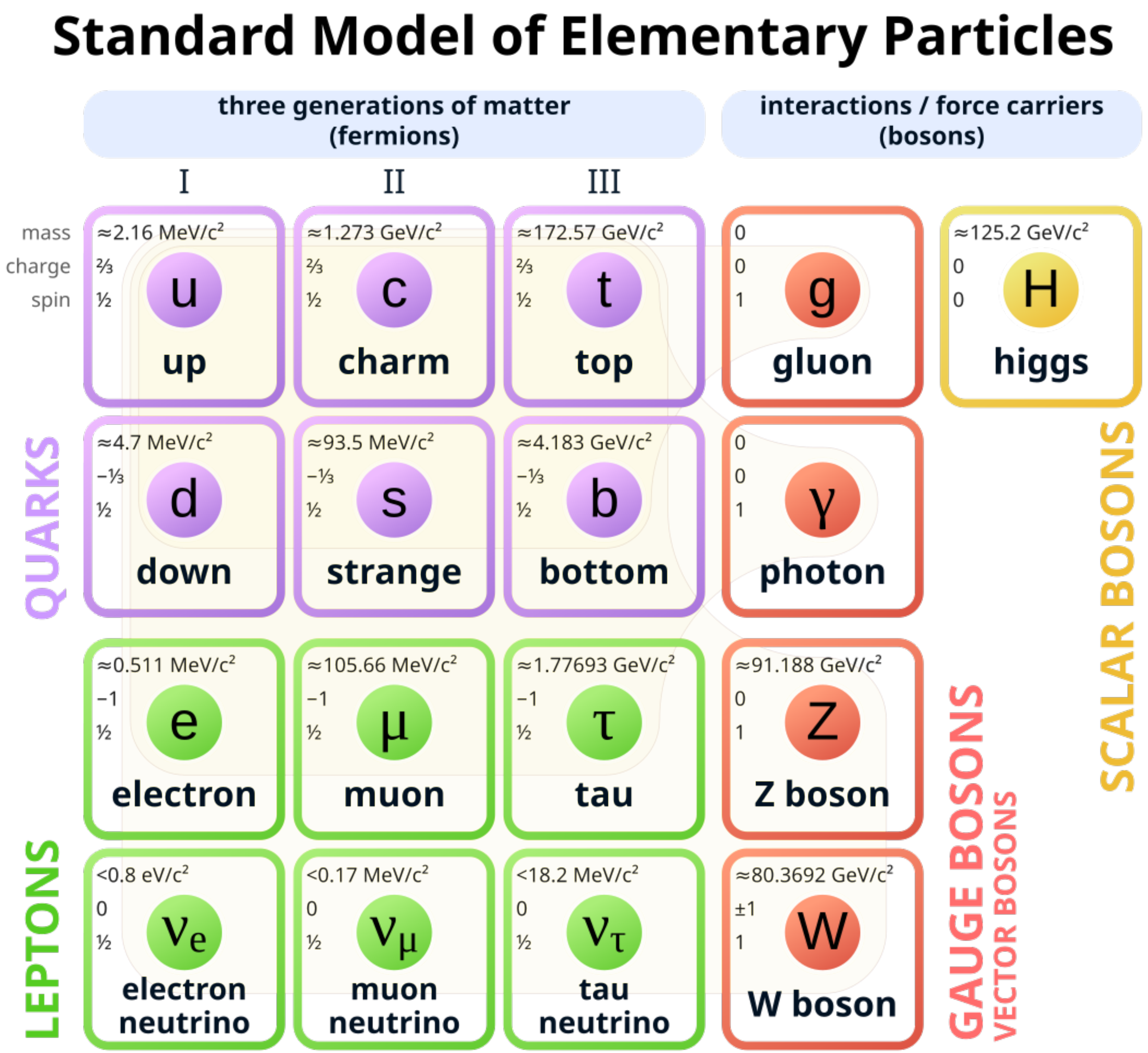
Recent Standard Model Measurements at the CMS experiment

报告人：安莹 (AN Ying)

时间：23/04/2026

Standard Model



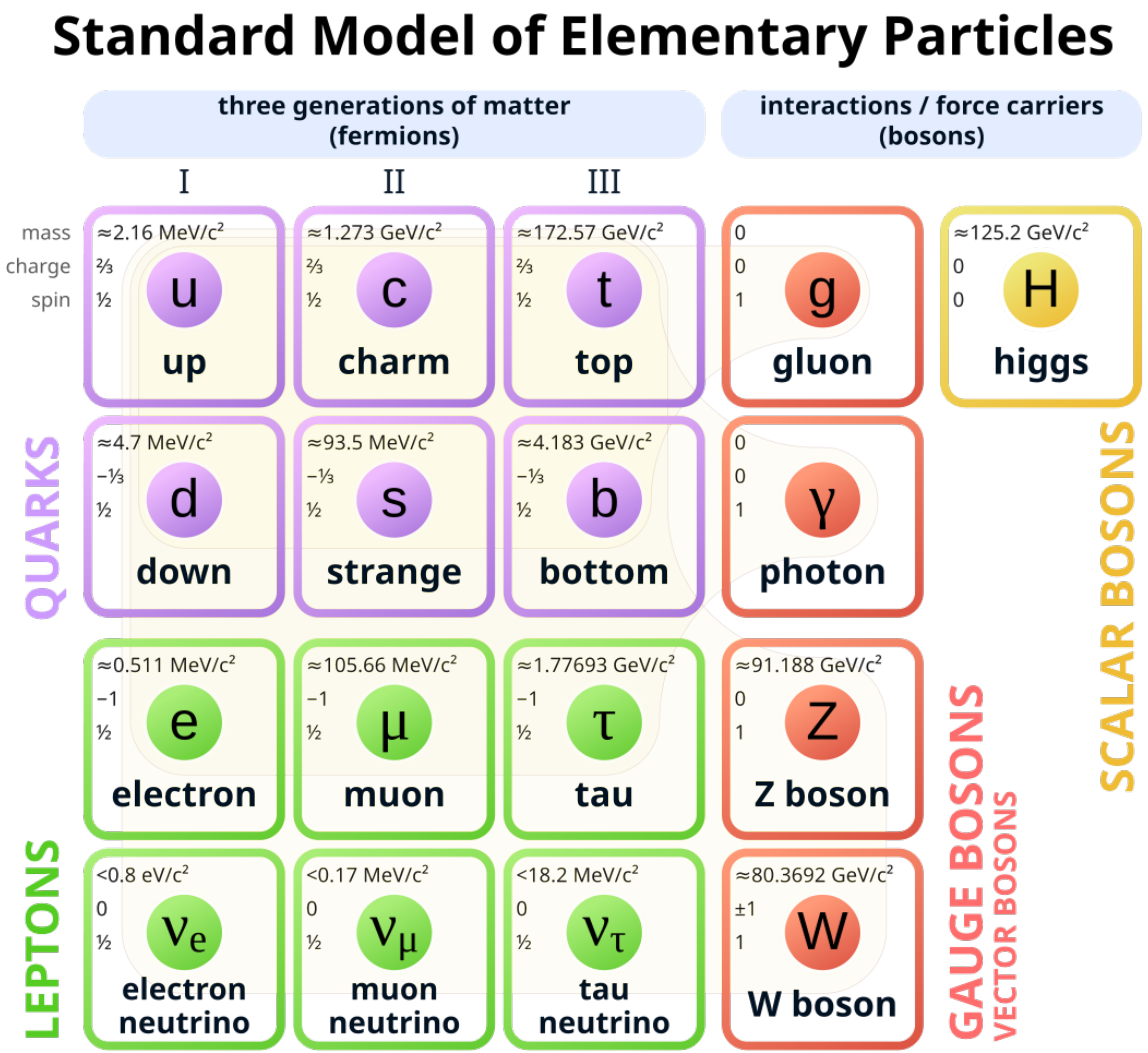
Quantum field theory based on gauge group:

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

It's widely successful:

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

Standard Model



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Leaves open questions:

limited precision agreement at high energy

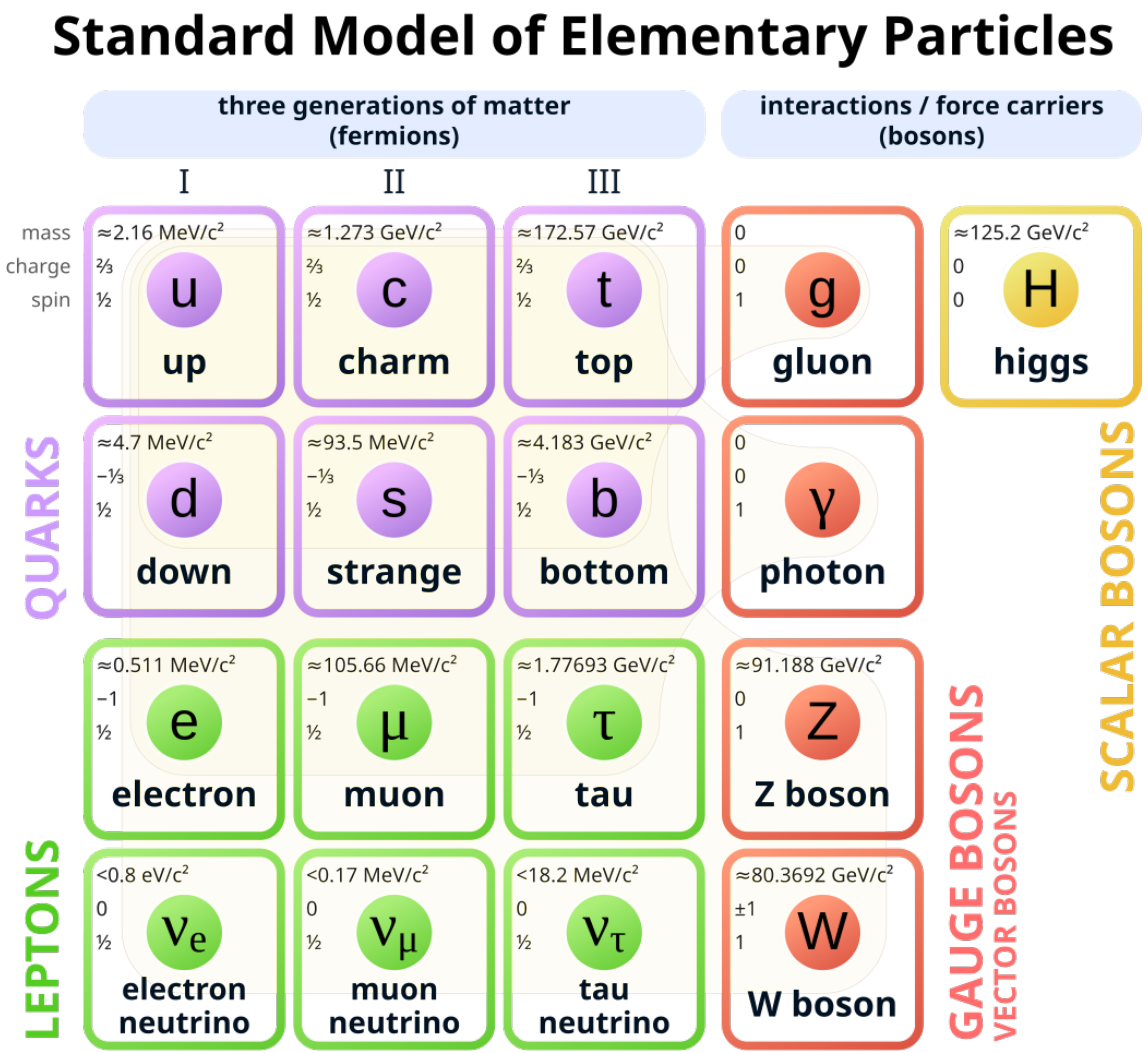
nature of dark matter

origin of neutrino masses

matter-antimatter asymmetry

…

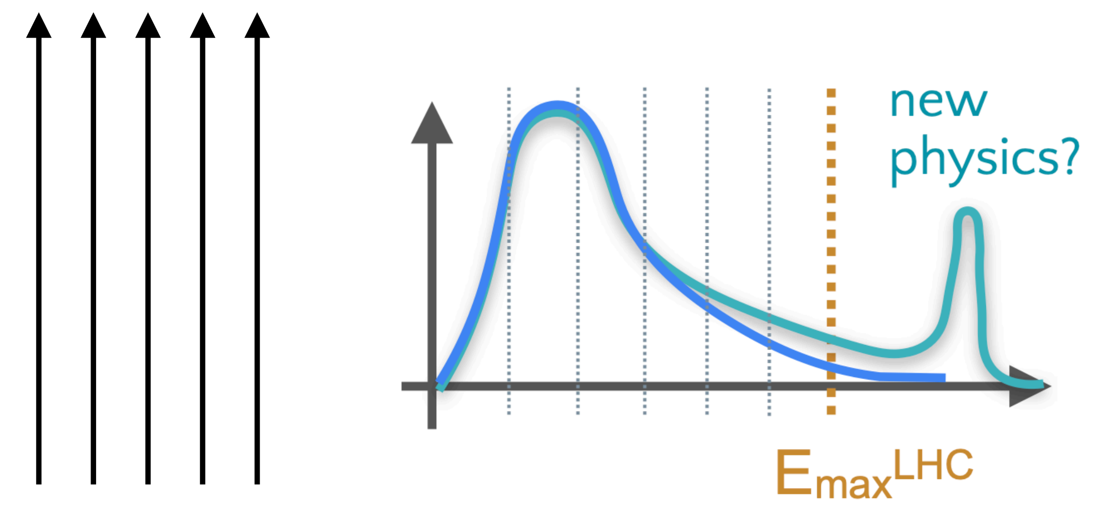
Standard Model



Look for new physics to answer open questions:

- Direct searches → new particles/decay
- Precision tests of the SM

  look for deviations from predictions



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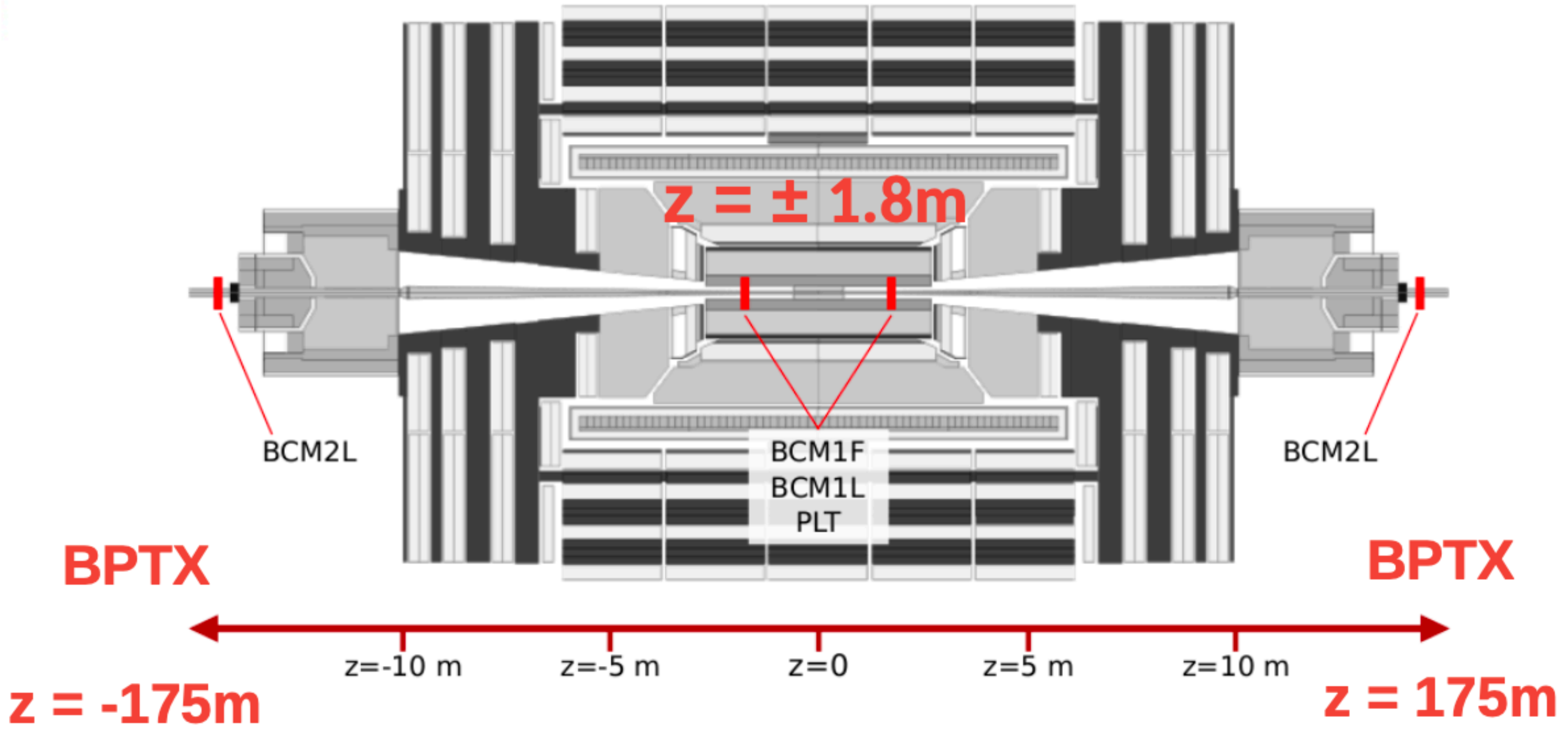
LHC — Luminosity

