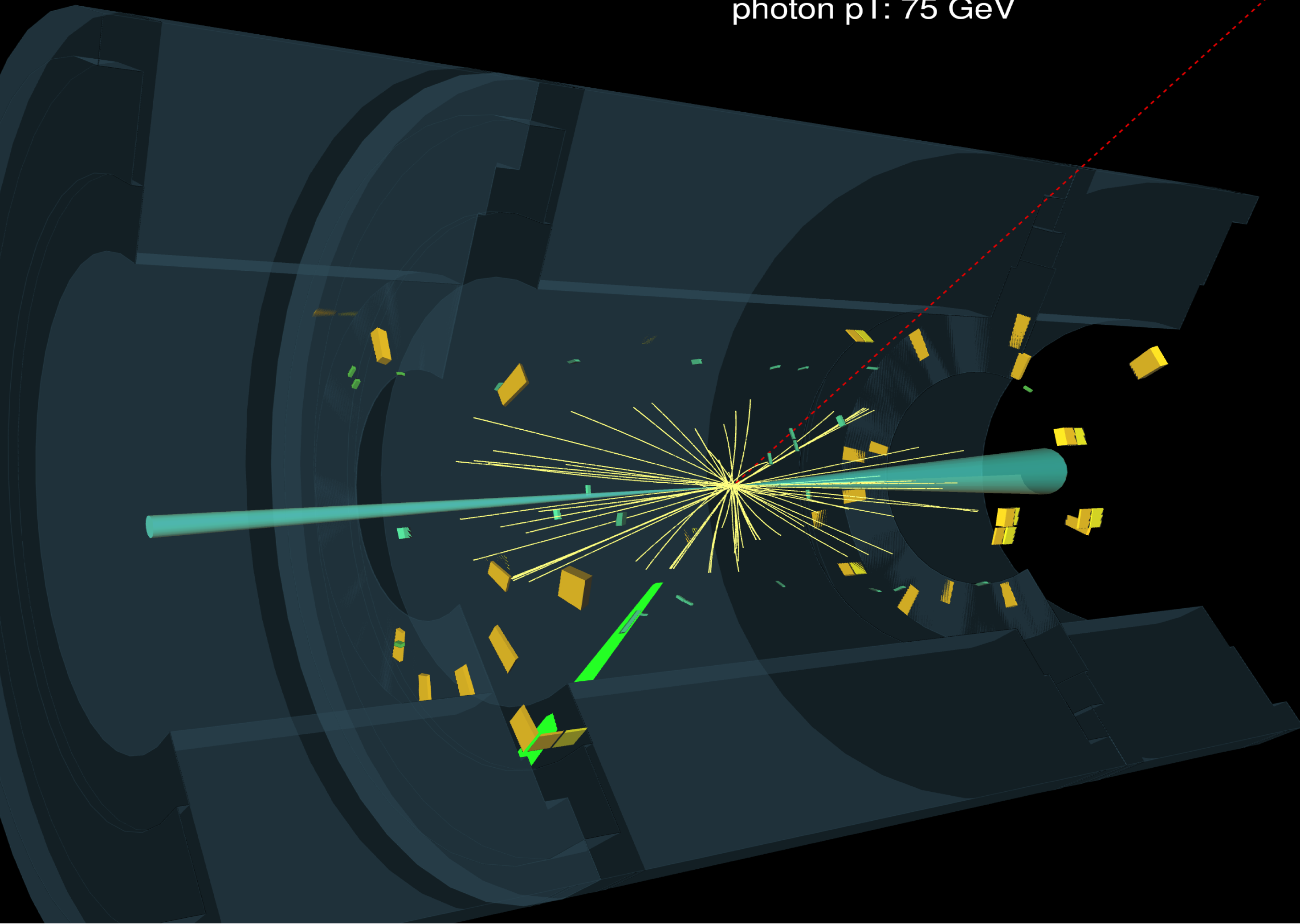
VBF production is an “irreducible” background for this search: same signature of two hard forward quarks



VBF Higgs Invisible + Photon

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

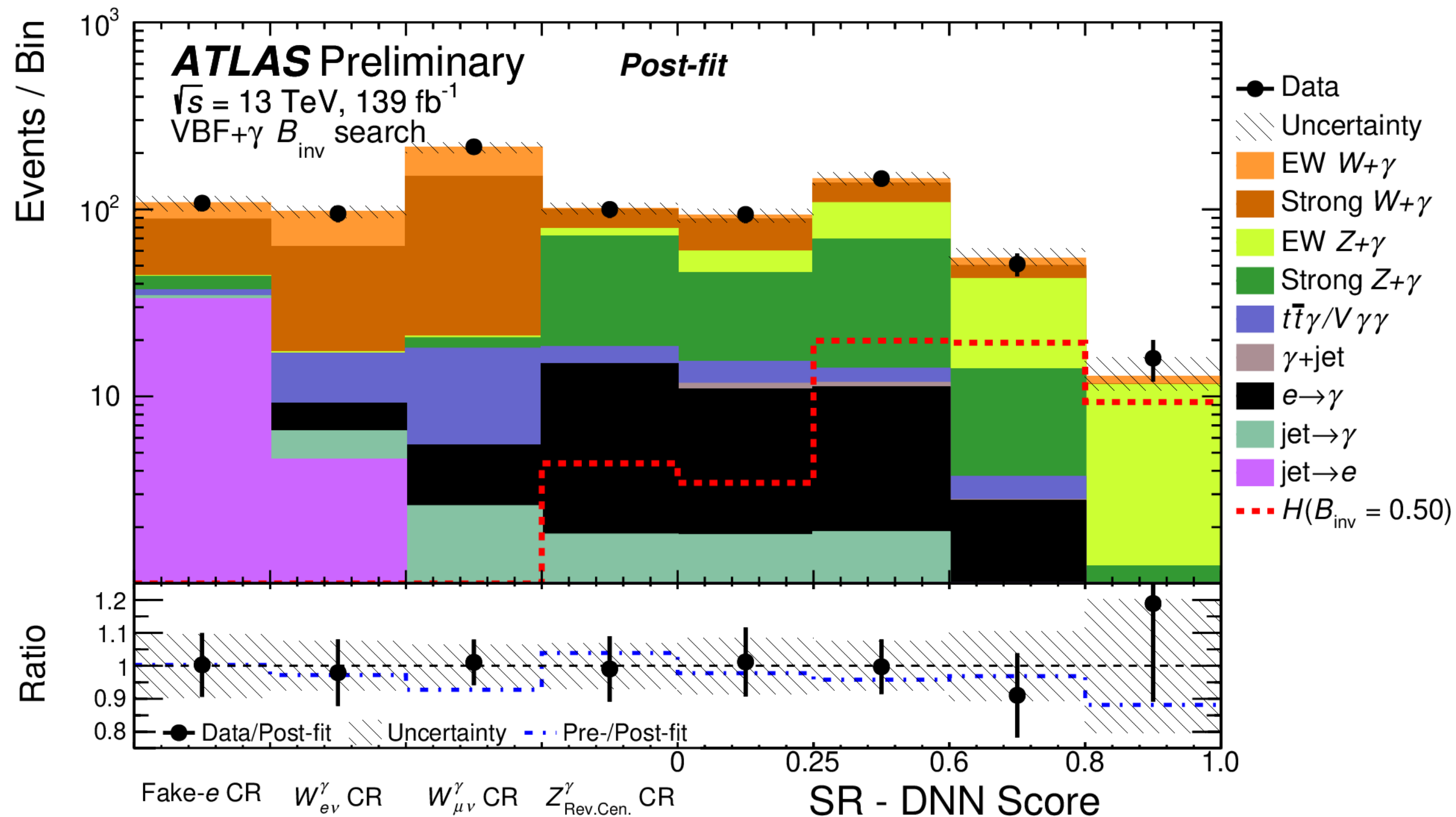
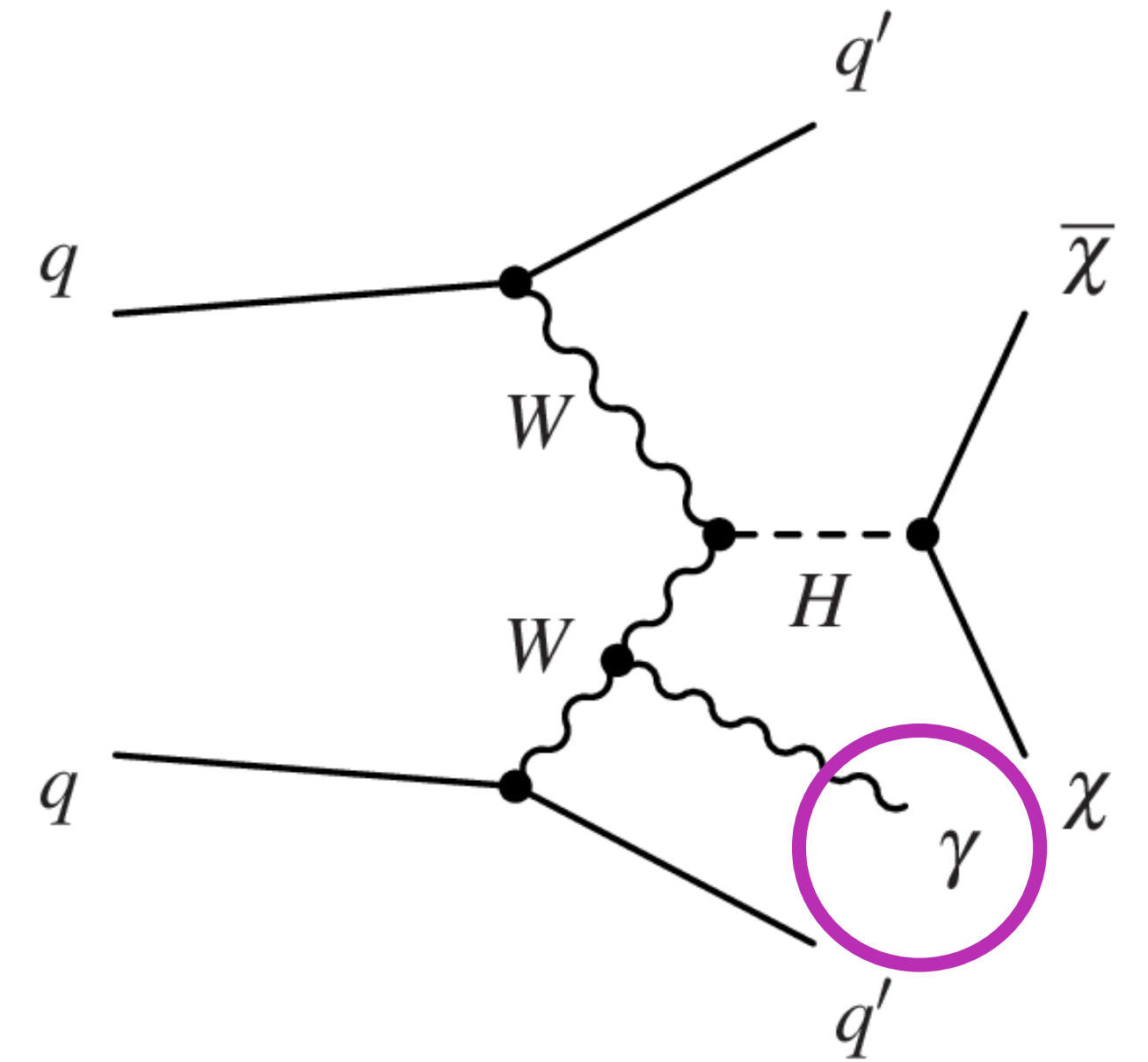
jj mass: 2700 GeV
MET: 198 GeV
mT: 193 GeV
photon pT: 75 GeV



VBF Higgs Invisible + Photon

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

Signal discrimination via **deep neural network training** method optimizes for $H \rightarrow \text{inv}$



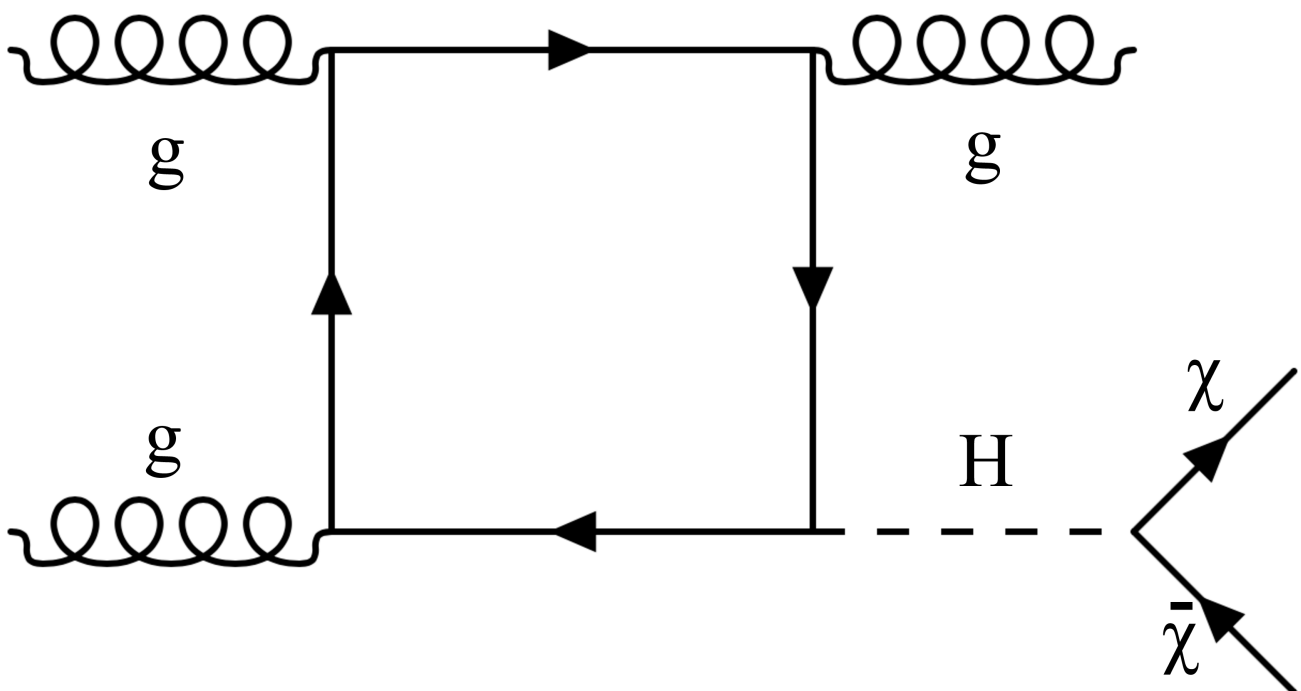
[ATLAS-CONF-2021-004](#)

$\text{BR}(H \rightarrow \text{inv}) < 37 \% (34\% \text{ exp})$

Higgs Production Modes

Higgs Production modes will determine the signature.

... and vector boson fusion!



Gluon fusion

[JHEP11\(2021\)153](#)

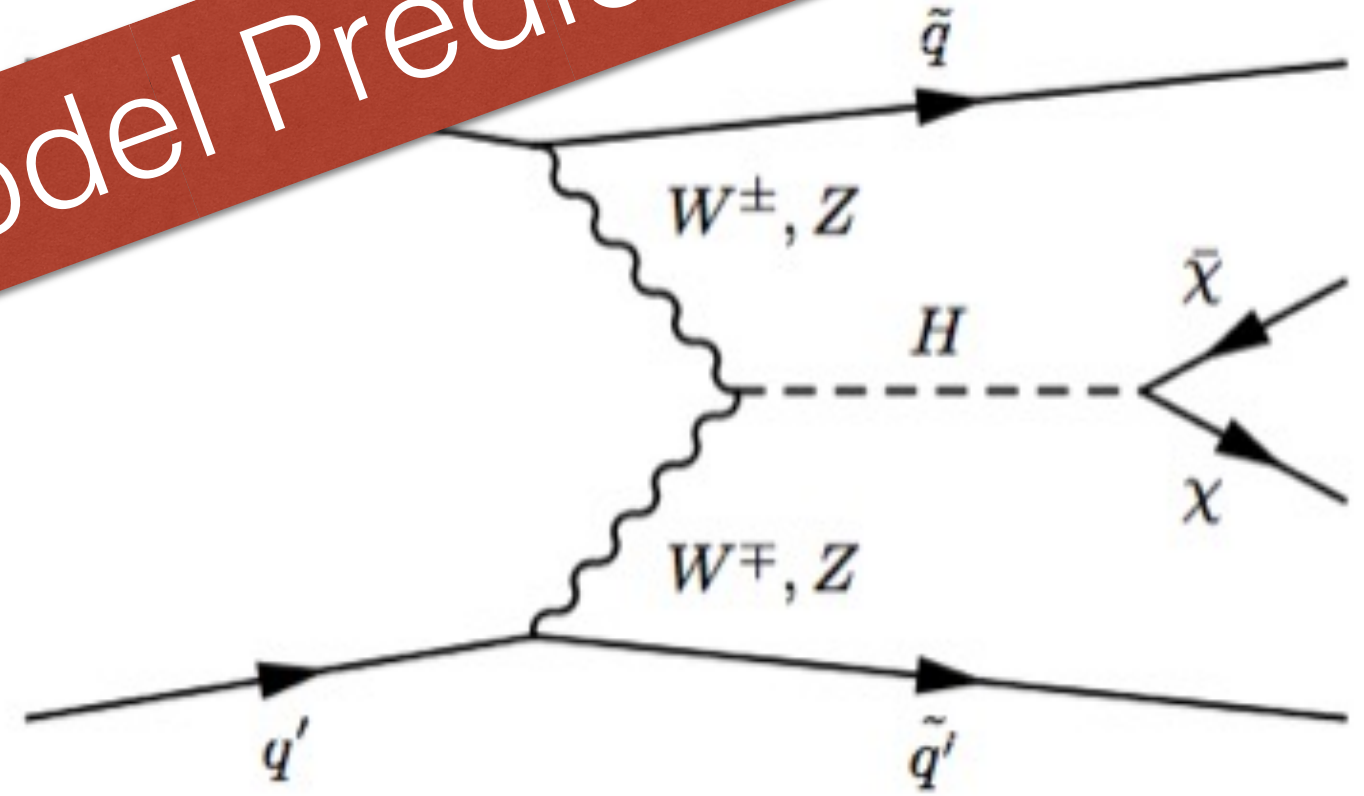
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[Submitted to Phys. Rev. D](#)

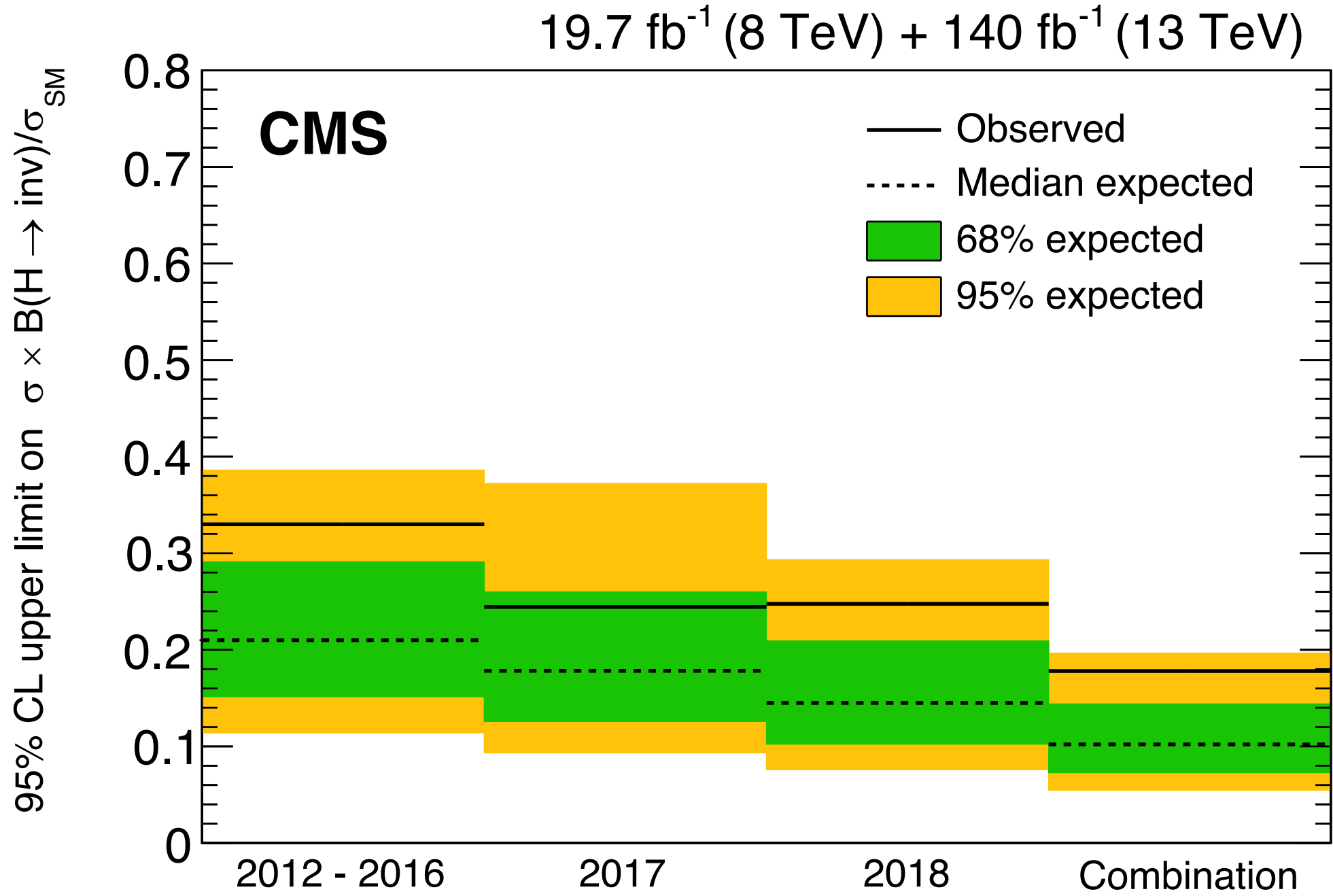
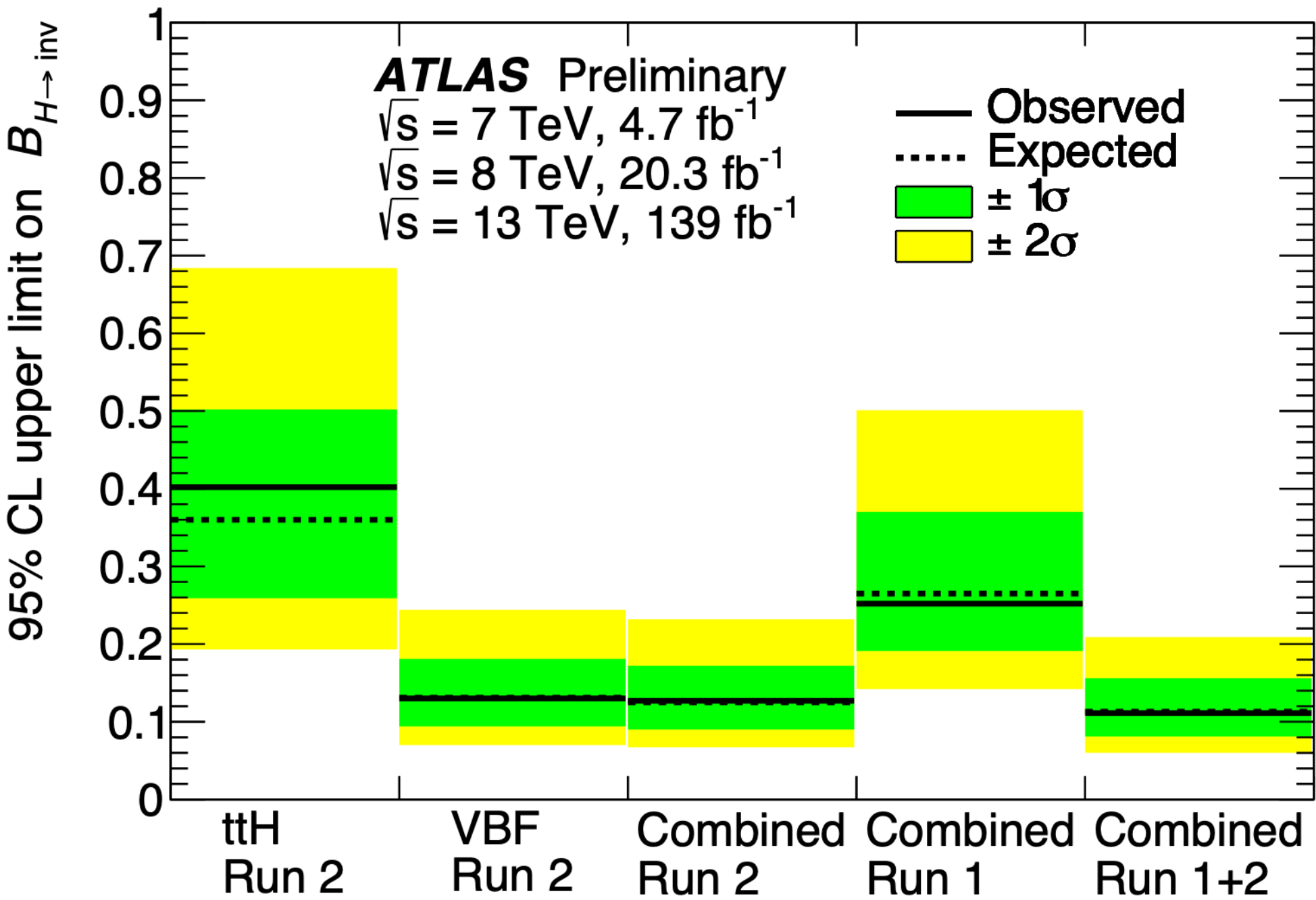
- Largest sensitivity among all approaches!
- Experimentally most challenging with 2 forward jets

No Significant Deviation from the Standard Model Prediction

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

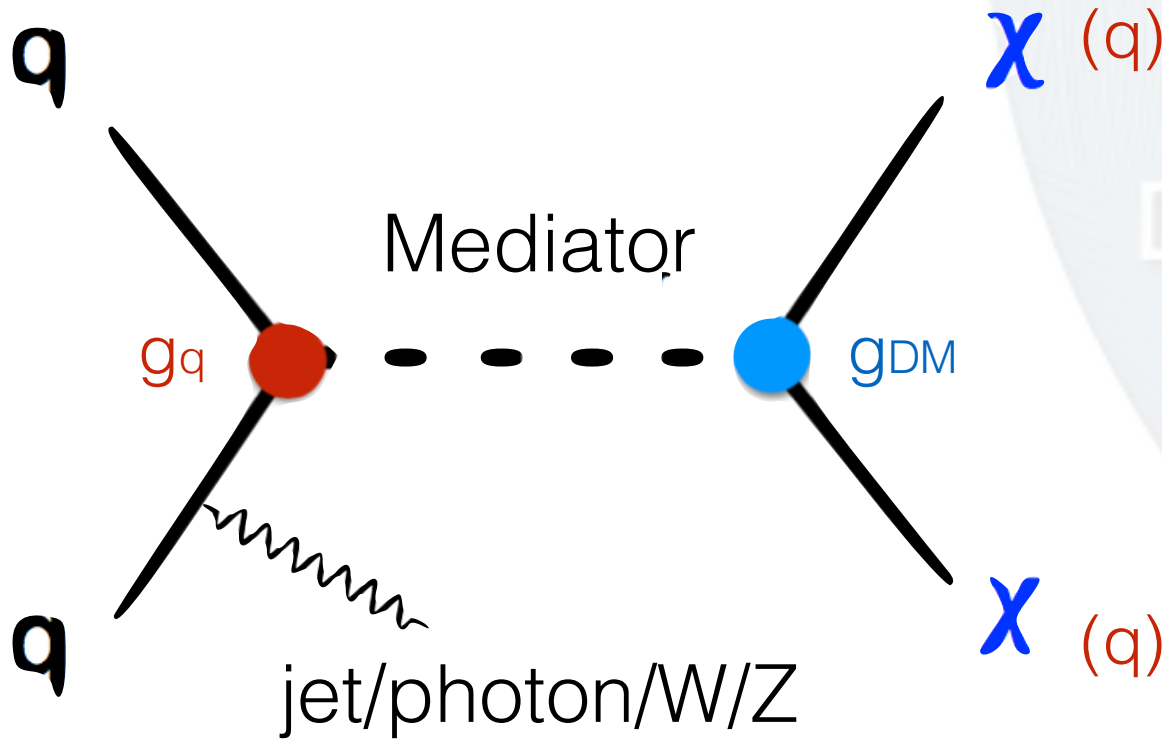
Note: Only a partial combination, more channels to be added.
 Updated CMS result is also in preparation

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

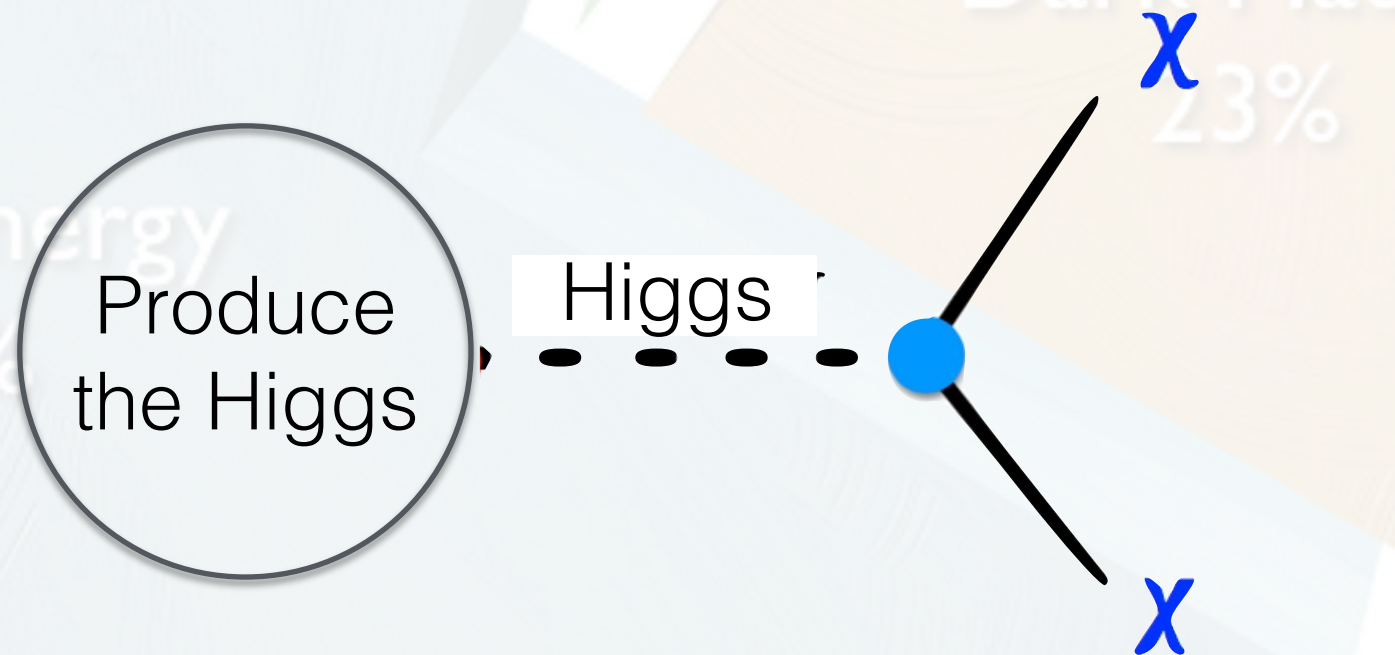
Main parameters of the model: mediator, two vertices, and a DM candidate



Extended to models with t-channel mediator and dark sectors

Higgs Portal

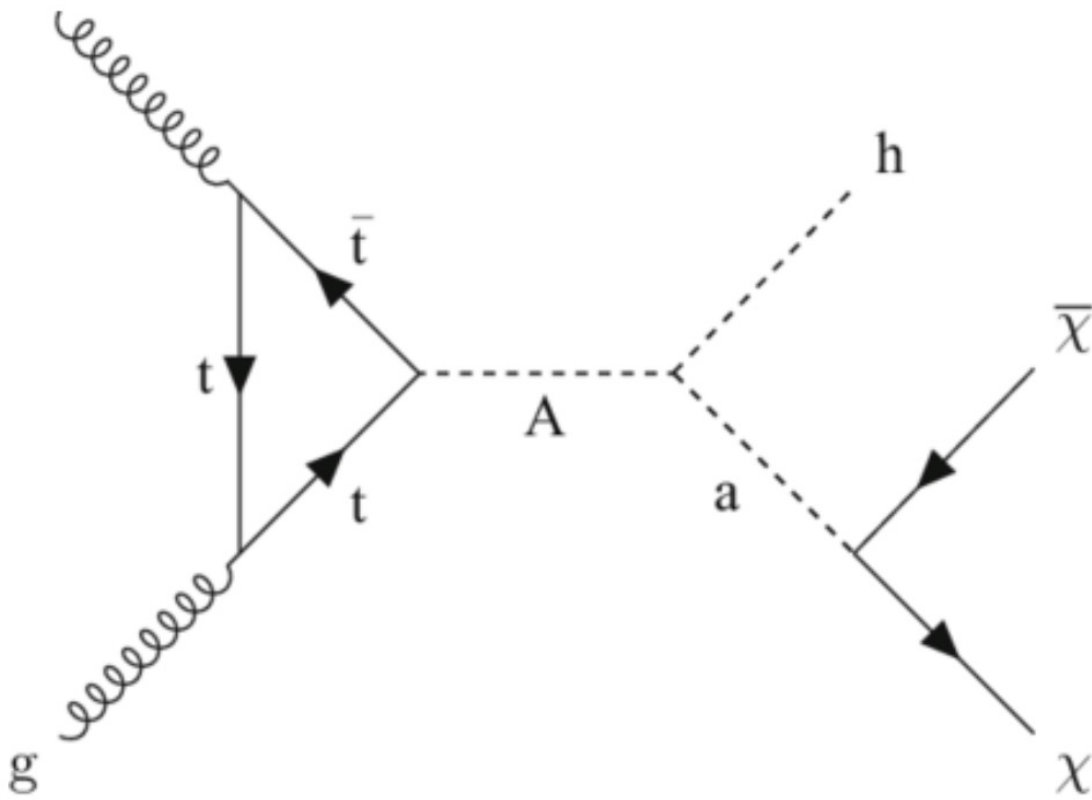
Known Higgs decay branching fractions allow decays to invisible particles ~20%



All Higgs production modes can be studied to tag the event

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 $m_A = m_H = m_{H^\pm}$;
- the pseudoscalar mediator mass m_a ;
- the DM mass m_χ ;
- the mixing angle $\sin \theta$ between the two CP-odd states a and A ;
- and VEV ratio $\tan \beta$.

