



Recent Standard Model Measurements at the CMS experiment

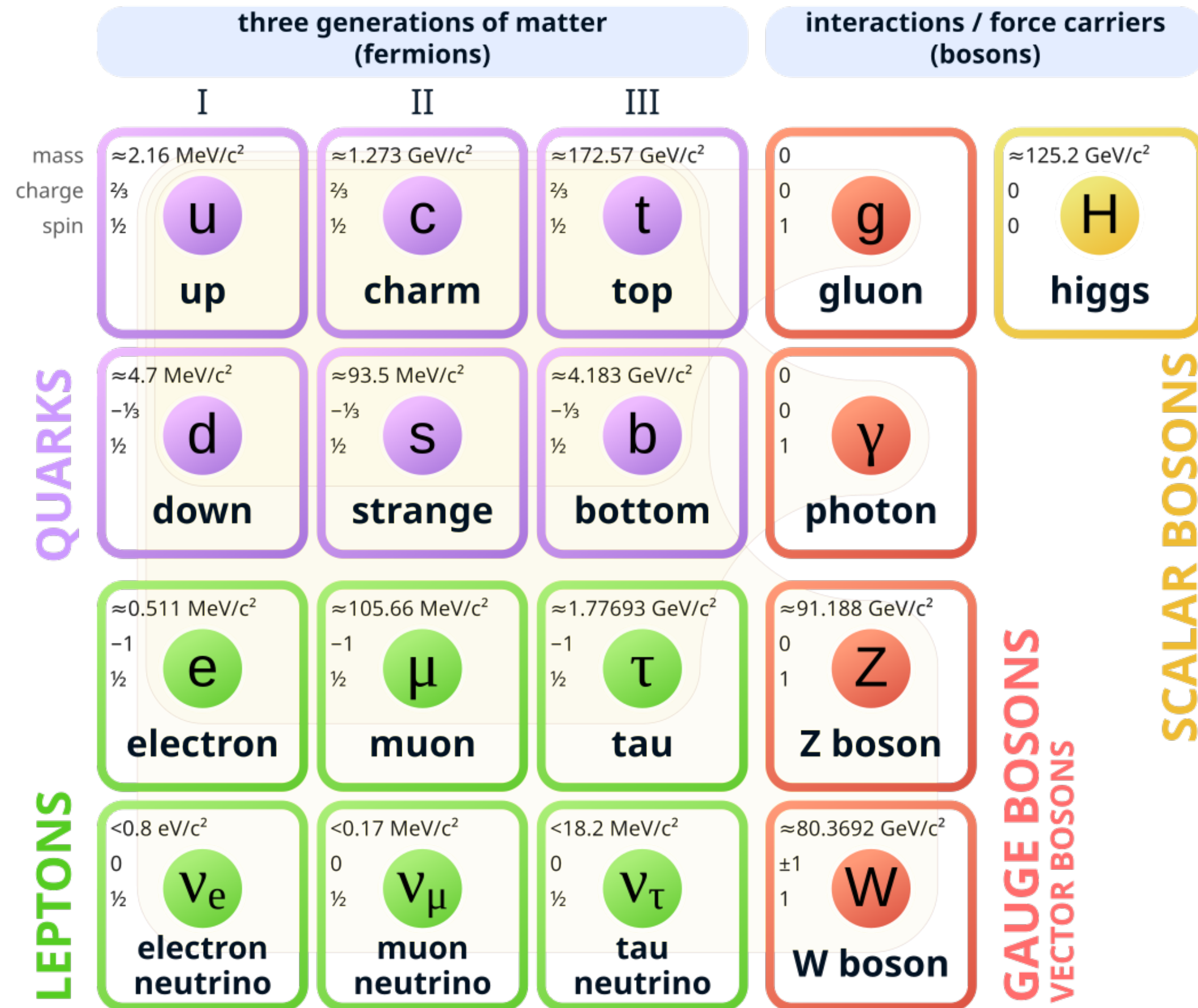


报告人：安莹 (AN Ying)

时间：24/07/2026

Standard Model

Standard Model of Elementary Particles



Quantum field theory based on gauge group:

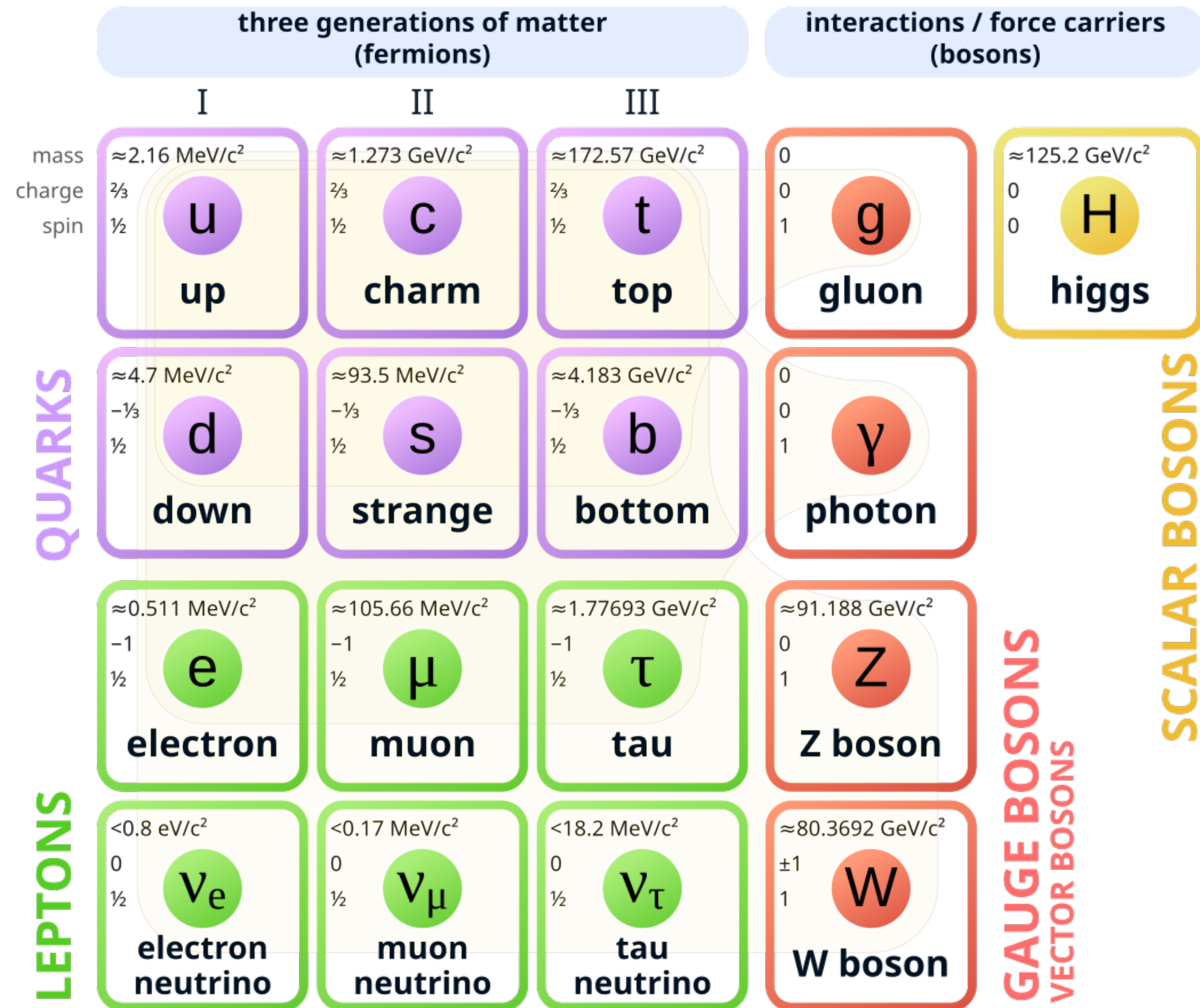
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

It's widely successful:

- describes three of the four fundamental interactions
- explains vast majority of experimental observations

Standard Model

Standard Model of Elementary Particles



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$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

It's widely successful:

- describes three of the four fundamental interactions
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Leaves open questions:

nature of dark matter

origin of neutrino masses

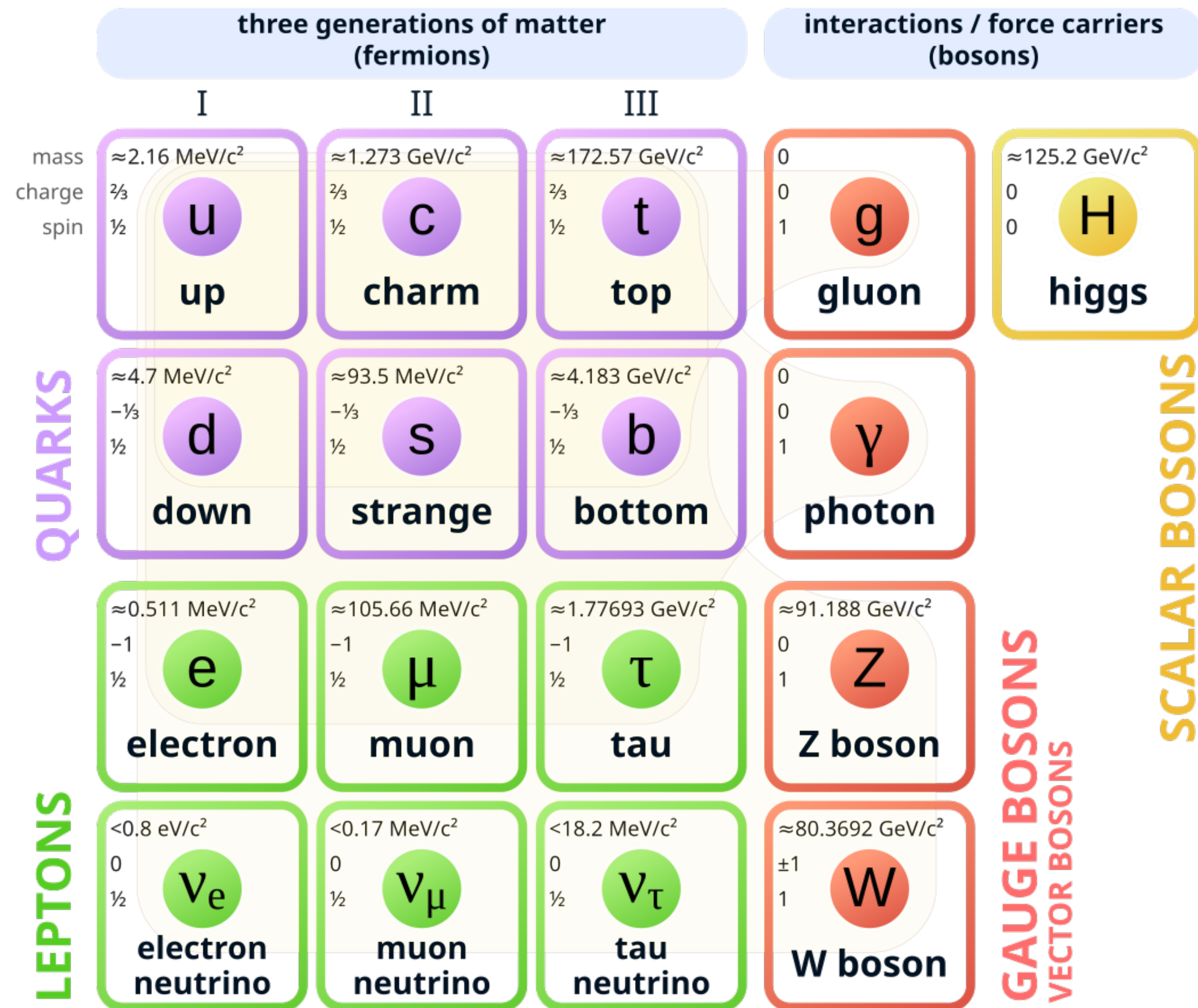
matter-antimatter asymmetry

limited precision agreement at high energy

...

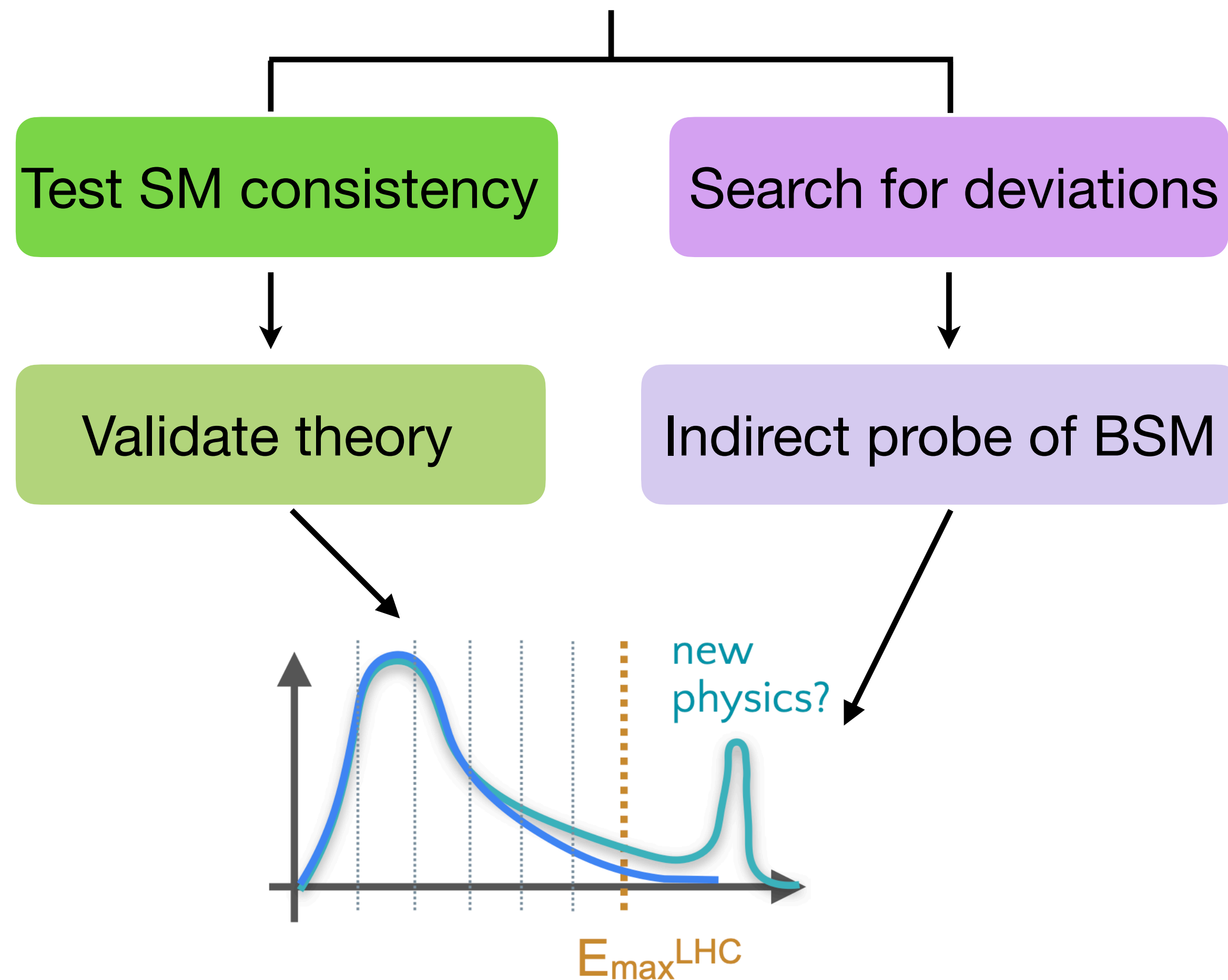
Standard Model

Standard Model of Elementary Particles



To answer open questions:

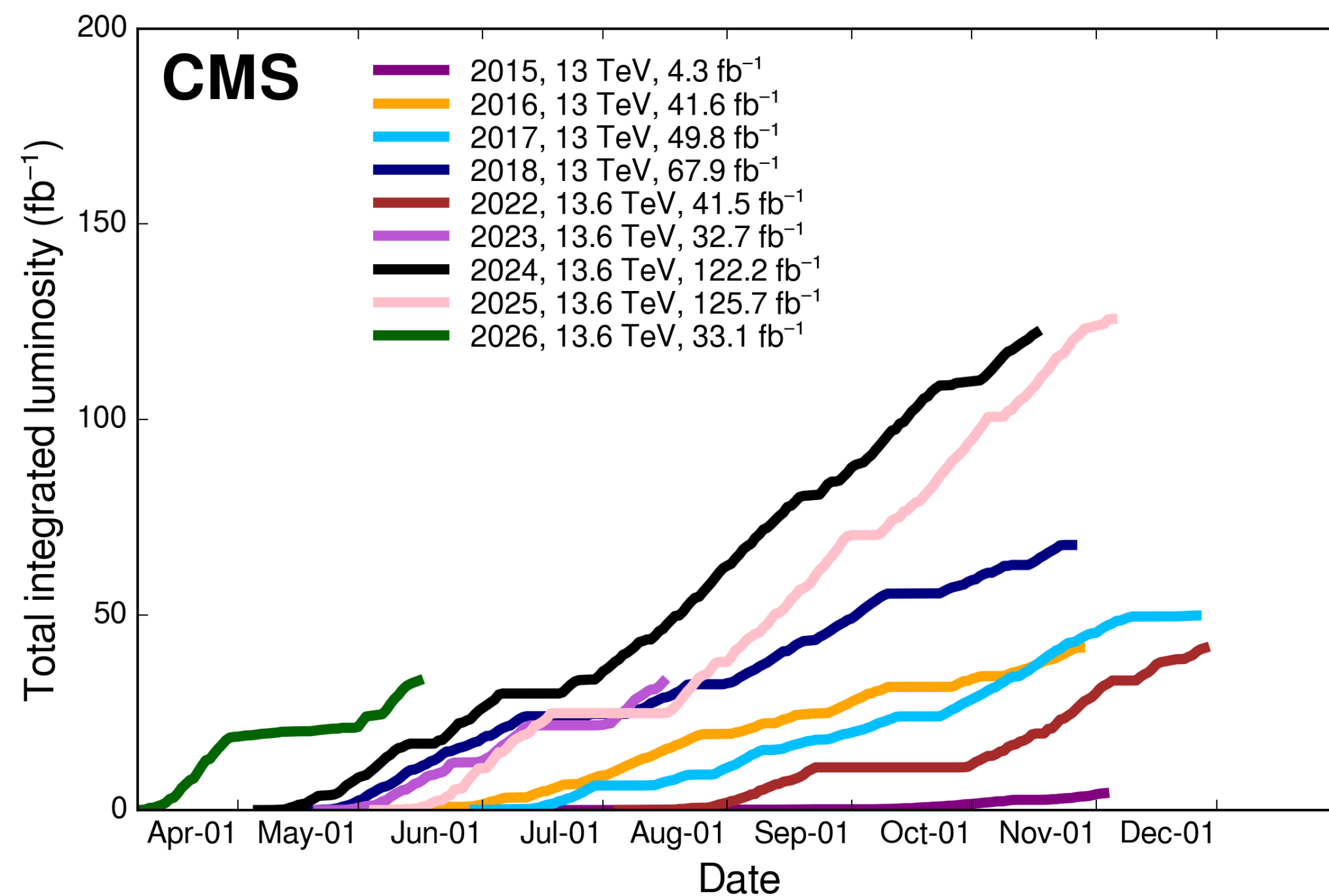
- Direct searches $\rightarrow$ new particles/decay
- Precision SM measurements



LHC — Luminosity

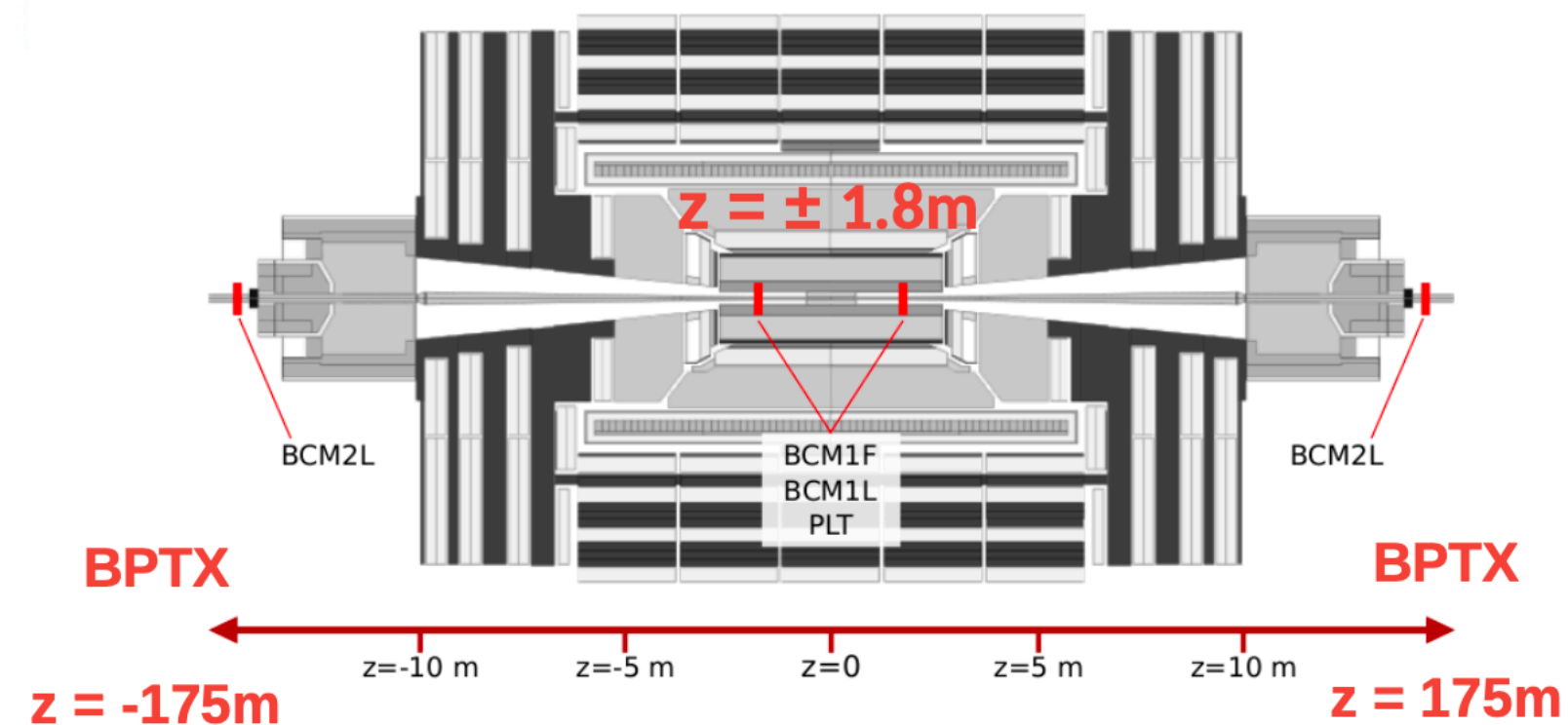
Integrated luminosity is the integral of instantaneous luminosity measured by the **B**eam **R**adiation **I**nstrumentation **L**uminosity system inside the tracker

$$L = \int \mathcal{L} dt \quad N = L \cdot \sigma$$

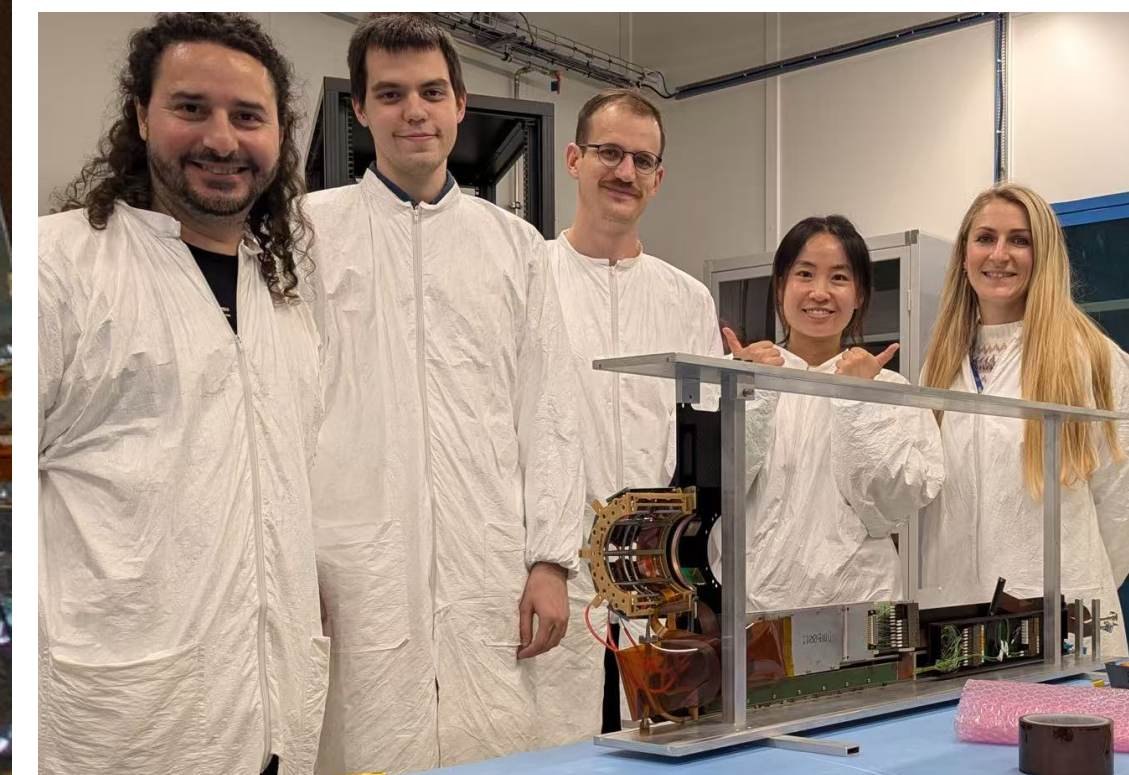
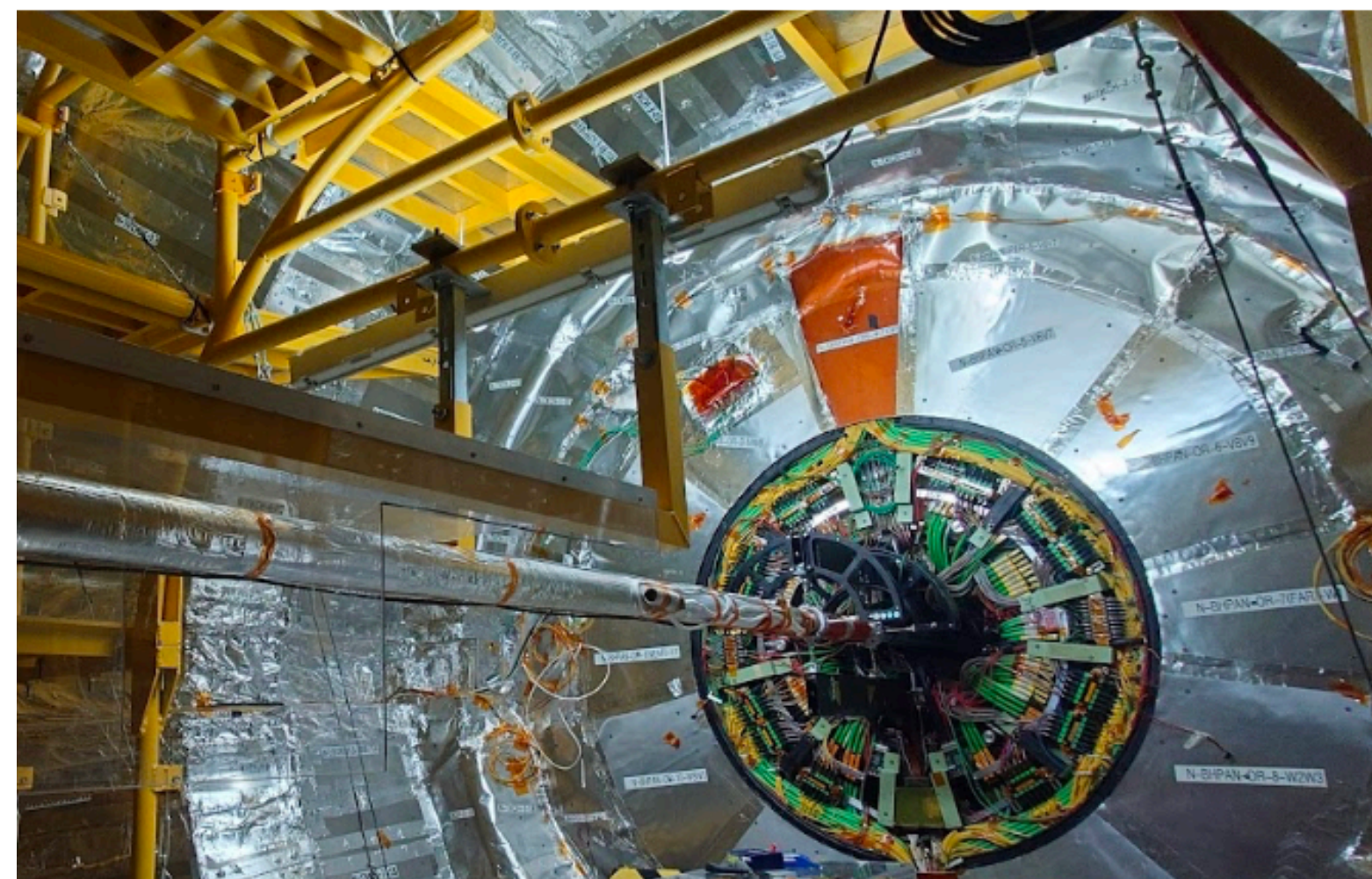
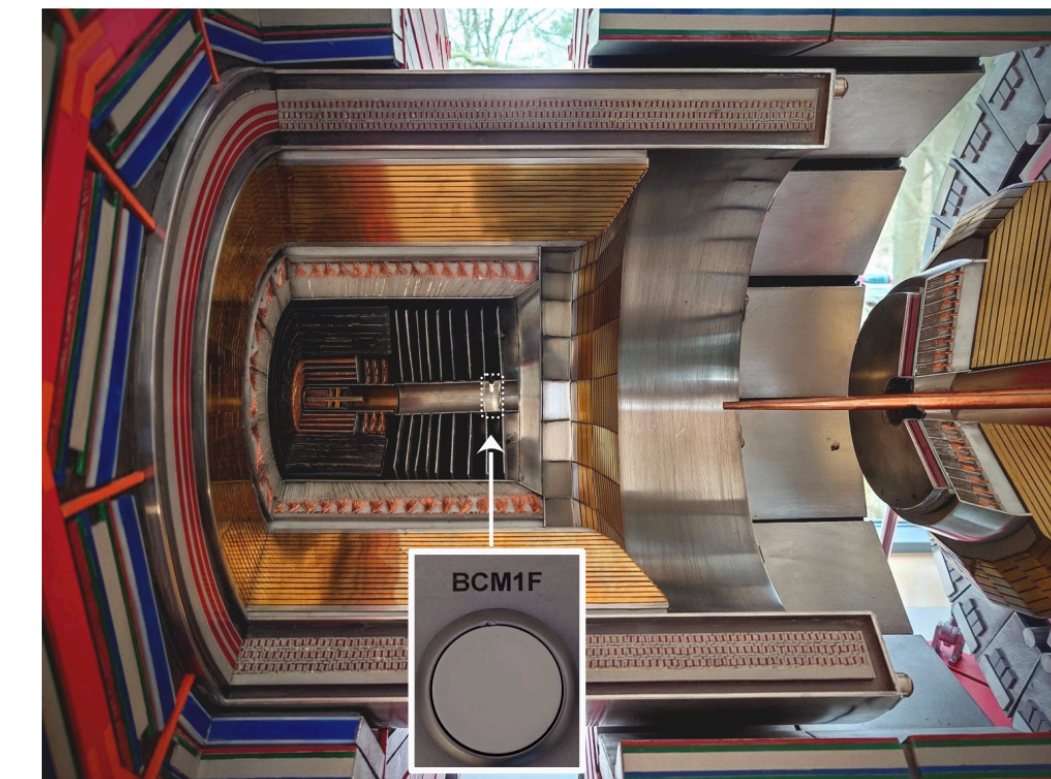


Run 3 pp: 326 fb⁻¹ recorded out of 355 fb⁻¹ (~92% eff.)

BRIL detector



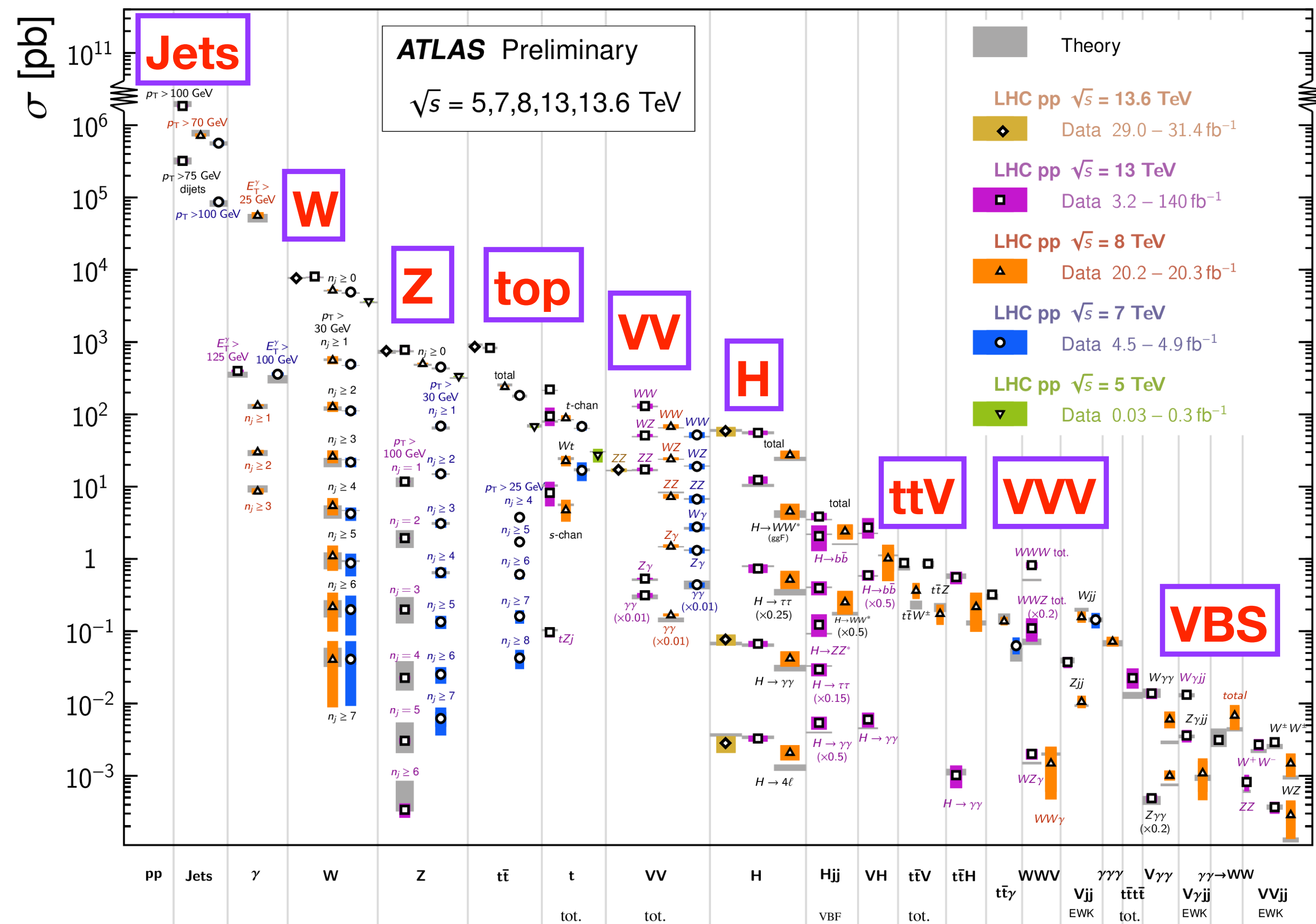
BCM1F: Inside tracker endcap, near beampipe



SM is everywhere, spanning distinct pp-collision processes with probabilities different by 10^{14} , as measured at LHC as of today

- Fundamental constants: α_s , top quark mass, W mass
- One cannot possibly search for BSM physics without understanding SM background
 - Calculations of all SM processes have finite precision
 - Some are particularly hard to calculate and need benchmark measurements
 - Some are not rigorously calculable at all (e.g., parton fragmentation and hadronization, underlying event, double parton scattering, parton density functions, exotic bound states of quarks, hadron decays)

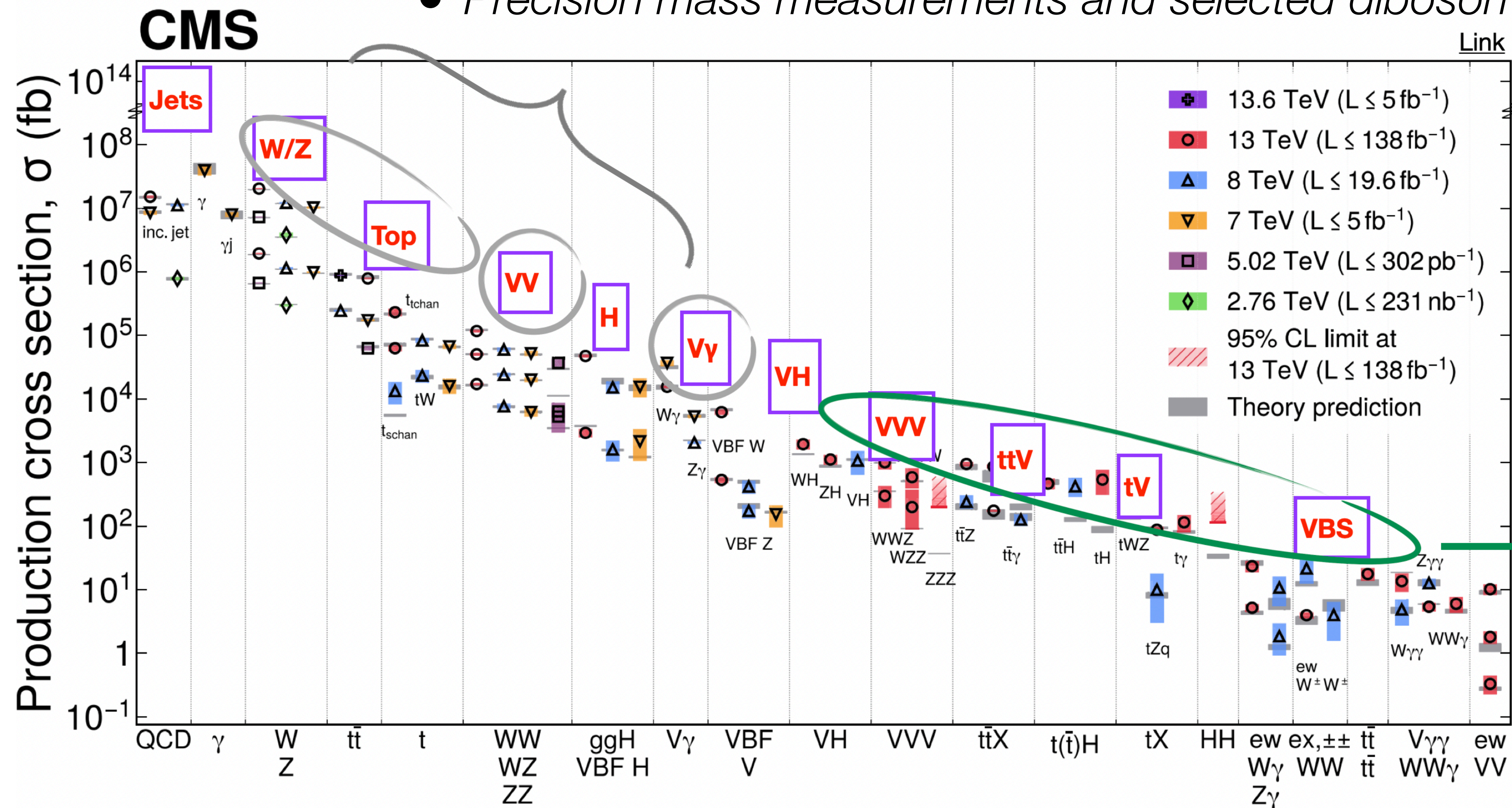
Status: June 2024



Representative precision frontiers

Brief results overview

- Precision mass measurements and selected diboson results*



Results overview and detailed discussion for selected productions

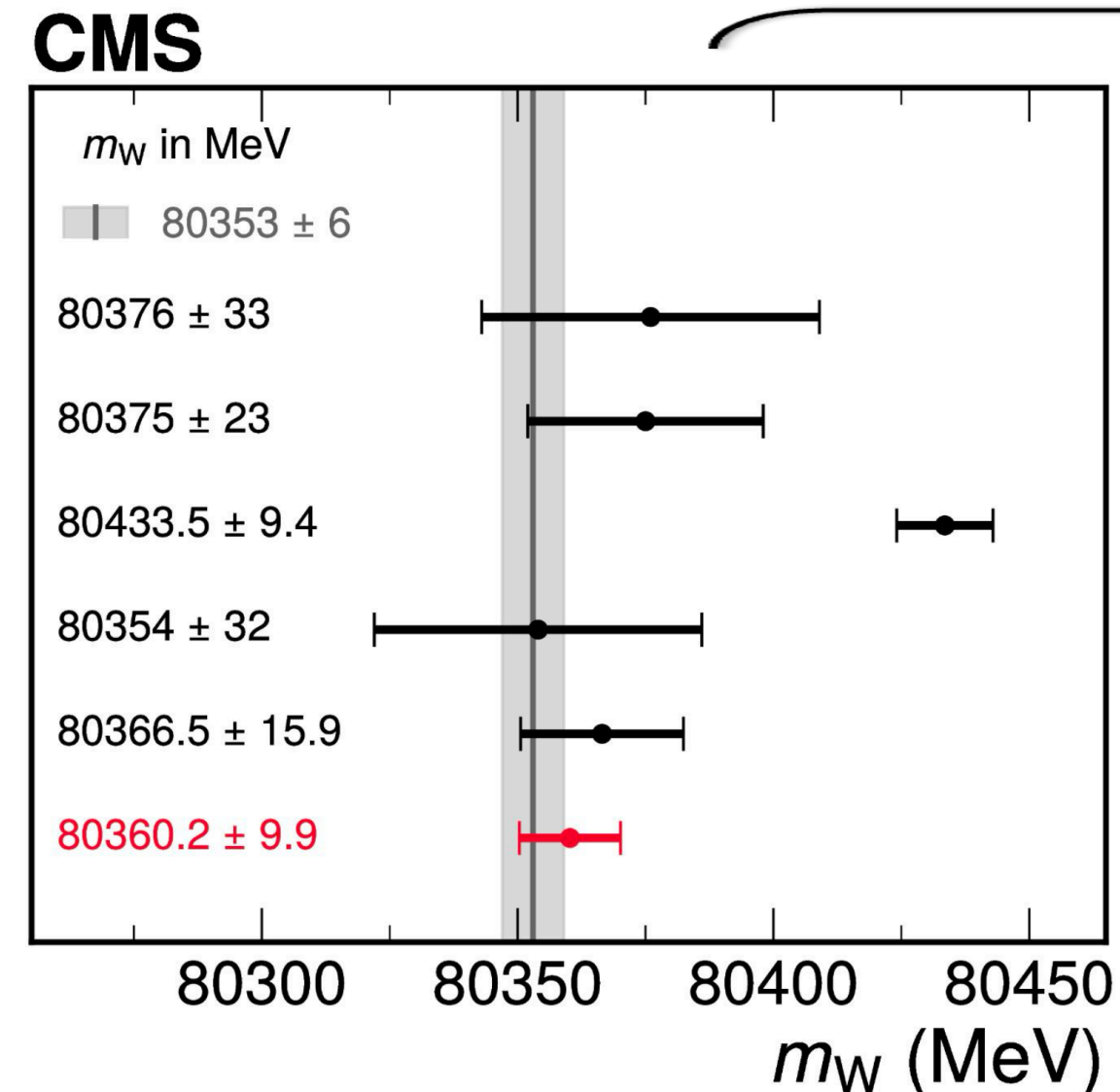
- Rare electroweak and top-associated processes*



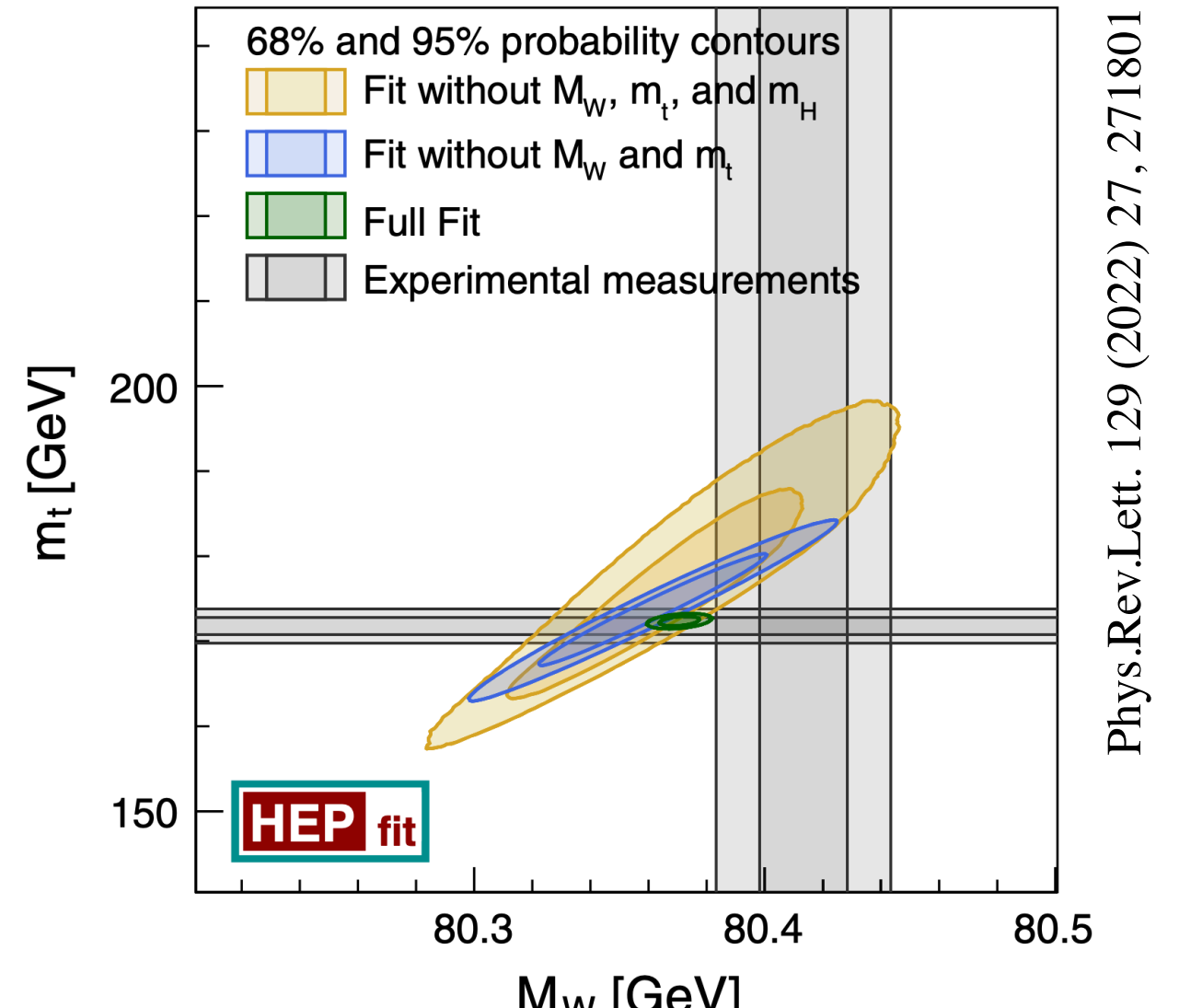
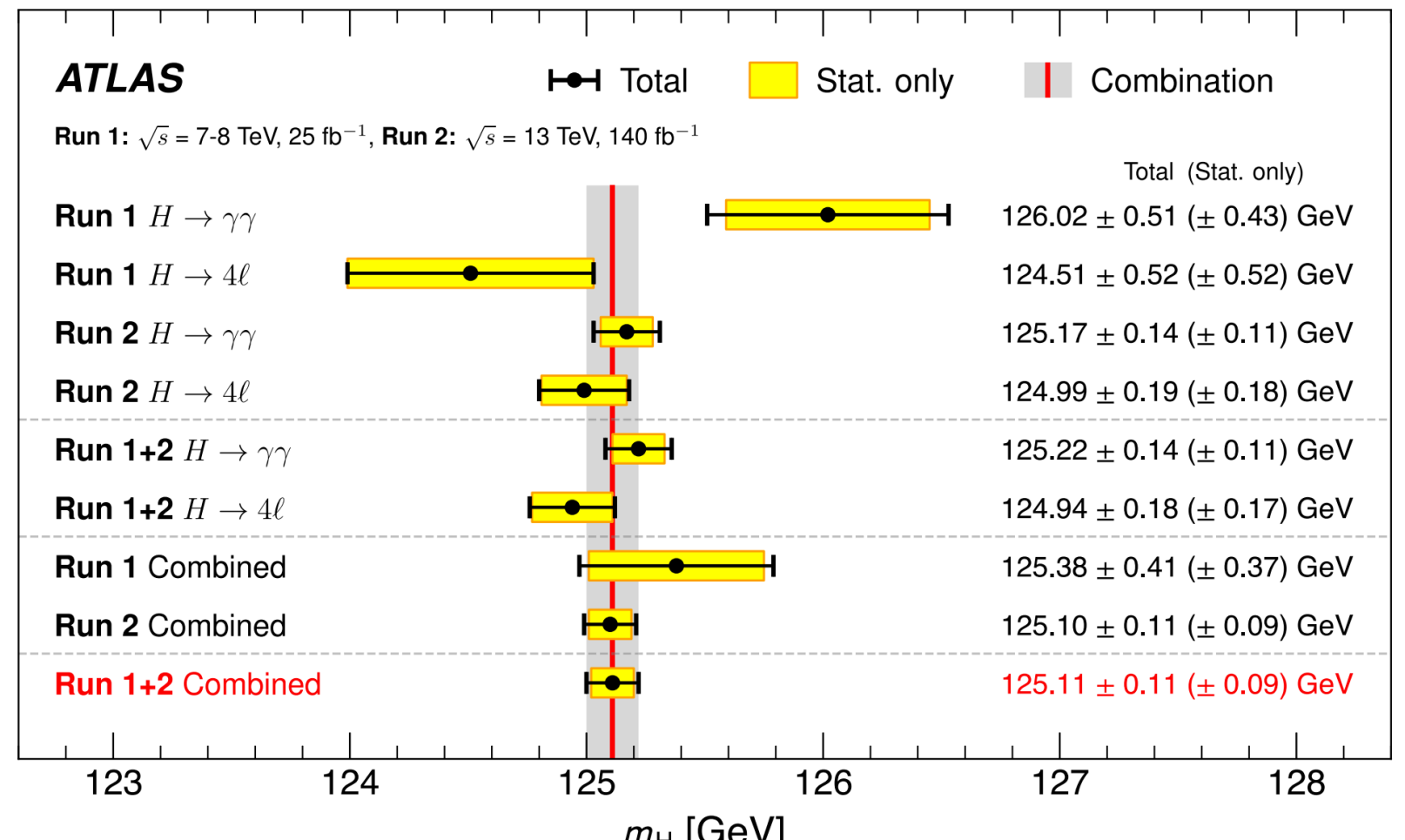
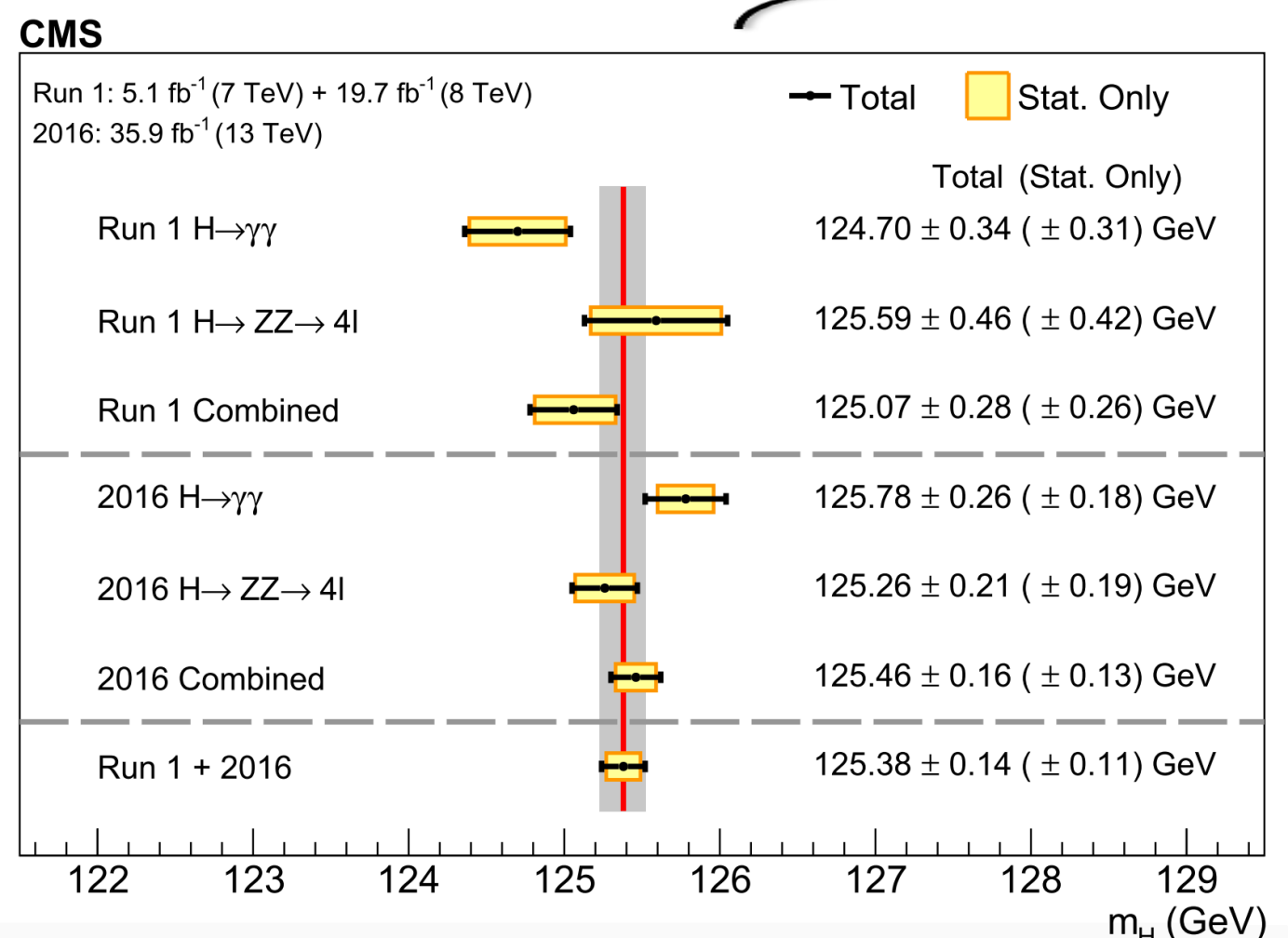
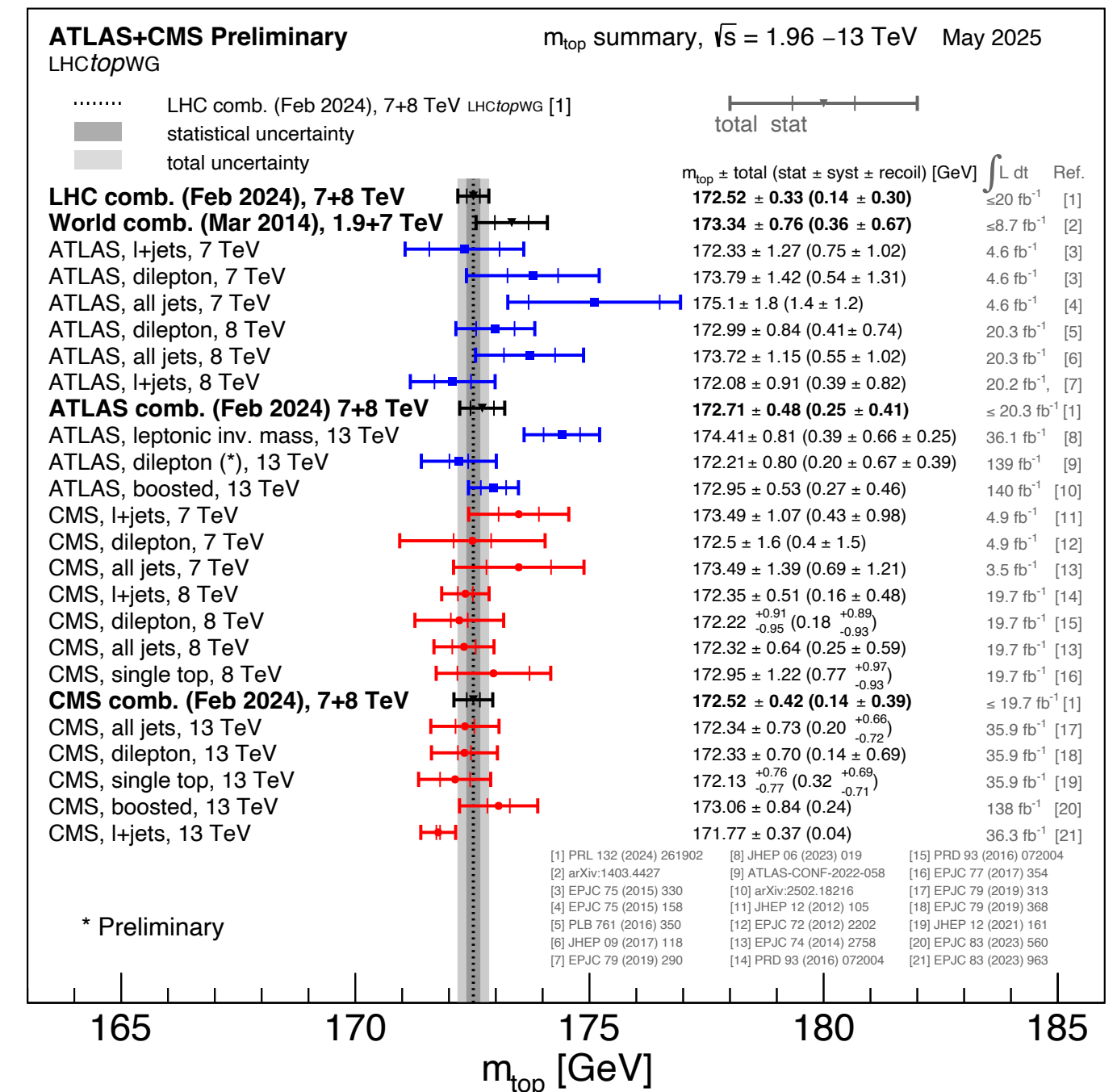
SM precision measurements — mass