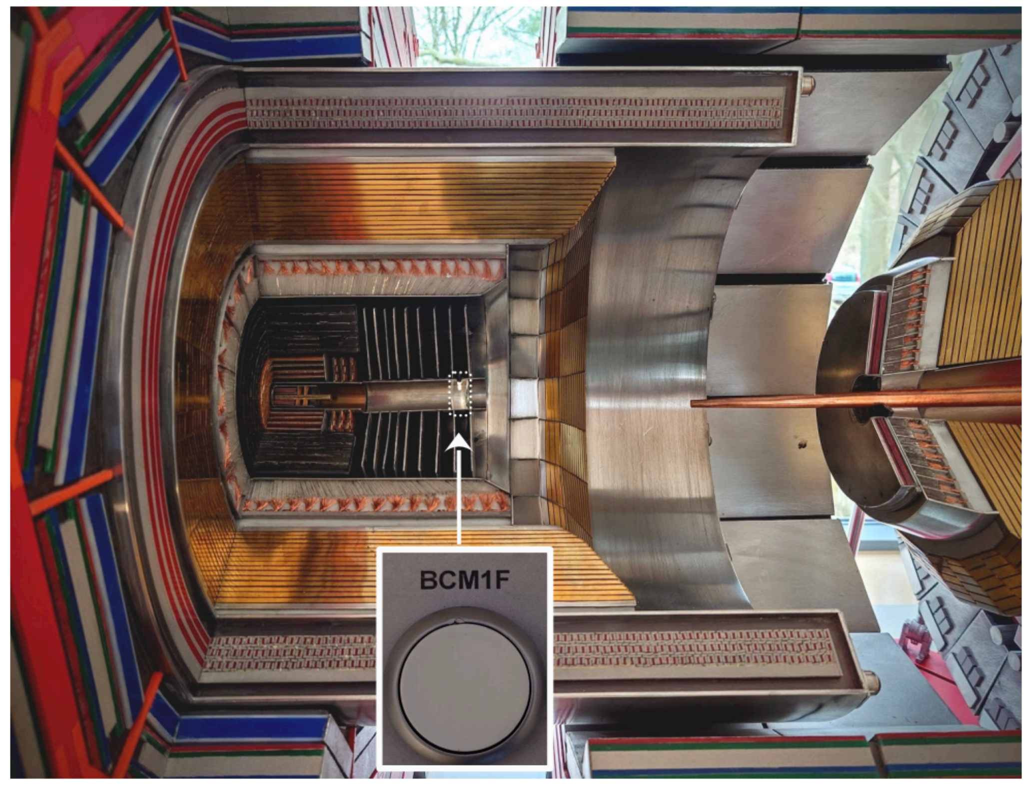
Integrated luminosity is the integral of instantaneous luminosity measured by the **B**eam **R**adiation **I**nstrumentation **L**uminosity system insides the tracker

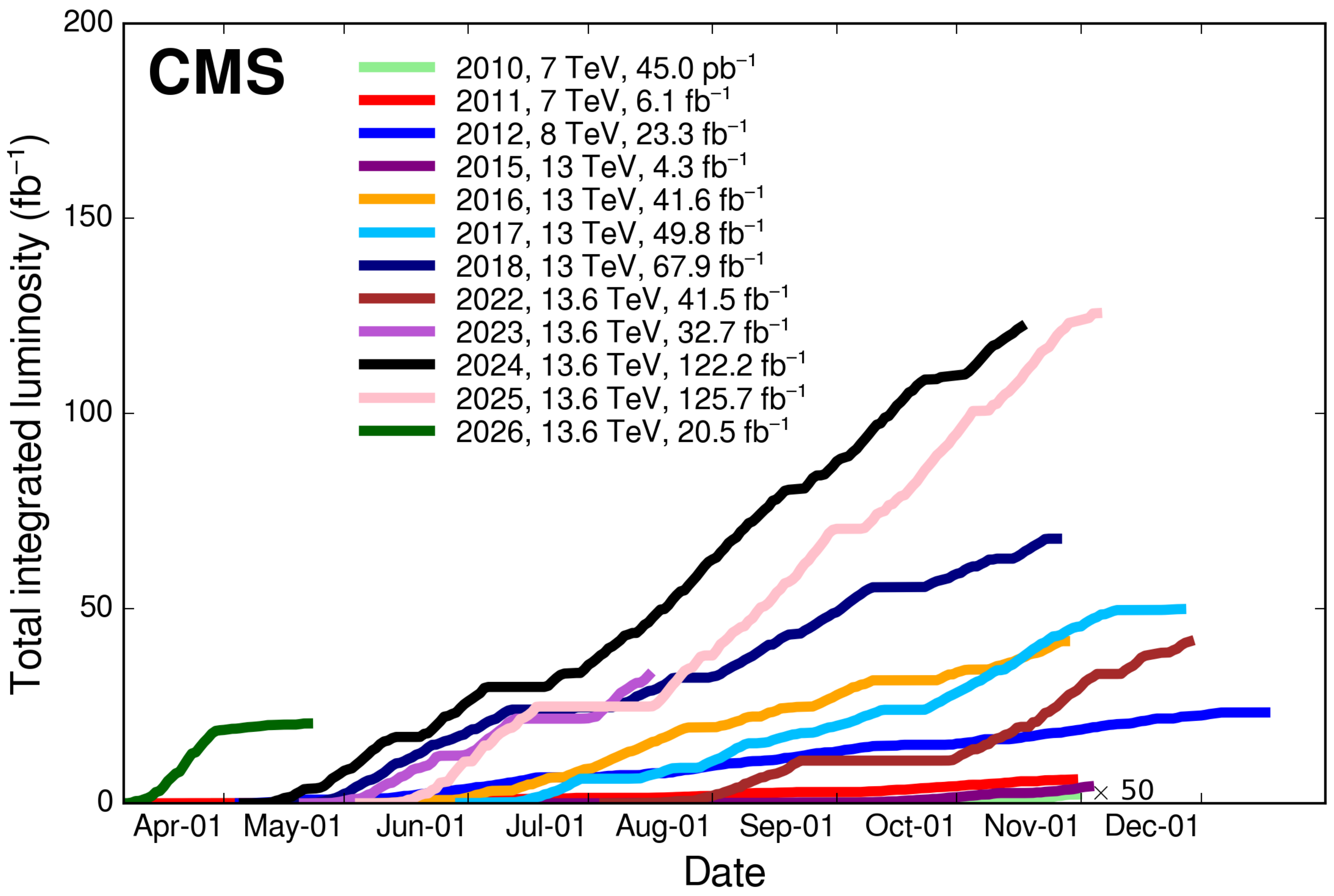
$$L = \int \mathscr{L} dt \qquad N = L \cdot \sigma$$

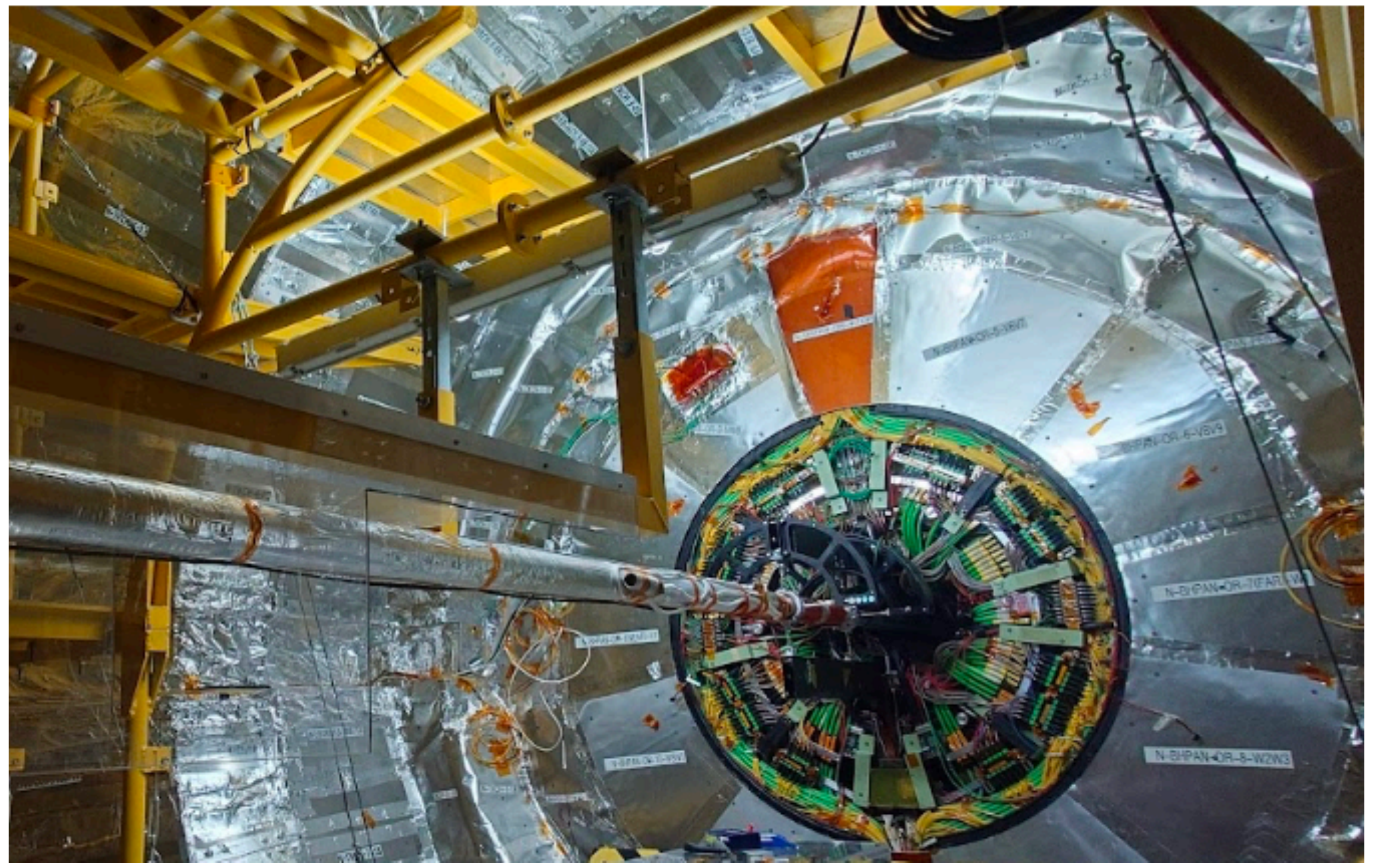
BRIL detector

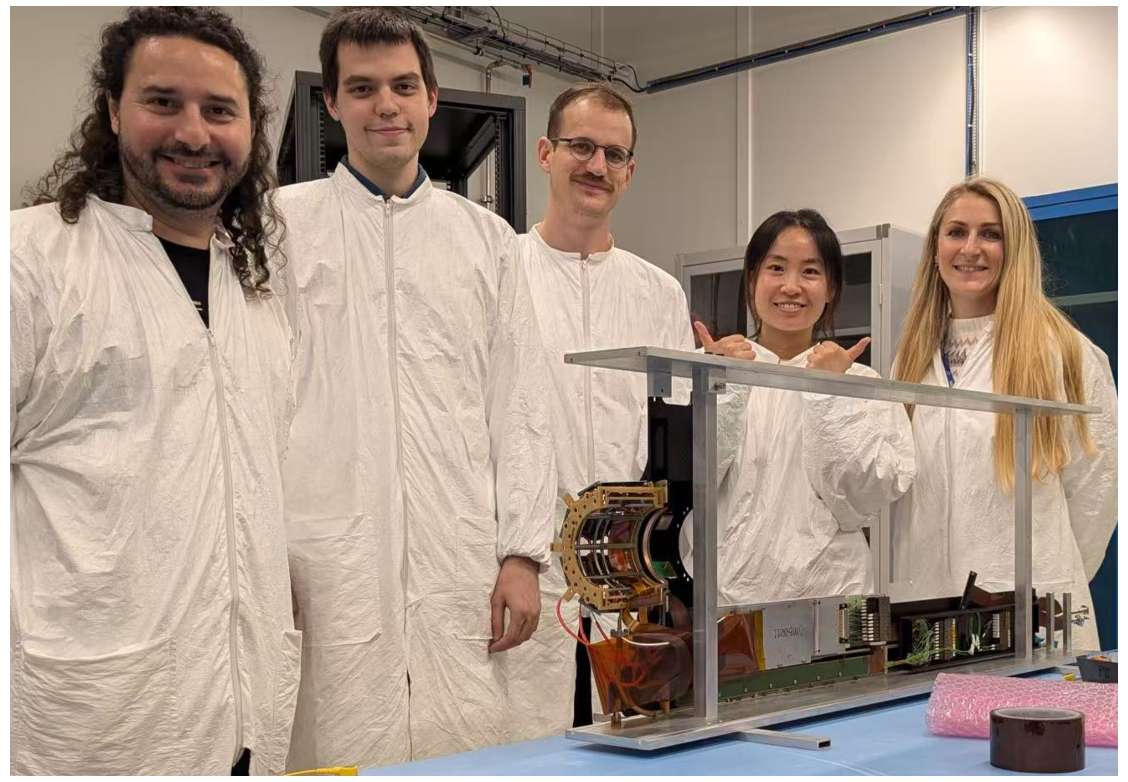


BCM1F: Inside tracker endcap, near beampipe







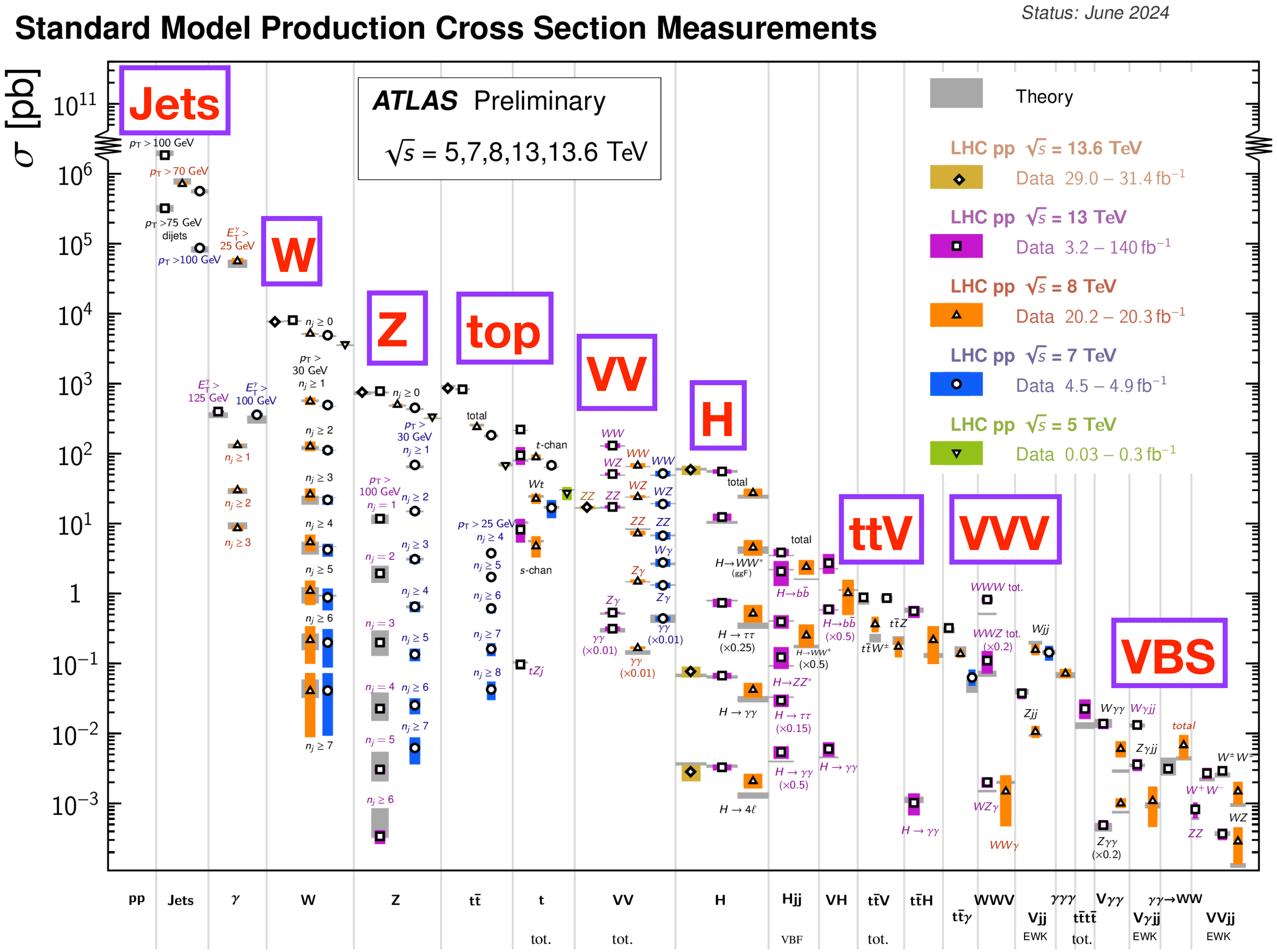


Why SM measurements

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

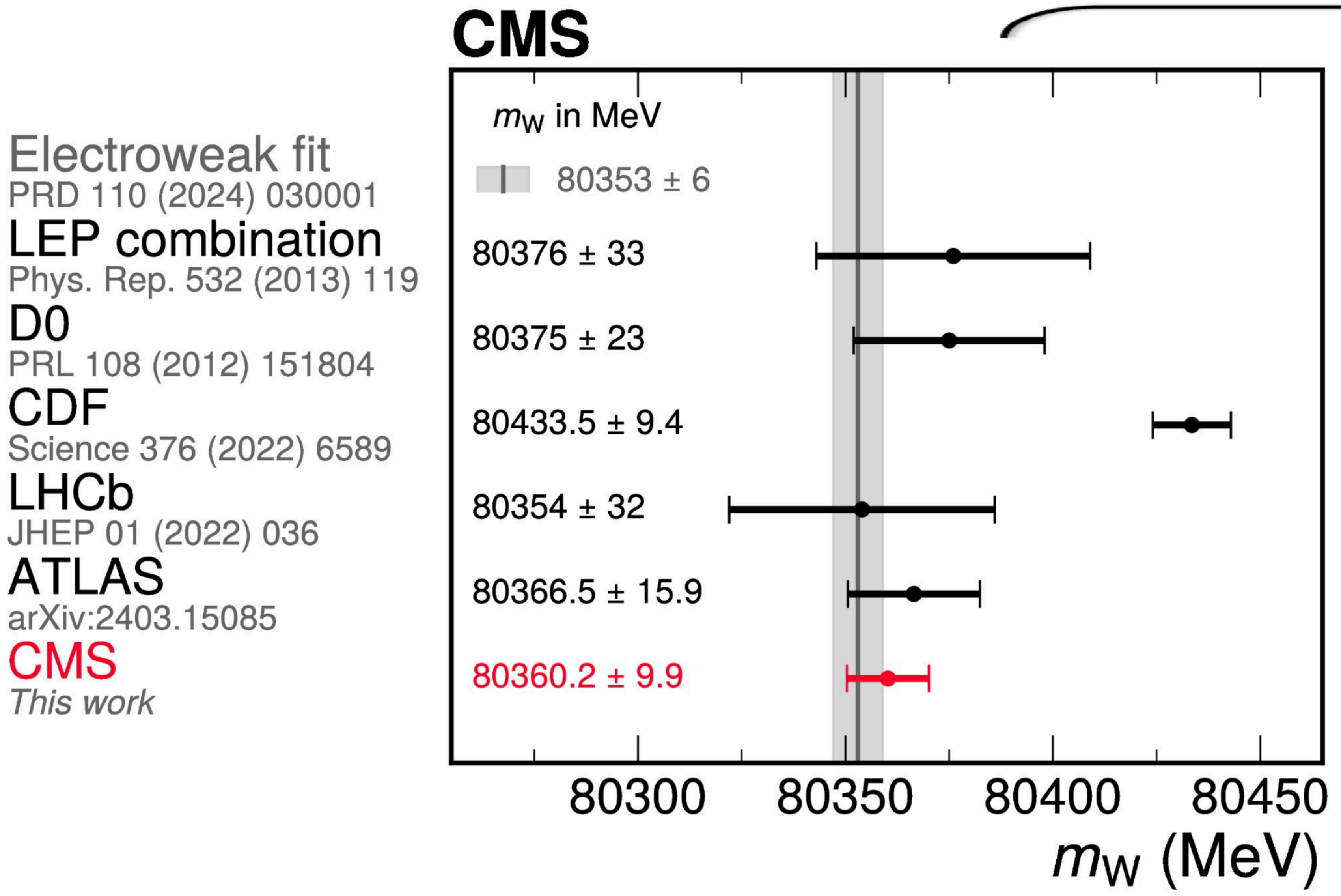
What do we mean by SM measurements and why do we do them at LHC?