@ **low $\tan\beta$** the **ggF** mechanism dominates

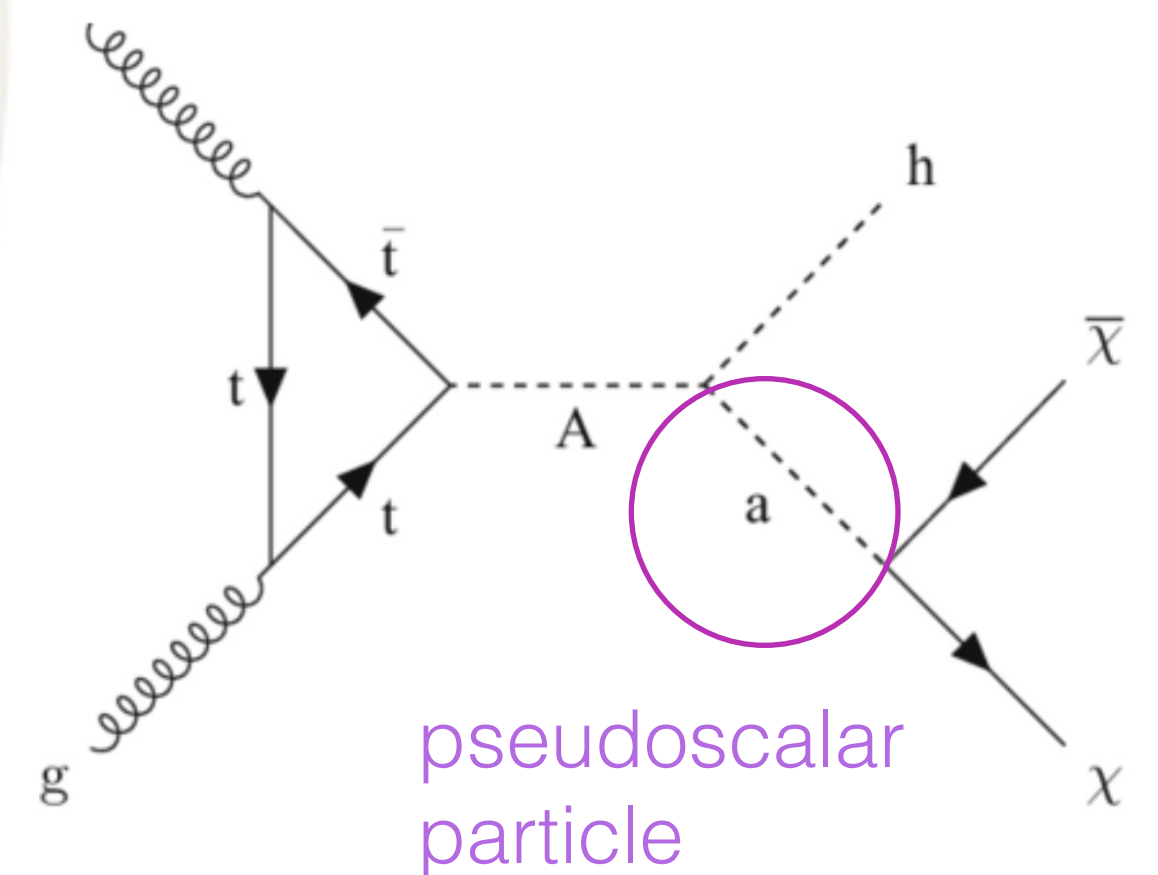
@ **higher $\tan\beta$** the **bbA** mechanism dominates

Wide variety of detector signatures, DM in association with:

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

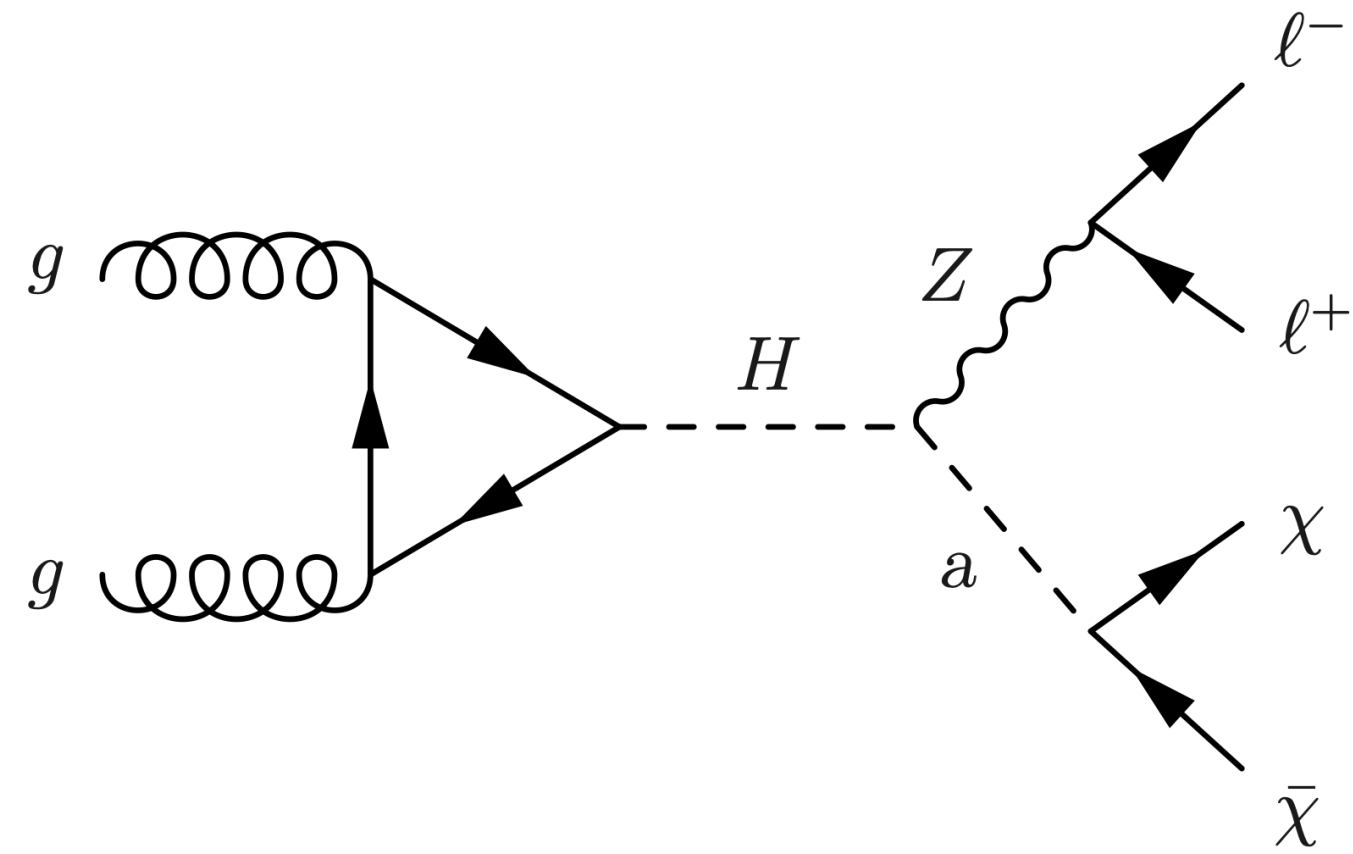
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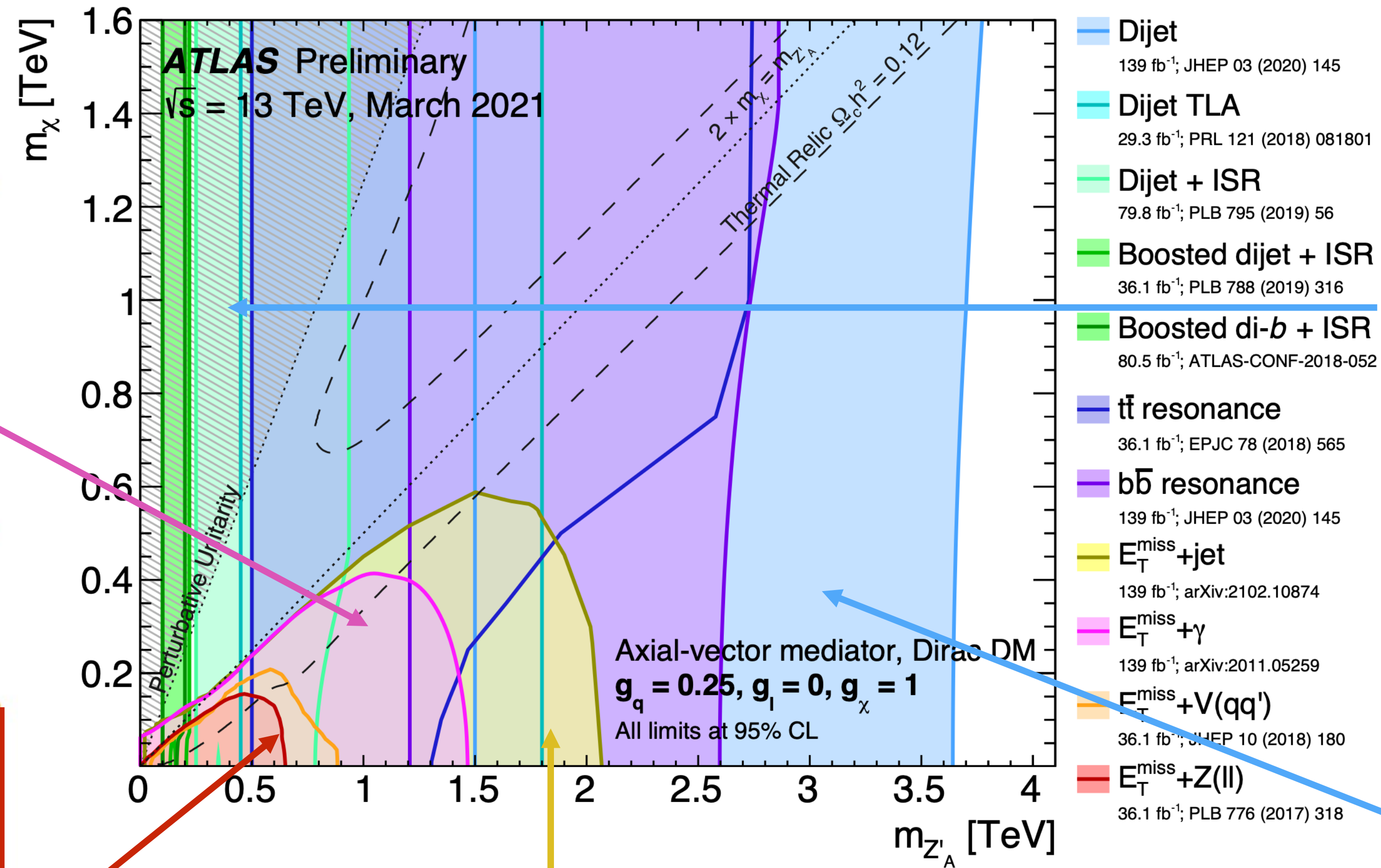
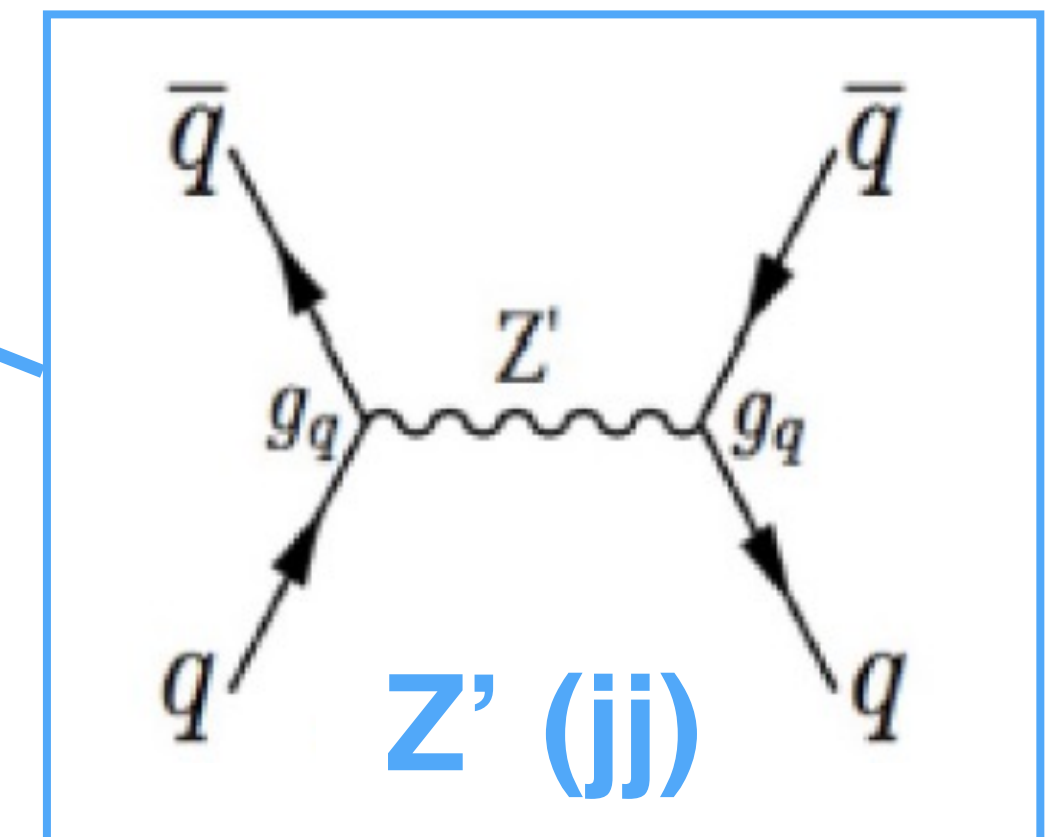
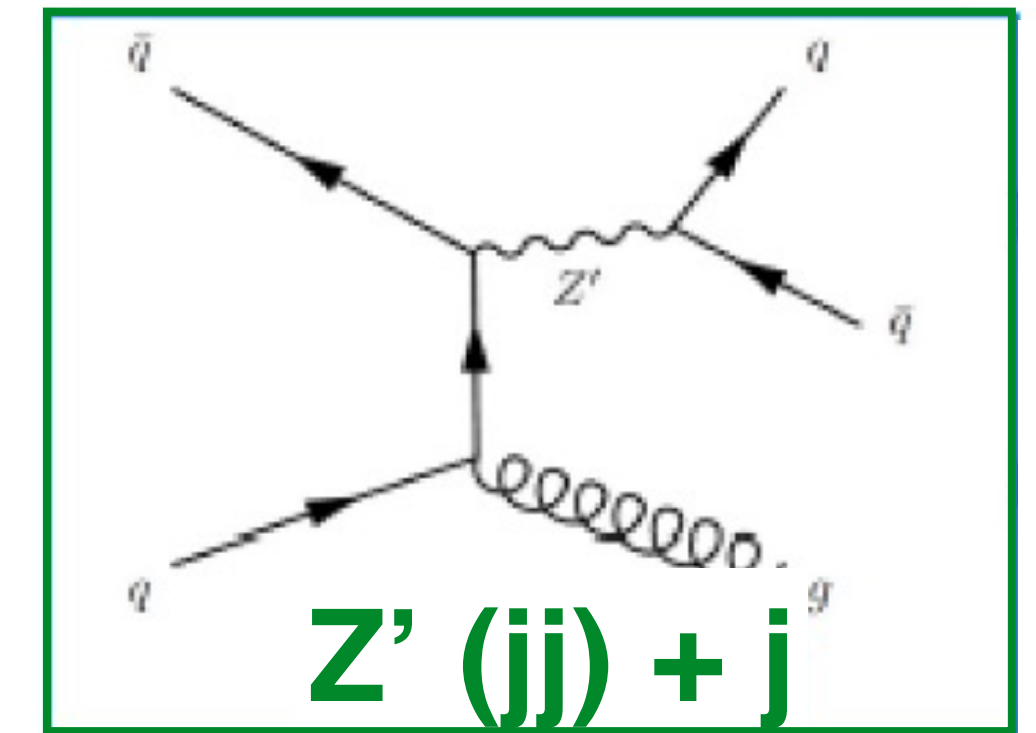
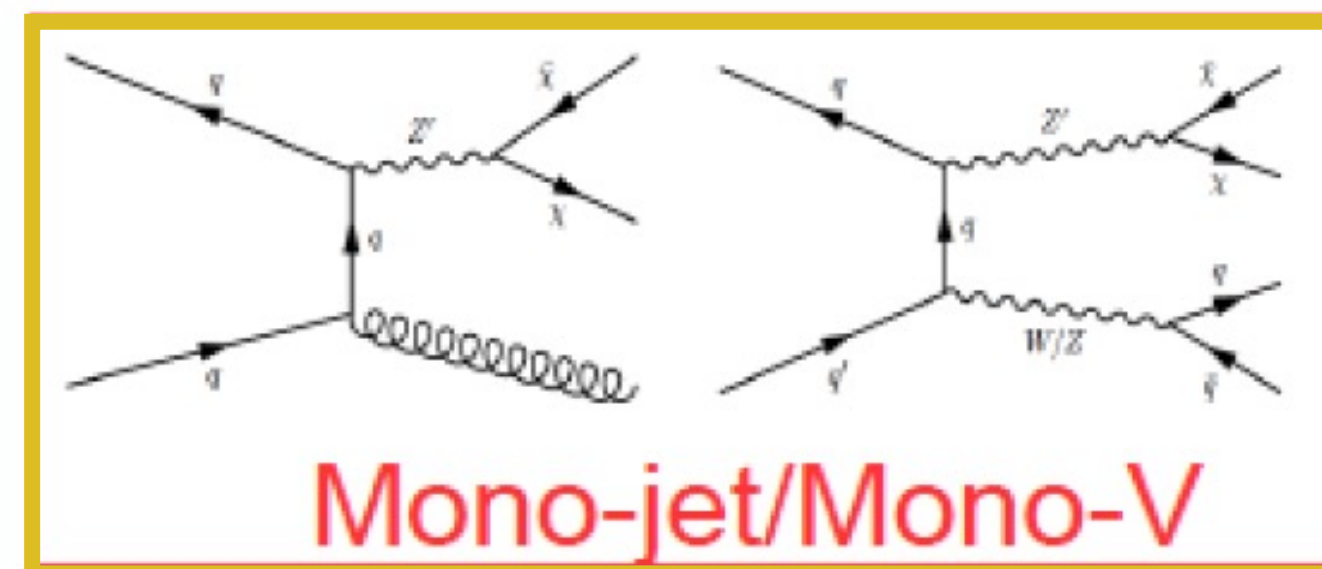
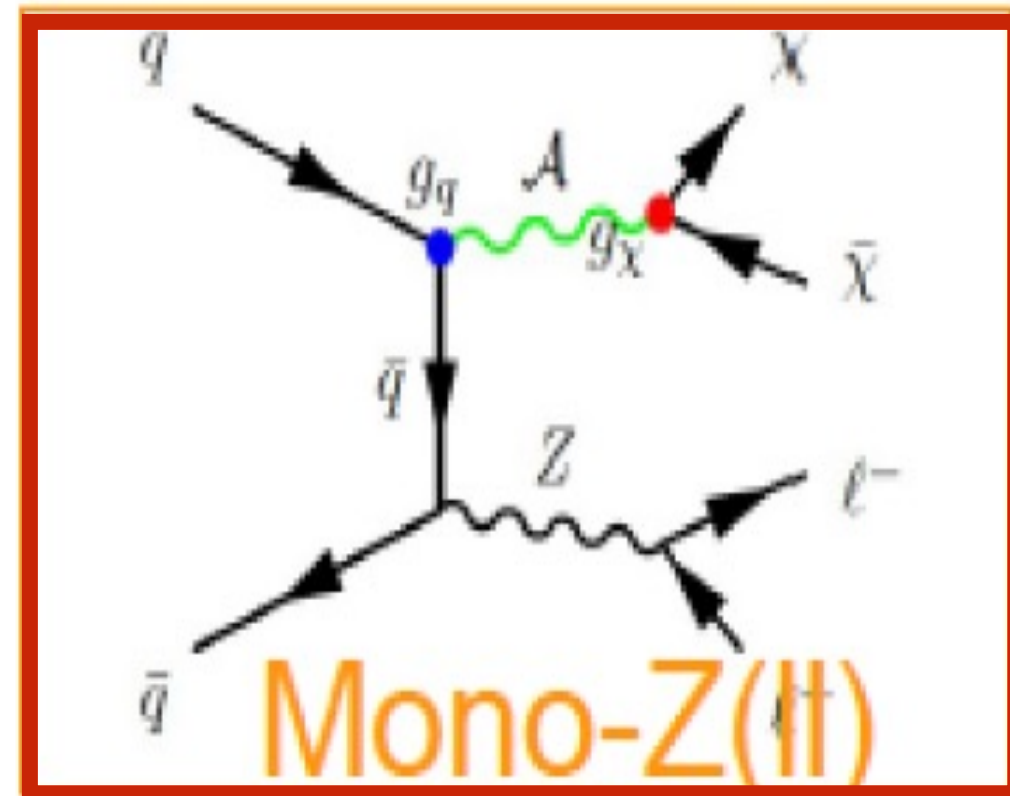
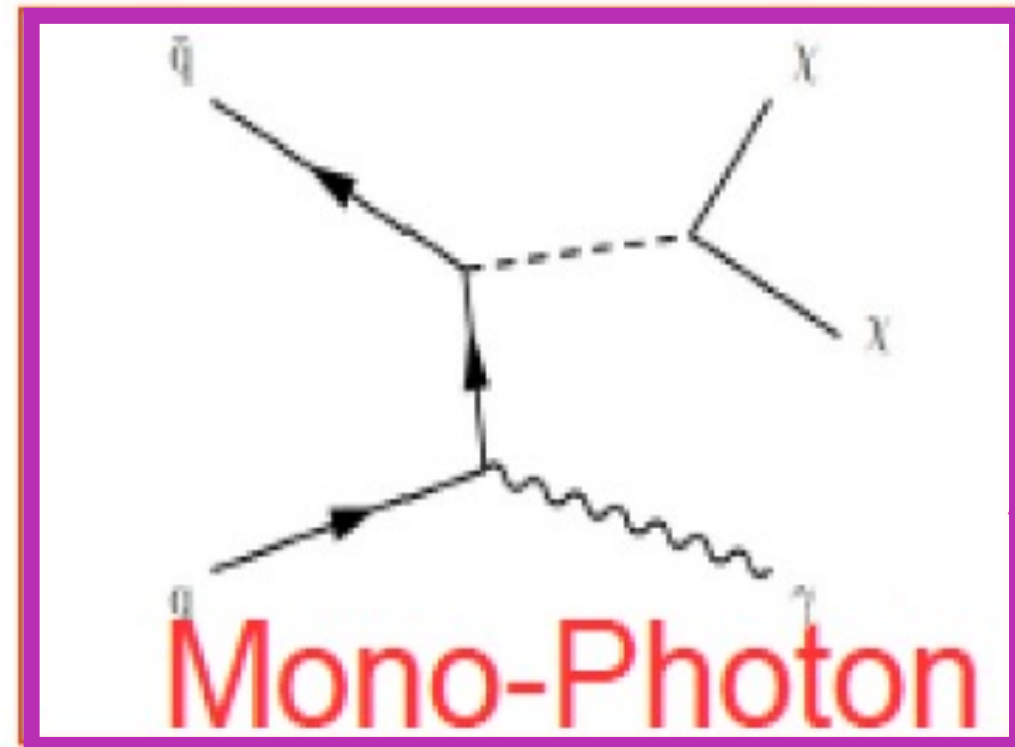
A more complete benchmark model with 14 parameters

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

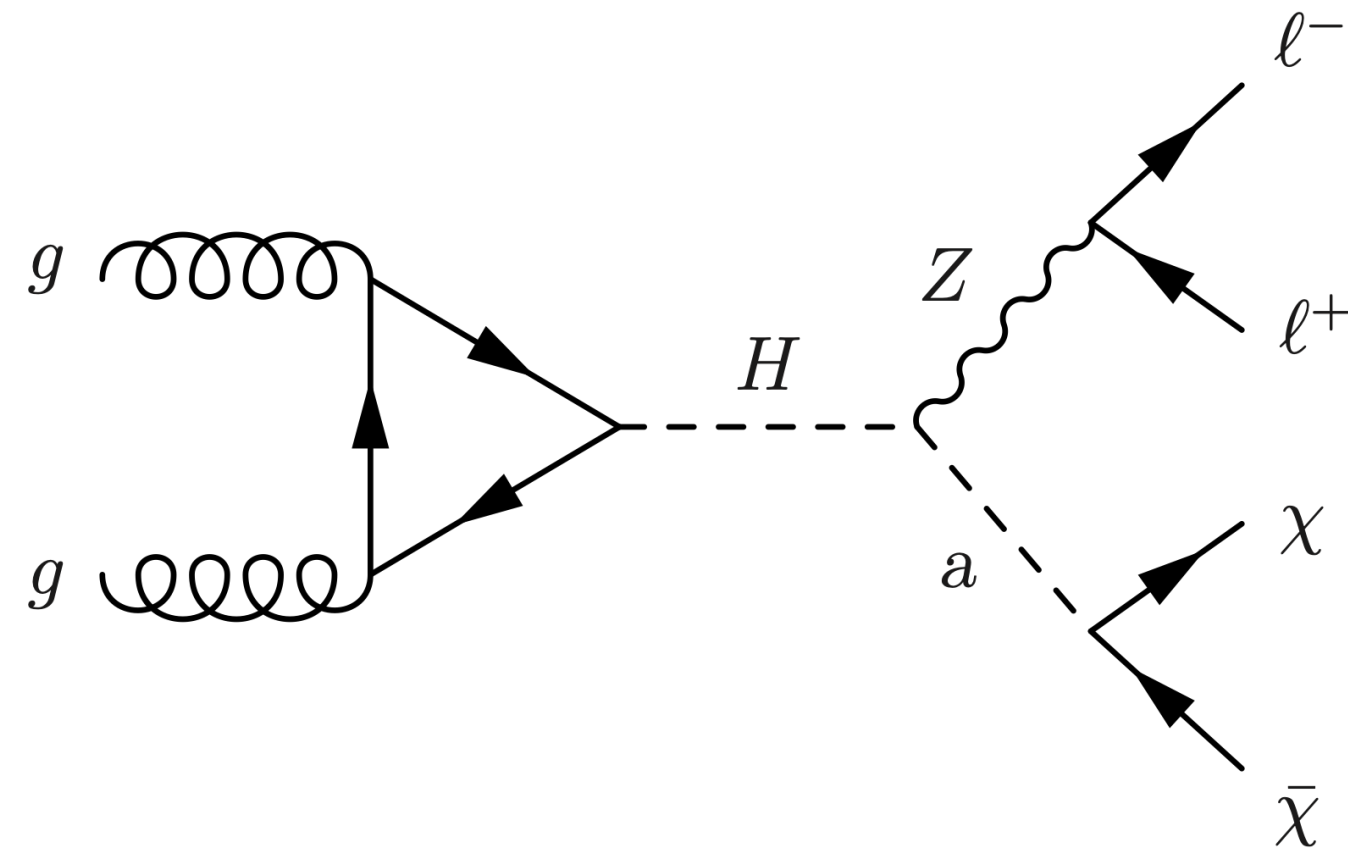


Strategy: look for two leptons (e, μ) compatible with a Z-boson + require large p_T^{miss} . Veto on any additional activity.

WIMP: It all comes together: Mono-mania



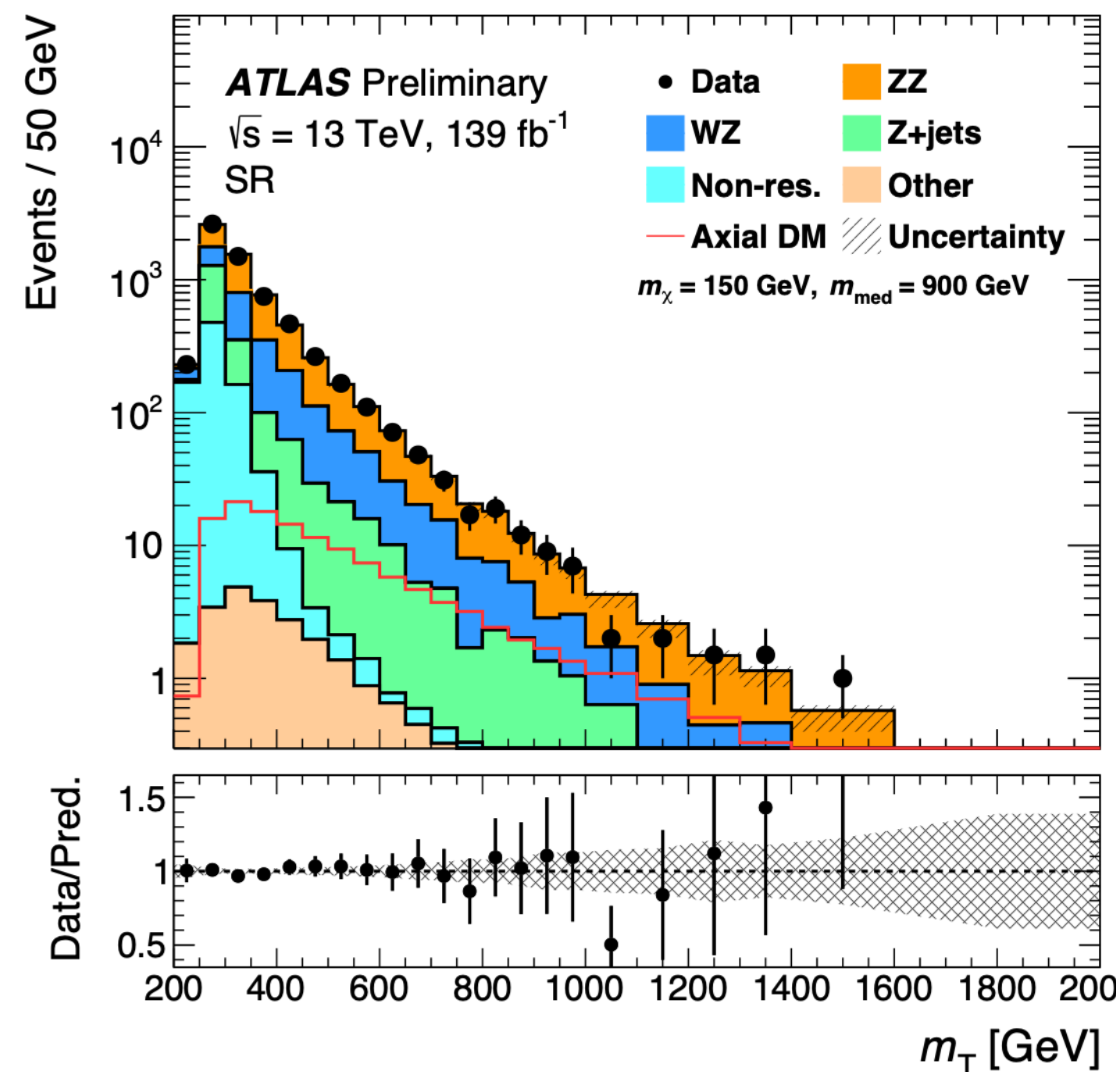
2HDM+a Models: Mono-Z(II)



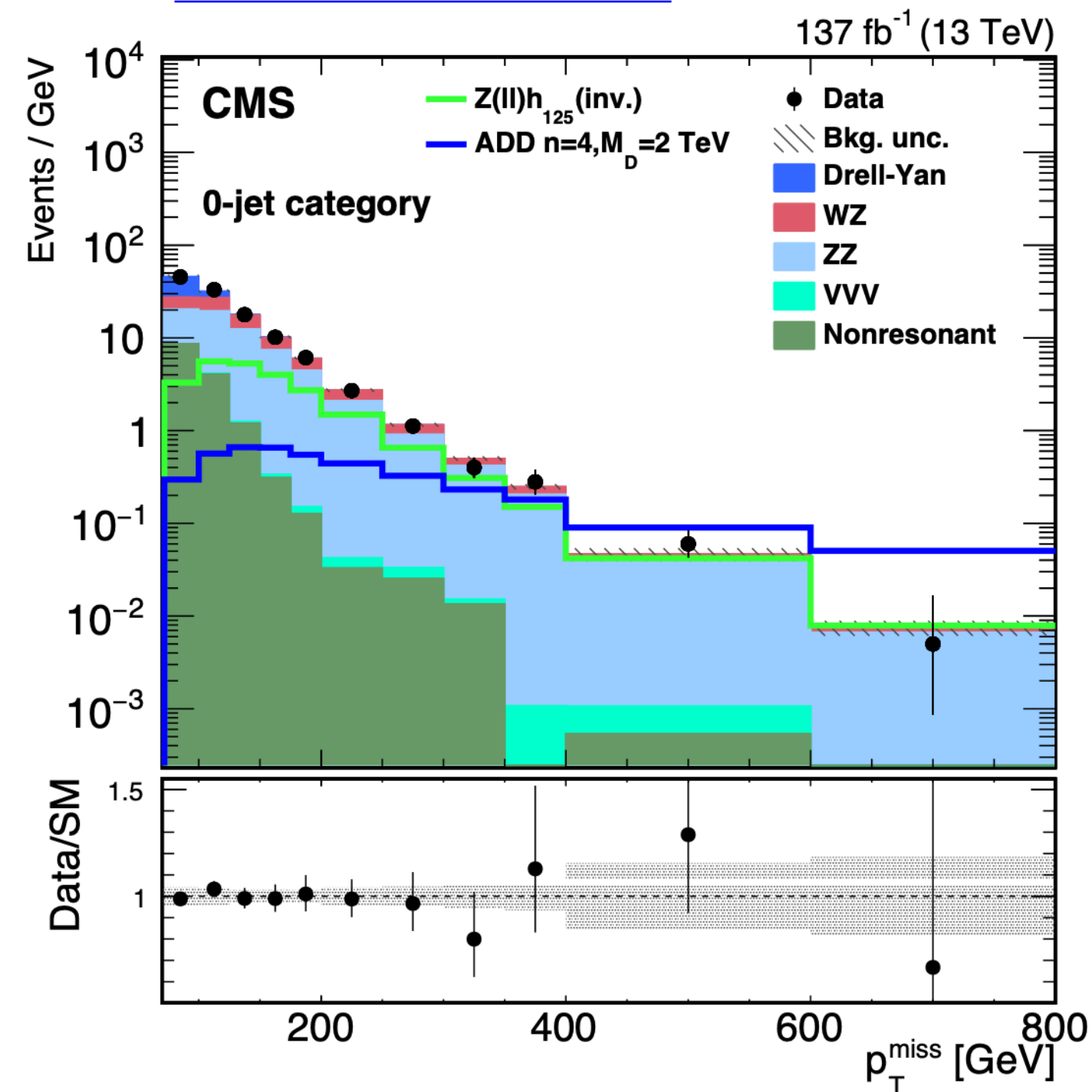
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Maximize the **sensitivity** in 2HDM+a parameter space by using the **transverse mass** observable.

ATLAS-CONF-2021-029



CMS-EXO-19-003

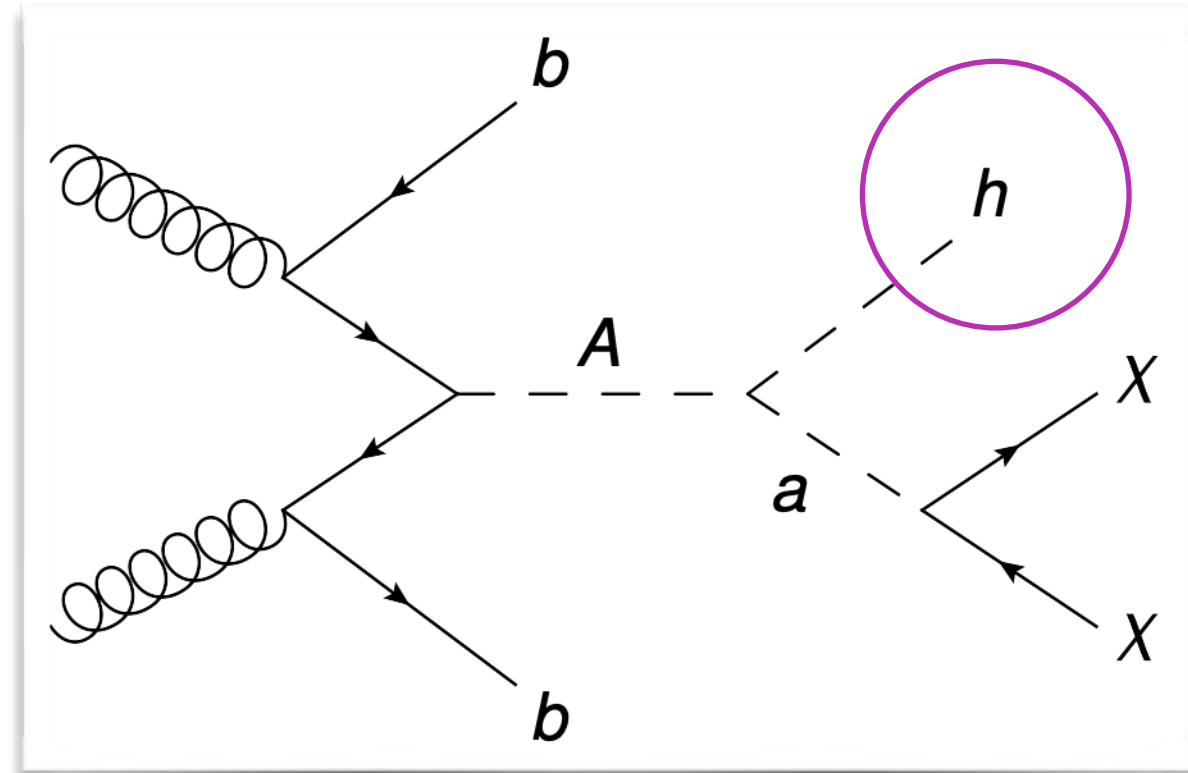


The dominant backgrounds: ZZ, WZ, WW, Z+jets and tt.