Top mass

Electroweak fit
PRD 110 (2024) 030001
LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arXiv:2403.15085
CMS
This work

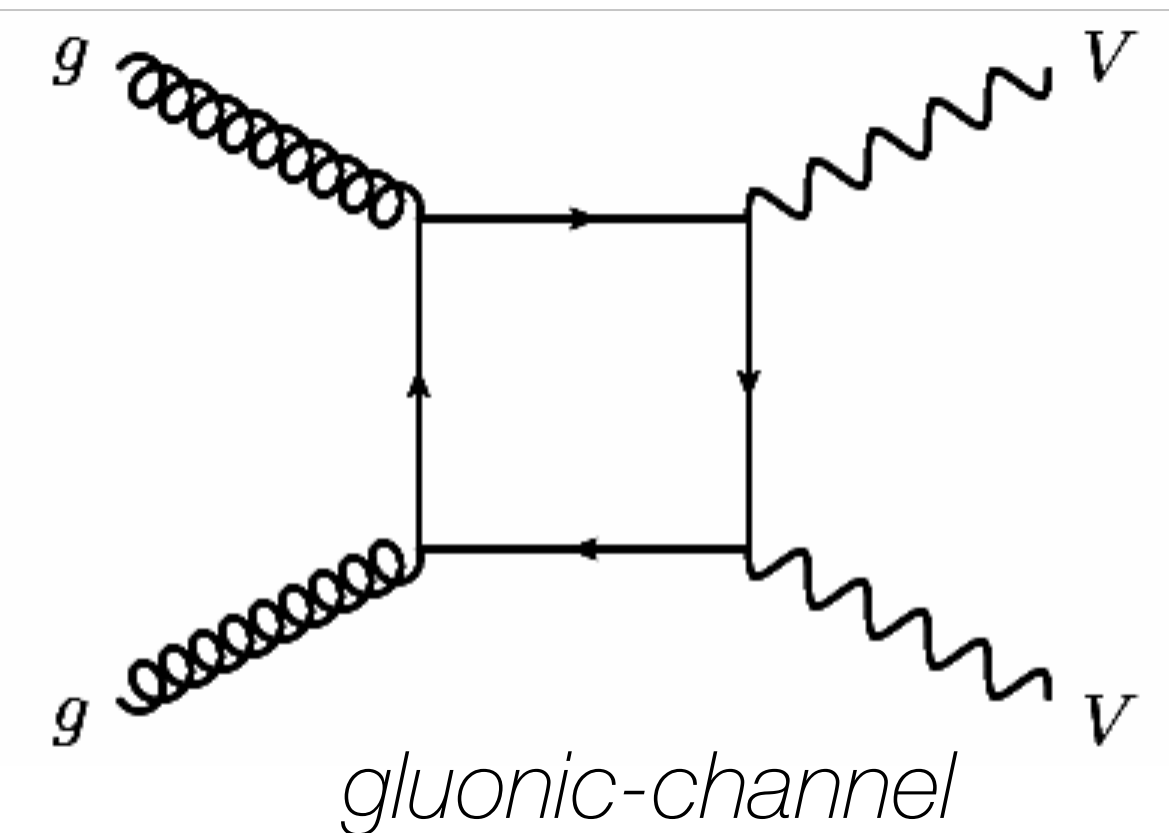
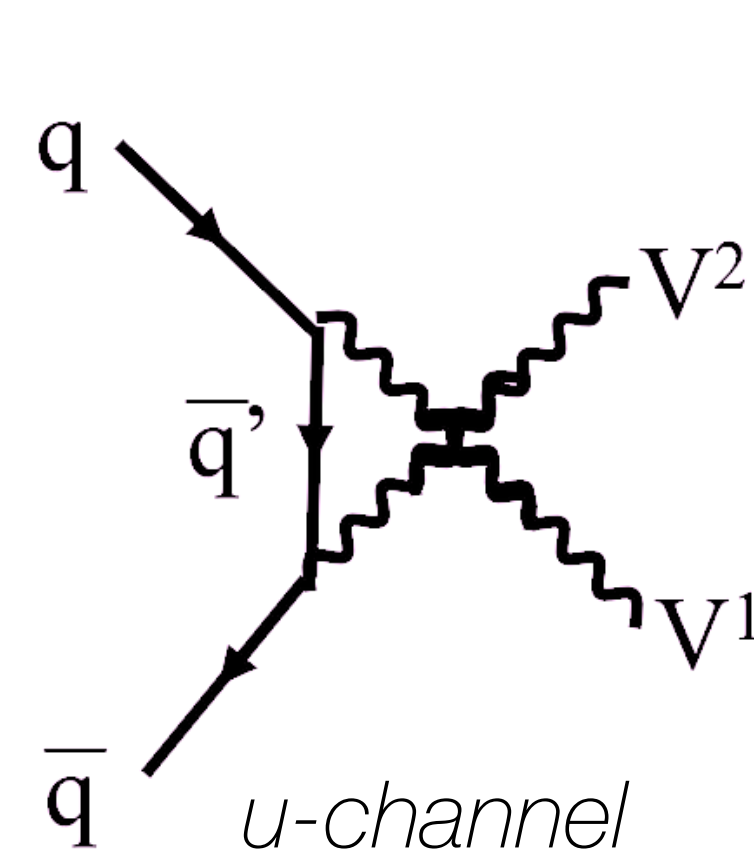
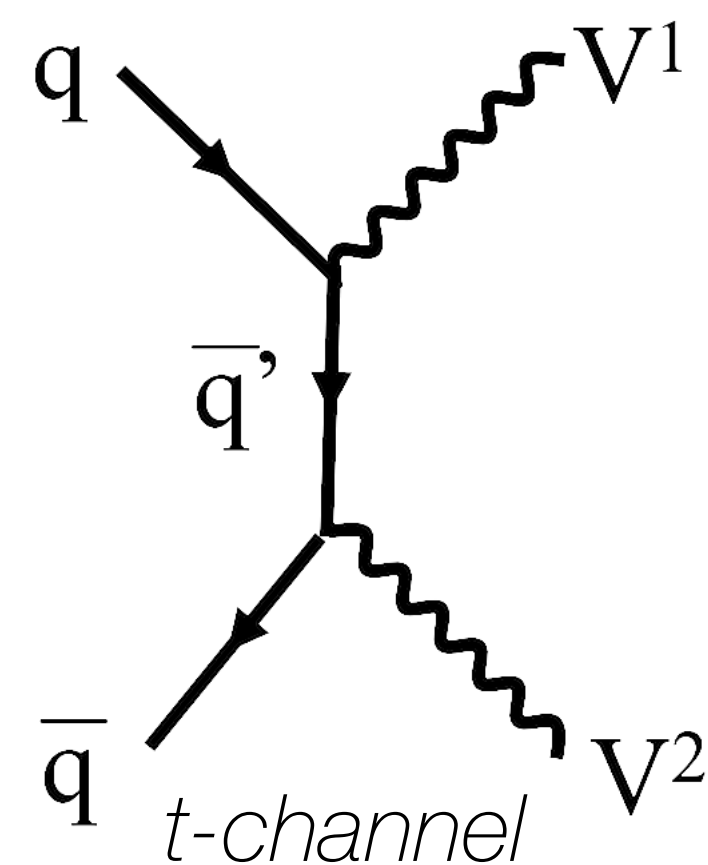
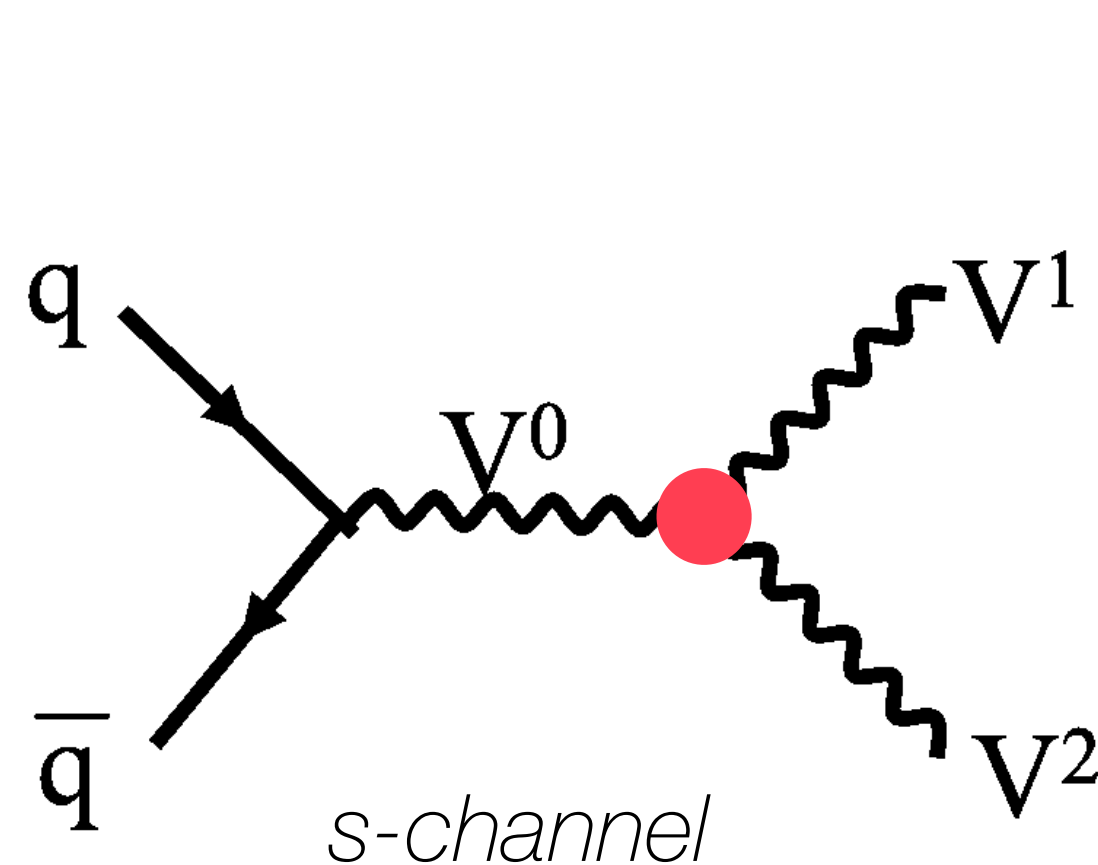


Source of uncertainty	Impact (MeV)	
	Nominal	Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample size	2.4	6.0
Total uncertainty	9.9	9.9



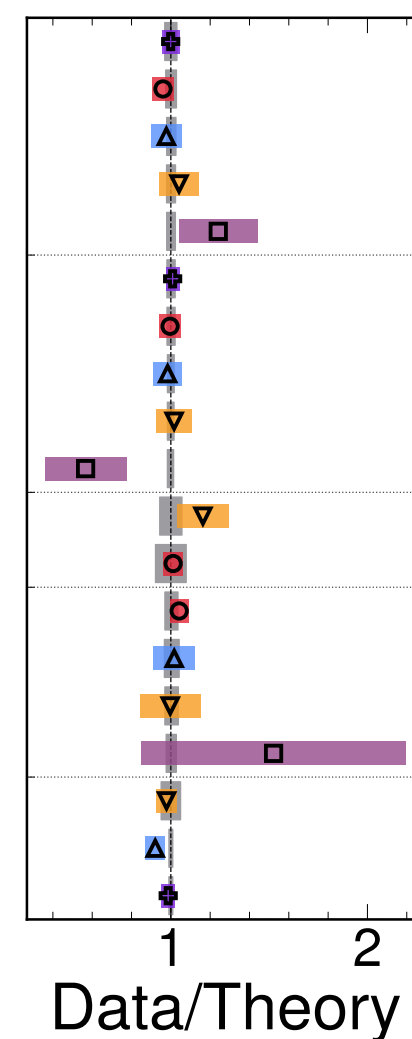
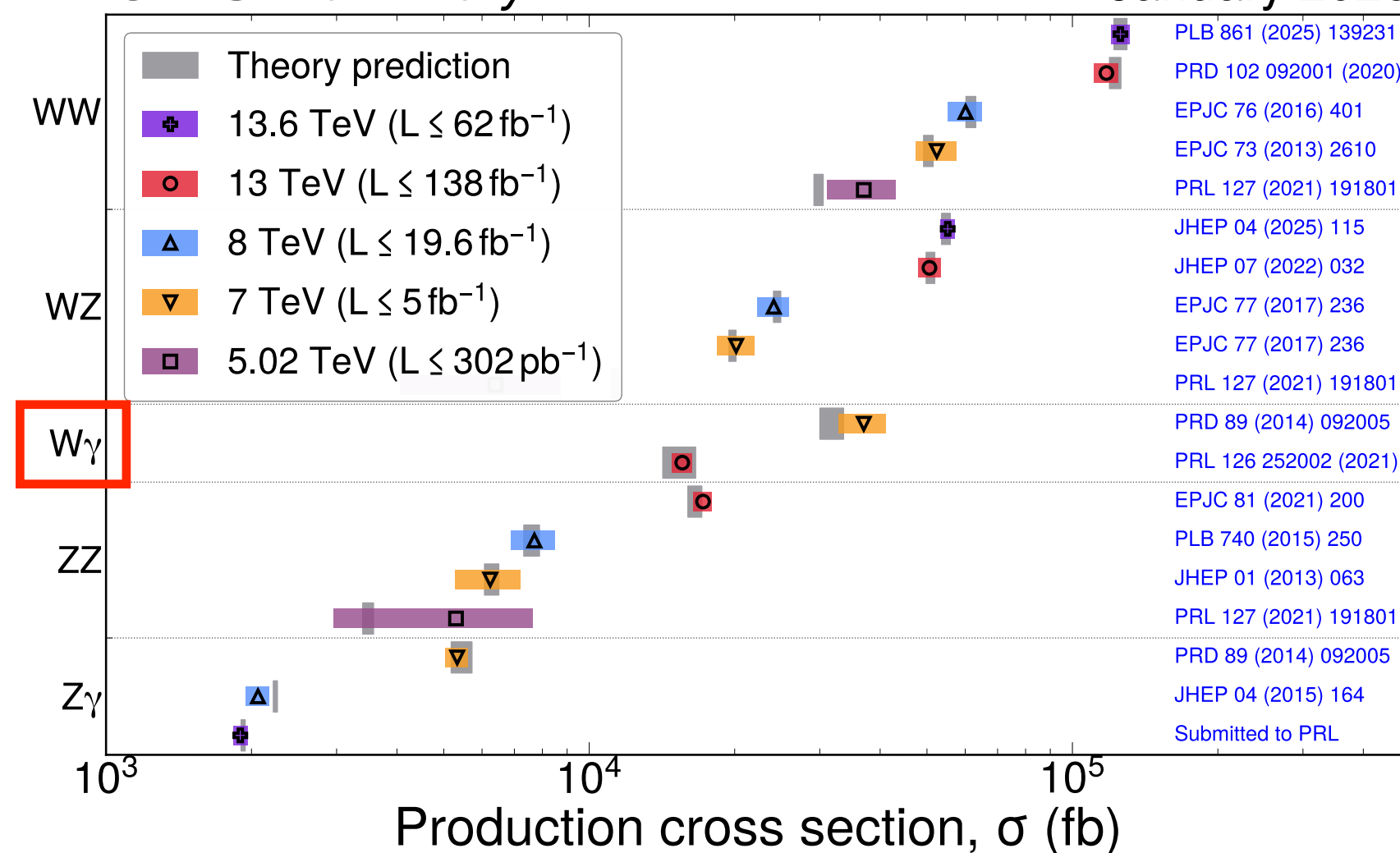
Diboson production — Motivation

Manifestation of gauge boson couplings at the LHC: production of final states with boson pairs (W,Z, γ)



CMS Preliminary

January 2026



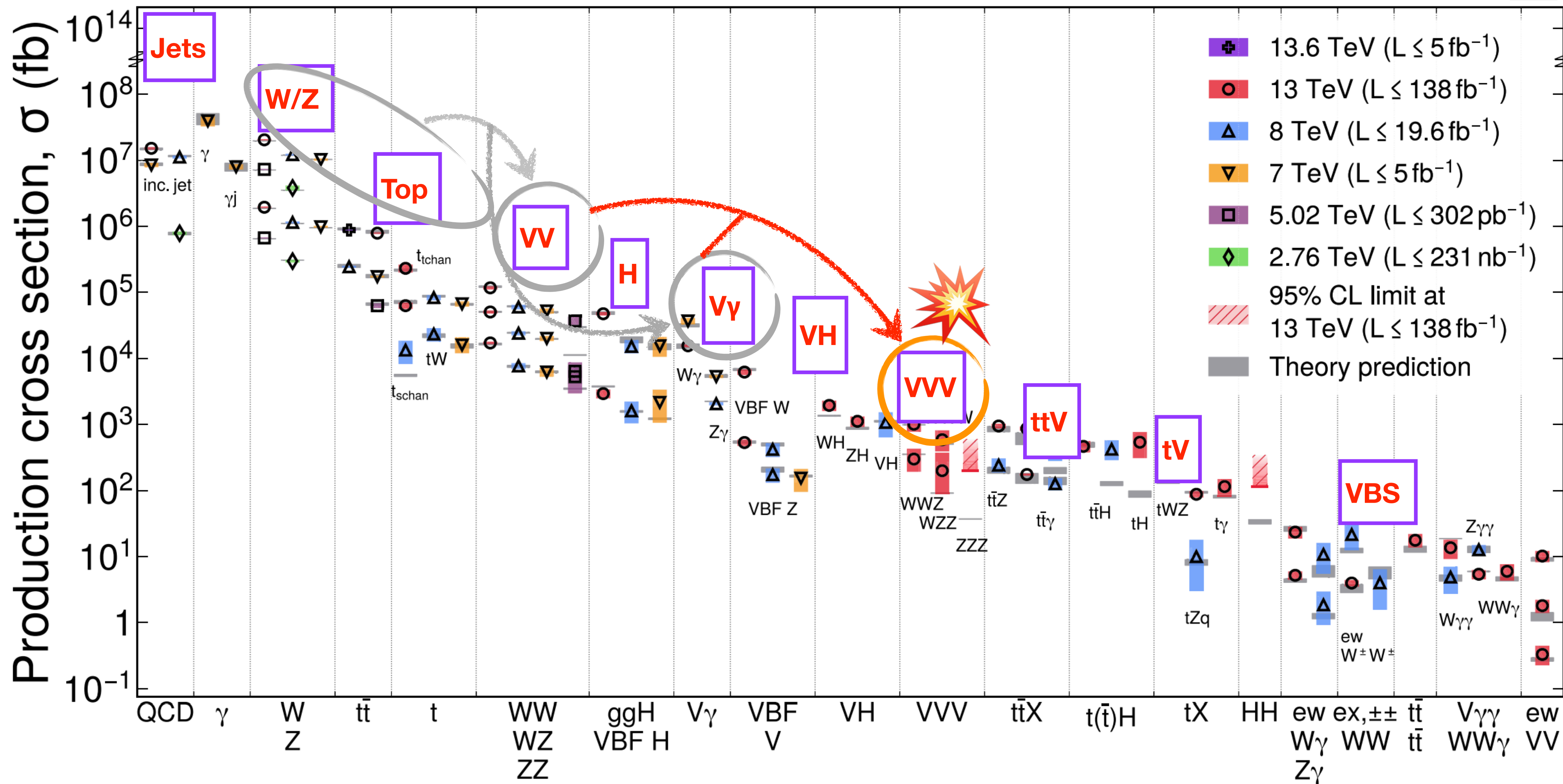
Prediction of the non-abelian SM gauge structure:

Couplings between gauge bosons

Measuring the coupling between the gauge bosons tests a central part of the SM

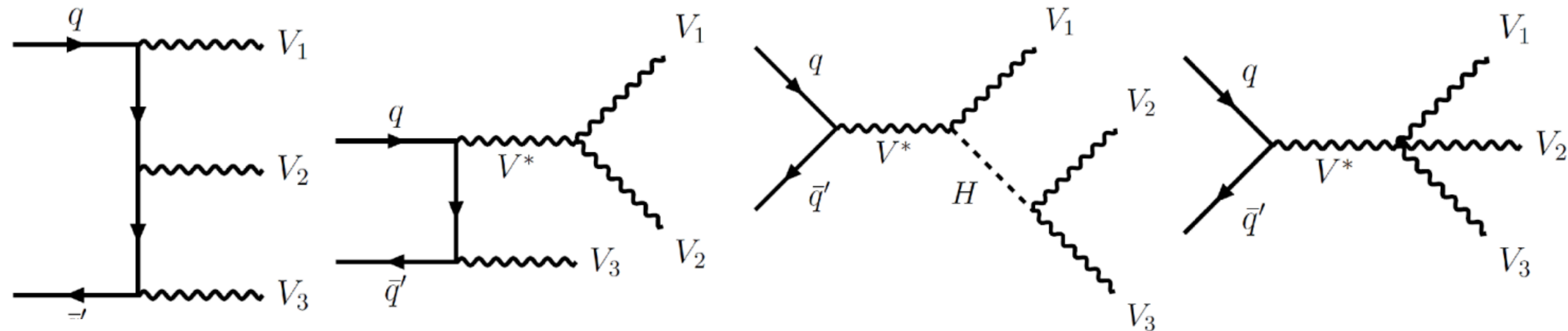
- We have achieved some progress in polarized diboson measurements, especially in WW and ZZ
- The study of polarisation in $V\gamma$ is also interesting to have a look

CMS

[Link](#)


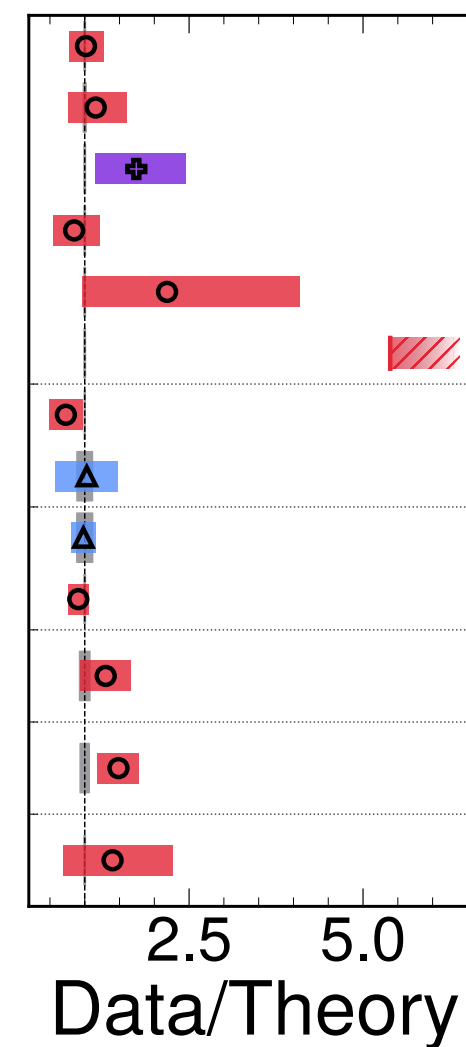
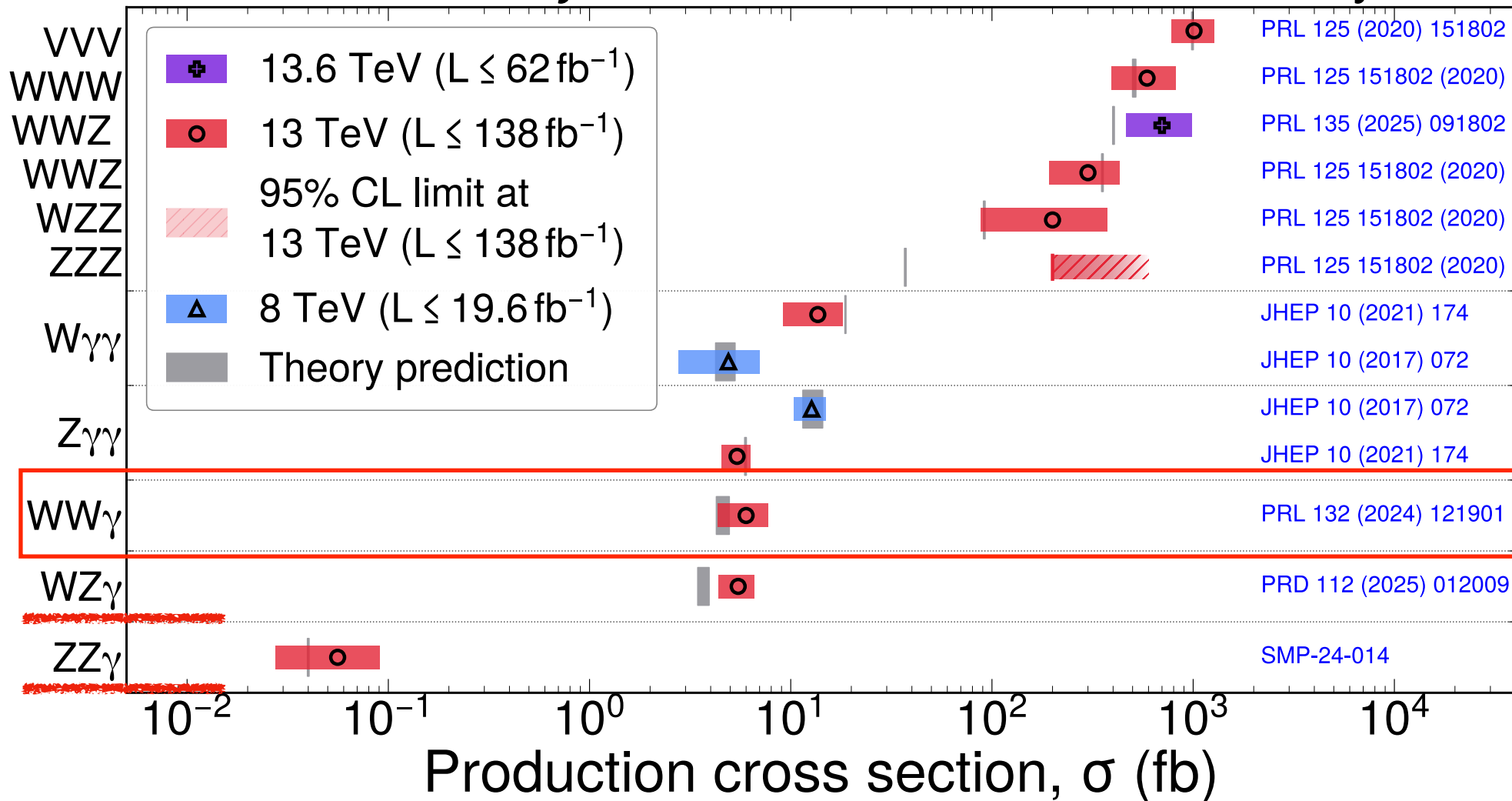
Triboson production — Motivation

- Direct measurement of gauge boson self-coupling and precision test of SM



CMS Preliminary

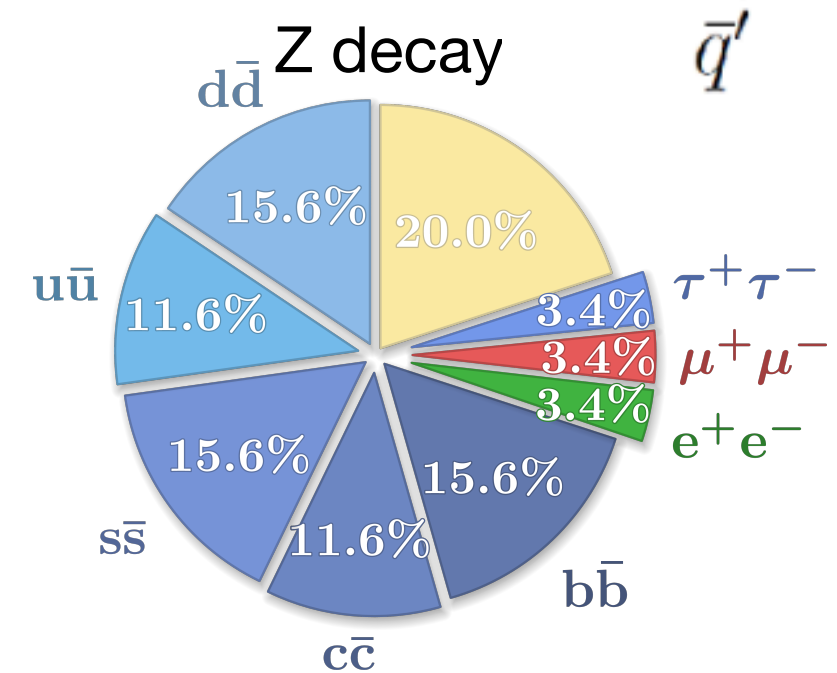
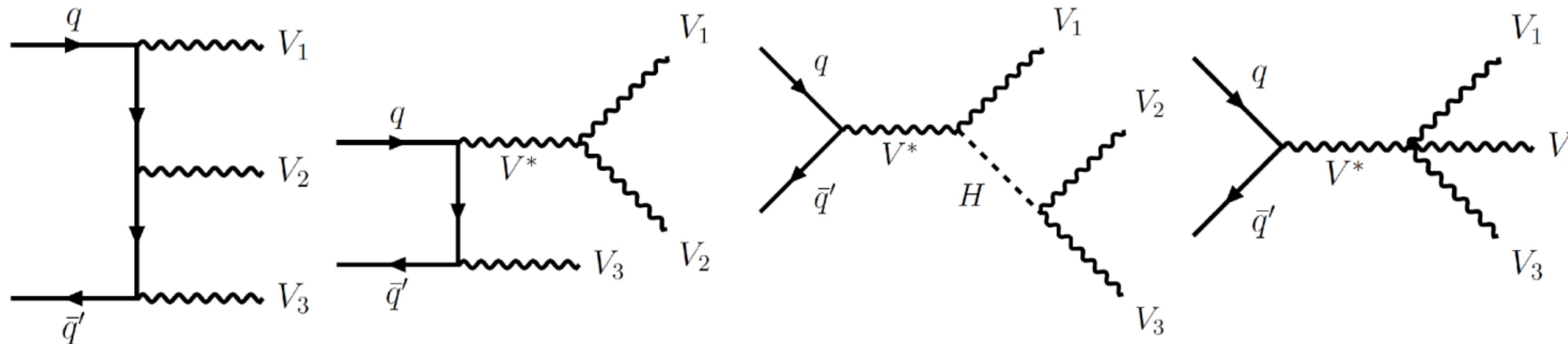
January 2026



- Finely balanced cancellations between QGC, TGC; Higgs amplitudes is needed to preserve unitarity at high CM energies
- Any anomalous HVV, QGC and TGC coupling can disturb the balance and create large cross-sections at high energies
- Complementary to vector boson scattering measurements

Triboson production – Introduction

- Direct measurement of gauge boson self-coupling and precision test of SM

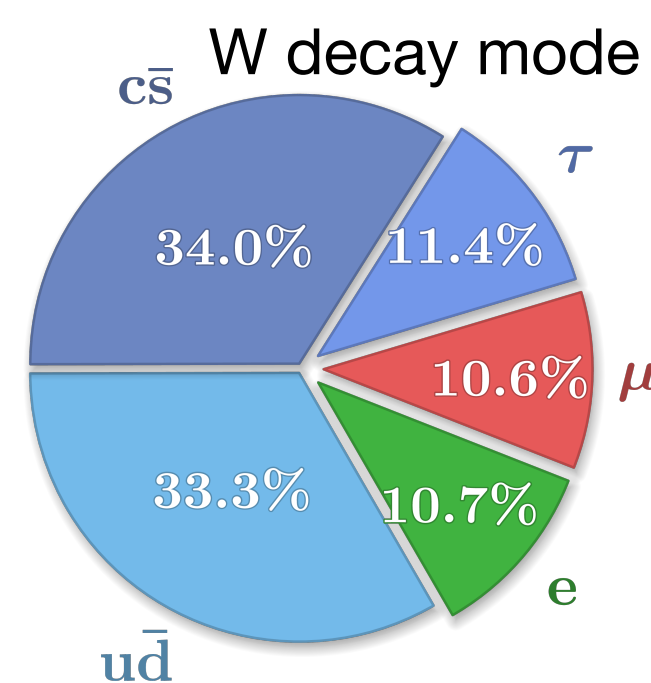


Leptonic final states are proper channels considering background components and reconstruction efficiency/resolution but with **limited statistics**

1. SM process that produce multi-leptons but one is lost
 - WZ, ZZ where a lepton is not detected
 - Top quark related backgrounds
2. $V\gamma$ events where the photon is misidentified as an electron
3. Nonprompt leptons originating from hadronic jets
4. Nonprompt photons originating from hadronic jets

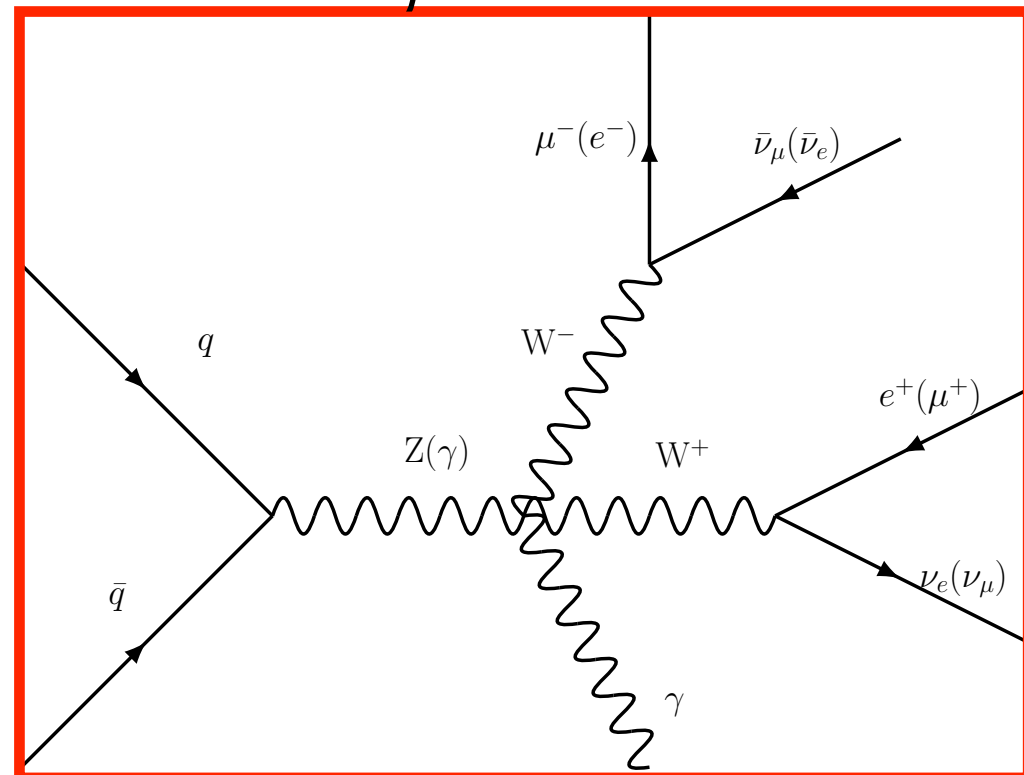
estimated by
normalizing MC
to data

Fully estimated
in-situ using
data

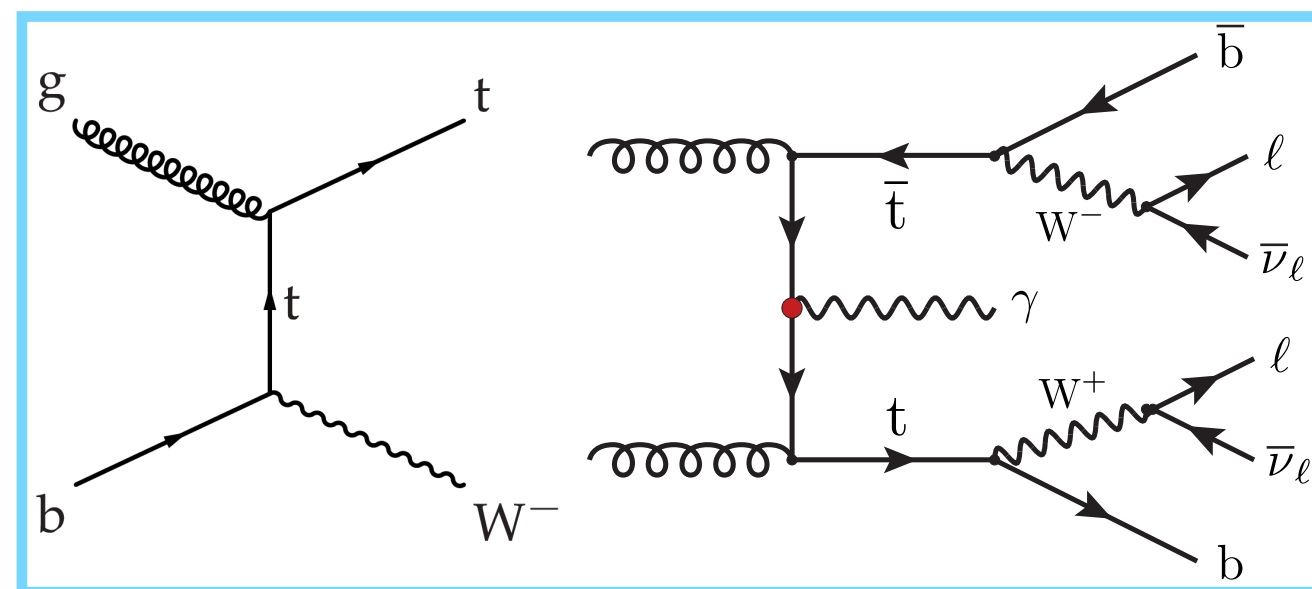


Triboson production — $WW\gamma$

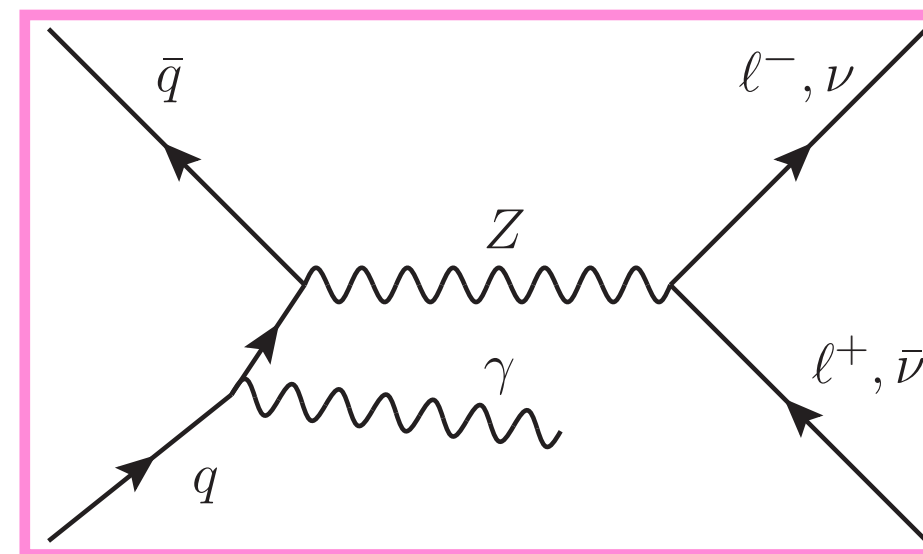
$e^\pm \nu_e \mu^\mp \nu_\mu \gamma$ final states



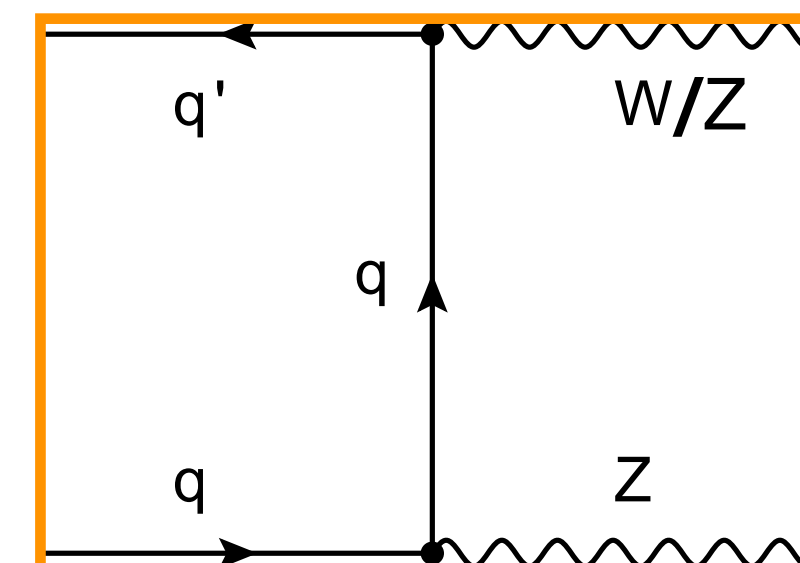
- $t\bar{t}\gamma$ and tW



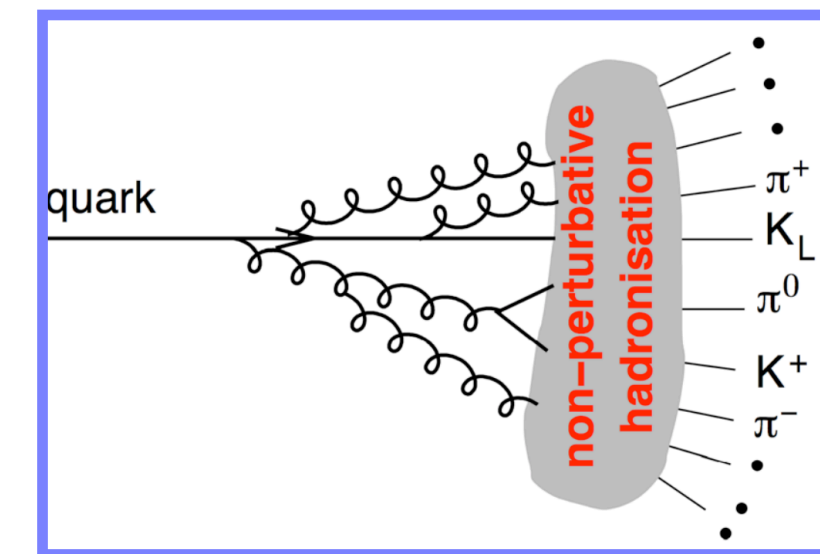
- $Z\gamma$ process



- Diboson

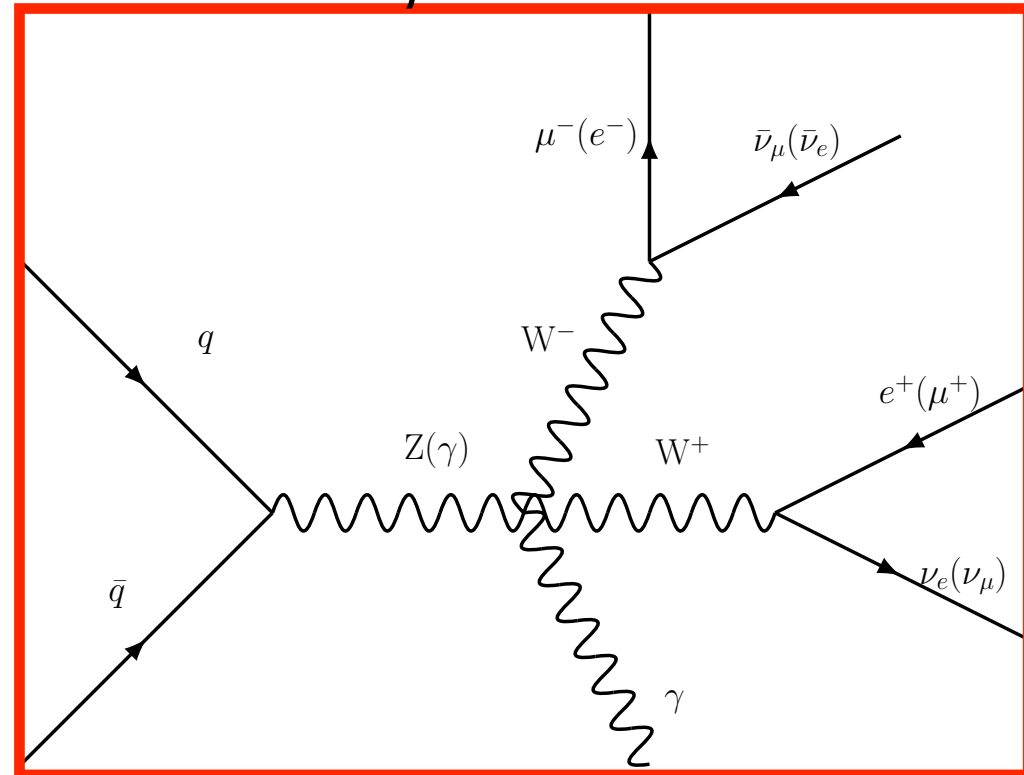


- Nonprompt bkg

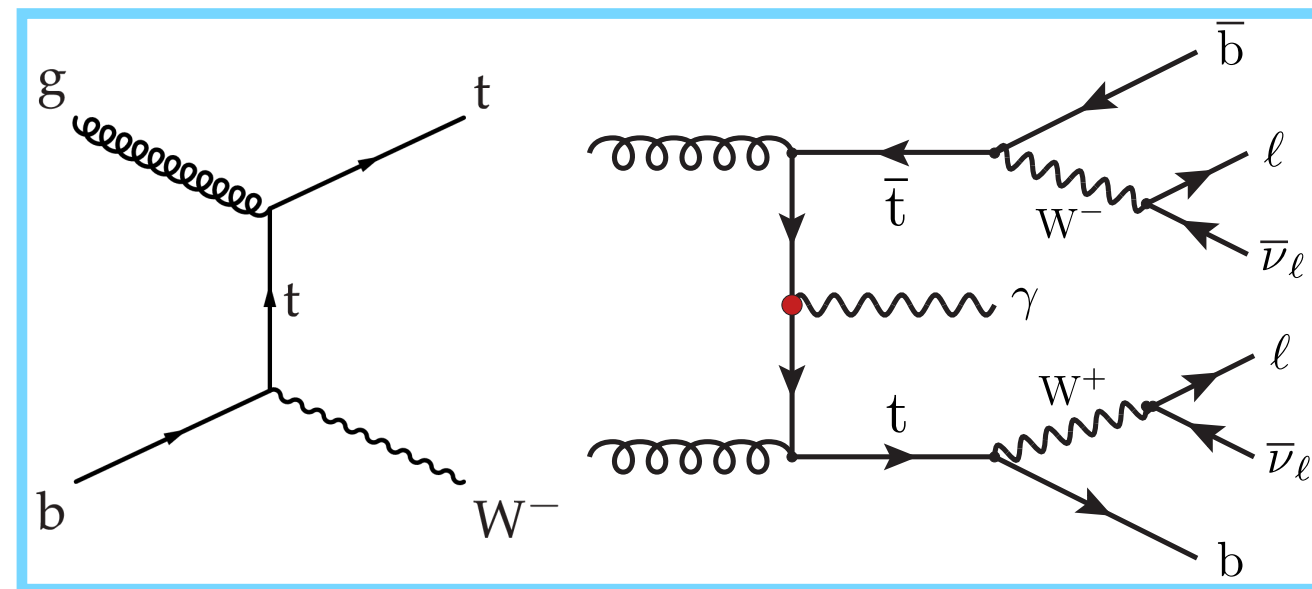


Triboson $WW\gamma$ analysis strategy

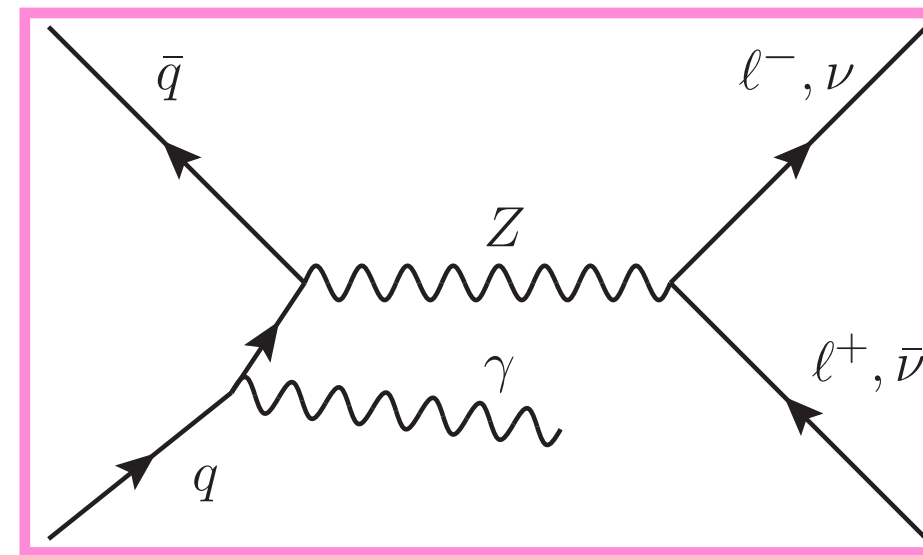
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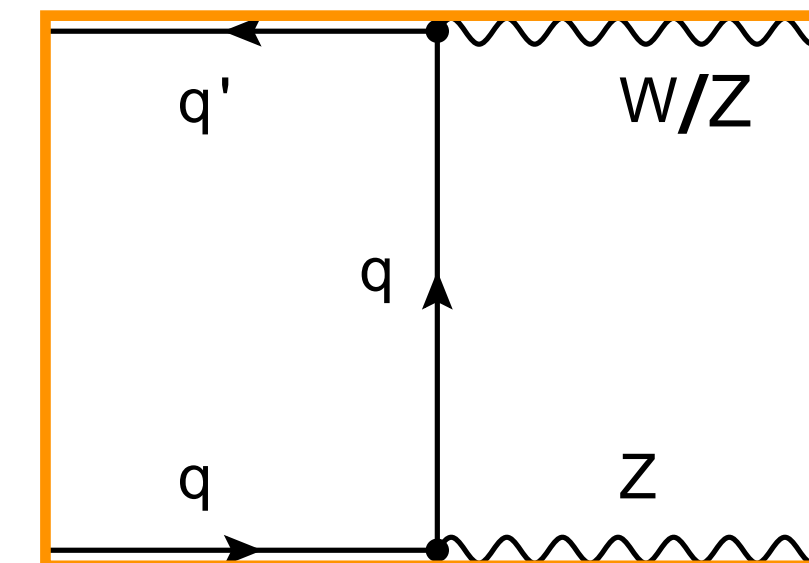
- $t\bar{t}\gamma$ and tW