- Fundamental constants: α_s, top quark mass, W mass
- Deviations may be a signal for new physics
- 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)



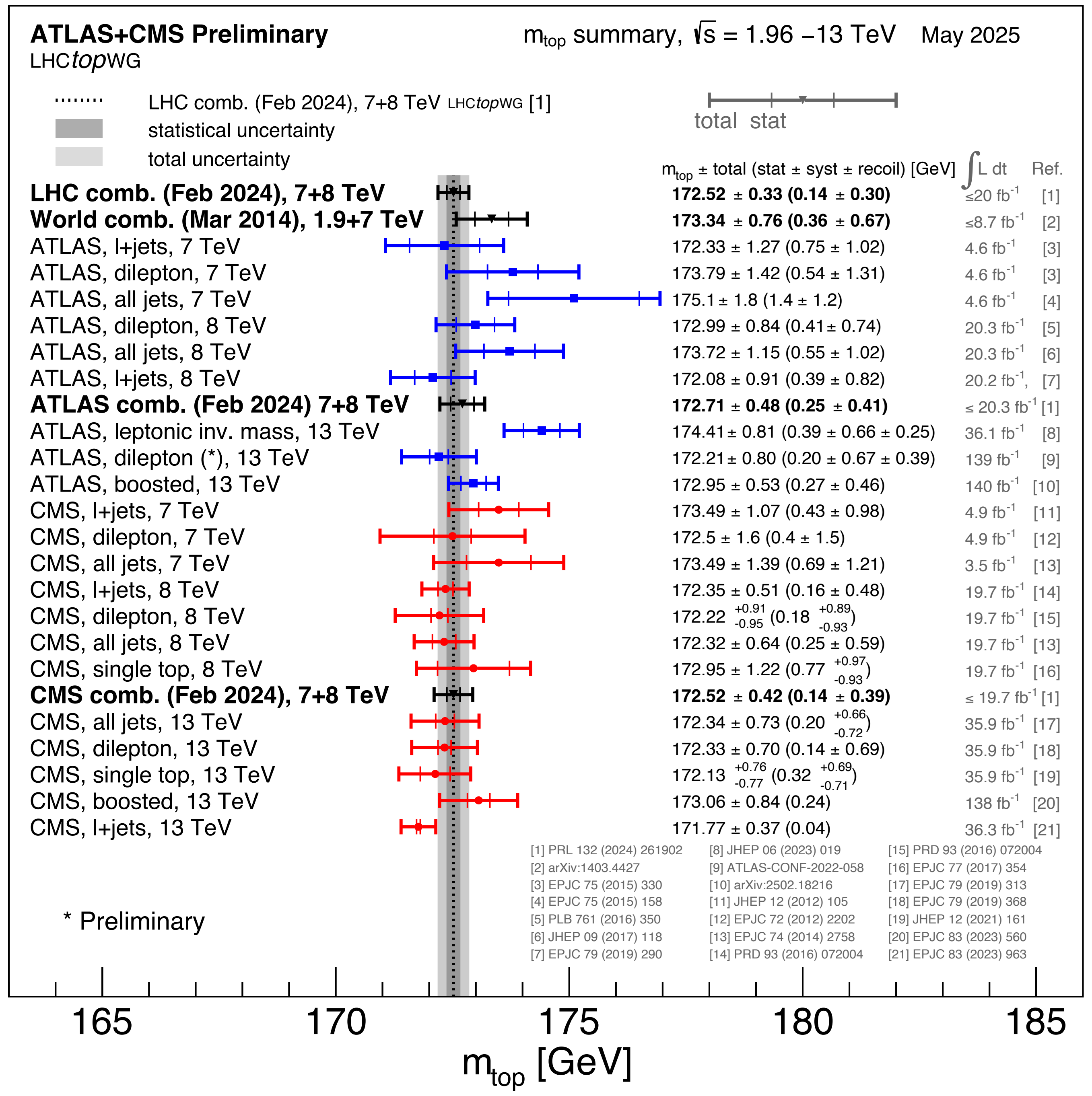
SM precision measurements — mass

W mass

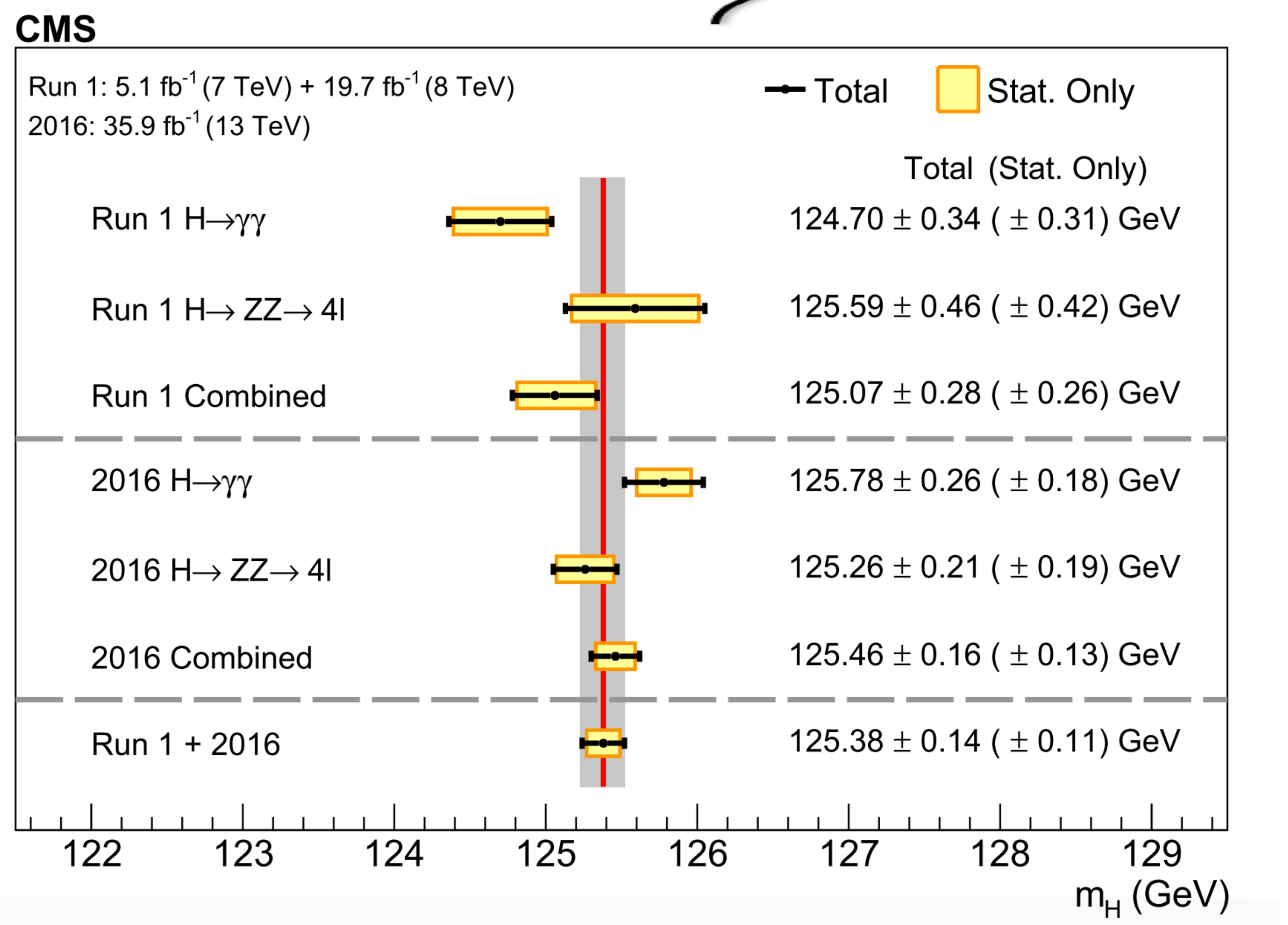


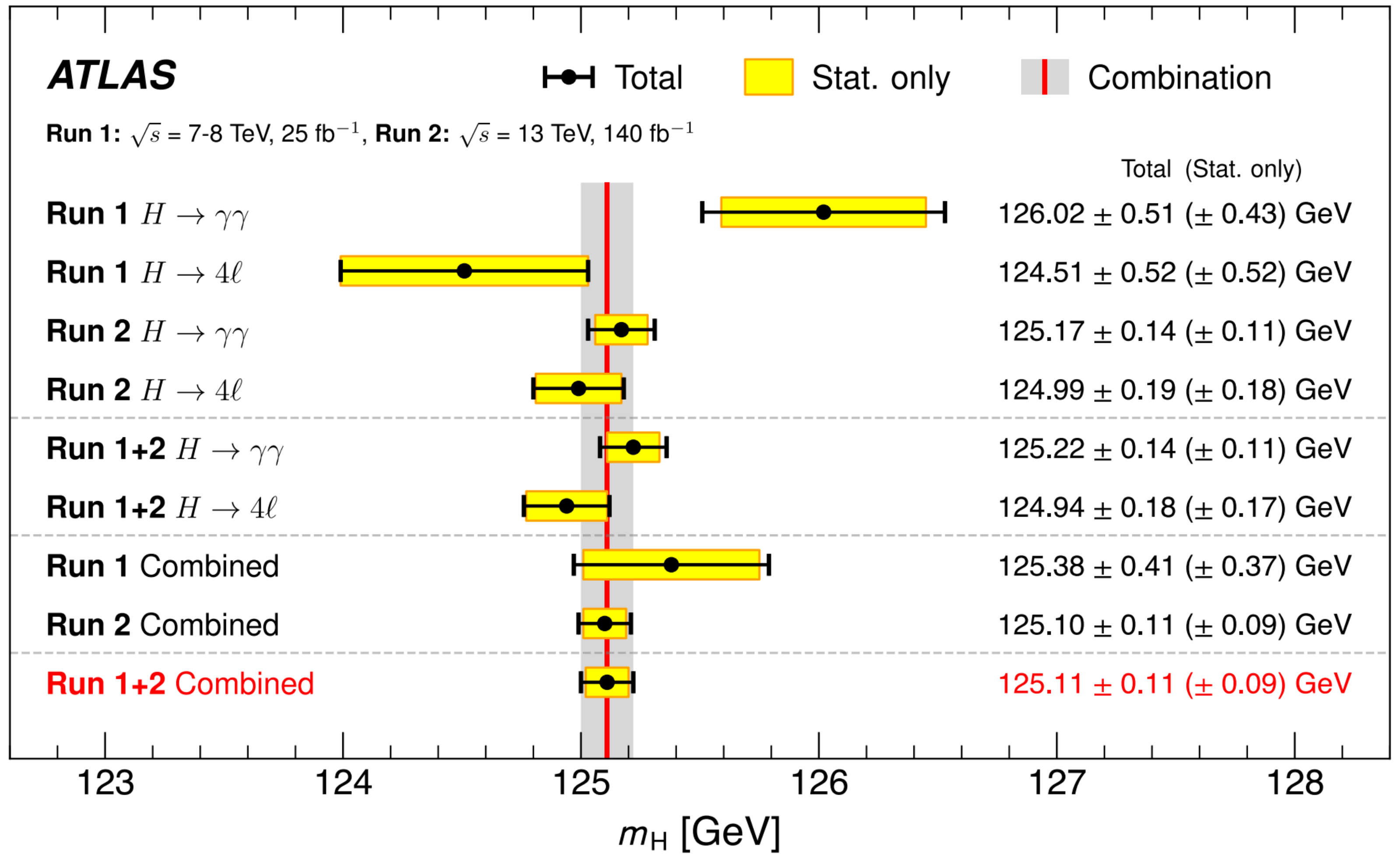
Source of uncertainty	Impact (MeV) Nominal	Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample size	2.4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