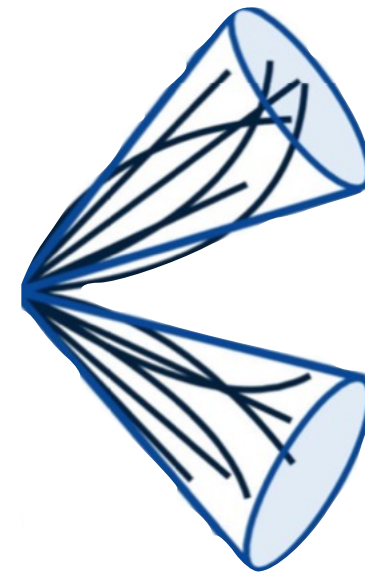
Estimated via control regions:

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

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



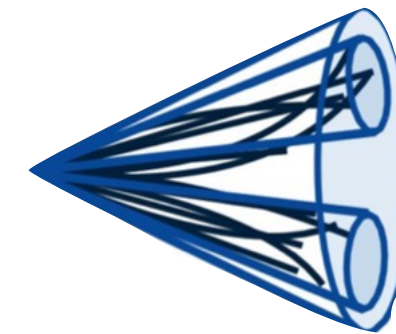
- resolved



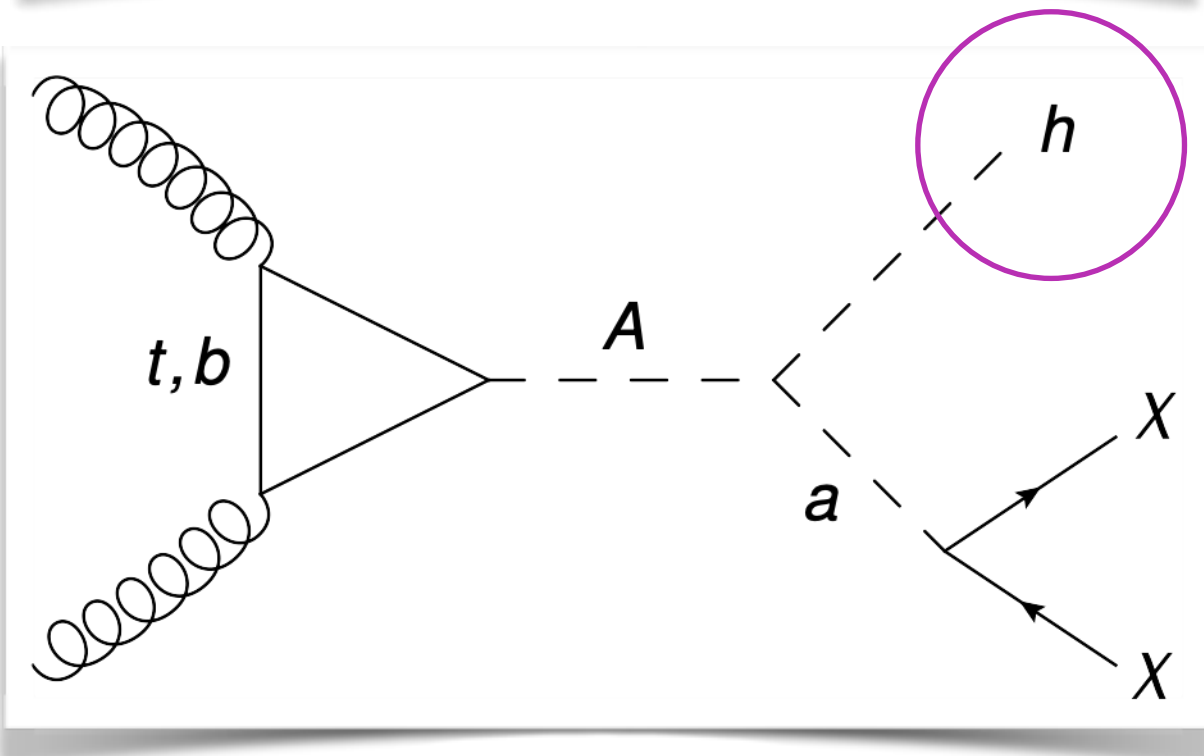
The analysis is split into:

+

- merged signal regions

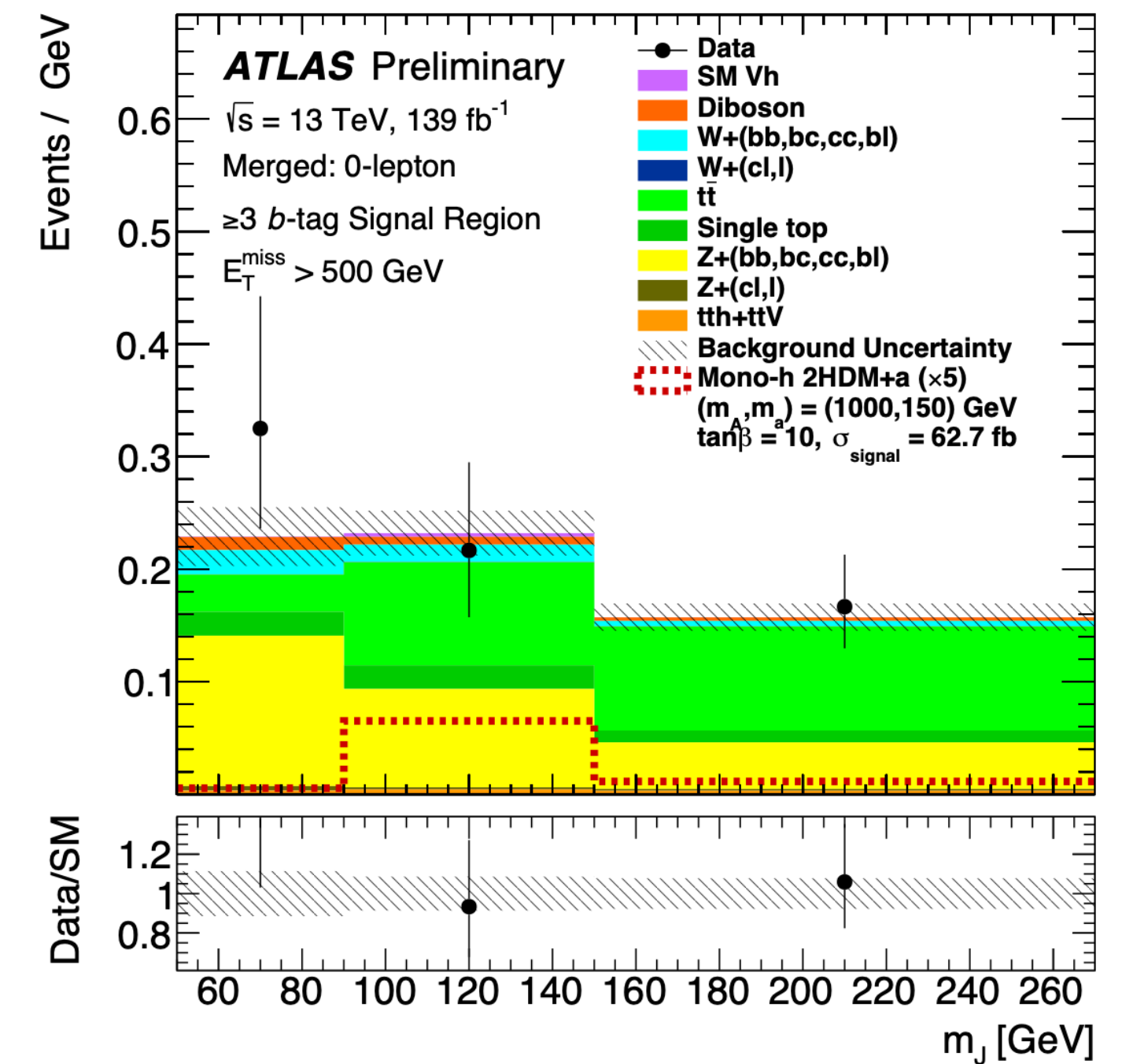
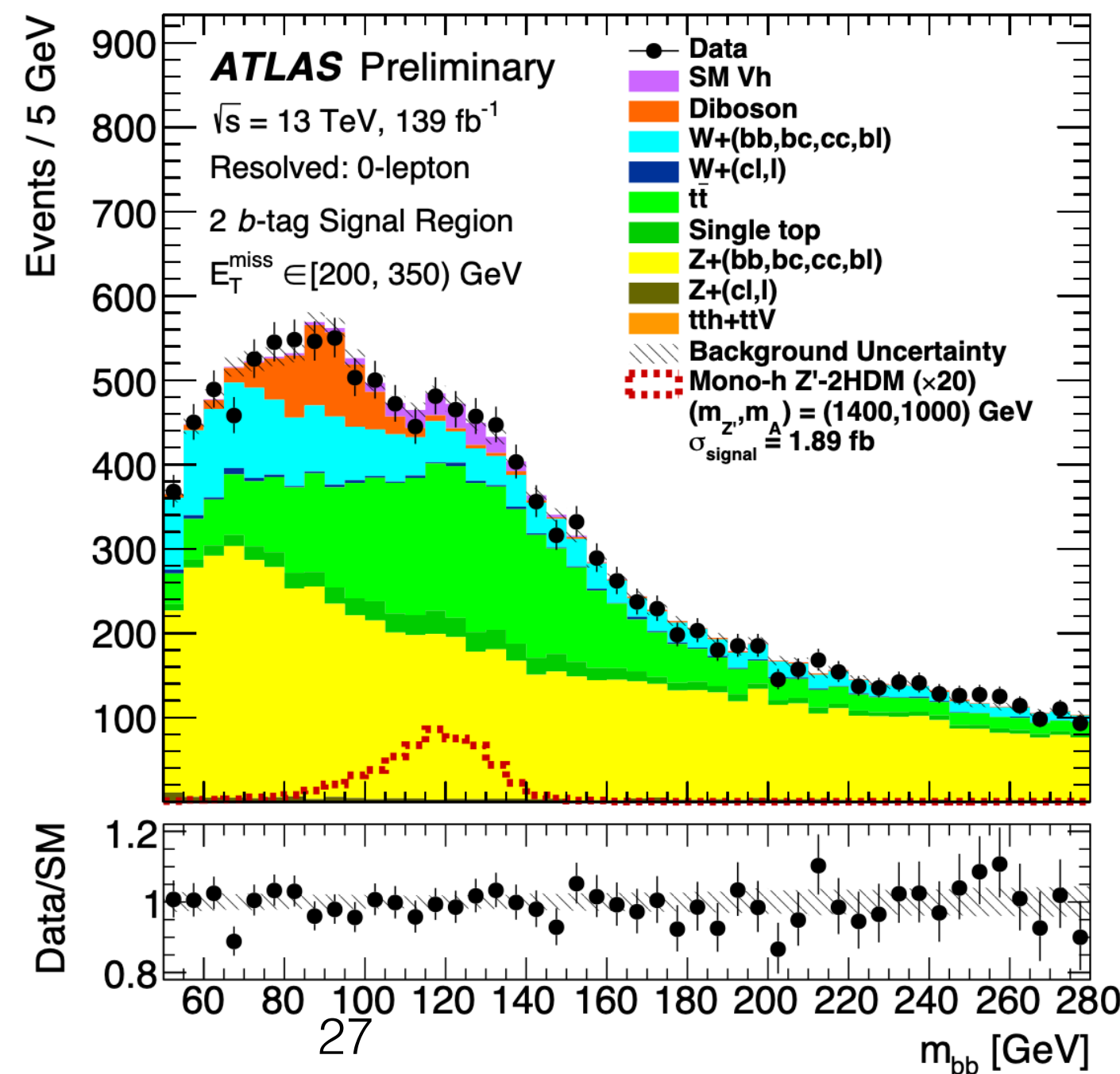


split further into 2 b-tagged jets and at least 3 b-tagged jets and in $p_{T\text{miss}}$ bins.

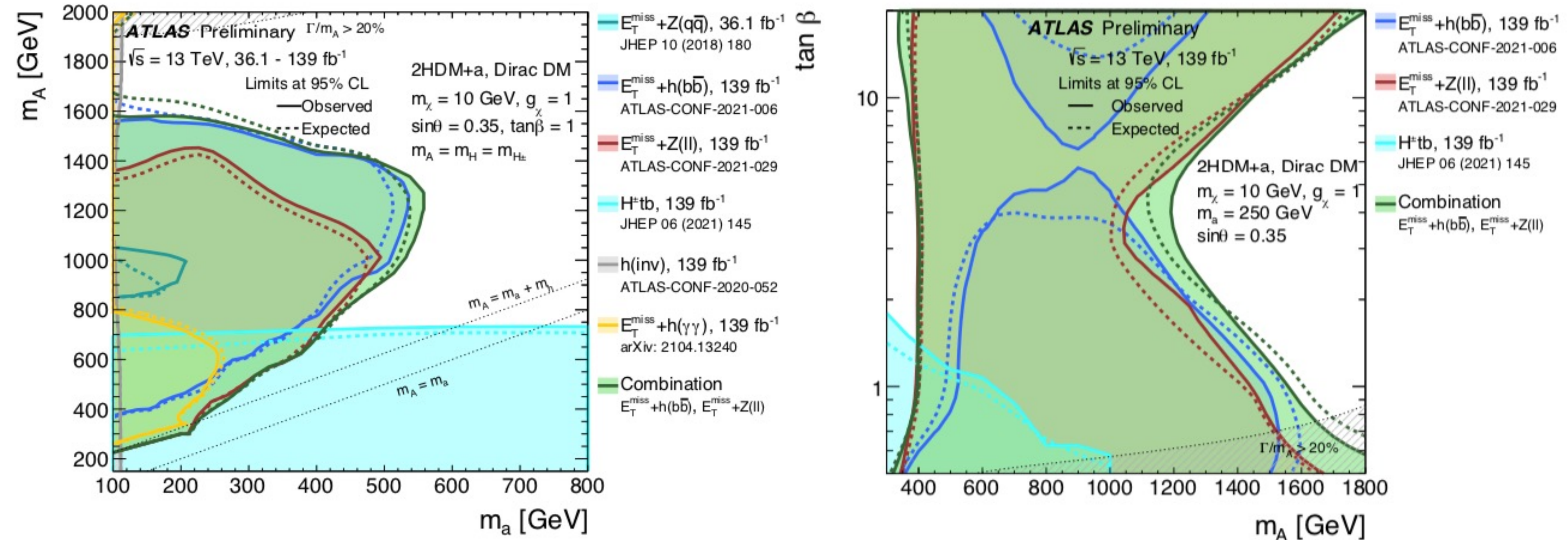


[ATLAS-CONF-2021-006](#)

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



2HDM+a Models - Putting it all together



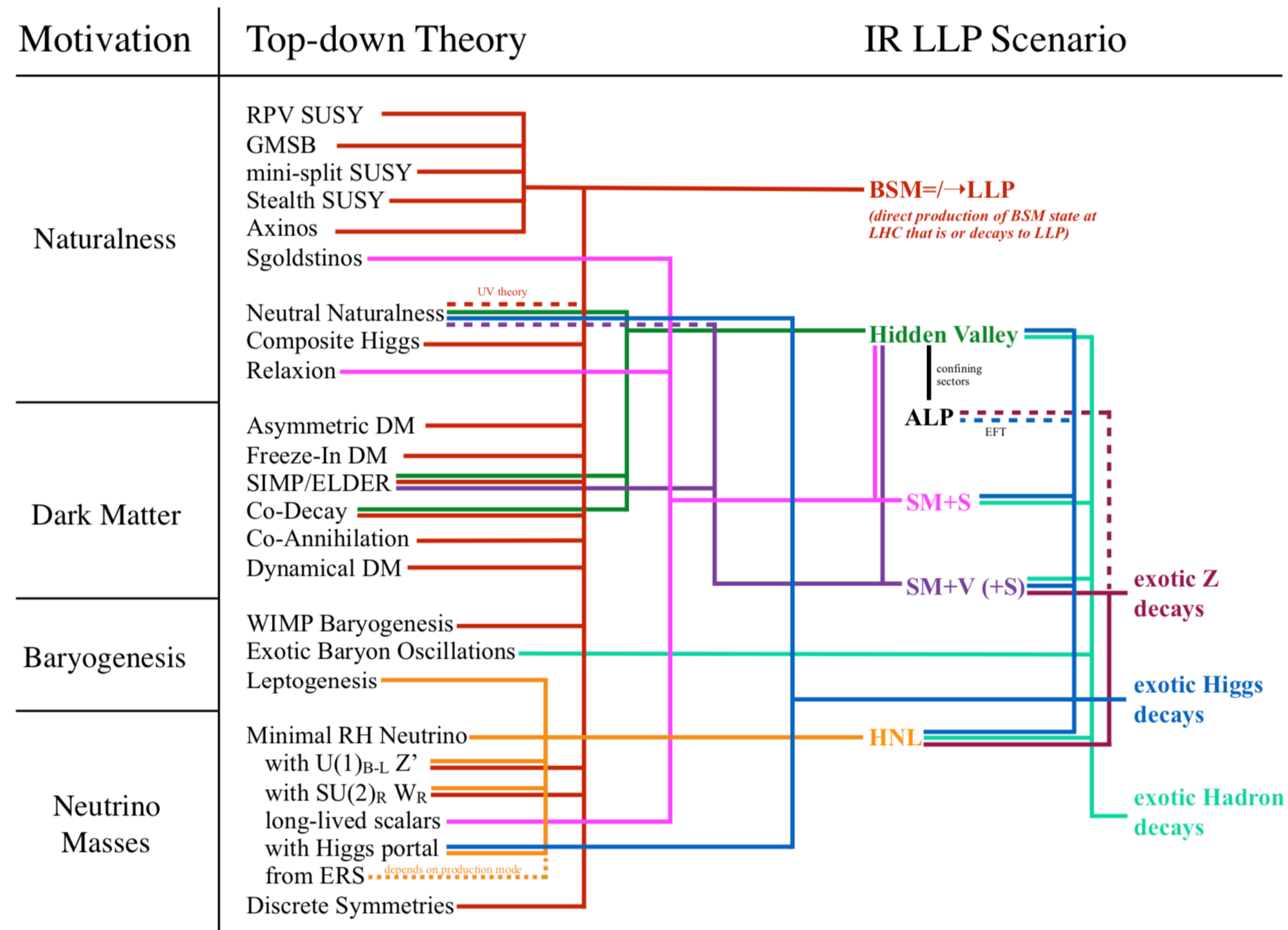
Combination only with Mono-H(bb) and Mono-Z(ll) channels.

[ATLAS-CONF-2021-036](#)

[CMS-EXO-18-011](#) targeting Z' 2HDM

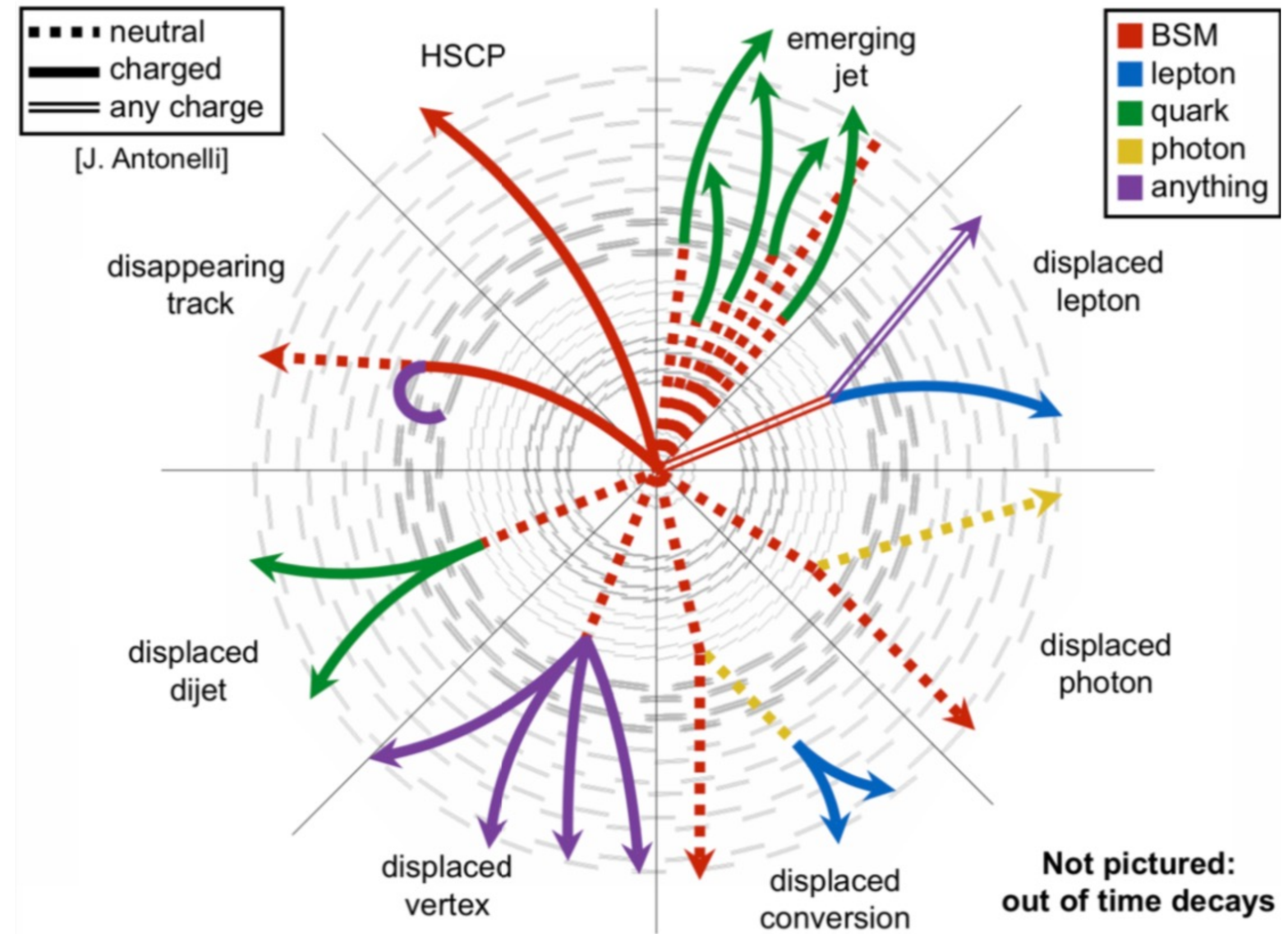
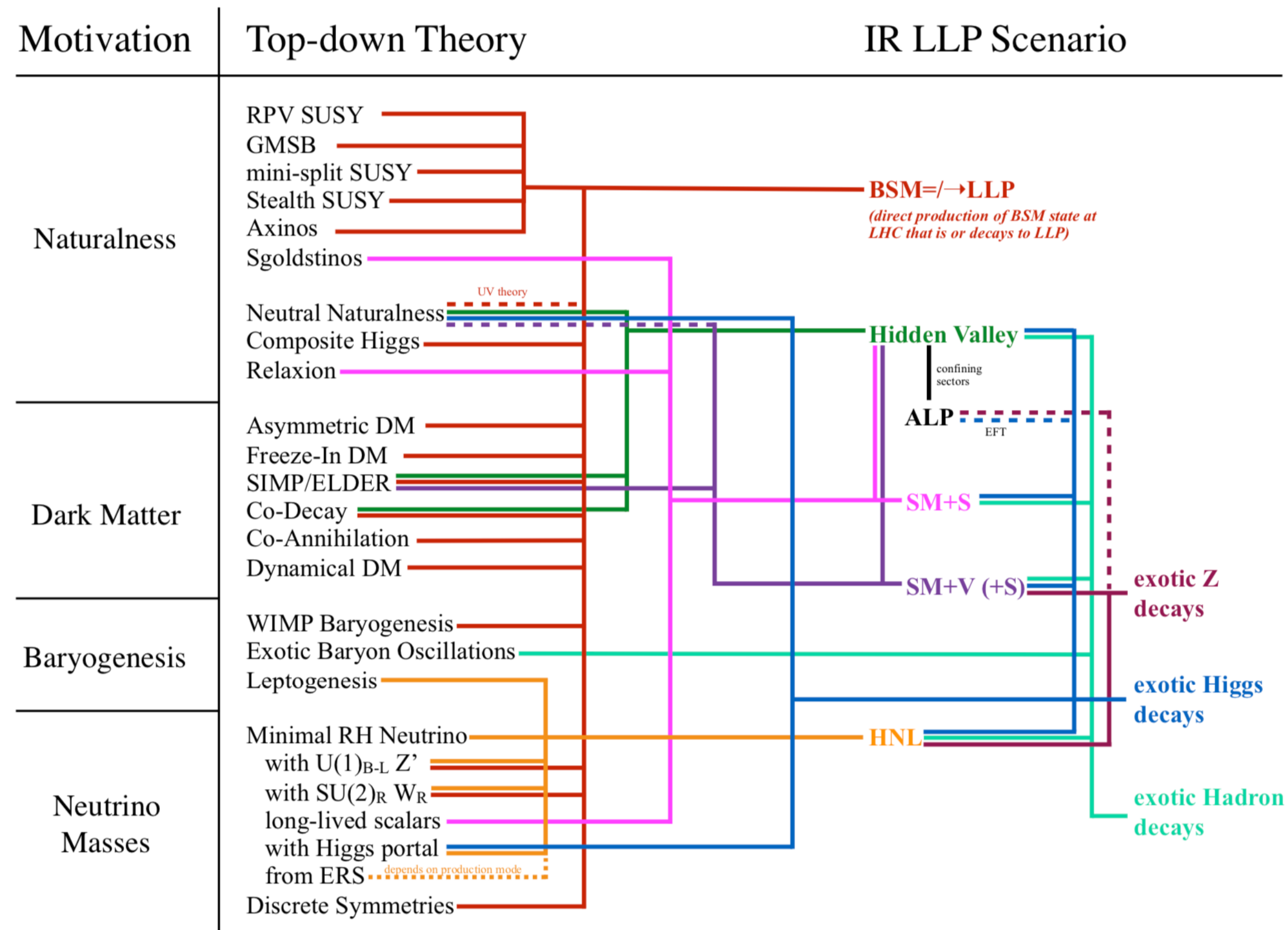
Long-lived signatures

1806.07396



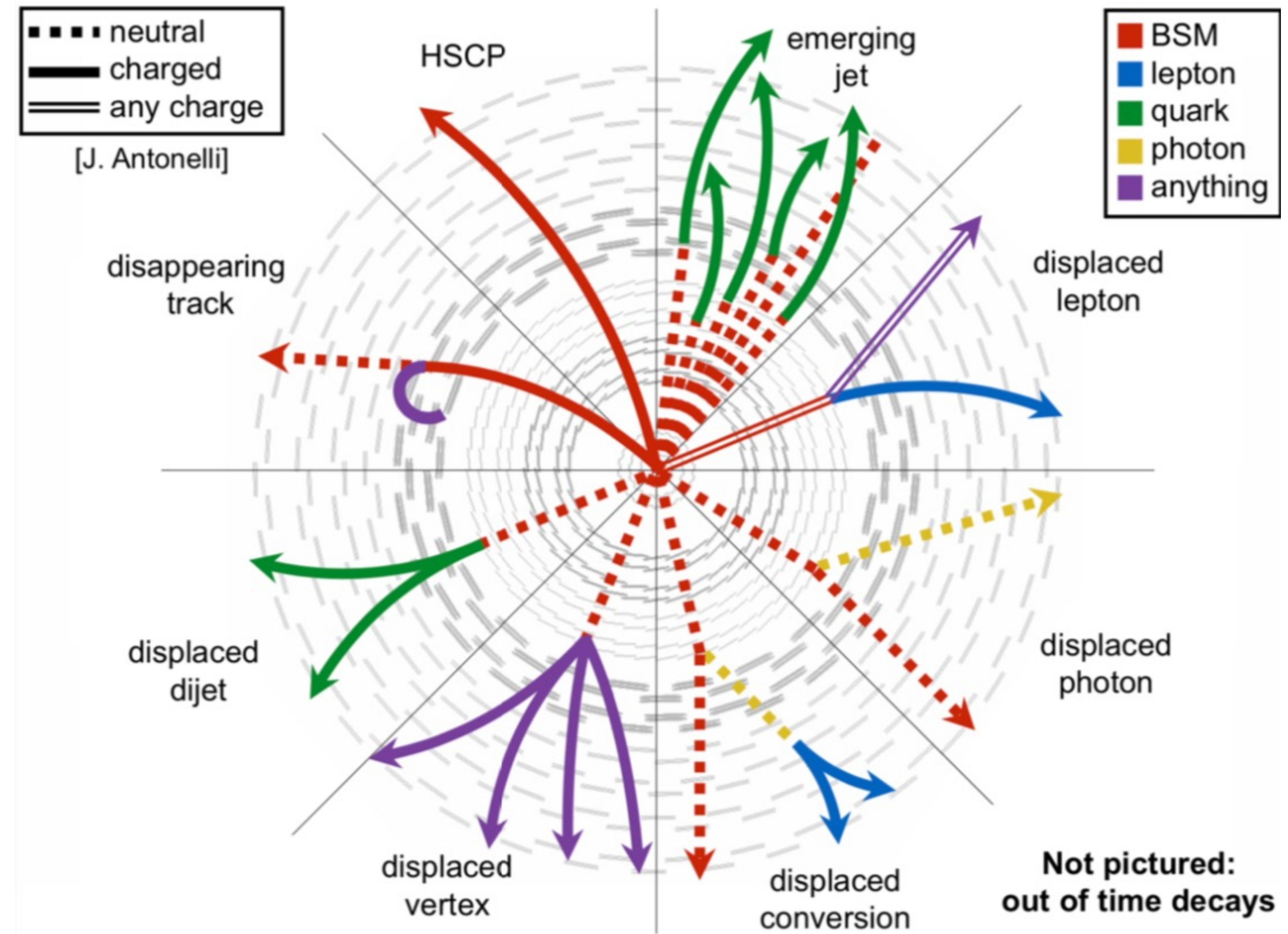
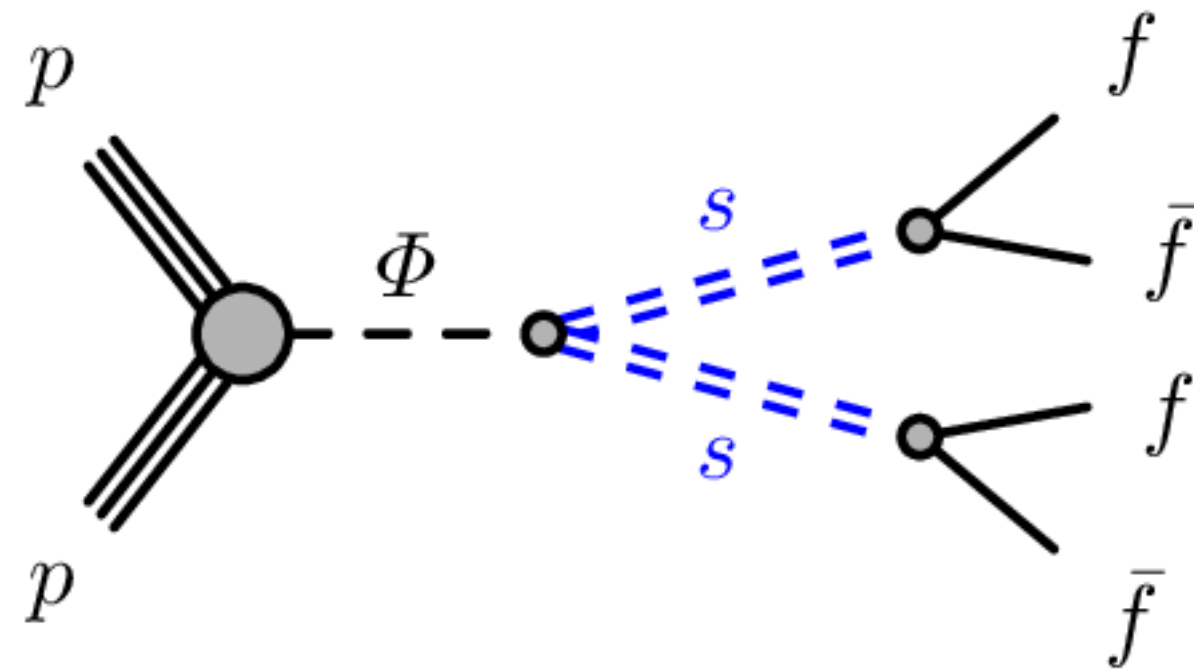
Long-lived signatures

1806.07396



Long-lived signatures and Exotic Higgs decays

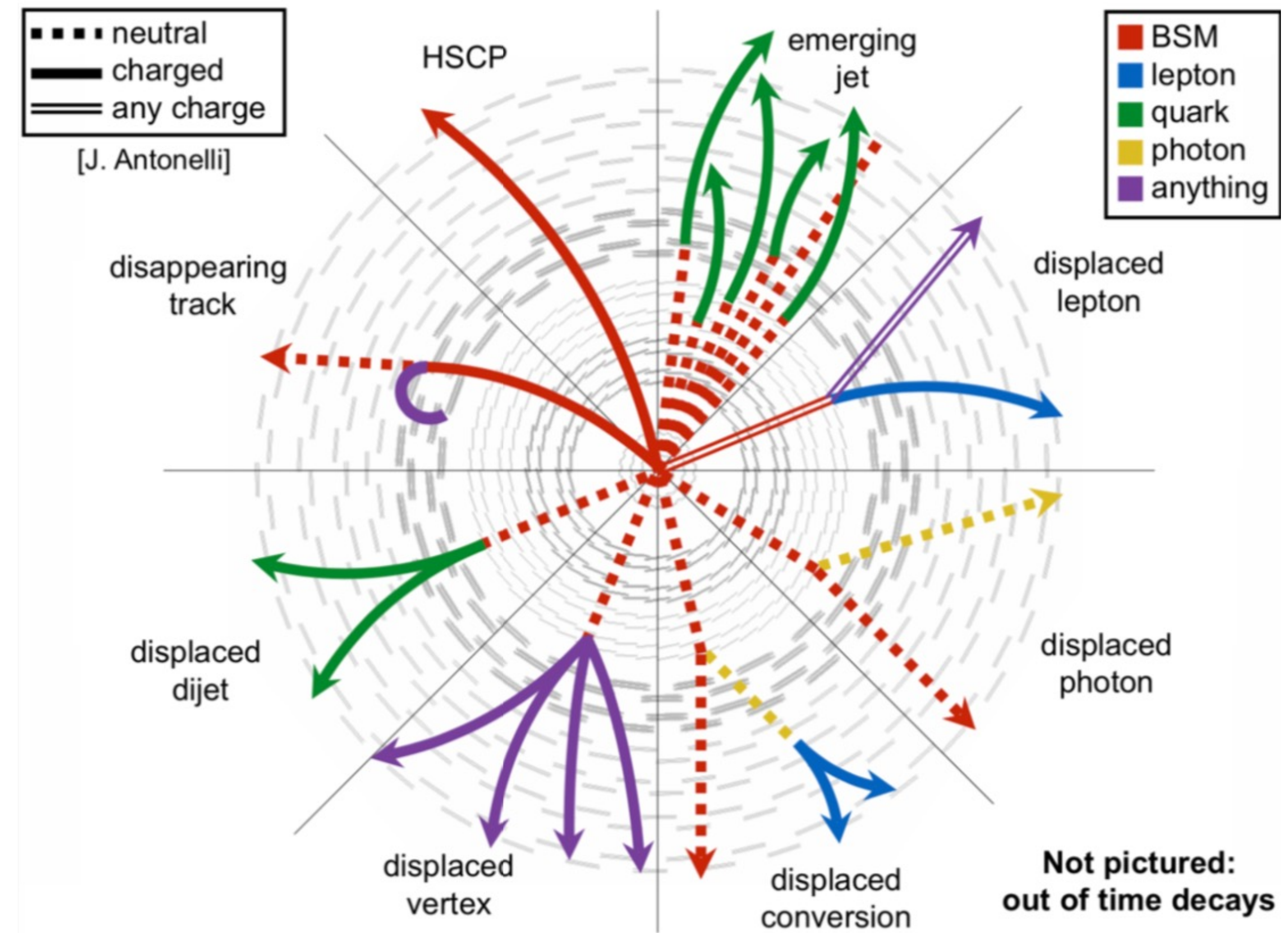
Sufficient freedom for exotic couplings
 $BR(H \rightarrow \text{Non-SM})$ could be up to $\mathcal{O}(10)\%$



Long-lived signatures and Exotic Higgs decays

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

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



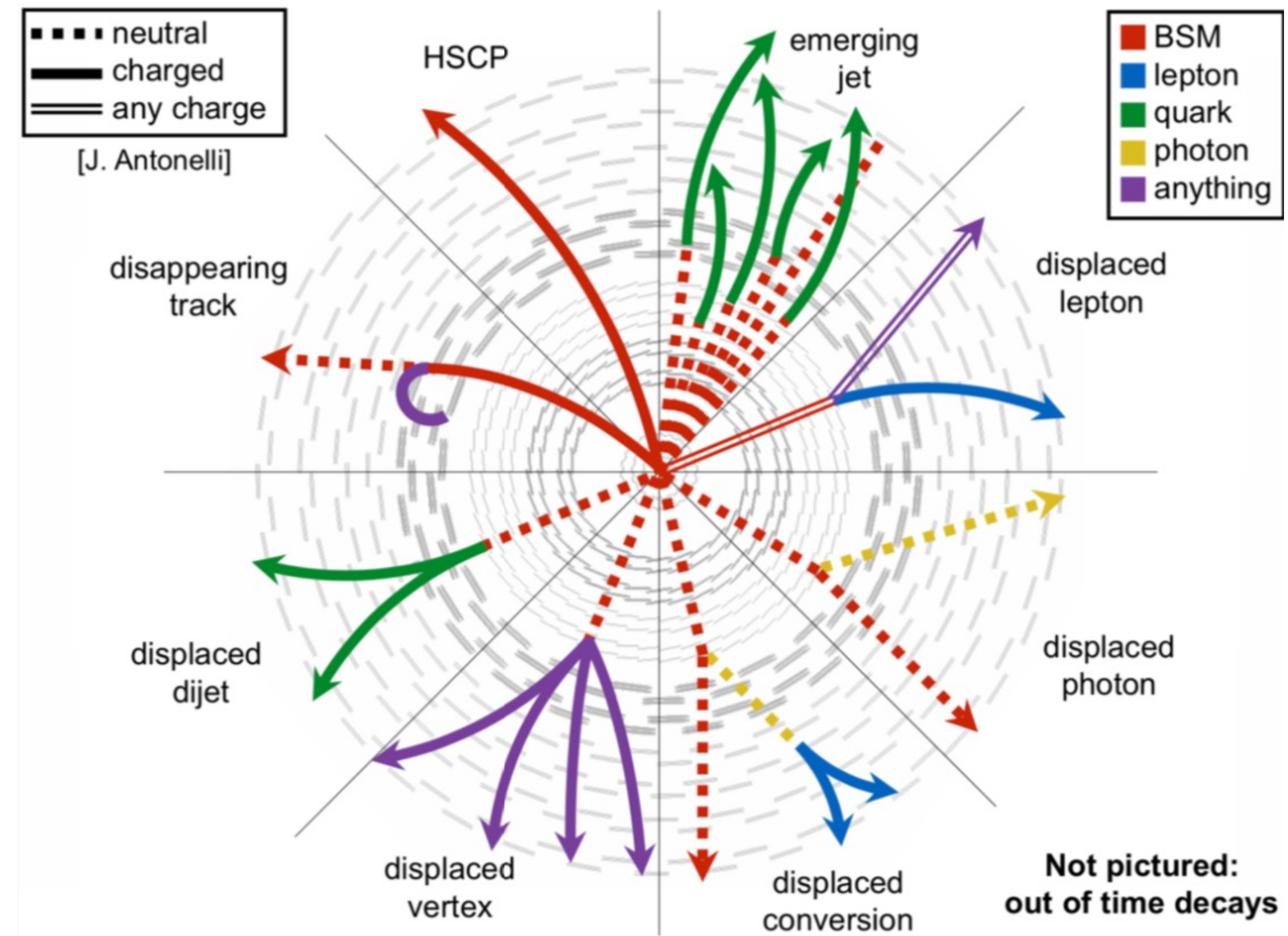
Long-lived signatures and Exotic Higgs decays

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

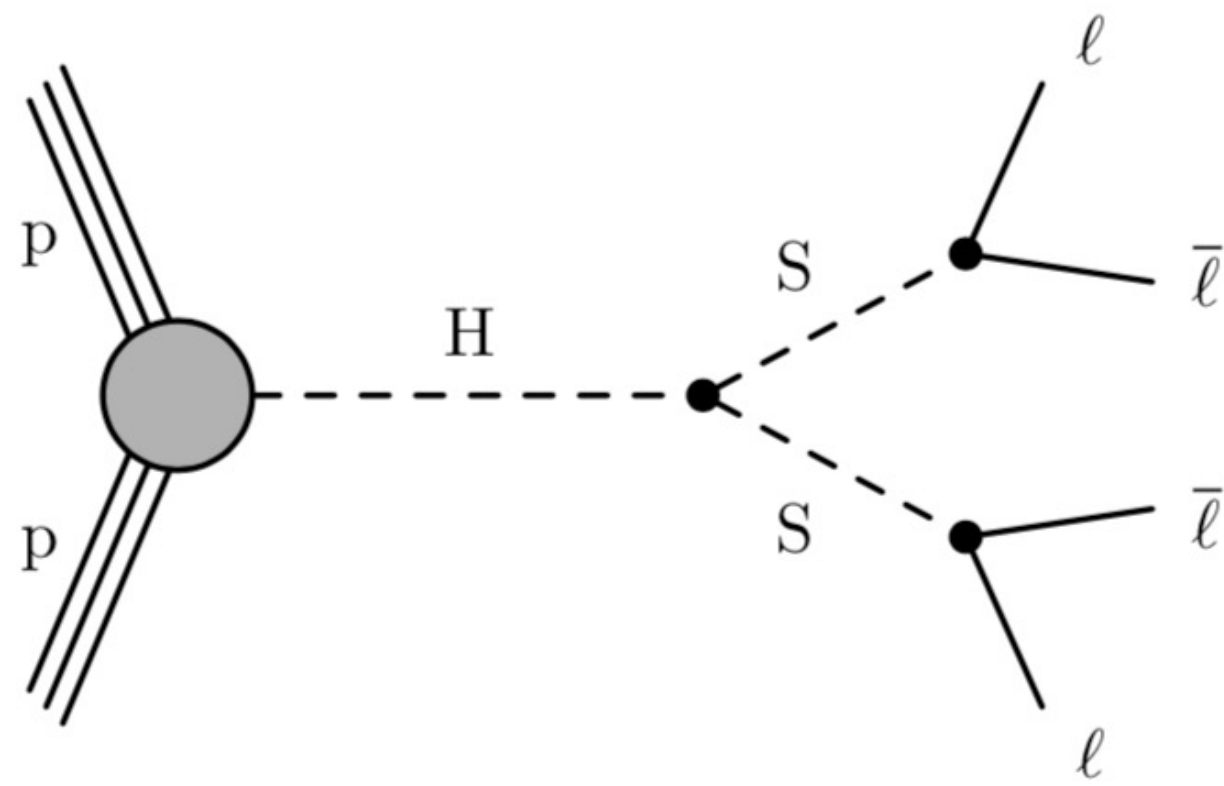
If the decay product is **light**, and/or couple with **small couplings** \rightarrow **long lived particle**