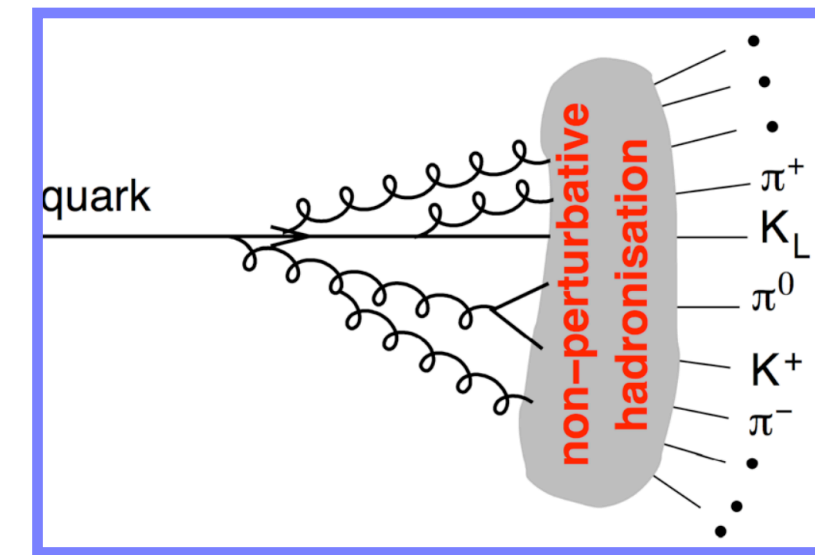
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- Diboson



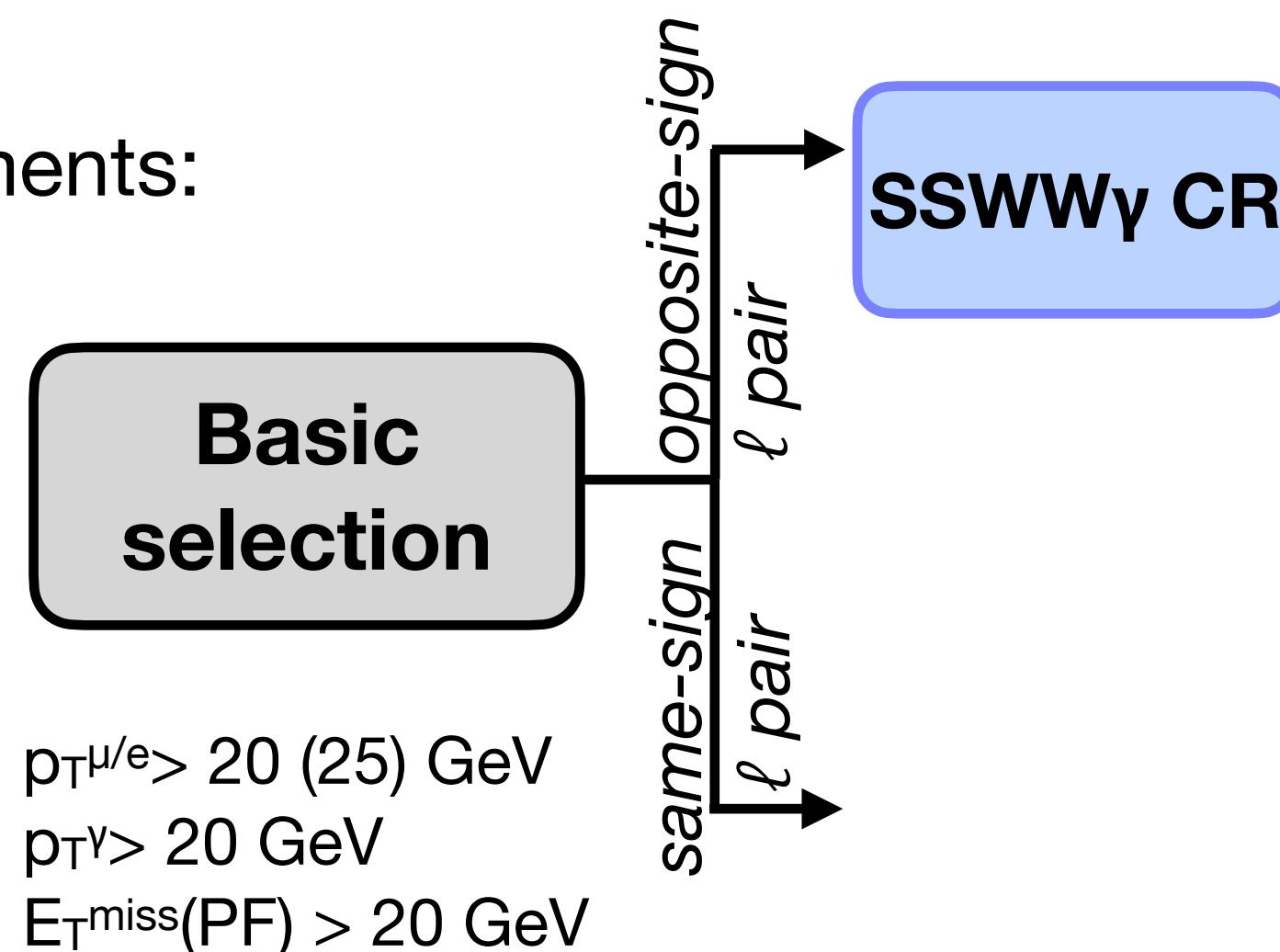
- Nonprompt bkg



MVA-ID is used to identify the leptons and photon for improving signal to background efficiency

In addition to basic requirements:

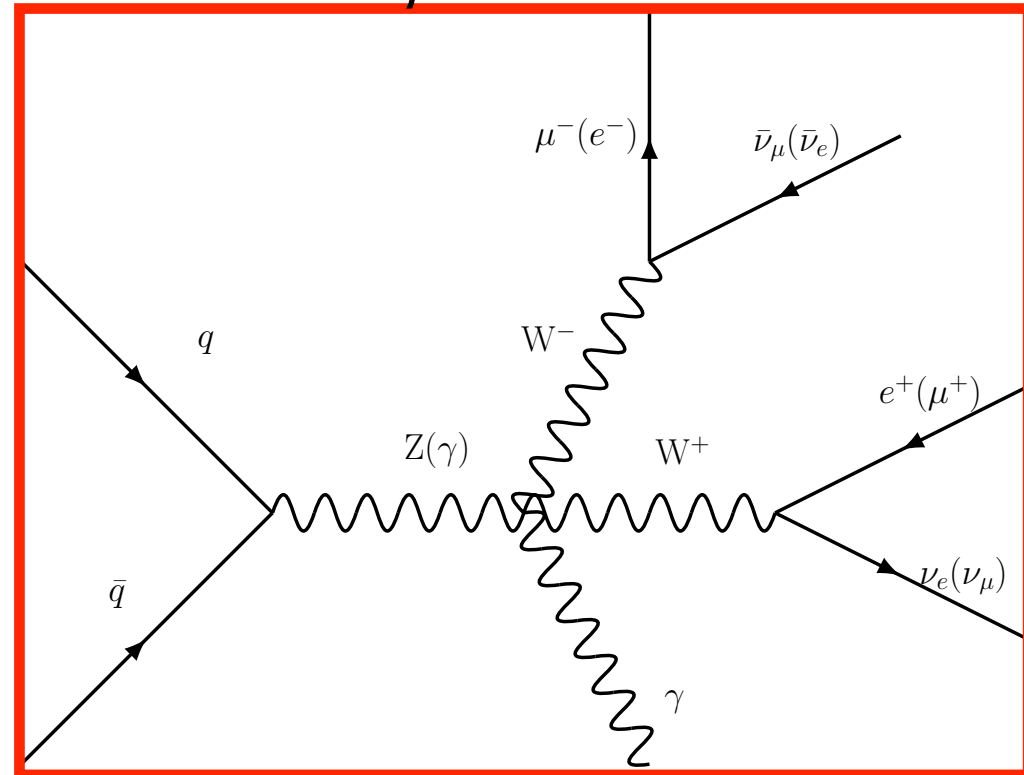
- $m_{\ell\ell} > 10$ GeV
- $p_{T^{\ell\ell}} > 15$ GeV
- $E_{T^{\text{miss}}}(\text{PF}) > 20$ GeV
- $m_{T^{WW}} > 10$ GeV



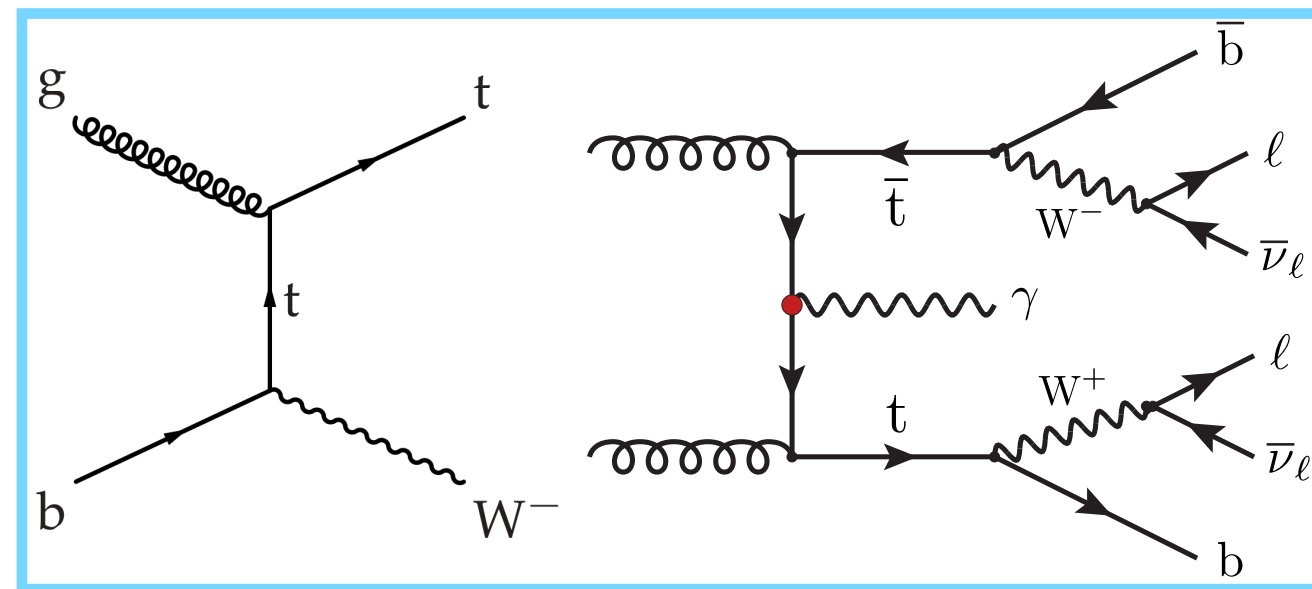
The region full of nonprompt backgrounds, can be used to constrain the nonprompt background by correlating the same systematic uncertainty in the SR

Triboson $WW\gamma$ analysis strategy

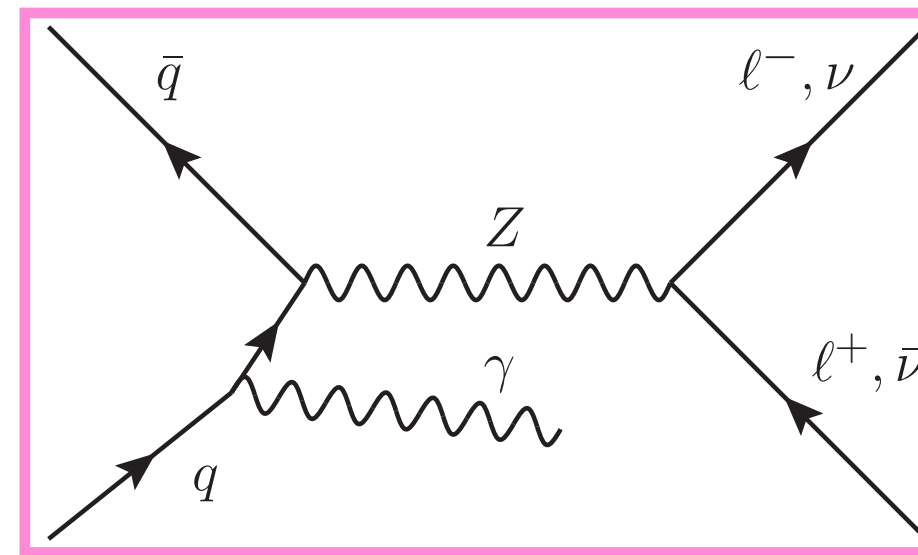
$e^\pm \nu_e \mu^\mp \nu_\mu \gamma$ final states



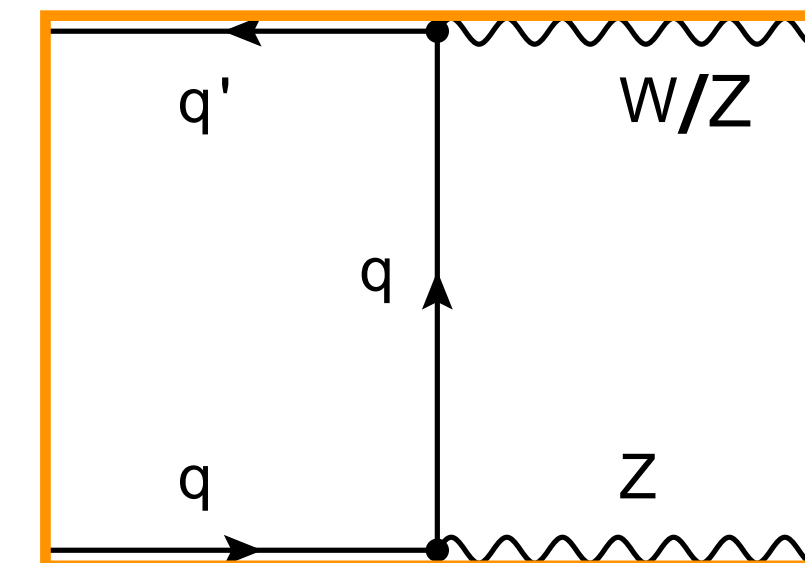
• $t\bar{t}\gamma$ and tW



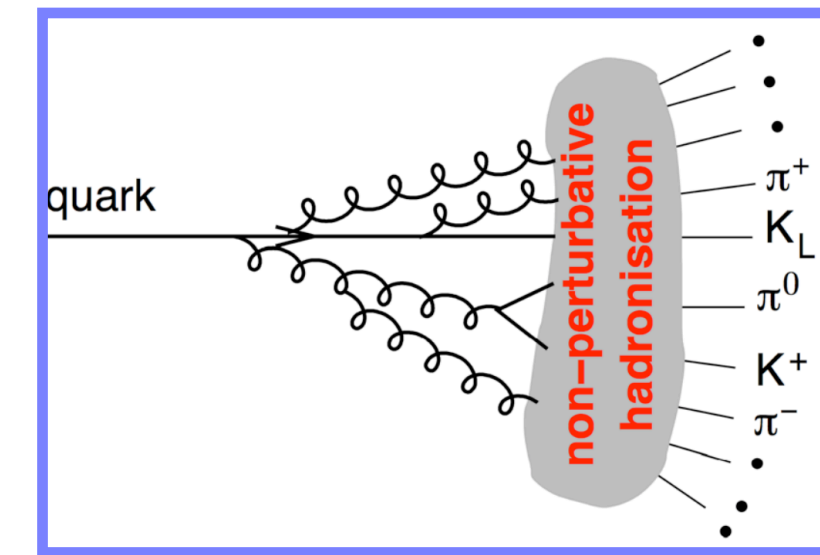
• $Z\gamma$ process



• Diboson



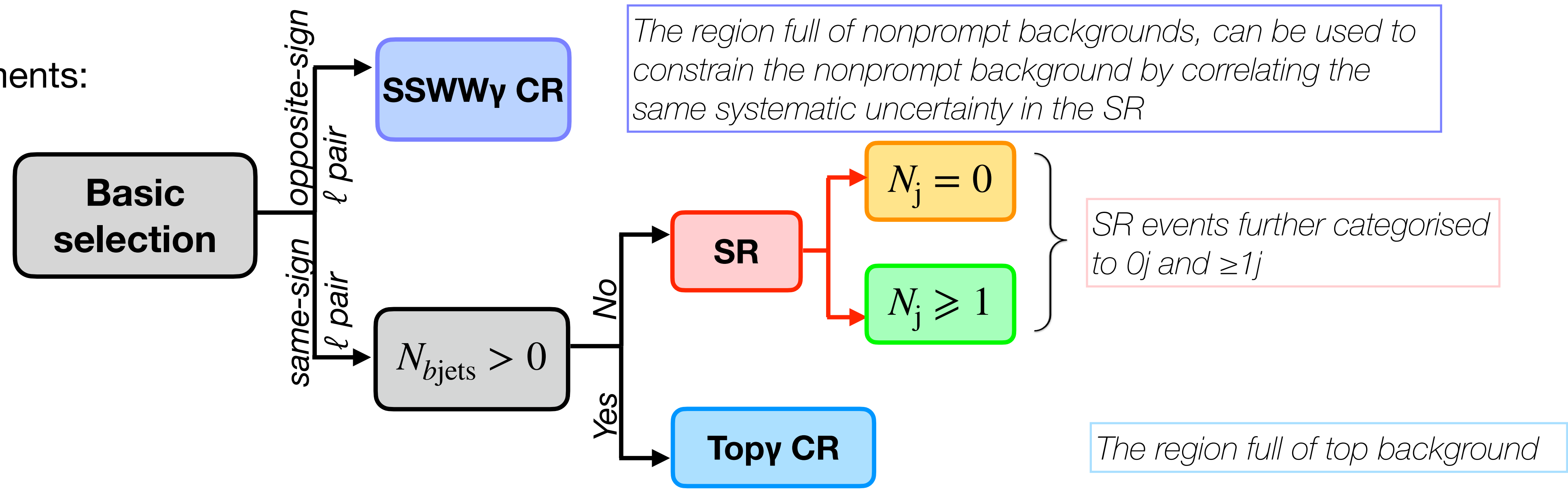
• Nonprompt bkg



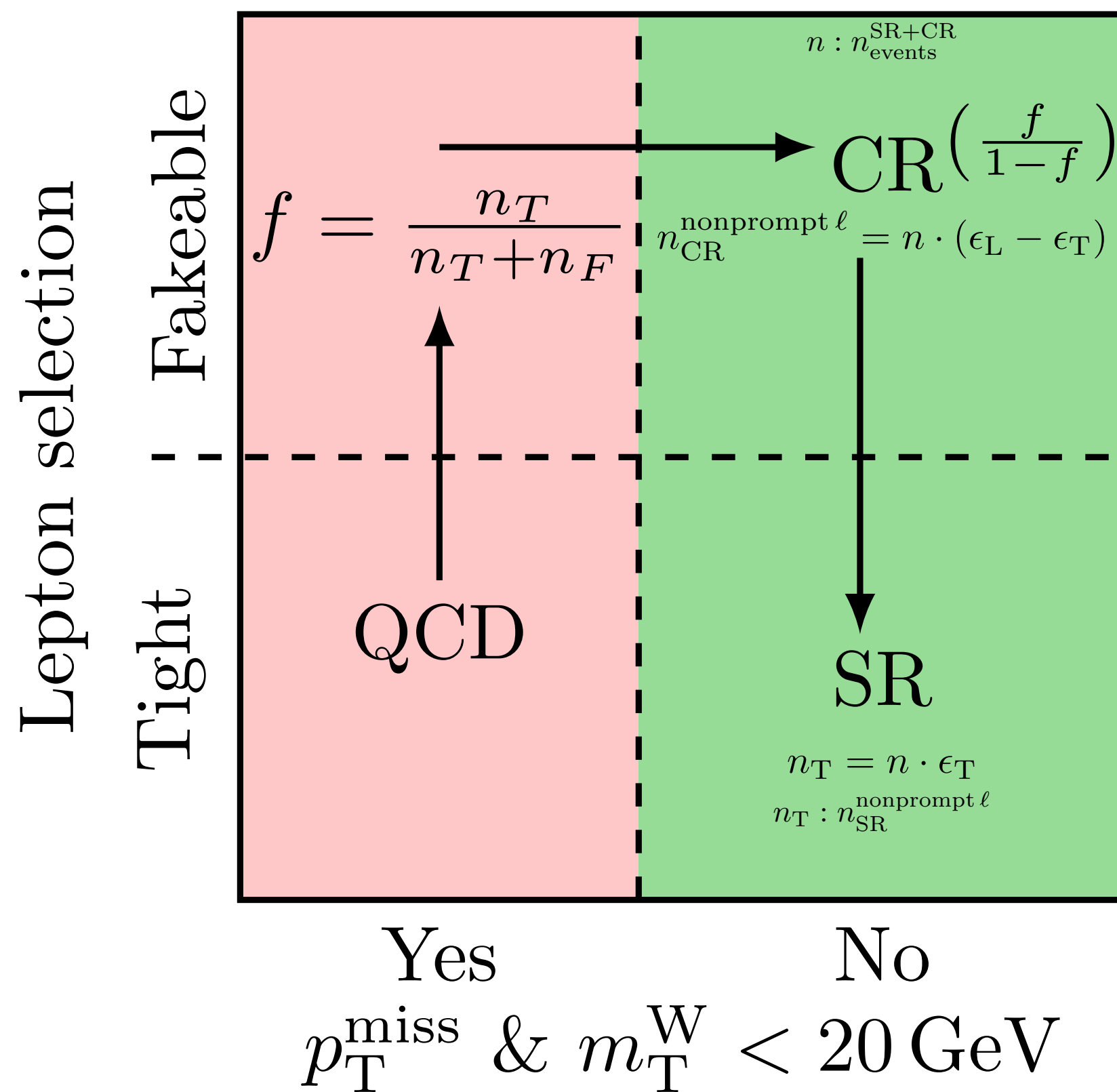
MVA-ID is used to identify the leptons and photon for improving signal to background efficiency

In addition to basic requirements:

- $m_{\ell\ell} > 10$ GeV
- $p_{T^\ell} > 15$ GeV
- $E_{T^{\text{miss}}}(\text{PF}) > 20$ GeV
- $m_{T^{WW}} > 10$ GeV



Nonprompt ℓ estimation



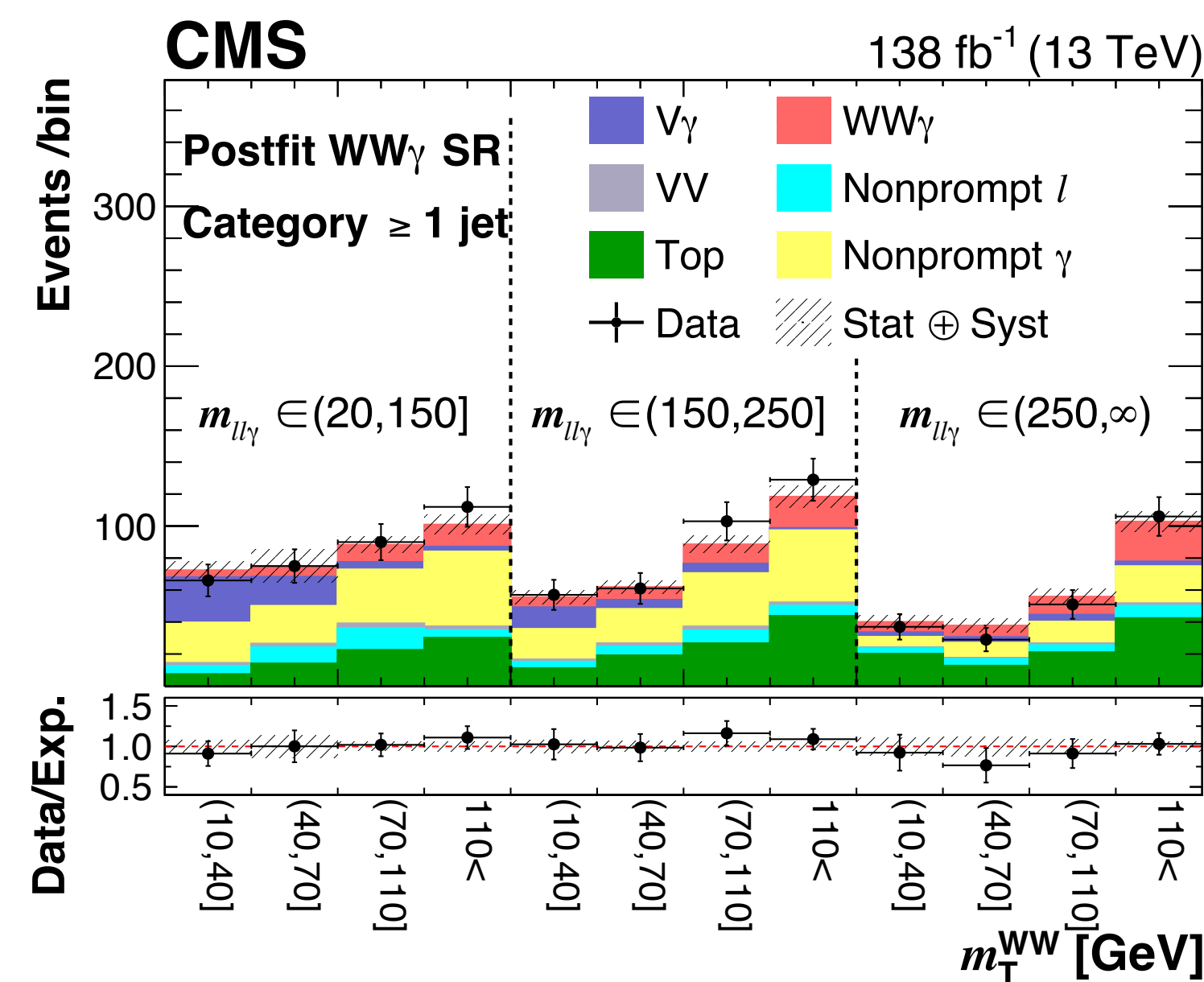
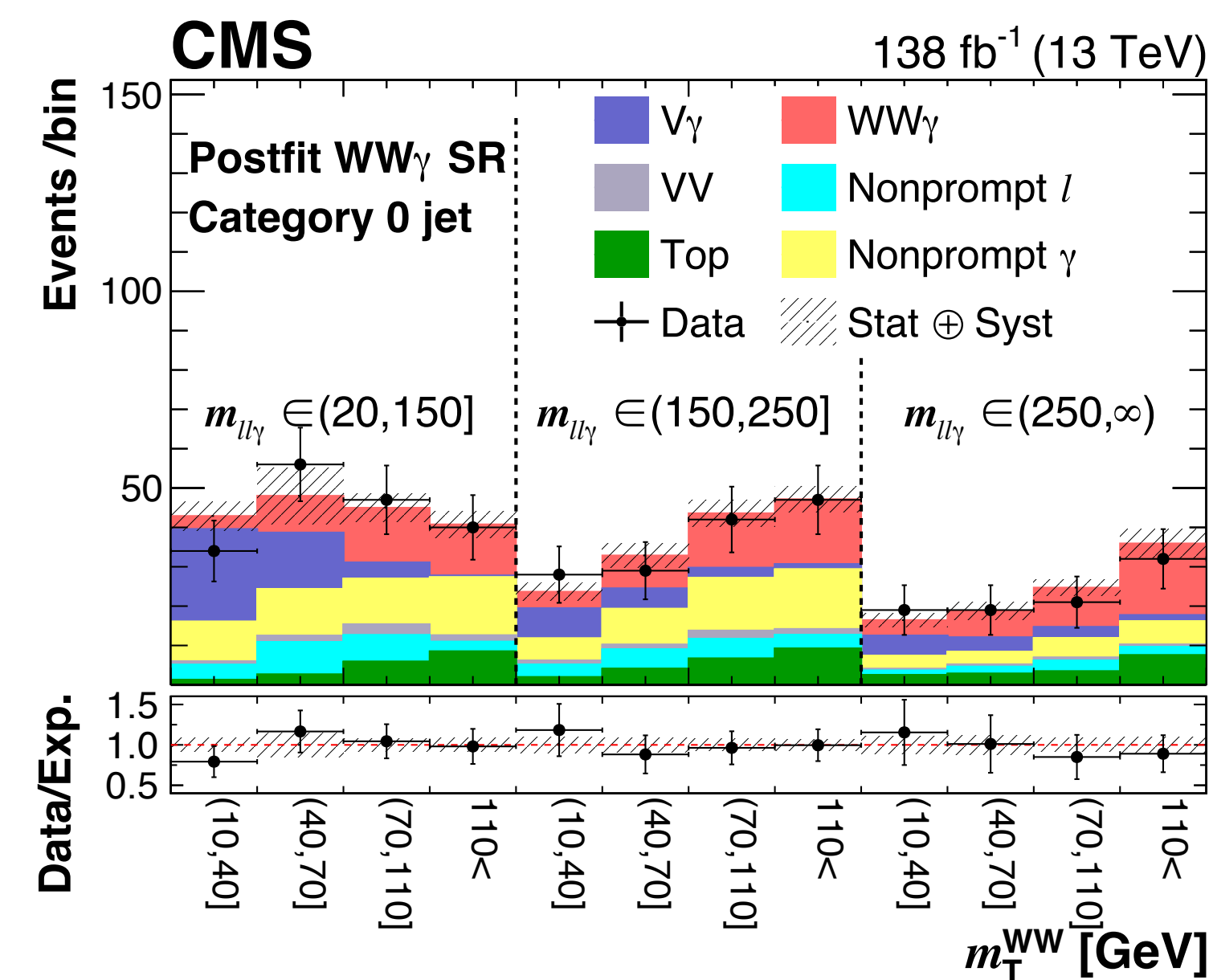
1. Build QCD jet-enriched region with requirements of
 - Exactly one lepton
 - $p_T^{\text{miss}} < 20 \text{ GeV}$ and $m_T^W < 20 \text{ GeV}$
 - At least one jet with $p_T > 30 \text{ GeV}$ and $\Delta R(\ell, j) > 0.4$
2. Measure the tight-to-loose rate $f = \frac{n_T}{n_T + n_F}$
 - n_T the number of leptons passing tight ℓ ID in QCD jet-enriched region
 - n_F the number of leptons passing fakeable ℓ ID in QCD jet-enriched region
3. Build nonprompt ℓ data-driven CR with fakeable ℓ ID and apply to SR with weights $f/(1-f)$

$$n_{\text{nonprompt } \ell}^{\text{SR}} = \sum_{ij} (\text{data}_{\text{CR}}^{ij} \times \frac{f^{ij}}{1-f^{ij}}) - \sum_{ij} (\text{prompt } \ell \text{ MC}_{\text{CR}}^{ij} \times \frac{f^{ij}}{1-f^{ij}})$$

Similar core idea for nonprompt photon estimation via data-driven

Triboson $WW\gamma$ results

- Simultaneous maximum likelihood **fit with control regions**
- POI of the signal and normalization of the relevant top are float



SR

$m_T^{WW}: [10, 40, 70, 110, \infty)$

$m_{\ell\ell\gamma}: [20, 150, 250, \infty)$

**Top
CR**

$m_T^{WW}: [10, \infty)$

**SSWW γ
CR**

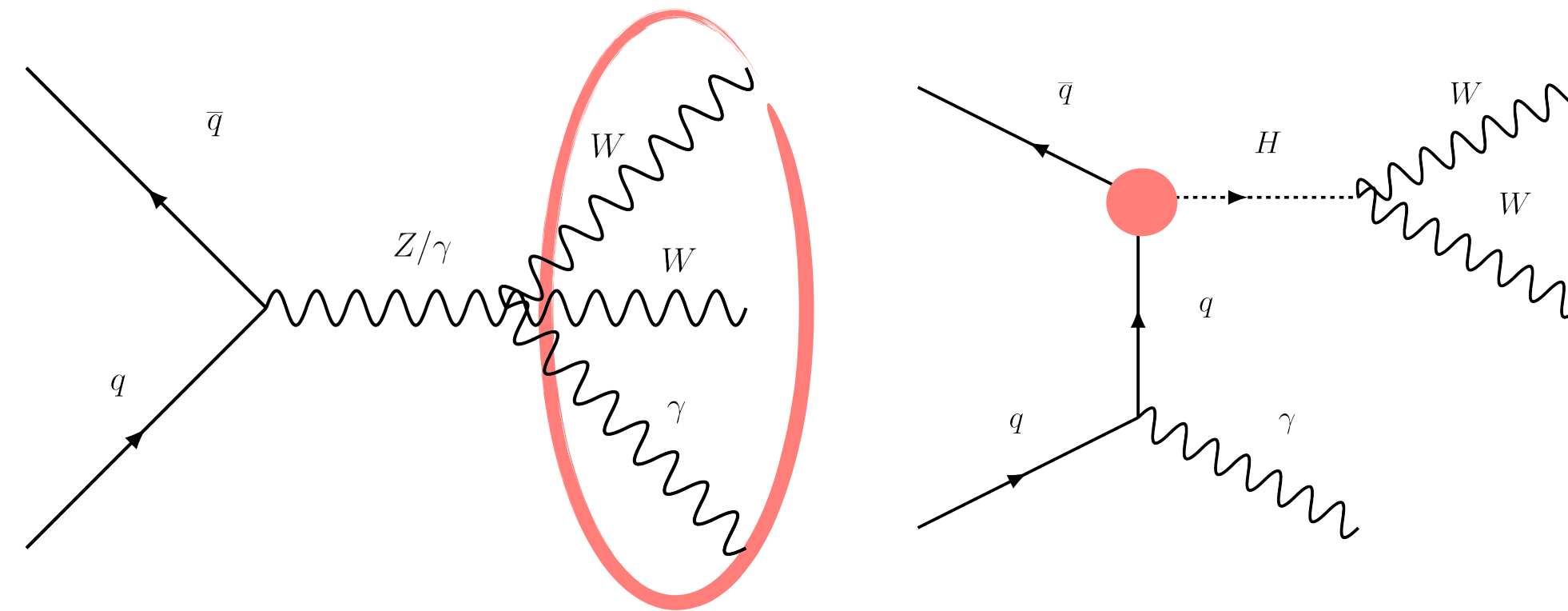
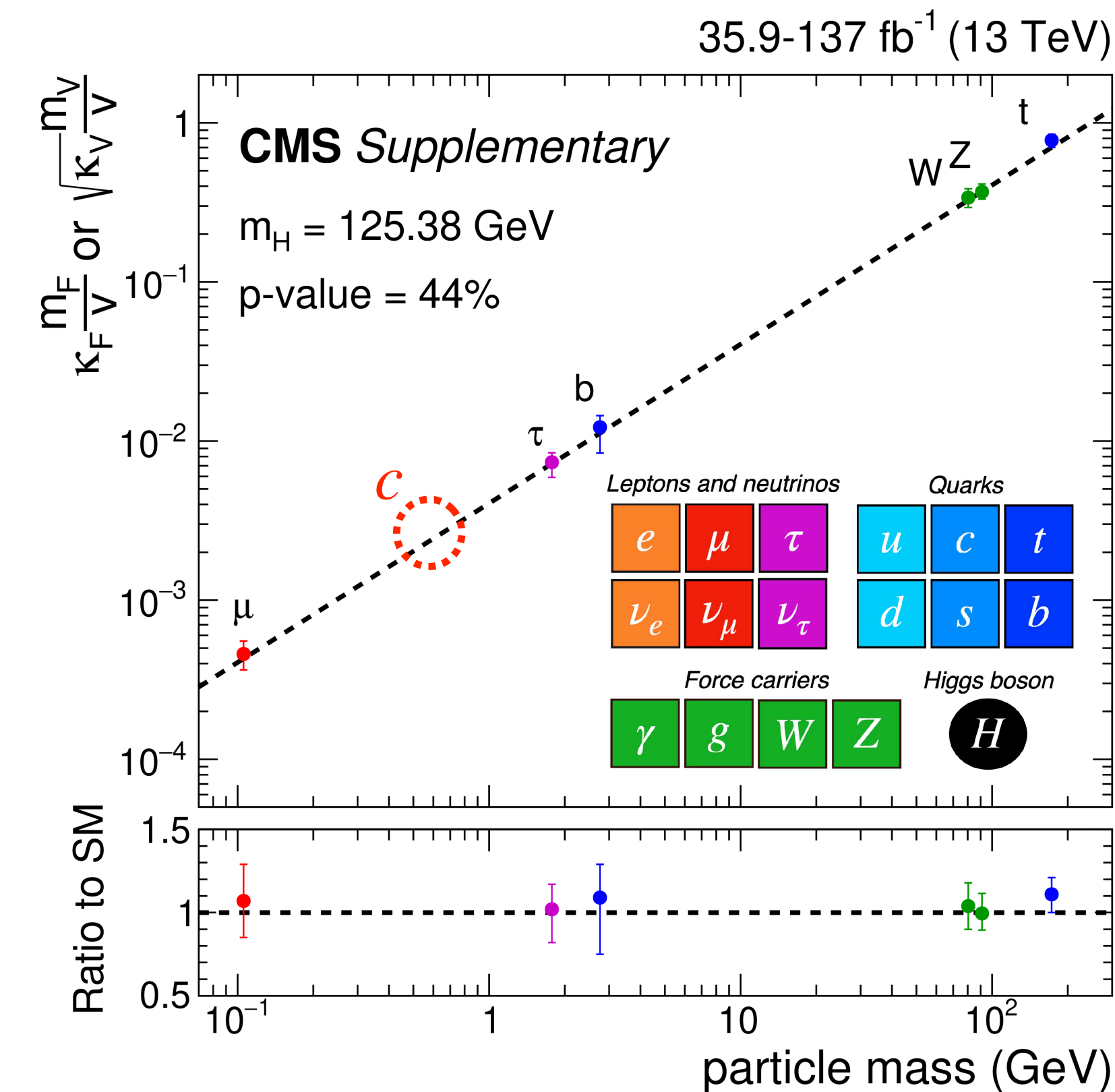
$m_T^{WW}: [10, 40, 70, 110, \infty)$

- Theoretical cross section from MadGraph at NLO QCD accuracy is:
 - $\sigma_{th} = 5.33 \pm 0.34$ (scale) ± 0.05 (PDF) fb

First observation, within uncertainties, measurements **agree with the SM** predictions

- Observed (Expected) significance is 5.6 (5.1) s.d.
- Measured results are:
 - $\mu_{comb} = 1.11 \pm 0.16$ (stat) ± 0.15 (syst) ± 0.13 (theo)
 - $\sigma_{fid} = 5.9 \pm 0.8$ (stat) ± 0.8 (syst) ± 0.7 (theo) fb

Triboson $H(\rightarrow WW)\gamma$ – Yukawa coupling interpretation



- Possible to constrain all light quarks Yukawa couplings

Higgs couplings with light fermions: next milestone @ LHC

Several channels to measure c-H coupling

- VH(cc): the most sensitive channel
- ggH(cc): the boosted region explored in CMS

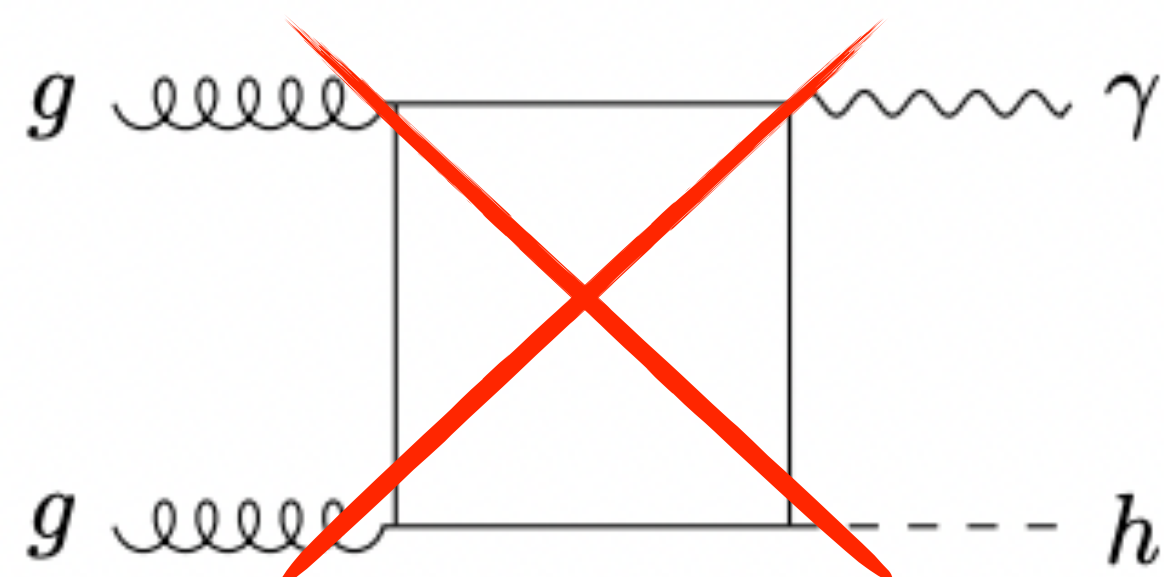
- H-s Yukawa coupling measurement is by $H \rightarrow \phi \gamma$ measurement [1]
- If translate the results [2] to κ_s , the $|\kappa_s| \approx 2.7 \times 10^4$

H-c coupling results	Exp. (Obs.) results
ATLAS VH(cc) ($Z \rightarrow \ell \ell, Z \rightarrow \nu \nu, W \rightarrow \ell \nu$) [EPJC 82 (2022) 717]	$ \kappa_c < 8.5$ (12.4)
CMS VH(cc) ($Z \rightarrow \ell \ell, Z \rightarrow \nu \nu, W \rightarrow \ell \nu$) [arXiv:2205.05550]	$1.1 < \kappa_c < 5.5$ ($\kappa_c < 3.4$)
CMS ggH(cc) [arXiv:2211.14181]	$\mu < 47$ (39)

[1] [https://doi.org/10.1007/JHEP07\(2018\)127](https://doi.org/10.1007/JHEP07(2018)127)

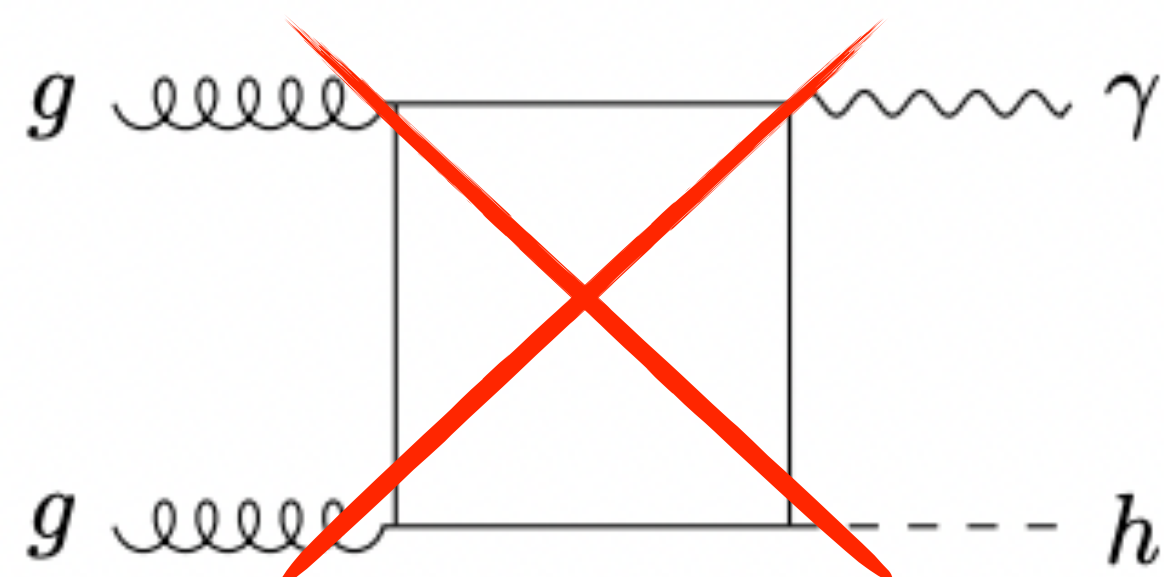
[2] <https://doi.org/10.1103/PhysRevD.101.115005>

Triboson $H(\rightarrow WW)\gamma$ – Yukawa coupling interpretation

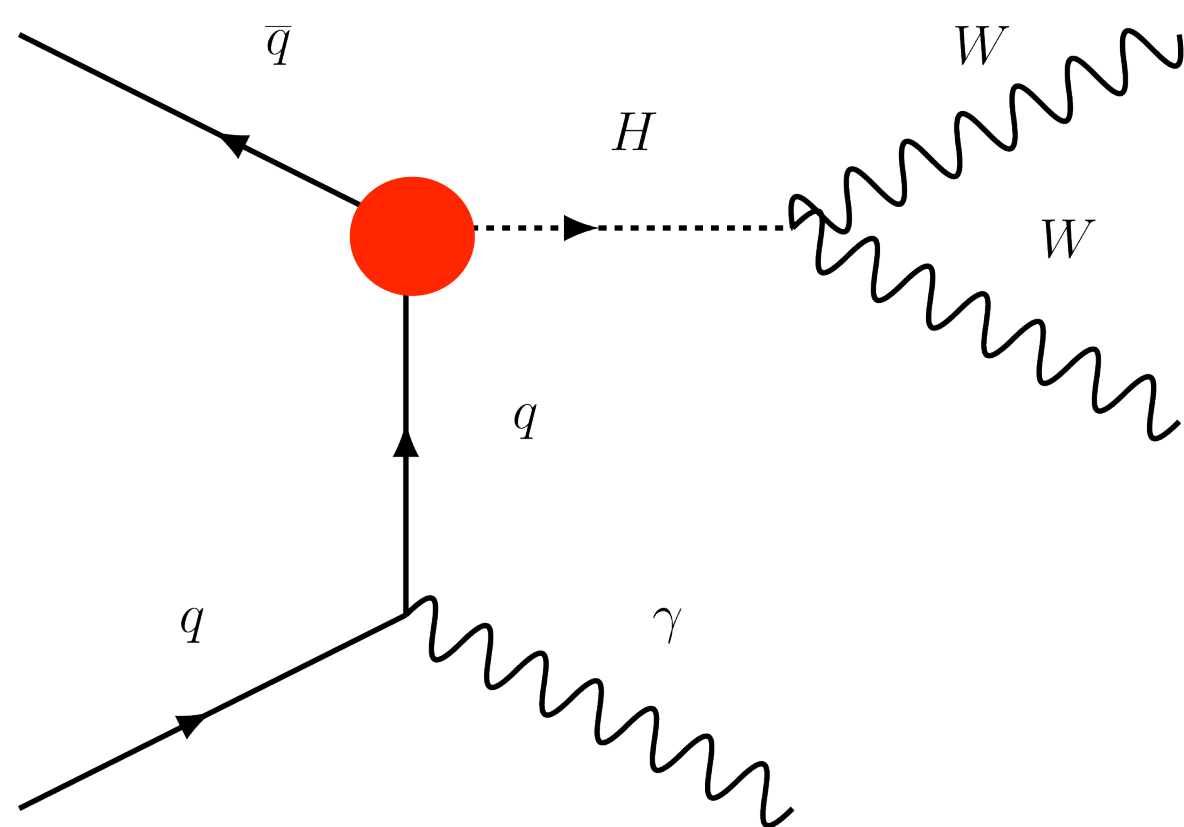


- Main background from gluon-initiated $H\gamma$ doesn't exist at LO due to Furry's theorem [1]
- Backgrounds in $H\gamma$ are sum of signal and backgrounds in the $WW\gamma$ measurement

Triboson $H(\rightarrow WW)\gamma$ – Yukawa coupling interpretation



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For $q = u, d, s$

1. MadGraph

- Model “*Higgs effective Lagrangian*”
- Quark masses in $\overline{\text{MS}}$ scheme from PDG are used
- Process: $q\bar{q} \rightarrow H\gamma$

2. JHU generator

- $H \rightarrow W^+W^- \rightarrow e^\pm \mu^\mp \nu_e \bar{\nu}_\mu$

For $q = c$

1. MadGraph

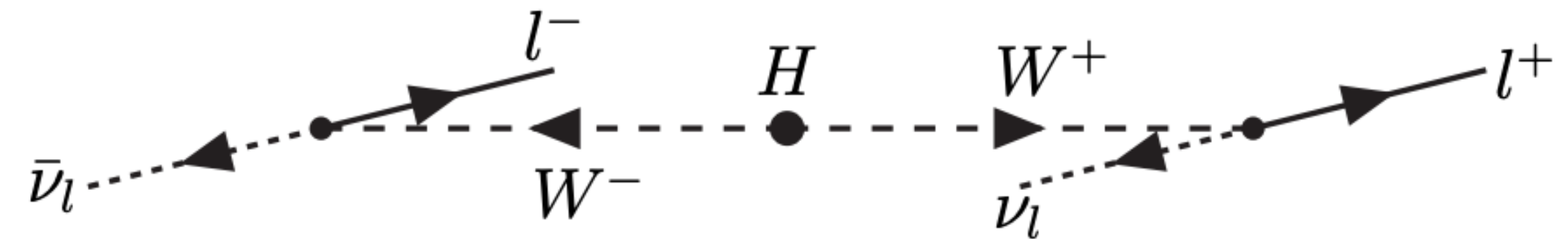
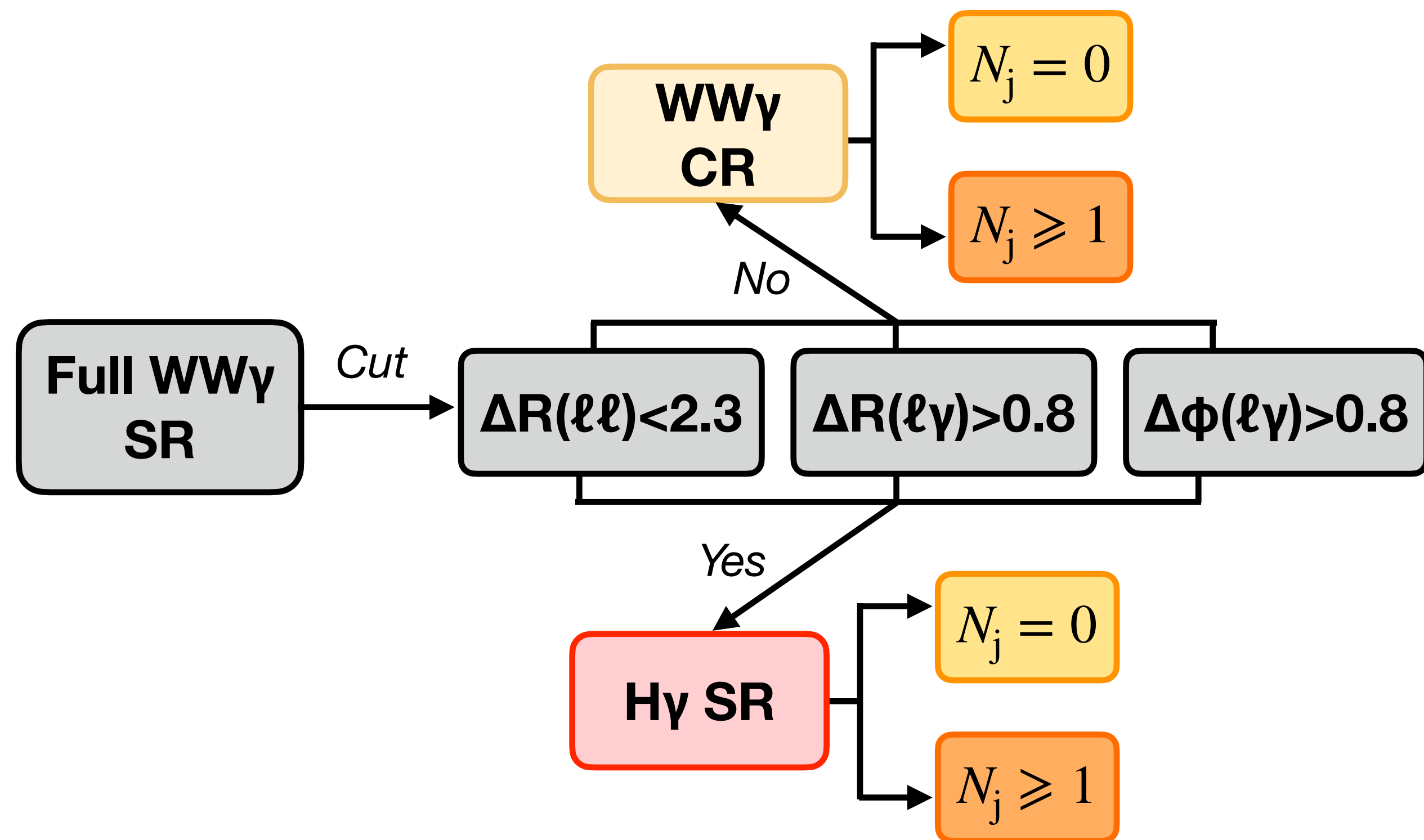
- **Model:** *loop_sm_MSbar_yb_yc-yc4FS*
 - Closely following theory studies for $b\bar{b}H$ (1409.5301)