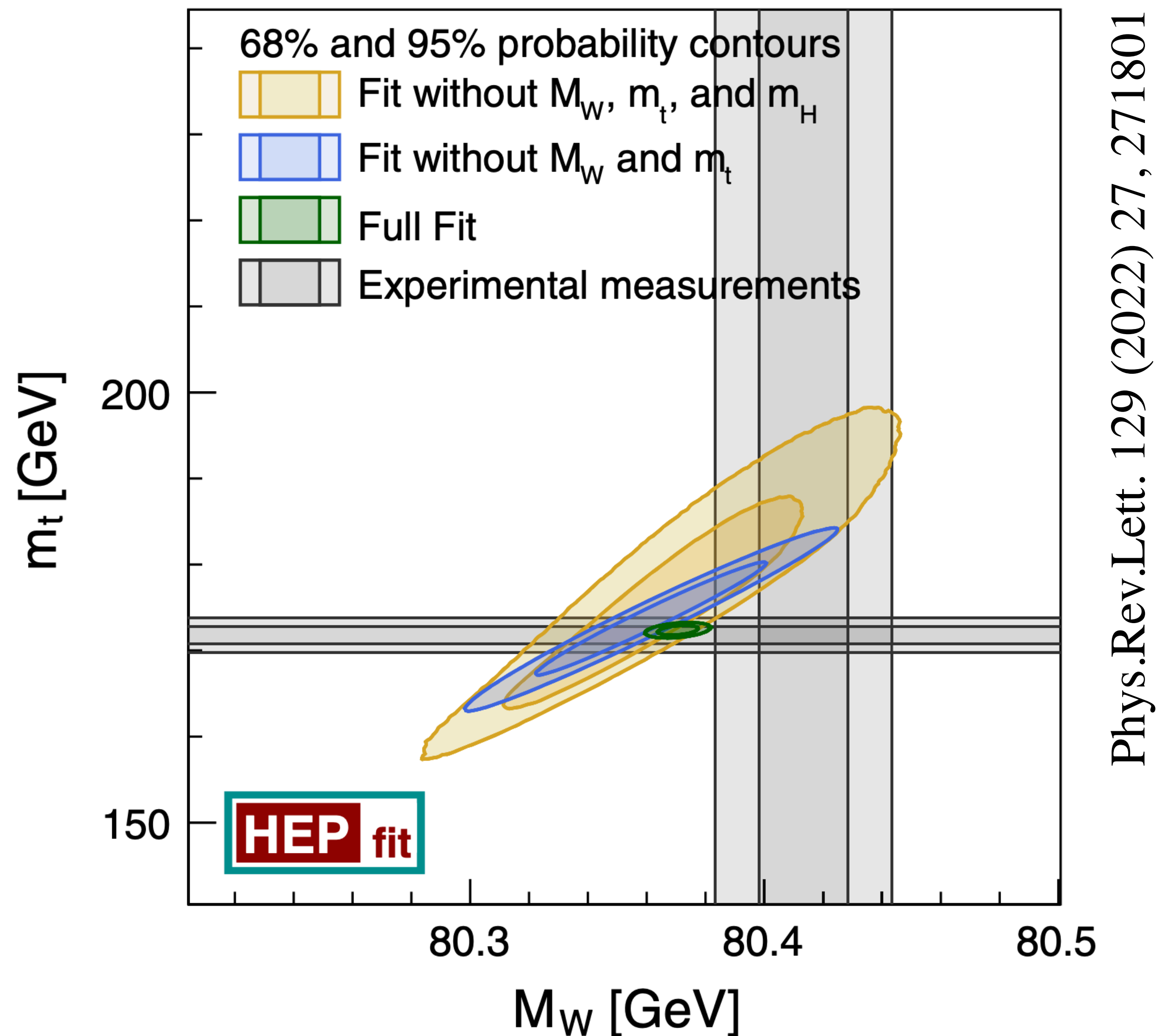
Top mass



Higgs mass







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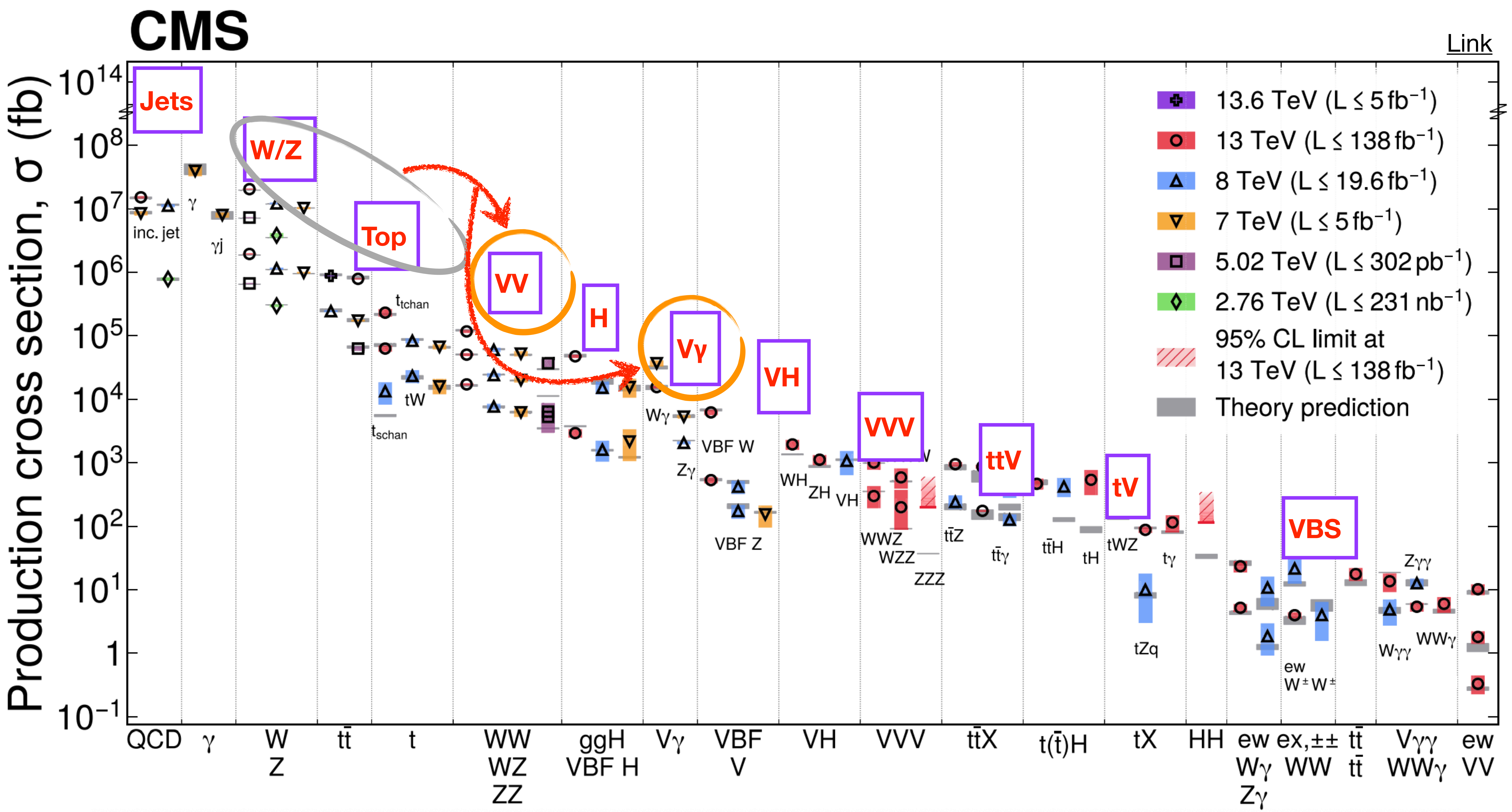
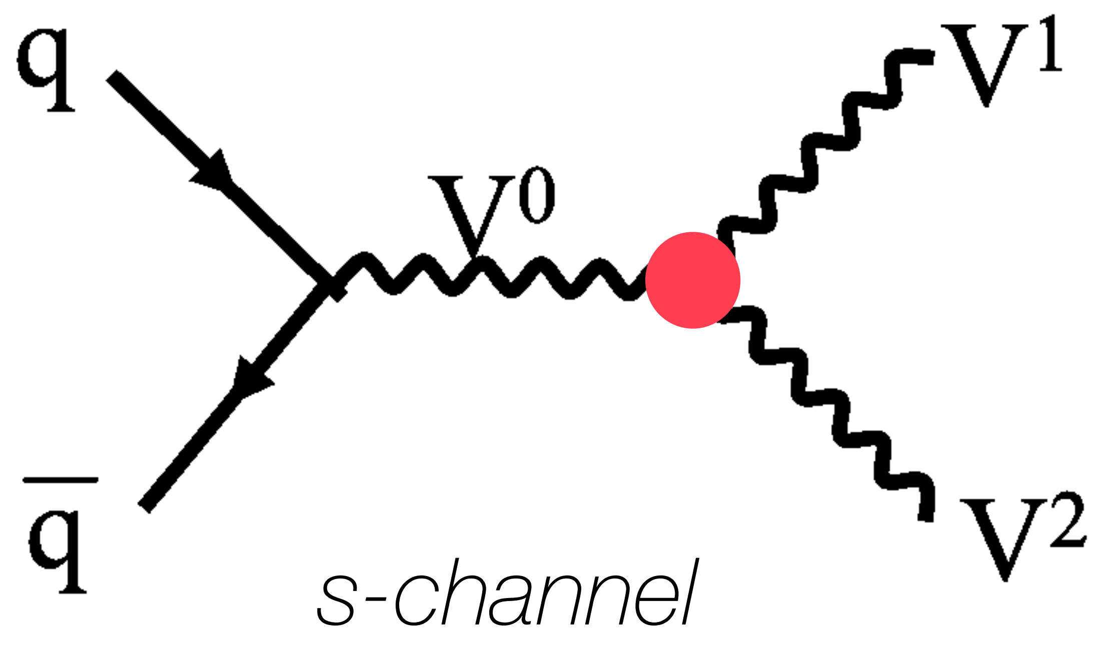
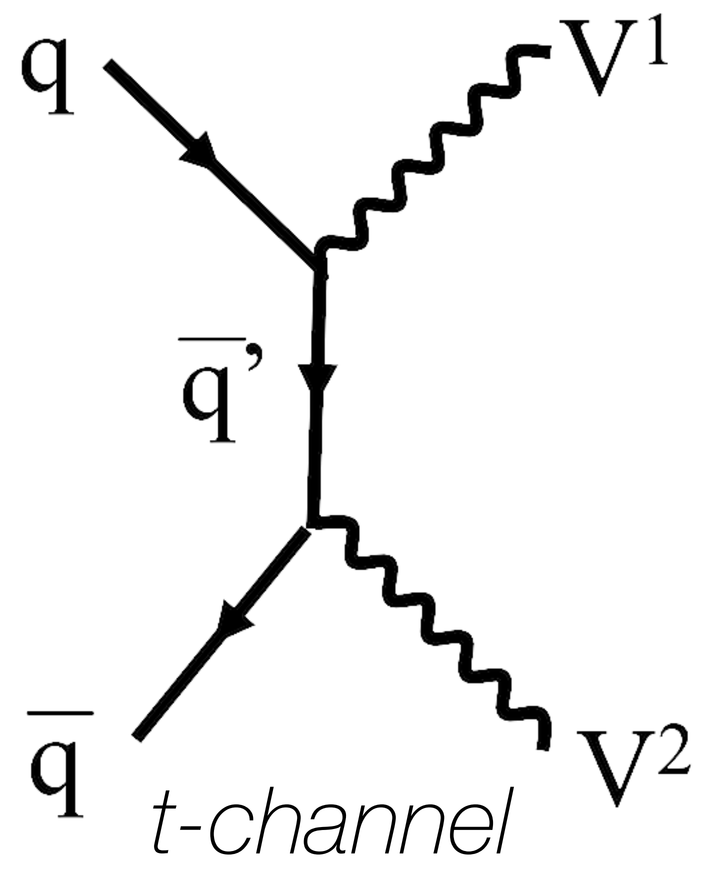
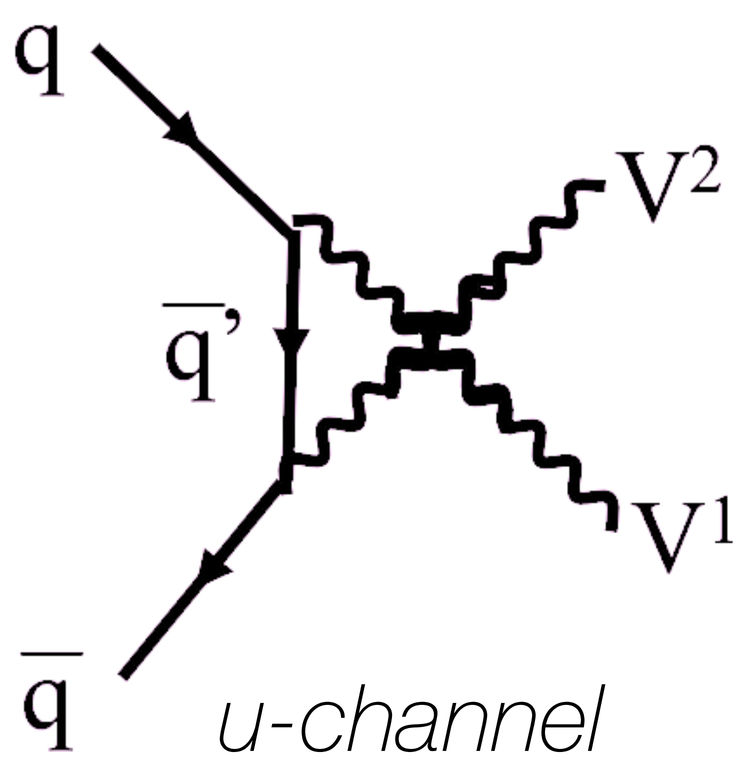

CMS
Link
Production cross section, σ (fb)
Jets
W/Z
Top
VV
H
Vγ
VH
VVV
ttV
tV
VBS
13.6 TeV (L ≤ 5 fb⁻¹)
13 TeV (L ≤ 138 fb⁻¹)
8 TeV (L ≤ 19.6 fb⁻¹)
7 TeV (L ≤ 5 fb⁻¹)
5.02 TeV (L ≤ 302 pb⁻¹)
2.76 TeV (L ≤ 231 nb⁻¹)
95% CL limit at 13 TeV (L ≤ 138 fb⁻¹)
Theory prediction
inc. jet
γ
γj
tchan
tW
tschan
Wγ
Zγ
VBF W
VBF Z
WH
ZH
VH
WWZ
WZZ
ZZZ
tt̄Z
tt̄γ
tt̄H
tH
tWZ
tγ
tZq
ew W±W±
Zγγ
Wγγ
WWγ
QCD
γ
W Z
tt̄
t
WW WZ ZZ
ggH VBF H
Vγ
VBF V
VH
VVV
tt̄X
t(t̄)H
tX
HH
ew Wγ Zγ
ex,±± WW
tt̄ tt̄
Vγγ WWγ
ew VV

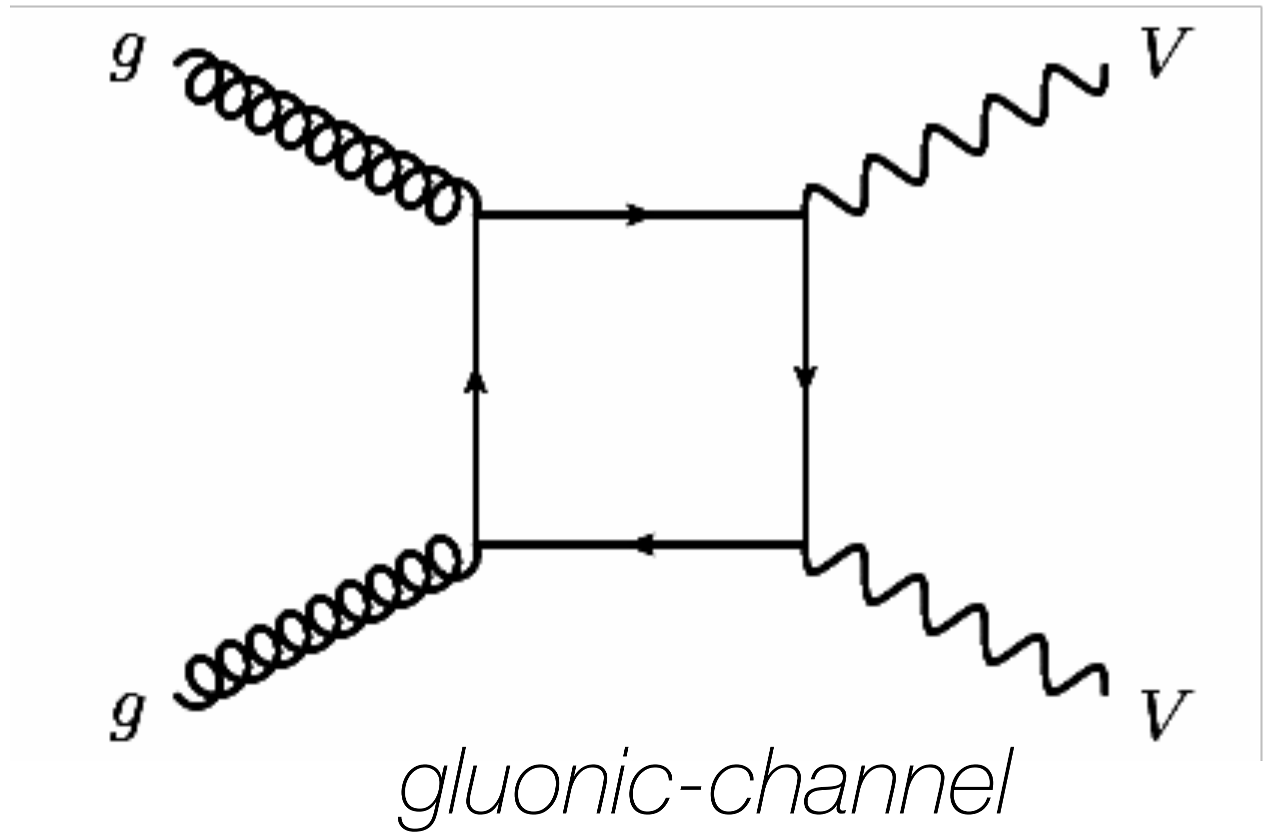
Diboson production — Motivation

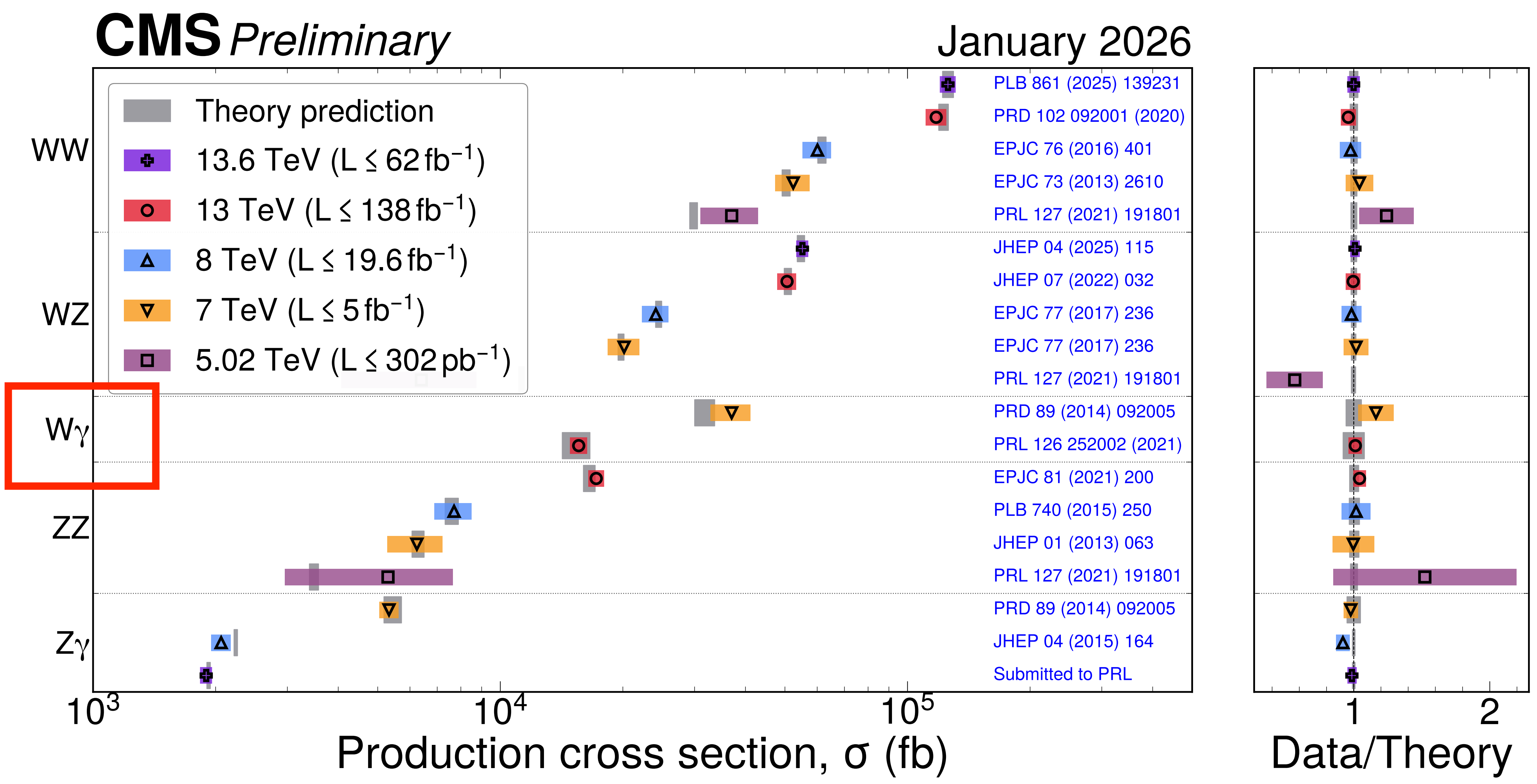
Manifestation of gauge boson couplings at the LHC: production of final states with boson pairs (W,Z,γ)









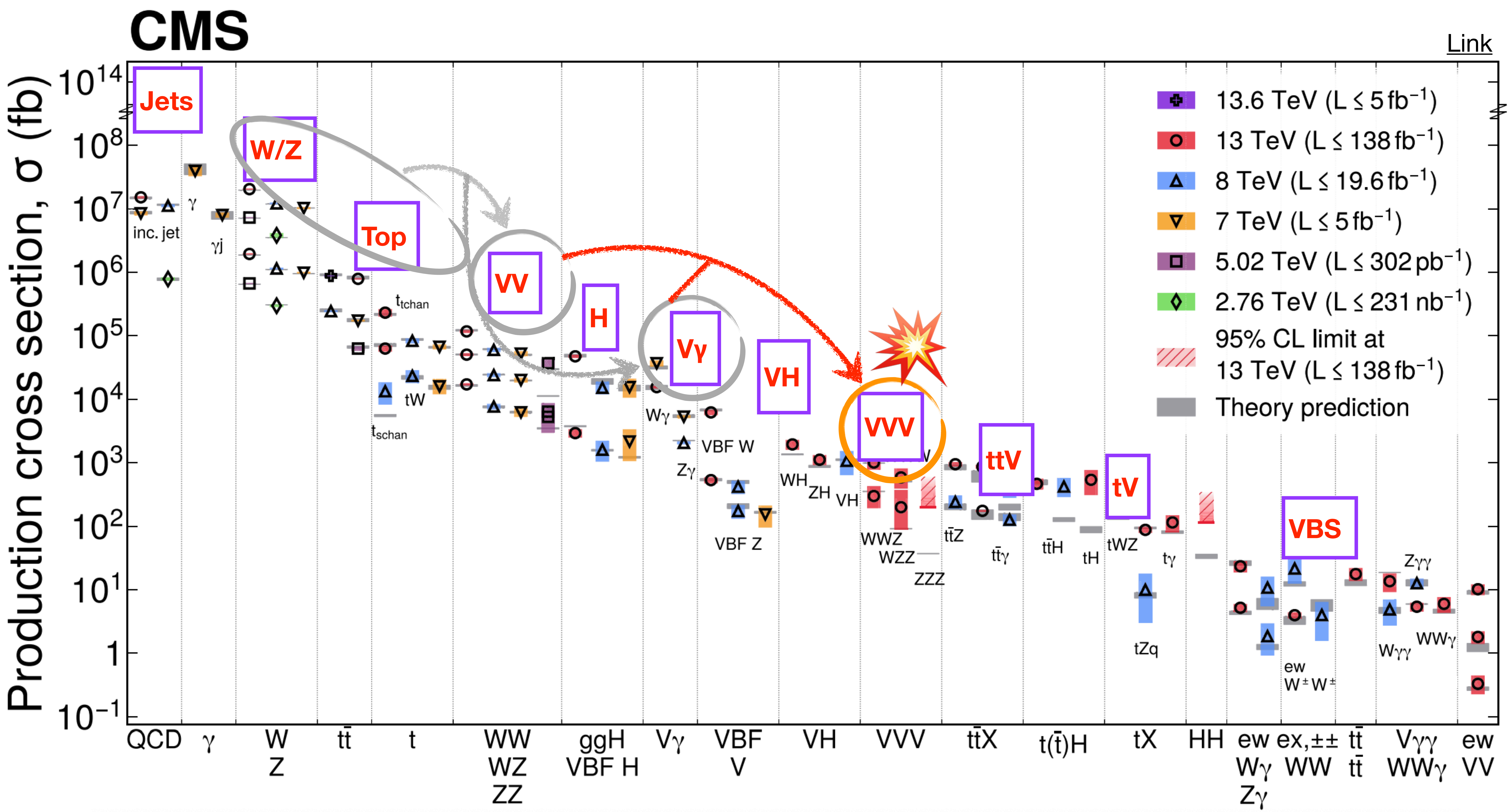


Prediction of the non-abelian SM gauge structure:

- Couplings between gauge bosons

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

- *Deviations could hint to new physics*
- *Complementary to direct search for new physics*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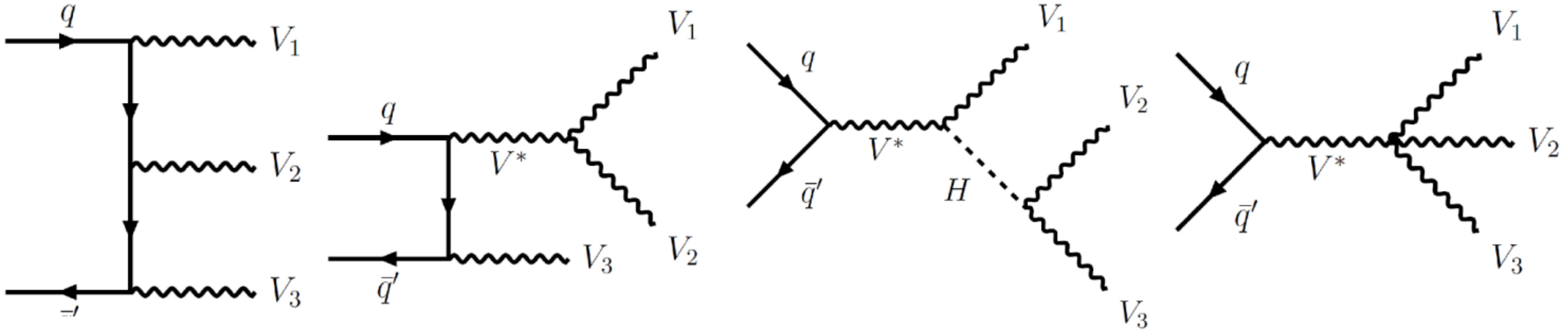
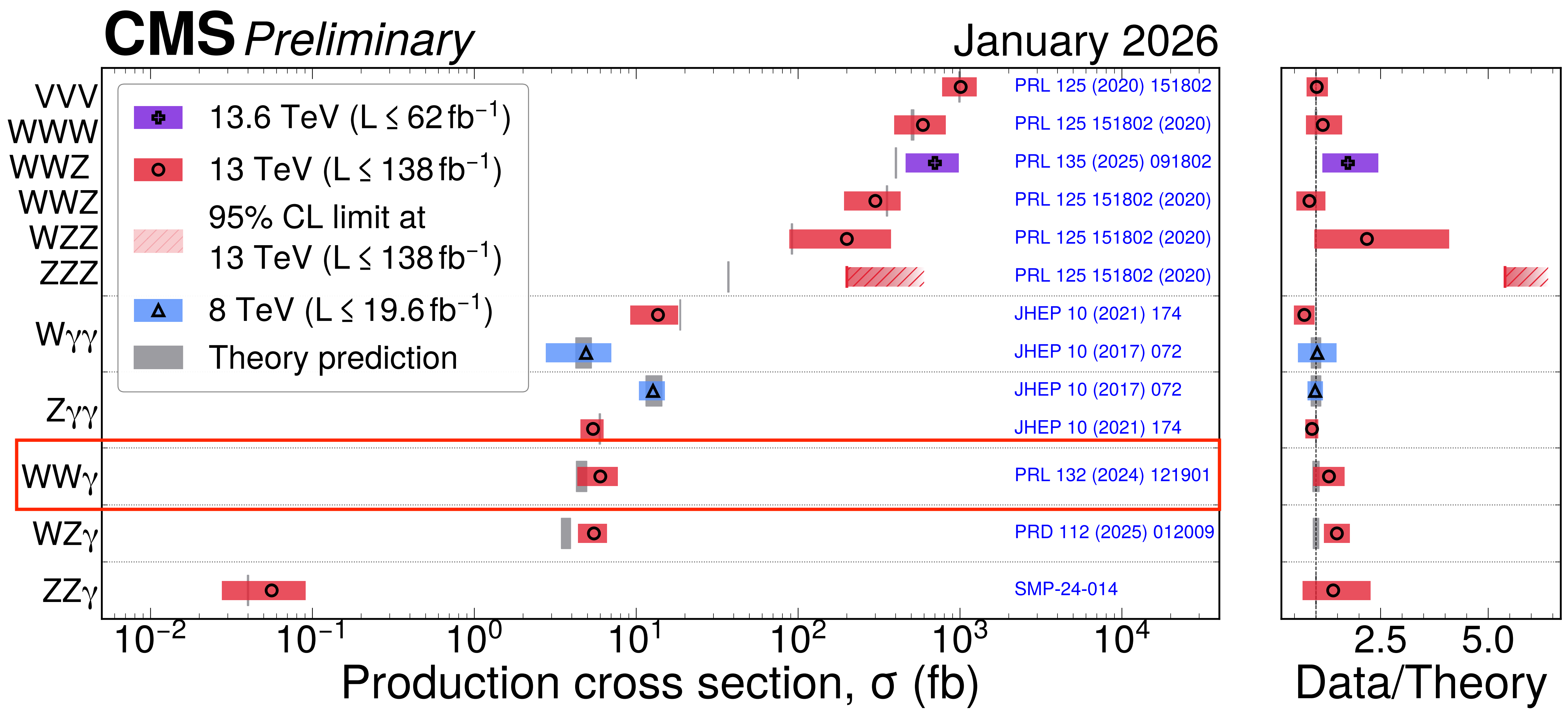
2.76 TeV (L ≲ 231 nb⁻¹)
95% CL limit at 13 TeV (L ≲ 138 fb⁻¹)
Theory prediction
QCD γ W Z tt̄ t WW WZ ZZ ggH VBF H Vγ VBF V VH VVV tt̄X t(t̄)H tX HH ew Wγ Zγ ex,±± WW tt̄ tt̄ Vγγ WWγ ew VV

Triboson production — Motivation

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

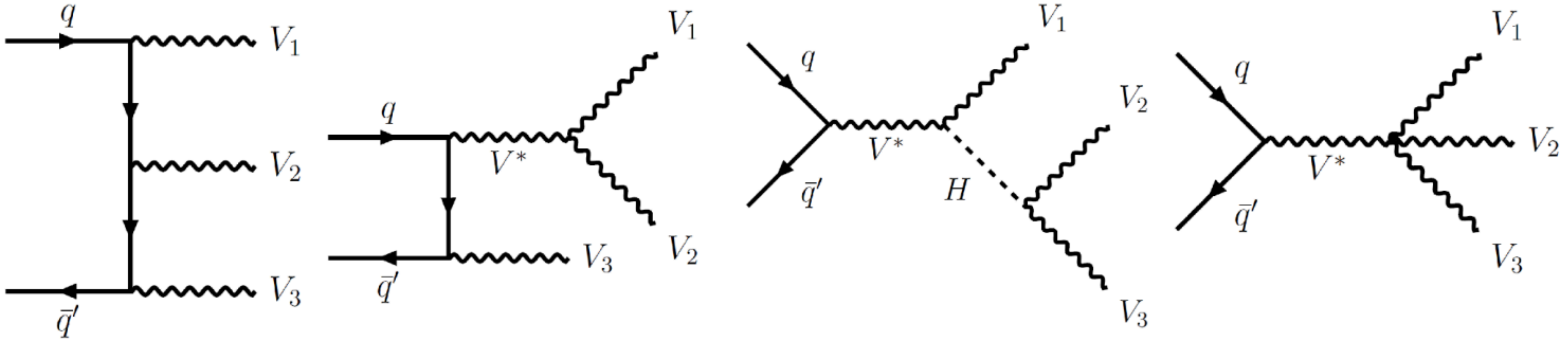


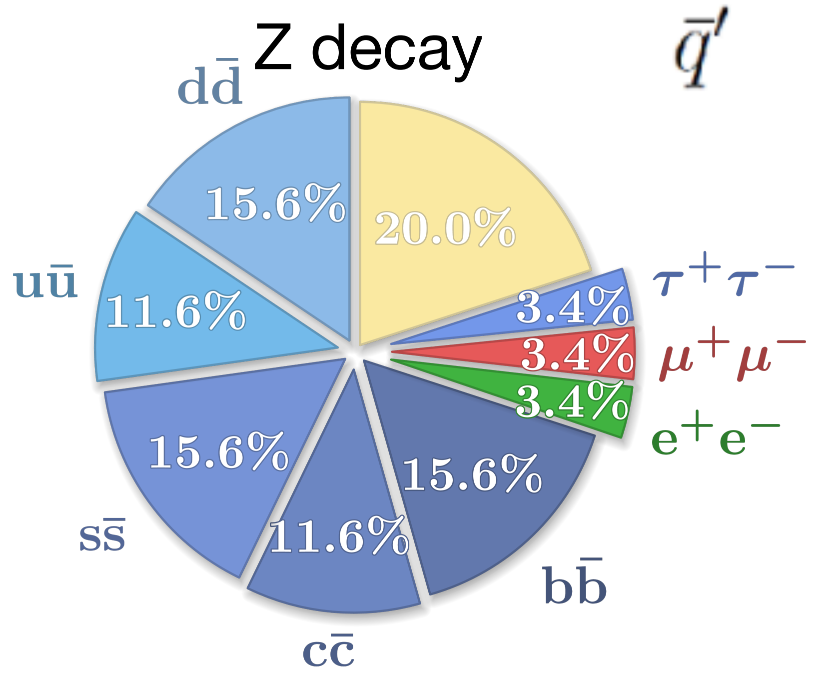


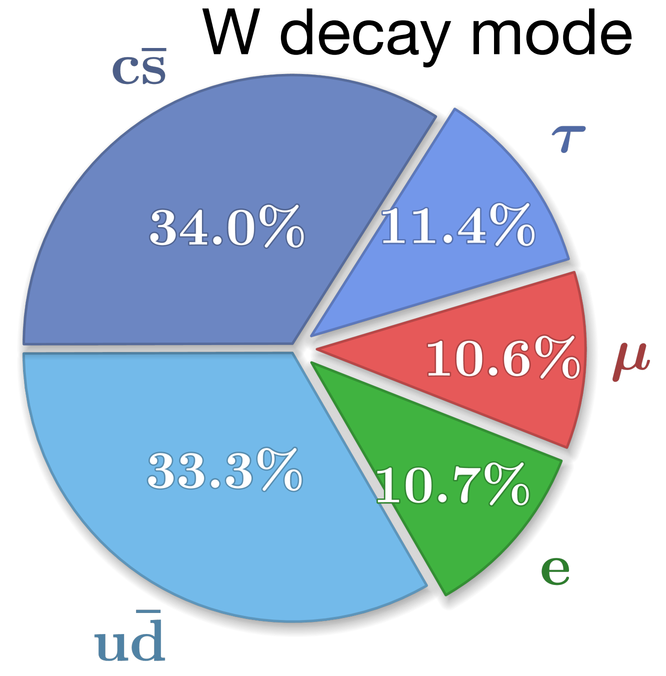
- Finely balanced cancellations between QGC, TGC; Higgs amplitudes is needed to preserve unitarity at high CM energies
- Any anomalous HVV, QGC and TGC coupling can disturb the balance and create large cross-sections at high energies
- Complementary to vector boson scattering measurements

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**

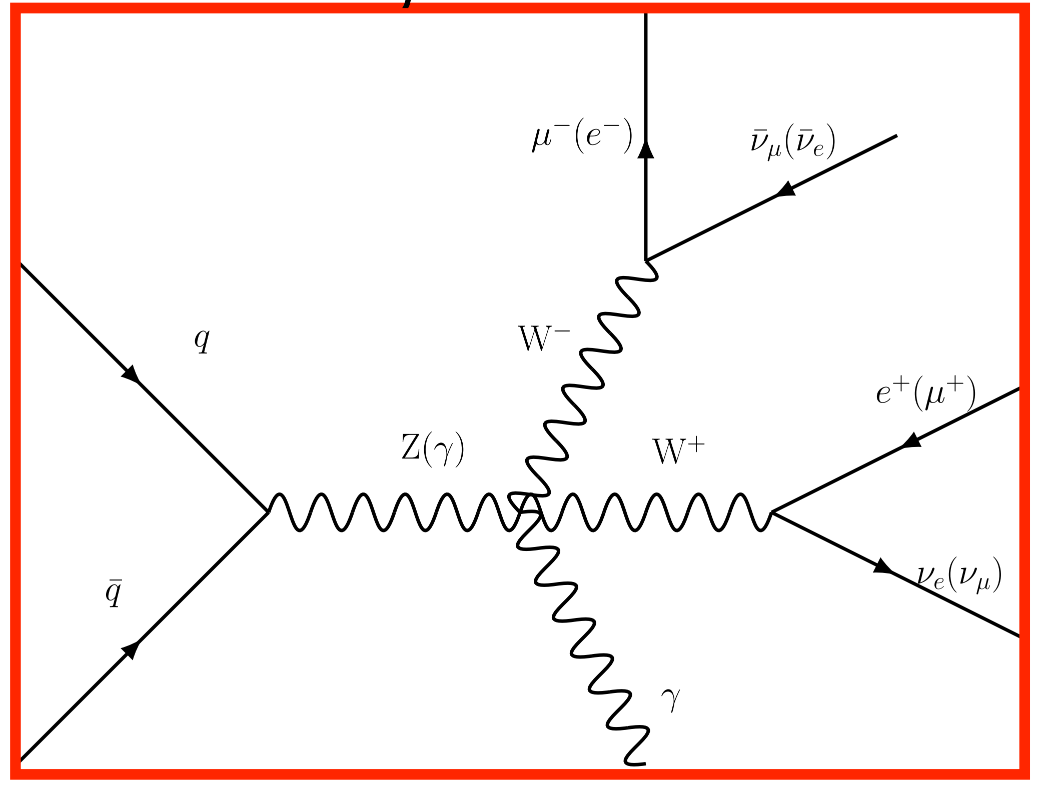
1. SM process that produce multi-leptons but one is lost
   - WZ, ZZ where a lepton is not detected
   - Top quark related backgrounds
2. Vγ events where the photon is misidentified as an electron
3. Nonprompt leptons originating from hadronic jets
4. Nonprompt photons originating from hadronic jets

(1) estimated by normalizing MC to data

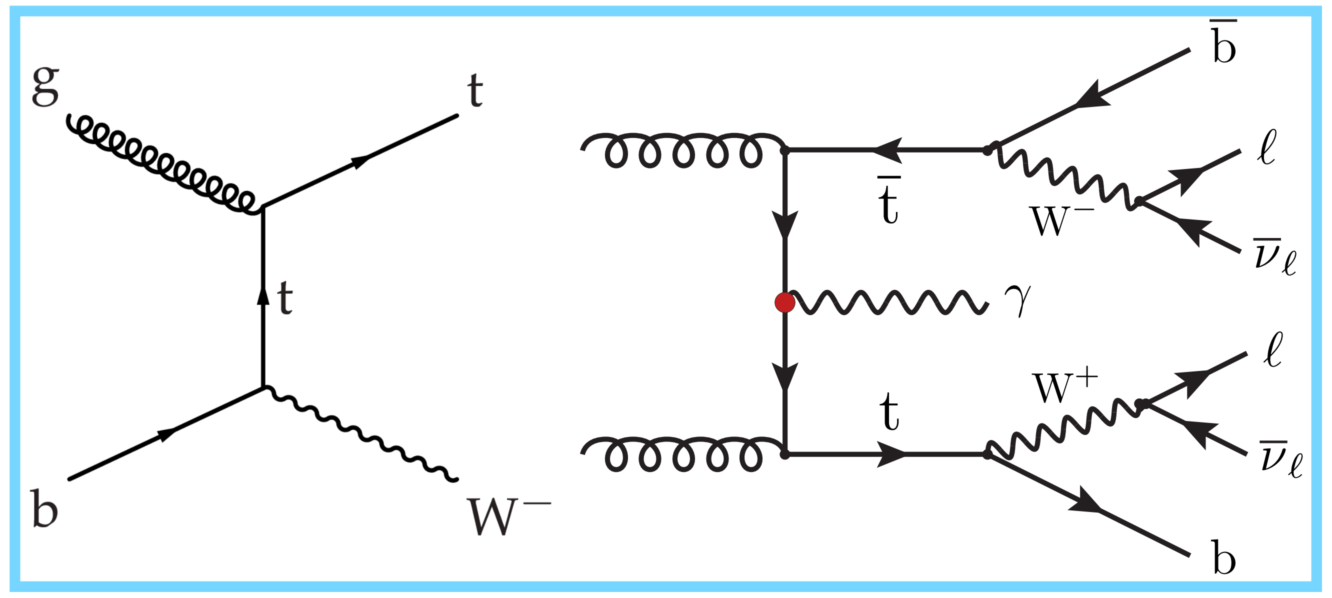
(2–4) Fully estimated in-situ using data