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

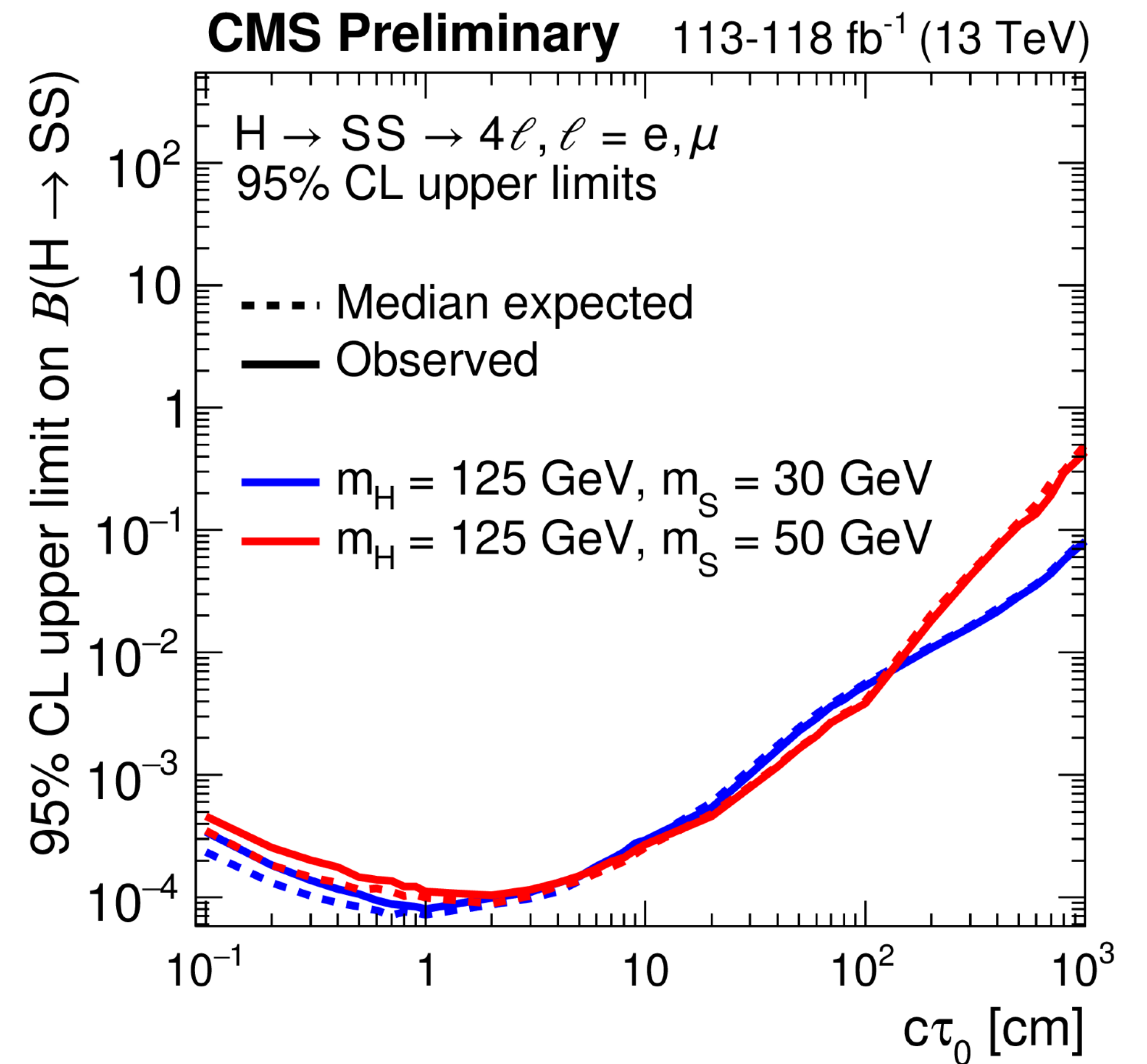
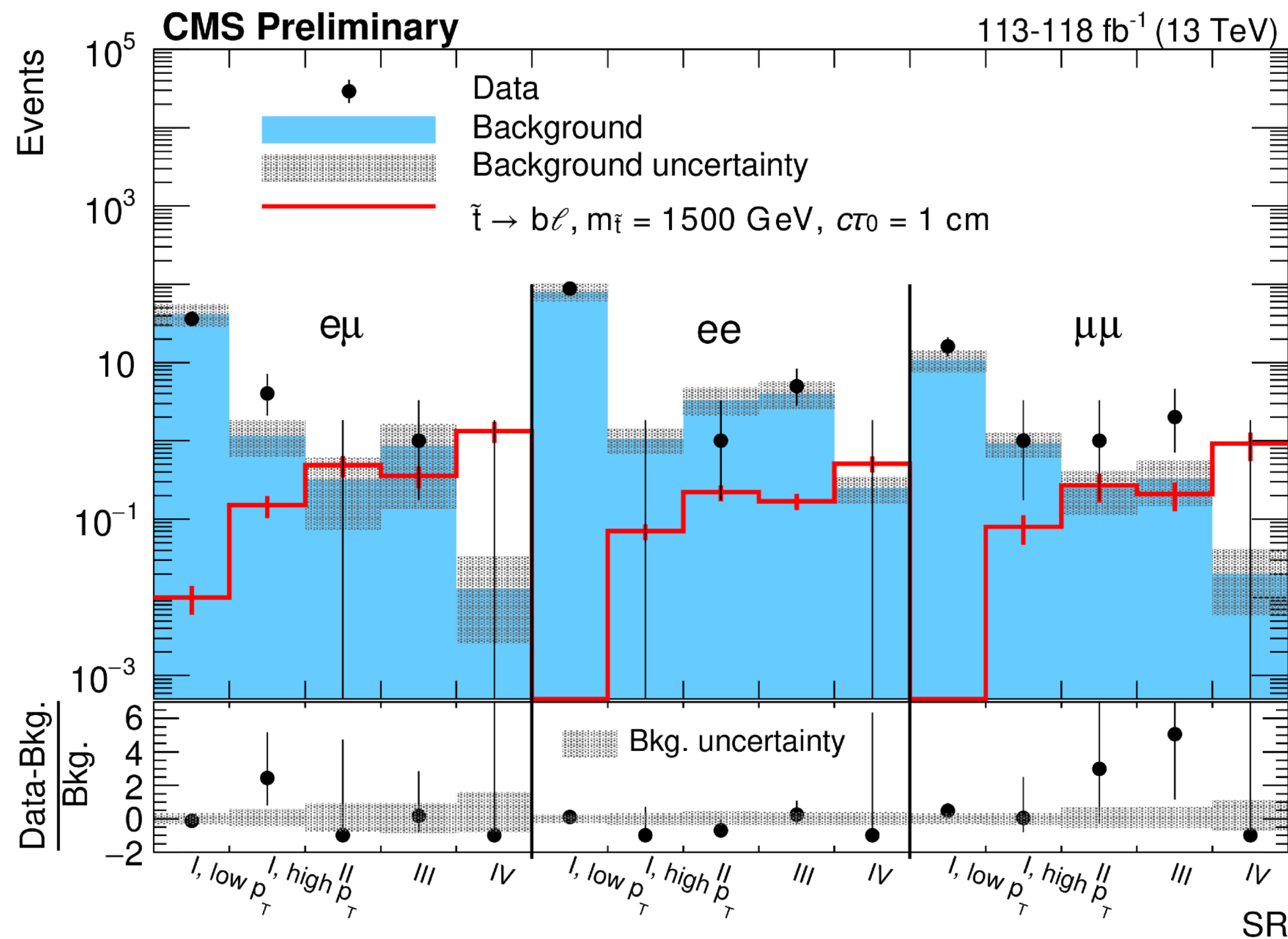


H → SS → 4l

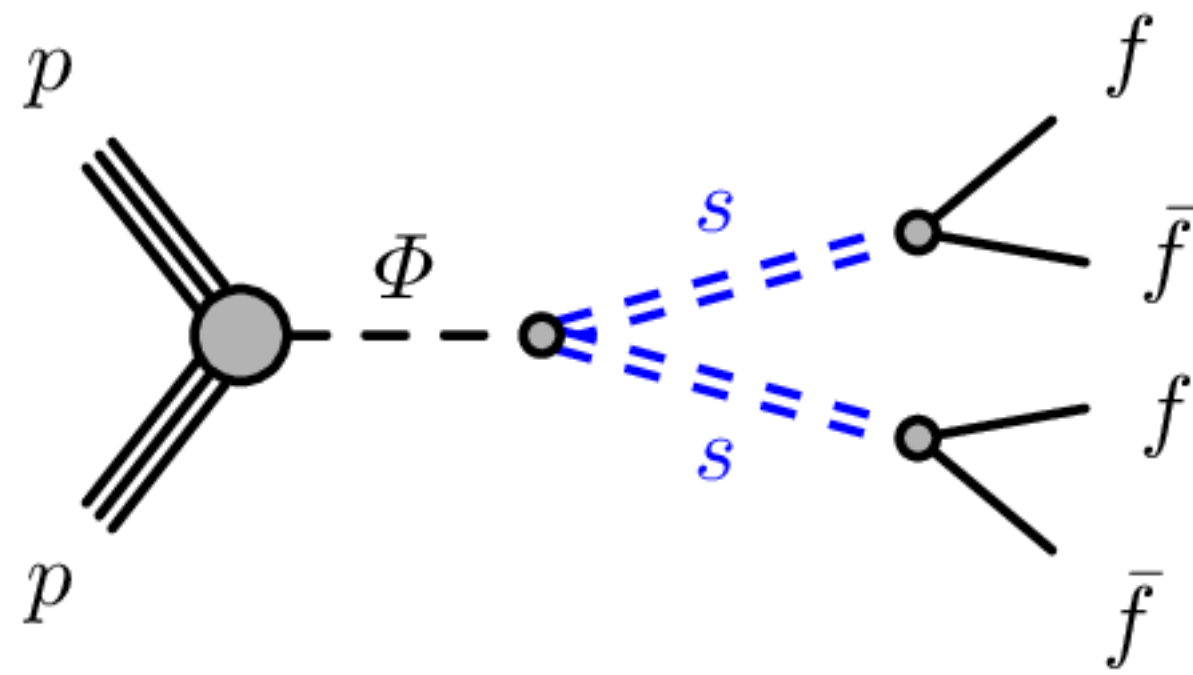


Strategy: Perform a very inclusive search for displaced leptons, without requiring a common vertex and look for $e\mu$, ee , $\mu\mu$ final states where both leptons have large transverse impact parameter

CMS-EXO-18-003



$$H \rightarrow SS \rightarrow 4j$$



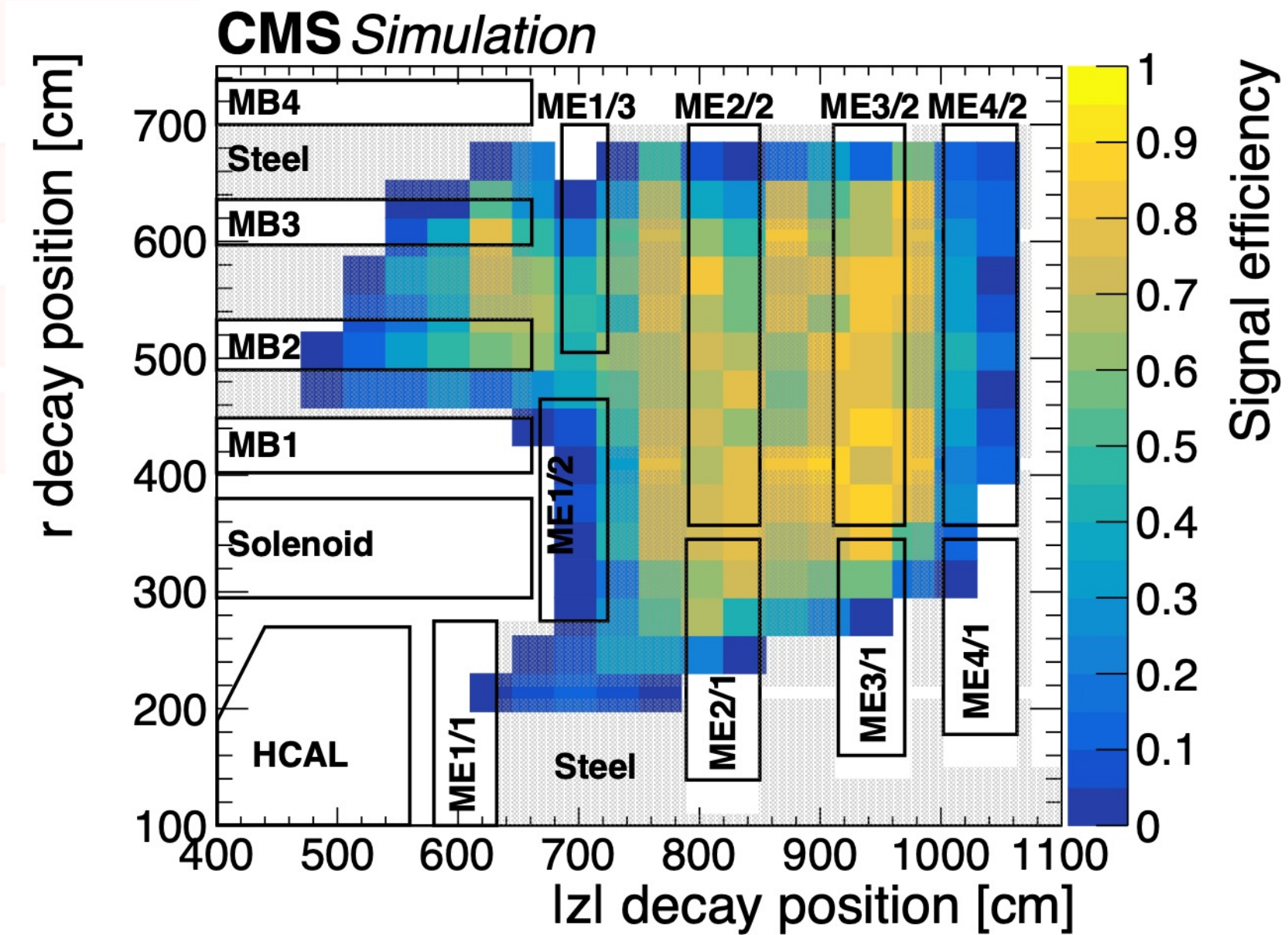
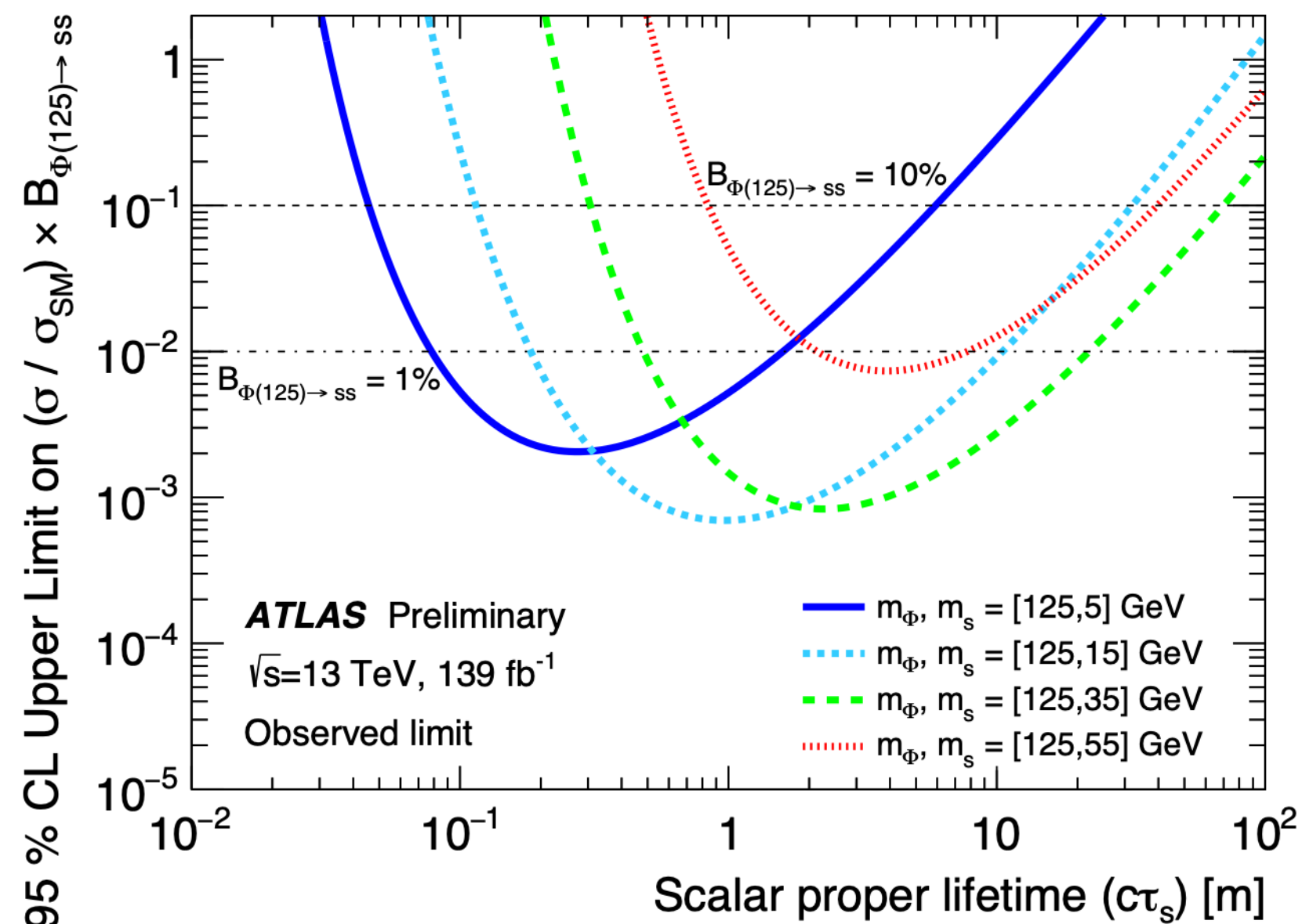
Strategy: Reconstruct decays of LLPs in the muon detectors. No tracks, no jets. Instead clusters in the muon system! Using the muon system like a “sampling calorimeter”

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

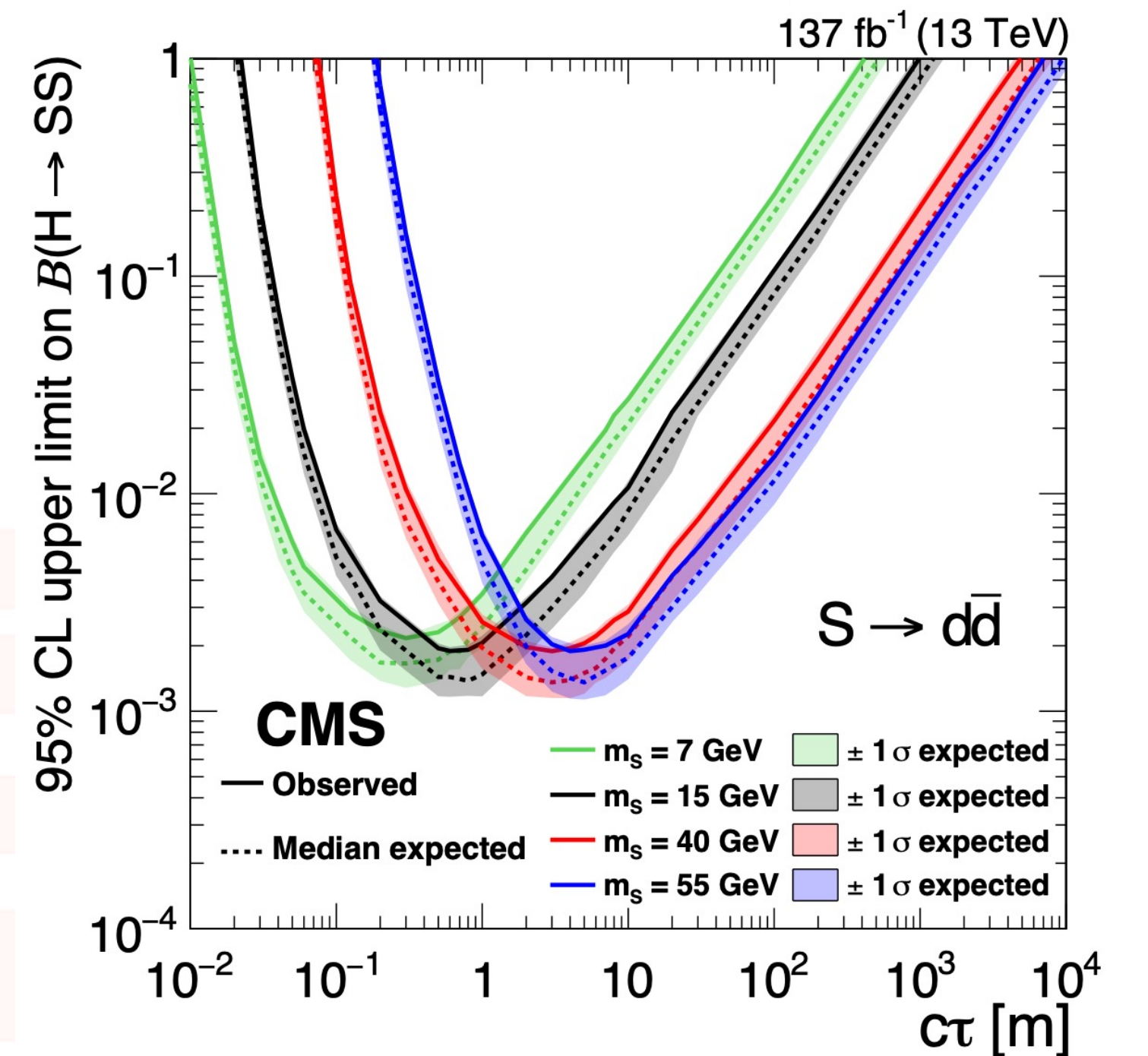
CMS triggers: MET based triggers (MET induced from an ISR jet requirement).

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

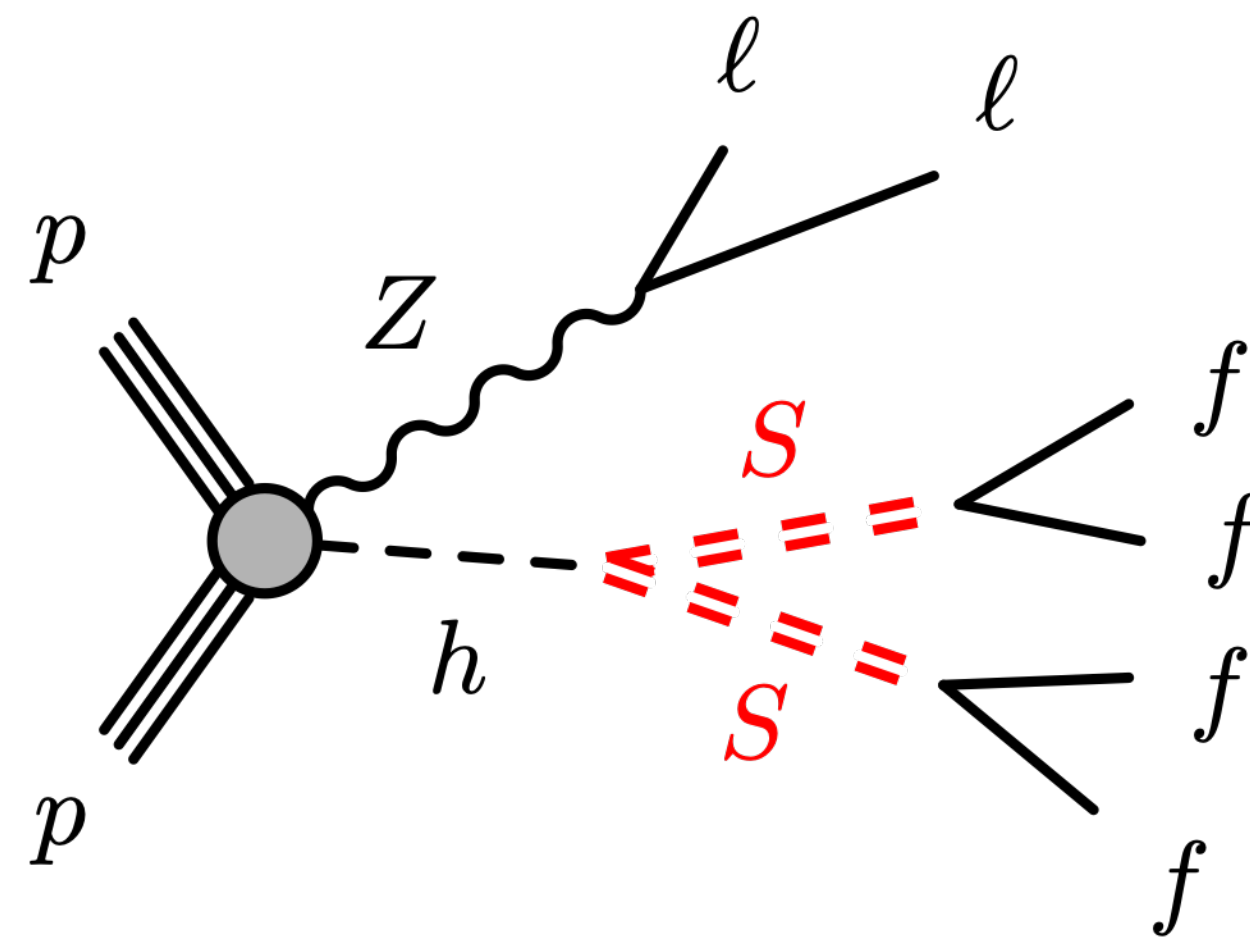
ATLAS-CONF-2021-032



CMS-EXO-20-015

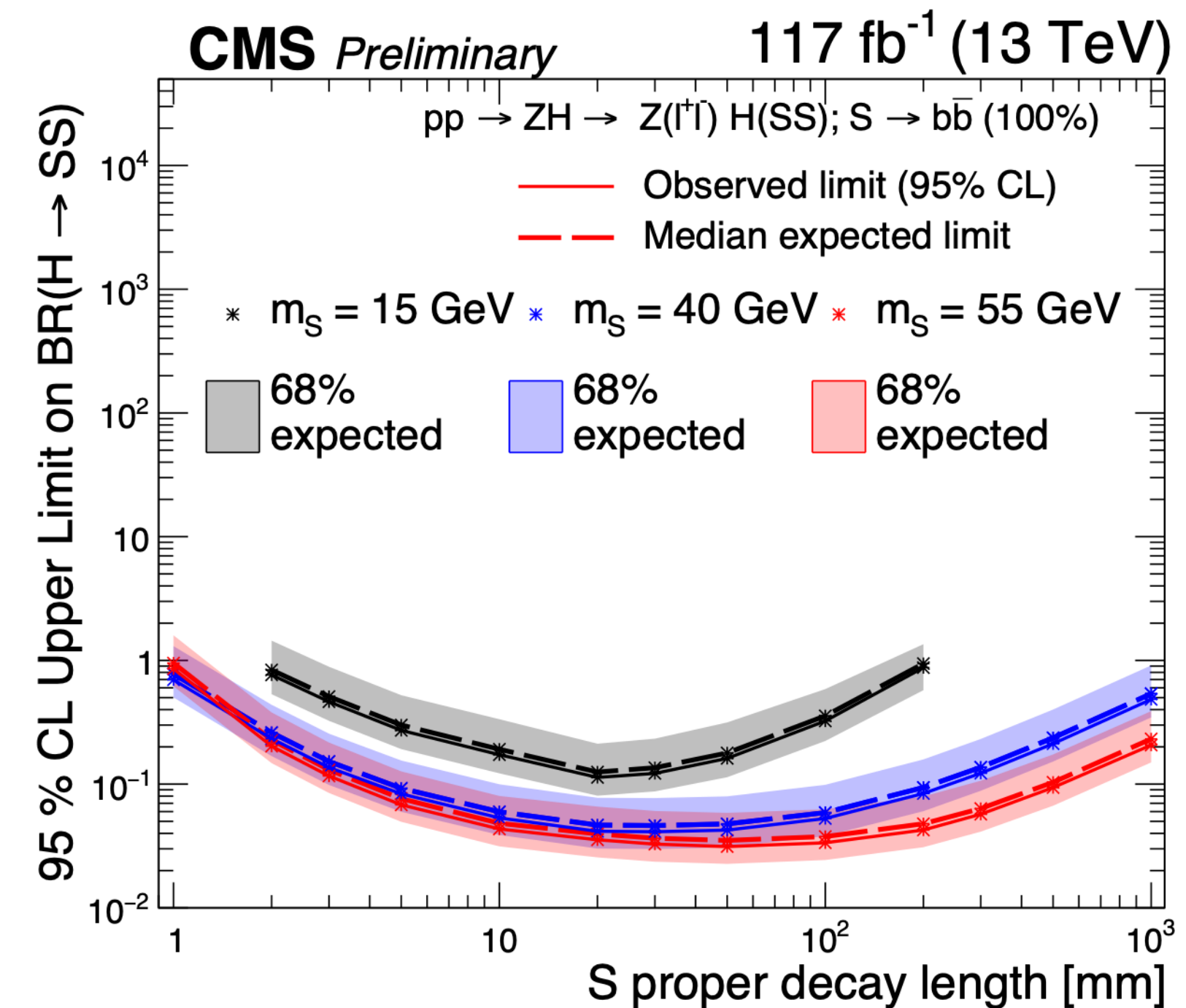
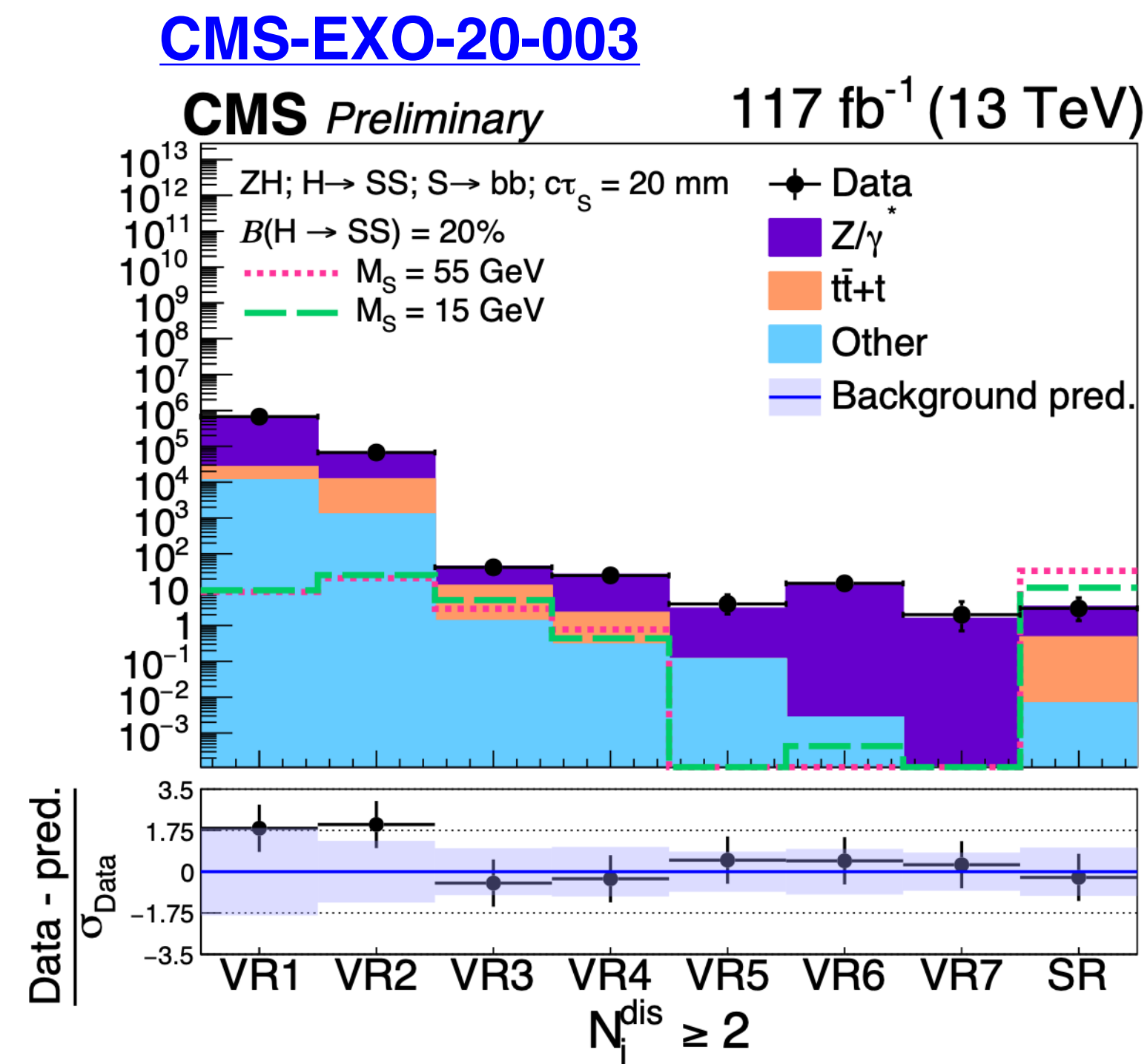
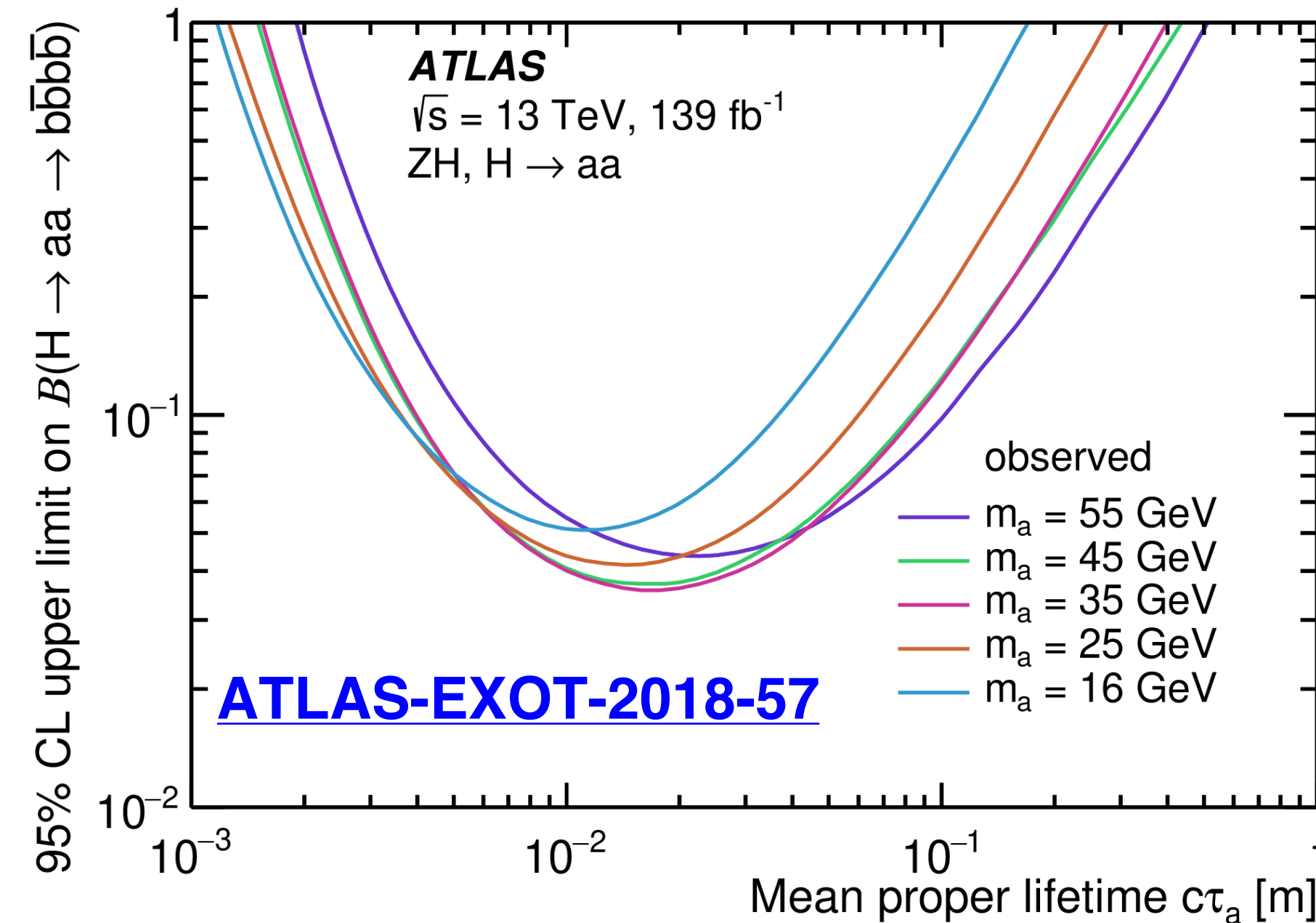


ZH → ZSS → 2l4b

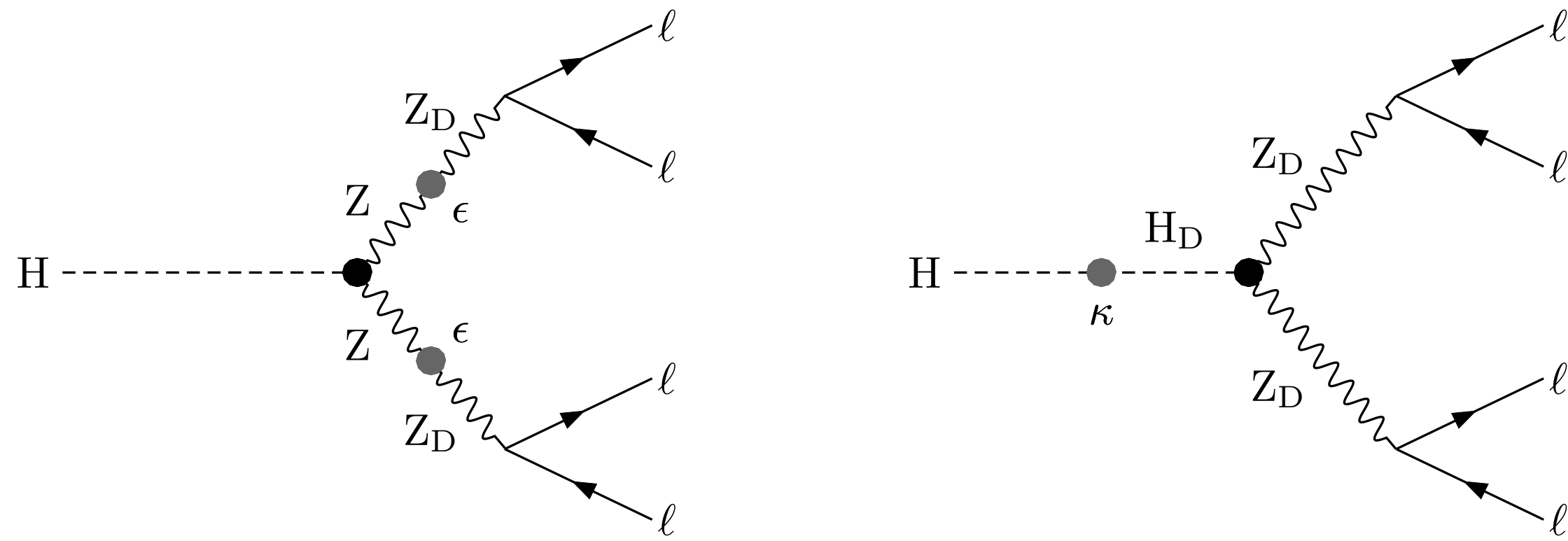


Prompt dilepton (used to trigger) and displaced jet final state associated production is **efficient** to access low pT LLP's jets!