- Process: $q\bar{q} \rightarrow H\gamma$ **[QCD]**

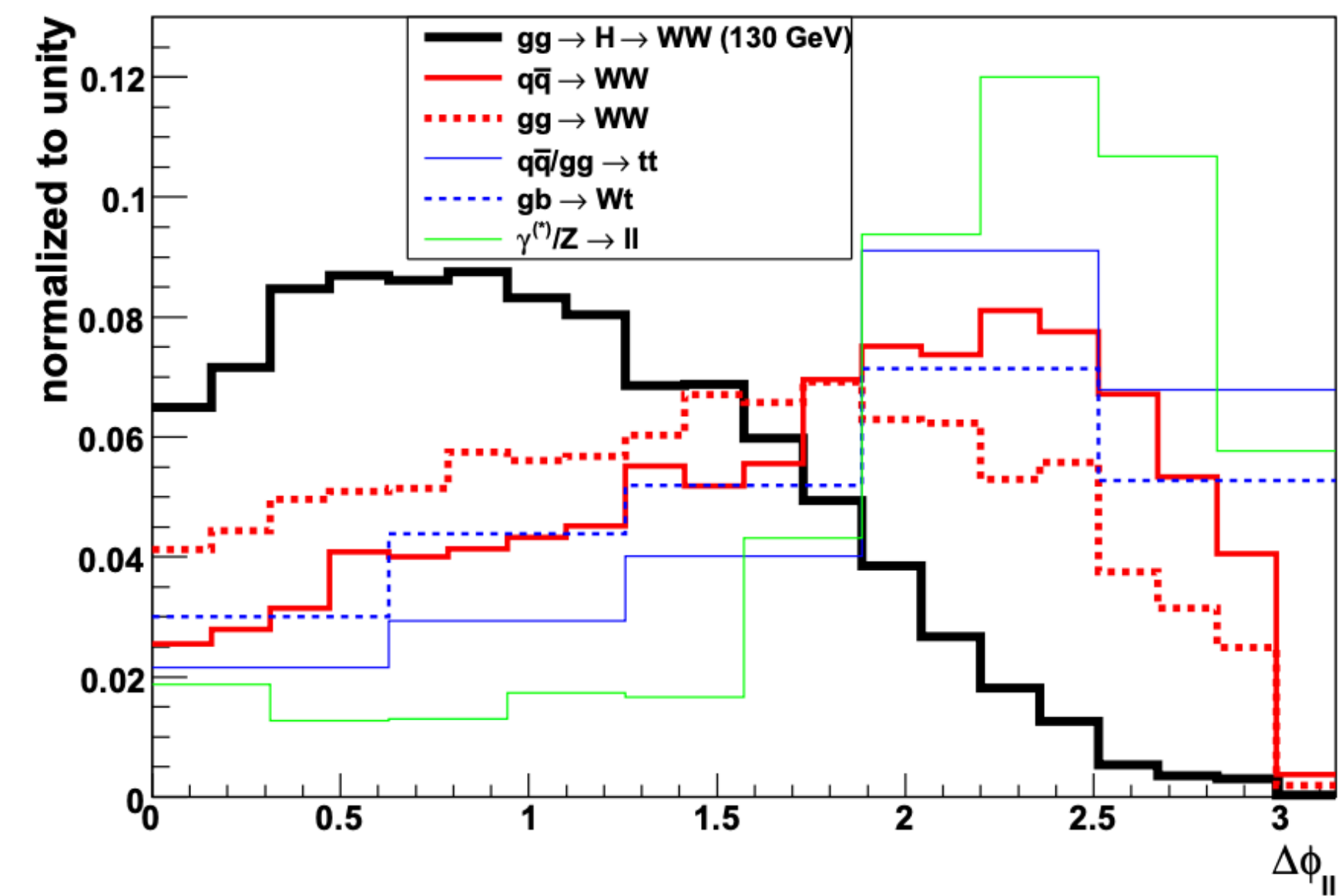
2. JHU generator

- $H \rightarrow W^+W^- \rightarrow e^\pm \mu^\mp \nu_e \bar{\nu}_\mu$

Triboson $H(\rightarrow WW)\gamma$ – Yukawa coupling interpretation



1. In the Higgs boson rest frame, the Higgs (spin 0) to two opposite-sign W bosons, traveling in opposite direction and with opposite relative spin orientation
2. The weak decay of the oppositely charged W bosons with opposite spin orientation results in two leptons that tend to travel in the same direction



Triboson $H(\rightarrow WW)\gamma$ – Yukawa coupling interpretation

Cross section limits

Process	σ upper limits obs. (exp.) [fb]
$u\bar{u} \rightarrow H + \gamma \rightarrow e\mu\nu_e\nu_\mu\gamma$	85 (67)
$d\bar{d} \rightarrow H + \gamma \rightarrow e\mu\nu_e\nu_\mu\gamma$	72 (58)
$s\bar{s} \rightarrow H + \gamma \rightarrow e\mu\nu_e\nu_\mu\gamma$	68 (49)
$c\bar{c} \rightarrow H + \gamma \rightarrow e\mu\nu_e\nu_\mu\gamma$	87 (67)

Flat direction: assuming all other SM *couplings are* scaled as κ_H , which is constrained as a function of κ_q , and $Br_{q\bar{q}}^{\text{SM}}$, so that signal strengths of all other Higgs boson processes in this decay channel are always unity [1]

↓

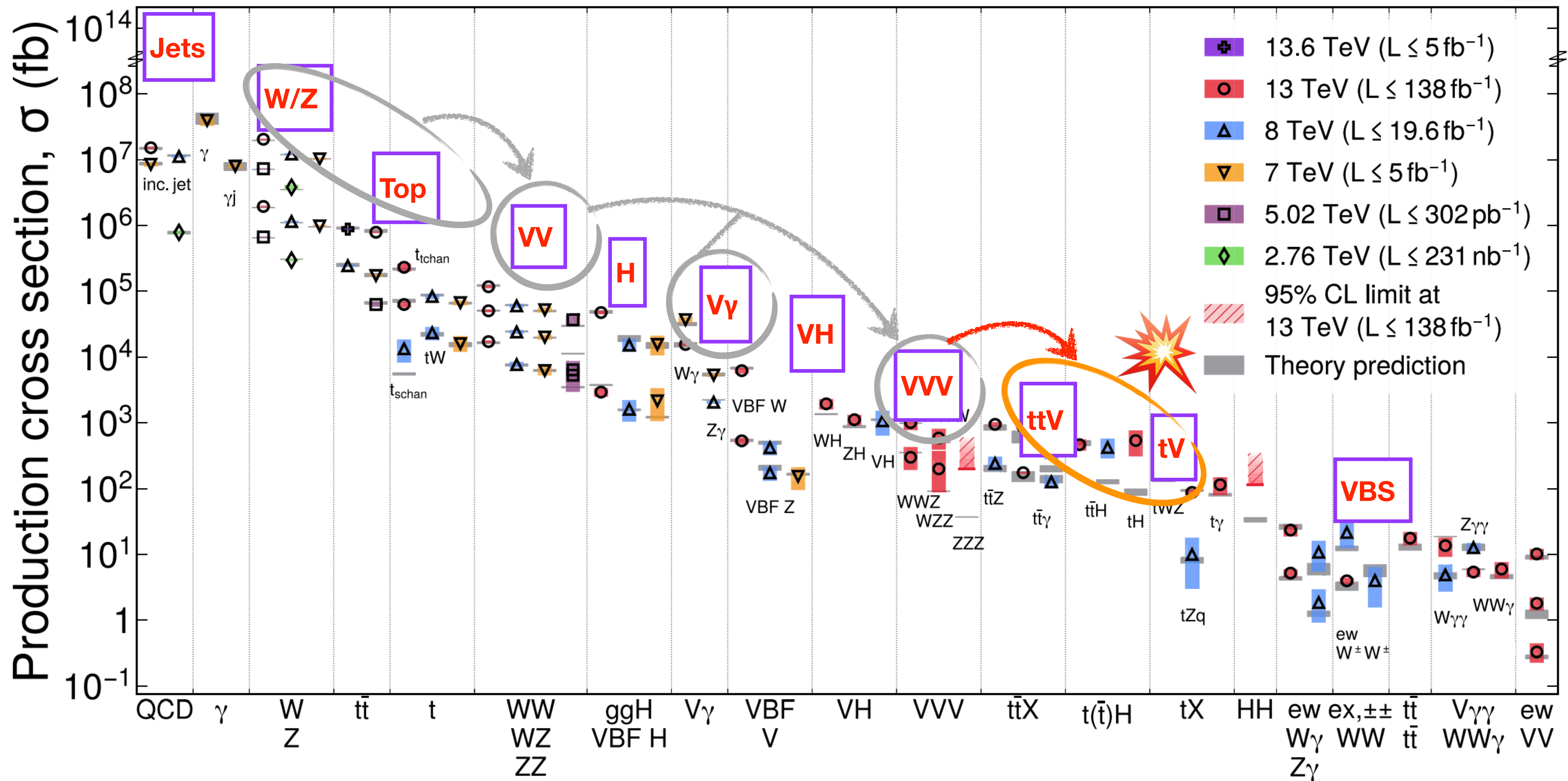
- $$\kappa_H^2 \approx \frac{1 - Br_{q\bar{q}}^{\text{SM}}}{2} + \frac{\sqrt{(1 - Br_{q\bar{q}}^{\text{SM}})^2 + 4Br_{q\bar{q}}^{\text{SM}}\kappa_q^2}}{2}$$
- $$H\gamma \text{ rate can be scaled with } \kappa_q^2 \times \frac{\kappa_H^2}{(1 - Br_{q\bar{q}}^{\text{SM}})\kappa_H^2 + Br_{q\bar{q}}^{\text{SM}}\kappa_q^2}$$

→

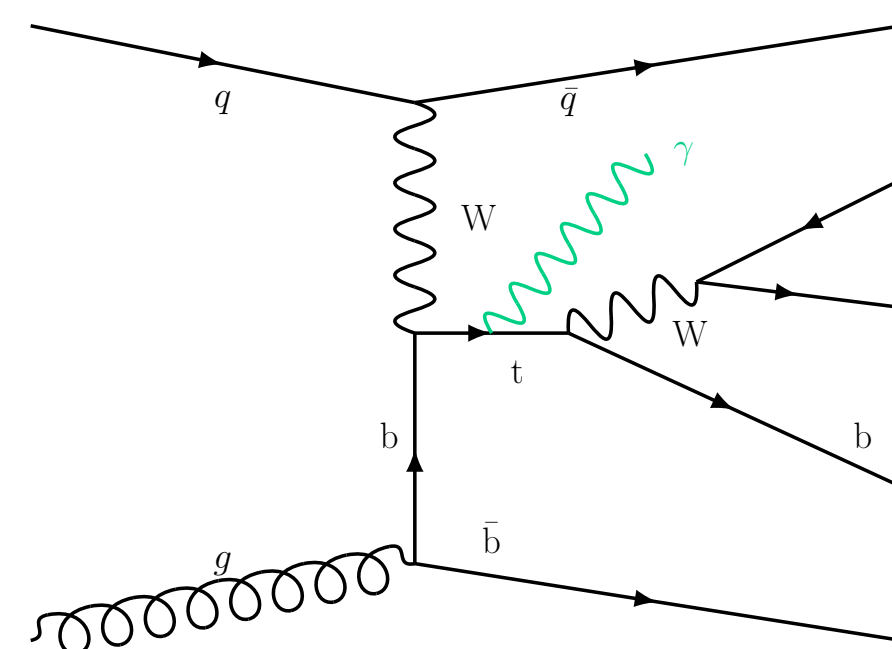
κ_q limits obs. (exp.) at 95% CL
$ \kappa_u \leq 16000$ (13000)
$ \kappa_d \leq 17000$ (14000)
$ \kappa_s \leq 1700$ (1300)
$ \kappa_c \leq 200$ (110)

CMS

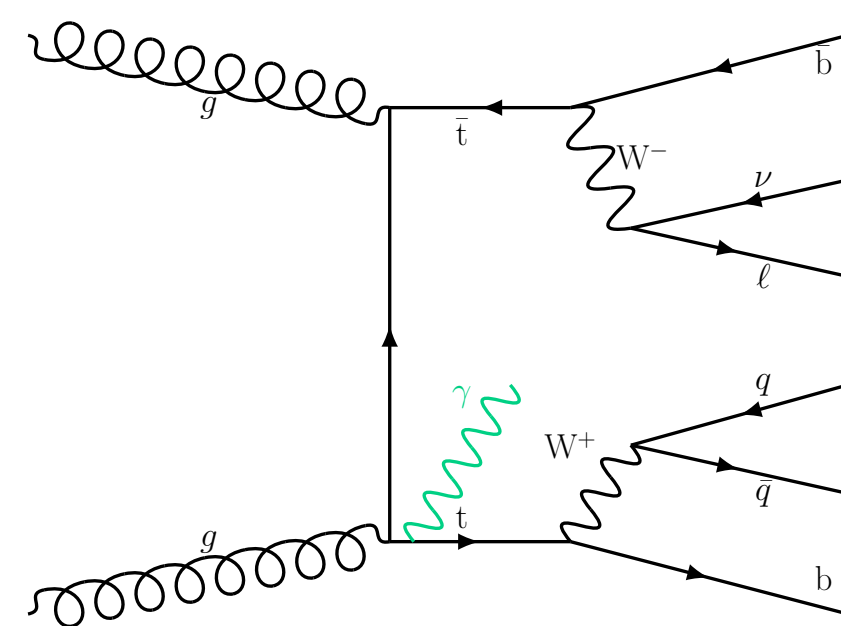
Link



Top couplings — with bosons



Low cross section ~ 1 pb



High cross section $\sim 500 \text{ pb}$

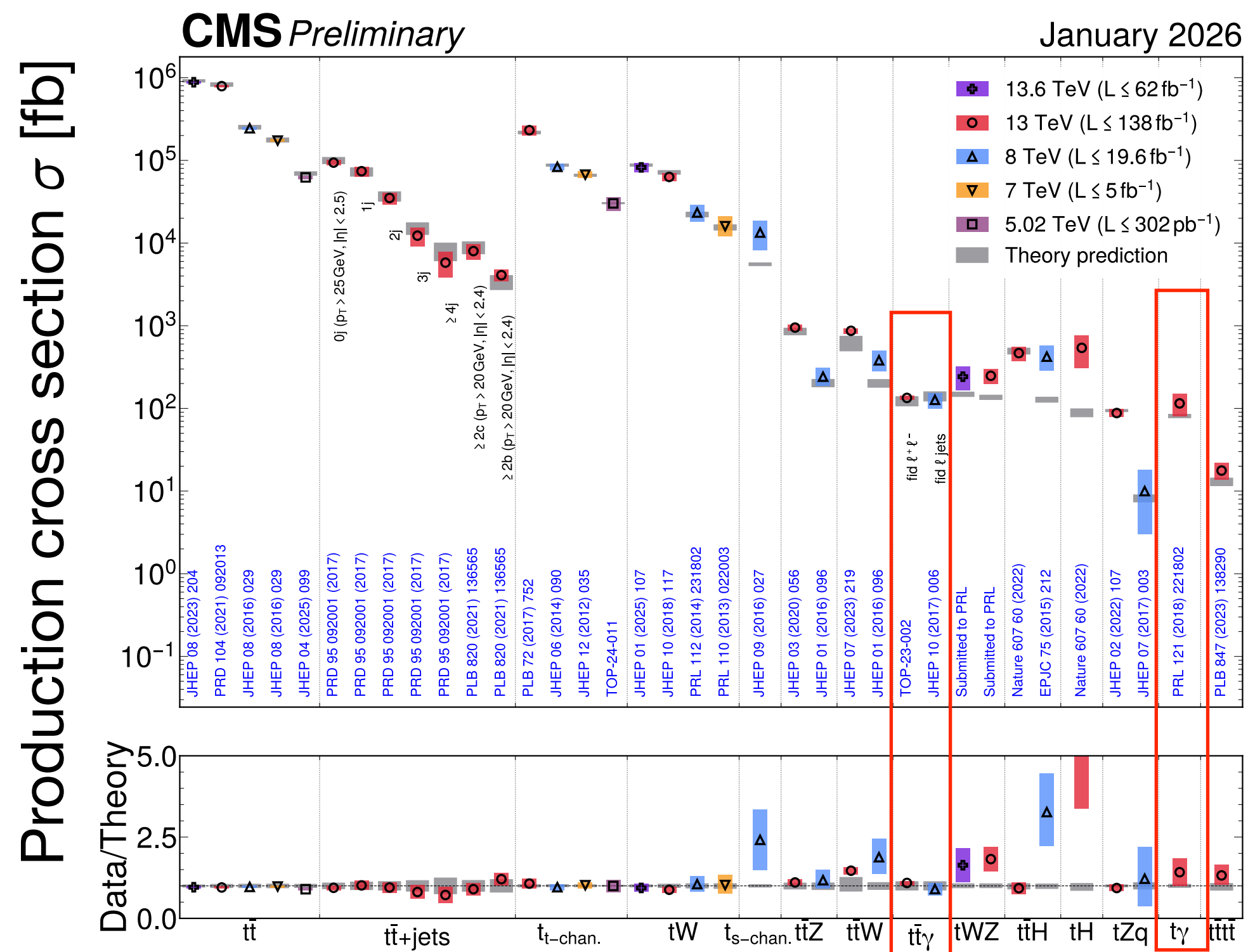
- $t\bar{t}q$ is rare production with only ~ 1 pb cross section at $\sqrt{s}=13$ TeV
- Complex background component
 - $N_\ell=1 \rightarrow$ large amount of background
 - $N_j=2 \rightarrow$ accurate jet modelling

- **Direct probe of the top-photon coupling**
 - Stringent test of SM predictions
 - Anomalous $t\text{-}\gamma$ electroweak coupling via EFT

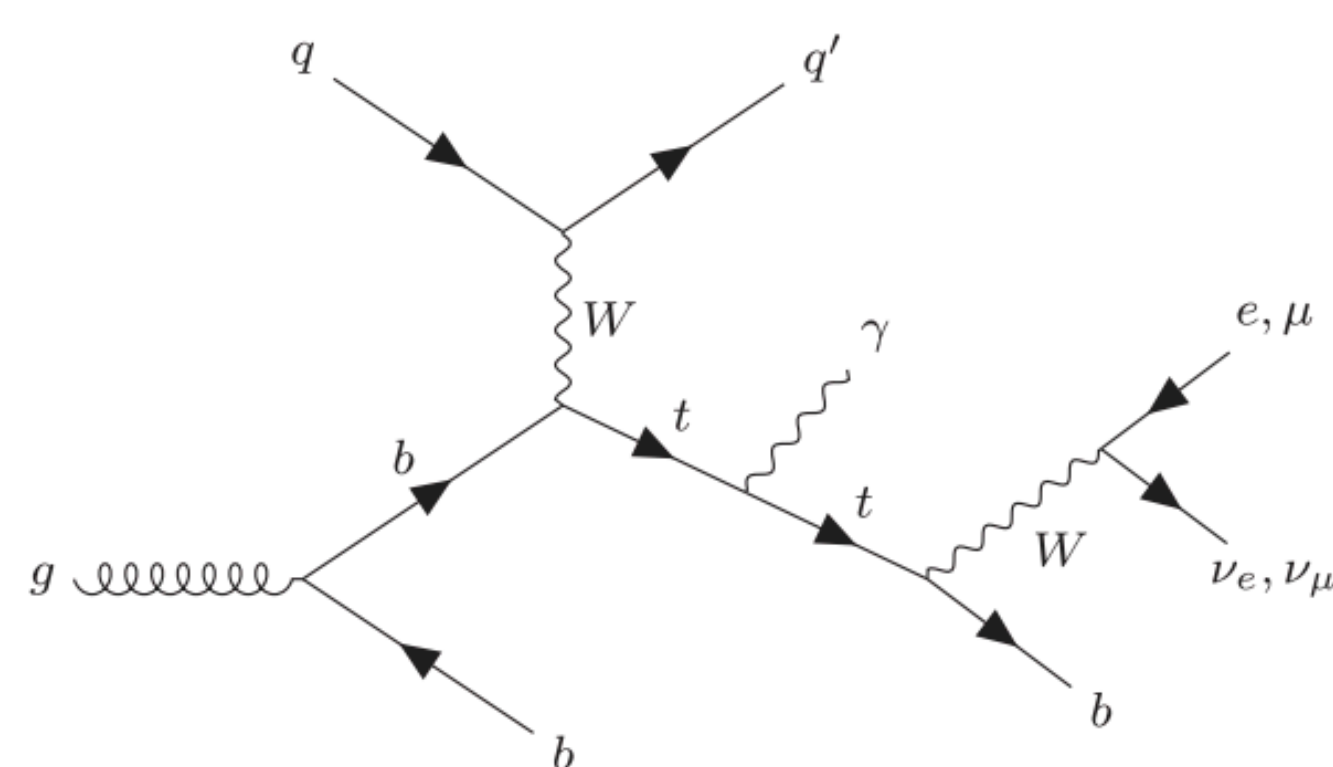
- The $t\bar{t}q$ evidence was reported by CMS in 2018
- ATLAS observed the process in 2023
- No differential results

- Full set of correlations between the two processes
- Possible for a more straightforward EFT interpretation

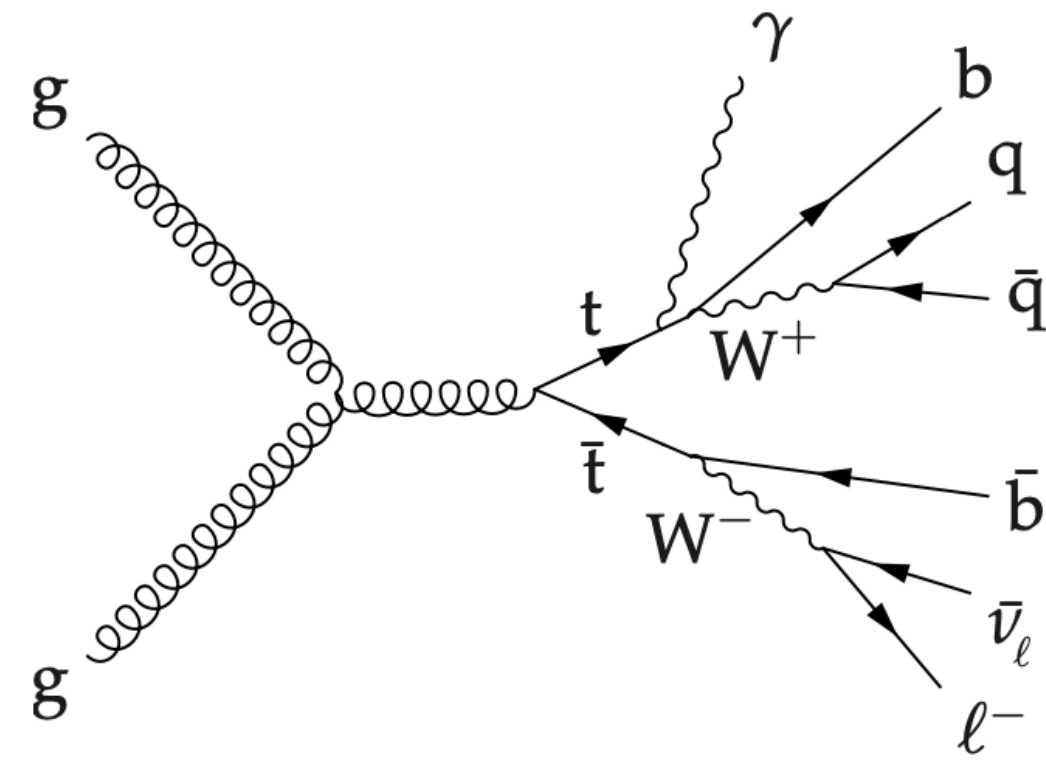
- **First-ever tyq differential cross sections**



Top couplings – Simultaneous $t\gamma q$ and $t\bar{t}\gamma$



Low cross section ~ 1 pb



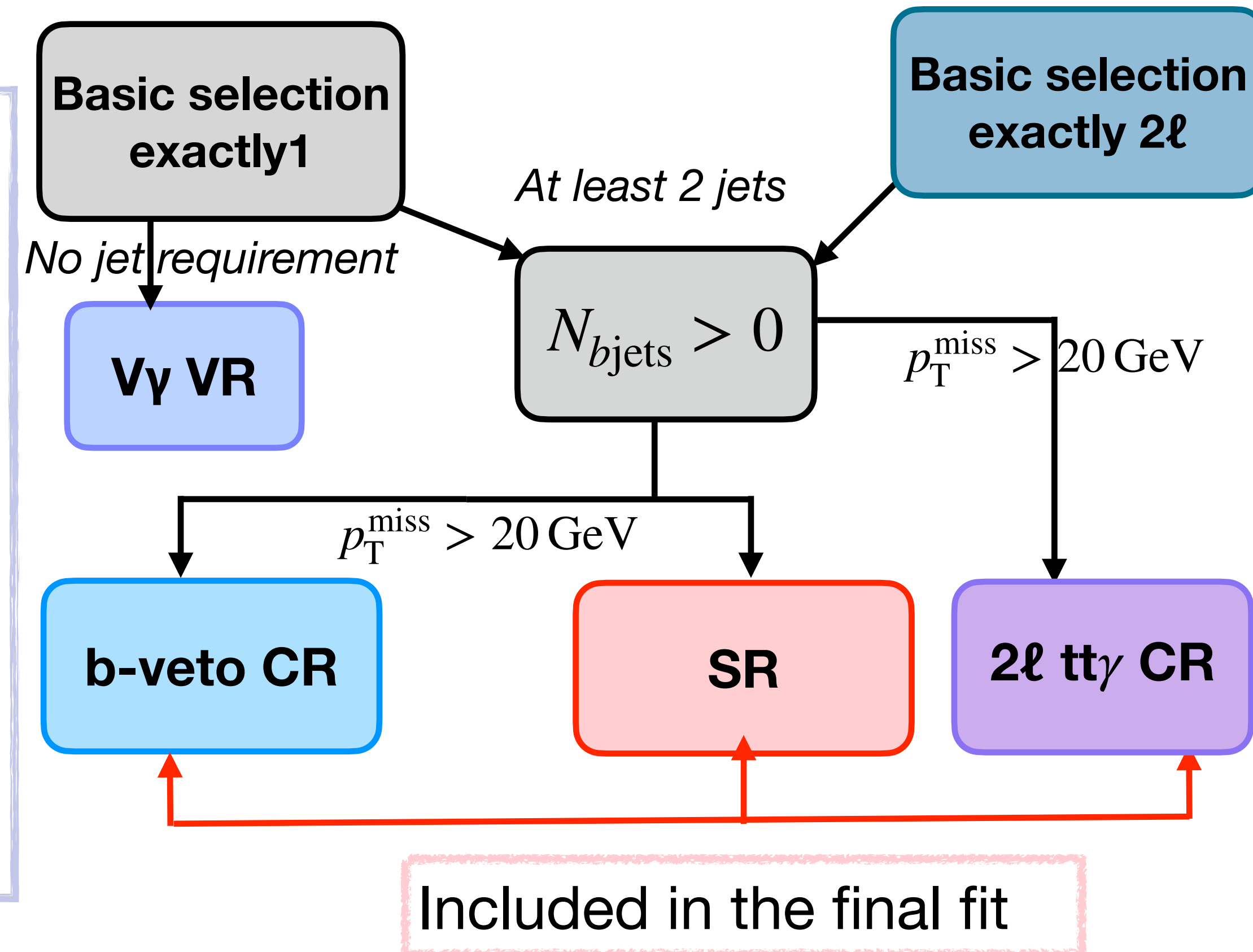
High cross section ~ 500 pb

Signal events ($N_\ell=1$, $N_\gamma \geq 1$, $N_j \geq 2$, $N_b \geq 1$):
exactly 1 lepton, at least 1 photon, at least 2 jets, of which at least 1 is b-jet

Separate signal and background: Train **BDT** to separate $t\gamma q$, $t\bar{t}\gamma$ and others

Background estimation/constraint ($t\bar{t}\gamma$ as signal):

- Simulation: V +Jets/ $V\gamma$ +Jets, tW / $tW\gamma$, TTV , VV
- Data-Driven backgrounds:
 - $j \rightarrow \gamma$ (nonprompt γ), $j \rightarrow \ell$ (nonprompt ℓ), double nonprompt, and $e \rightarrow \gamma$ (mainly in e channel)
- Define proper control regions
 - Constrain normalisations of main and data-driven backgrounds



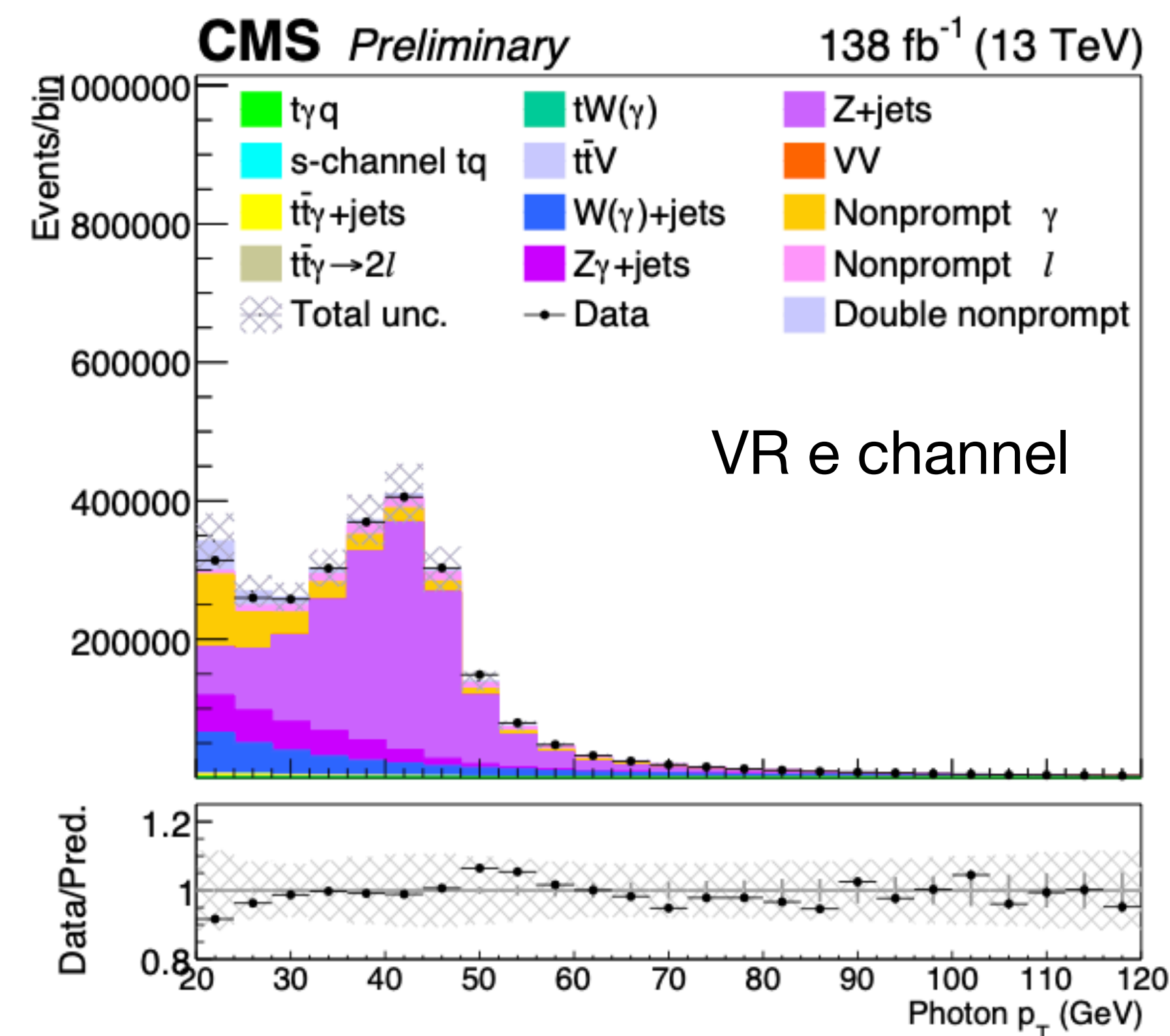
Electron mis-identification estimation

- **Misidentified electron contribution is mainly from productions of**
 - $Z(ee)\gamma$: significant in electron channel; causing discrepancies in $m_{\ell\gamma}$ distribution
 - $t\bar{t}\gamma \rightarrow 2\ell(ee, e\mu)$: non-trivial in both electron and μ channels; no obvious shape dependency
 - Diboson (WZ, ZZ)

- **Discrepancies can be cured by applying a normalization factor derived from $m_{\ell\gamma}$ distribution checked in $V\gamma$ VR**

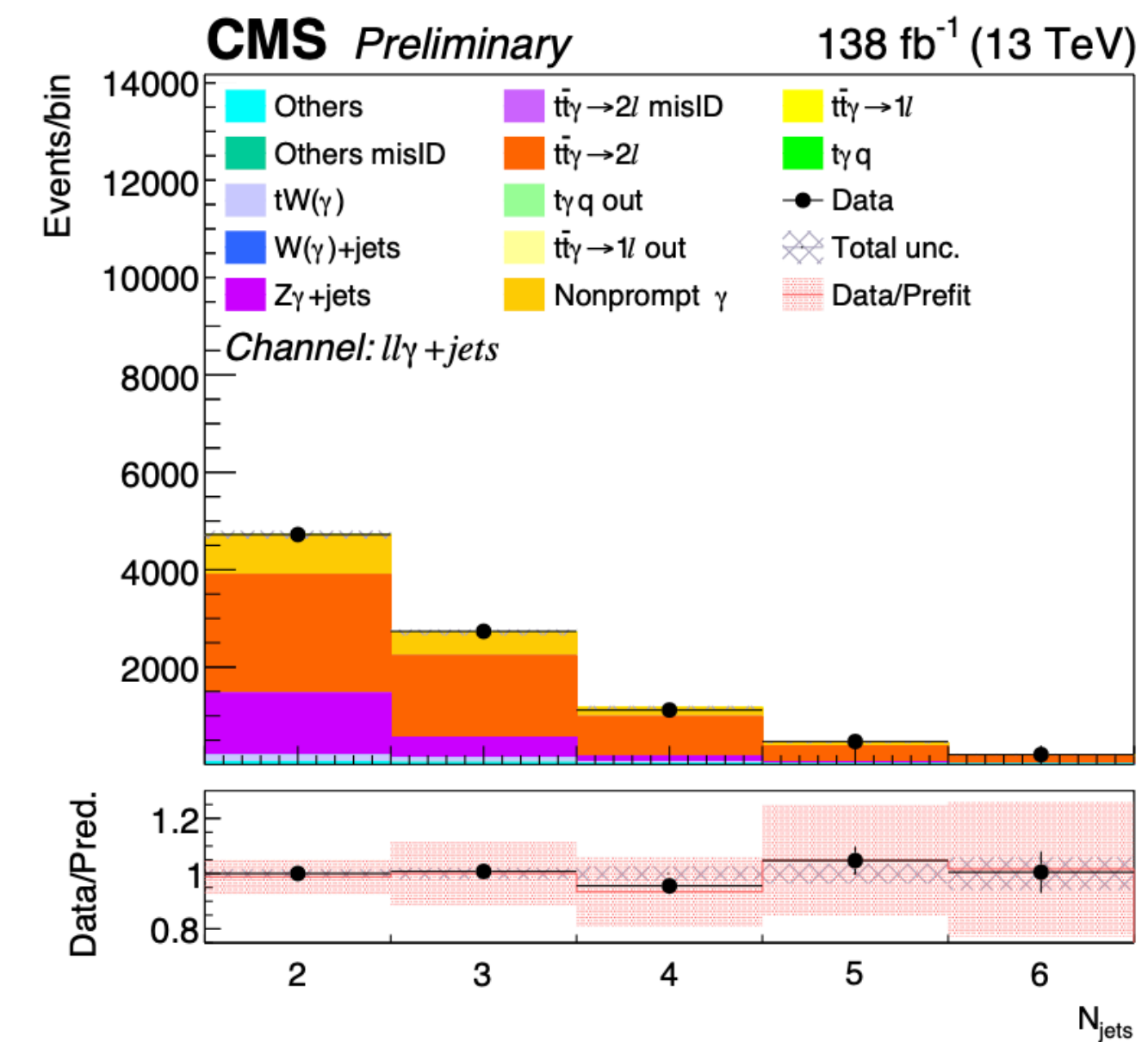
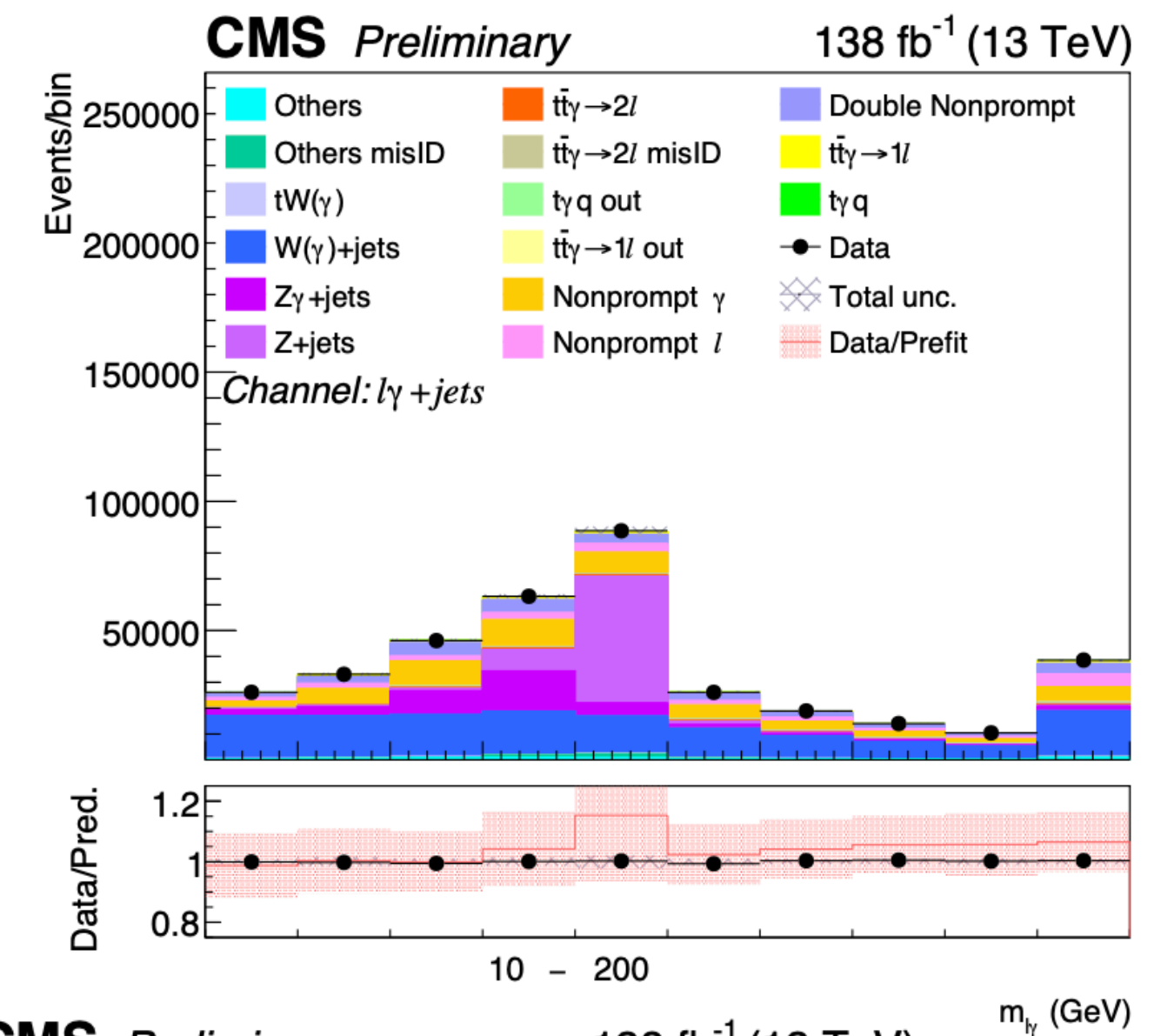
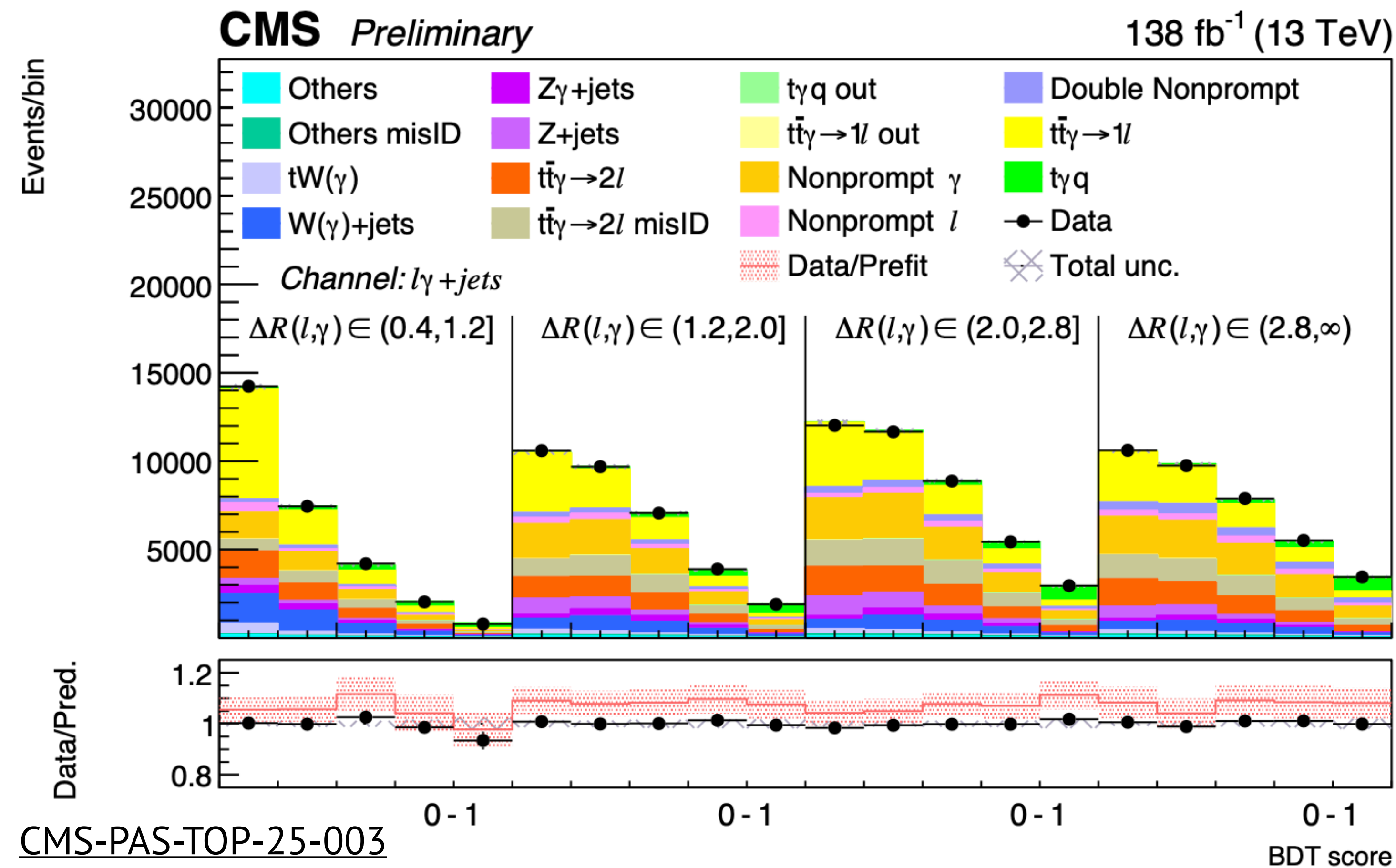
Validation by checking agreement from other kinematic distributions in $V\gamma$ VR

Float the misID normalisation in the fit

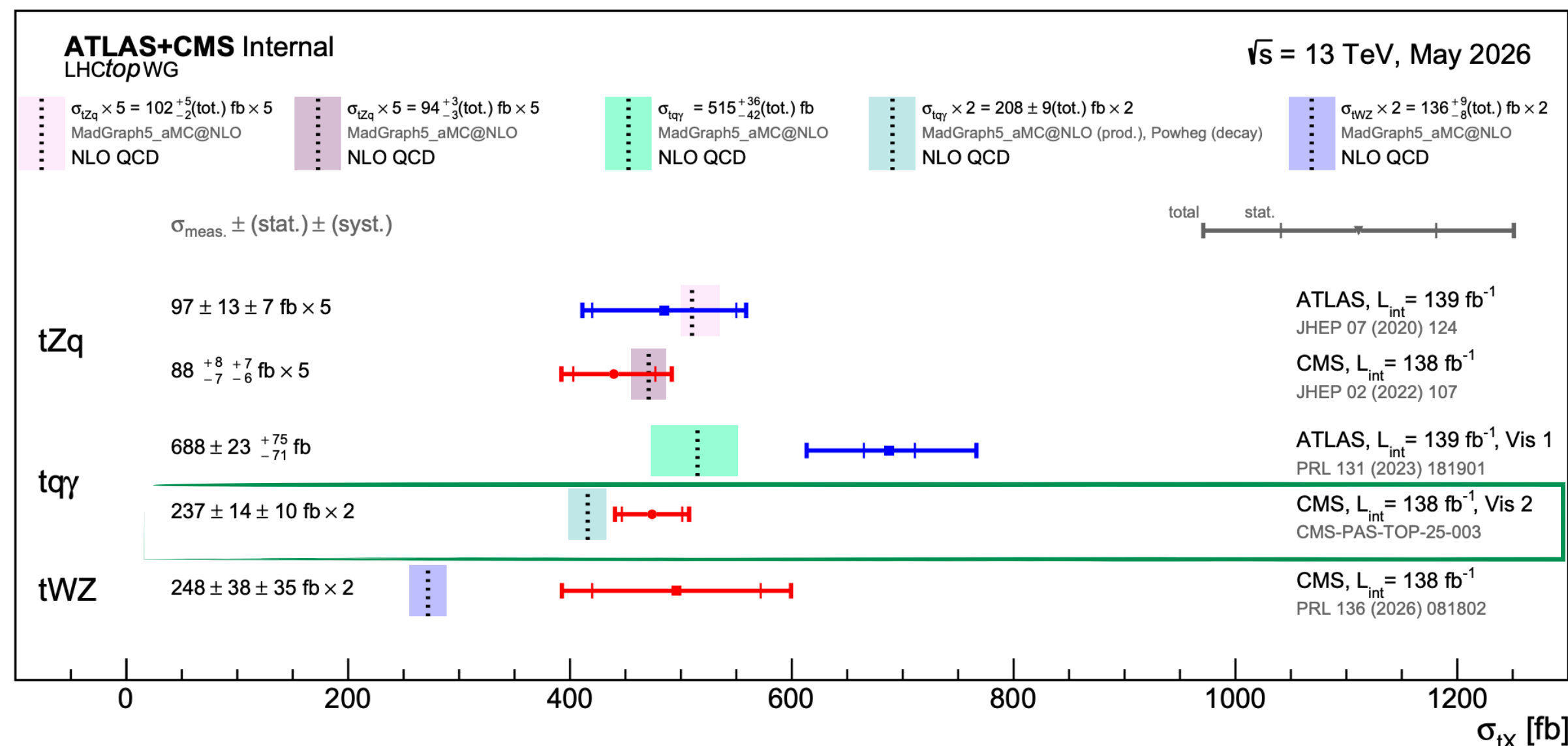


Good agreement in the VR region with our background estimation

- A BDT is trained in the signal region with $t\bar{t}q$ production photon as signal and others as backgrounds
- Simultaneous fit for events in SR and CRs
- POIs are signal strengths of $t\bar{t}q$ and $t\bar{t}\gamma$
- All systematic uncertainties are considered



Simultaneous $t\gamma q/t\bar{t}\gamma$ inclusive fit results

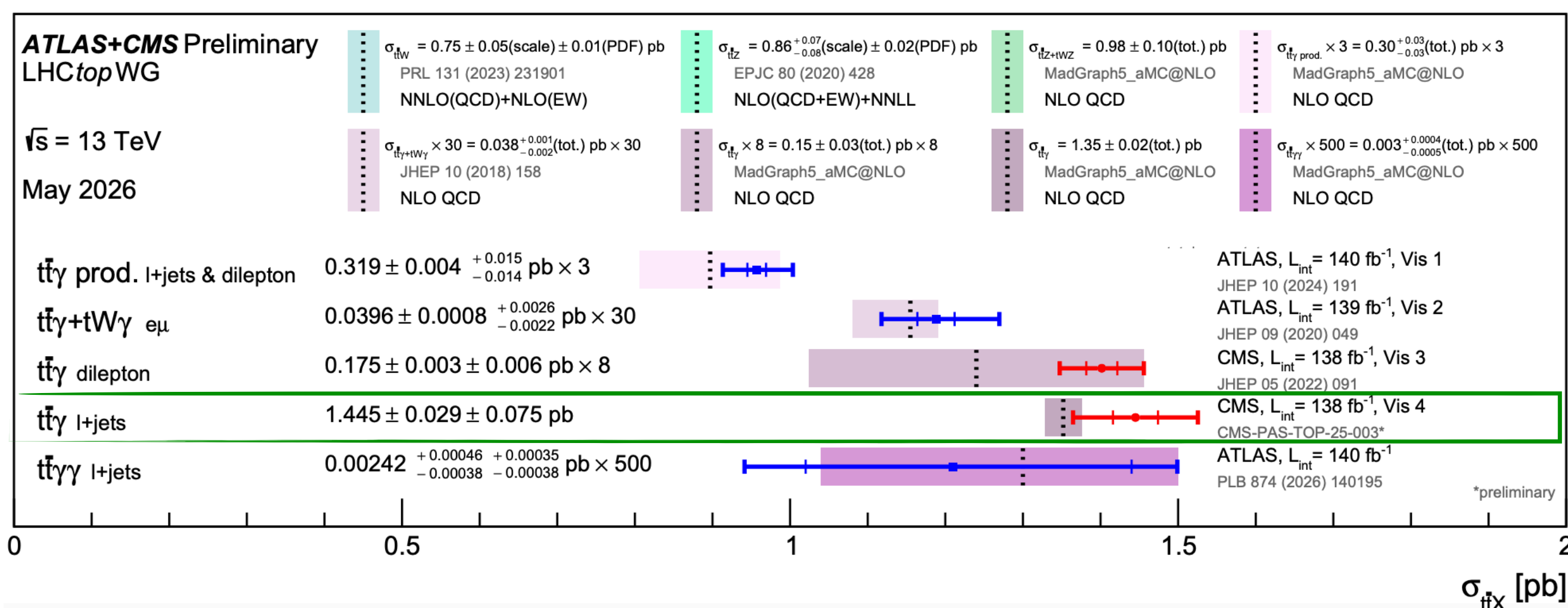


$$\mu_{t\gamma q} = 1.141^{+0.082}_{-0.080} = 1.141^{+0.067}_{-0.066} (\text{syst})^{+0.047}_{-0.047} (\text{stat})$$

$$\sigma_{\text{tot. } t\gamma q}^{\text{mea.}} = 236.87^{+17.0}_{-16.6} \text{ fb},$$

$$\mu_{t\bar{t}\gamma \rightarrow 1\ell} = 1.055^{+0.059}_{-0.059} = 1.055^{+0.055}_{-0.055} (\text{syst})^{+0.021}_{-0.021} (\text{stat})$$

$$\sigma_{\text{tot. } t\bar{t}\gamma \rightarrow 1\ell}^{\text{mea.}} = 1445.24^{+80.8}_{-80.8} \text{ fb}$$



Previous ATLAS $t\gamma q$: $N_{\ell}=1, N_{\gamma} \geq 1, N_b \geq 1, N_{\nu} \geq 1$

$$\sigma(tq\gamma+tq \rightarrow \ell\nu b\gamma) = 303 \pm 9(\text{stat})^{+33}_{-32}(\text{syst}) \text{ fb}$$

Previous CMS $t\bar{t}\gamma \rightarrow 1\ell$: $N_{\ell}=1, N_{\gamma} \geq 1(\text{barrel}), N_j \geq 3, N_b \geq 1$