Triboson production — WWγ

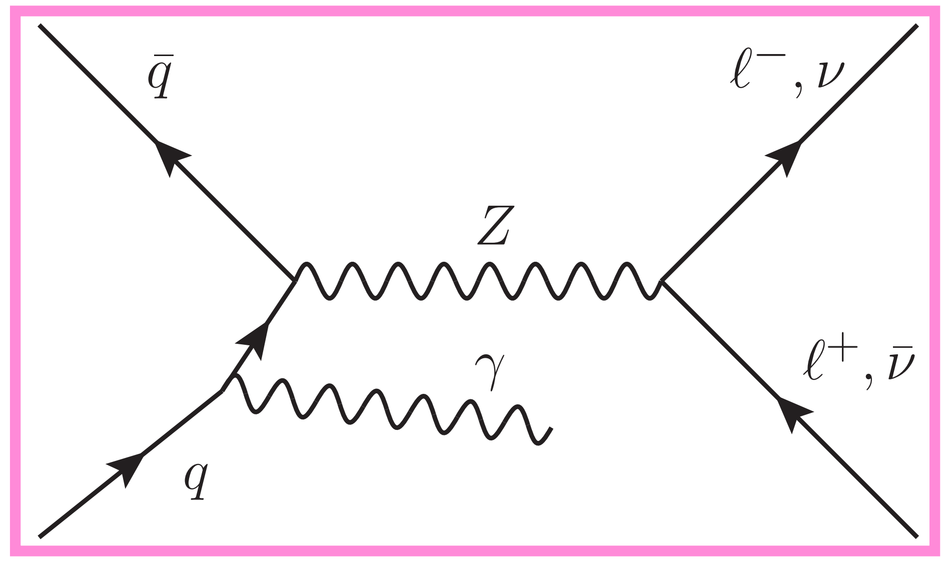
$e^{\pm}\nu_e\mu^{\mp}\nu_\mu\gamma$ final states



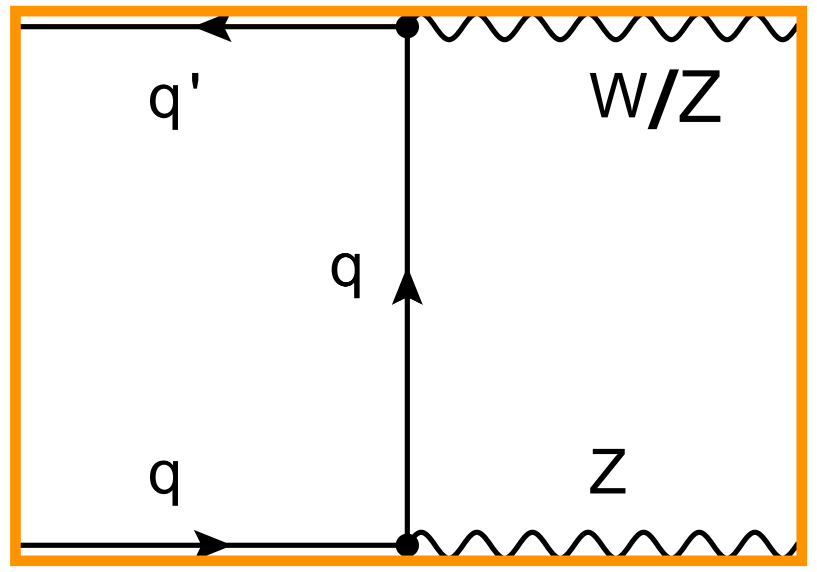
- $t\bar{t}$γ and tW



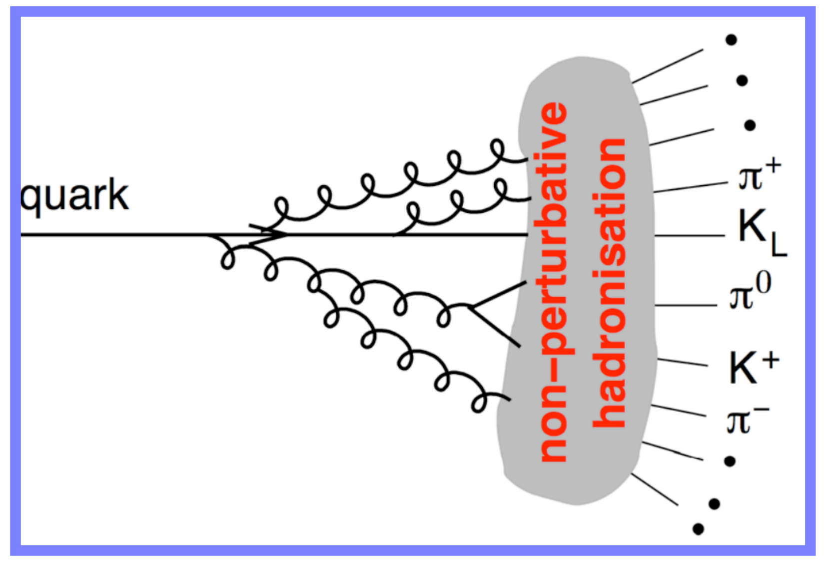
- Zγ process



- Diboson

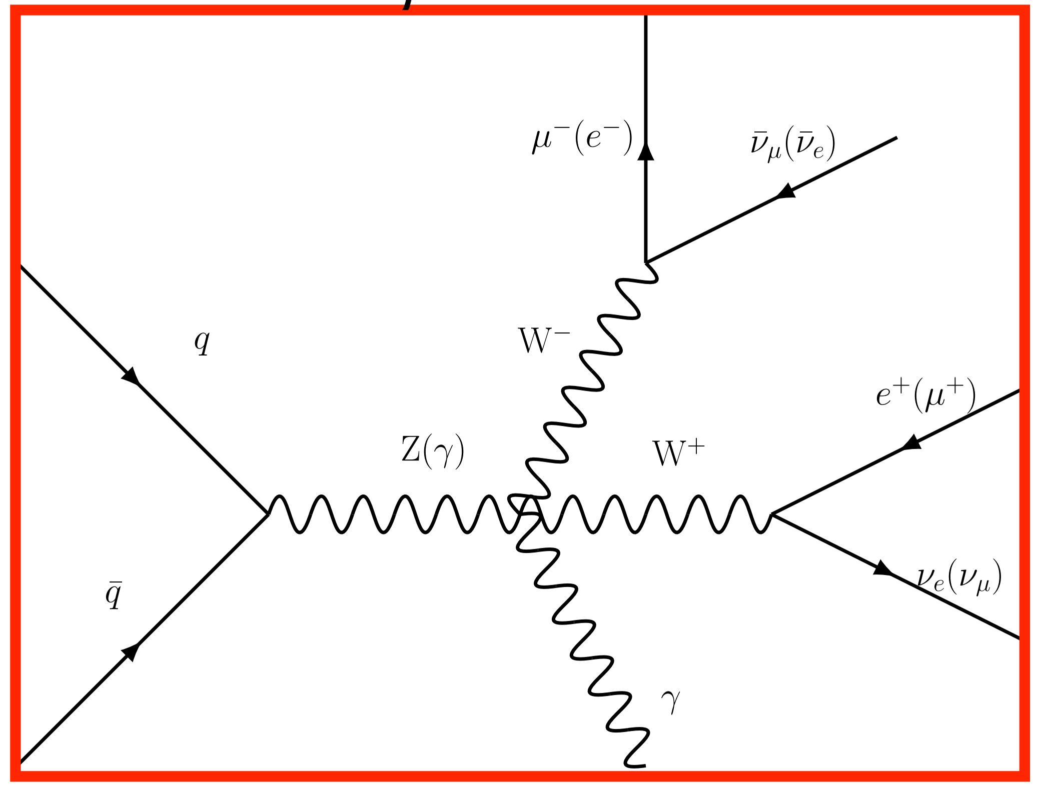


- Nonprompt bkg



Triboson WWγ analysis strategy

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



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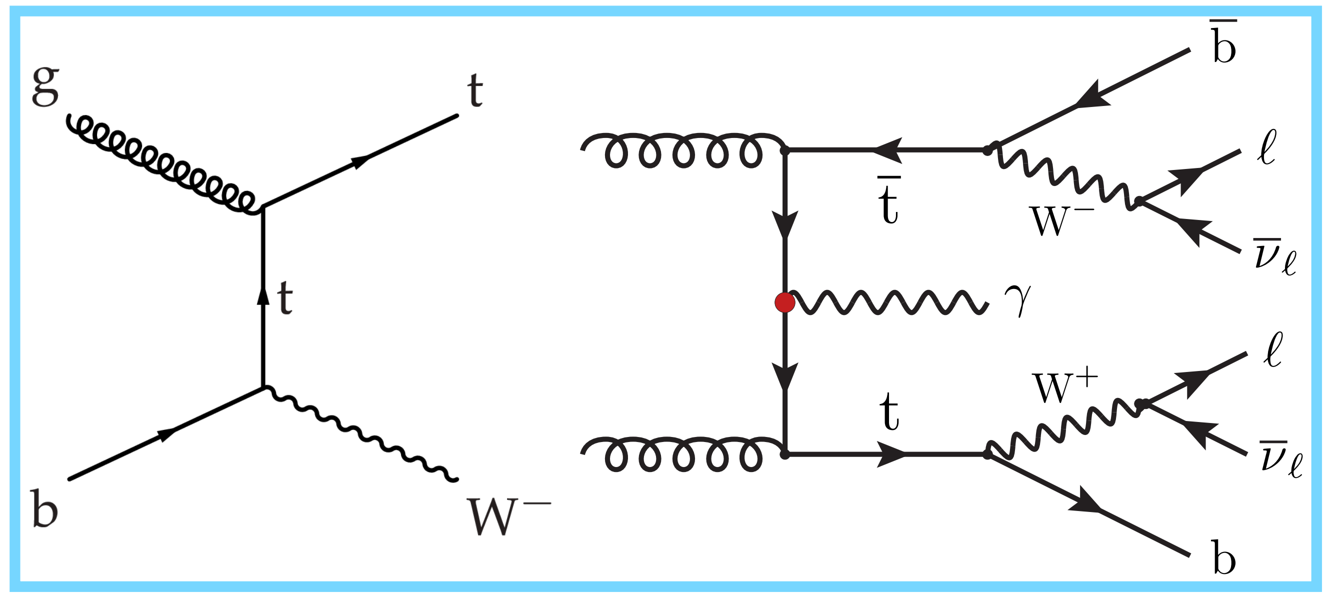

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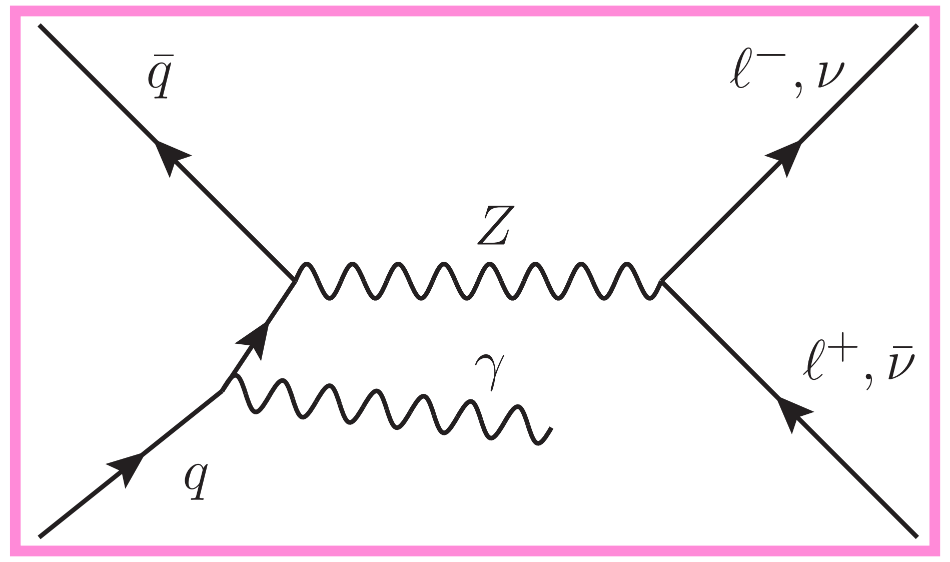

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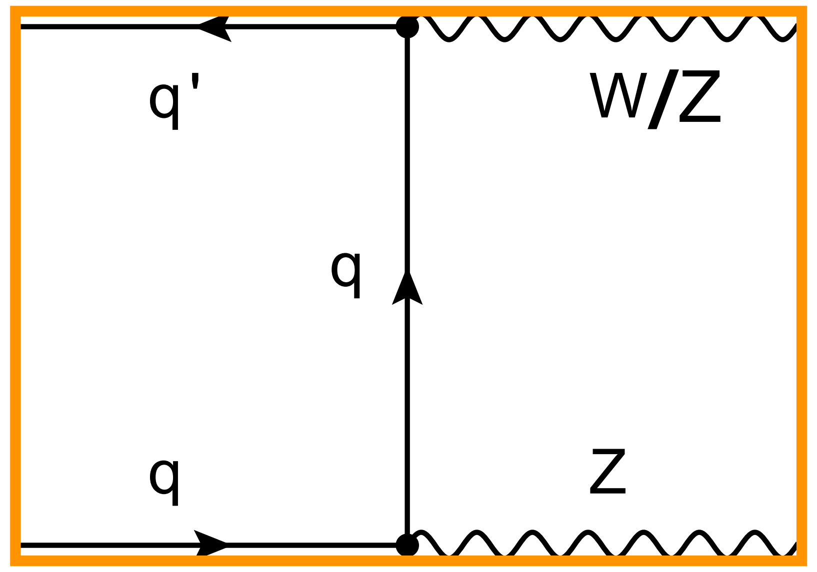

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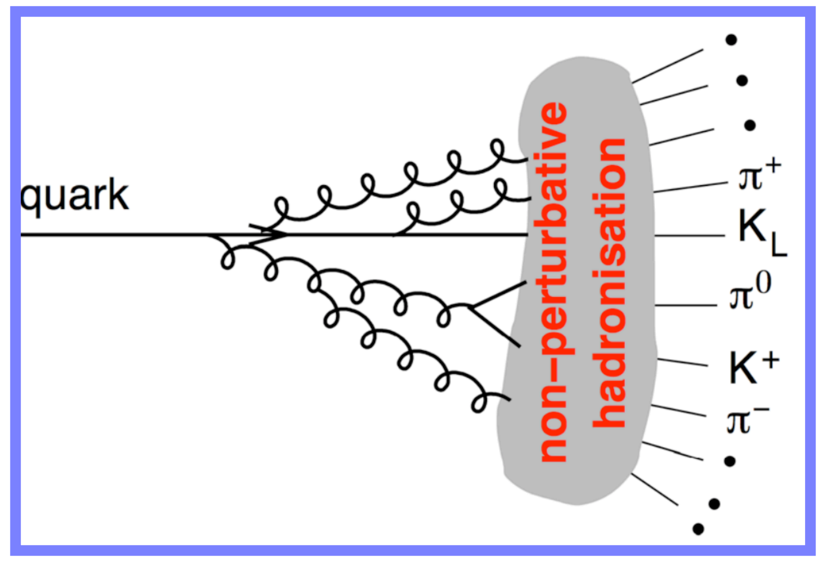
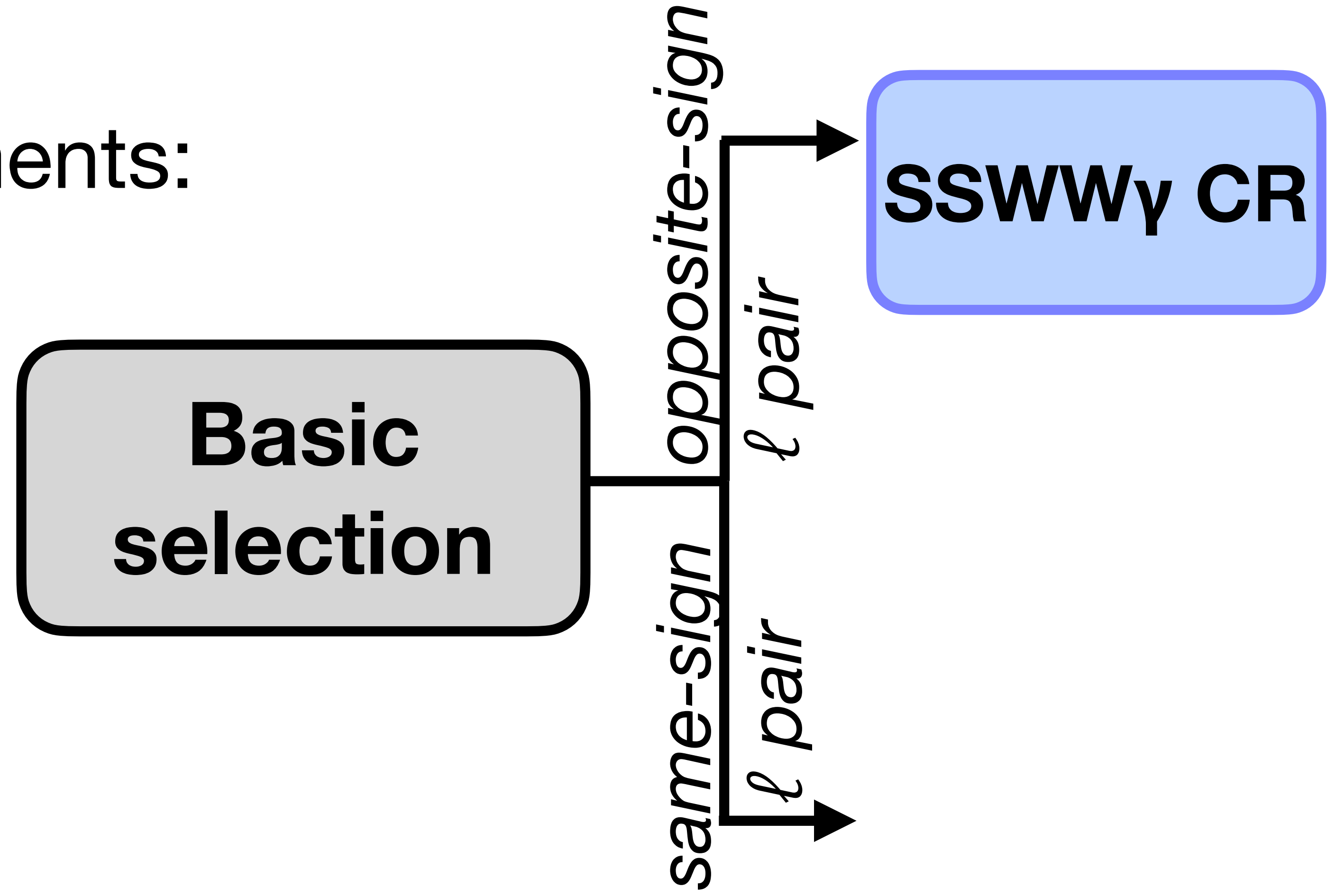