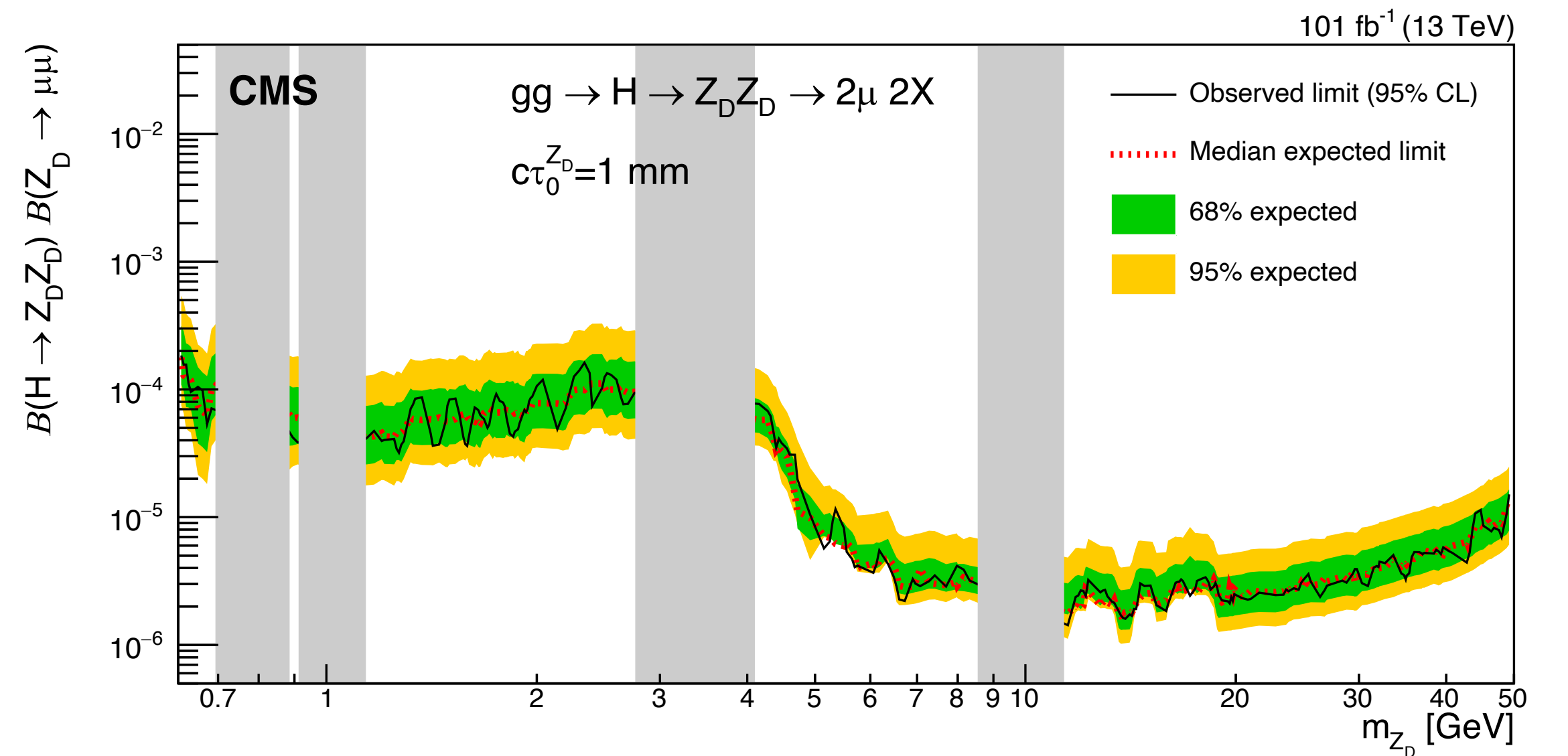
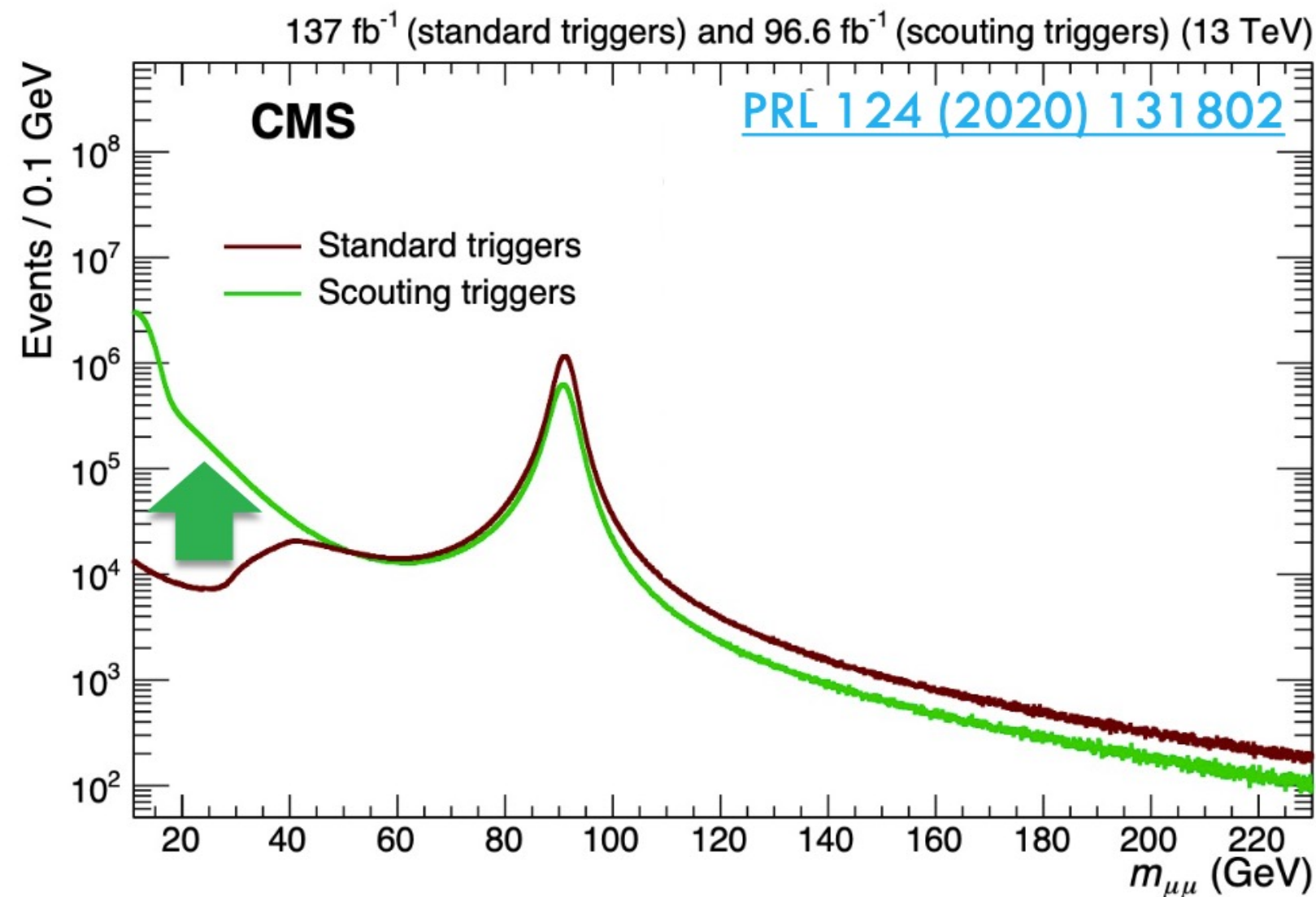
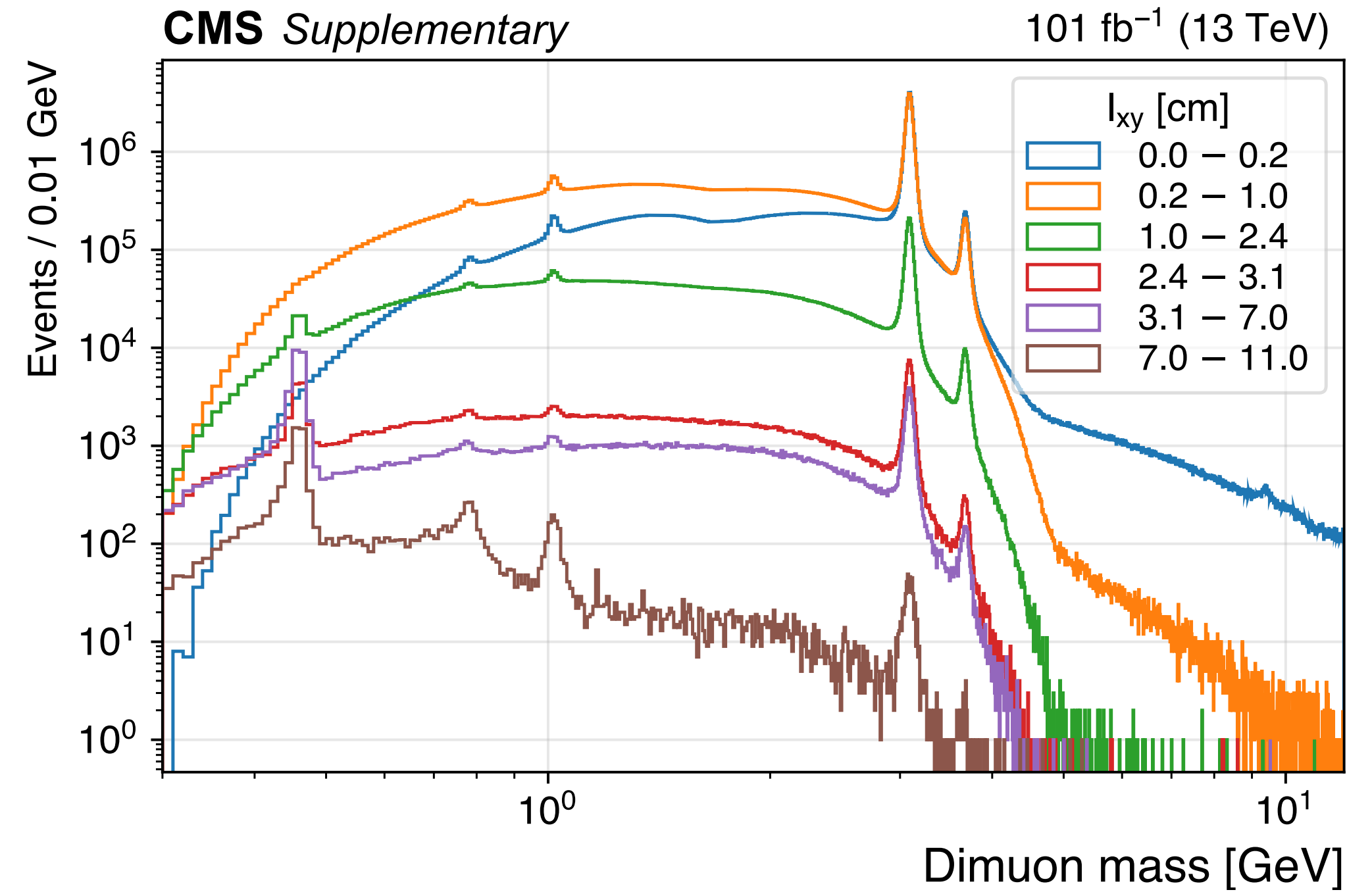
Displaced jet tagging relying on tracks' IP, transverse angle, PV-association



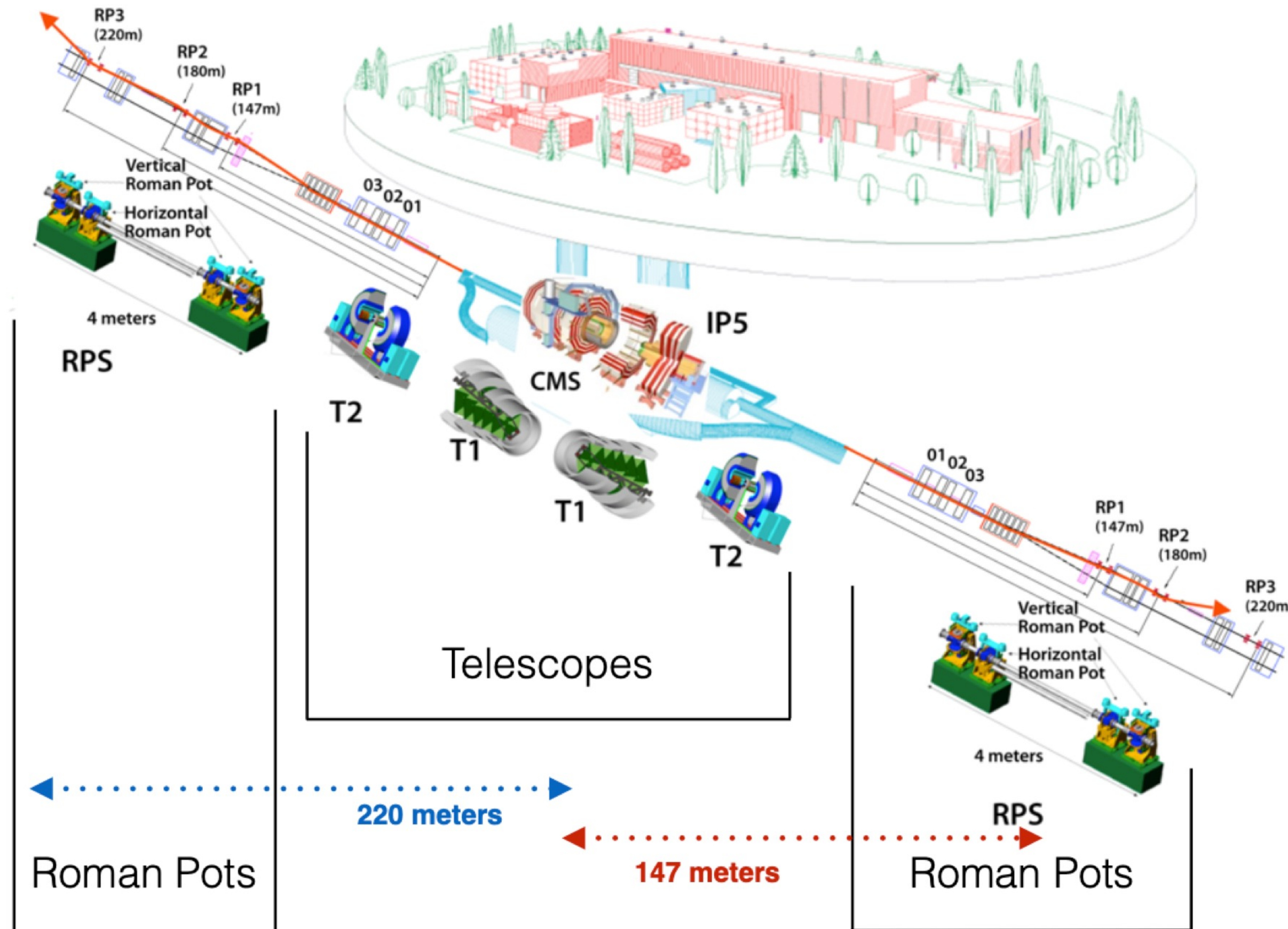
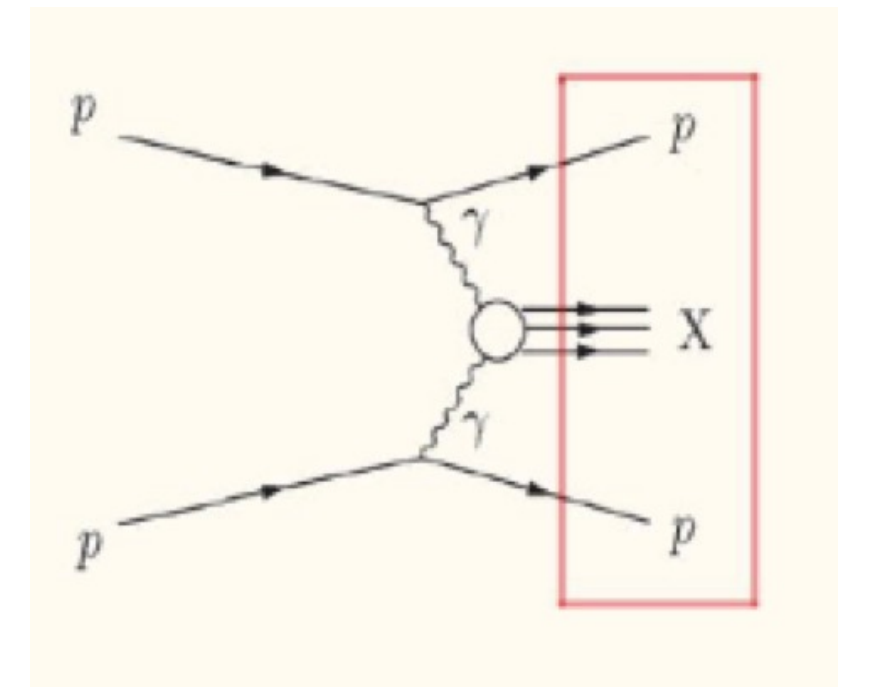
Displaced dimuons with scouting



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



Precision Proton Spectrometer



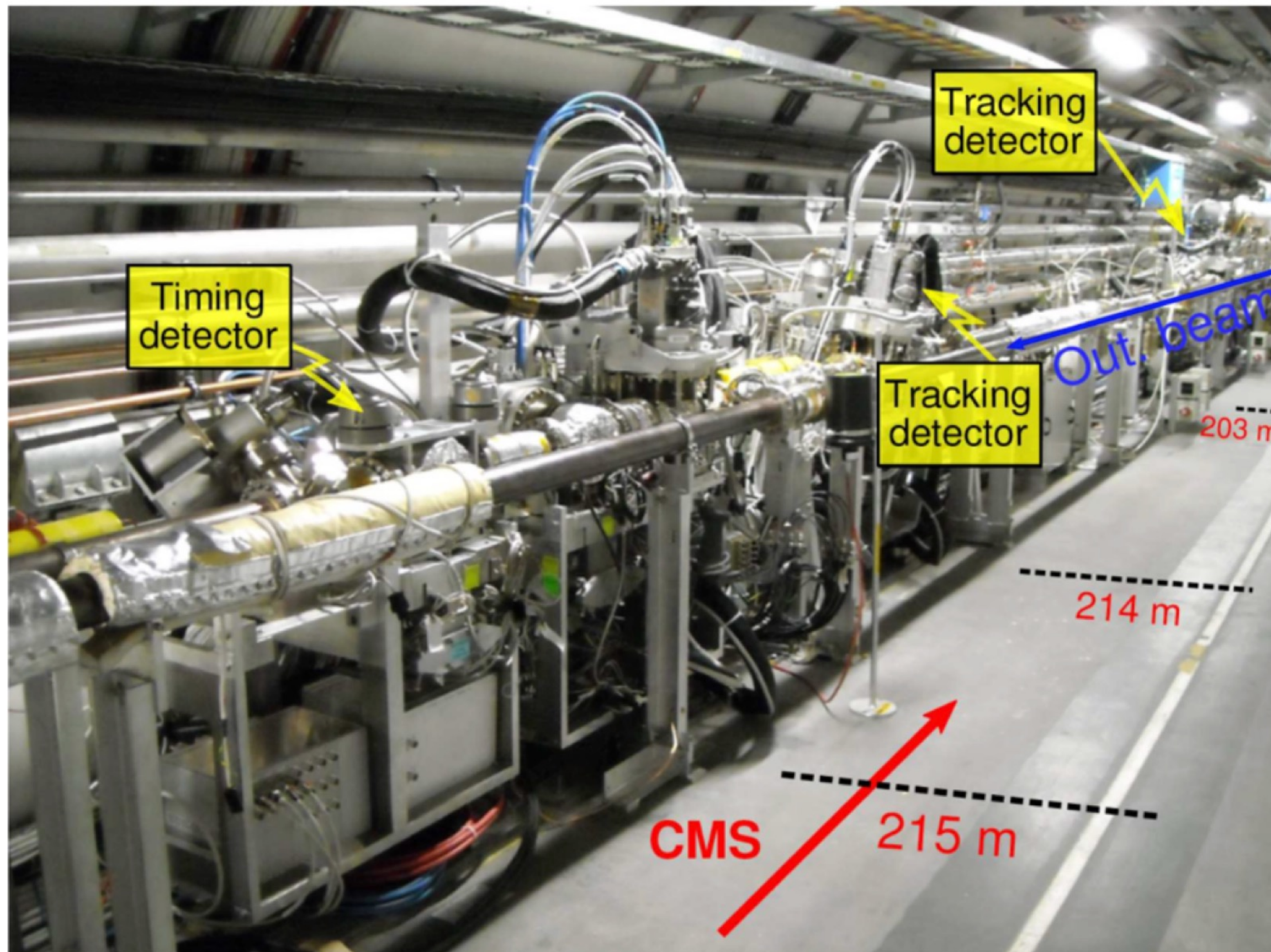
TOTEM experiment is designed to take **precise measurements** of protons as they emerge from collisions **at small angles**.

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:

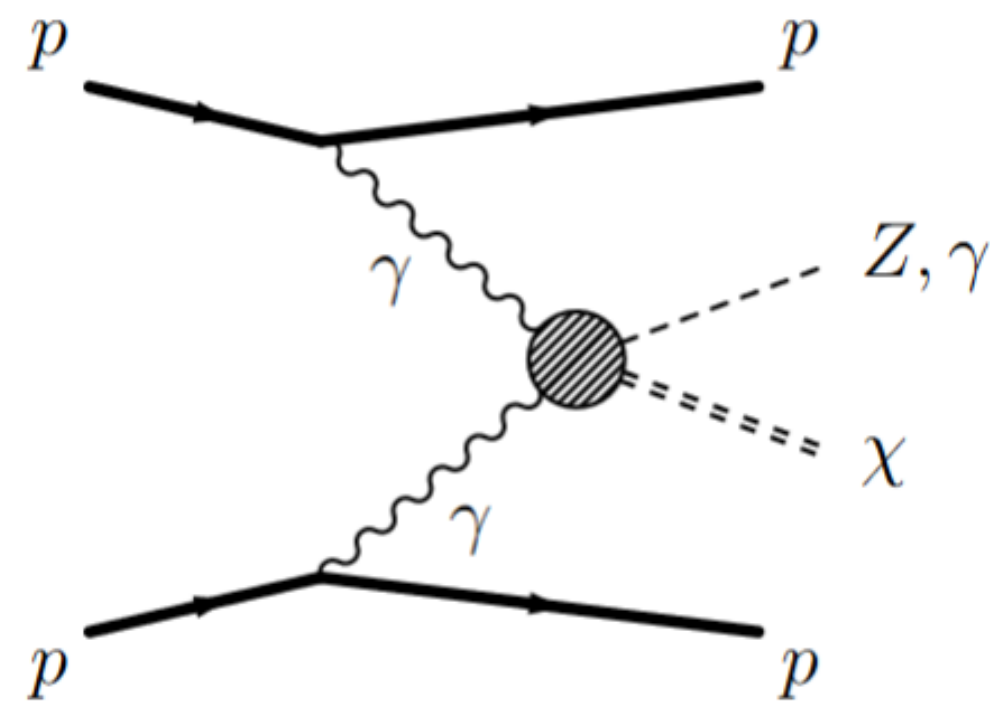
- closure of event kinematics (full 13 TeV energy reconstructed)
- effective background rejection

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

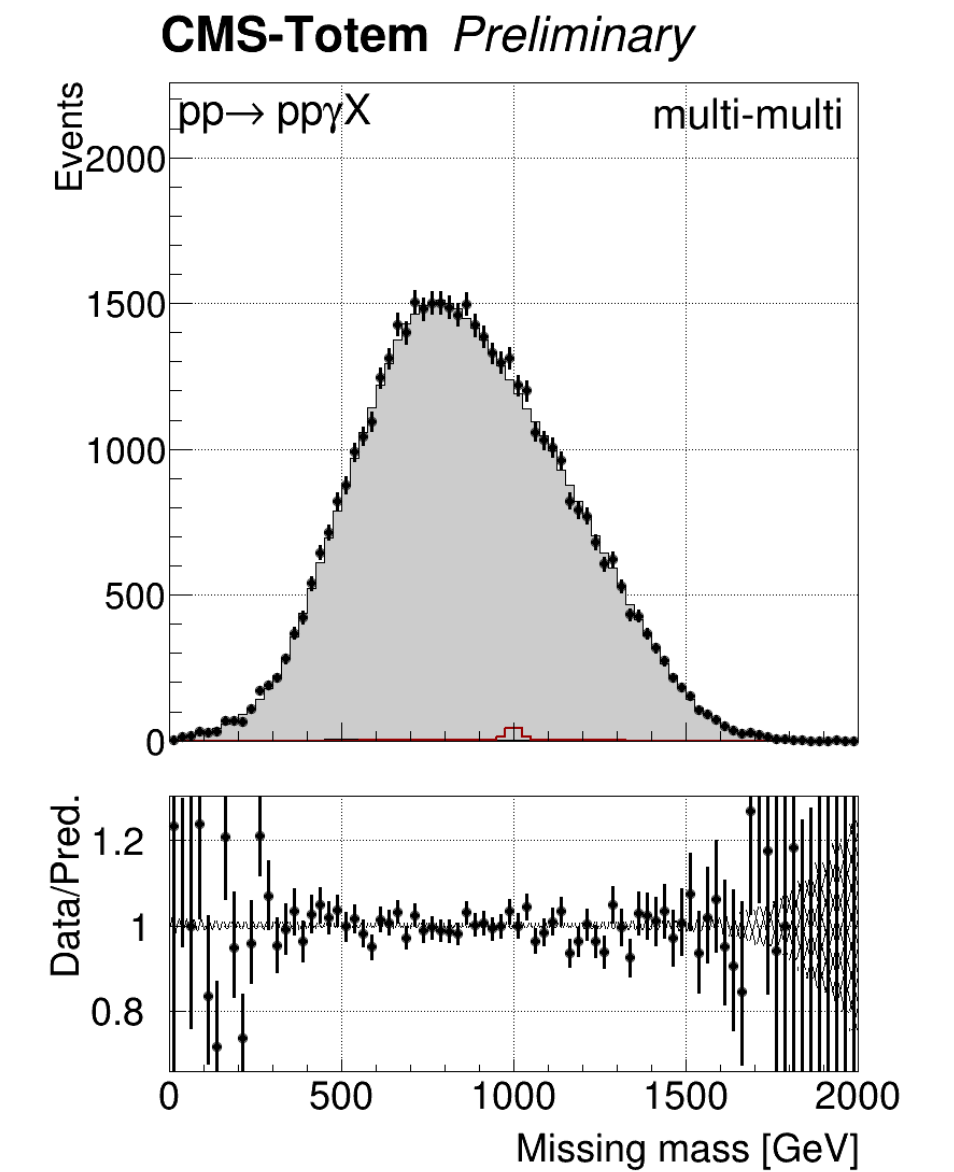
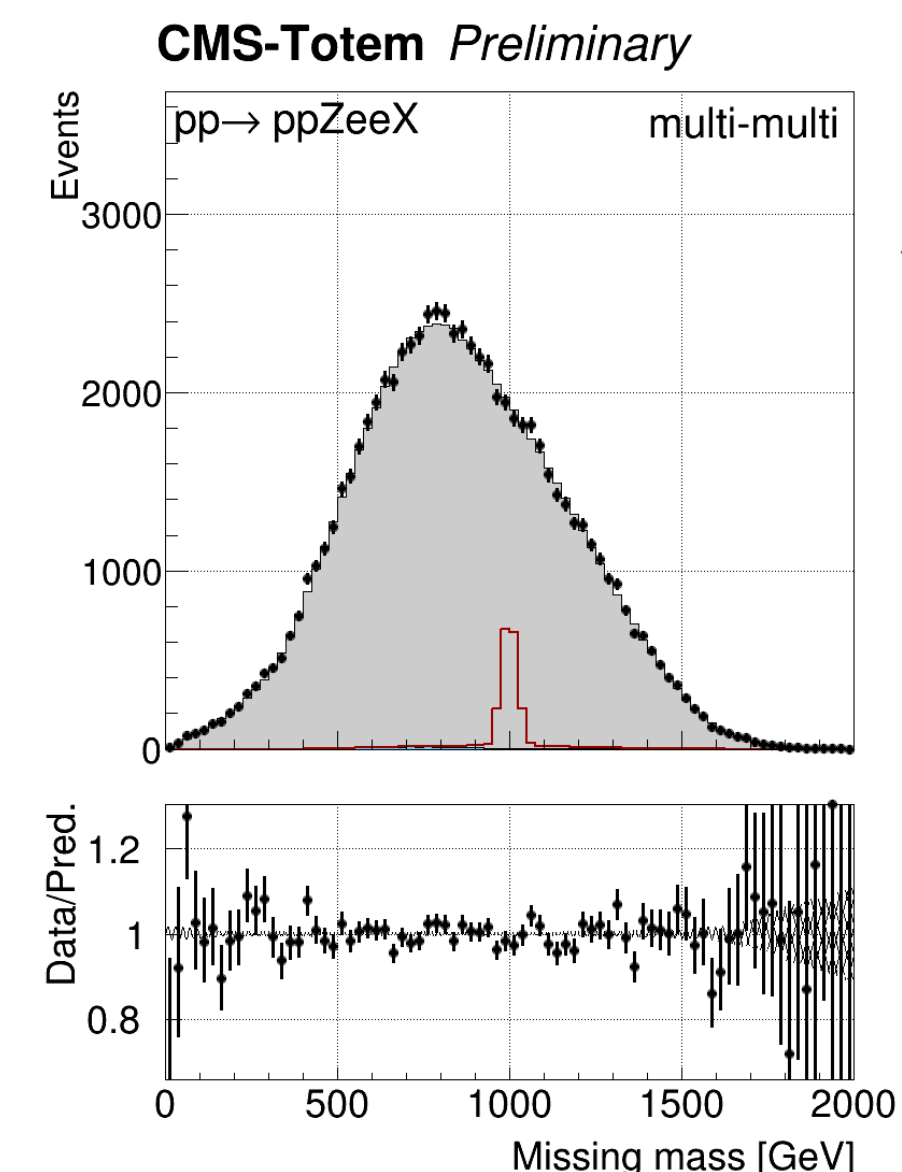
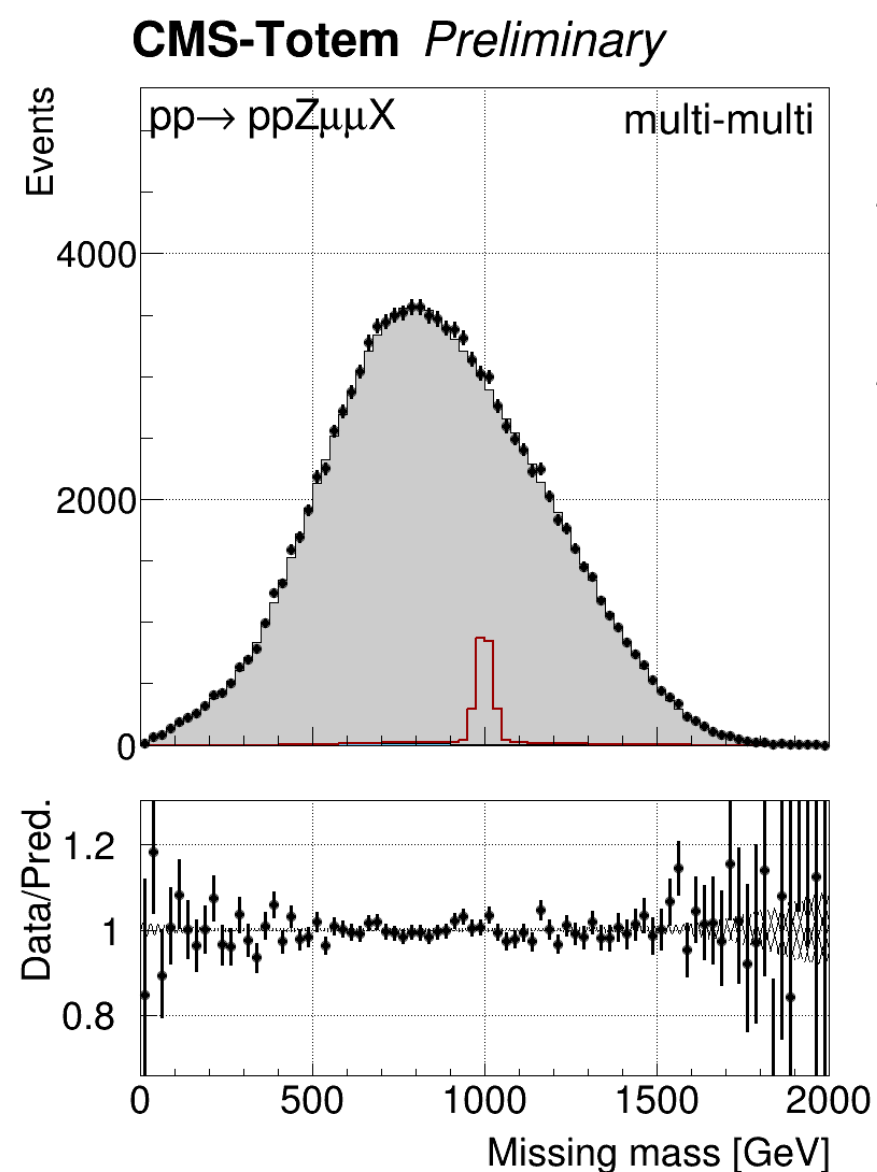
A search for new physics in central exclusive production using the missing mass technique with the CMS-TOTEM precision proton spectrometer [EXO-19-009](#)