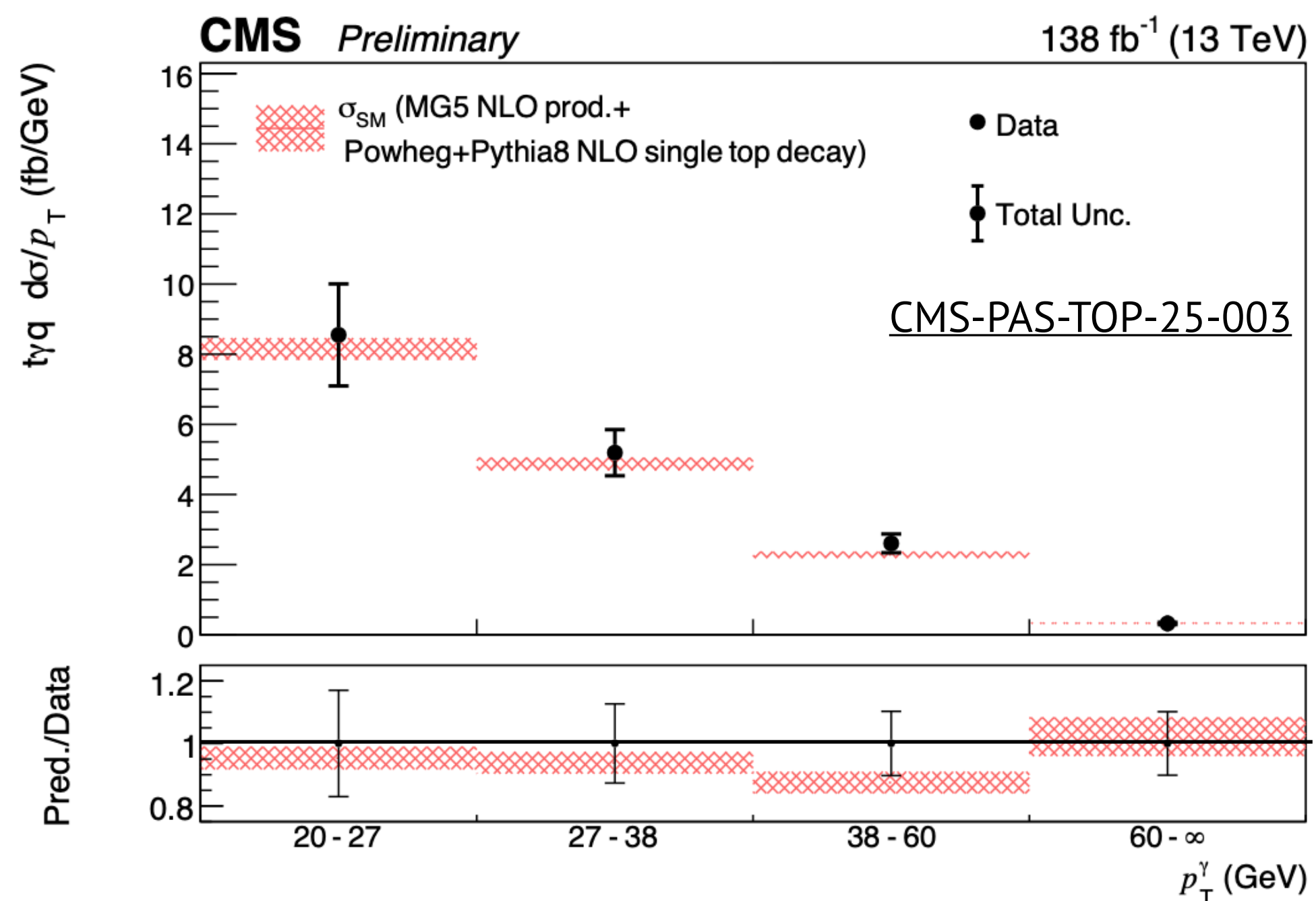
$$\sigma(t\bar{t}\gamma) = 798 \pm 7(\text{stat}) \pm 48(\text{syst}) \text{ fb}$$

Previous ATLAS $t\bar{t}\gamma \rightarrow 1\ell$: $N_{\ell}=1, N_{\gamma} \geq 1, N_j \geq 4, N_b \geq 1$

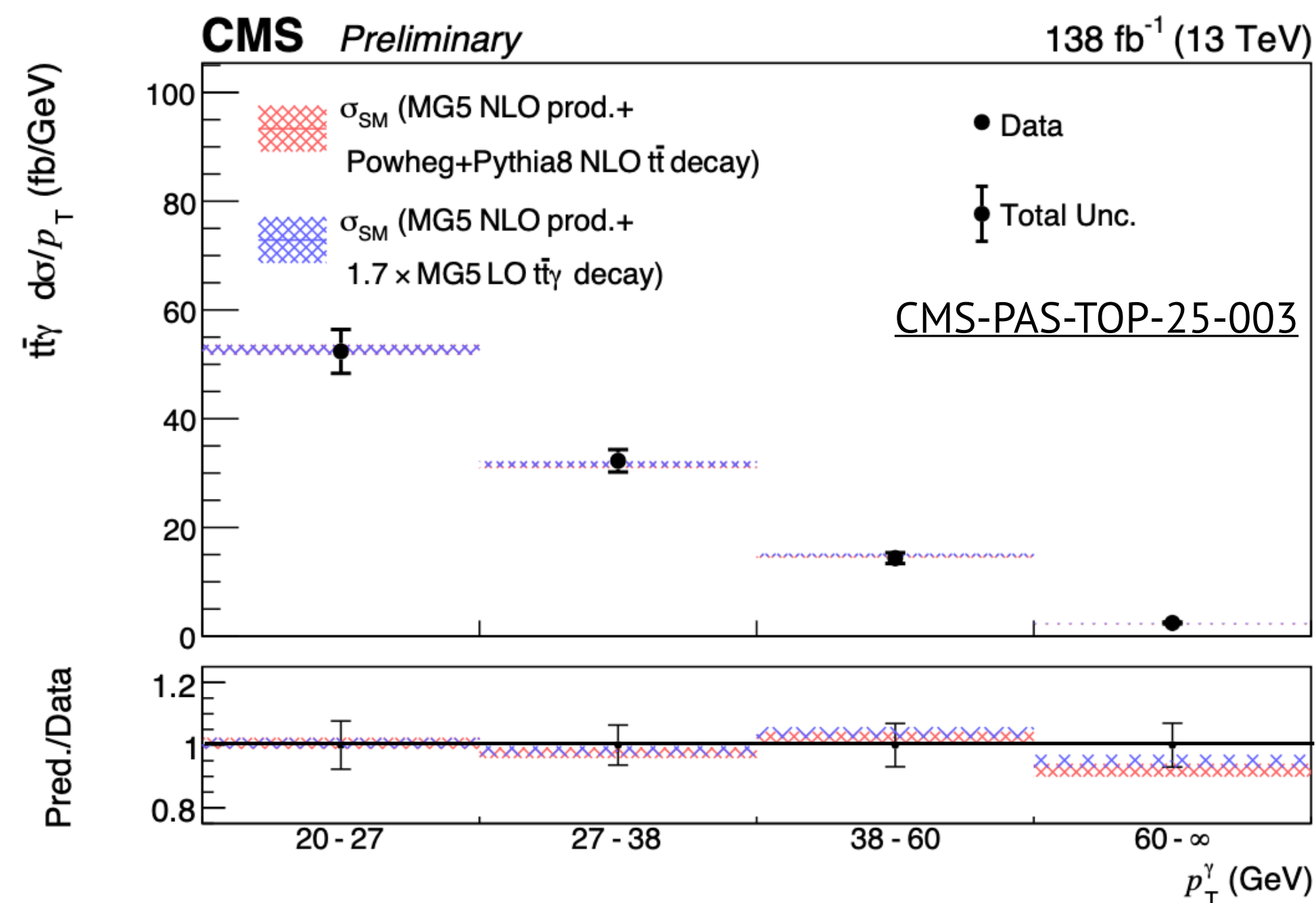
$$\sigma_{t\bar{t}\gamma}^{\text{Single lepton}} = 704^{+49}_{-46} \text{ fb} = 704 \pm 5(\text{stat})^{+49}_{-46}(\text{syst}) \text{ fb}$$

Simultaneous $t\gamma q/t\bar{t}\gamma$ differential fit

- Photon p_T , lepton p_T , $m_{\ell\gamma}$, $\Delta R(\ell, \gamma)$, $\eta_{\text{light } j}$, N_{jets} are measured at particle level
- $\Delta R(t_{\ell}, \gamma)$ and leptonic top quark charge are measured at parton level

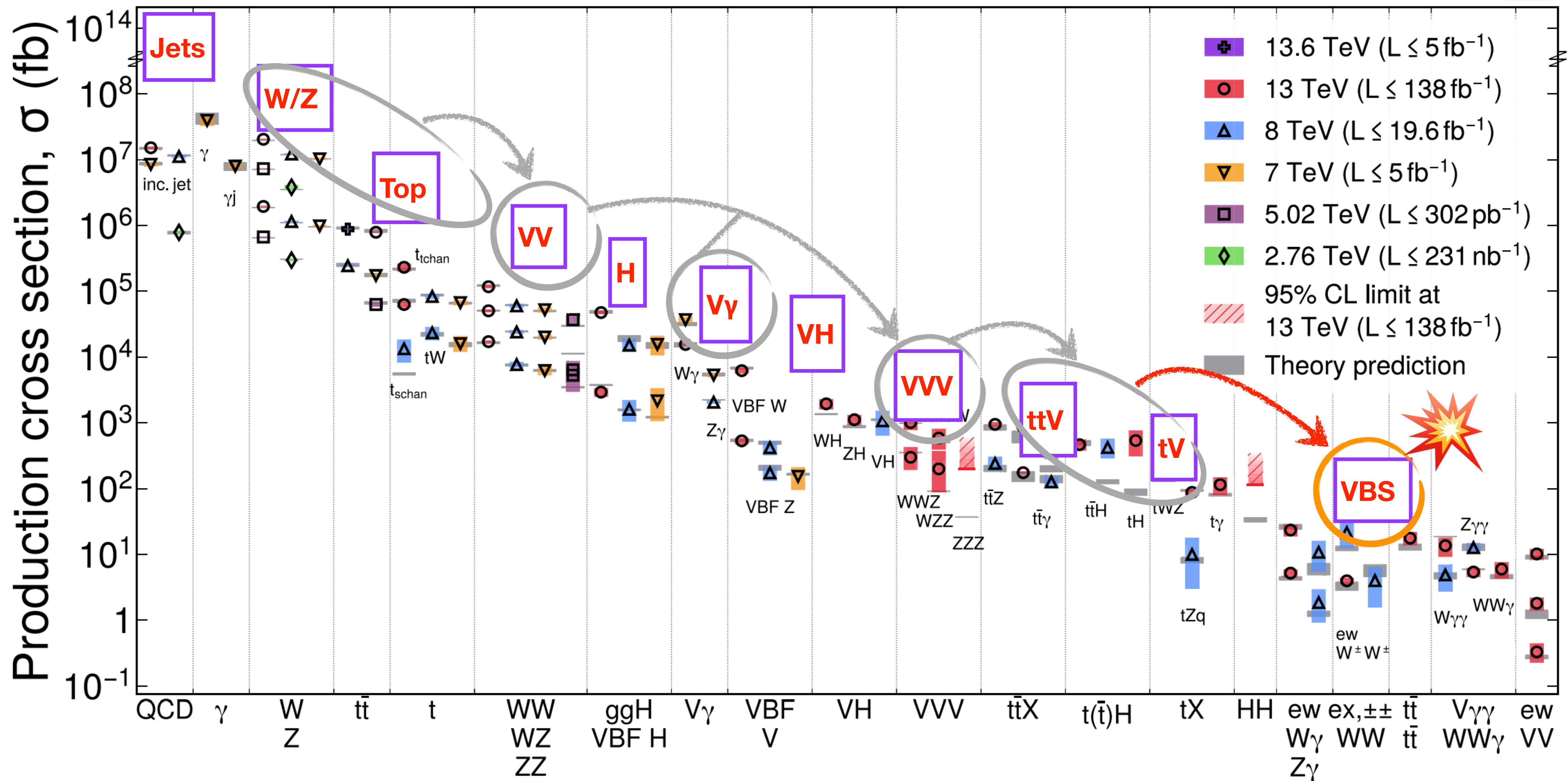


Data compared to **MG5 NLO prod. γ + Powheg+Pythia8 NLO decay γ**



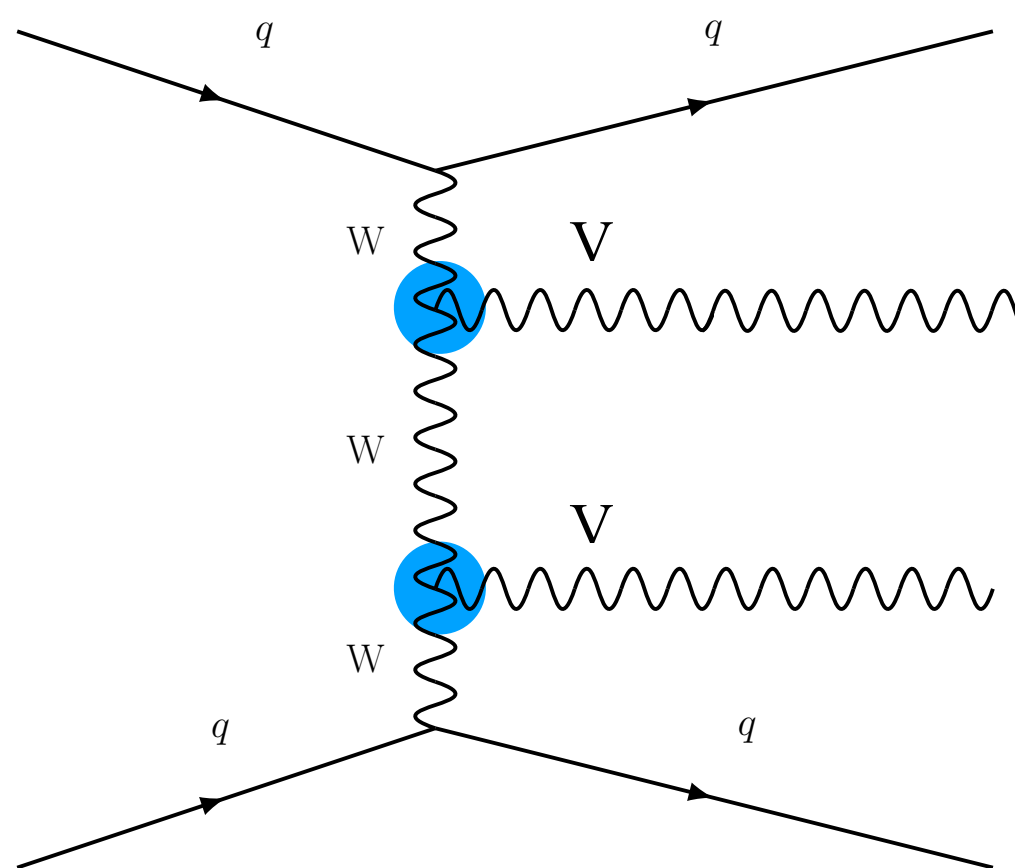
Data compared to **MG5 NLO prod. γ + 1.7×MG5 LO decay γ (or Powheg+Pythia8 NLO decay γ)**

CMS

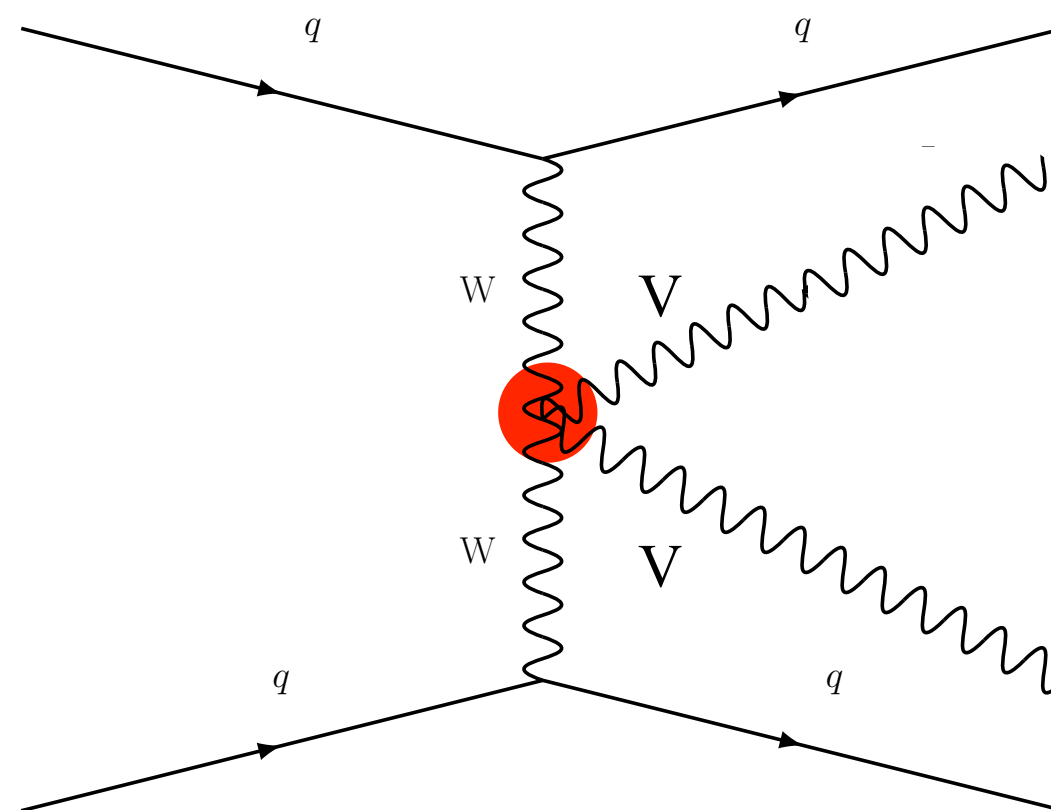
[Link](#)


VBS production — Motivation

TGC: Triple gauge couplings



QGC: Quartic gauge couplings



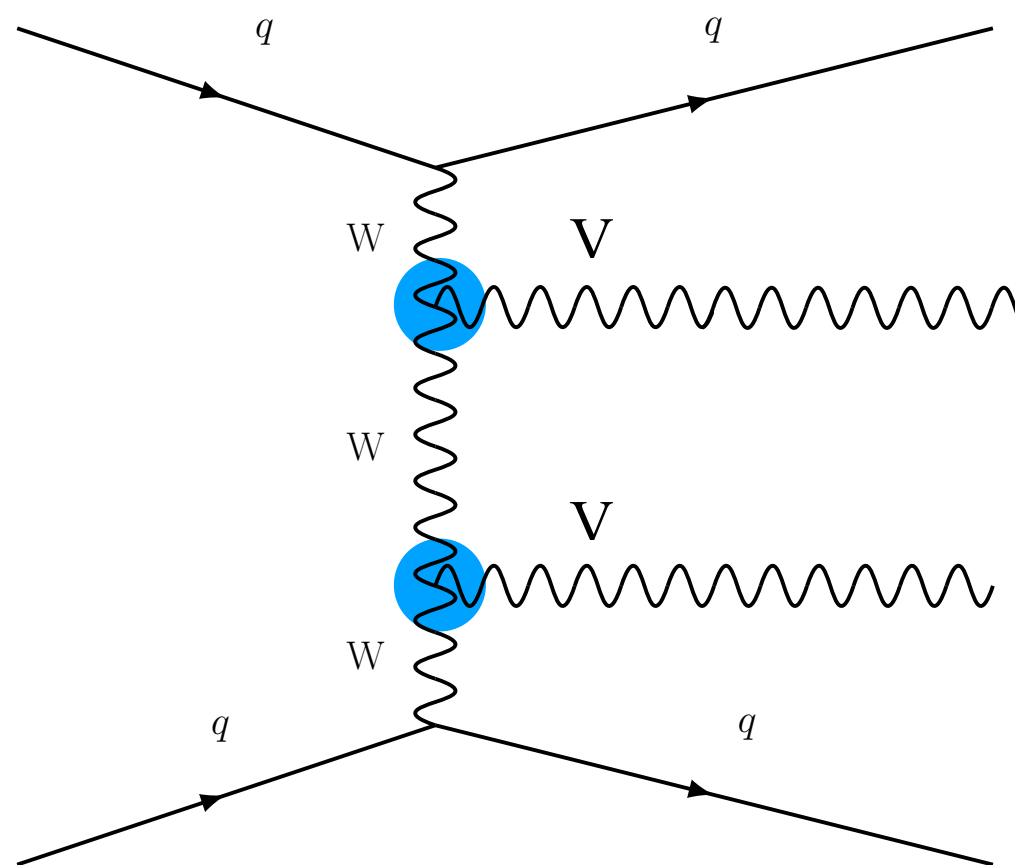
Multiboson couplings:

- T(Q)GC: WWZ , $WW\gamma$, $WWZ\gamma$, $WW\gamma\gamma$, etc.
- BSM TGC: $ZZ\gamma$, $Z\gamma\gamma$, etc
- BSM QGC : $ZZ\gamma$, $ZZZ\gamma$, $Z\gamma\gamma\gamma$, etc

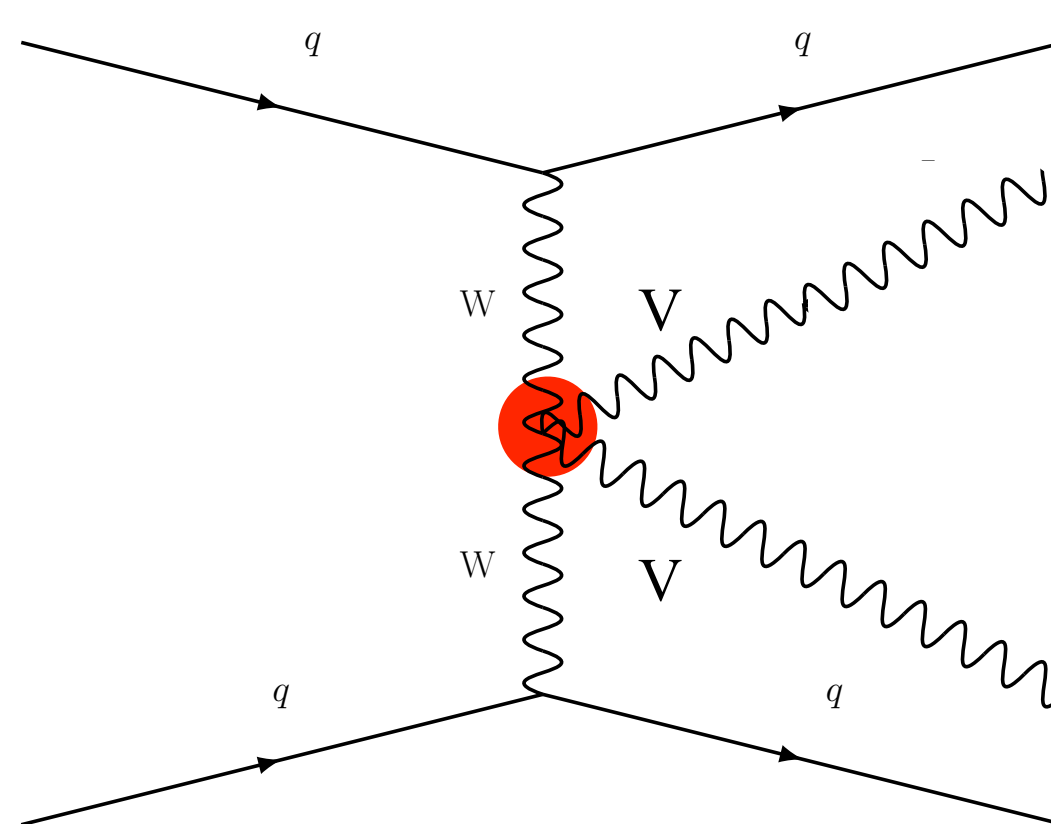
- ☒ Test SM for the electroweak sector
- ☒ Provide platform for anomalous couplings

VBS production — Motivation

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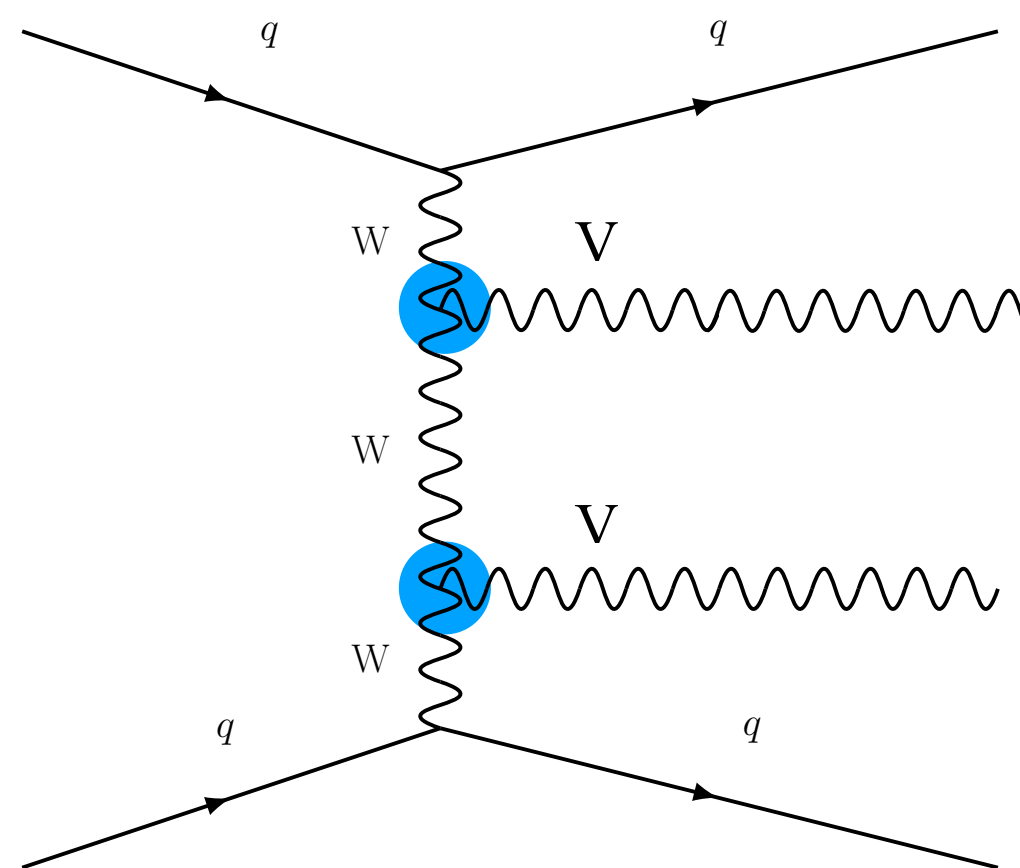
The Higgs boson contribution cancels exactly the E^2 dependence of the cross section at high energy in **massive VBS only**

Important process to investigate **electroweak symmetry breaking (EWSB)**

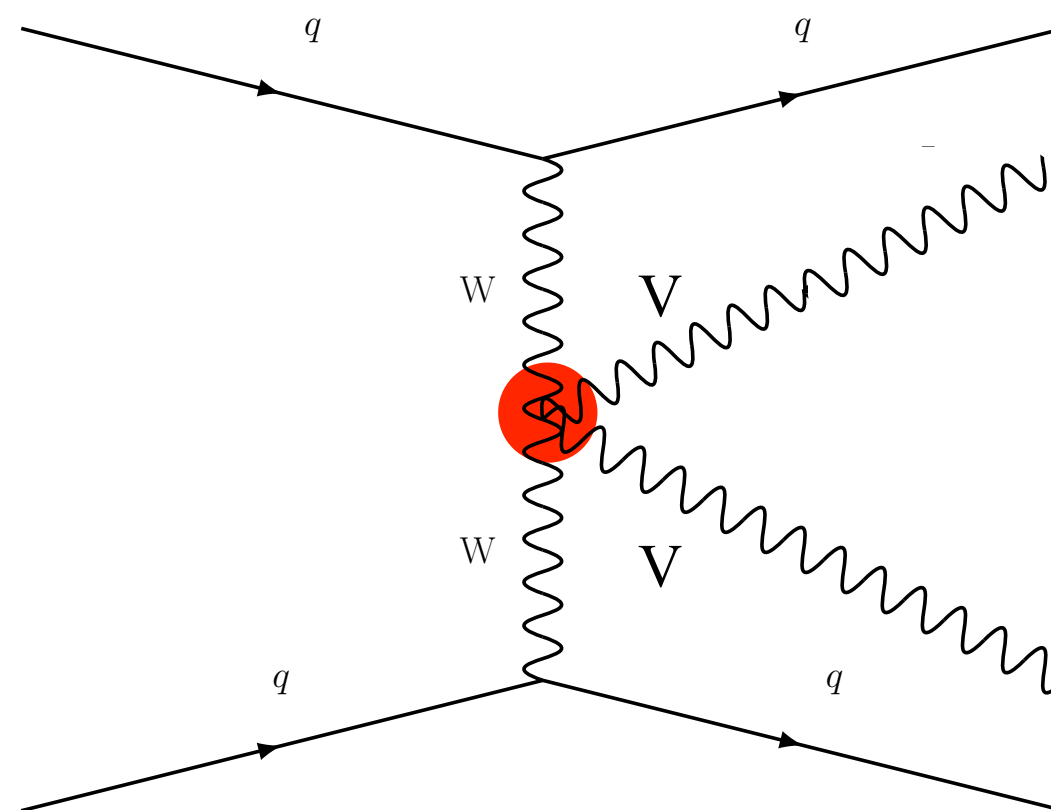
- ☒ Unitarity preservation visible in massive $V_L V_L$ scattering
- ☒ Probe the nature of EW symmetry breaking

VBS production — Motivation

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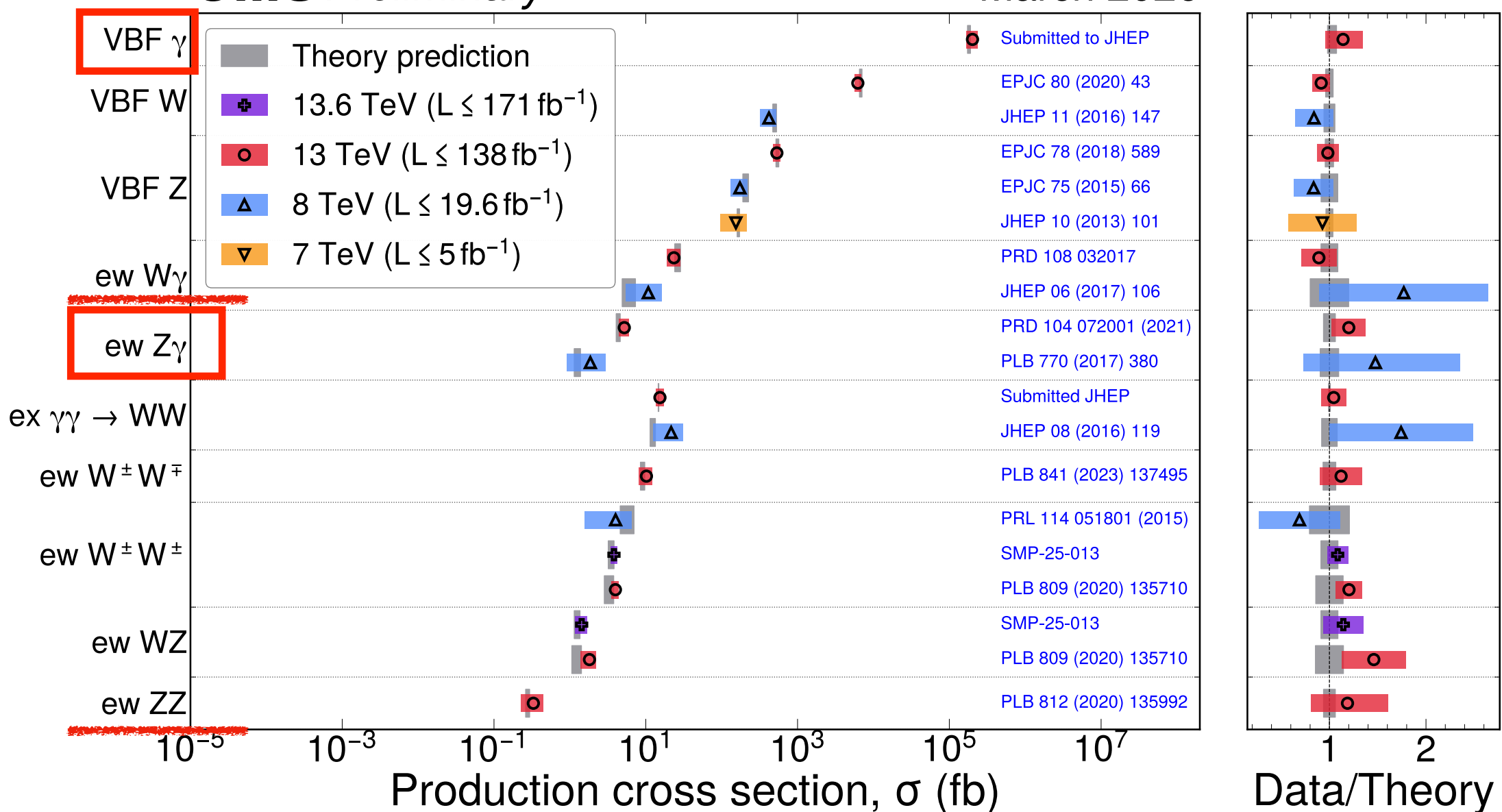
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- ☒ Test SM for the electroweak sector
- ☒ Provide platform for anomalous couplings

CMS Preliminary

March 2026



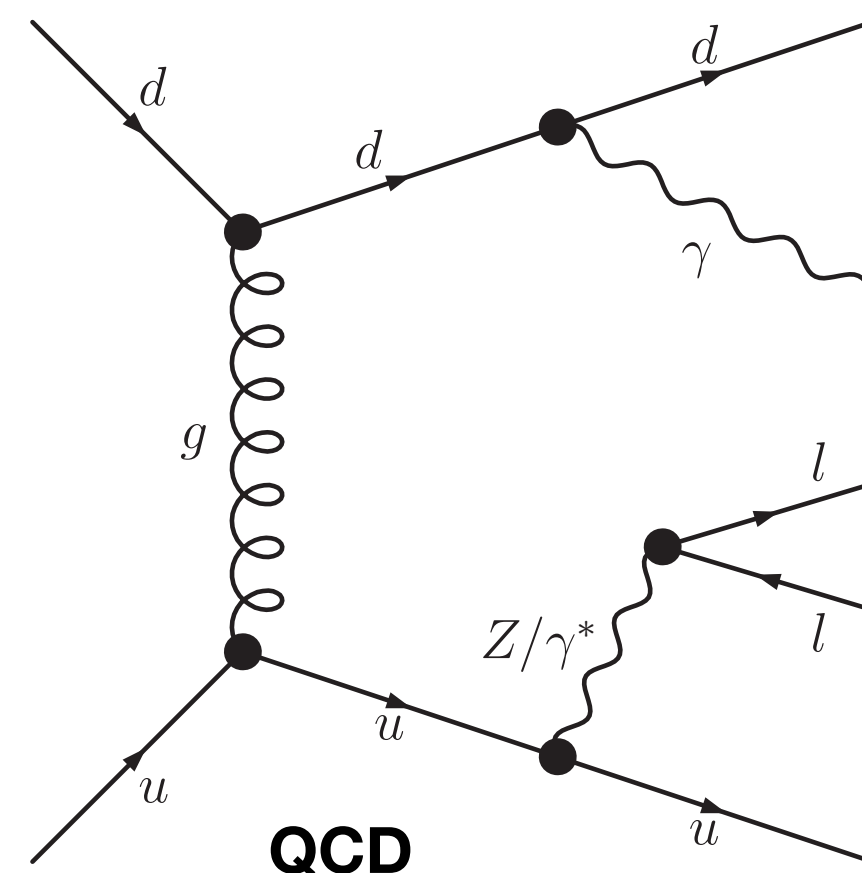
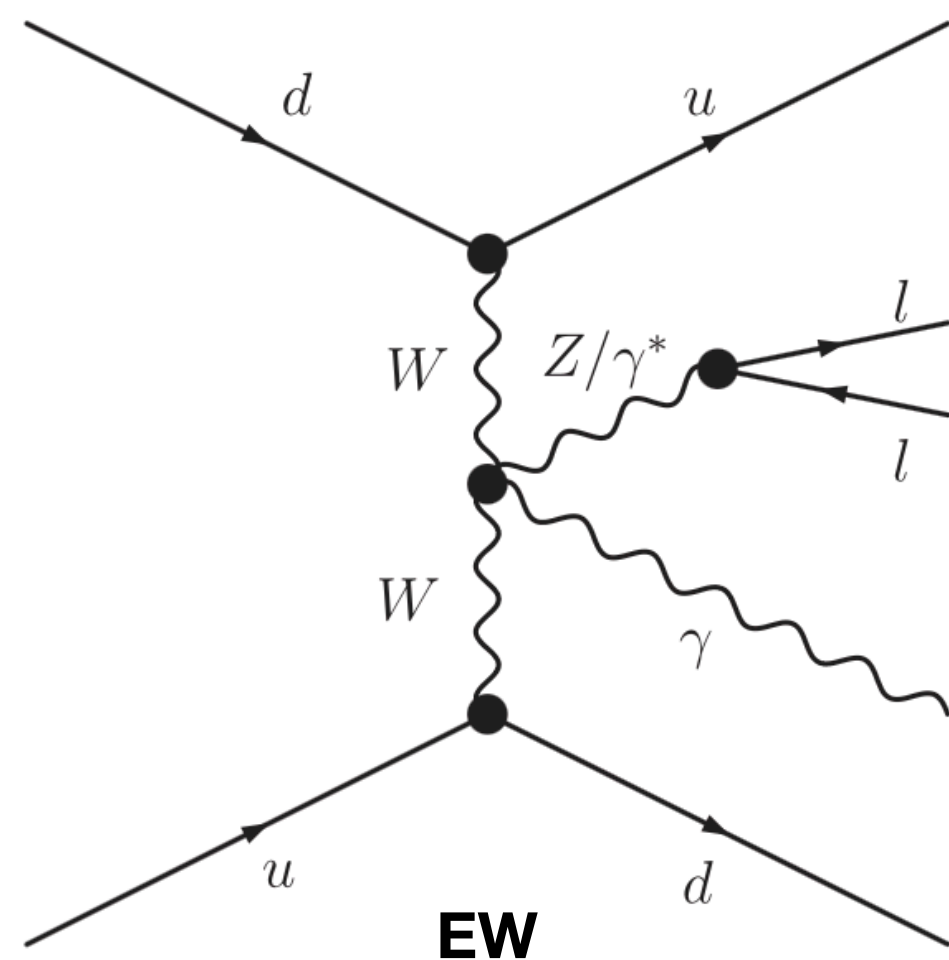
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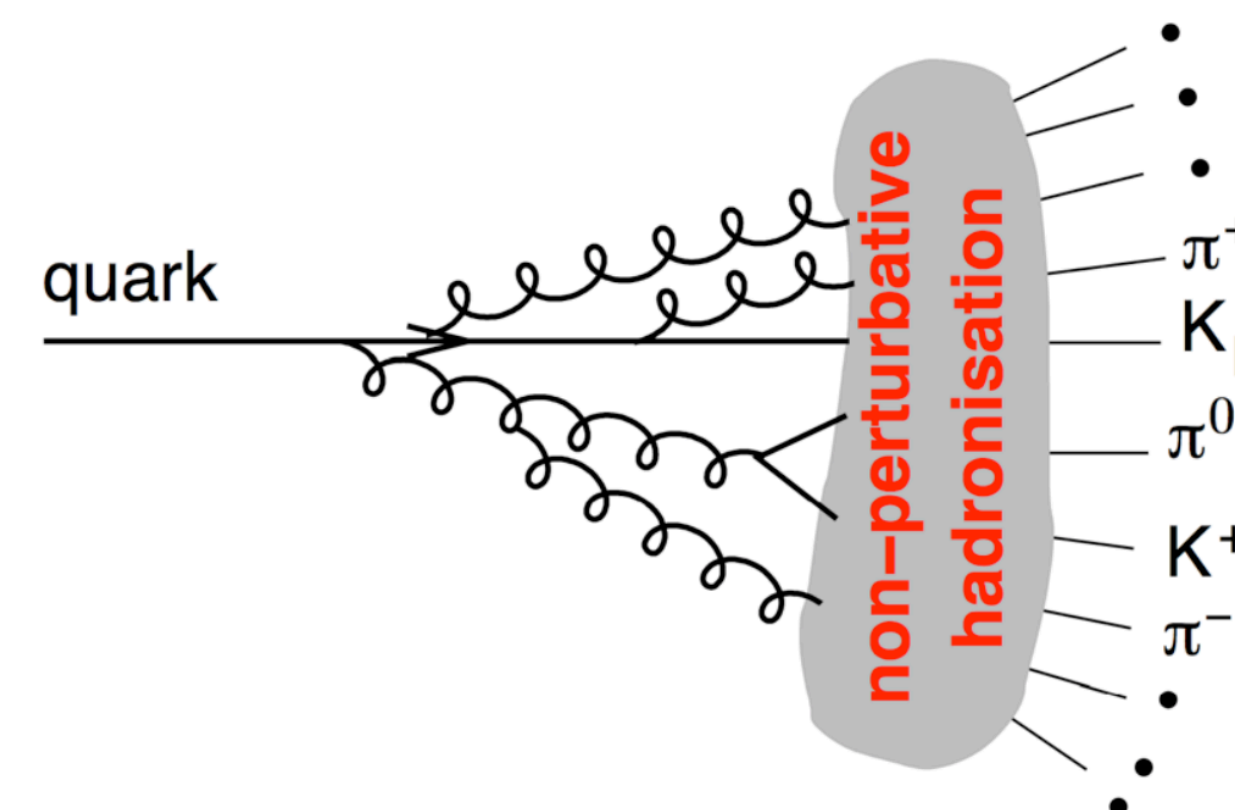
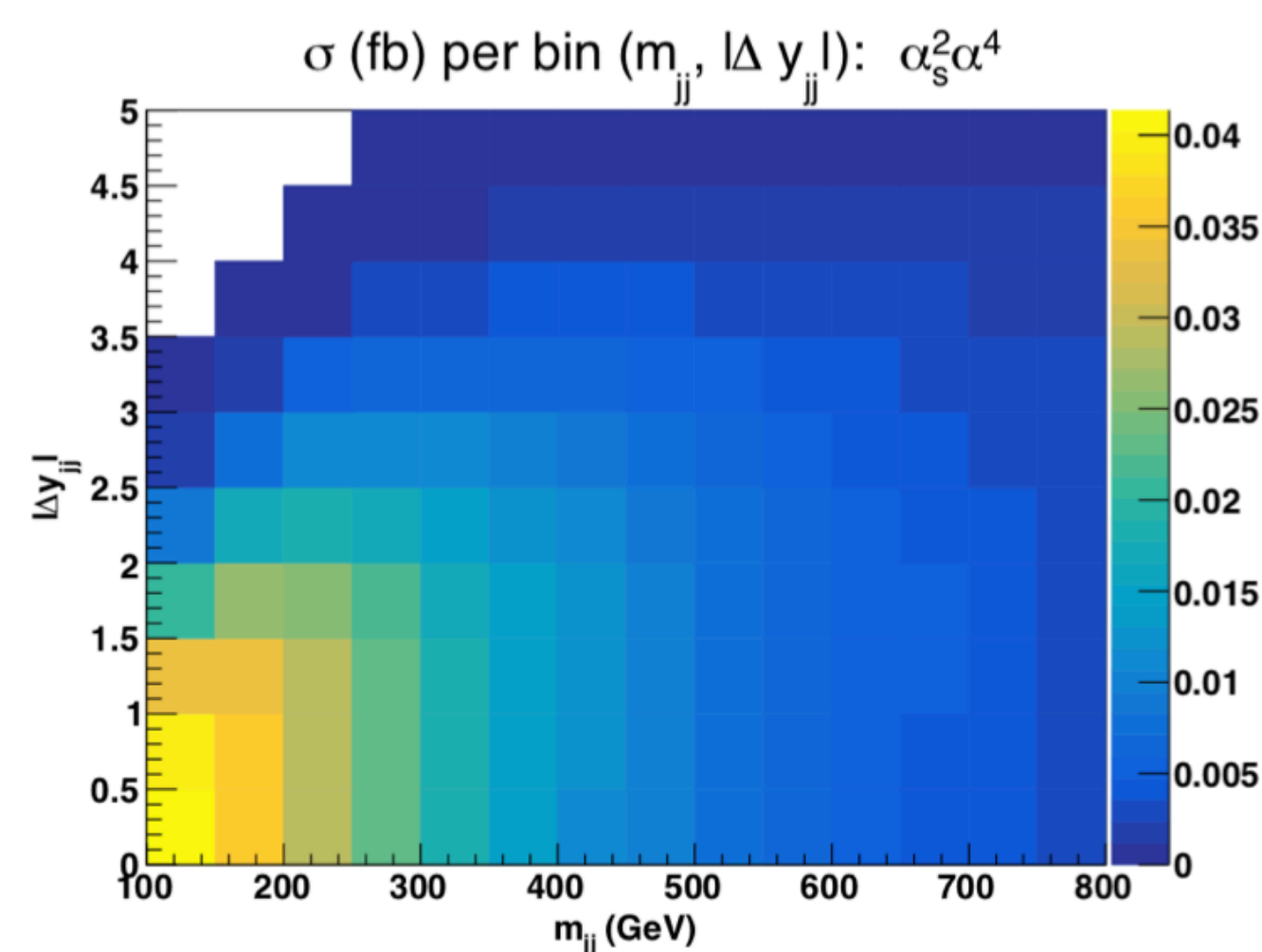
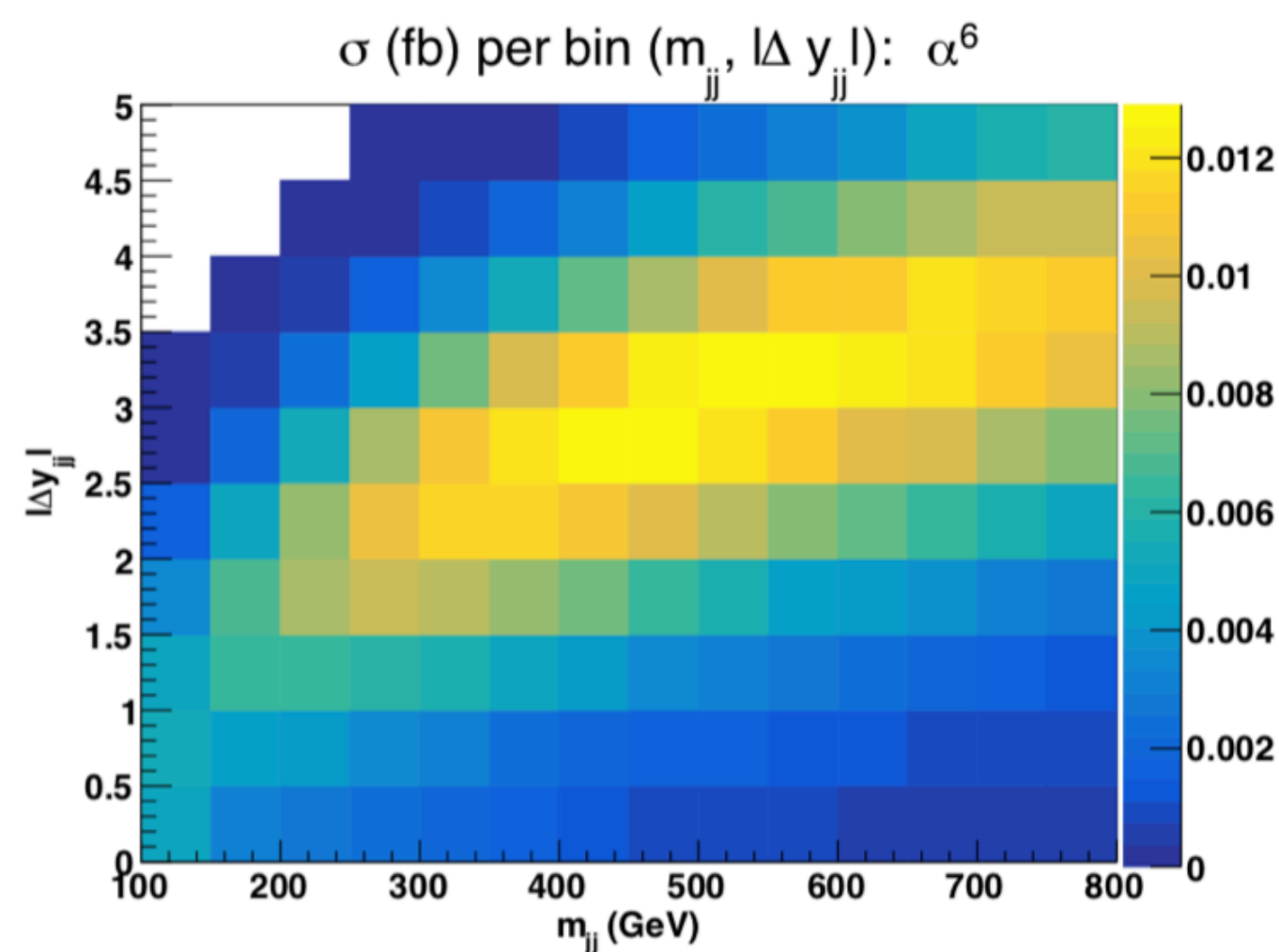
- ☒ Unitarity preservation visible in **massive $V_L V_L$** scattering
- ☒ Probe the nature of EW symmetry breaking

EW ZZ observation by combining 4ℓ and $2\ell 2\nu$ channels

VBS $Z\gamma$ analysis strategy



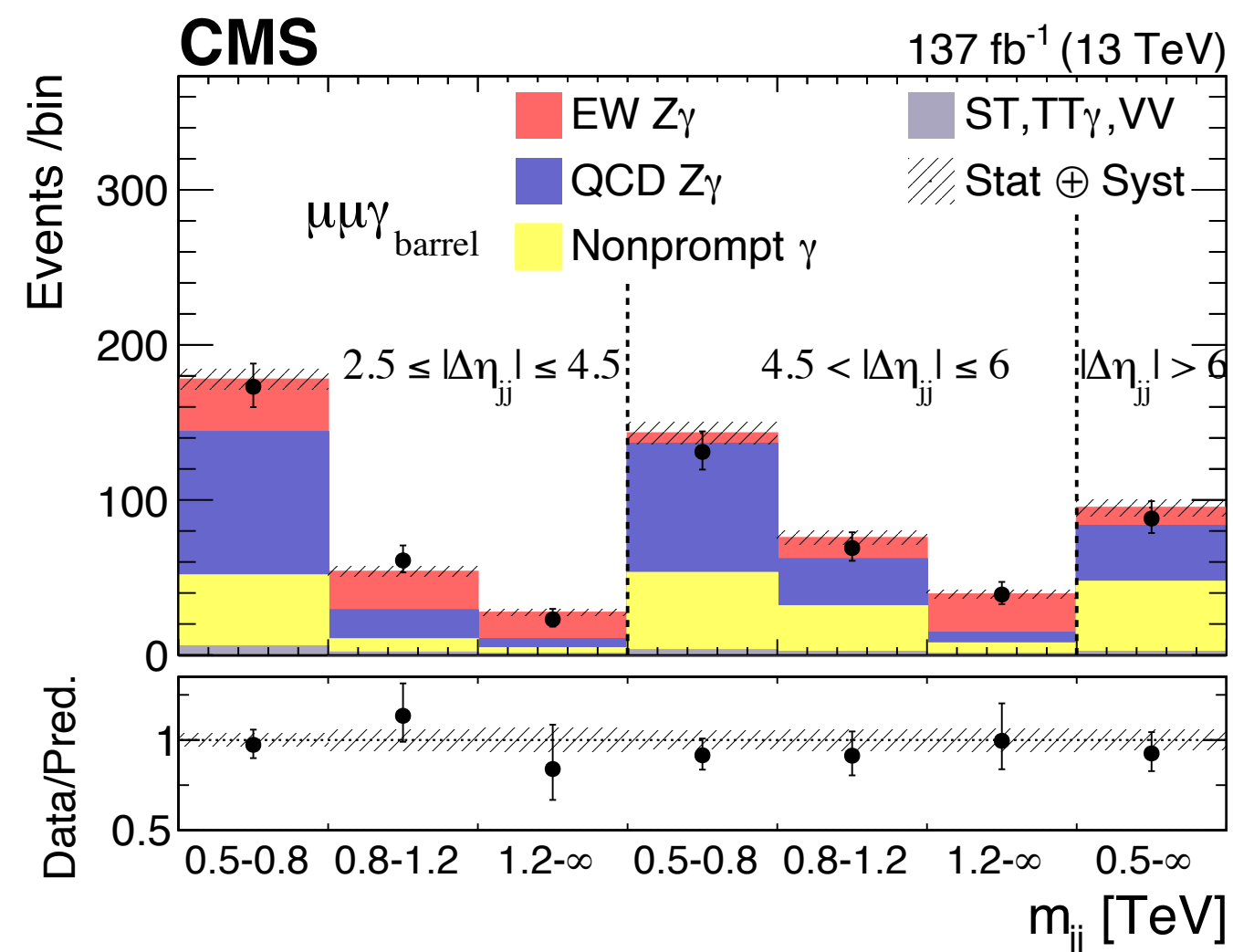
- **EW VBS:** six fermions final state at leading order $\mathcal{O}(\alpha^6)$
- **Irreducible background:**
 - QCD-induced $\mathcal{O}(\alpha^4\alpha_s^2)$ (large)
 - Interference: between EW and QCD $\mathcal{O}(\alpha^5\alpha_s)$ (small)
 - Diboson, $t\bar{t}\gamma$, tW , etc (small)
- **Reducible** background: mis-ID of final state particles



Nonprompt γ background

Main background is from corresponding QCD production which can be suppressed by the VBS kinematic variables like $m_{jj} > 500$, $\Delta\eta_{jj} > 2.5$, so the cut-based ID is mainly used to identify leptons and photon