MVA-ID is used to identify the leptons and photon for improving signal to background efficiency

In addition to basic requirements:

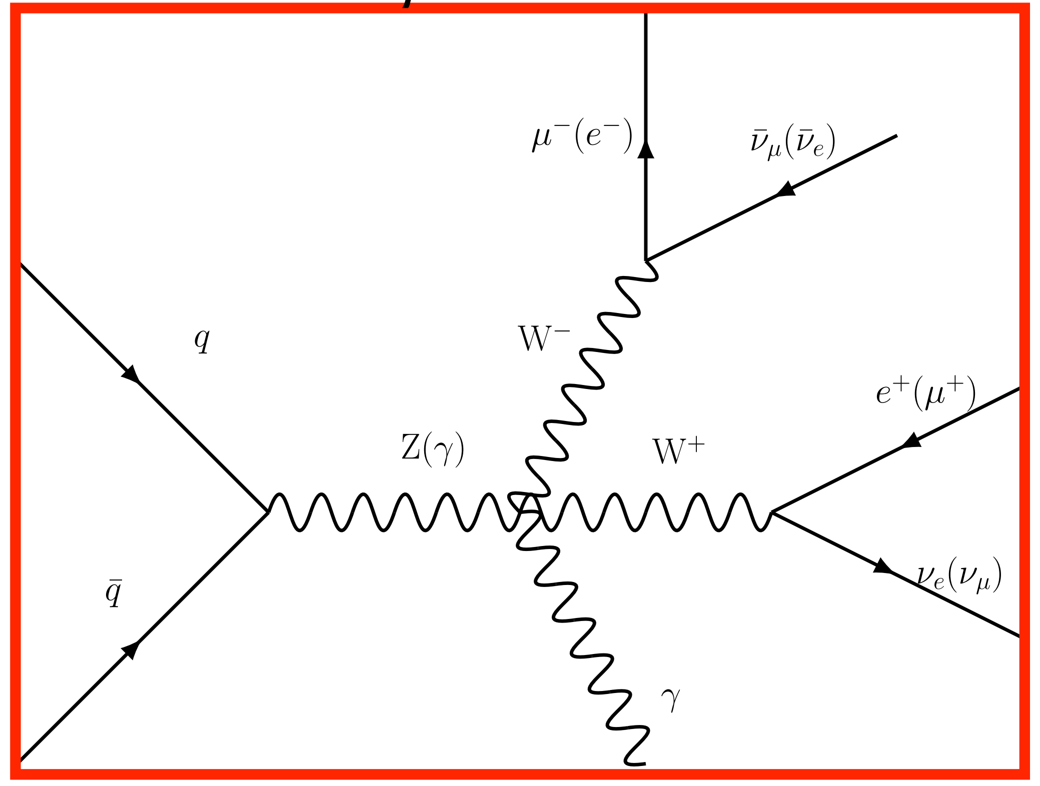
- $m_{\ell\ell}$ > 10 GeV
- $p_T^{\ell\ell}$ > 15 GeV
- E_T^{miss}(PF) > 20 GeV
- m_T^{WW} > 10 GeV



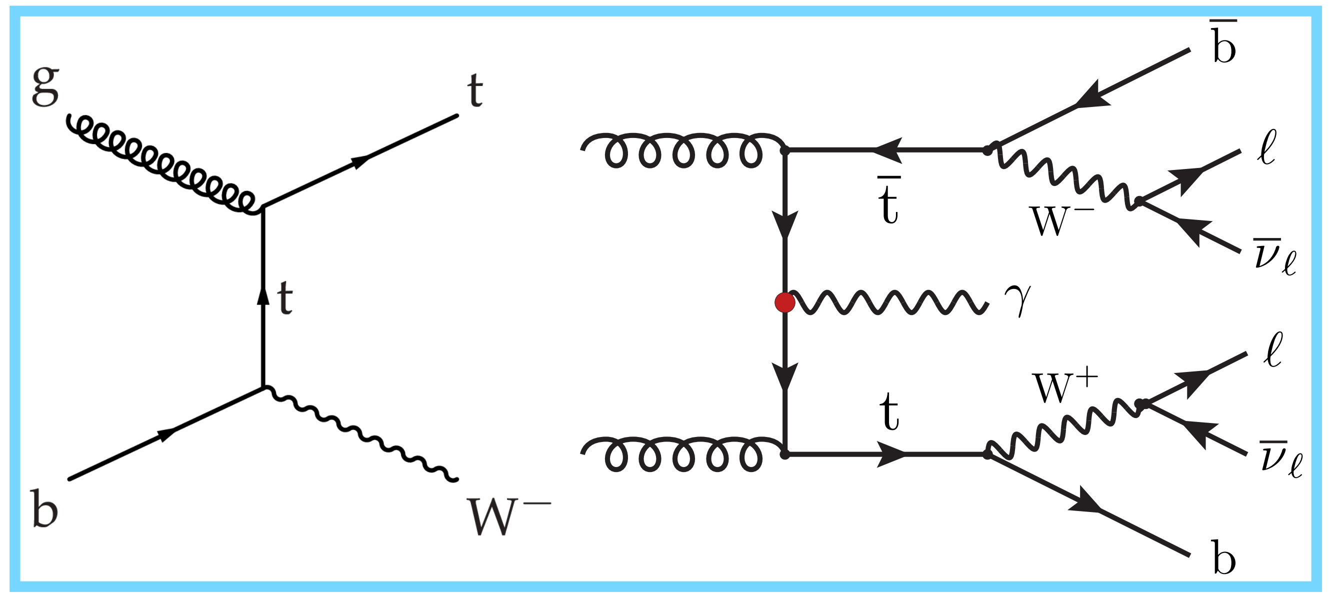
The region full of nonprompt backgrounds, can be used to constrain the nonprompt background by correlating the same systematic uncertainty in the SR

Triboson WWγ analysis strategy

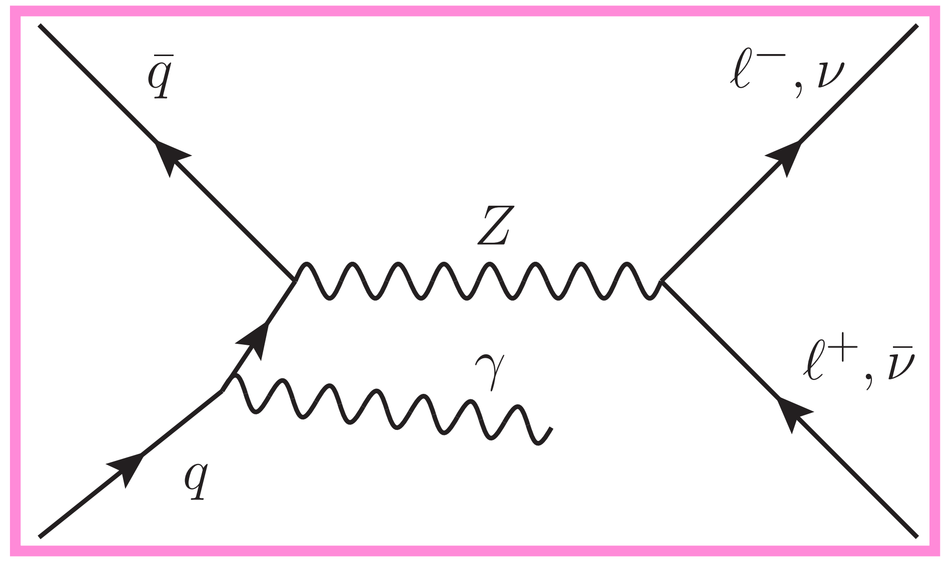
$e^{\pm}\nu_e\mu^{\mp}\nu_\mu\gamma$ final states



- $t\bar{t}$γ and tW



- Zγ process



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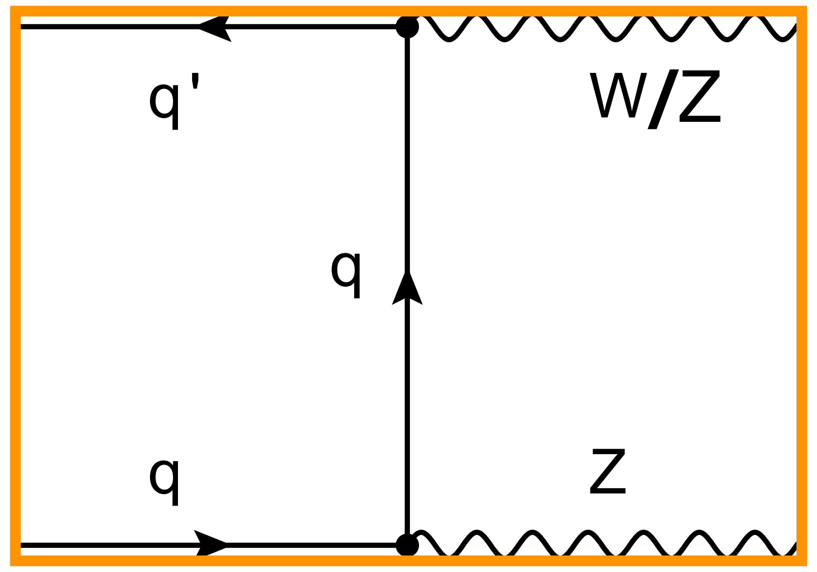

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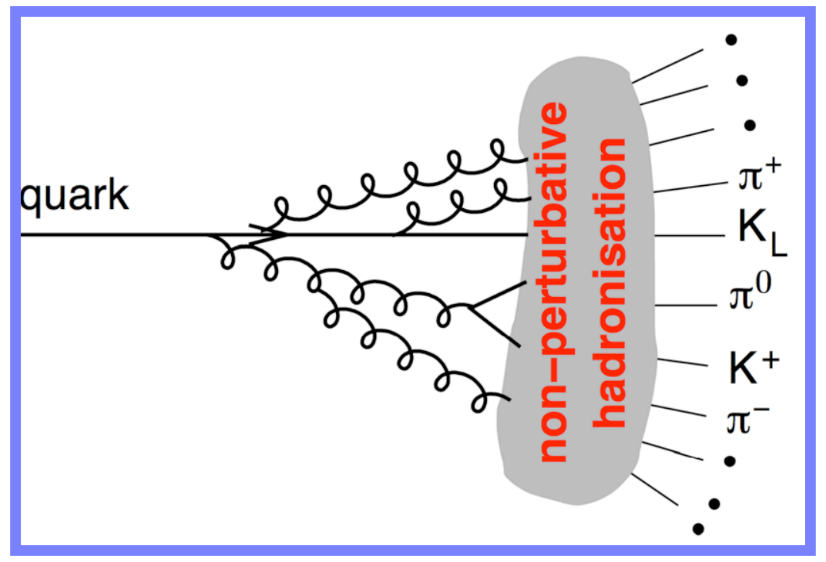

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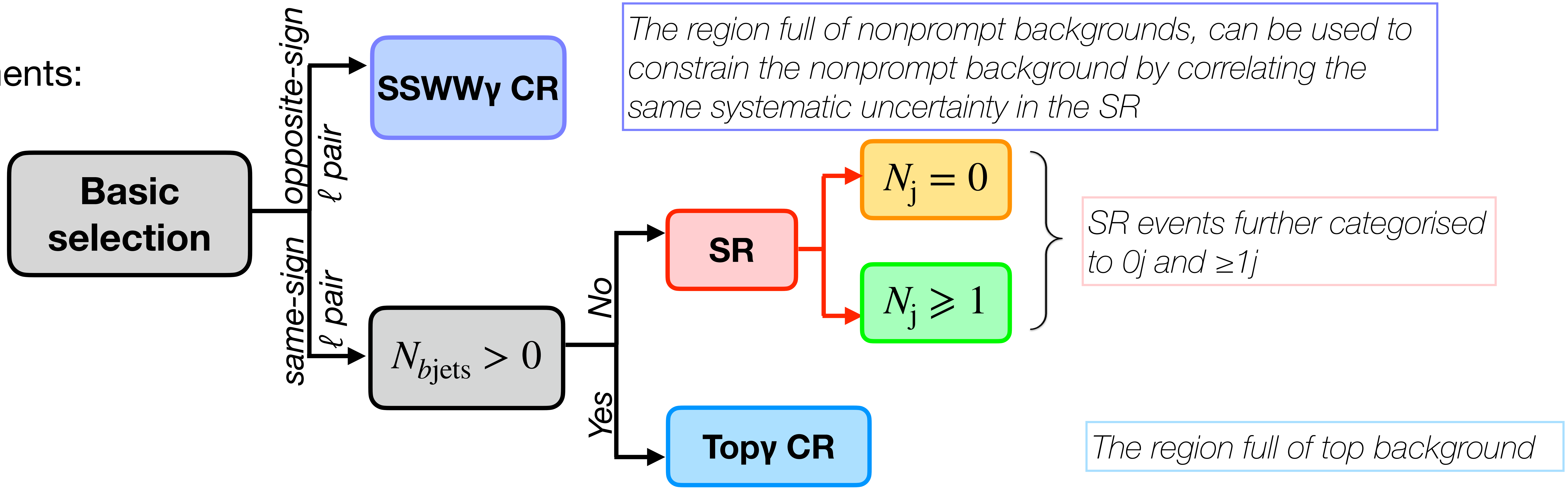
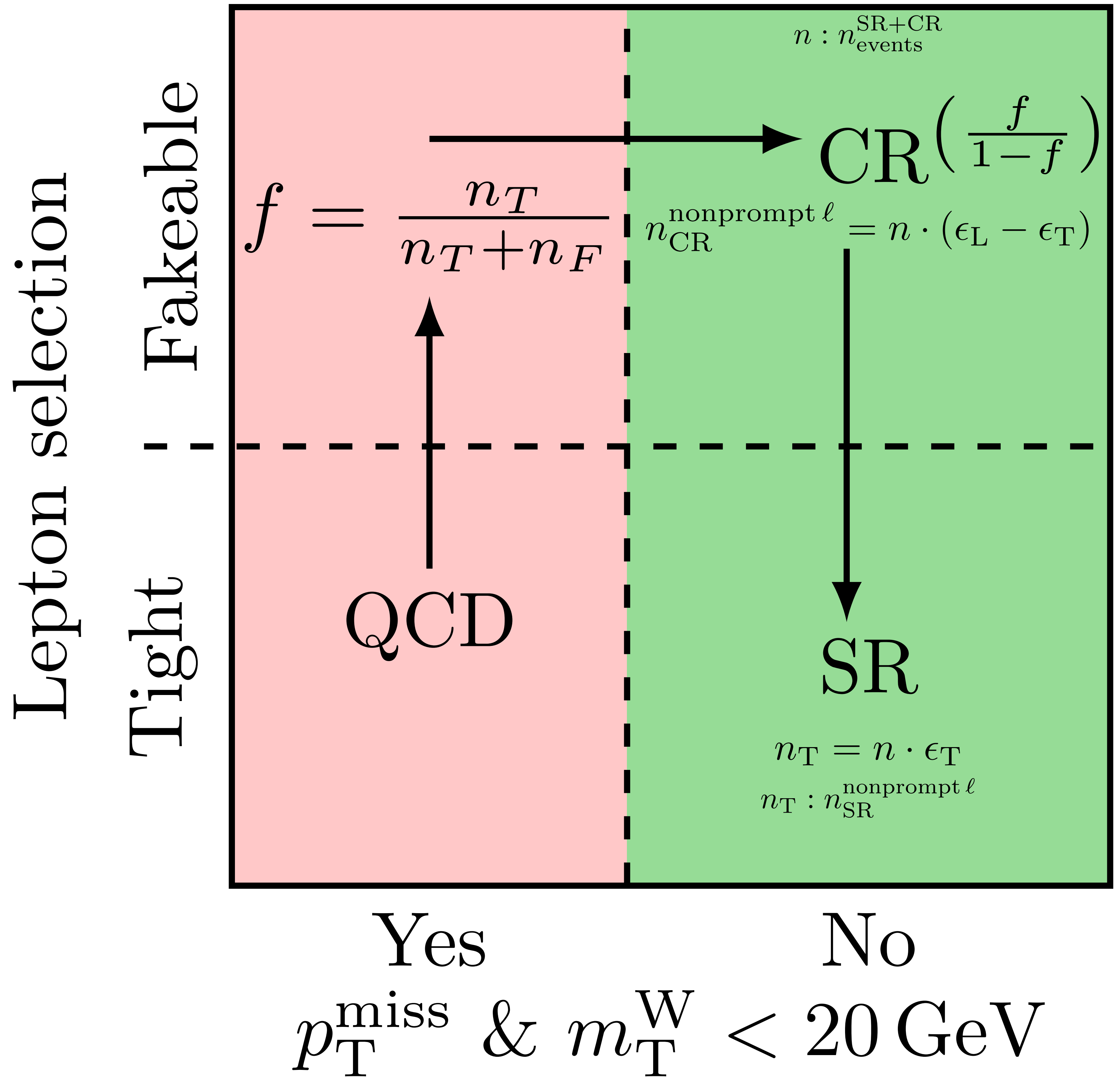


Nonprompt ℓ estimation



1. Build QCD jet-enriched region with requirements of
   - Exactly one lepton
   - $p_T^{miss} < 20$ GeV and $m_T^W < 20$ GeV
   - At least one jet with $p_T > 30$ 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 $f/(1-f)$