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

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

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



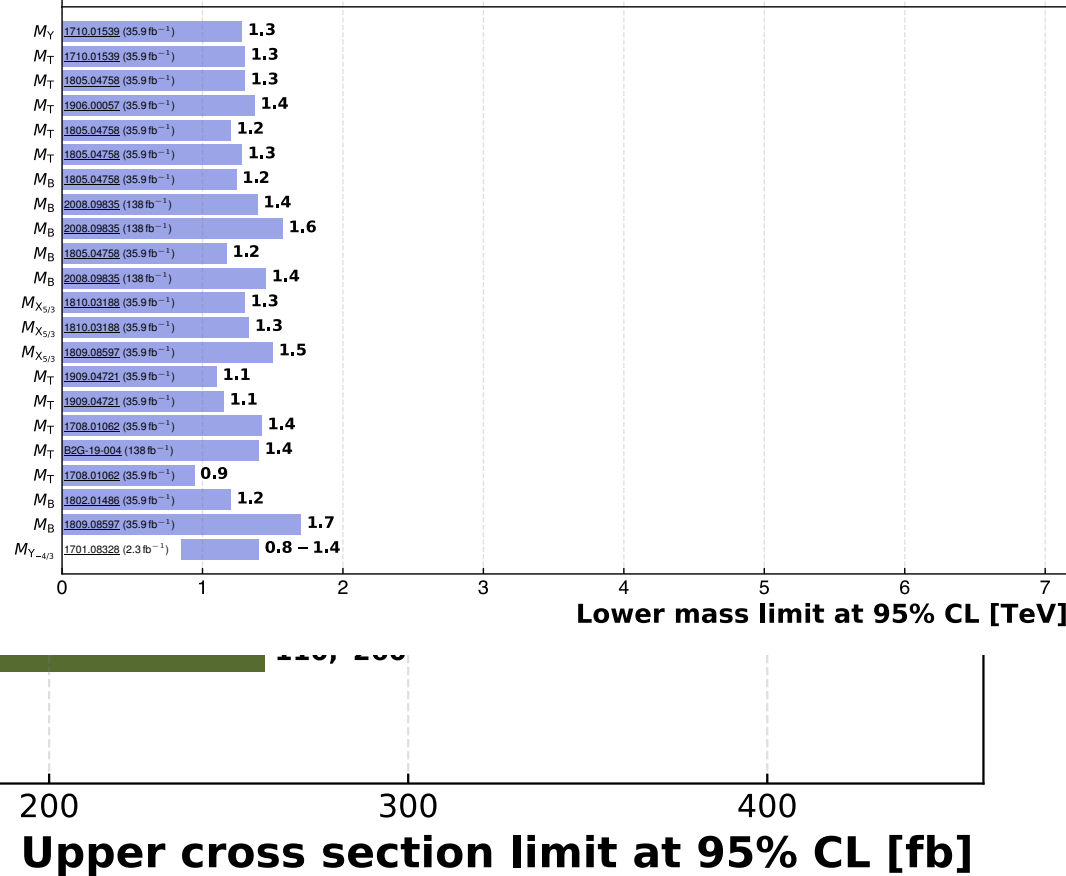
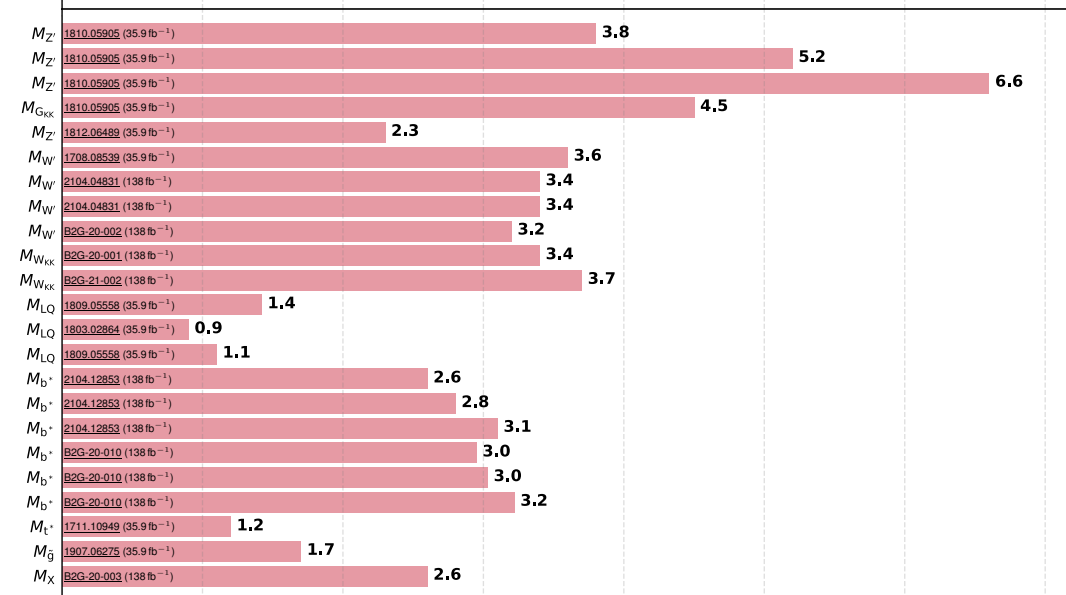
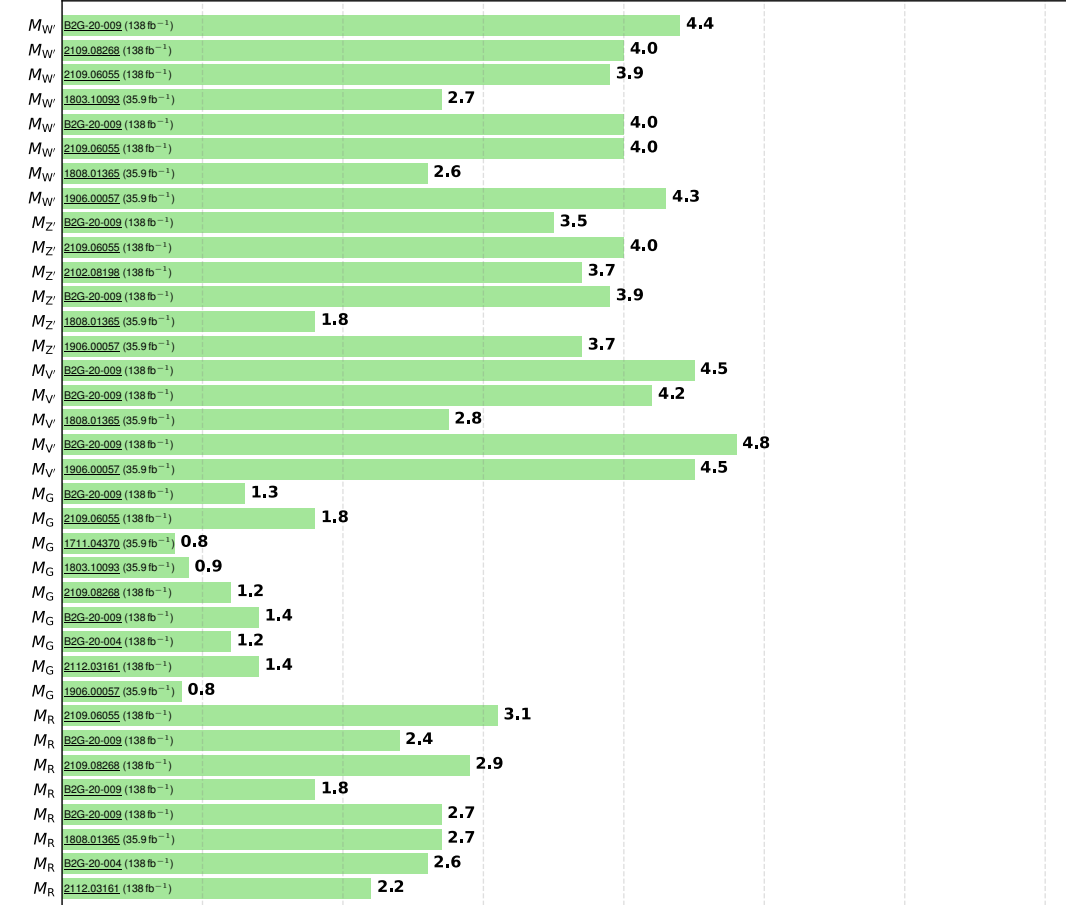
That was just looking at one question... We have many...

ATLAS Heavy Particle Searches* - 95% CL

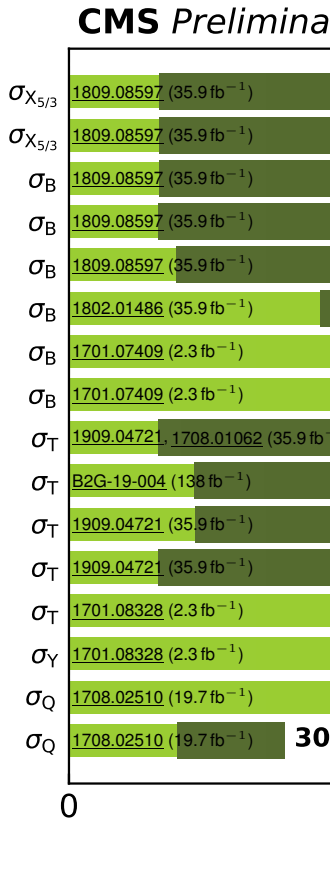
Status: July 2022

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$		
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	M_D	
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_S	
	ADD QBH	-	$2 j$	-	139	M_{th}	
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{th}	
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	G_{KK} mass	
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass	
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	$1 e, \mu$	$2 j / 1 j$	Yes	139	G_{KK} mass	
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	G_{KK} mass	
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass	
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass
SSM $Z' \rightarrow \tau\tau$		2τ	-	-	36.1	Z' mass	
Leptophobic $Z' \rightarrow bb$		-	$2 b$	-	36.1	Z' mass	
Leptophobic $Z' \rightarrow tt$		$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass	
SSM $W' \rightarrow \ell\nu$		$1 e, \mu$	-	Yes	139	W' mass	
SSM $W' \rightarrow \tau\nu$		1τ	-	Yes	139	W' mass	
SSM $W' \rightarrow tb$		-	$\geq 1 b, \geq 1 J$	-	139	W' mass	
HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B		$1 e, \mu$	$2 j / 1 j$	Yes	139	W' mass	
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$ model C		$3 e, \mu$	$2 j$ (VBF)	Yes	139	W' mass	
HVT $W' \rightarrow WH \rightarrow \ell\nu bb$ model B		$1 e, \mu$	$1-2 b, 1-0 j$	Yes	139	W' mass	
HVT $Z' \rightarrow ZH \rightarrow \ell\nu \nu\bar{\nu} bb$ model B	$0 e, \mu$	$1-2 b, 1-0 j$	Yes	139	Z' mass		
LRSM $W_R \rightarrow \mu N_R$	2μ	$1 j$	-	80	W_R mass		
CI	CI $q\bar{q}q$	-	$2 j$	-	37.0	Λ	
	CI $\ell\ell q$	$2 e, \mu$	-	-	139	Λ	
	CI $e\bar{e}bs$	$2 e, \mu$	$1 b$	-	139	Λ	
	CI $\mu\mu bs$	2μ	$1 b$	-	139	Λ	
	CI $t\bar{t}tt$	$\geq 1 e, \mu$	$\geq 1 j$	Yes	36.1	Λ	
DM	Axial-vector med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	m_{med}	
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	m_{med}	
	Vector med. Z' -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	m_{med}	
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	m_{med}	
LQ	Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	Yes	139	LQ mass	
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	Yes	139	LQ mass	
	Scalar LQ 3 rd gen	1τ	$2 b$	Yes	139	LQ mass	
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	LQ mass	
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 b$	-	-	139	LQ mass	
	Scalar LQ 3 rd gen	$0 e, \mu, \geq 1 \tau, 0-2 j, 2 b$	-	-	139	LQ mass	
	Vector LQ 3 rd gen	1τ	$2 b$	Yes	139	LQ mass	
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu/\geq 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass	
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass	
	VLQ $T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS)\geq 3 e, \mu, \geq 1 j$	$\geq 1 j$	Yes	36.1	$T_{5/3}$ mass	
	VLQ $T \rightarrow Ht/Zt$	$1 e, \mu, \geq 1 b, \geq 3 j$	-	-	139	T mass	
	VLQ $Y \rightarrow Wb$	$1 e, \mu, \geq 1 b, \geq 1 j$	-	-	36.1	Y mass	
	VLQ $B \rightarrow Hb$	$0 e, \mu, \geq 2b, \geq 1j, \geq 1J$	-	-	139	B mass	
	VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	τ' mass	
	Resonances	$Z' \rightarrow \ell\ell$ ($\Gamma/M_Z=1\%$)	-	-	-	3.8	
		$Z' \rightarrow \ell\ell$ ($\Gamma/M_Z=10\%$)	-	-	-	5.2	
		$Z' \rightarrow \ell\ell$ ($\Gamma/M_Z=30\%$)	-	-	-	6.6	
$G_{KK} \rightarrow \ell\ell$ (Kaluza-Klein)		-	-	-	4.5		
$Z' \rightarrow t\bar{t}$ (Zt, tH)		-	-	-	2.3		
$W \rightarrow tb$ (L, RH)		-	-	-	3.6		
$W \rightarrow tb$ ($0f, RH$)		-	-	-	3.4		
$W \rightarrow tb$ ($0f, LH$)		-	-	-	3.4		
$W \rightarrow tb$ (Tb) ($M_{0f} = 2/3 M_W$)		-	-	-	3.2		
$W_{\alpha\beta} \rightarrow RW \rightarrow WWW$ (L)		-	-	-	3.4		
Very heavy fermions	$W_{\alpha\beta} \rightarrow RW \rightarrow WWW$ ($0f + 1f$)	-	-	-	3.7		
	$LQ \rightarrow \ell t u$	-	-	-	1.4		
	$LQ \rightarrow \ell t t$	-	-	-	0.9		
	$LQ \rightarrow b b \nu$	-	-	-	1.1		
	$b' \rightarrow tW$ ($0f, LH$)	-	-	-	2.6		
	$b' \rightarrow tW$ ($0f, RH$)	-	-	-	2.8		
	$b' \rightarrow tW$ ($0f, LH+RH$)	-	-	-	3.1		
	$b' \rightarrow tW$ ($0f + 1f, LH$)	-	-	-	3.0		
	$b' \rightarrow tW$ ($0f + 1f, RH$)	-	-	-	3.0		
	$b' \rightarrow tW$ ($0f + 1f, LH+RH$)	-	-	-	3.2		
Resonances	$t' \rightarrow tgg$	-	-	-	1.2		
	Stealth $\tilde{g} \rightarrow \tilde{q}\bar{q}$ ($y + 2j$ jets, $M_{\tilde{g}} = 0.2 \text{ TeV}$)	-	-	-	1.7		
	$X \rightarrow aa$ ($bbbb, M_a = 0.1 \text{ TeV}, M_{\tilde{a}}/M = 8$)	-	-	-	2.6		
	$YY \rightarrow bWbW$	-	-	-	1.3		
	$TT \rightarrow bWbW$	-	-	-	1.3		
	$TT \rightarrow tZtZ$	-	-	-	1.3		
	$TT \rightarrow tHtH$	-	-	-	1.4		
	TT (Singlet)	-	-	-	1.2		
	TT (Doublet)	-	-	-	1.3		
	$BB \rightarrow tWtW$	-	-	-	1.2		
Resonances	$BB \rightarrow bZbZ$	-	-	-	1.4		
	$BB \rightarrow bHbH$	-	-	-	1.6		
	BB (Singlet)	-	-	-	1.2		
	BB (Doublet)	-	-	-	1.4		
	$X_{5/3} X_{5/3} \rightarrow tWtW$ (Singlet)	-	-	-	1.3		
	$X_{5/3} X_{5/3} \rightarrow tWtW$ (Doublet)	-	-	-	1.3		
	$X_{5/3} \rightarrow tW$ (Singlet, $\Gamma/M_{5/3}=30\%$)	-	-	-	1.5		
	$T \rightarrow tH$ (Singlet, $\Gamma/M_T=10\%$)	-	-	-	1.1		
	$T \rightarrow tH$ (Singlet, $\Gamma/M_T=30\%$)	-	-	-	1.1		
	$T \rightarrow tZ$ (Singlet, $\Gamma/M_T=10\%$)	-	-	-	1.4		
Resonances	$T \rightarrow tZ$ (Singlet, $\Gamma/M_T=30\%$)	-	-	-	1.4		
	$T \rightarrow tZ$ (Doublet, $\Gamma/M_T=10\%$)	-	-	-	0.9		
	$B \rightarrow bH$ (Doublet, $\Gamma/M_B=30\%$)	-	-	-	1.2		
	$B \rightarrow tW$ (Doublet, $\Gamma/M_B=30\%$)	-	-	-	1.7		
	$Y_{4/3} \rightarrow bW$	-	-	-	0.8 - 1.4		
	$M_{\tilde{g}}$ 1708.02510 (19.7 fb^{-1})	-	-	-	1.3		
	$M_{\tilde{t}_1}$ 1710.01539 (35.9 fb^{-1})	-	-	-	1.3		
	$M_{\tilde{t}_2}$ 1805.04758 (35.9 fb^{-1})	-	-	-	1.3		
	$M_{\tilde{b}_1}$ 1908.04057 (35.9 fb^{-1})	-	-	-	1.4		
	$M_{\tilde{b}_2}$ 1805.04758 (35.9 fb^{-1})	-	-	-	1.2		
Resonances	$M_{\tilde{X}_{5/3}}$ 1810.03188 (35.9 fb^{-1})	-	-	-	1.3		
	$M_{\tilde{X}_{3/3}}$ 1810.03188 (35.9 fb^{-1})	-	-	-	1.3		
	M_{Q_1} 1708.02510 (19.7 fb^{-1})	-	-	-	0.7		
	M_{Q_2} 1708.02510 (19.7 fb^{-1})	-	-	-	0.6		
	M_{Q_3} 1708.02510 (19.7 fb^{-1})	-	-	-	0.4		
	M_{Q_4} 1708.02510 (19.7 fb^{-1})	-	-	-	0.6		
	M_{Q_5} 1708.02510 (19.7 fb^{-1})	-	-	-	0.8		
	$M_{\tilde{g}}$ 1708.02510 (19.7 fb^{-1})	-	-	-	1.3		
	$M_{\tilde{t}_1}$ 1710.01539 (35.9 fb^{-1})	-	-	-	1.3		
	$M_{\tilde{t}_2}$ 1805.04758 (35.9 fb^{-1})	-	-	-	1.3		

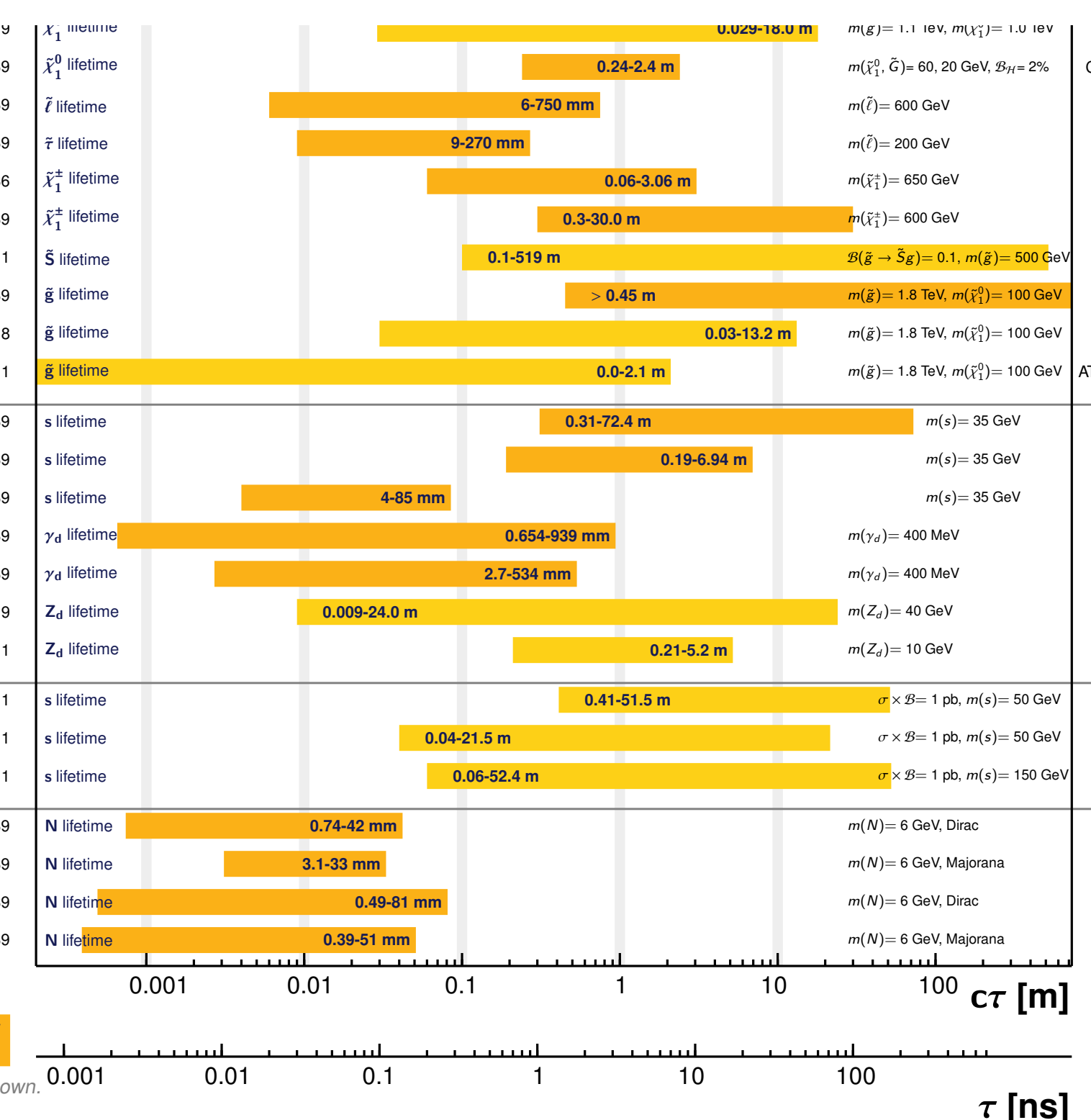
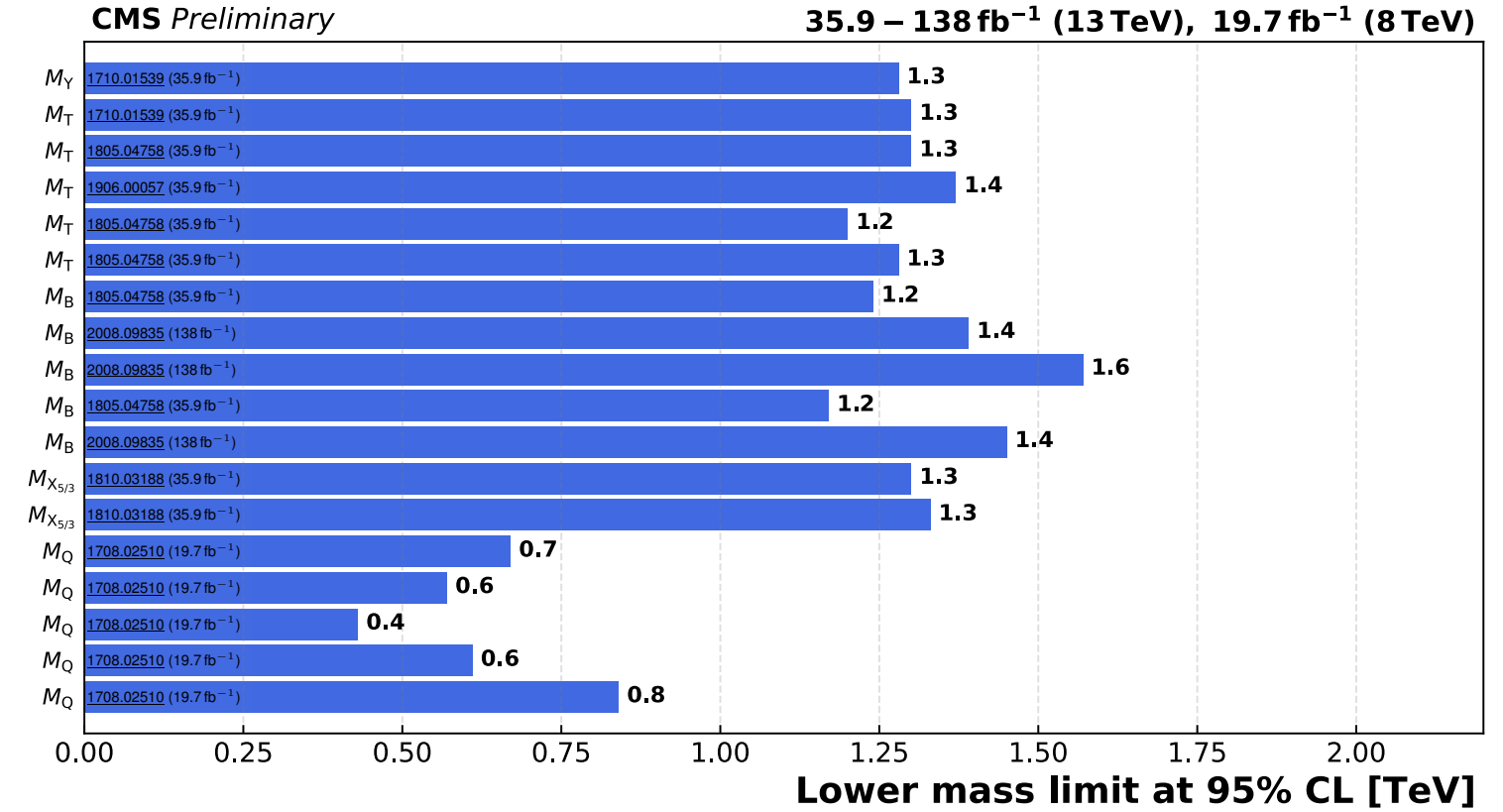
Overview of CMS B2G Results March 2022
CMS Preliminary 2.3 – 138 fb⁻¹ (13 TeV)



Overview of CMS B2G Results November 2021



Overview of CMS B2G Results November 2021
CMS Preliminary 35.9 – 138 fb⁻¹ (13 TeV), 19.7 fb⁻¹ (8 TeV)



Vector-like quark single production

$X_{5/3} t q, X_{5/3} \rightarrow tW$ (RH)	1809.08597 (35.9 fb^{-1})
$X_{5/3} t q, X_{5/3} \rightarrow tW$ (LH)	1809.08597 (35.9 fb^{-1})
$Btq, B \rightarrow tW$ (RH)	1809.08597 (35.9 fb^{-1})
$Bbq, B \rightarrow tW$ (RH)	1809.08597 (35.9 fb^{-1})
$Bbq, B \rightarrow tW$ (LH)	1809.08597 (35.9 fb^{-1})
$Bbq, B \rightarrow bH$ (LH)	1802.01486 (35.9 fb^{-1})
$Bbq, B \rightarrow bZ$ (LH)	1701.07409 (2.3 fb^{-1})
$Btq, B \rightarrow bZ$ (LH)	1701.07409 (2.3 fb^{-1})
$Ttq, T \rightarrow tZ$ (RH)	$1909.04721, 1708.01062$ (35.9 fb^{-1})
$Tbq, T \rightarrow tZ$ (LH)	1820.19004 (138 fb^{-1})
$Ttq, T \rightarrow tH$ (RH)	1909.04721 (35.9 fb^{-1})
$Tbq, T \rightarrow tH$ (LH)	1909.04721 (35.9 fb^{-1})
$Tbq, T \rightarrow bW$ (LH)	1701.08328 (2.3 fb^{-1})
$Y_{-4/3} b q, Y_{-4/3} \rightarrow bW$	1701.08328 (2.3 fb^{-1})
$Qq, Q \rightarrow qZ$	1708.02510 (19.7 fb^{-1})
$Qq, Q \rightarrow qW$	1708.02510 (19.7 fb^{-1})

AT Sta Vector-like quark pair production

$YY \rightarrow bWbW$	1.3
$TT \rightarrow bWbW$	1.3
$TT \rightarrow tZtZ$	1.3
$TT \rightarrow tHtH$	1.4
TT (Singlet)	1.2
TT (Doublet)	1.3
$BB \rightarrow tWtW$	1.2
$BB \rightarrow bZbZ$	1.4
$BB \rightarrow bHbH$	1.6
BB (Singlet)	1.2
BB (Doublet)	1.4
$X_{5/3} X_{5/3} \rightarrow tWtW$ (Singlet)	1.3
$X_{5/3} X_{5/3} \rightarrow tWtW$ (Doublet)	1.3
QQ (Singlet)	0.7
QQ (Doublet)	0.6
$QQ \rightarrow qHqH$	0.4
$QQ \rightarrow qZqZ$	0.6
$QQ \rightarrow qWqW$	0.8

SUSY

$GSM \chi_1^0 \rightarrow \ell \bar{\ell}$	displaced dimuon	32.9	χ_1^0 lifetime	0.029-18.0 m
GMSB	non-pointing or delayed γ	139	$\tilde{\ell}$ lifetime	0.24-2.4 m
GMSB $\tilde{\ell} \rightarrow \ell \tilde{G}$	displaced lepton	139	$\tilde{\tau}$ lifetime	6-750 mm
GMSB $\tilde{\tau} \rightarrow \tau \tilde{G}$	displaced lepton	139	$\tilde{\chi}_1^{\pm}$ lifetime	9-270 mm
AMS $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-$	disappearing track	136	$\tilde{\chi}_1^{\pm}$ lifetime	0.06-3.06 m
AMS $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-$	large pixel dE/dx	139	$\tilde{\chi}_1^{\pm}$ lifetime	0.3-30.0 m
Stealth SUSY	2 MS vertices	36.1	\tilde{S} lifetime	0.1-519 m
Split SUSY	large pixel dE/dx	139	\tilde{g} lifetime	> 0.45 m
Split SUSY	displaced vtx + E_T^{miss}	32.8	\tilde{g} lifetime	0.03-13.2 m
Split SUSY	$0 \ell, 2-6$ jets + E_T^{miss}	36.1	\tilde{g} lifetime	0.0-2.1 m

Higgs BR = 10%

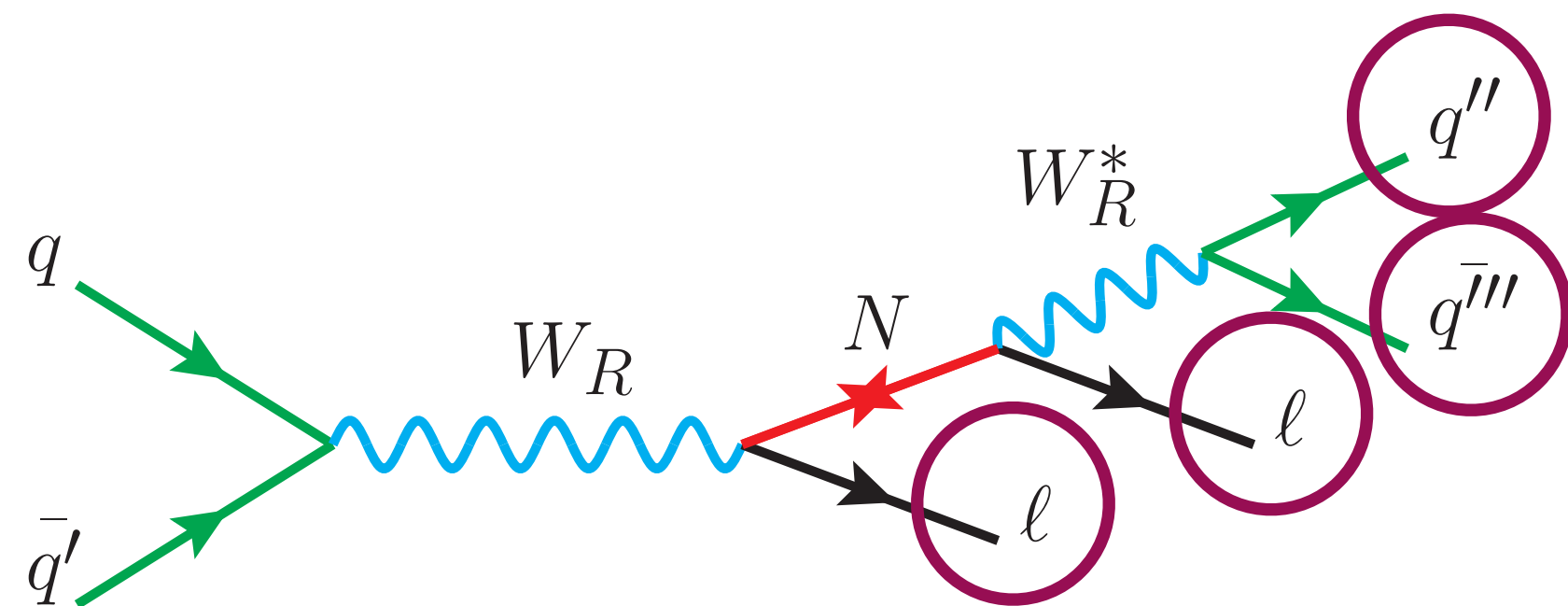
$H \rightarrow s\bar{s}$	2 MS vertices	139	s lifetime	0.31-72.4 m
$H \rightarrow s\bar{s}$	2 low-EMF trackless jets	139	s lifetime	0.19-6.94 m
VH with $H \rightarrow s\bar{s} \rightarrow bbbb$	$2\ell + 2$ displ. vertices	139	s lifetime	4-85 mm
FRVZ $H \rightarrow 2\gamma_d + X$	2μ -jets	139	γ_d lifetime	0.654-939 mm
FRVZ $H \rightarrow 4$				

Some highlights with excesses from Run2

Search for W_R boson and a N: Strategy

The **dominant production** process for the 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 ($g_L = g_R$).



Resolved Category

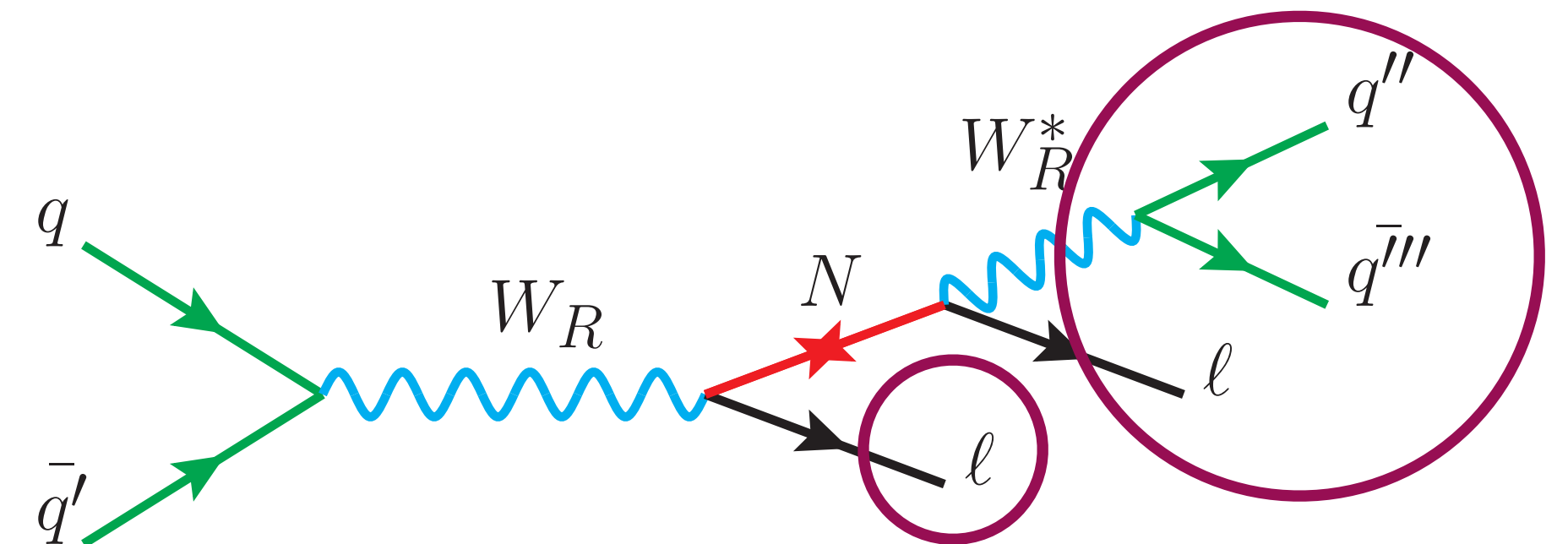
Trigger on single lepton, then ...

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

Considering only ee and $\mu\mu$ lepton pairs

Boosted Category (New**)

W_R is heavy compared to the N ($m_{W_R}/m_N > 10$).