VBS $Z\gamma$ results

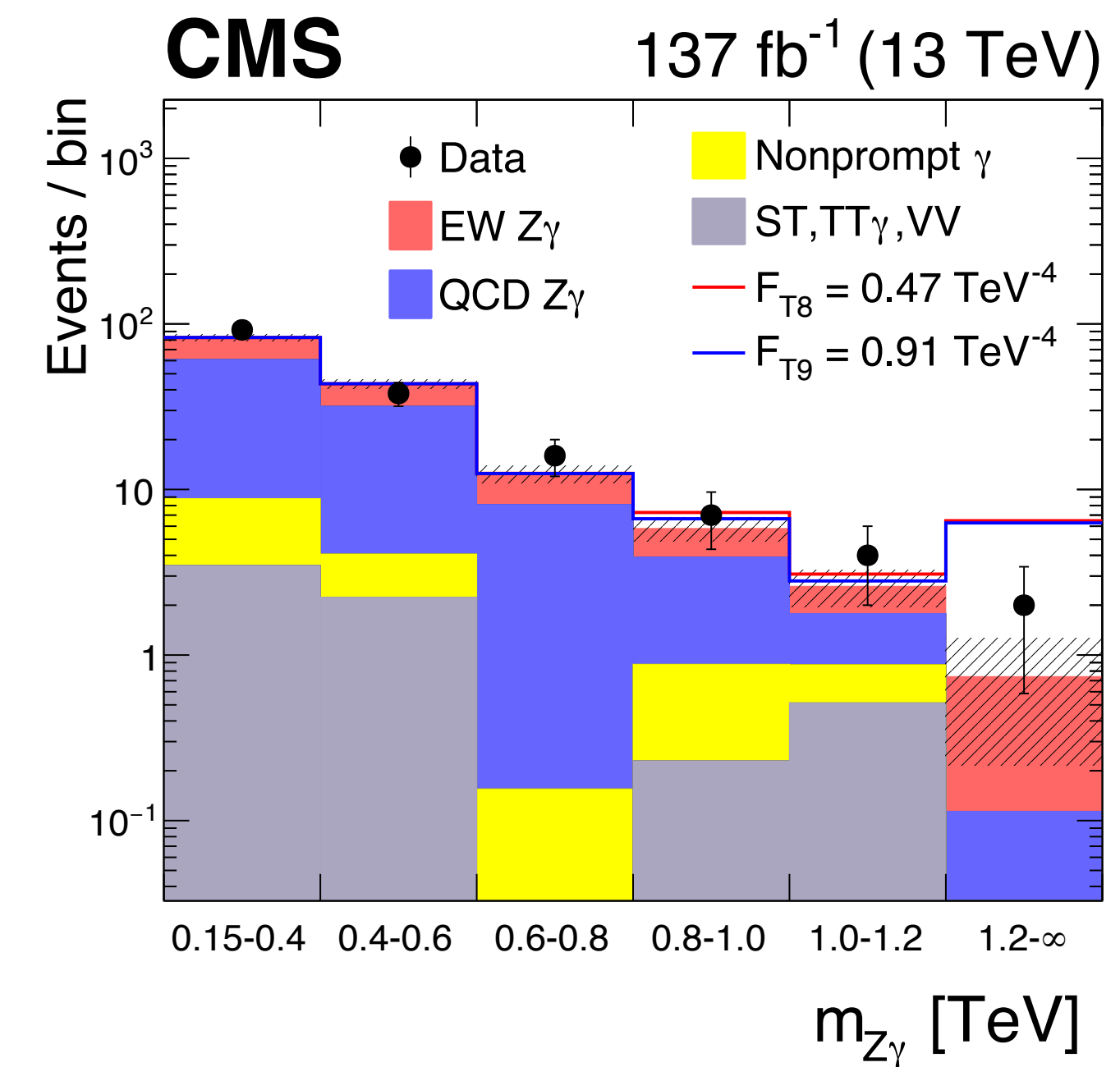
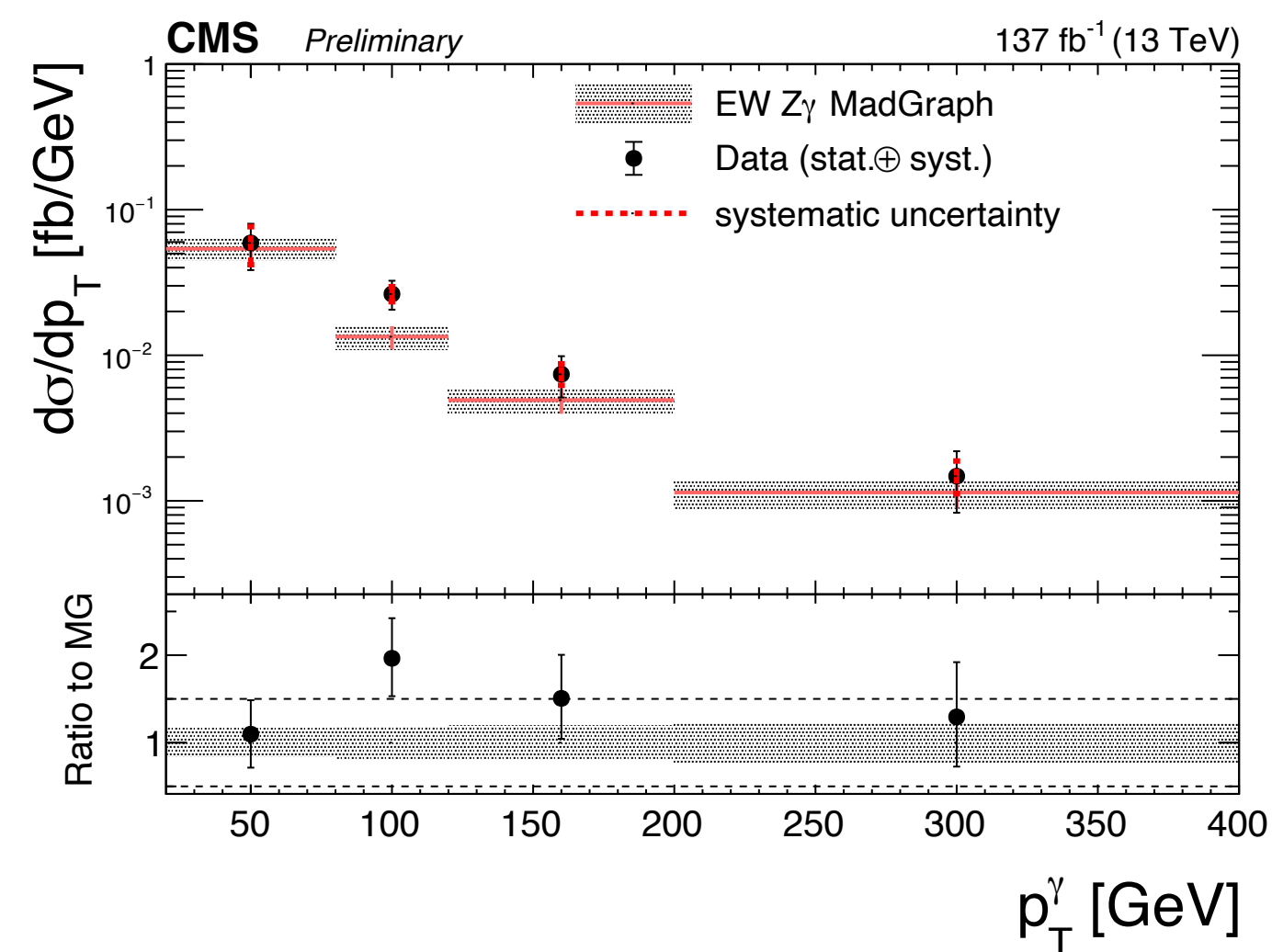
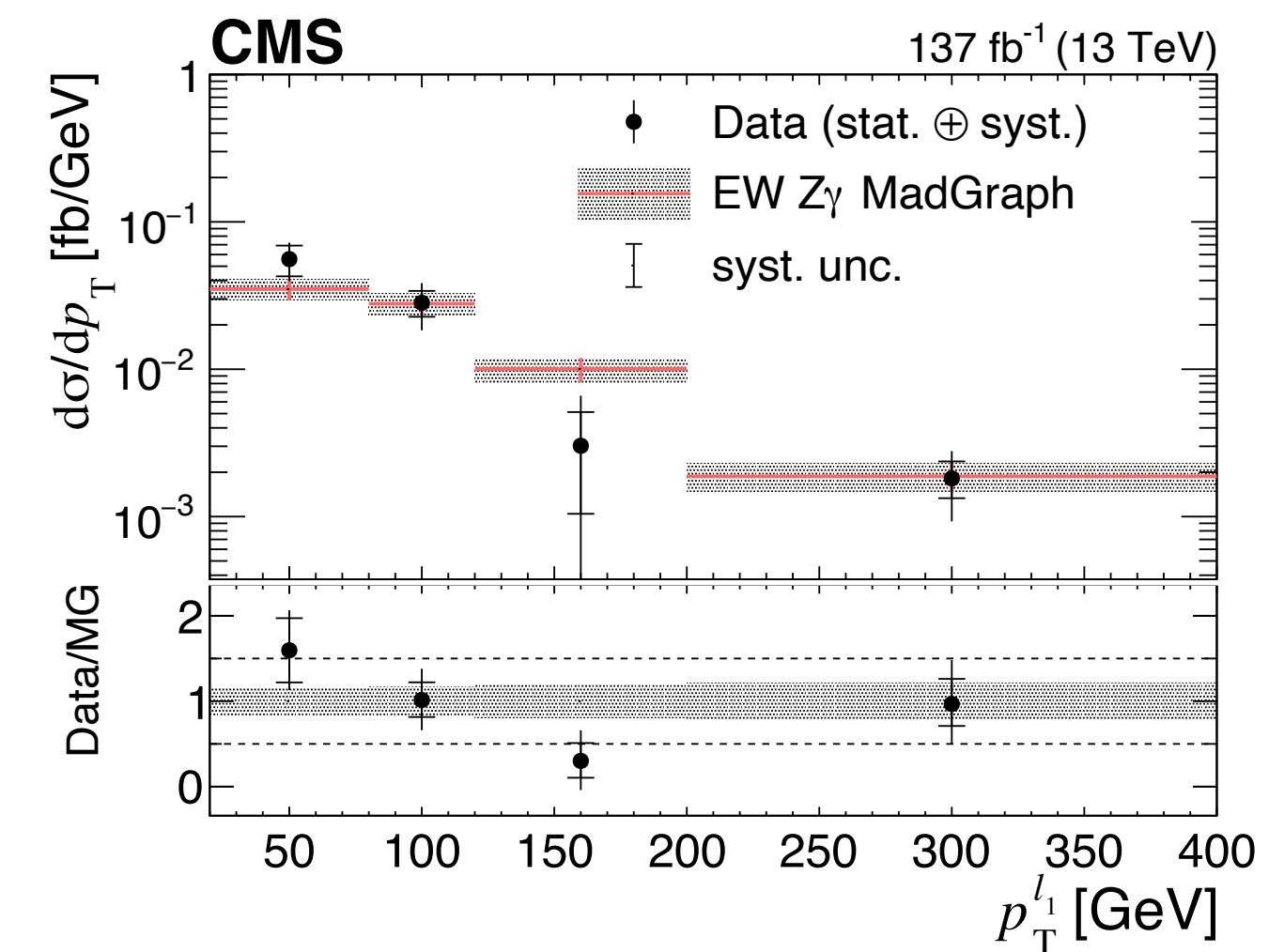


The observed (expected) significance is 9.4 σ (8.5 σ).

- $\sigma_{EW}^{SM\text{ pred.}} = 4.34 \pm 0.26 \text{ (scale)} \pm 0.06 \text{ (PDF)} \text{ fb}$
- $\mu = 1.20^{+0.12}_{-0.12} \text{ (stat)}^{+0.14}_{-0.12} \text{ (syst)}$
- $\sigma_{\text{mea.}} = 5.21 \pm 0.52 \text{ (stat)} \pm 0.56 \text{ (syst)} \text{ fb}$

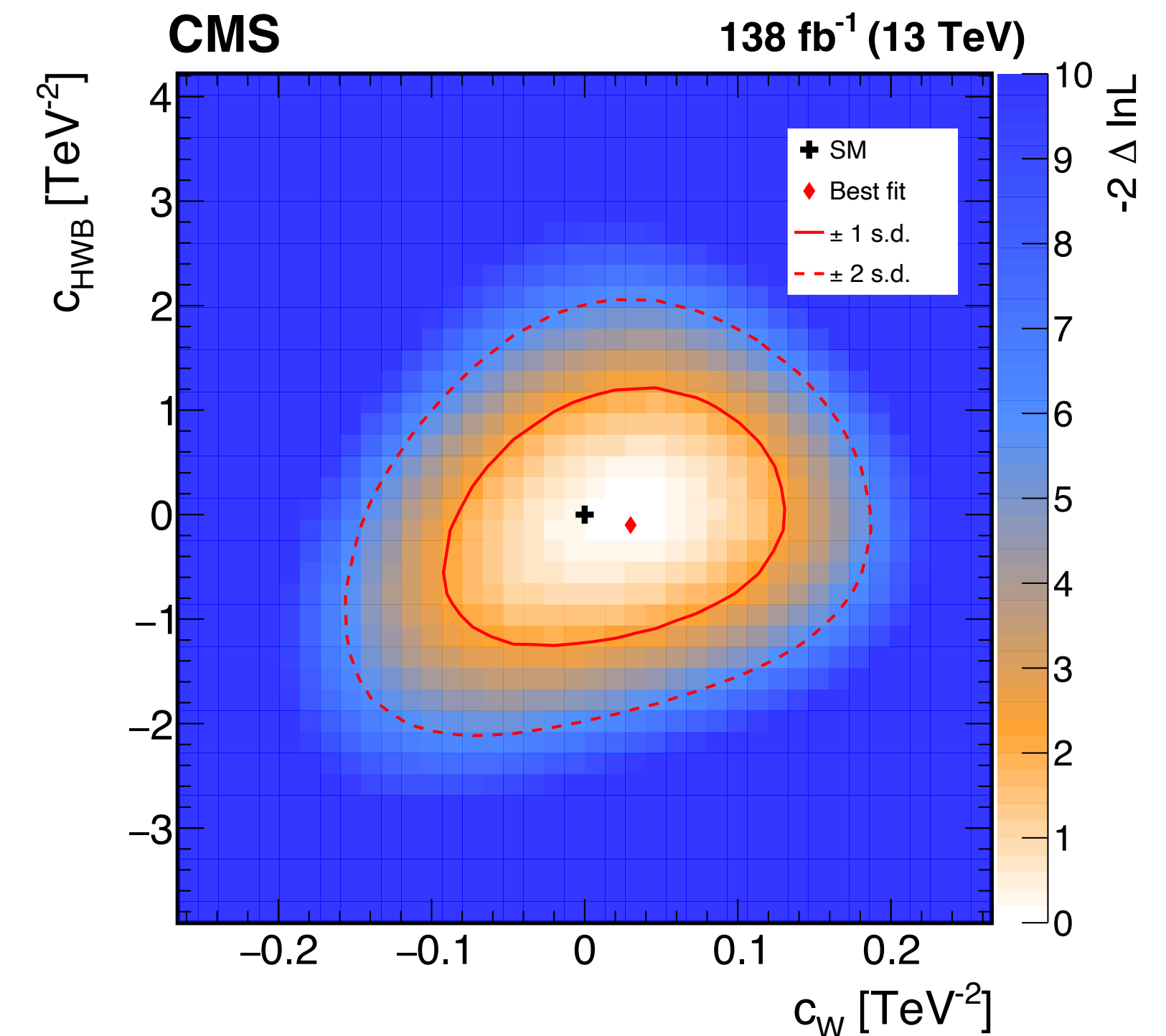
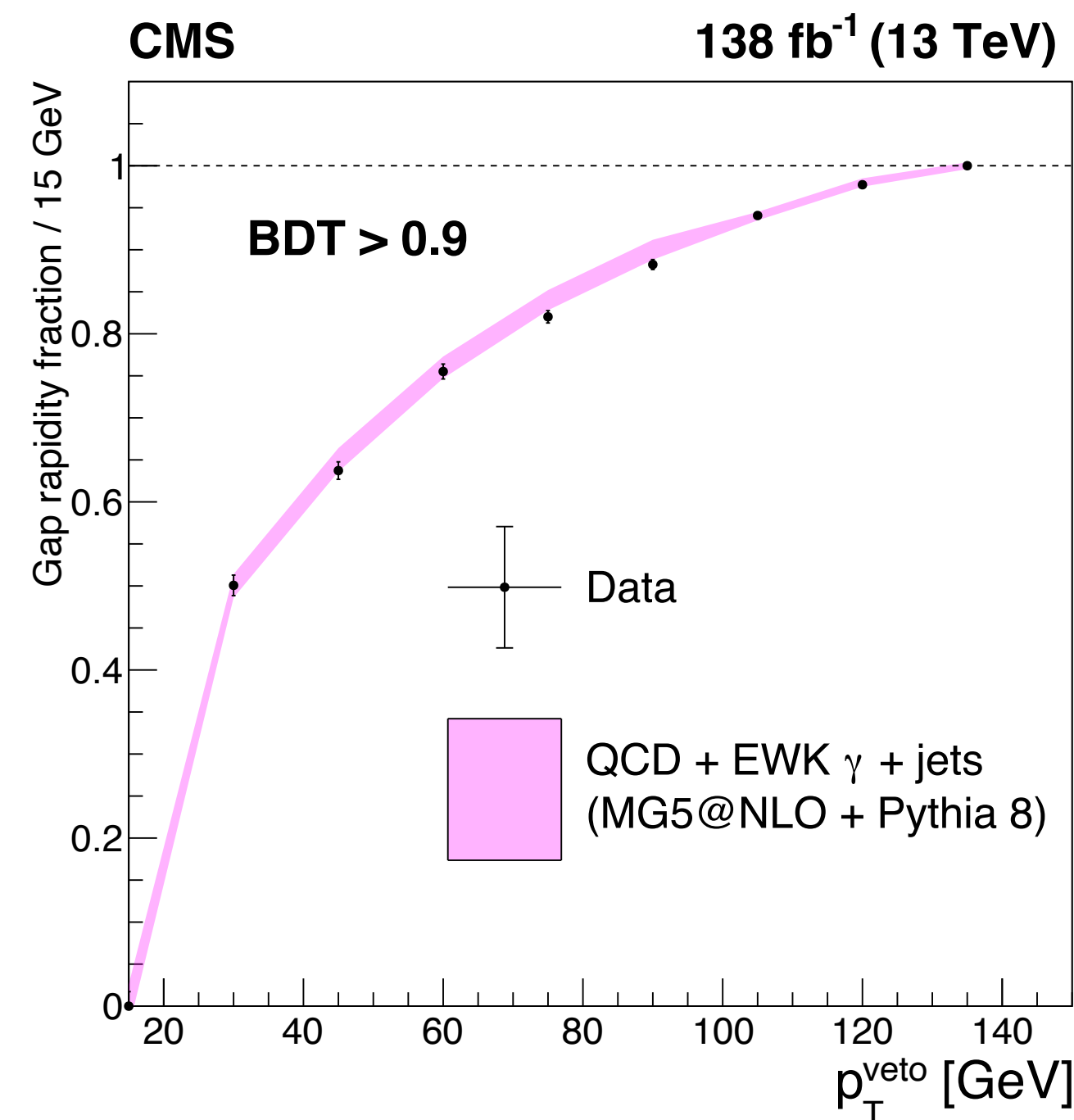
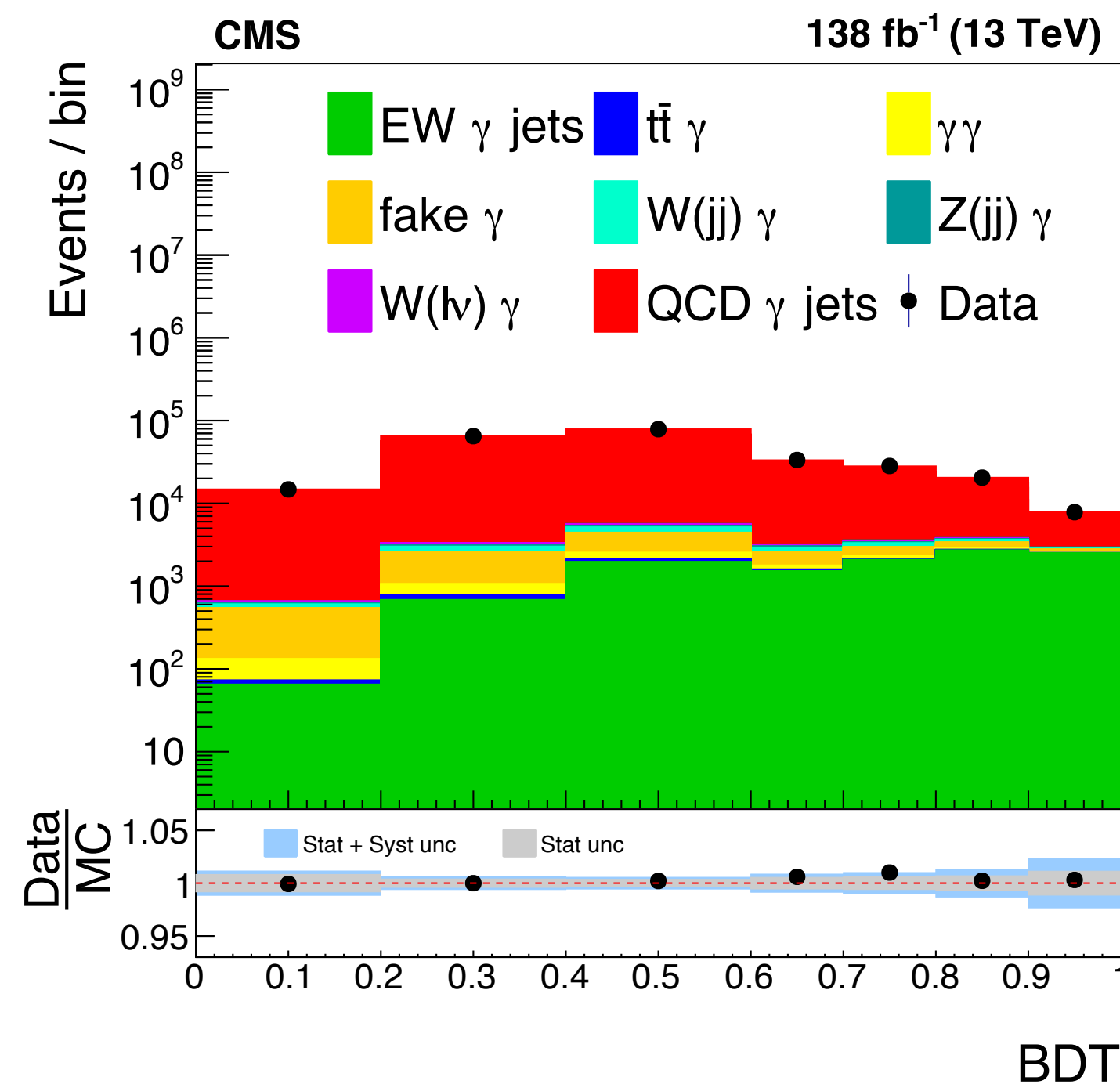
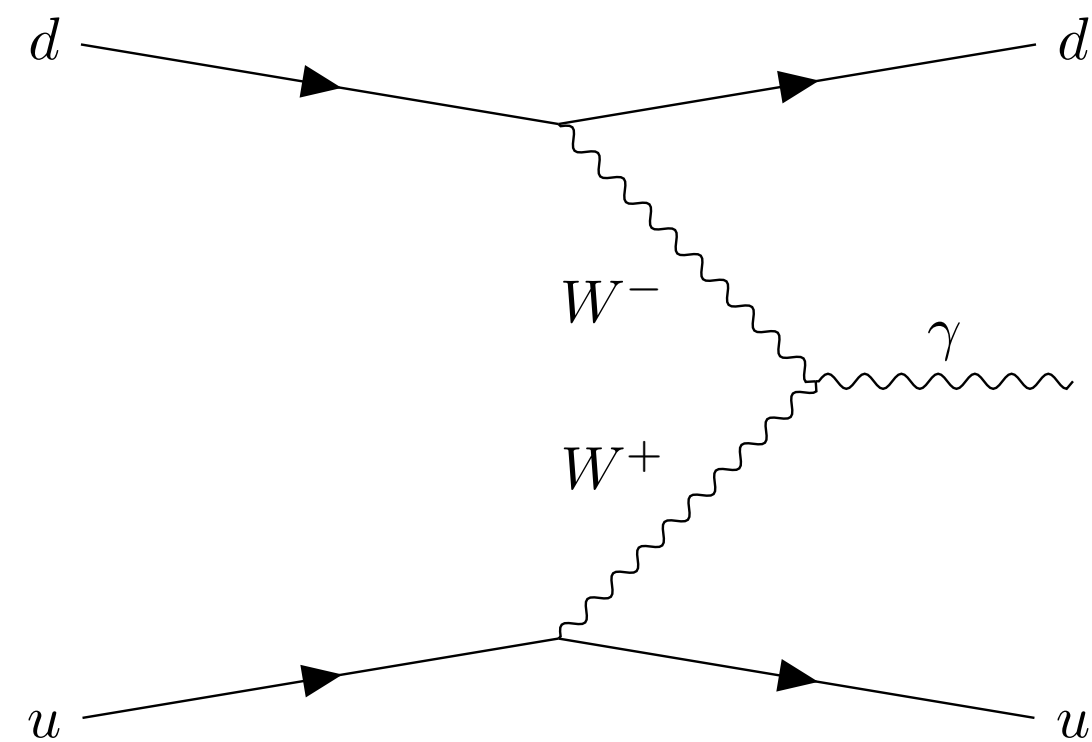
- Extended the SM Lagrangian with higher dimensional operators maintaining SU(2)×U(1) gauge symmetry:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}^{(6)} + \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}^{(8)} + \dots$$

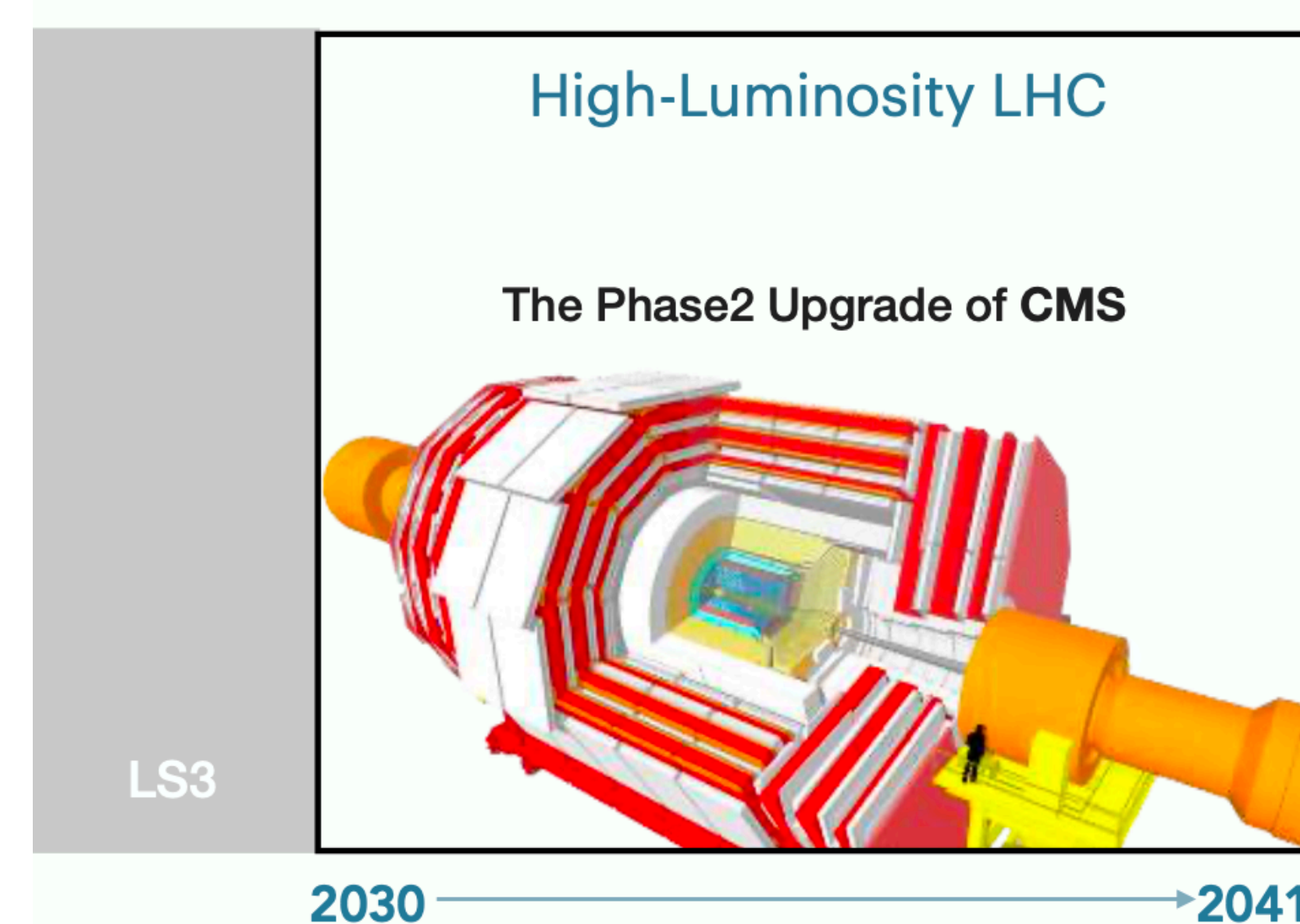
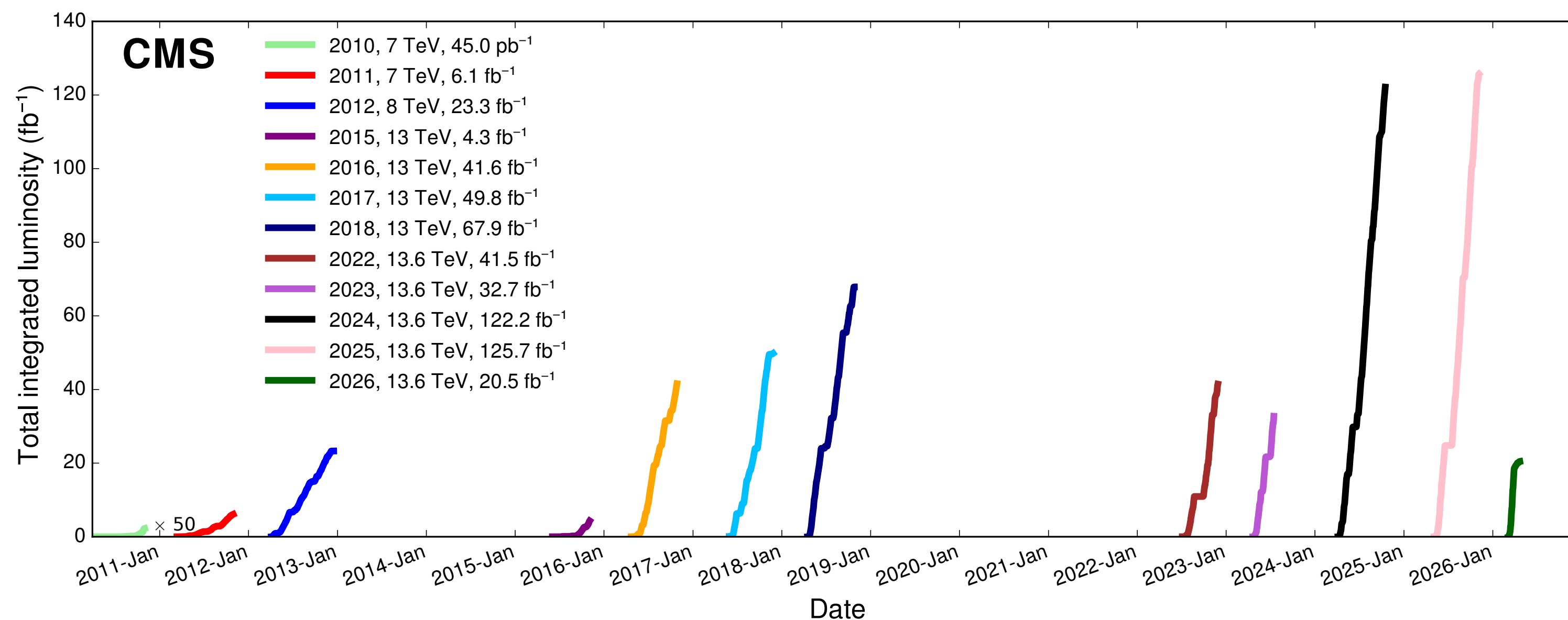


VBF γ results

- The first measurement for VBF γ due to challenges on background modelling
- For events of $p_T(\gamma) > 200$ GeV, we have:
 - Inclusive and differential cross sections
 - Gap rapidity test for Monte Carlo generator modelling
 - SMEFT interpretation on operator of c_W and c_{HWB}



LHC status and prospect



A remarkable breadth of physics results



Higgs boson discovering

Natural SUSY searches
Exclude large part of parameter space

Probing QGP



Study of Yukawa coupling
Observation 3rd generation
Evidence 2nd generation

Shift to precision physics
 m_W , m_{top} , $\sin^2\theta_W$

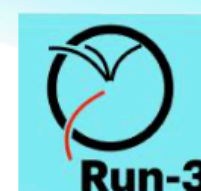
Observation of VBS

Heavy flavour physics
Ultra-rare decay $B_s \rightarrow \mu^+ \mu^-$

Recent highlights

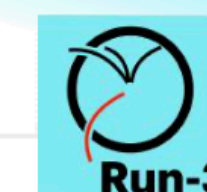


Precision physics
Higgs boson physics
top quark physics
Searches



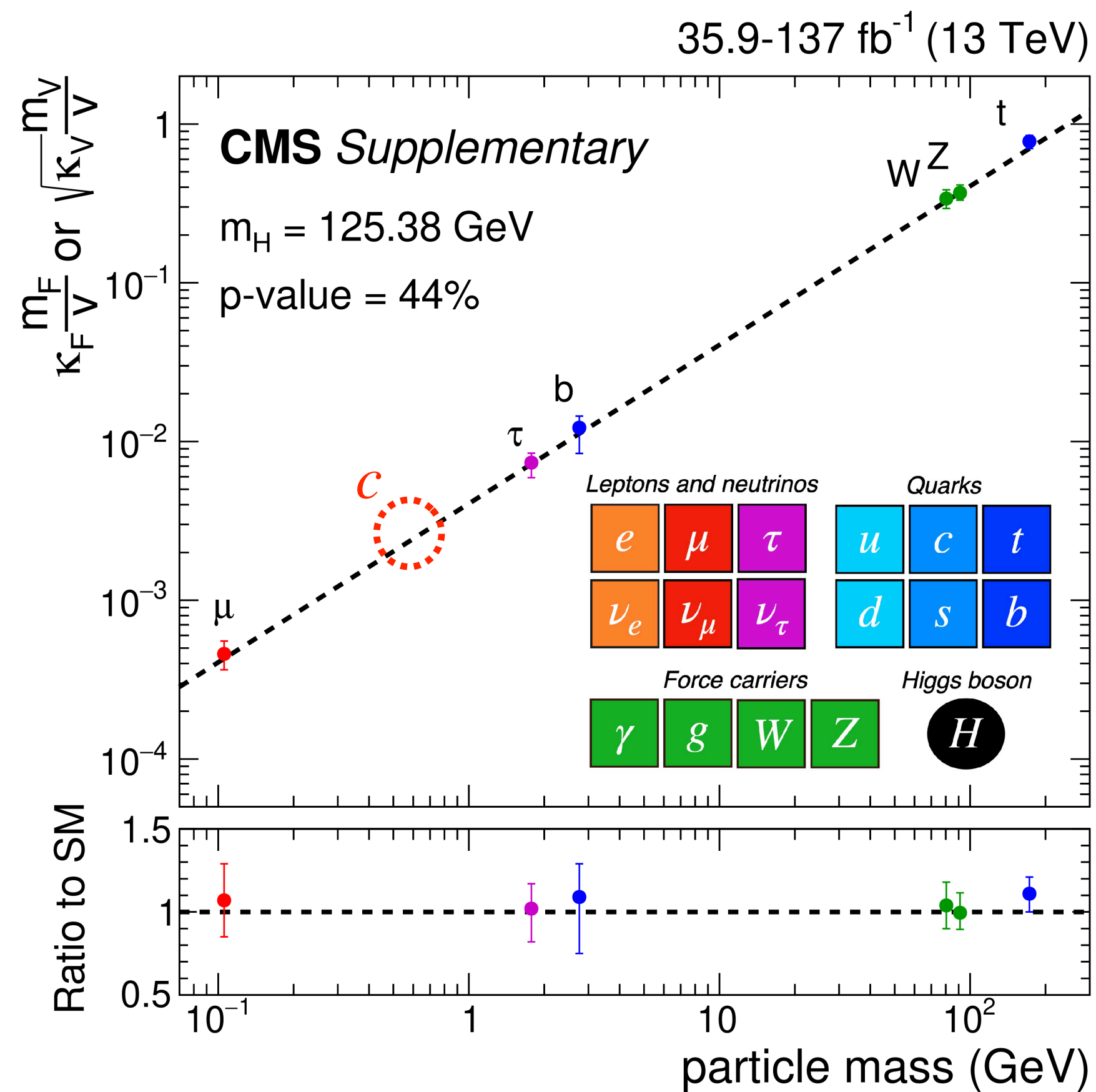
Flavour physics
Heavy ions physics

Performance in 2025

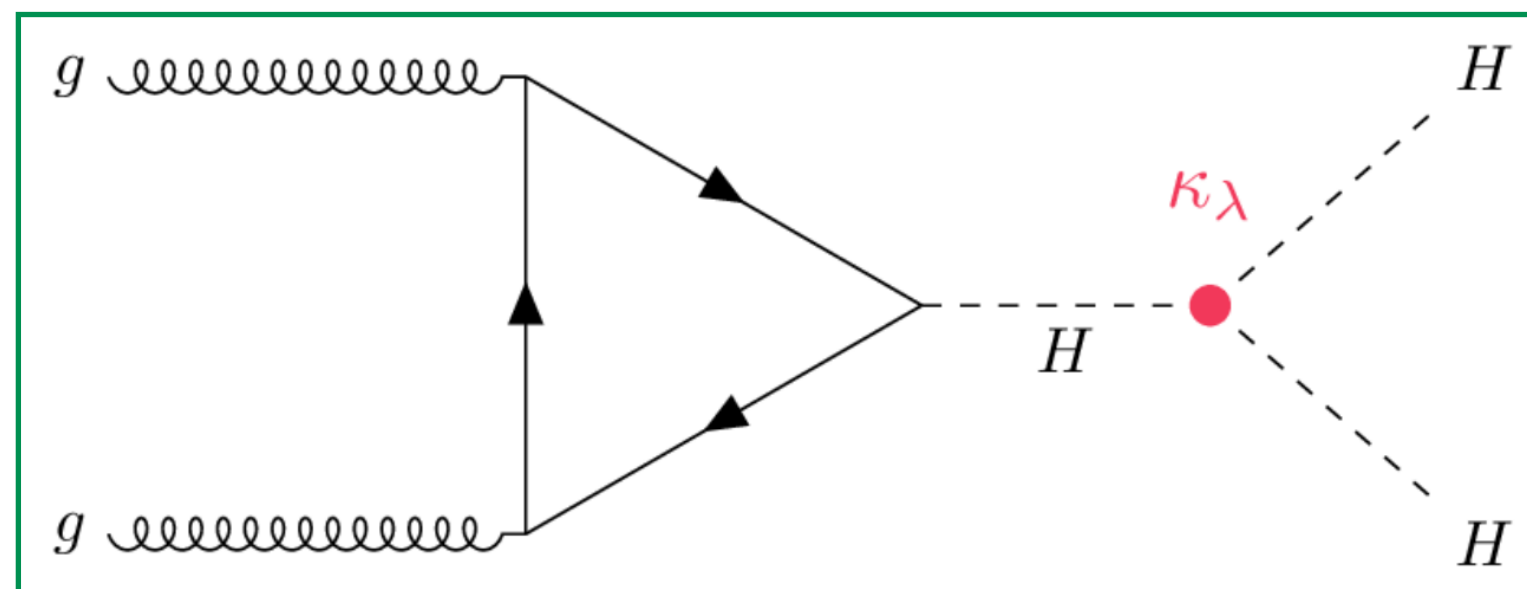


Towards the HL-LHC

LHC status and prospect

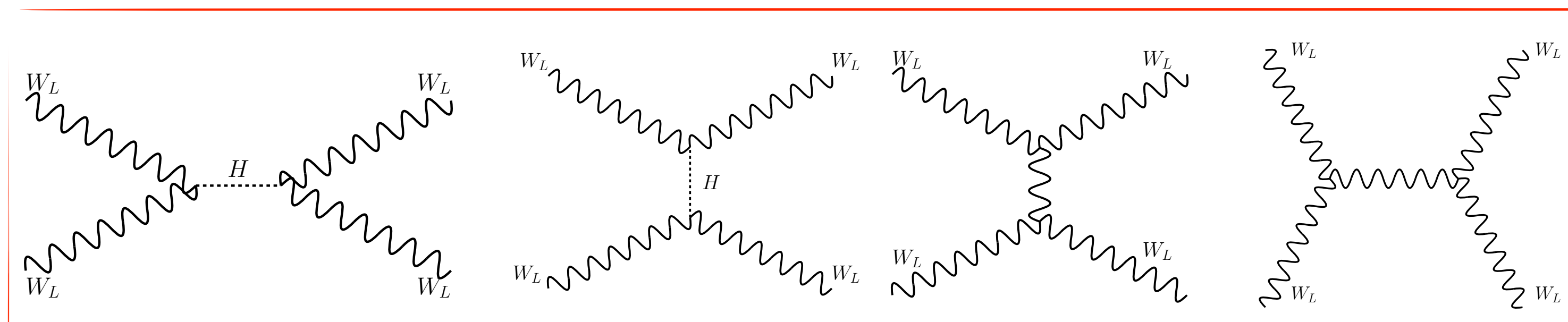


Higgs boson to the 2nd fermions couplings

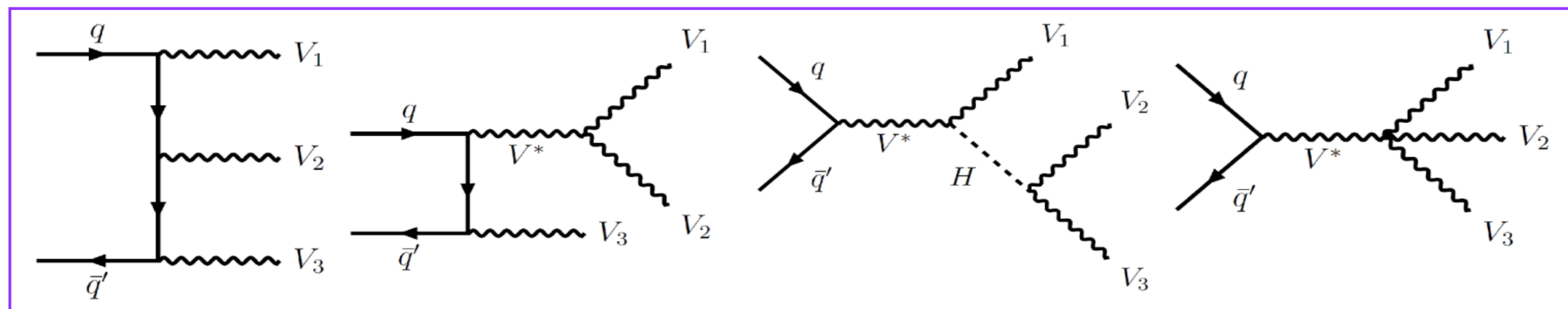


Higgs boson self-coupling

polarised VBS $V_L V_L \rightarrow V_L V_L$

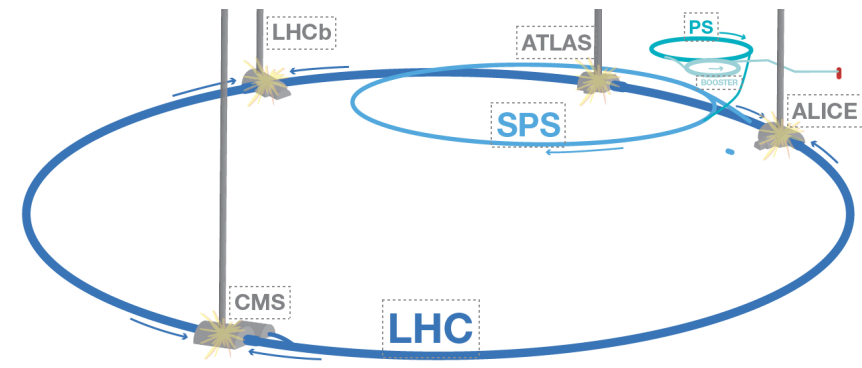


precision rare process measurement in high energy regime

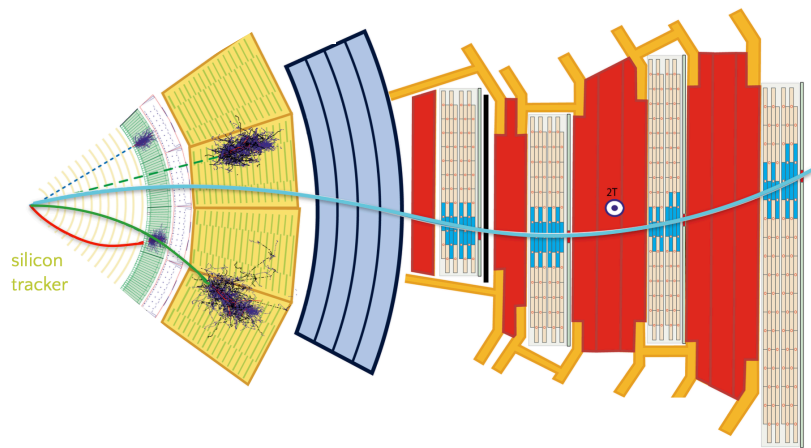


Summary

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

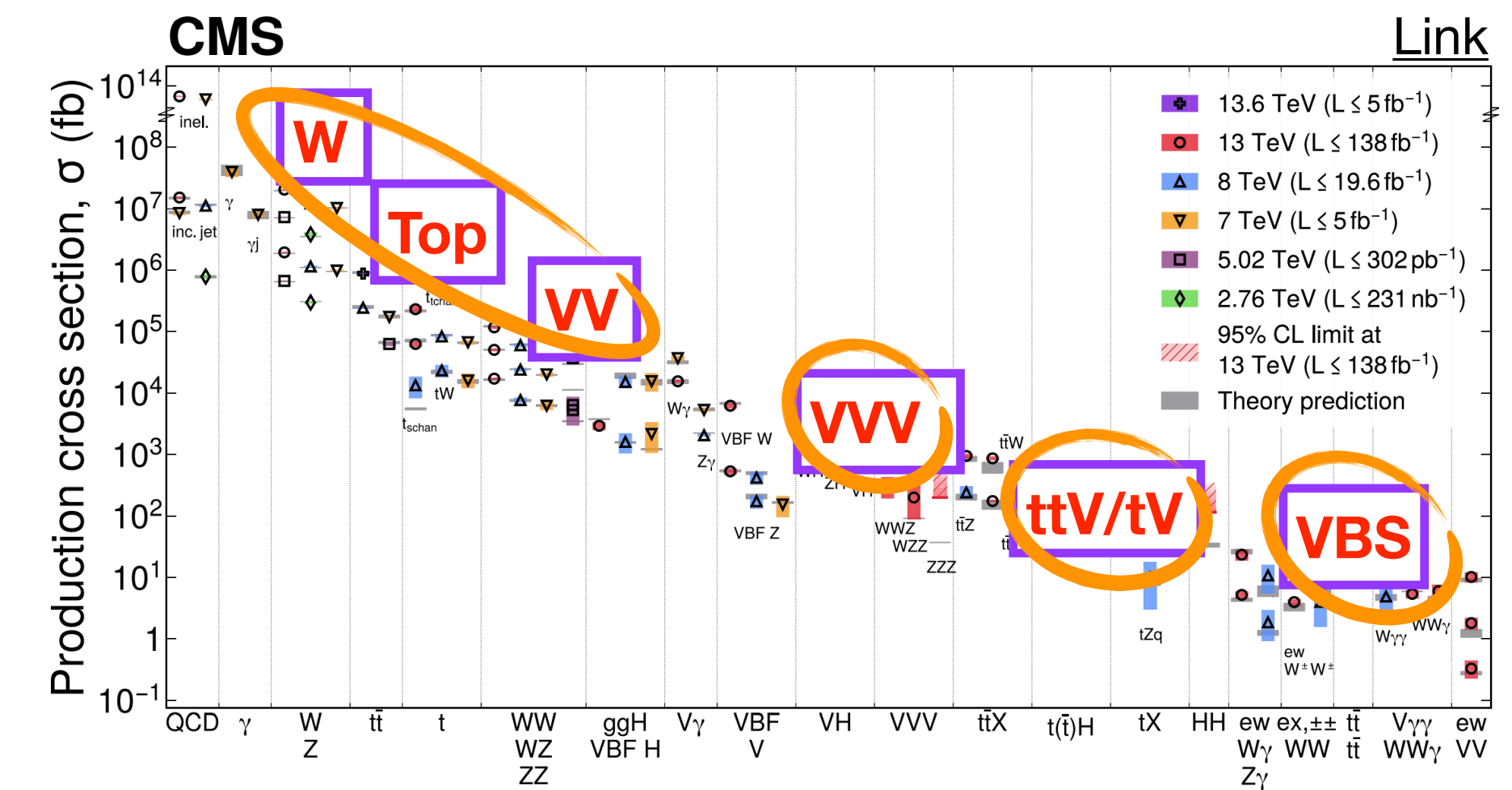


- The SM theory overview
- The recent CMS SM results
 - Fundamental mass results summary
 - Diboson and triboson productions
 - Top-gauge boson coupling production
 - VBS production
- The status and prospects of physics from LHC collisions



Standard Model of Elementary Particles

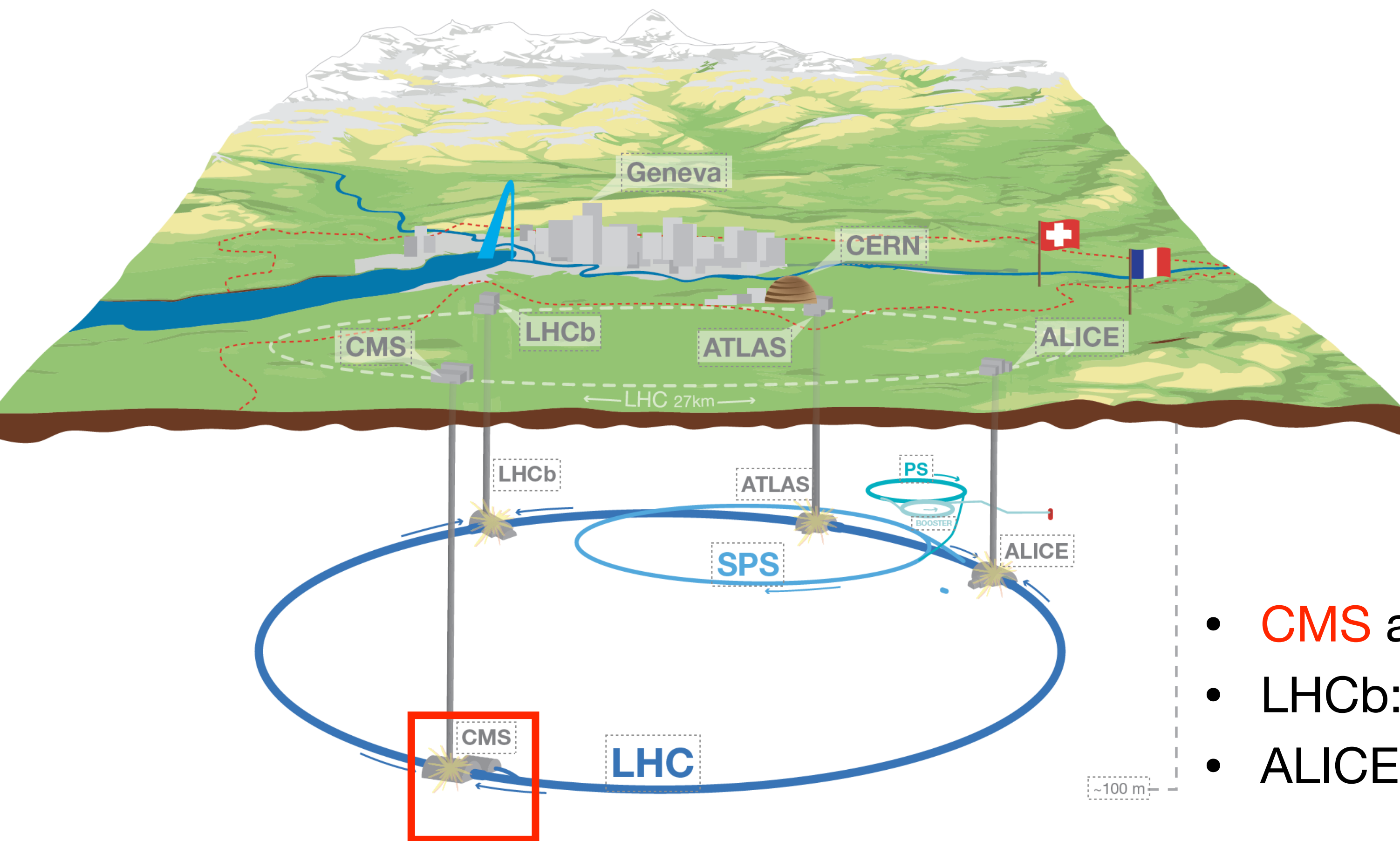
three generations of matter (fermions)					interactions / force carriers (bosons)	
mass	≈2.16 MeV/c ²	≈1.273 GeV/c ²	≈172.57 GeV/c ²		0	≈125.2 GeV/c ²
charge	2/3	2/3	2/3		0	0
spin	1/2	1/2	1/2		1	0
	u up	c charm	t top		g gluon	H higgs
	d down	s strange	b bottom		γ photon	
	e electron	μ muon	τ tau		Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino		W W boson	



With the ongoing Run 3 and the future HL-LHC, we are entering an era where **precision and rare-process measurements** will play an increasingly **central role in particle physics**, and where we expect to **achieve a new generation of representative results**

Backup

Large hadron collider (LHC)



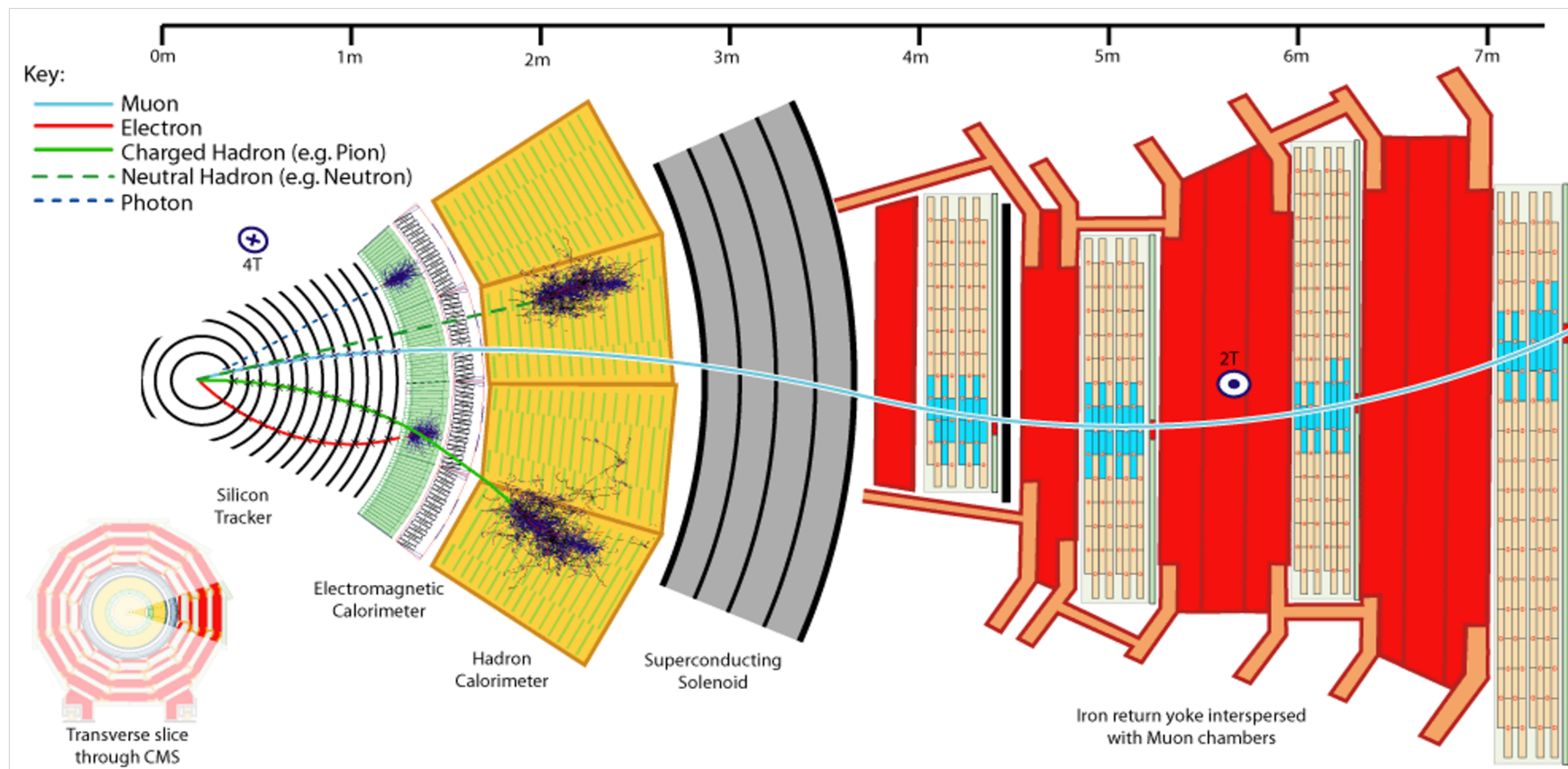
- Located in the French-Swiss border
- 27 km circumference
- ~175m underground
- Operating since 2008
- Superconducting magnets to accelerate protons up to 7 TeV

- **CMS** and ATLAS: Two general purpose experiments
- LHCb: Flavour (b) physics (main interest)
- ALICE: Analysis of ion-ion collisions (main interest)

- Completed two data-taking periods Run 1 and Run 2 at $\sqrt{s} = 7(8)$ and 13 TeV
- Run 3 data-taking at $\sqrt{s} = 13.6$ TeV is ongoing

The Compact Muon Solenoid (CMS)

- The detector can directly detect only “sufficiently stable” particles with lifetimes long enough to exit the **beam pipe** and enter the detector: $(c\tau)\gamma > 2 \text{ cm}$, where $\gamma = E/m$
- The list of “stable” particles are really limited including:
 - $e^\pm, \mu^\pm, \gamma$
 - Some neutral and charged hadrons $\pi^\pm, K^\pm, K_L, n$, and p

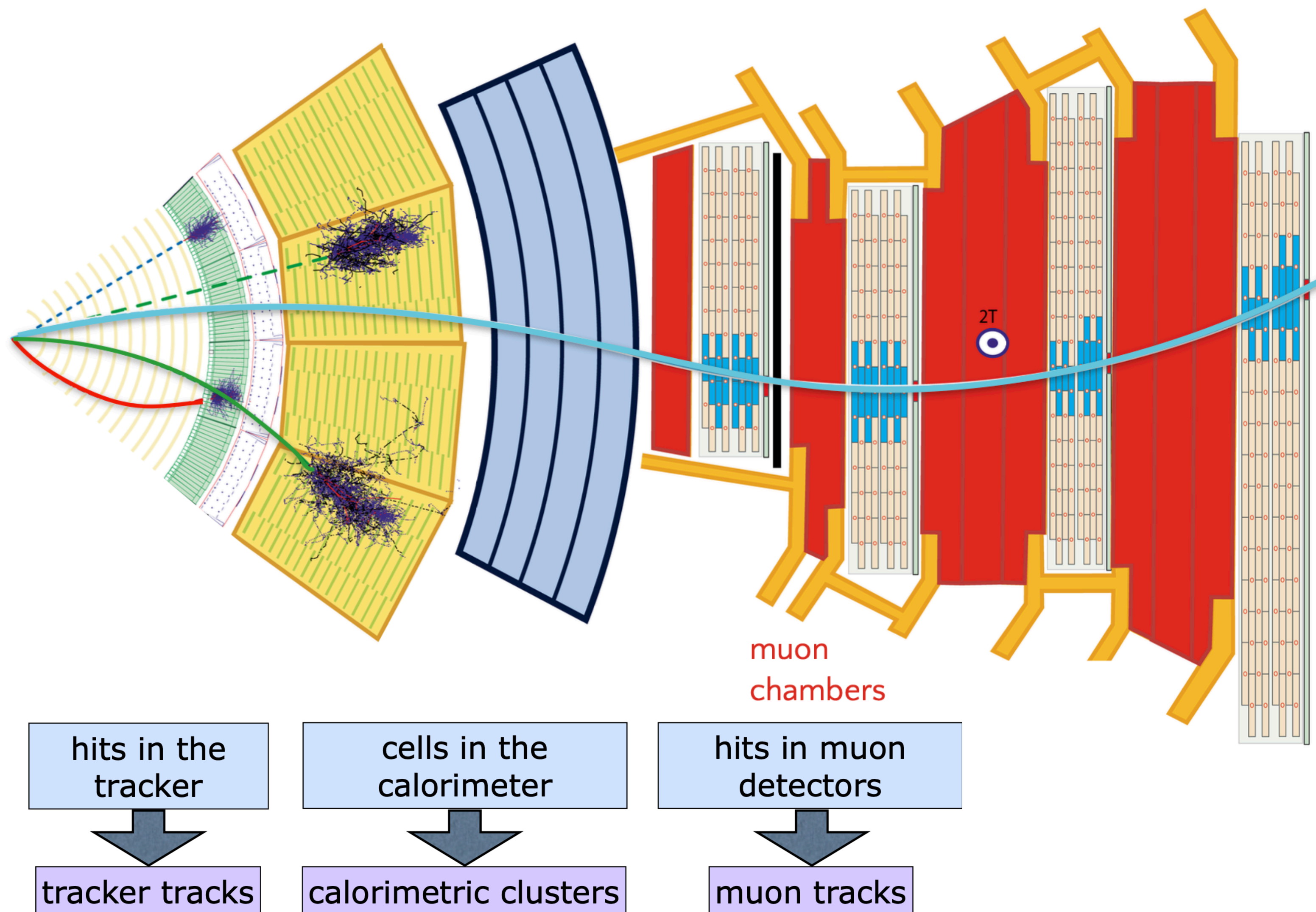


CMS detector

- Layered structure for different particle reconstruction
- Measure momentum and charge of charged particles
- Collect and measure photon and electron
- Collect energy of hadrons
- Track muon trajectory

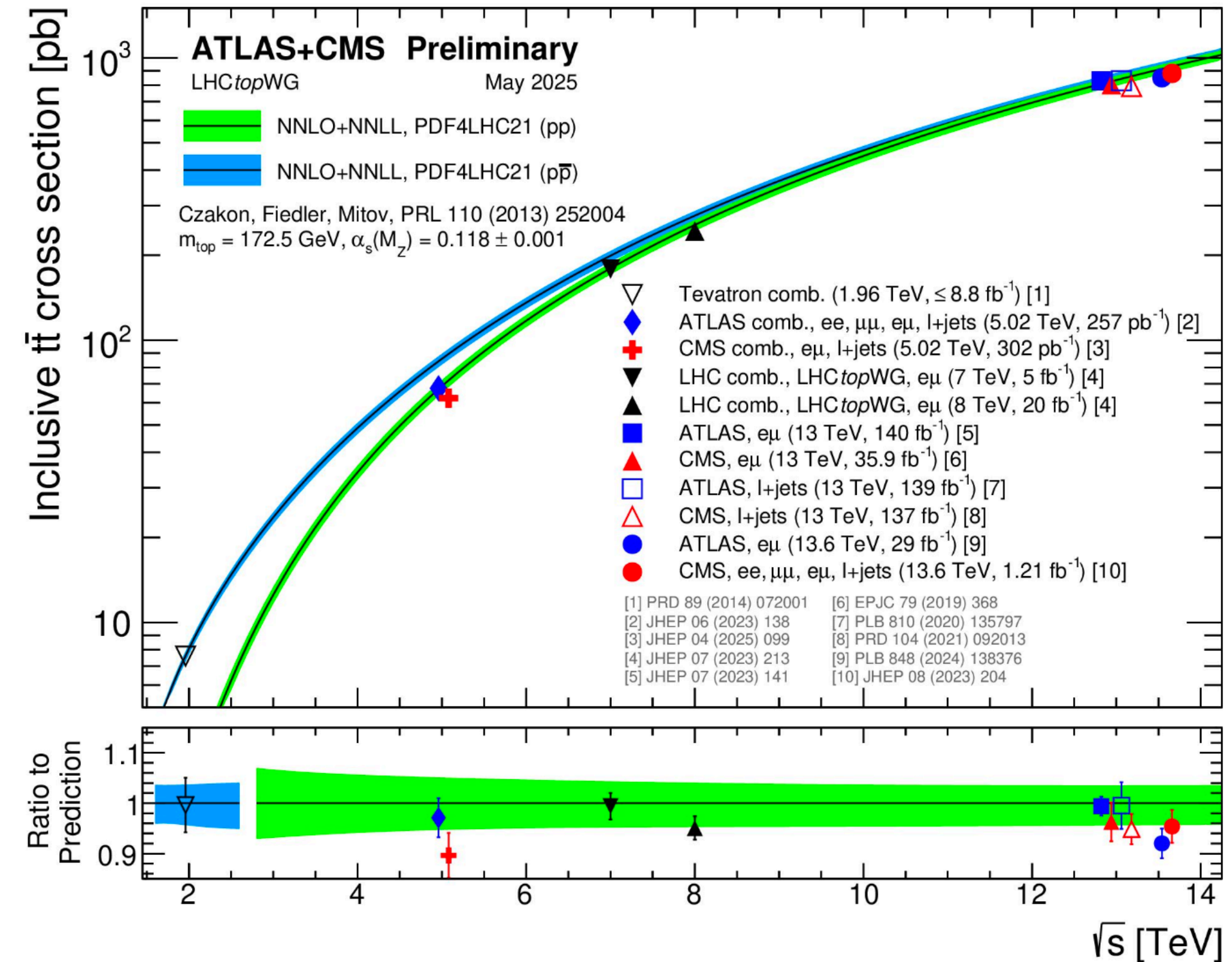
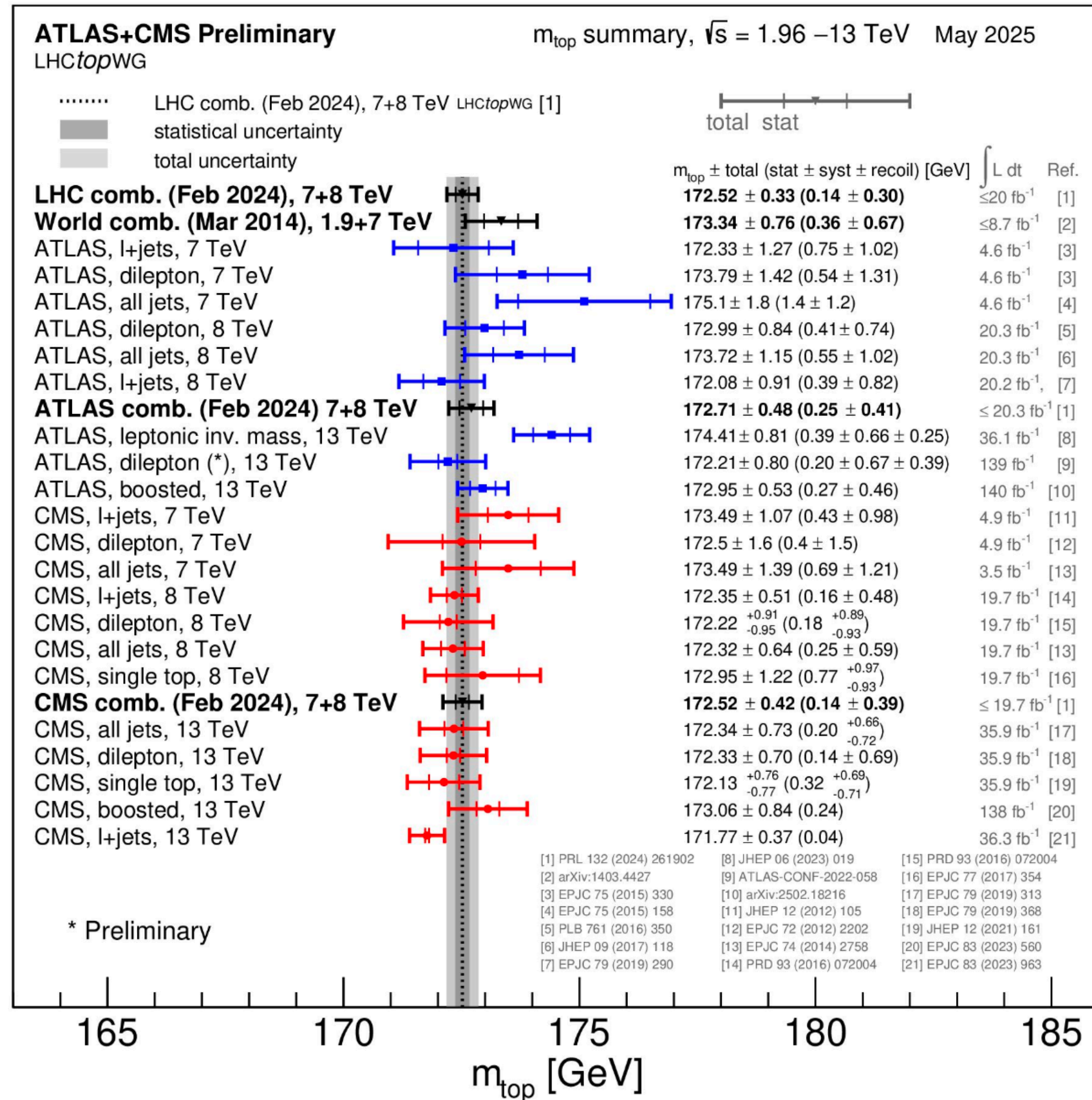
○ Information from all sub-detectors combined to reconstruct particles

○ The **particle-flow (PF)** algorithm *link the single objects* with geometrical requirements on the extrapolated trajectories and *create blocks to reconstruct and identify particle candidates*



PF algorithm is the base of the physics analysis

Top mass – Overview

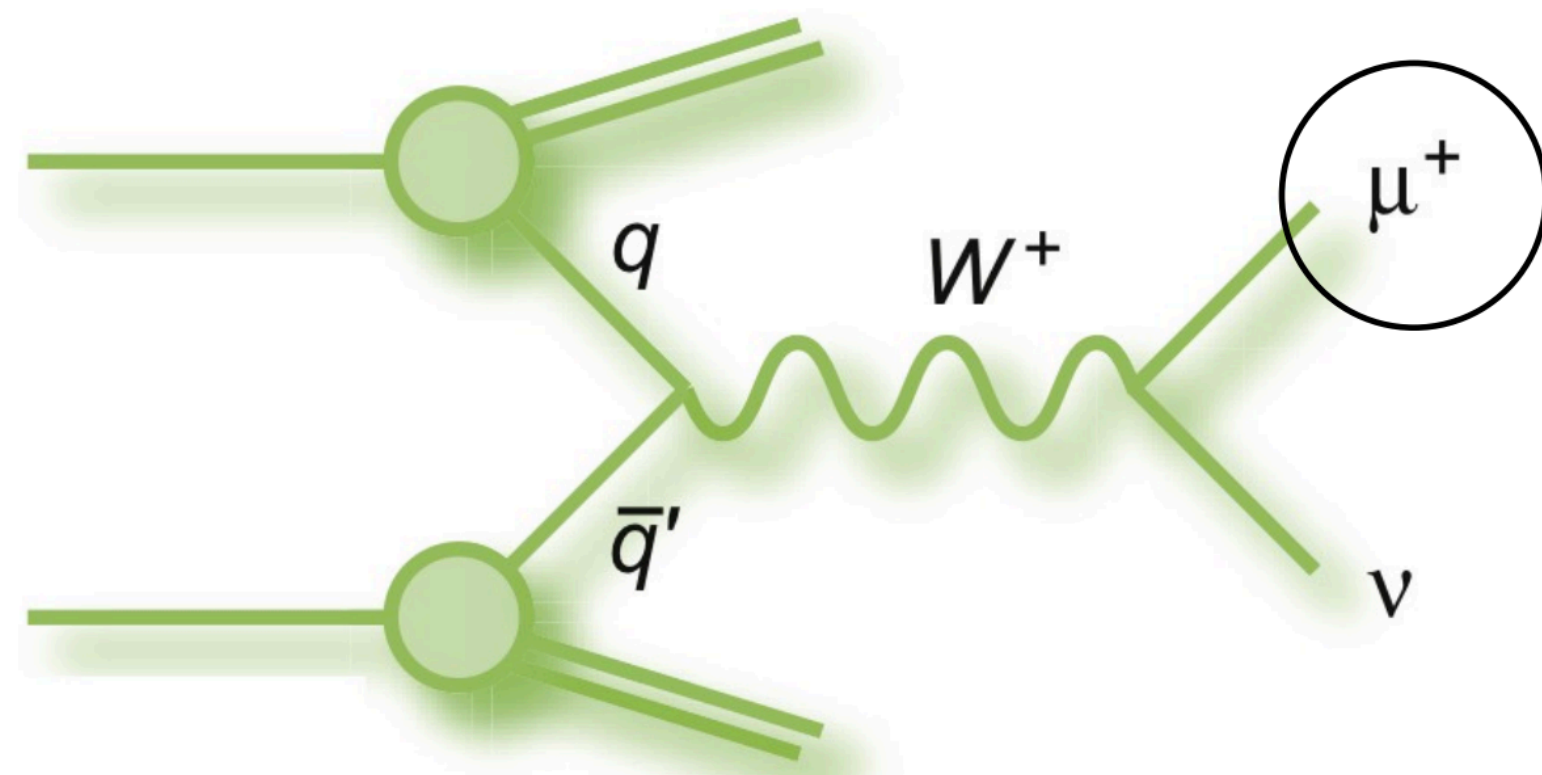


- Direct measurement:** m_t is extracted by comparing the distribution of a reconstructed mass-sensitive observable with its Monte Carlo (MC) prediction
- Indirect measurement:** experimental observables of production, such as the total cross-section, are compared to fixed-order calculations performed in well-defined mass schemes (pole mass, $\bar{M}\text{S}$, etc.)

W mass — Measurement strategy

Muons can be measured best, using muon kinematics only with per mille precision required

- **Straightforward single muon selection:** track quality criteria, loose transverse impact parameter cut, and isolation
- Selected events are about 90% $W \rightarrow \mu\nu$
- **Nonprompt background** from data-driven estimate
 - Mostly from B and D decays with smaller contribution from π or K decay-in-flight
- **Prompt backgrounds from simulation** with all relevant corrections/uncertainties
 - $W \rightarrow \tau \nu$, $Z \rightarrow \mu\mu$ (mostly with one muon out-of-acceptance), $Z \rightarrow \tau\tau$, top, diboson



W mass — Measurement strategy

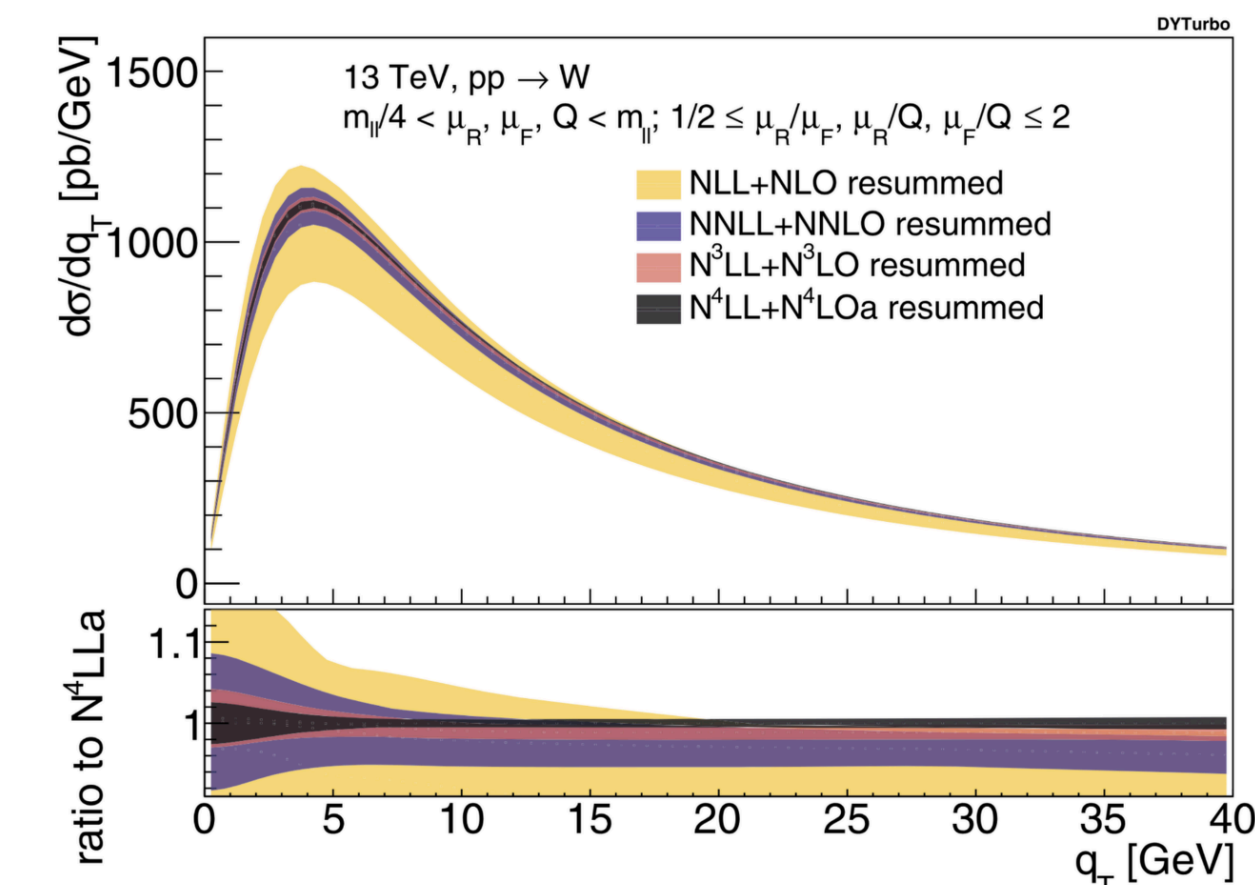
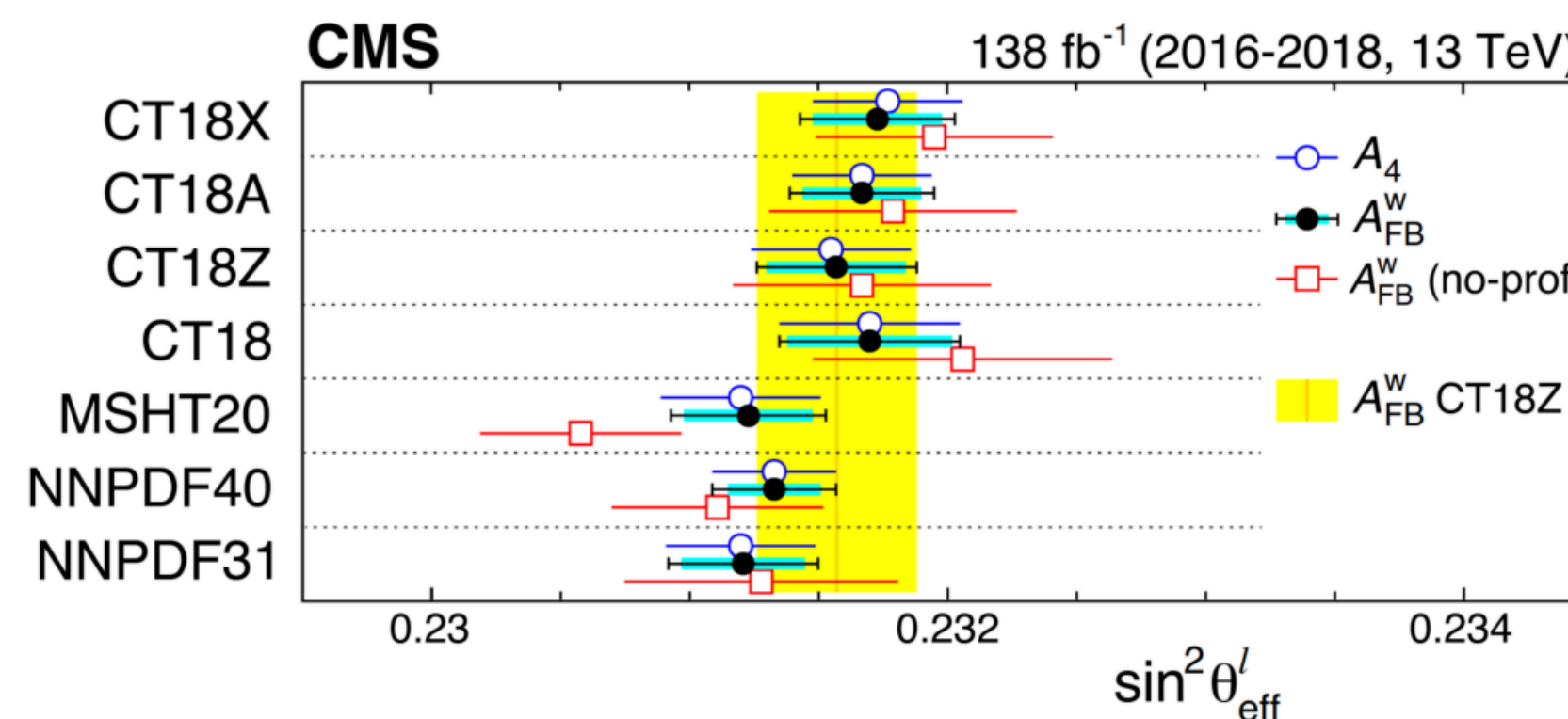
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Theoretical and **experimental uncertainties** are important for extracting mass results

- PDFs are a key challenge, with precision measurements showing strong PDF dependence
- Different QCD effects are relevant at different p_T^V regions and translate to p_T^μ spectrum
 - Fixed order, resummation, non-perturbative
- Angular coefficients provide a factorized description of W production and its theoretical uncertainties
- Muon momentum scale calibration
- Muon efficiency and etc.

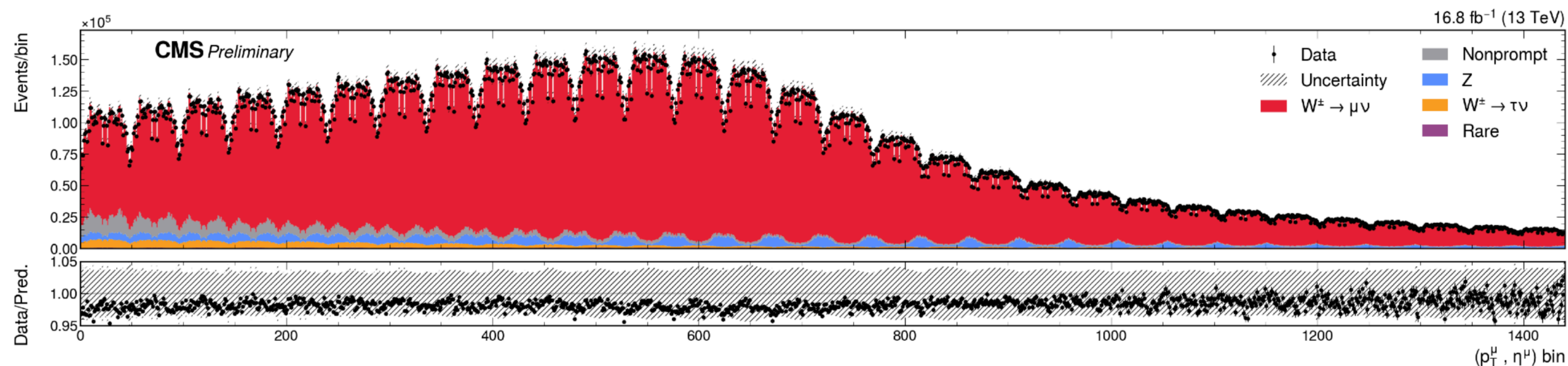
$$\underbrace{\frac{d\sigma}{dp_T^2 dm dy}}_{\text{W differential cross section}} = \underbrace{\frac{d\sigma}{dp_T^2 dm dy}}_{\text{Unpolarized cross section}} \underbrace{\left[(1 + \cos^2 \theta^*) + \sum_{i=0}^7 A_i(p_T, m, y) \right]}_{\text{Angular coefficients encode W polarization}} \underbrace{P_i(\cos \theta^*, \phi^*)}_{\text{Spherical harmonics encode W decay}}$$



W mass — Measurement strategy

m_W extracted from profile likelihood fit to 3D muon p_T - η -charge distribution (minimal sensitivity to PU)

- p_T binning chosen as a compromise between sensitivity and good statistical behaviour
- Thousands of bins and systematic variations optimized Tensorflow-based fitting framework



Enabling feature of the measurement: **Systematic variations** in W p_T , rapidity, decay angles from QCD uncertainties, PDFs, have a different effect on the muon kinematics as compared to a change in m_W PDF and boson p_T modeling uncertainties are strongly constrained in-situ by the data

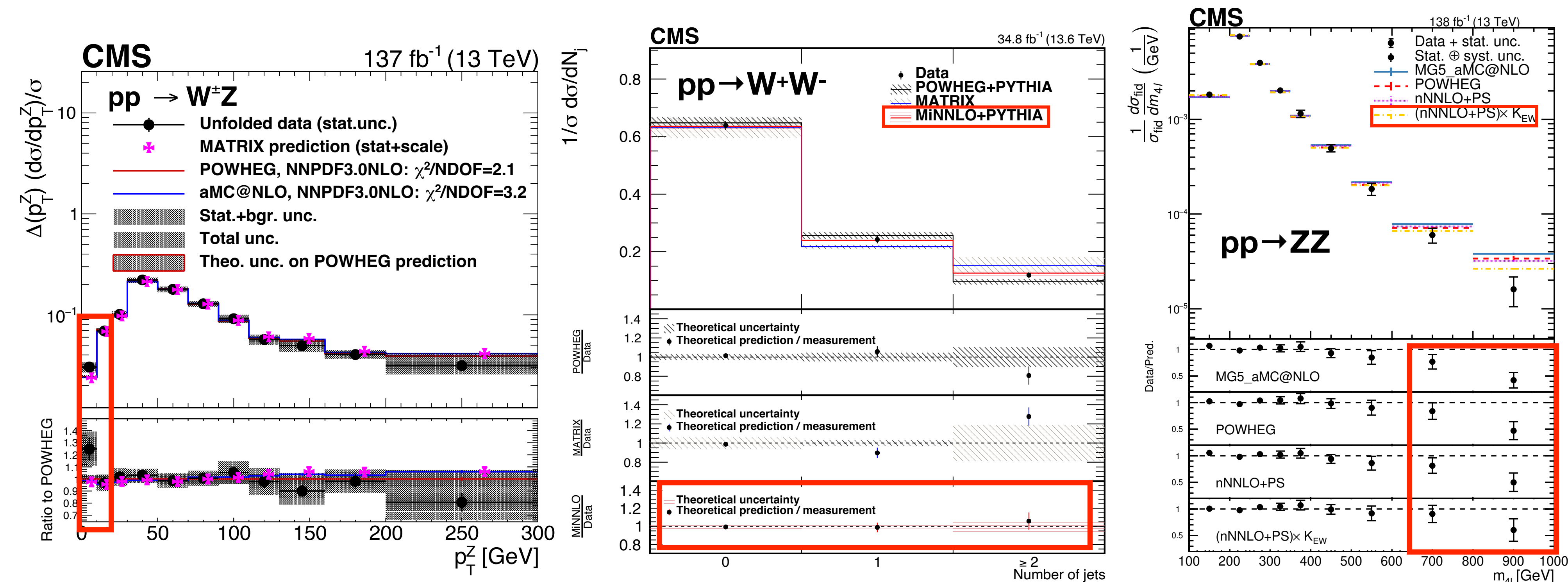
Thousand work are done here, details seen its publication

Diboson production - Results

Diboson production has been widely measured at the LHC by CMS and ATLAS over a wide range of center-of-mass energy up to 13.6 TeV

The **massive** diboson (WW, WZ, ZZ) has accurate predictions including higher-order corrections

- *provide stringent tests of the Standard Model*
- *serving as a precision benchmark for electroweak interactions and background modeling for rare processes*



- low p_T^V for WZ from soft and collinear QCD radiations not well described
- Differential jet multiplicity in WW is best described by Powheg MiNNLO v2+Pythia (NNLO in QCD)
- Discrepancies towards higher $m_{4\ell}$ in ZZ due to missing higher order EW corrections

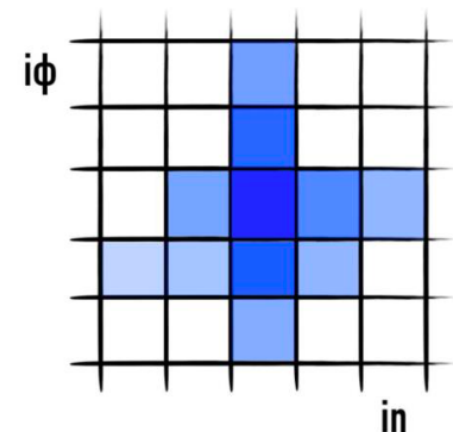
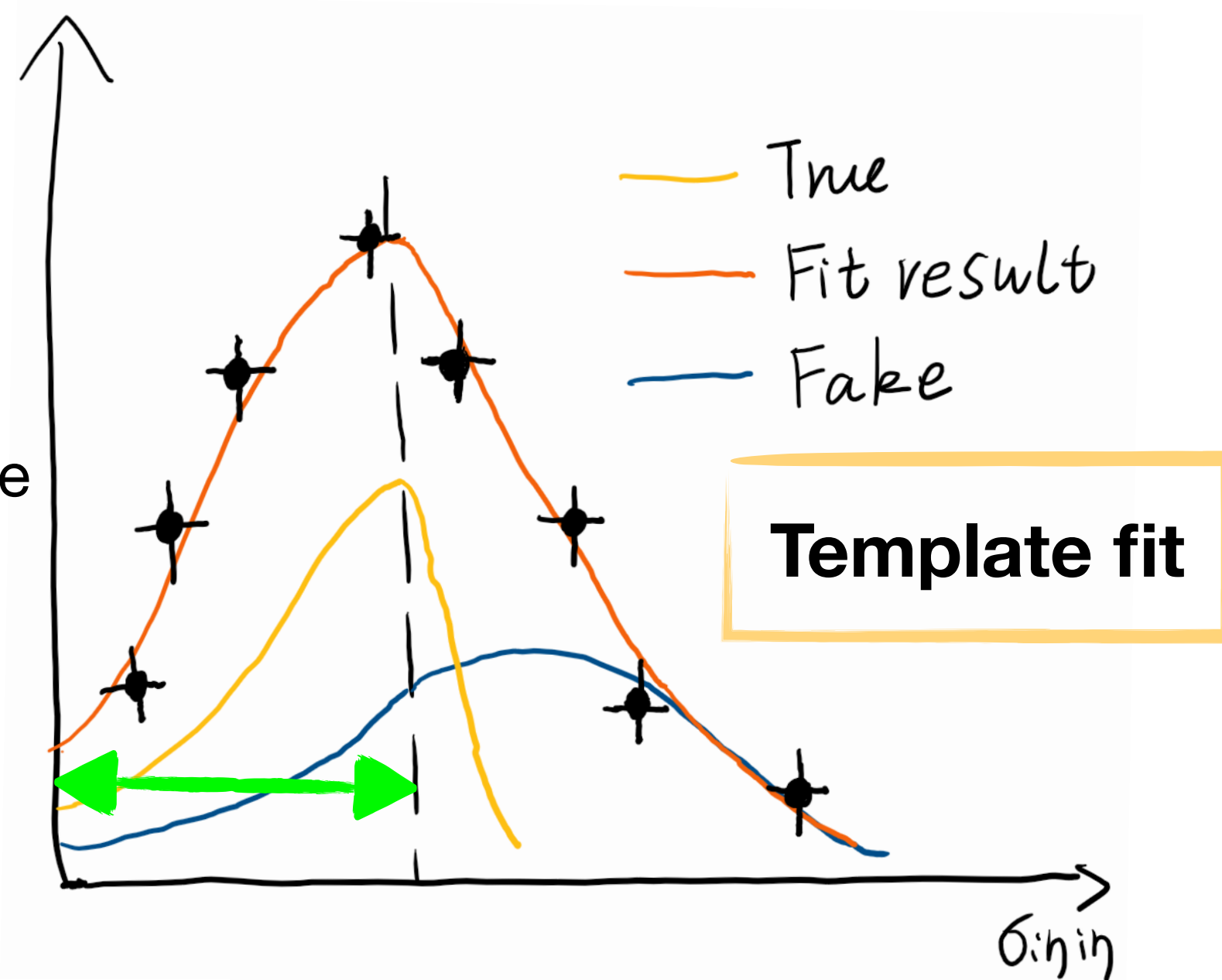
Nonprompt γ estimation — template fit

The main strategy of the nonprompt photon estimation is to build an **orthogonal region** to the SR **from data** with proper **weights** as functions of interesting variables applied

$$n_{fake-in-SR}^{predicted} = n_{tot} \times \underbrace{\epsilon_{fake-fraction}}_{\text{Numerator}} = \underbrace{N_{fake-in-CR}^{unweighted}}_{\text{Denominator}} \times \text{weights}$$

Fake photon enriched sample by **inverting the isolation variables** in the photon ID in data

The shape of the histograms as pdf



$$\sigma_{ii\eta\eta} = \sqrt{\frac{\sum_i^{5 \times 5} w_i (\eta_i - \bar{\eta}_{5 \times 5})^2}{\sum_i^{5 \times 5} w_i}}$$

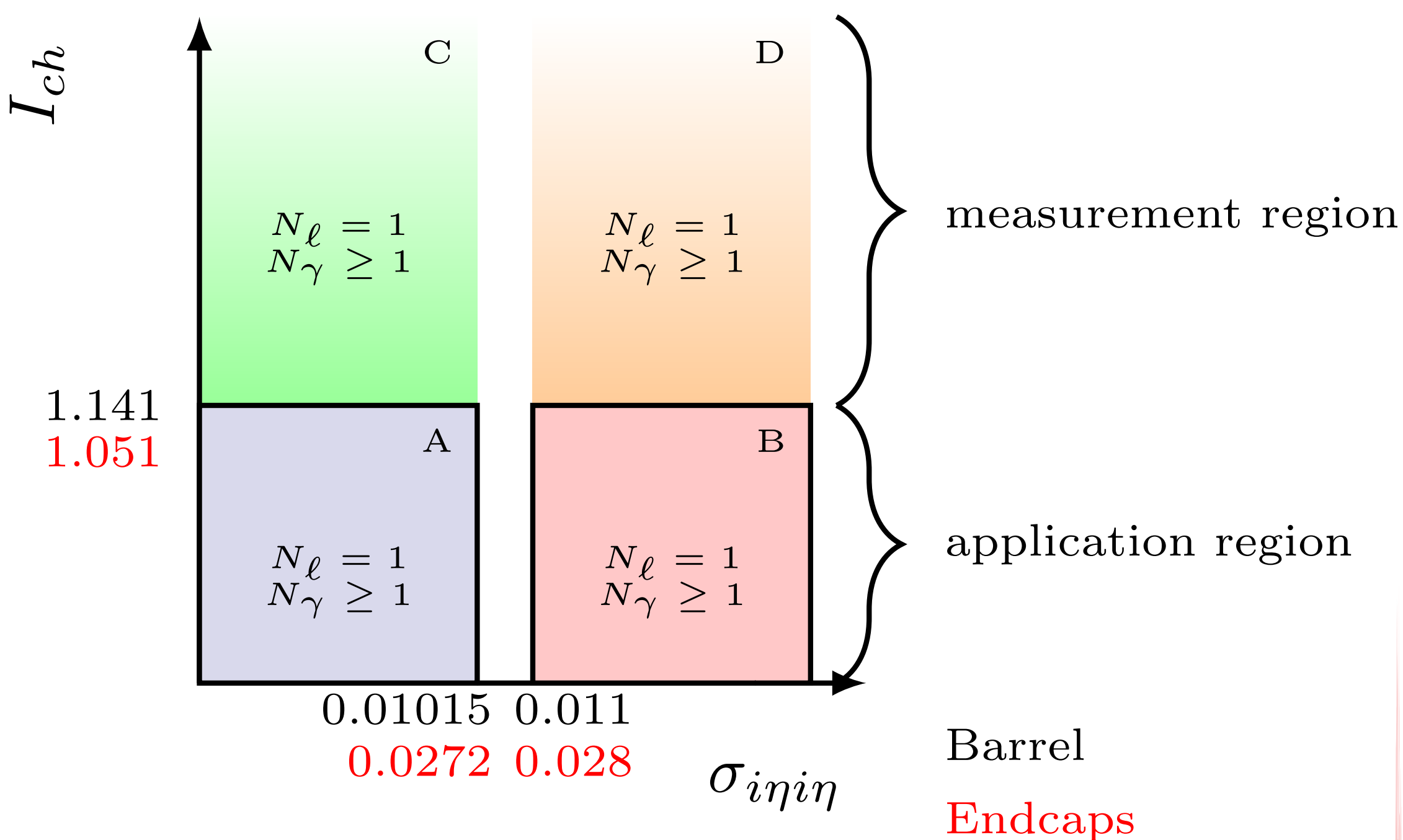
$w_i \neq 0$, if $E_i > 0.9\%$ of $E_{5 \times 5}$

Based on the dilepton+jets events

	Based on the dilepton+jets events
Data	Remove $\sigma_{ii\eta\eta}$ cut
True Template	Remove $\sigma_{ii\eta\eta}$ cut $\Delta R(\gamma^{\text{reco}}, \gamma^{\text{gen}}) < 0.3$ Get shape from simulation
Fake template	Remove $\sigma_{ii\eta\eta}$ cut Invert the charged isolation variable Get shape from data

Background estimation – Nonprompt γ

- Under the selection of exactly one lepton and at least one photon $N_\ell=1$, $N_\gamma \geq 1$
- The ABCD regions are built by varying the charge isolation and $\sigma_{i\eta i\eta}$
- Assuming the nonprompt photon performance in C and D is similar with in A and B, the nonprompt photon fake rate can be estimated and corrected by the following equations

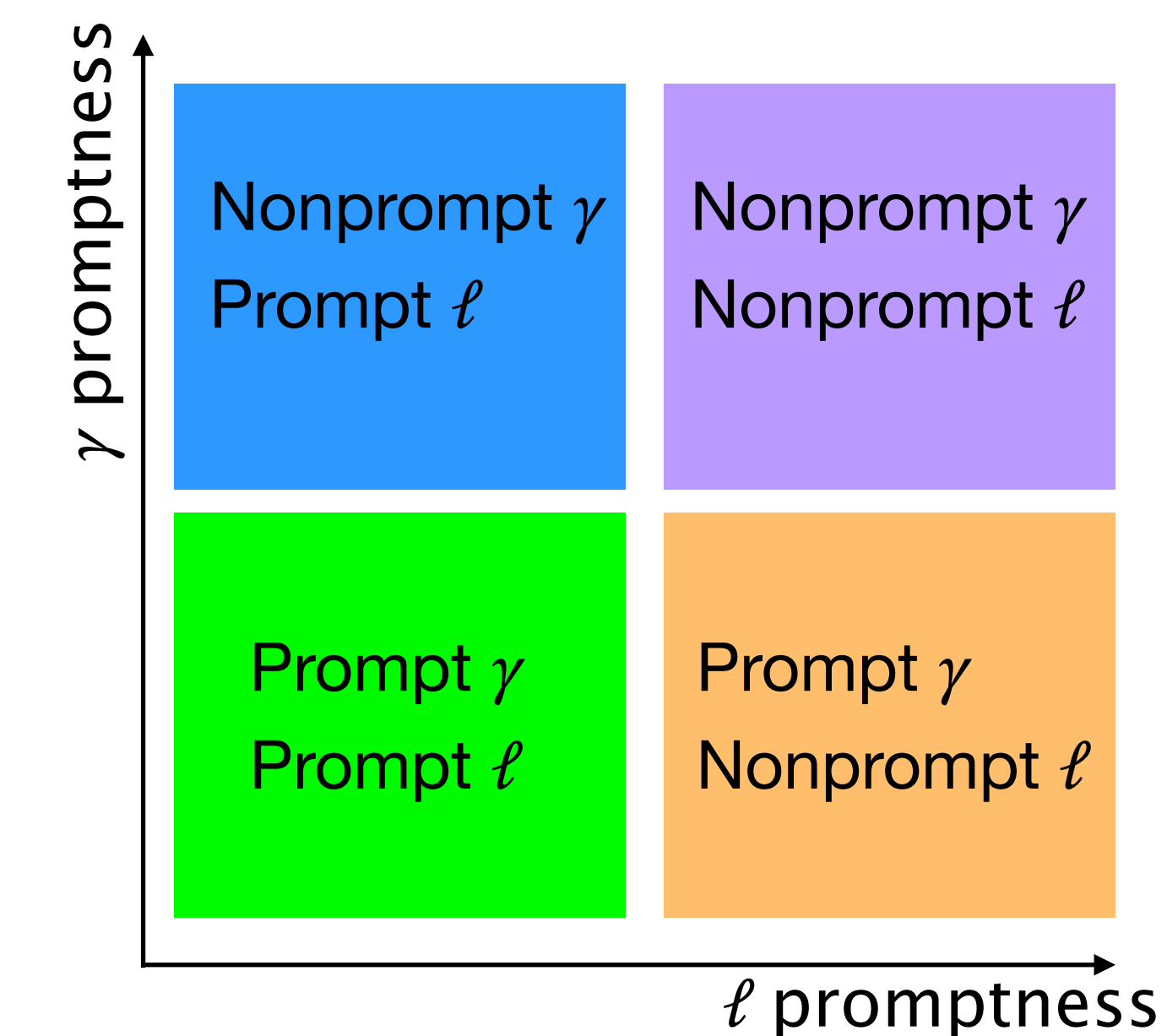


$$\text{fake rate}^{ij} = \frac{\text{Data}_C^{ij} - (\text{prompt} + \text{ele mis.}) \text{MC}_C^{ij}}{\text{Data}_D^{ij} - (\text{prompt} + \text{ele mis.}) \text{MC}_D^{ij}}$$

$$k_{\text{MC}}^{ij} = \frac{\text{nonprompt MC}_A^{ij}}{\text{nonprompt MC}_B^{ij}} \div \frac{\text{nonprompt MC}_C^{ij}}{\text{nonprompt MC}_D^{ij}}$$

$$\begin{aligned} \text{nonprompt contribution} = & \sum_{ij} (\text{data}_B^{ij} \times \text{fake rate}^{ij} \times k_{\text{MC}}^{ij}) \\ & - \sum_{ij} ((\text{prompt} + \text{ele mis.}) \text{MC}_B^{ij} \times \text{fake rate}^{ij} \times k_{\text{MC}}^{ij}) \end{aligned}$$

Double Nonprompt & ele misID



If we use these two data-driven samples simultaneously, the nonprompt ℓ/γ , and double nonprompt contributions are **double counted, especially important for single lepton channel**

- Double nonprompt fake rates: $w_{\gamma}^{\text{fake}} \times w_{\ell}^{\text{fake}}$

$$\begin{aligned}
 & (N_{\text{nonprompt}\gamma} - N_{\text{double nonprompt}}) \\
 & + (N_{\text{nonprompt}\ell} - N_{\text{double nonprompt}}) \\
 & + N_{\text{double nonprompt}}
 \end{aligned}$$

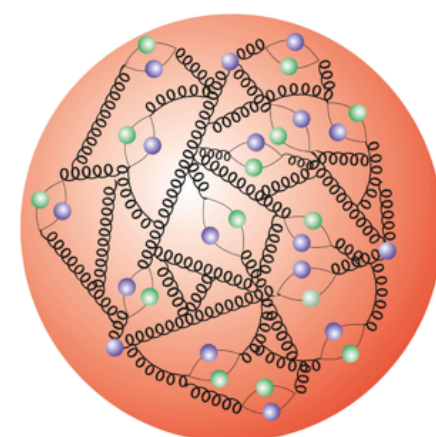
Systematics

Systematic uncertainty	Impact from inclusive fit [%]		Impact from differential fit [%]	
	$\mu_{t\gamma q}$	$\mu_{t\bar{t}\gamma\rightarrow 1\ell}$	$\sum_i \mu_{t\gamma q}^i$	$\sum_i \mu_{t\bar{t}\gamma\rightarrow 1\ell}^i$
MC statistical uncertainties	+4.2, −4.2	+2.5, −2.8	+4.8, −4.8	+2.6, −2.6
Theoretical uncertainties	+4.0, −3.9	+3.1, −2.9	+2.9, −2.8	+3.0, −2.8
Jet energy correction	+1.7, −1.9	+2.1, −2.1	+3.3, −3.2	+1.0, −1.2
N_{jet} modeling	+1.5, −2.0	+3.7, −3.9	+0.7, −0.5	+2.1, −1.9
b tagged and PU jet ID	+1.3, −1.3	+1.0, −1.0	+0.7, −0.7	+0.6, −0.7
misID normalization	+2.1, −2.1	+1.4, −1.6	+1.9, −2.1	+1.9, −1.9
Related to lepton and γ	+1.1, −1.2	+1.6, −1.4	+0.9, −0.8	+1.5, −1.4
Nonprompt bkg. estimate	+1.2, −1.4	+0.4, −0.6	+2.4, −2.5	+1.4, −1.4
Others	+2.0, −2.0	+0.1, −0.3	+1.3, −1.2	+0.2, −0.4
Integrated luminosity	+0.6, −0.9	+1.3, −1.1	+0.6, −0.5	+0.9, −0.8
Total systematic uncertainty	+6.7, −6.6	+5.5, −5.5	+6.3, −6.3	+4.8, −4.8