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

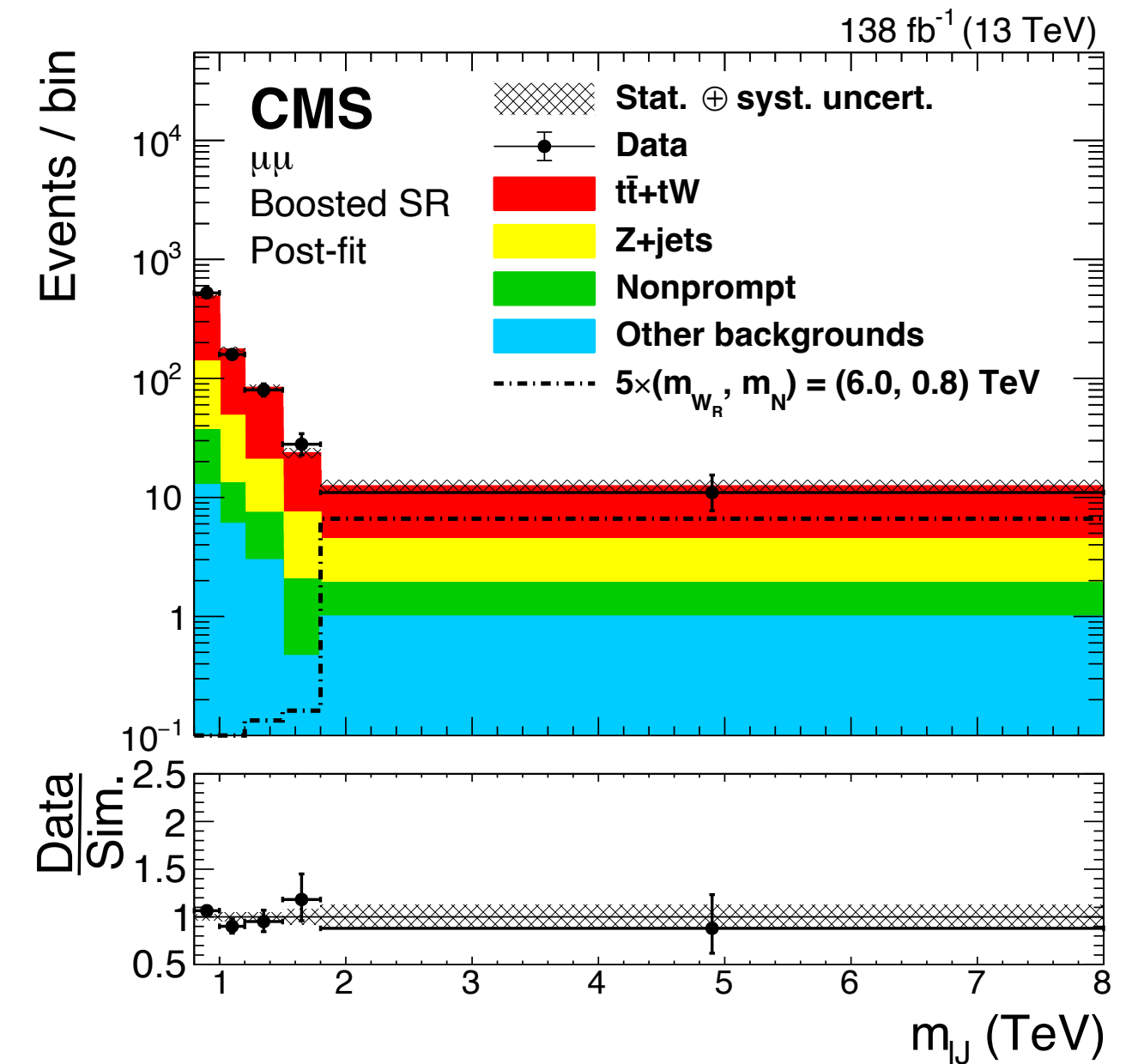
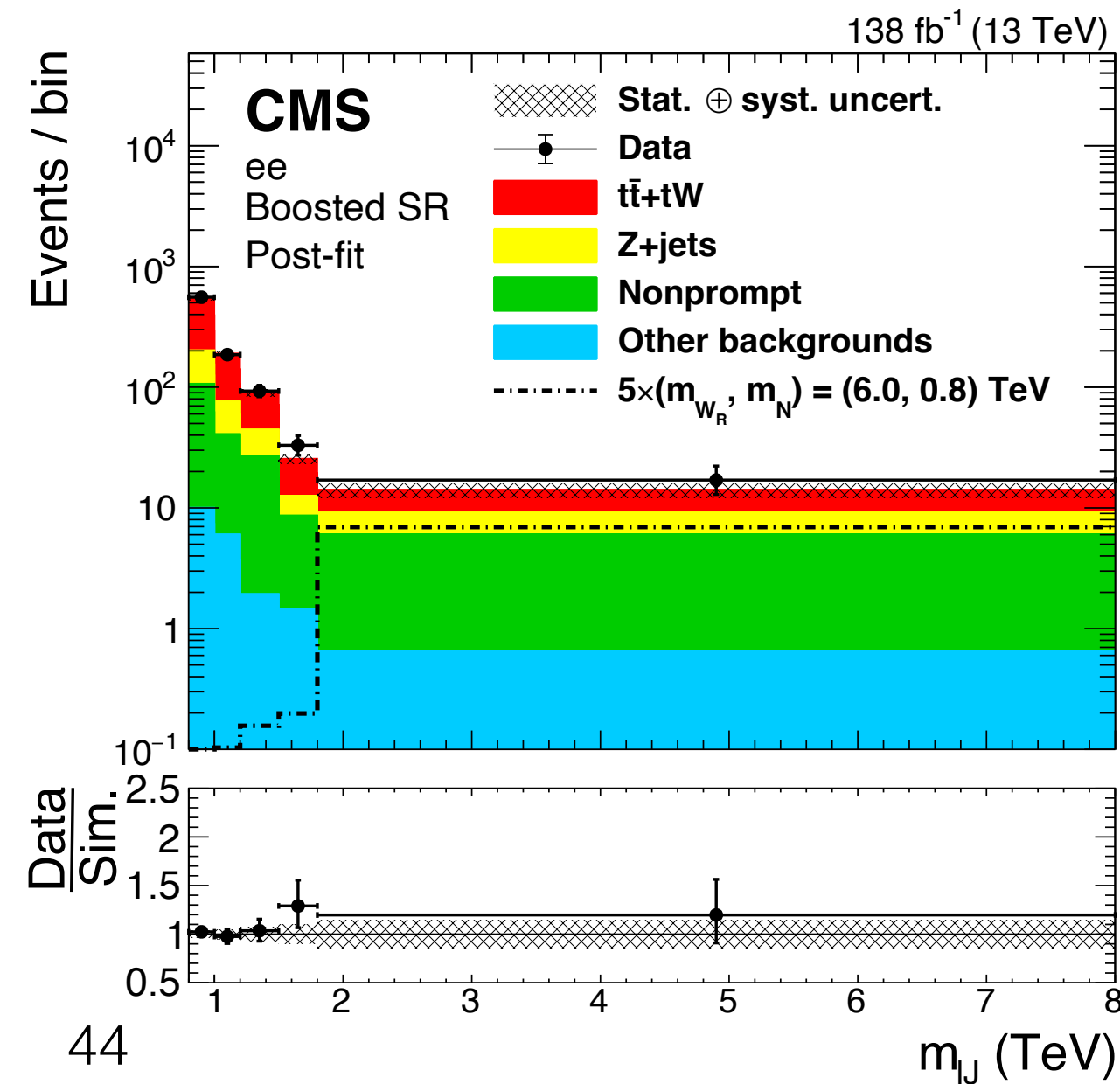
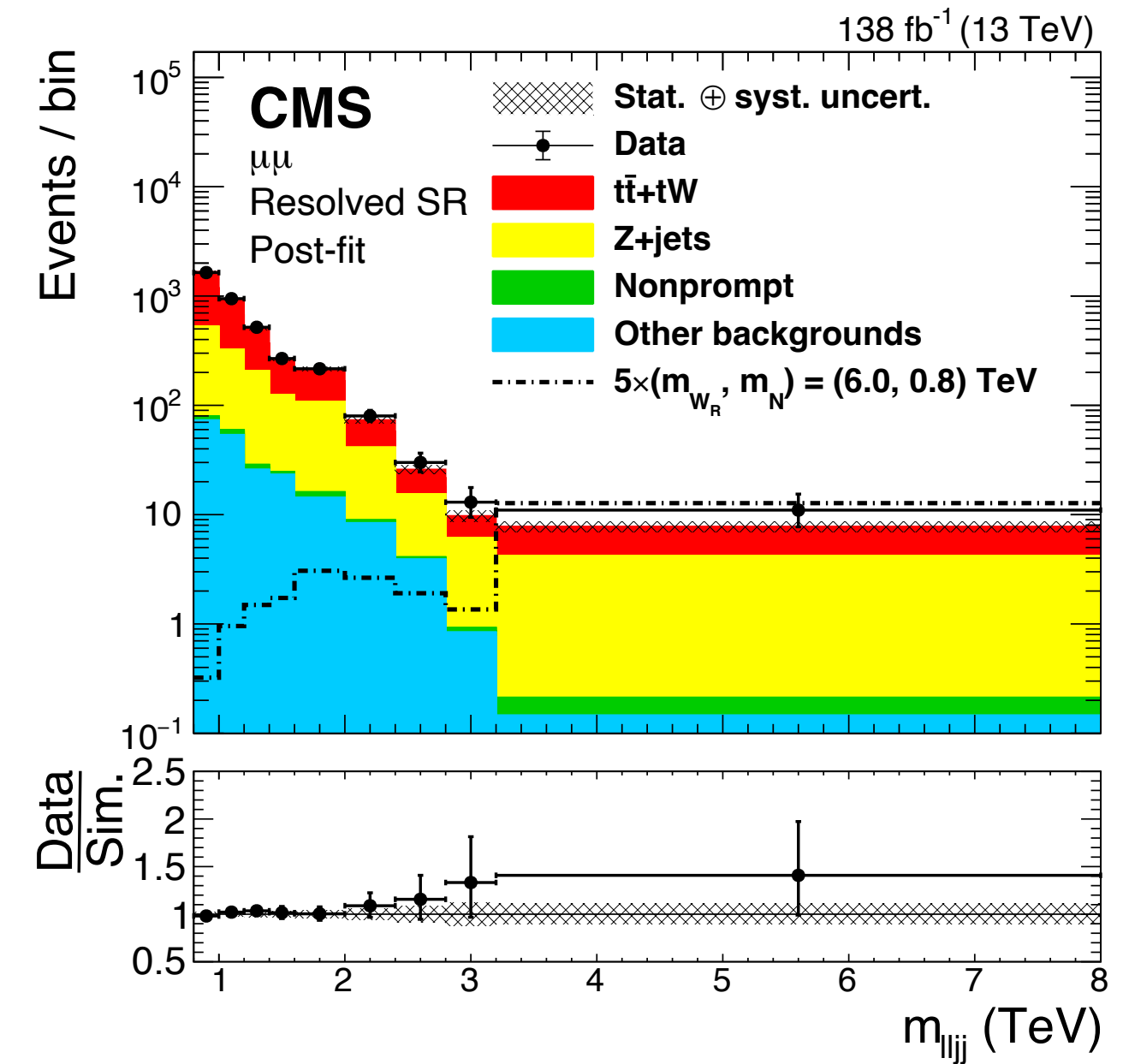
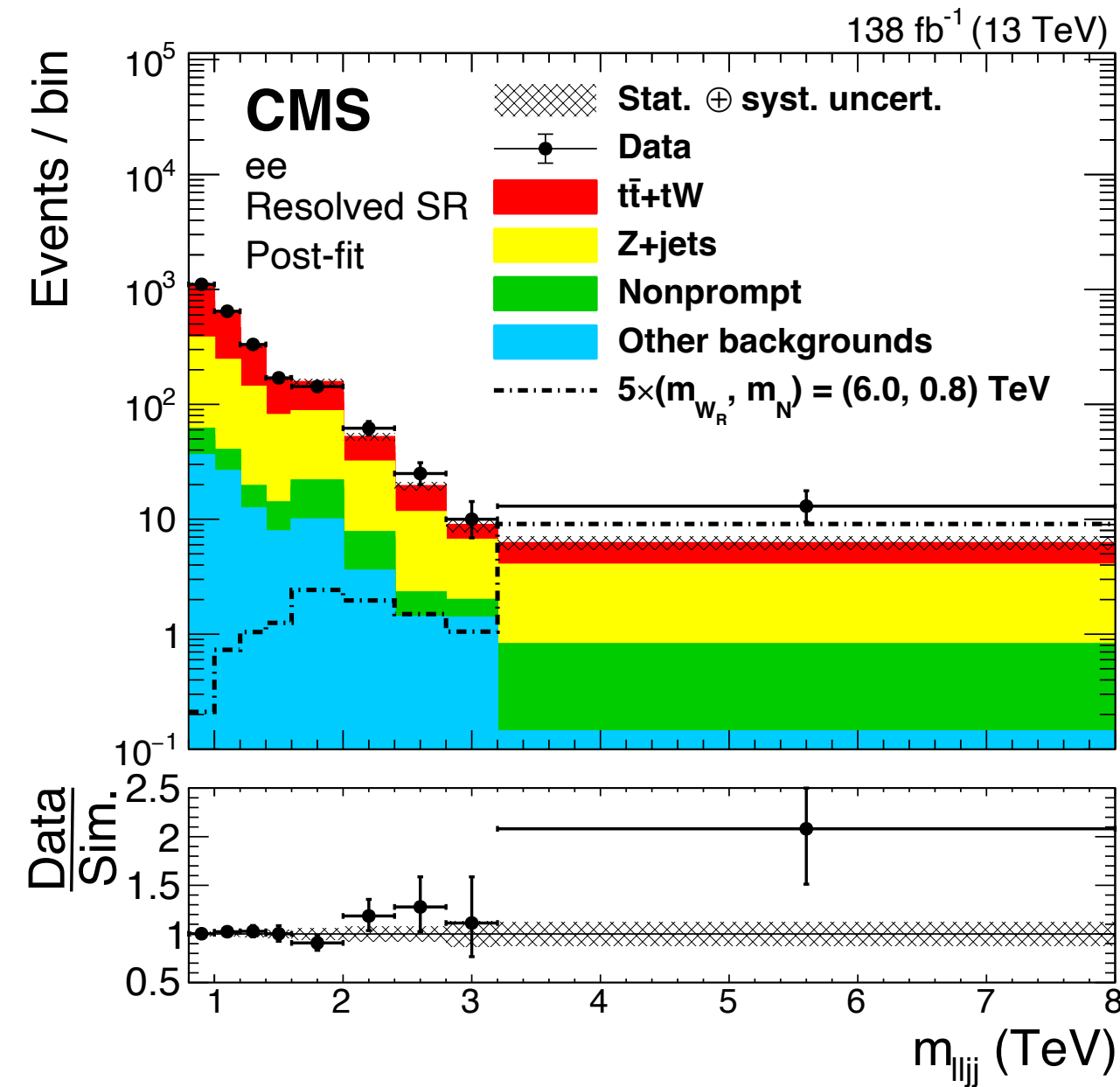
The lepton subjet fraction algorithm: checking the consistency of the jet with three subjets, where one subjet is dominated by the four-momentum of a lepton.

Search for W_R boson and a N : Results

A maximum-likelihood fit is performed on the m_{ljj} (m_{lJ}) distributions in the resolved (boosted) SRs and CRs, with the systematic uncertainties as nuisance parameters.

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

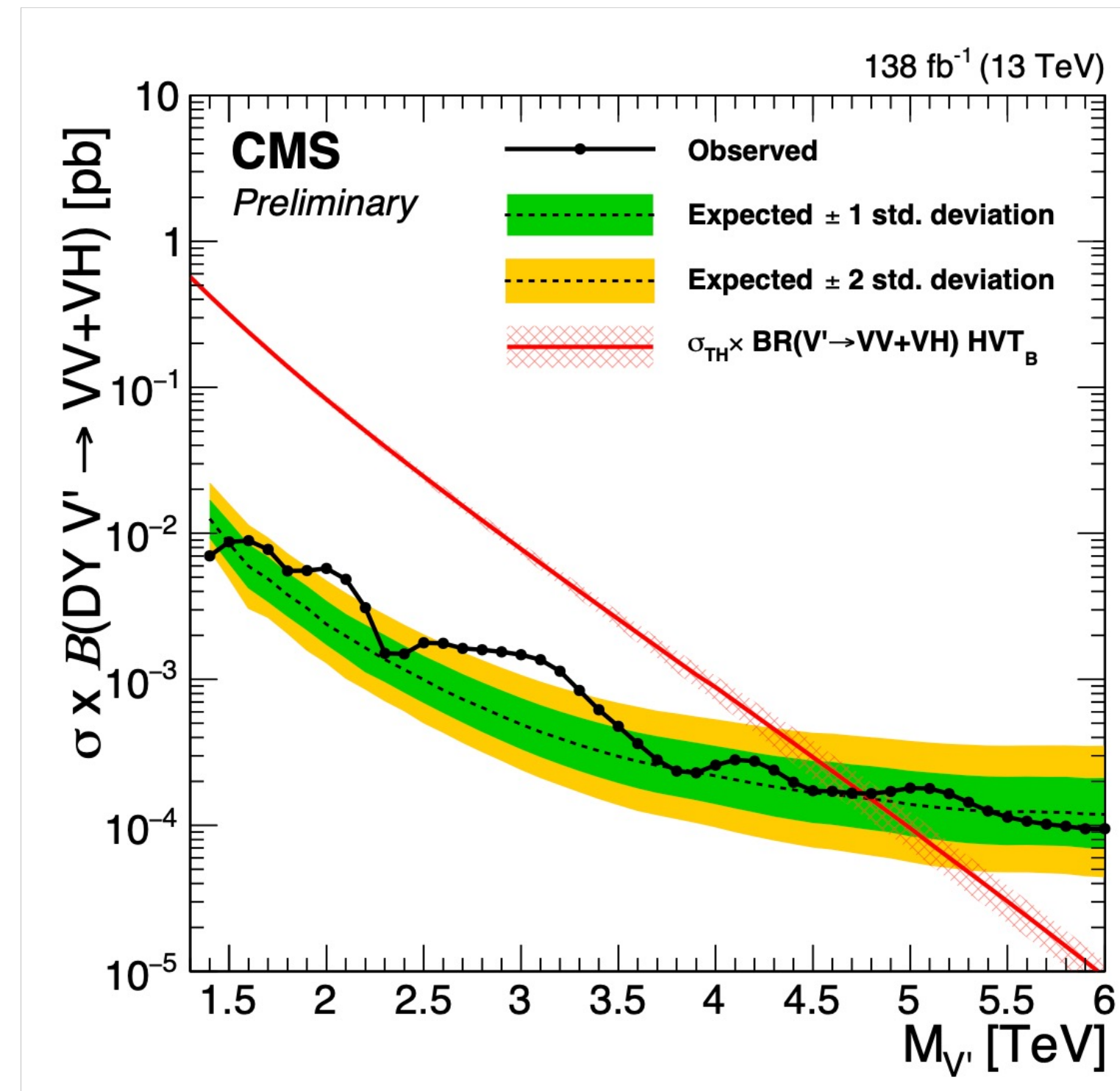
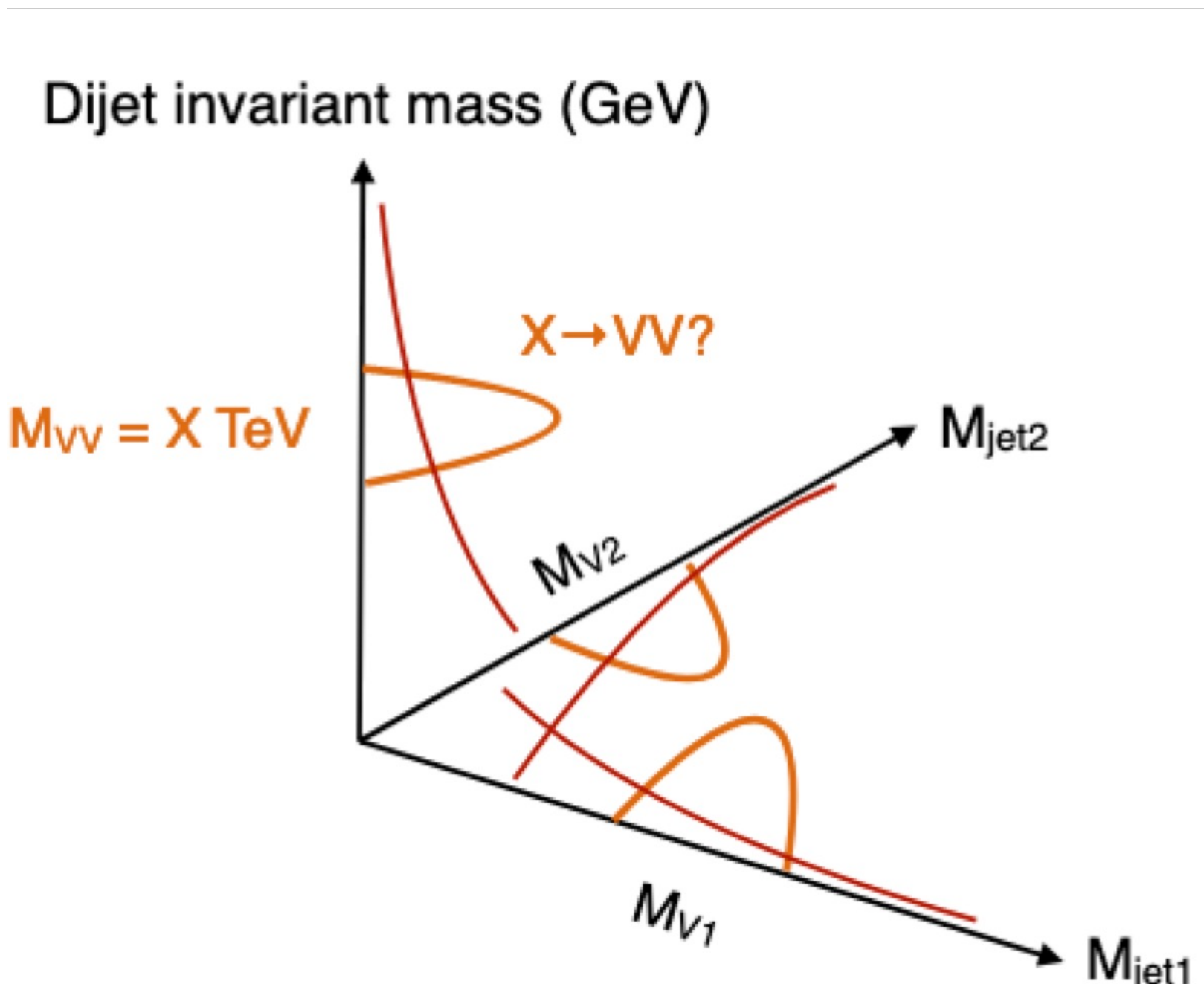
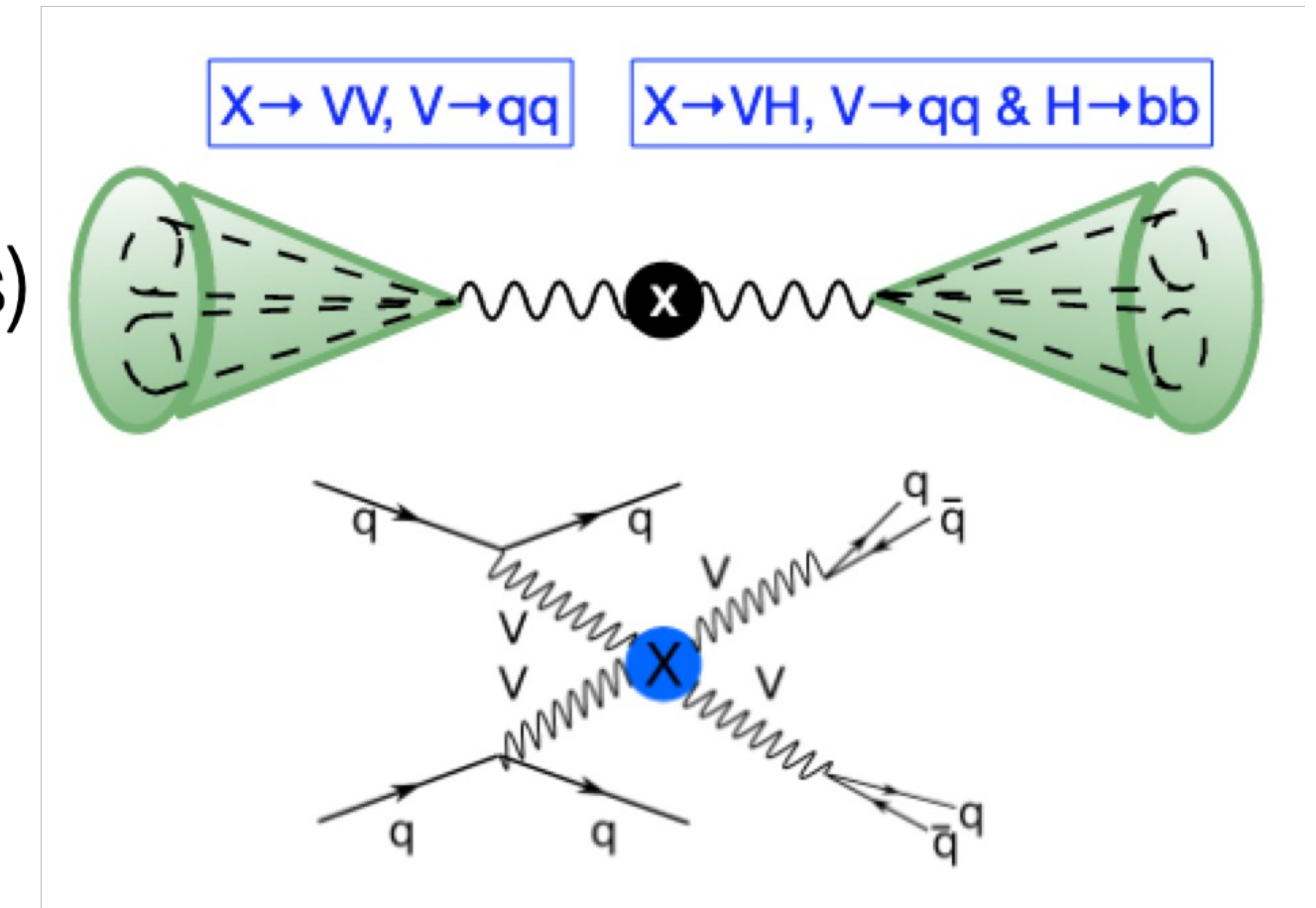
$(m_{W_R}, m_N) = (6.0, 0.8) \text{ TeV}$ mass point corresponding to a **local (global) significance of 2.95σ (2.78σ)**.



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

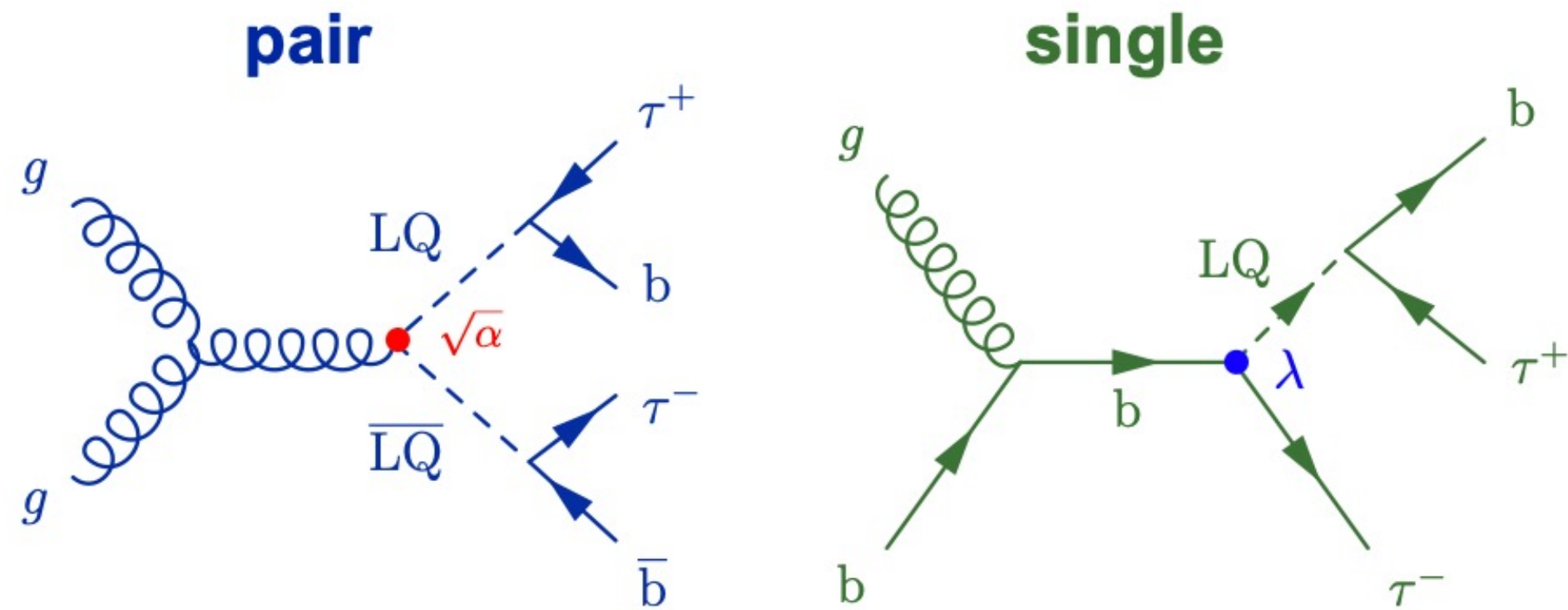
- Using 2 large cone jets (resonance decay products), and 2 small cone jets (VBF tags)
- Tag the jets with ML algorithms to distinguish from QCD



2 excesses in VV decay modes only:

Local significant: 3.6 σ
Global significance: 2.3 σ

Third-generation Leptoquark

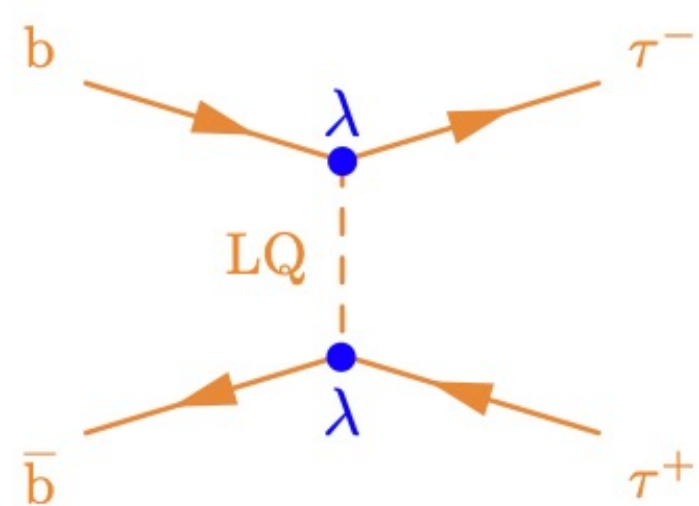


For a representative LQ mass of 2 TeV and a coupling strength of 2.5, an excess with a significance of **3.4 sigma** above the SM expectation is observed in the data.

discriminating variable:

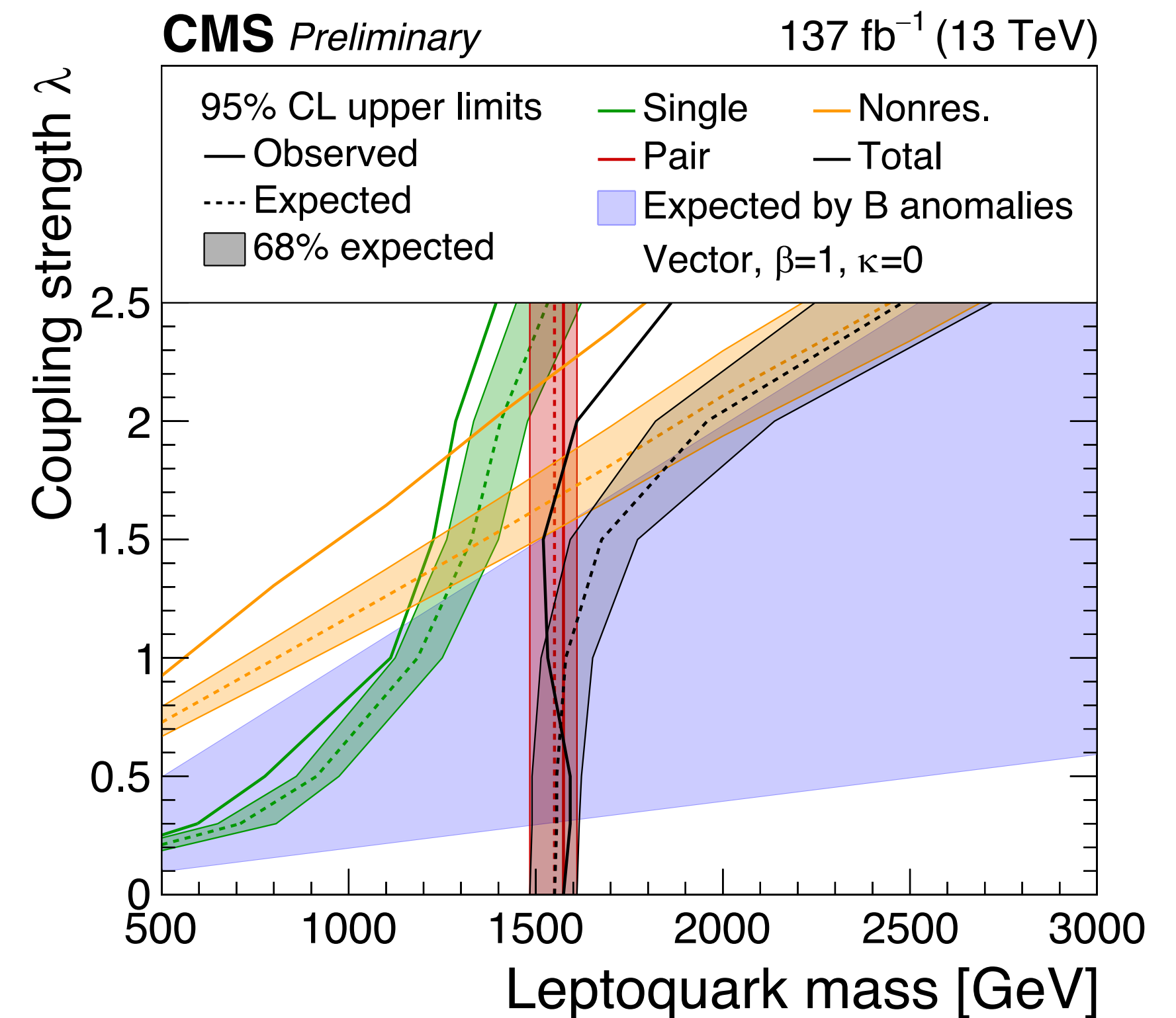
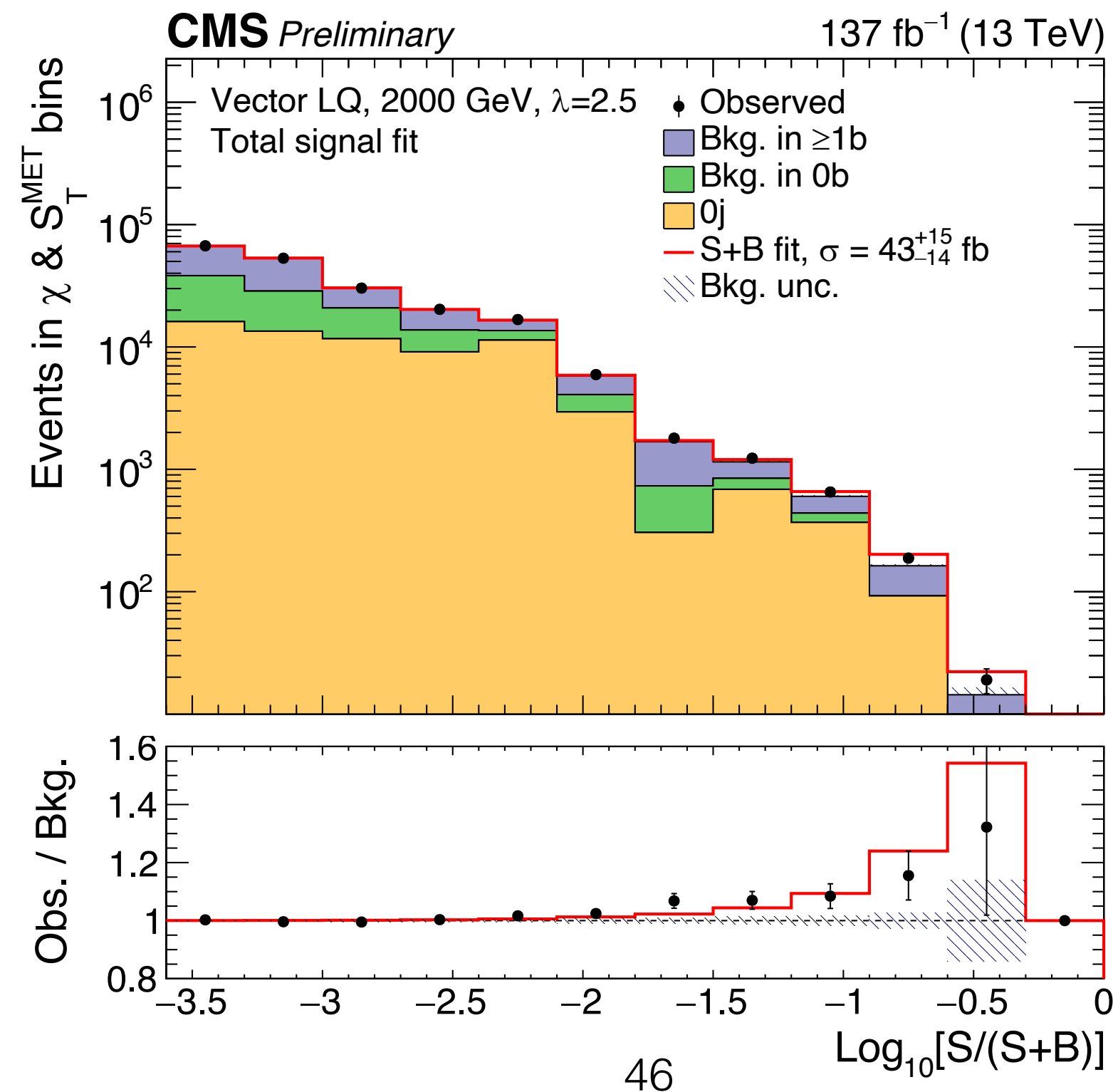
$$S_T^{\text{MET}} = p_T^{\tau_1} + p_T^{\tau_2} + p_T^j + \text{MET}$$

nonresonant



discriminating variable:

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



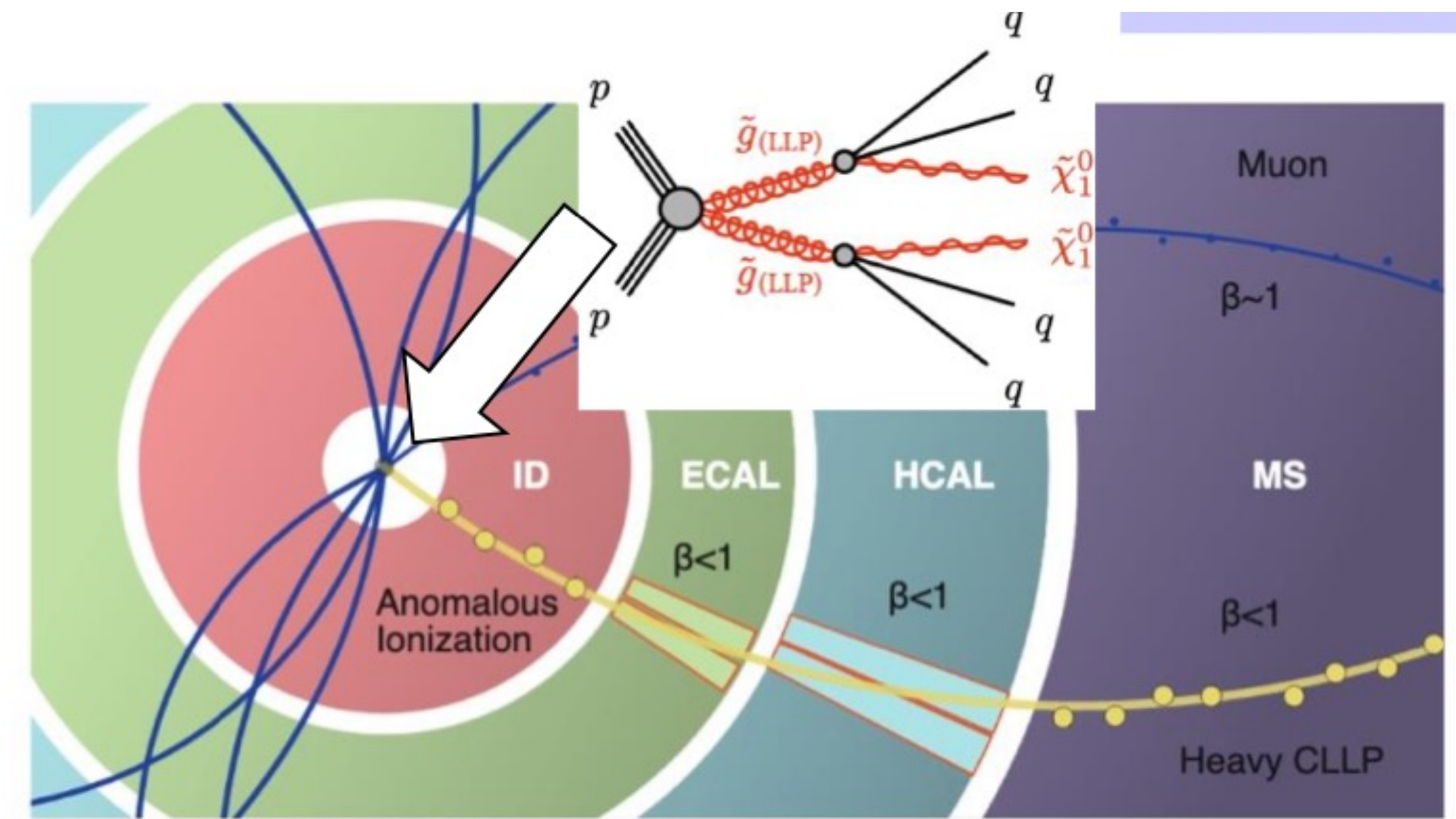
Heavy, long-lived, charged particles

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

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

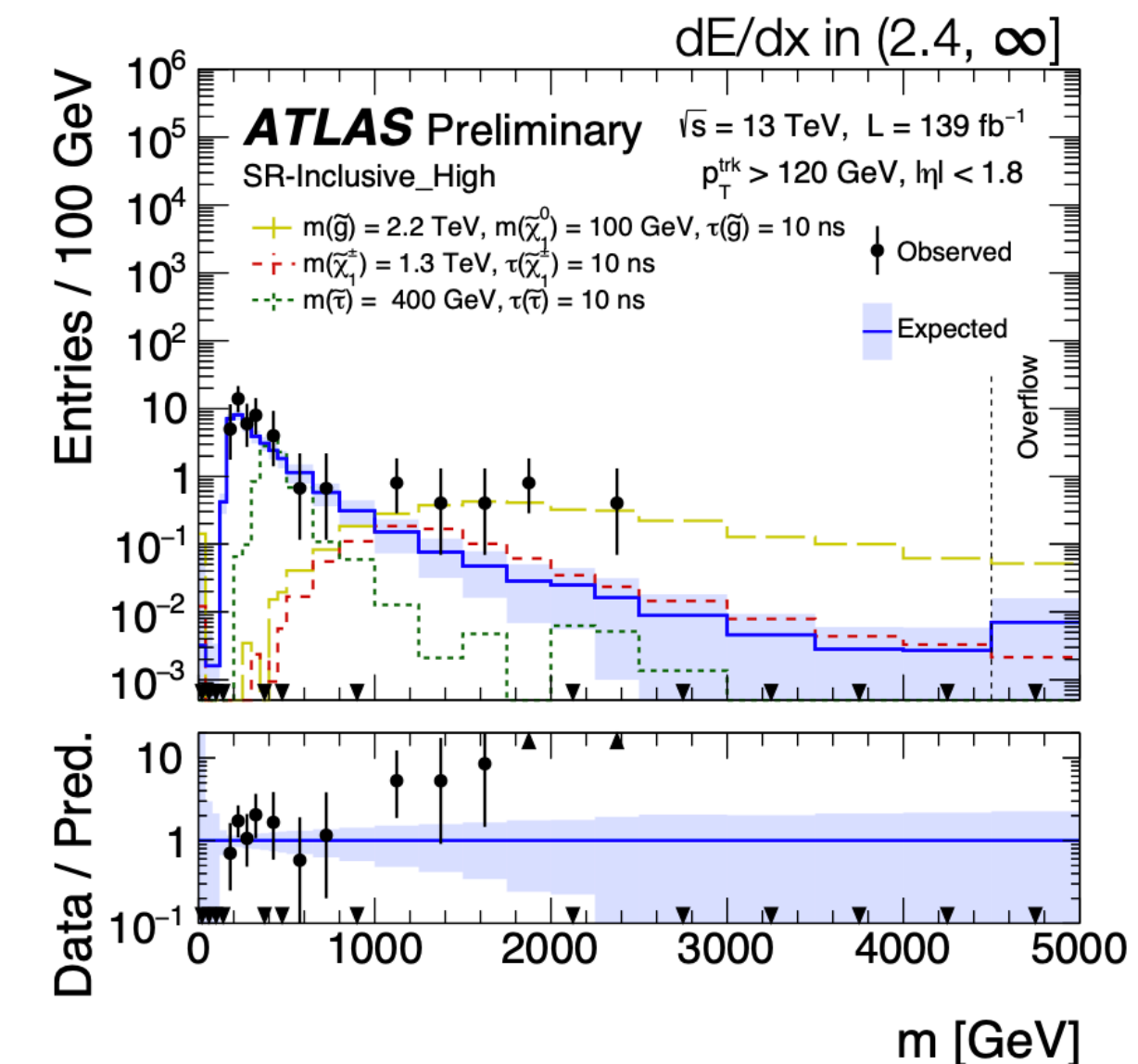
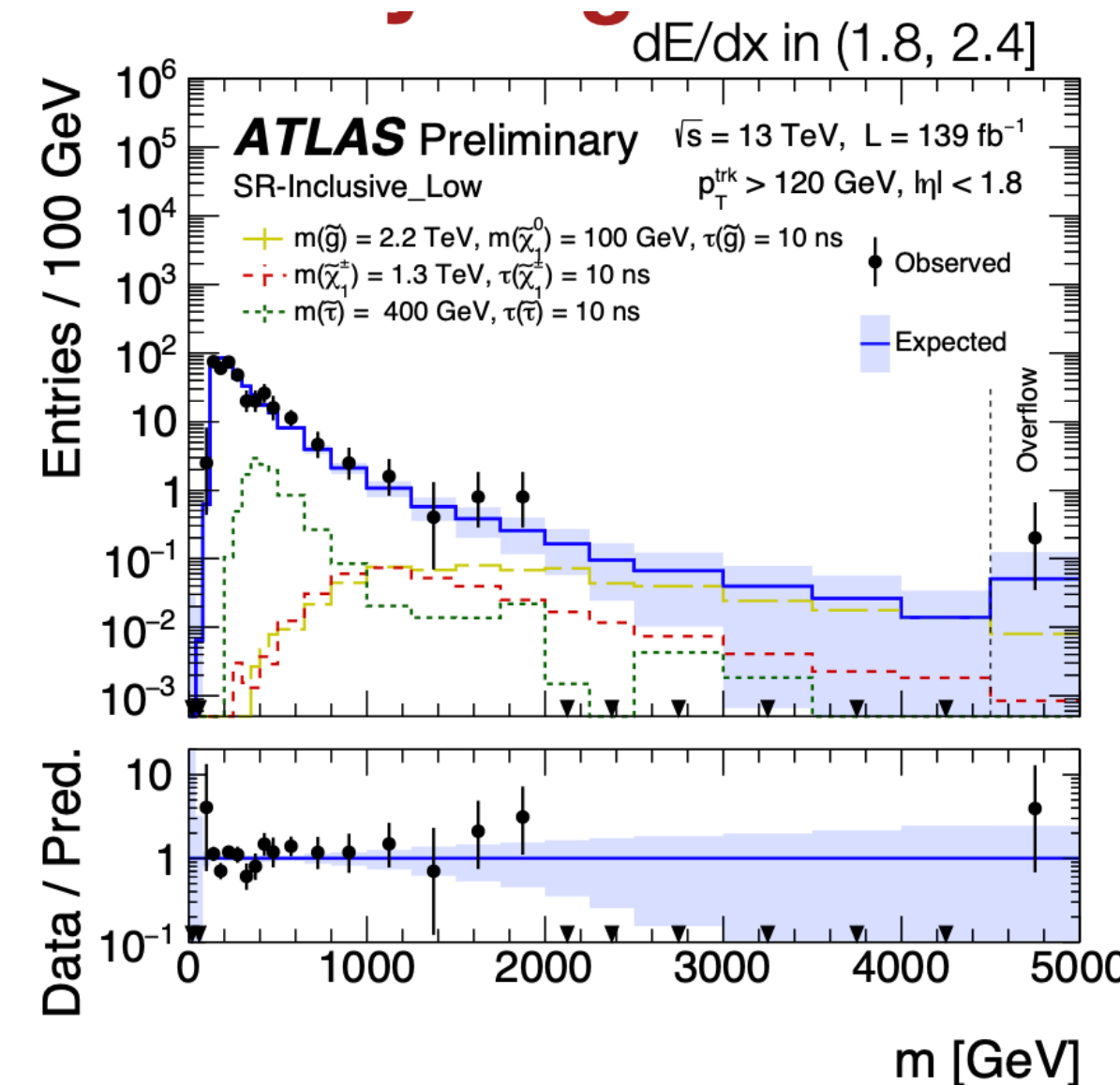
Strategy:

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

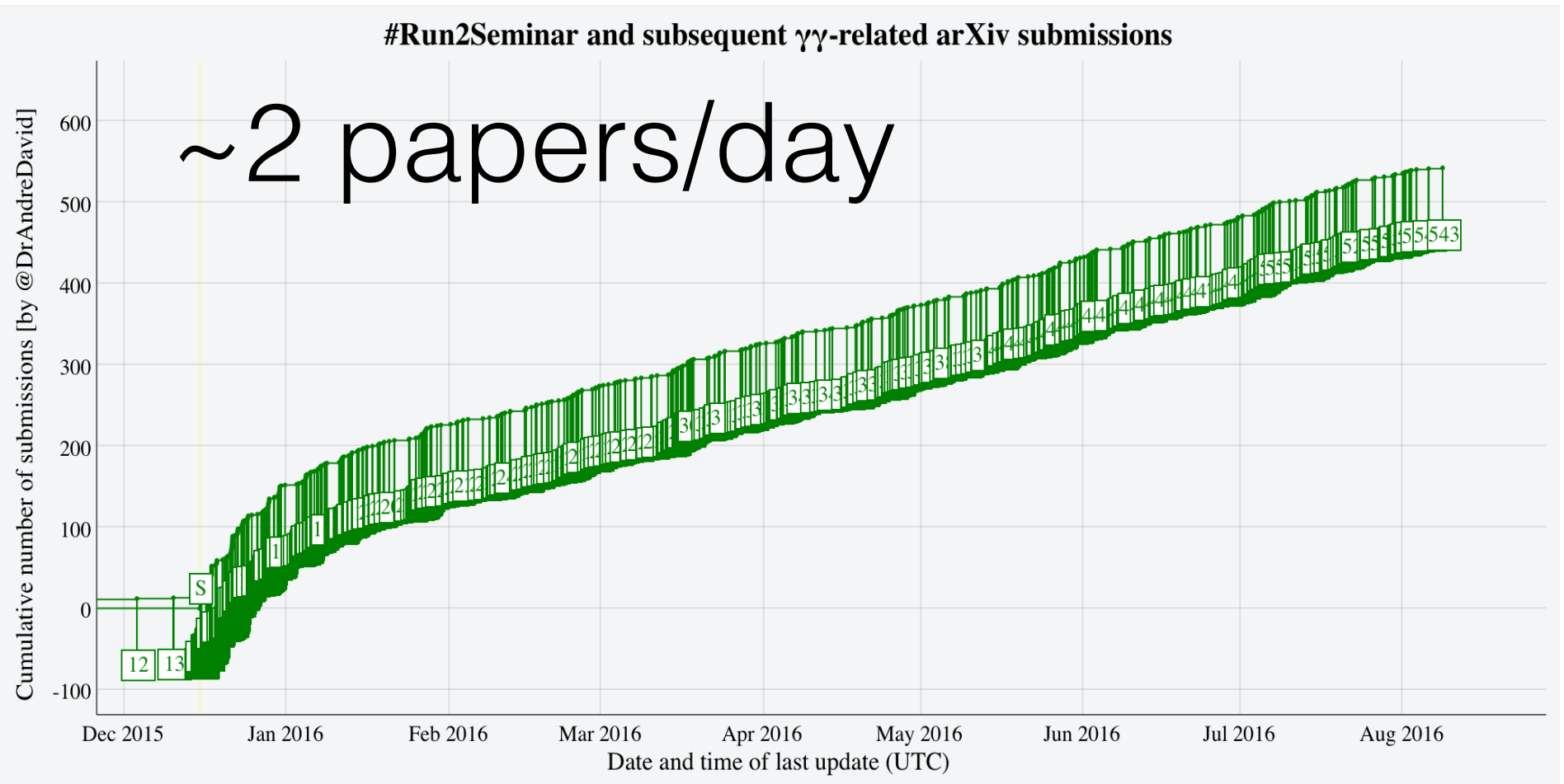
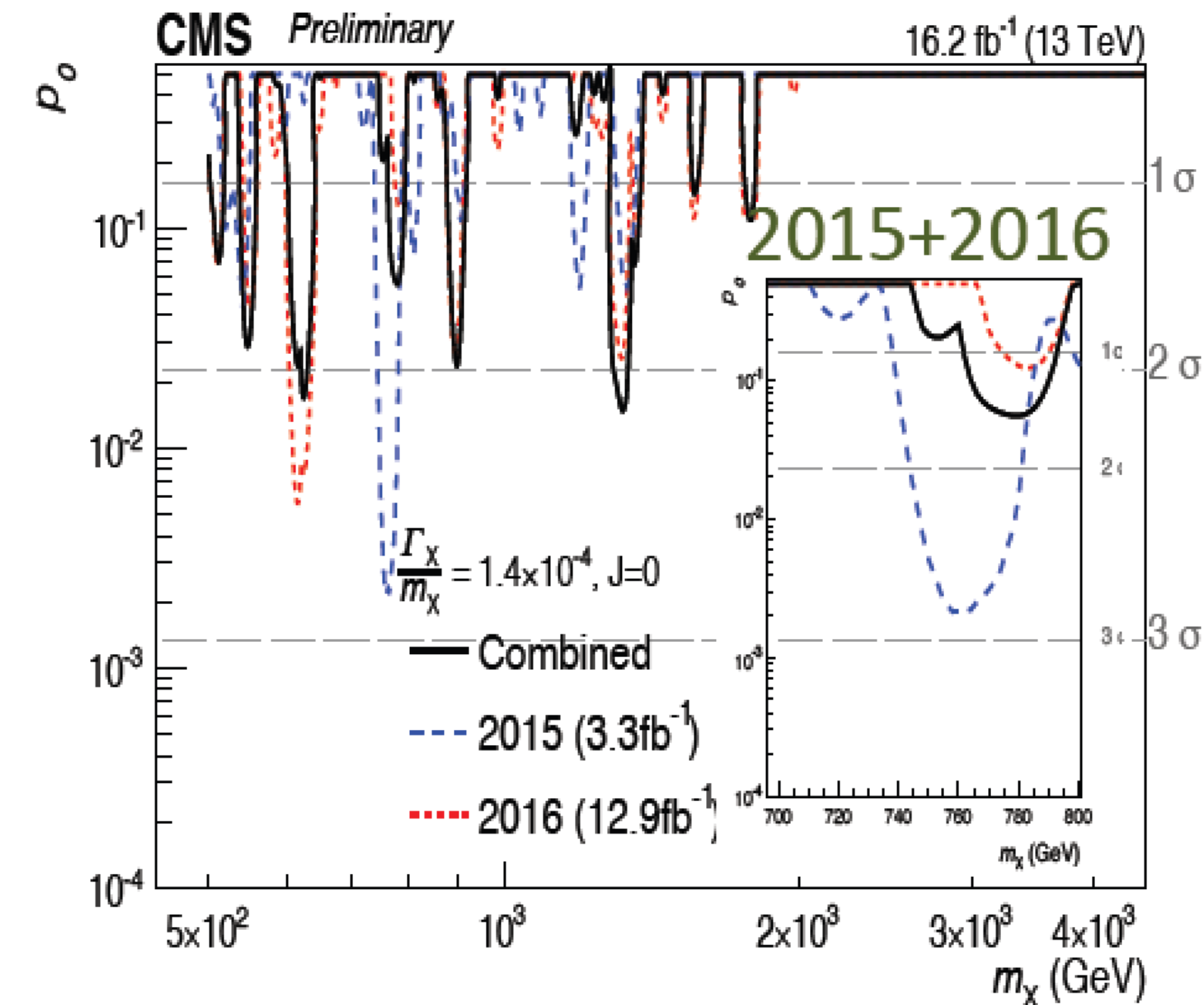
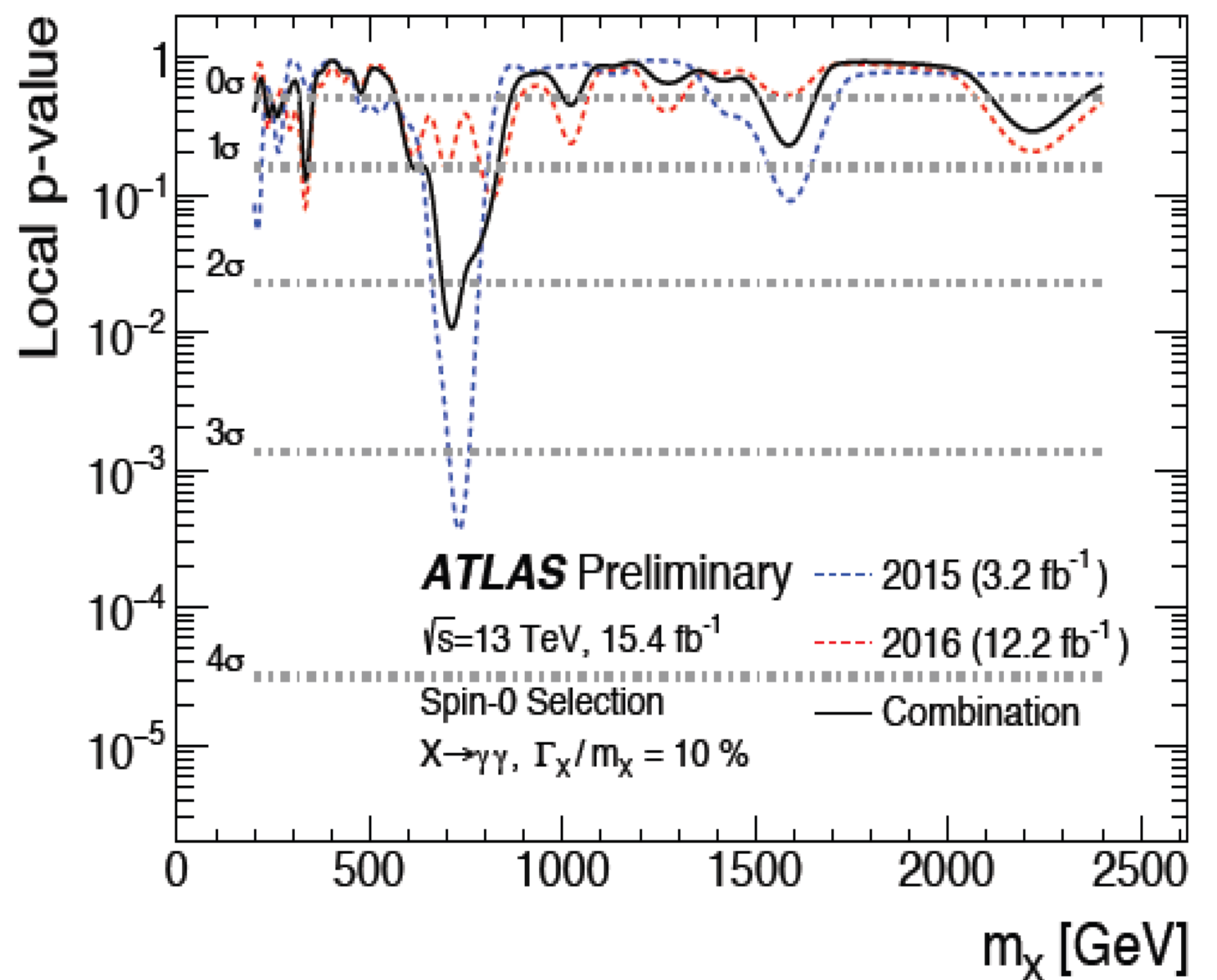
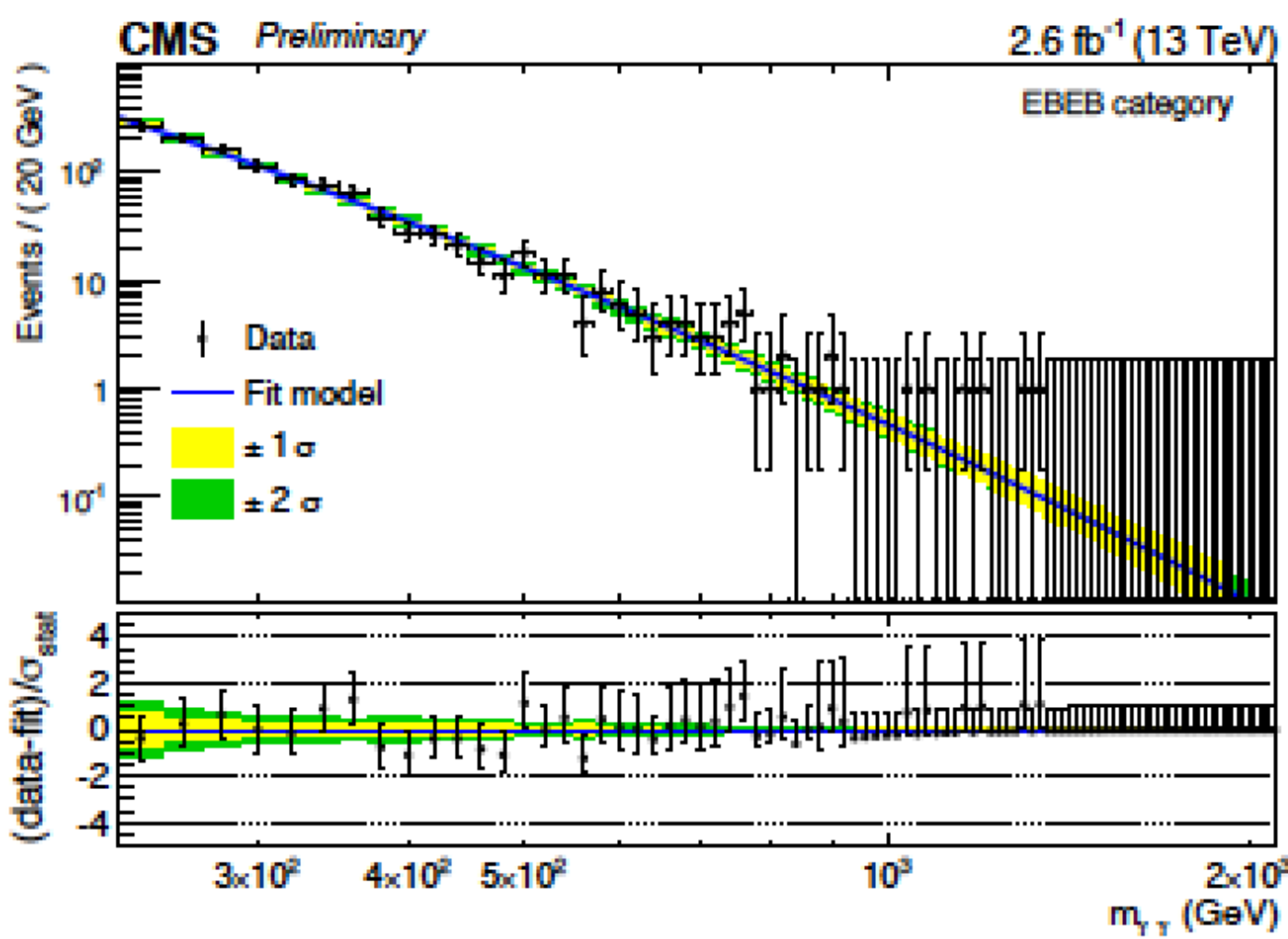
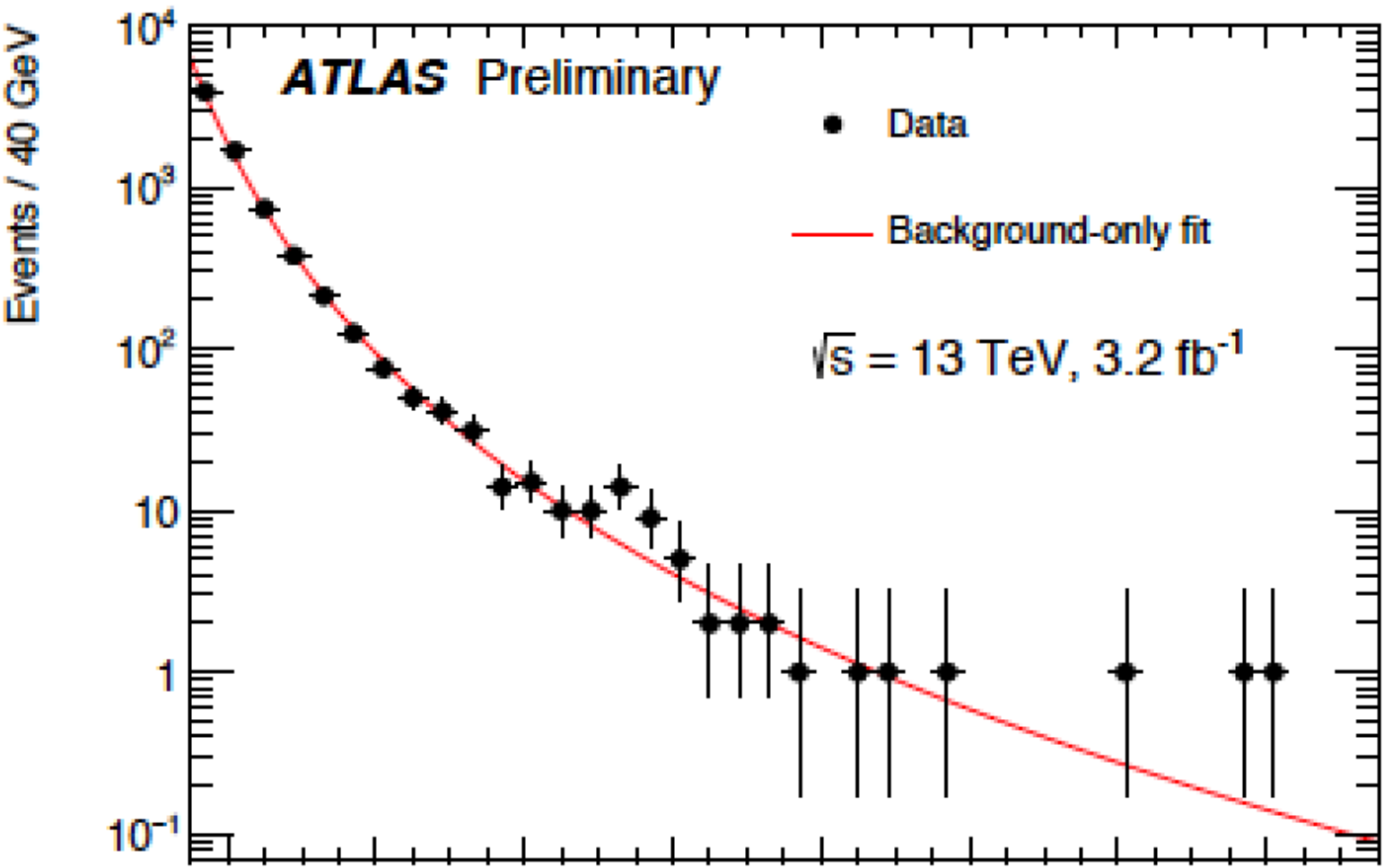


Excess in the high dE/dx signal region at $m > 1$ TeV. It is 3.3 sigma global for a particle mass hypothesis of 1.4 TeV

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 $\beta \sim 1$. Not LLP?



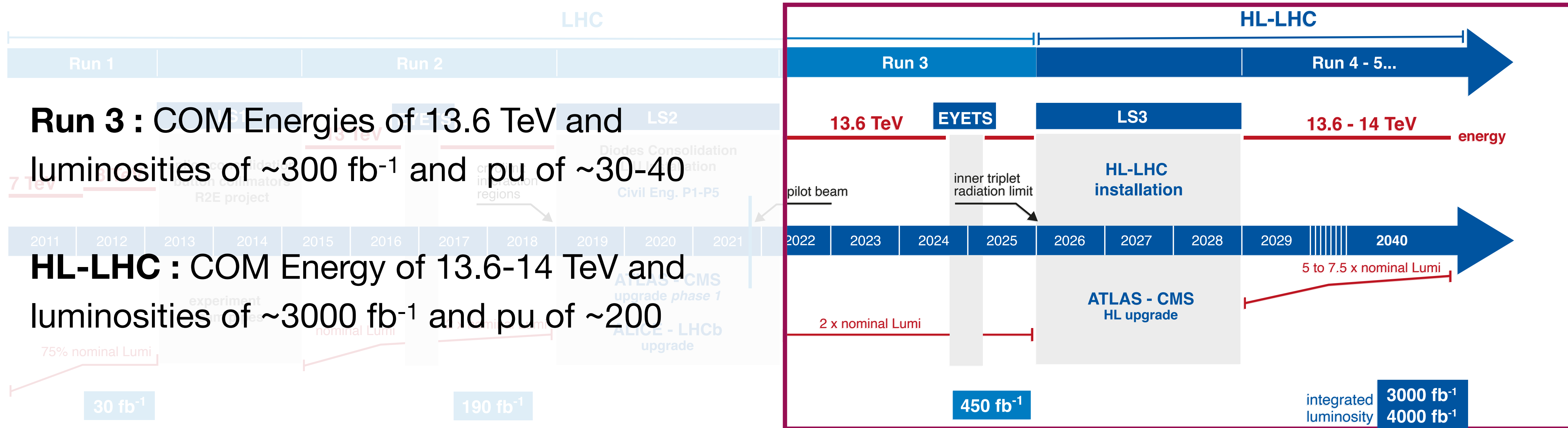
Careful with “Discoveries”: Remember 750 GeV bump?



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

But nothing in 2016...

Data Taking

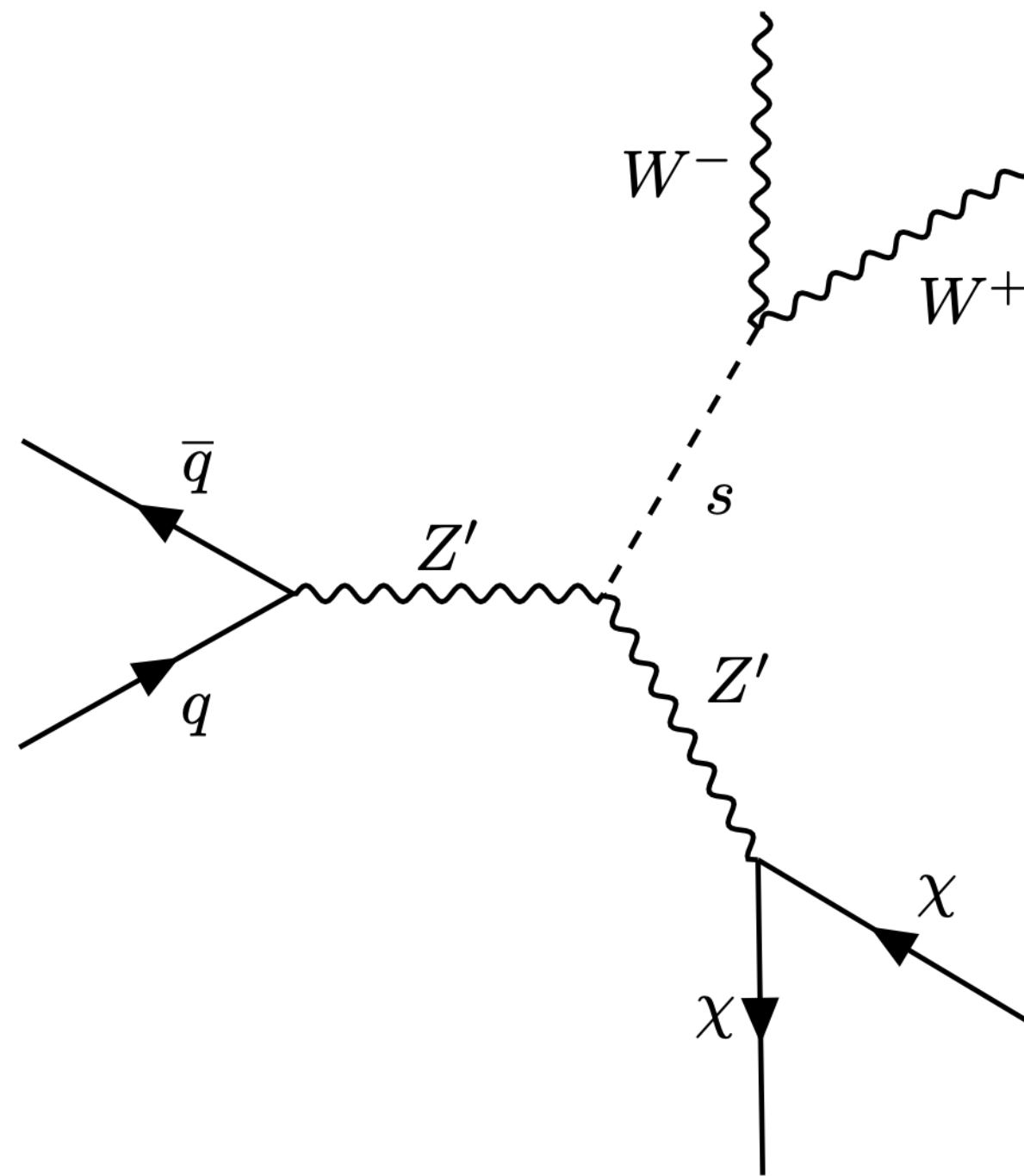


Major ATLAS and CMS upgrades:

- 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.

Dark Higgs (WW)

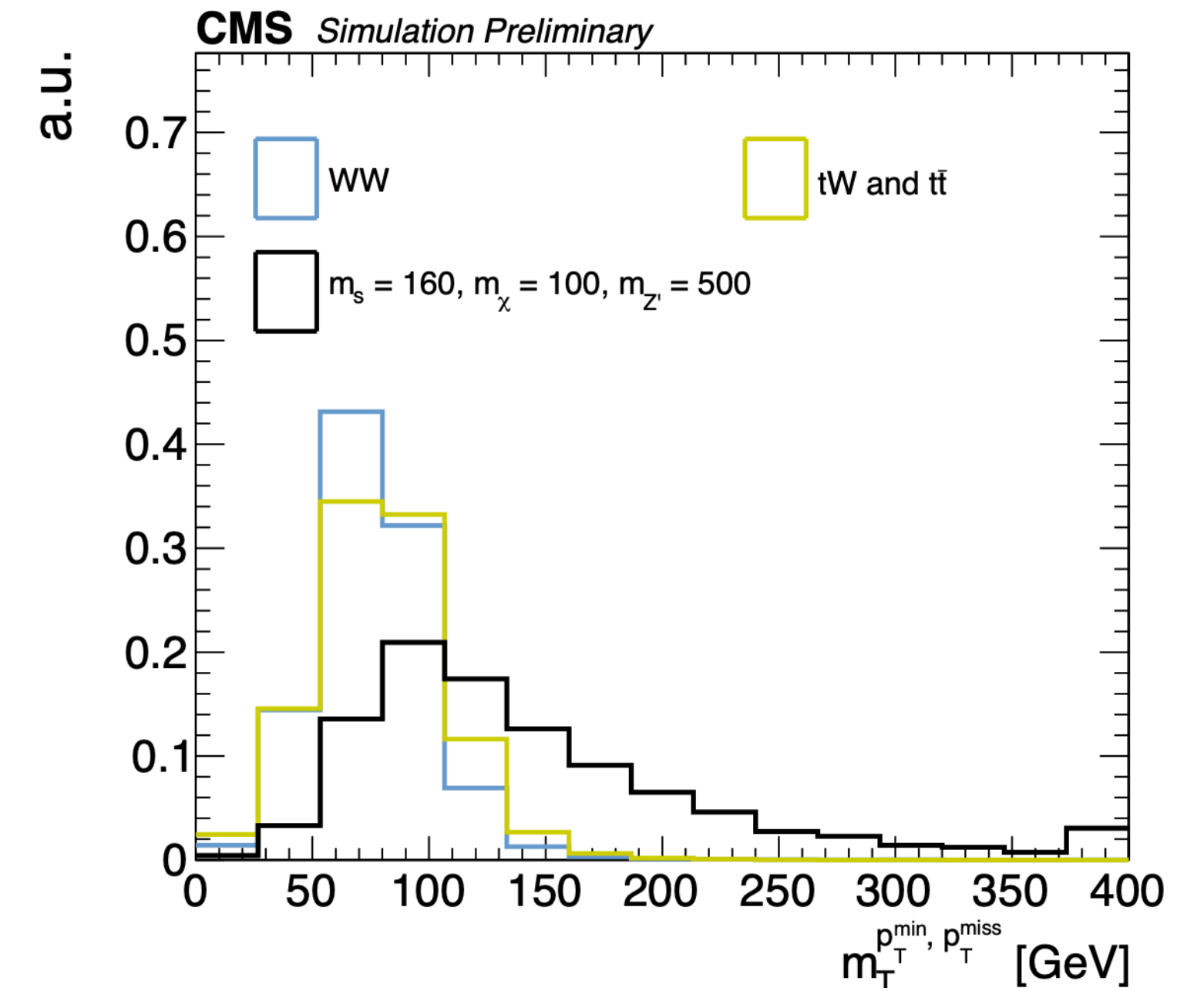


DM particles acquire their mass through their interactions with a Dark Higgs boson.

Signal extraction: 3D ML fit to $\Delta R(\ell\ell)$, $m_{\ell\ell}$, $m_T(\ell\text{min} + p_T)$

Model parameters are:

- DM mass: m_χ ,
- Z' mass: $m_{Z'}$,
- dark Higgs mass: m_s ,
- Z' couplings to quarks (g_q)
- Z' couplings to DM (g_χ),
- the mixing angle between SM and the dark Higgs bosons ($\sin \theta$).



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