VBS $Z\gamma$ systematics and results

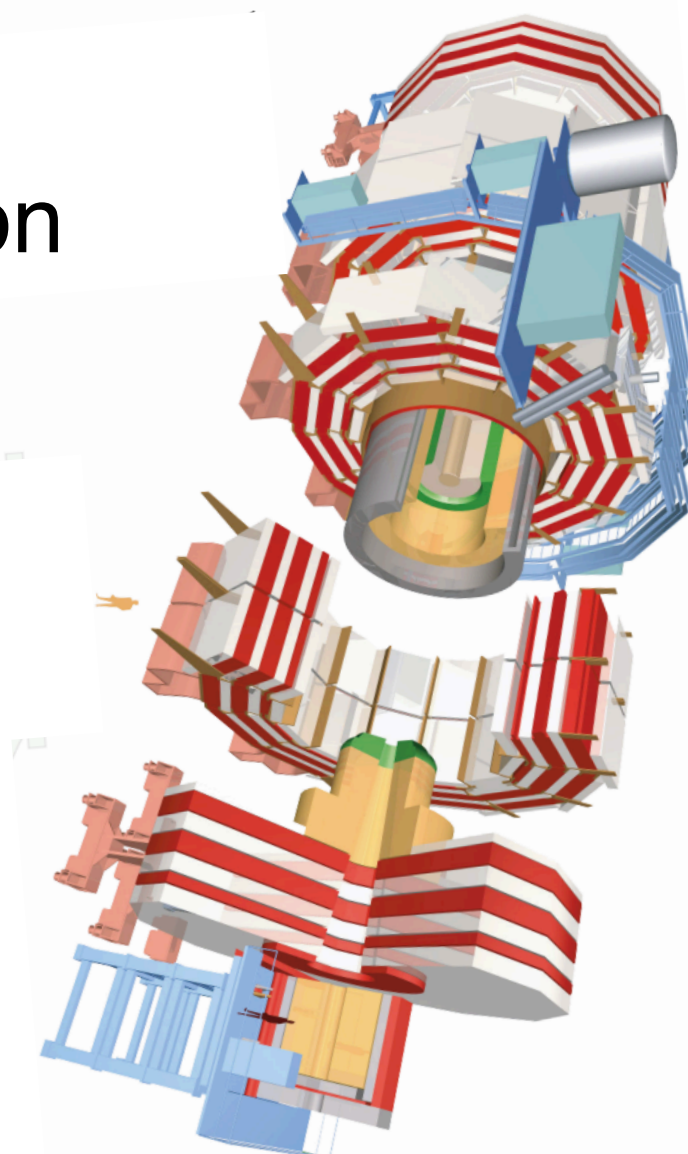
Theoretical uncertainties:

- PDF and α_s
- Factorization and renormalization scale
- Parton shower



Experimental uncertainties:

- Particle energy correction and identification efficiency
 - Jet and e/ γ energy correction
 - Lepton ID, isolation efficiency
 - Etc.
- Luminosity, pileup, L1 prefiring and etc.
- **Background modelling**
 - Nonprompt γ (ℓ) data-driven estimation

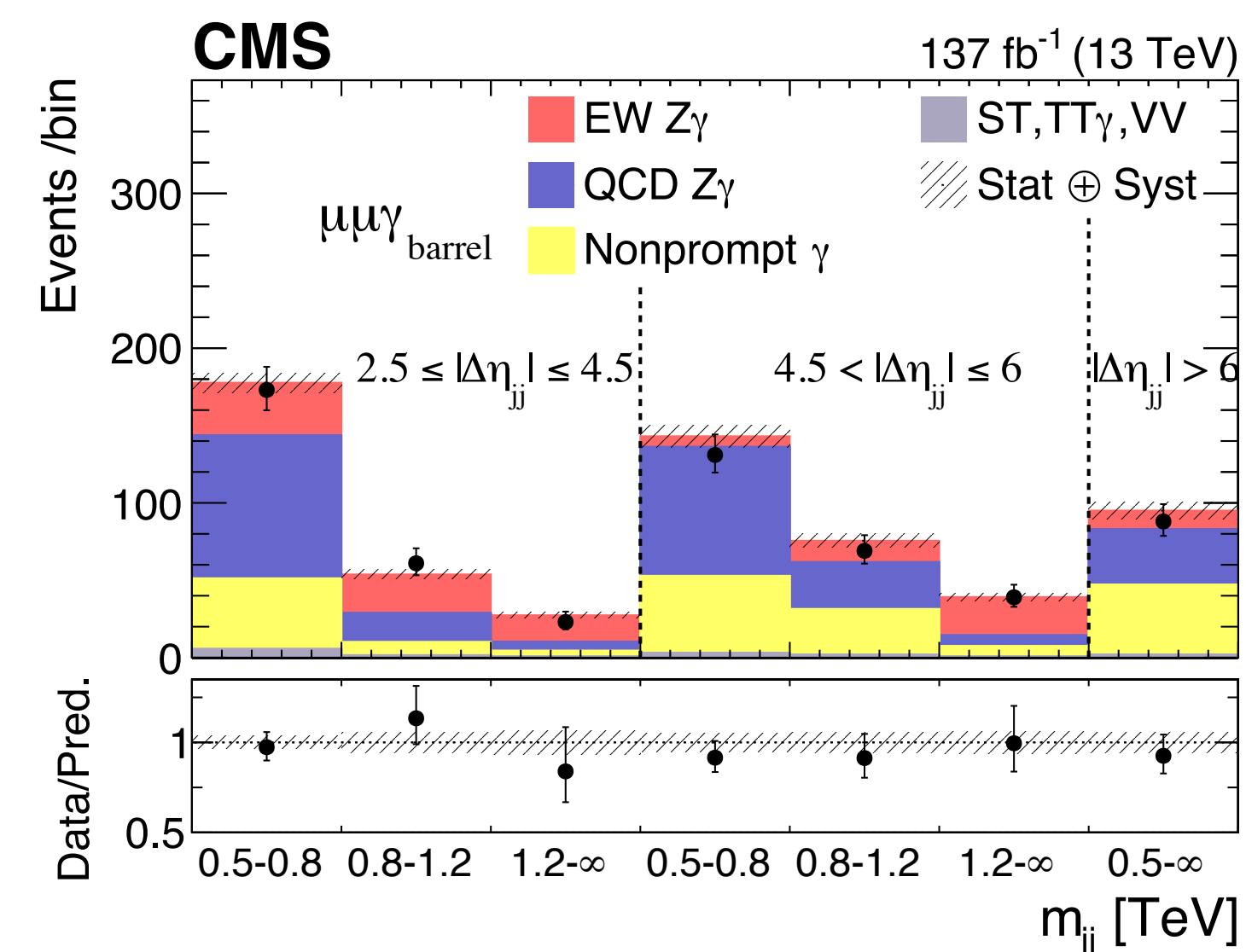


$$\sigma_{tot}^{pp \rightarrow X}(\mu_F, \mu_R) = \sum_{i,j} \int dx_1 dx_2 f_{i,p}(x_1, \mu_F) f_{j,p}(x_2, \mu_F) \hat{\sigma}_{ij}^{ij \rightarrow X}(x_1 x_2 S, \mu_F, \mu_R)$$

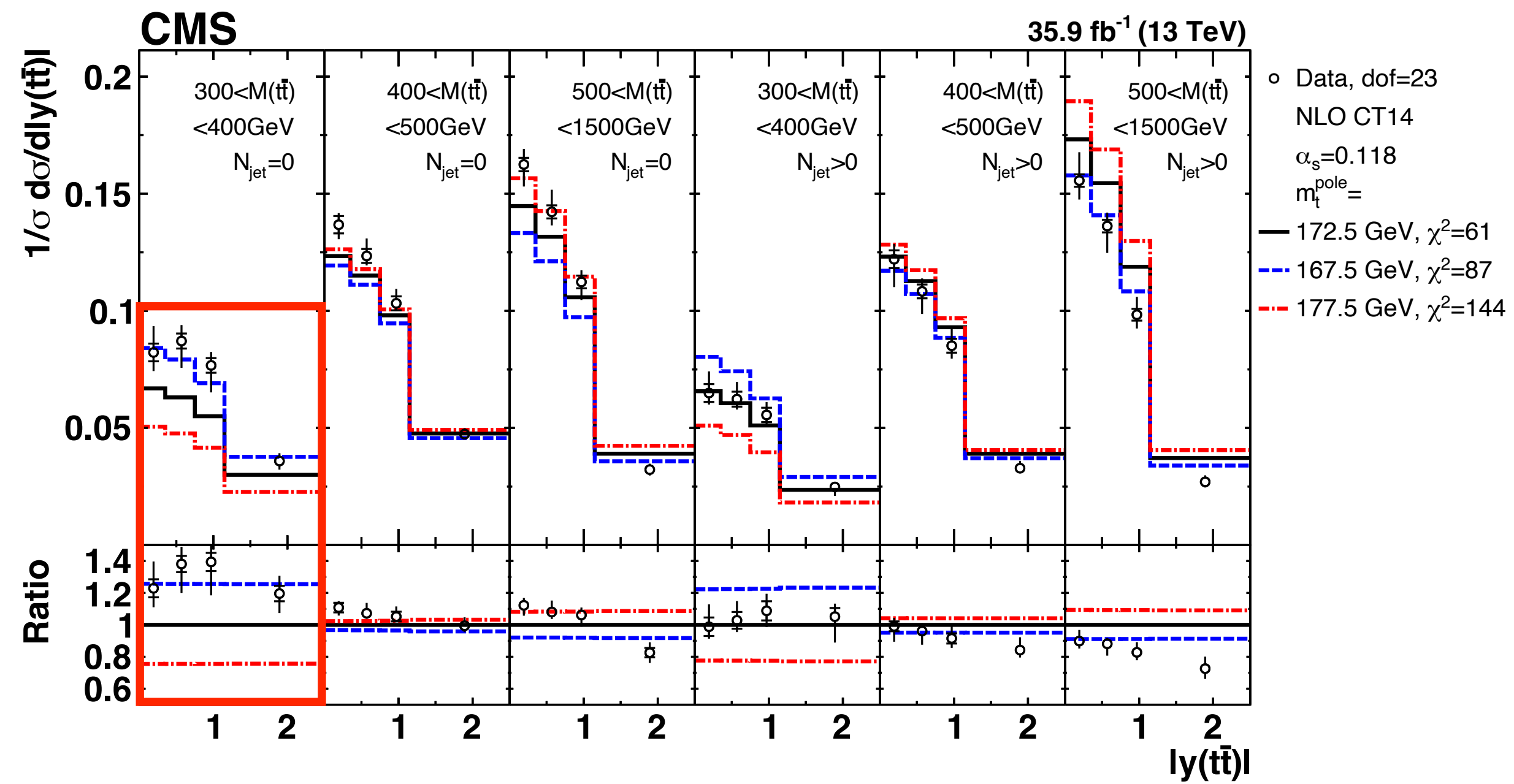
Gaussian constrained pdf

$$\mathcal{L}(\vec{\mu}; \vec{\theta}) = \prod_j^N \text{Poisson}(n_j | \mu \cdot s_j(\vec{\theta}) + b_j(\vec{\theta})) \cdot p(\vec{\theta} | \vec{\theta})$$

- N : the number of bins in the signal and control regions
- μ : the signal strength also called POI (parameter of interest)
- n_j : the number of observed events in data
- s_j : the expected event yields for the signal
- b_j : the expected event yields for the signal



Top Production at threshold

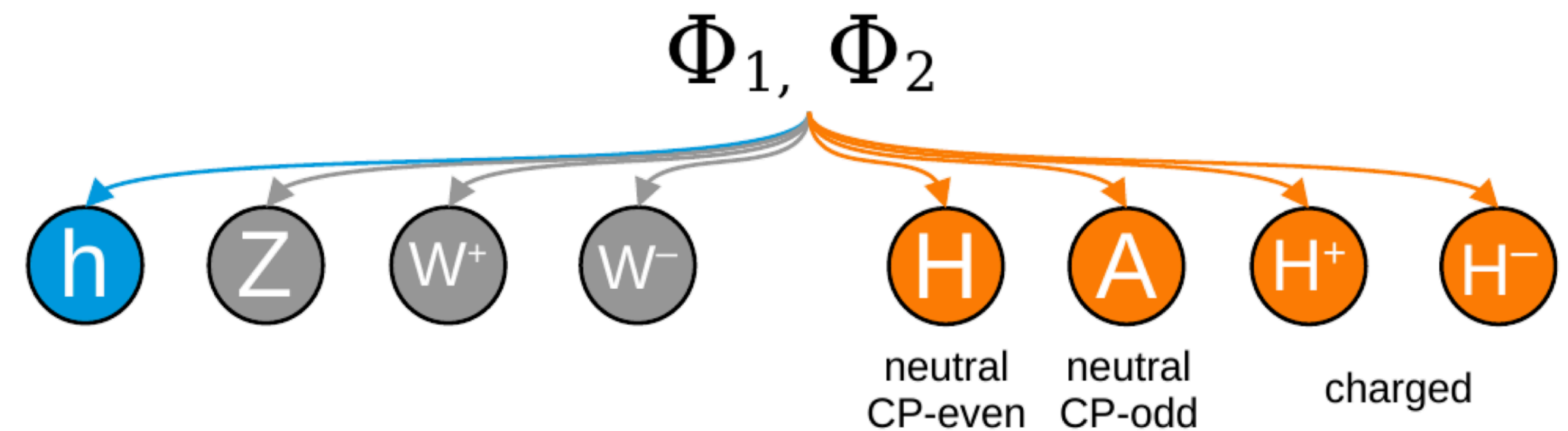


The excess of data is apparent in the low $m_{t\bar{t}}$ region!

Top Production at threshold

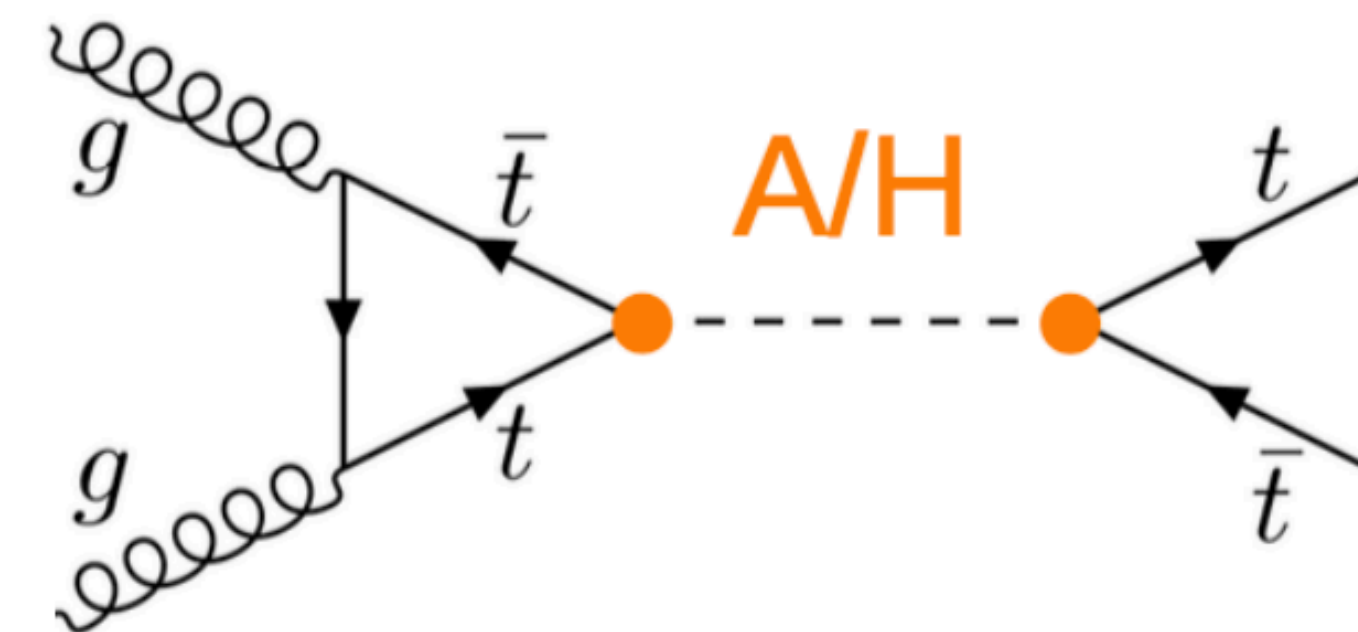
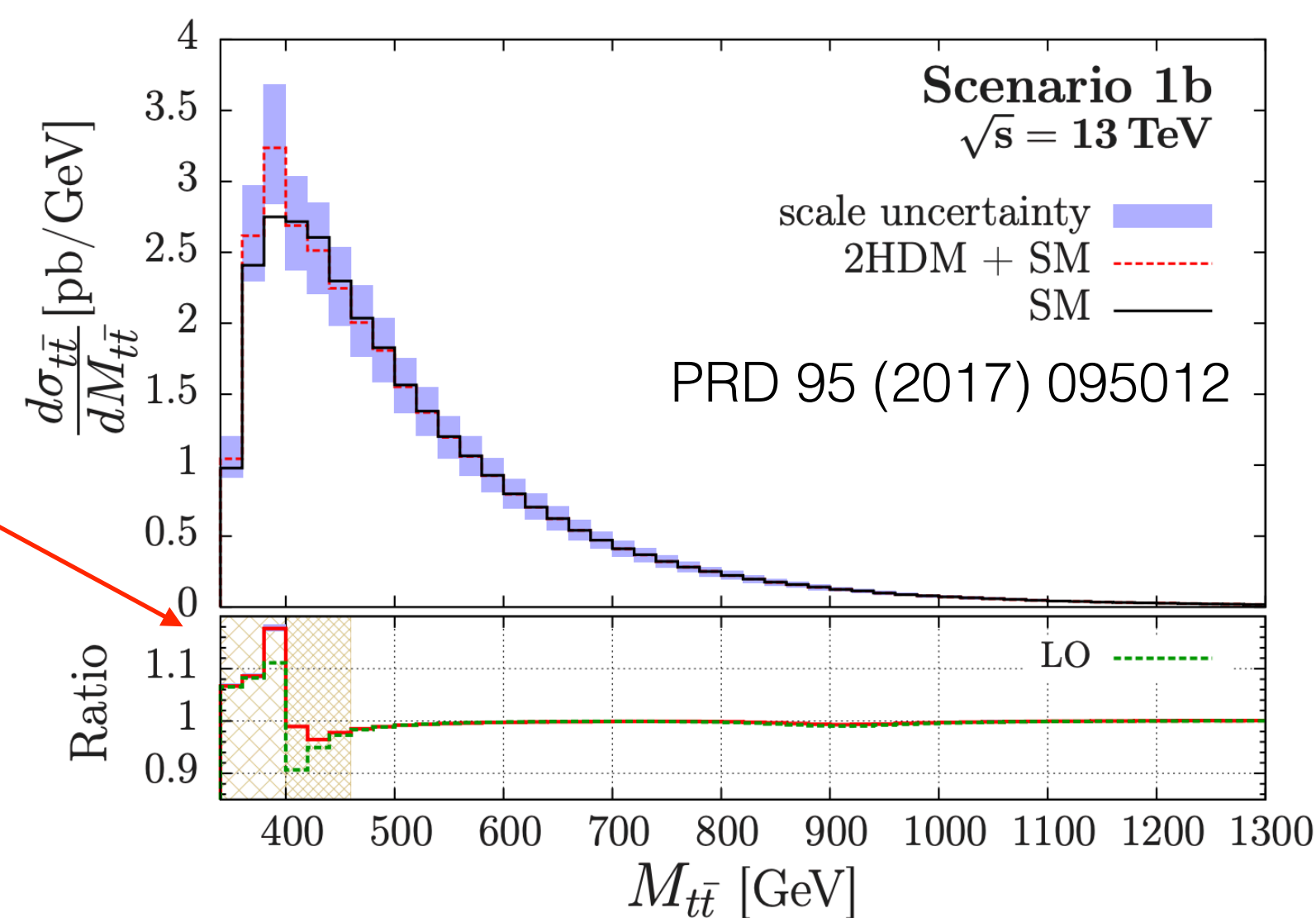
New physics?

Two Higgs Doublet Model (2HDM)



- simplest extended Higgs model
- if couplings are Yukawa-like: strongest couplings to top quarks
- $m_A, m_H > 2m_t$: decay to top quark pairs

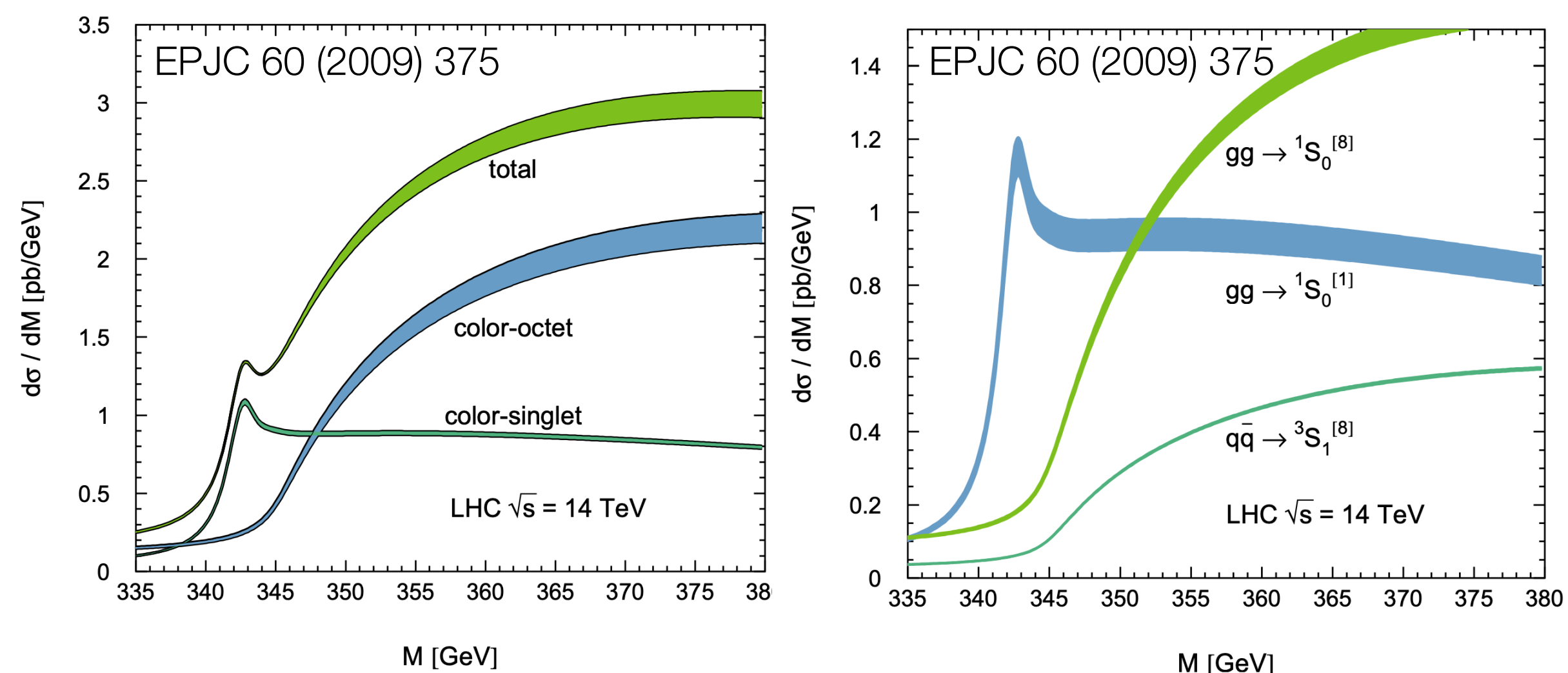
peak-dip structure



Top Production at threshold

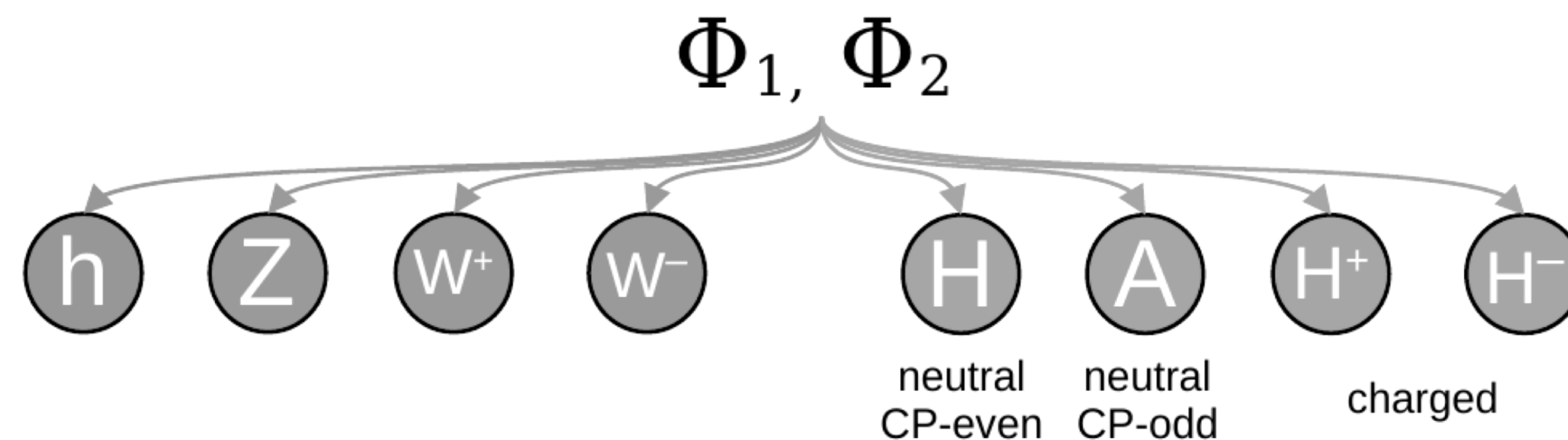
New unobserved SM phenomenon?

QCD predicts SM $t\bar{t}$ (quasi)bound states close to the $t\bar{t}$ threshold in **non-relativistic (NR) QCD** calculations (the prediction was made even before the top quark discovery)

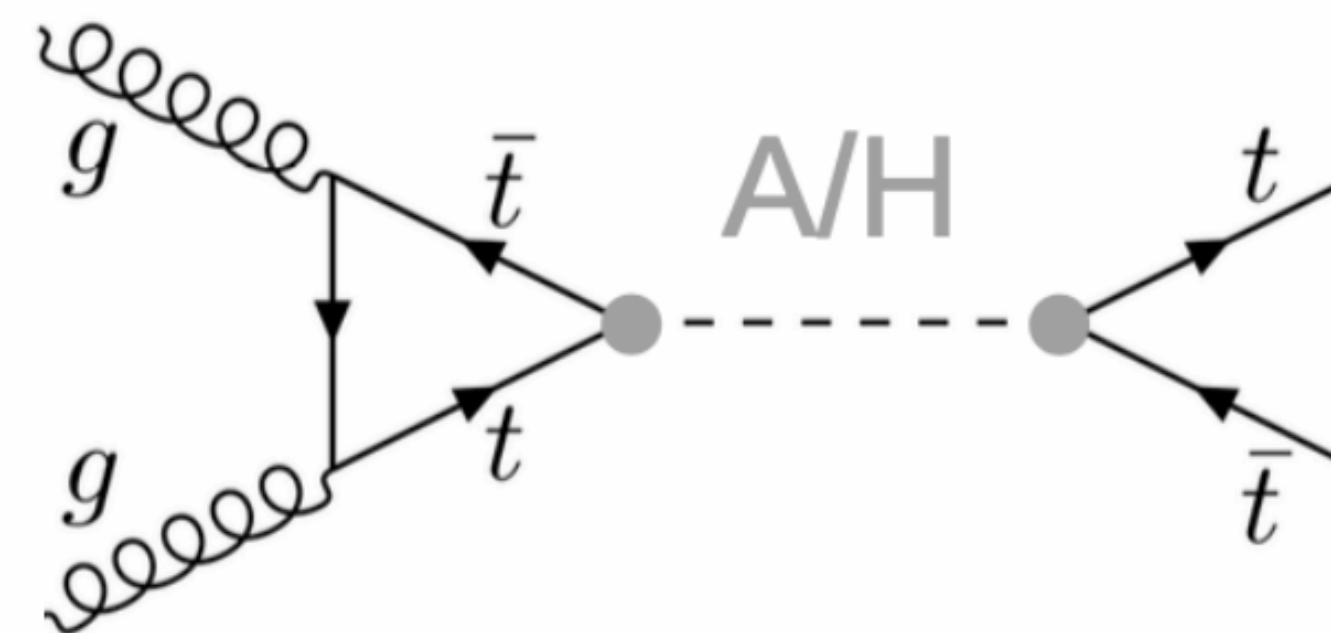


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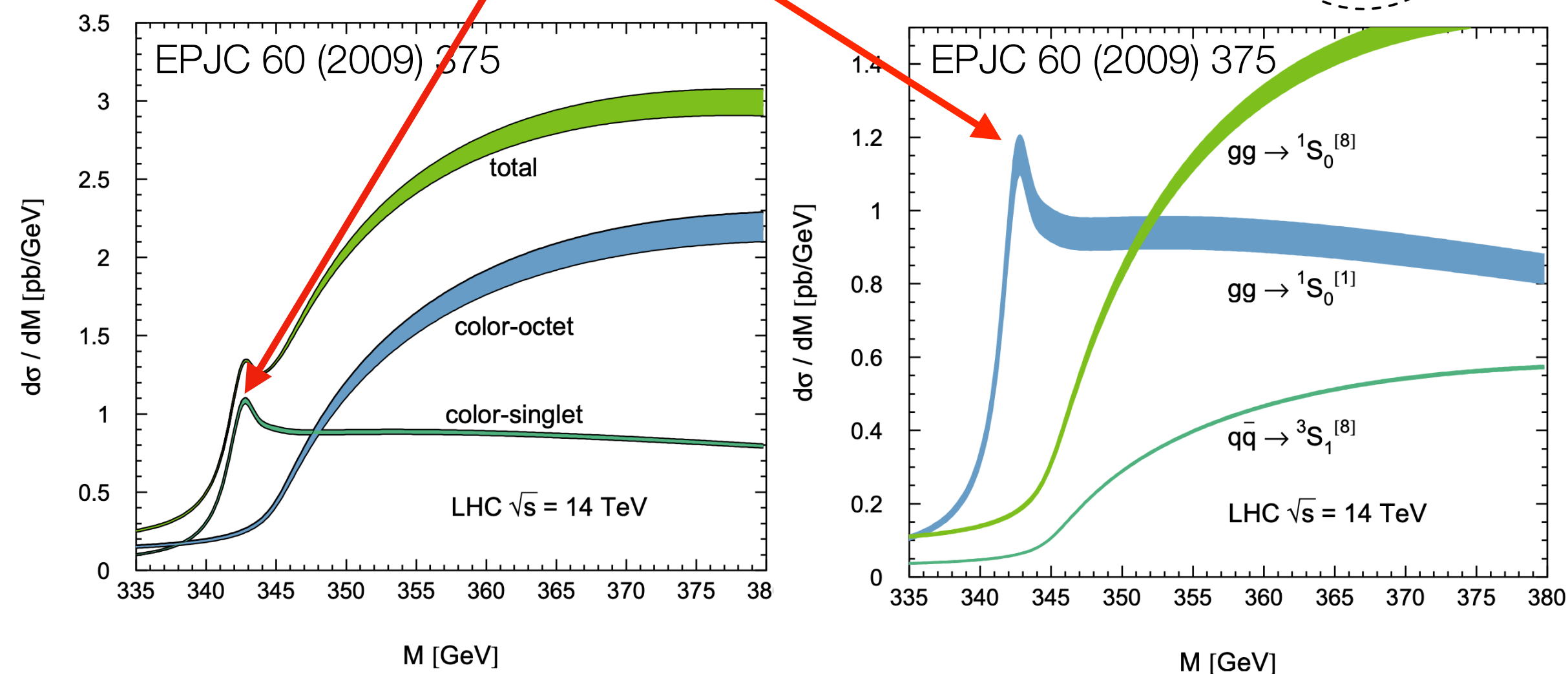
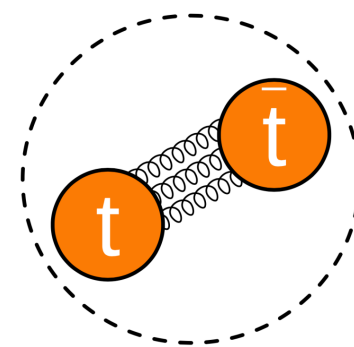


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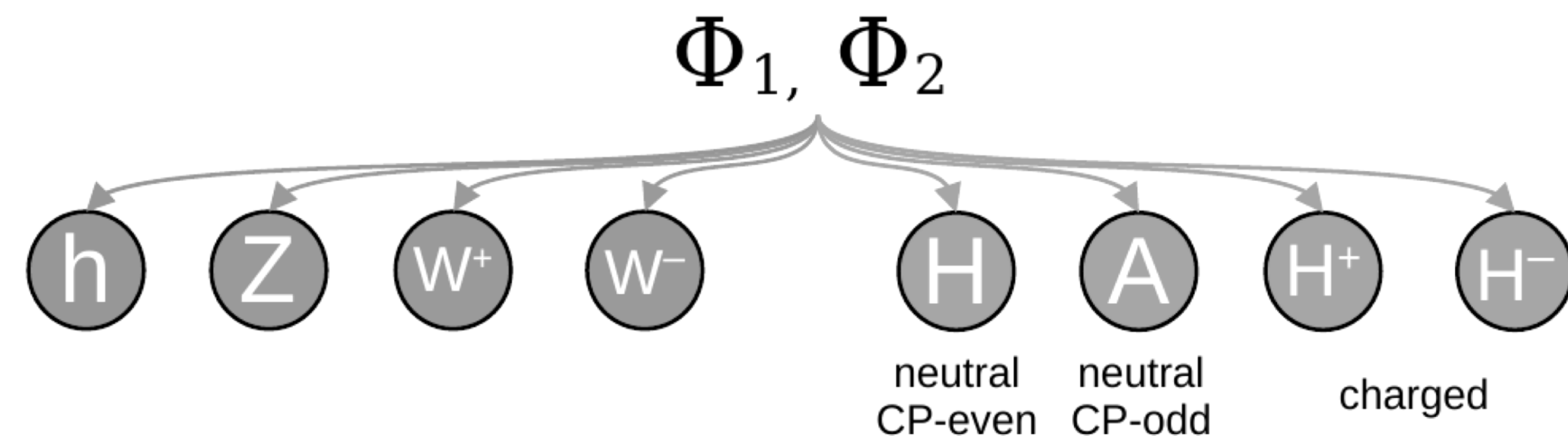
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- pseudoscalar color-singlet toponium η_t : $^1S_0[1]$ spin-0, CP-odd

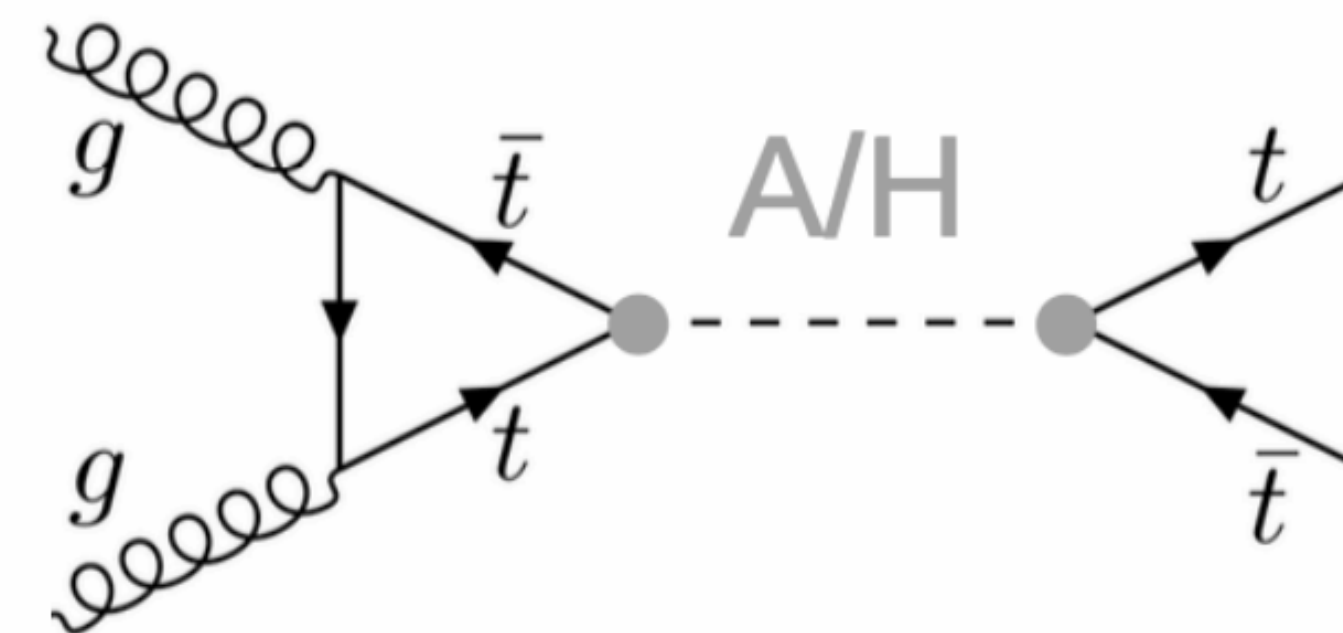


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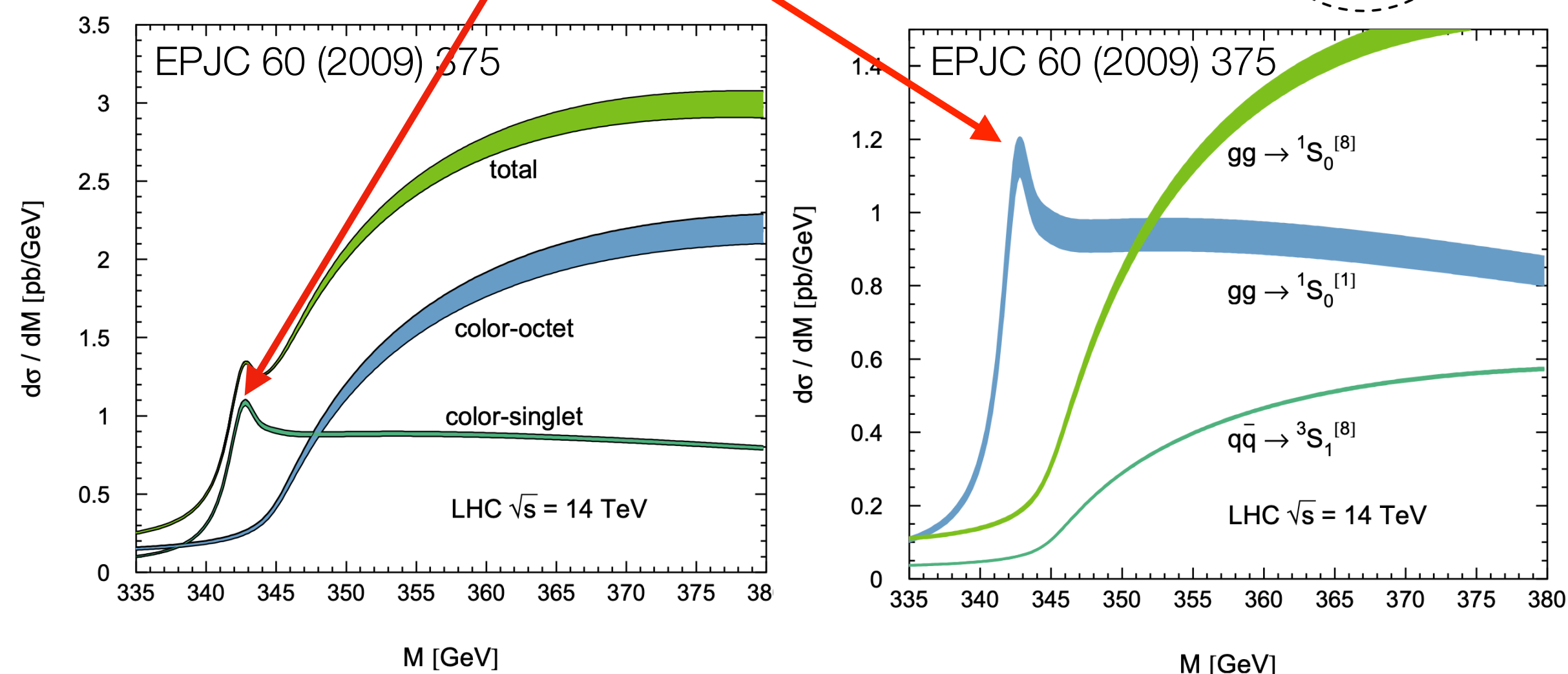
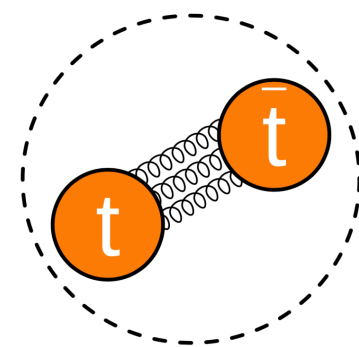


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Approximating $t\bar{t}$ bound states:

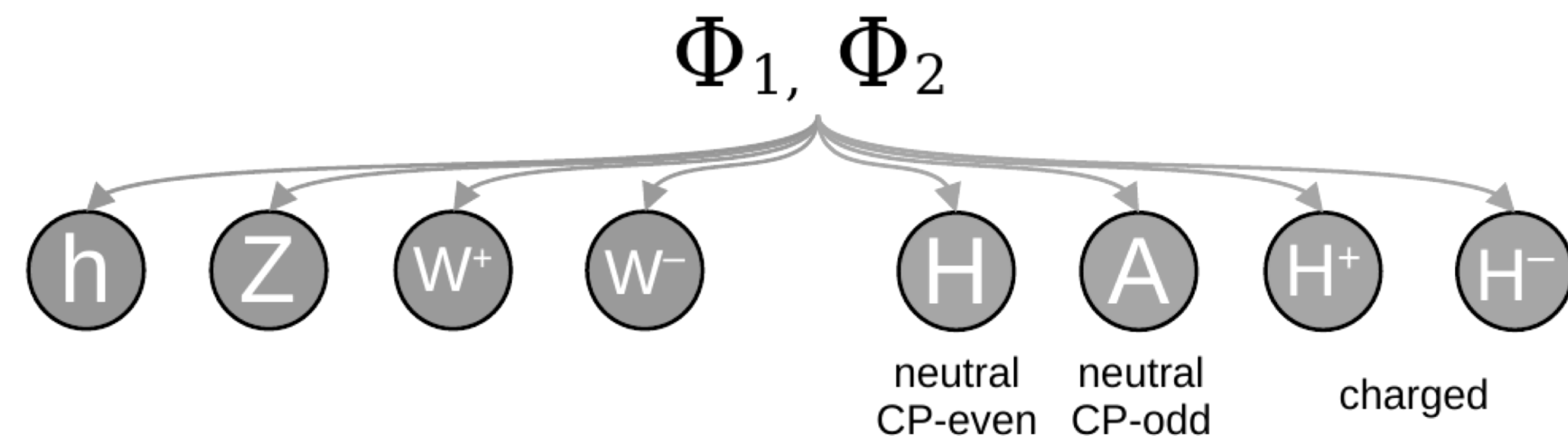
- simplified model *JHEP* 03 (2024) 099
- generic particle with direct couplings to gluons and tops, mass and width from fit to NRQCD

$$m(\eta_t) = 2m_t - 2 \text{ GeV} = 343 \text{ GeV}$$

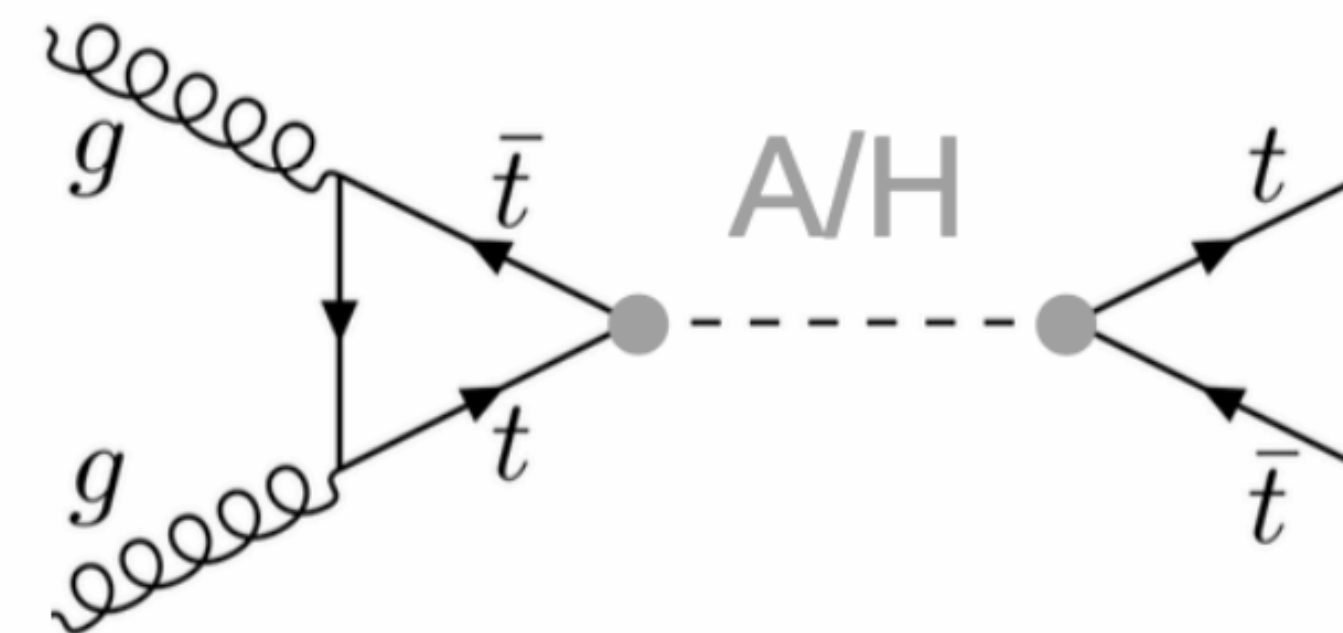
$$\Gamma(\eta_t) = 2\Gamma_t = 2.8 \text{ GeV}$$

New physics?

Two Higgs Doublet Model (2HDM)

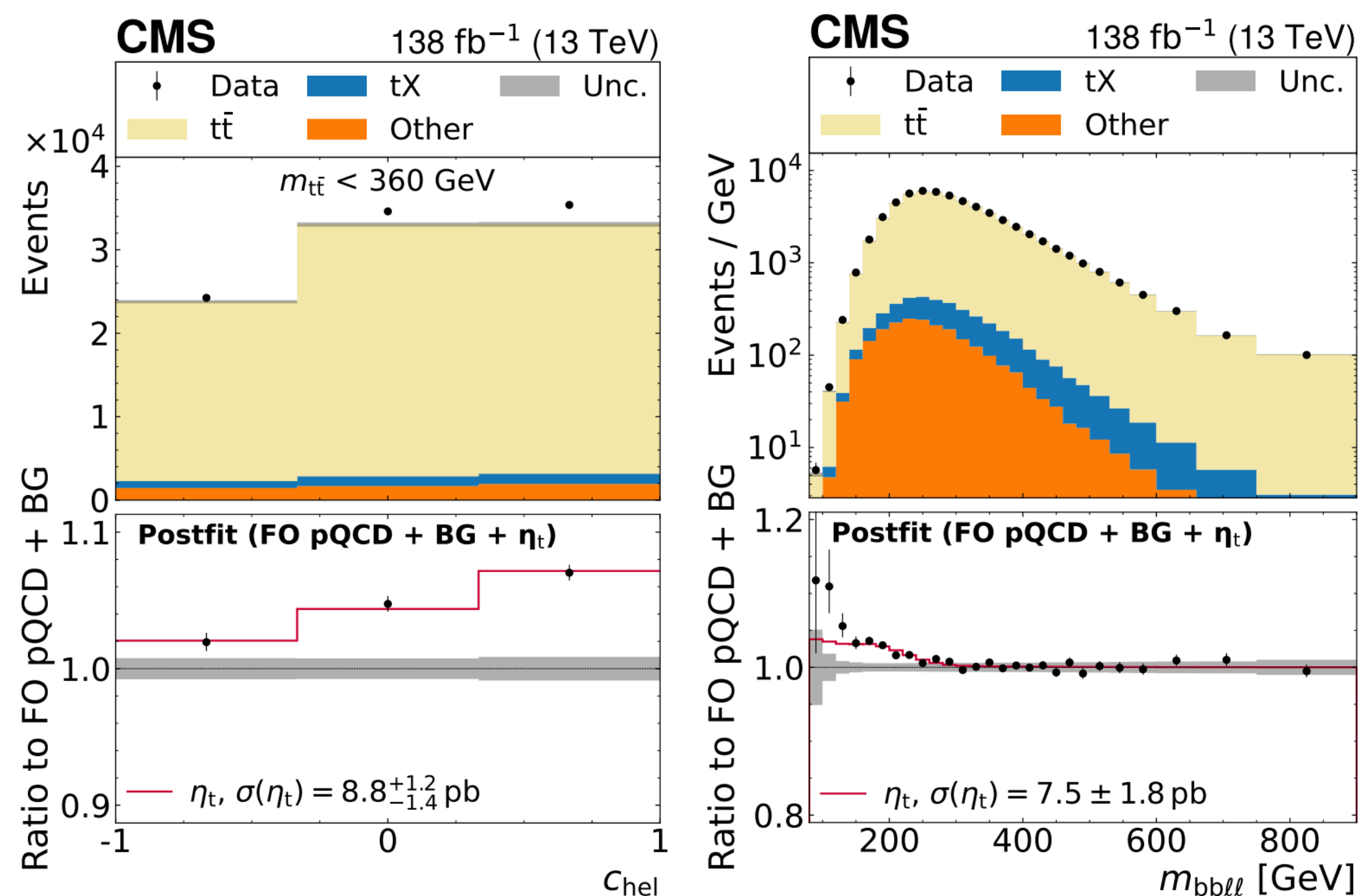


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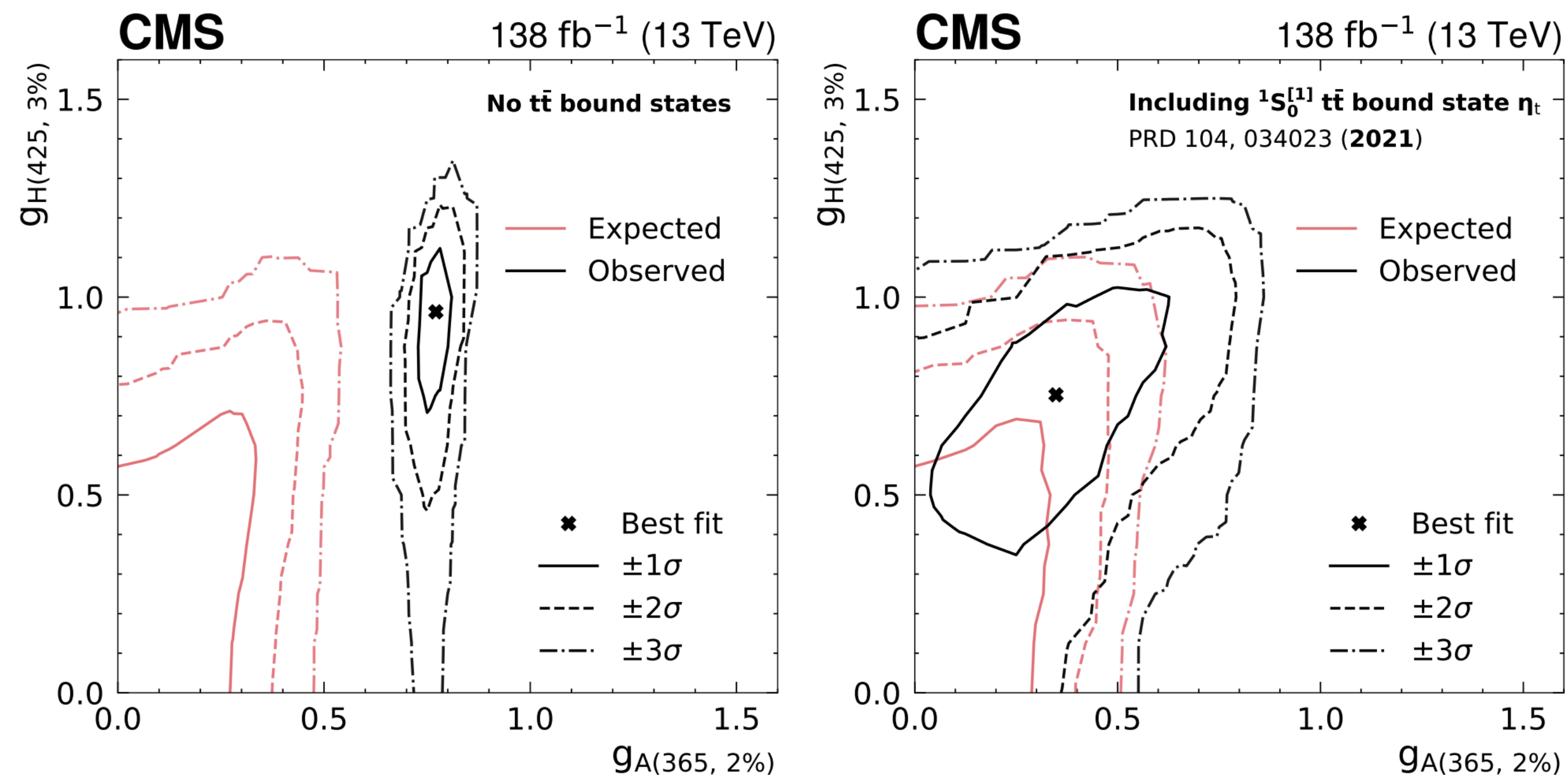
Top Production at threshold

New unobserved SM phenomenon



- An excess is observed ($>5\sigma$) with respect to the model of only non-resonant $t\bar{t}$ production from perturbative QCD
- Compatible with the formation of a $^1S_0[1]$ toponium quasi-bound state η_t
- Measured cross section of $\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}$ pb based on a simplified model inspired by NR QCD

New physics?



- Incorporating quasi-bound state η_t , eliminating the need for additional exotic pseudoscalar or scalar boson
- Exclusion limits at the 95% CL are set on the coupling strength between top quarks and new bosons, covering mass ranges of 365–1000 GeV
 - Coupling values as low as 0.4 (0.6) are excluded for the pseudoscalar (scalar) case