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

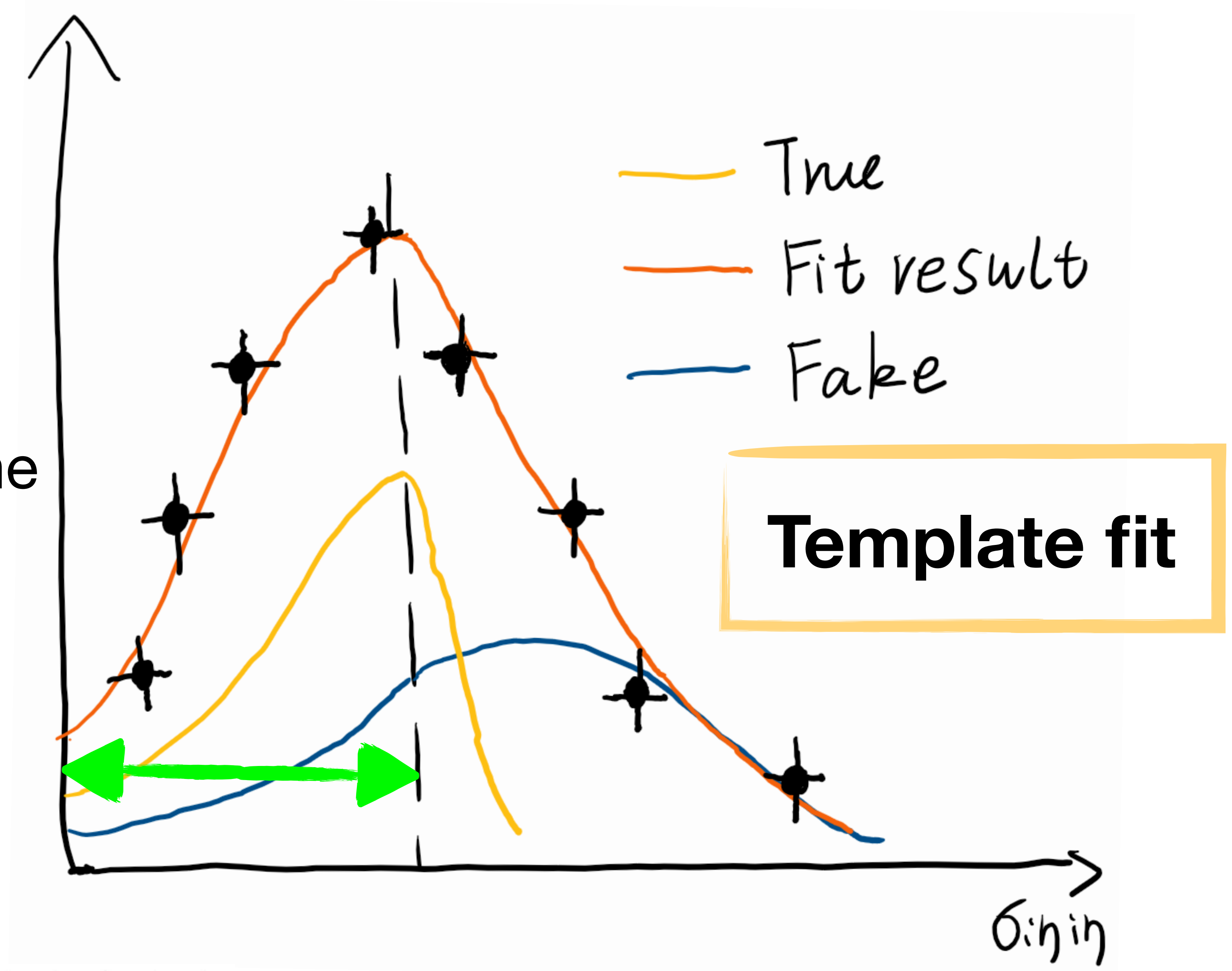
Nonprompt γ estimation — template fit

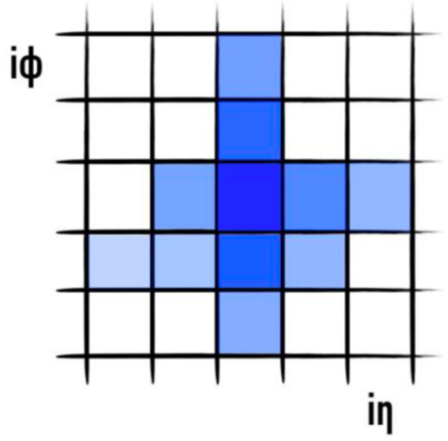
The main strategy of the nonprompt photon estimation is to build an **orthogonal region** to the SR **from data** with proper **weights** as functions of interesting variables applied

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

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

The shape of the histograms as pdf





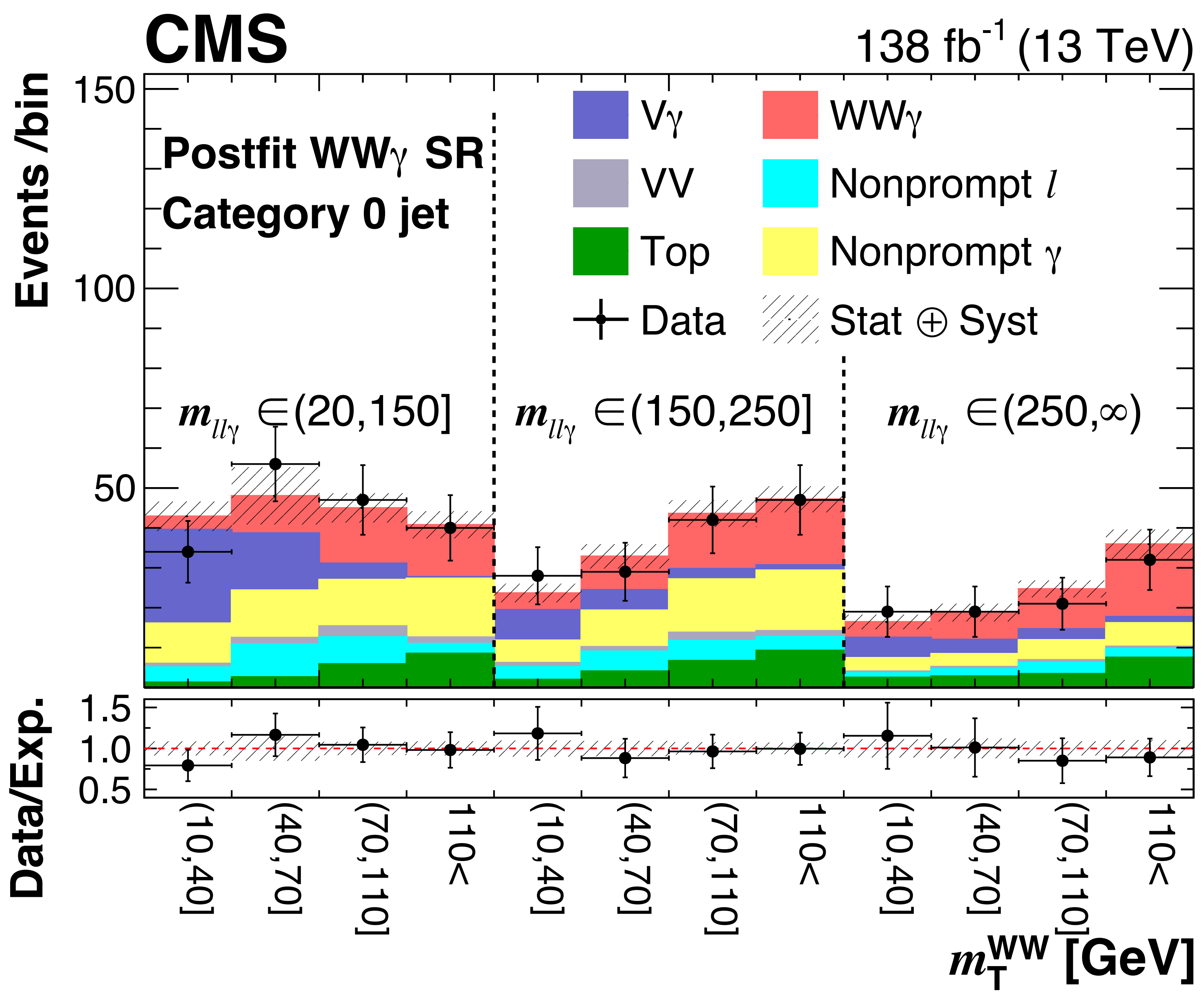
$$\sigma_{i\eta i\eta} = \sqrt{\frac{\sum_i^{5\times5} w_i(\eta_i - \bar{\eta}_{5\times5})^2}{\sum_i^{5\times5} w_i}}$$

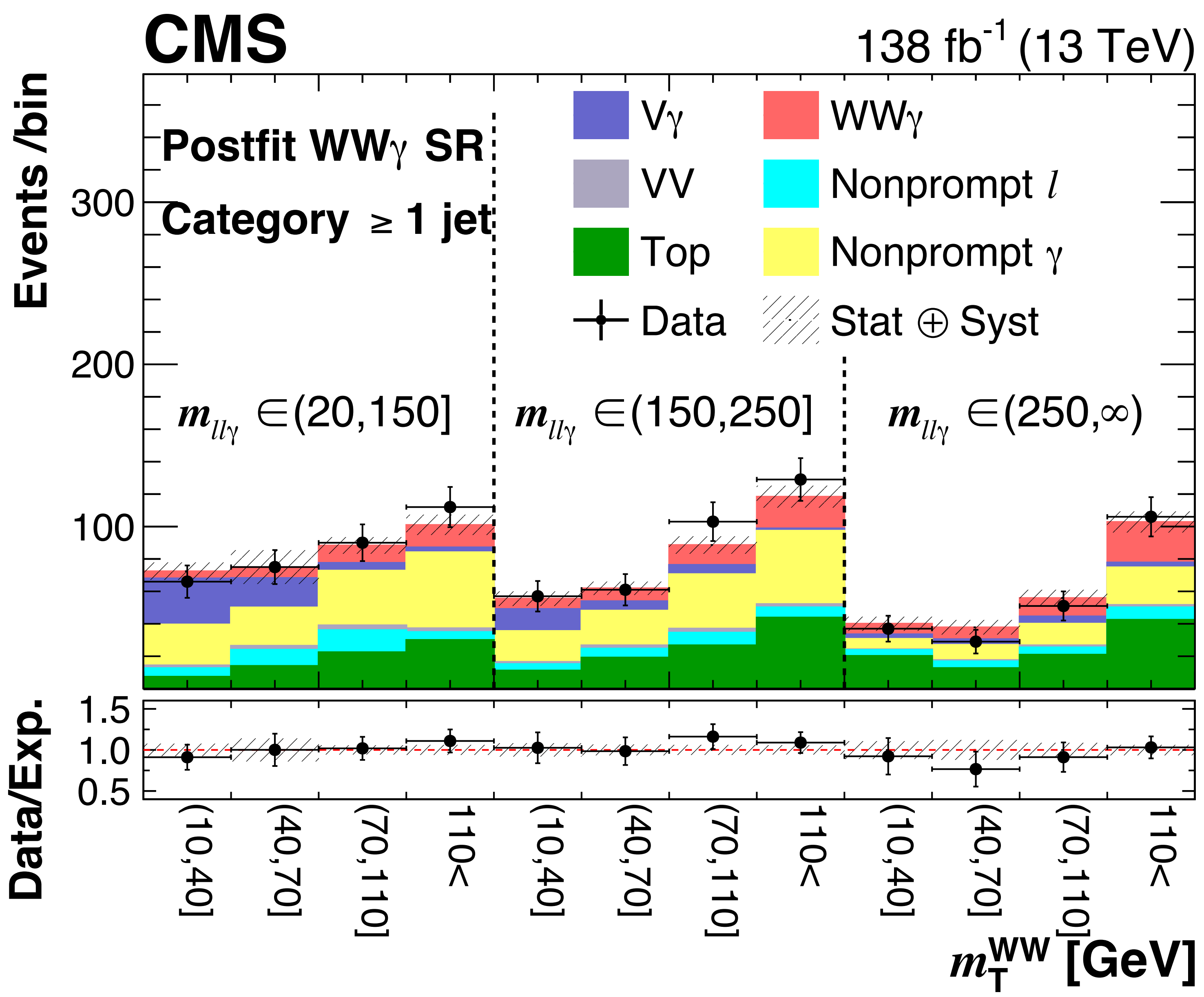
$w_i \neq 0$, if E_i > 0.9% of E_{5x5}

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

Triboson WWγ 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, ∞)

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

Topγ CR

m_T^{WW}: [10, ∞)

SSWWγ CR

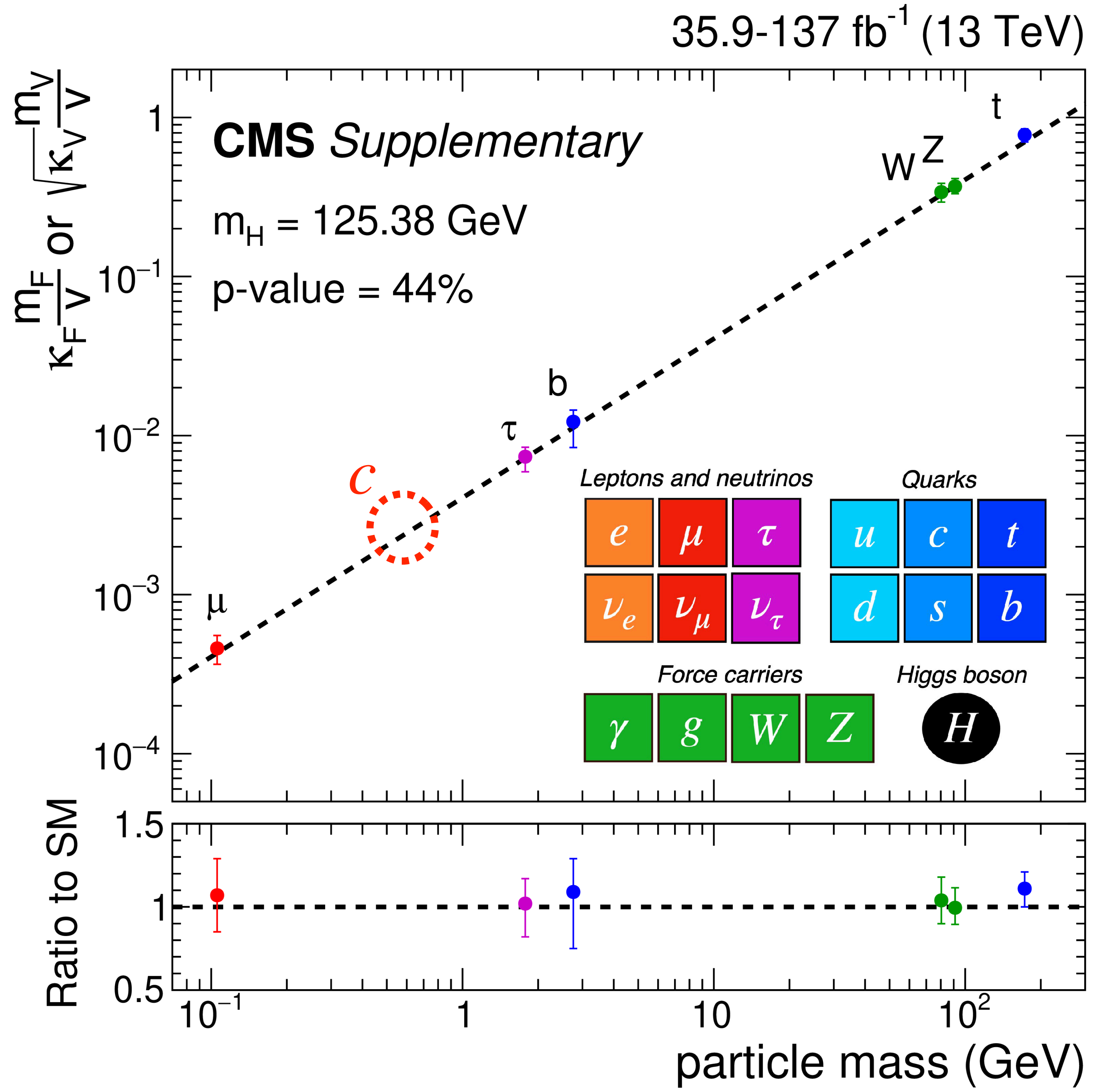
m_T^{WW}: [10, 40, 70, 110, ∞)

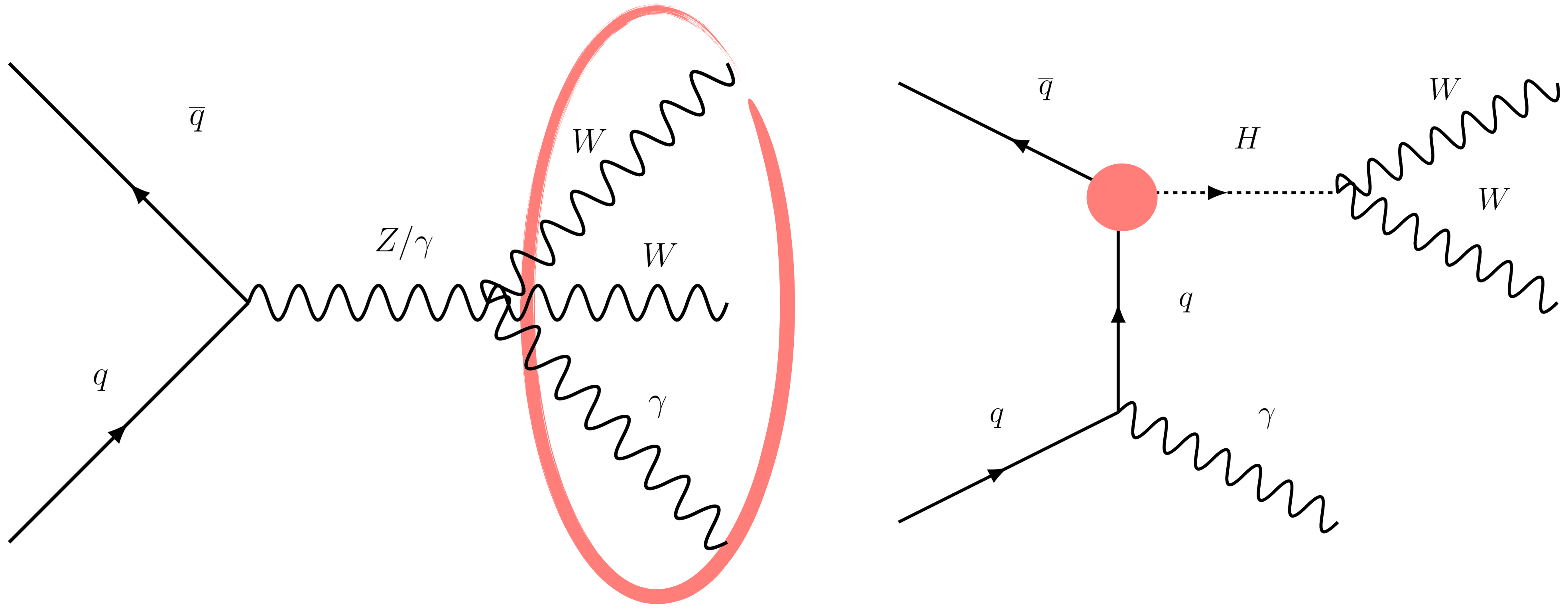
- Theoretical cross section from MadGraph at NLO QCD accuracy is:
  - $\sigma_{\text{th}} = 5.33 \pm 0.34\,(\text{scale}) \pm 0.05\,(\text{PDF})$ fb

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

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

Triboson H(→WW)γ — 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

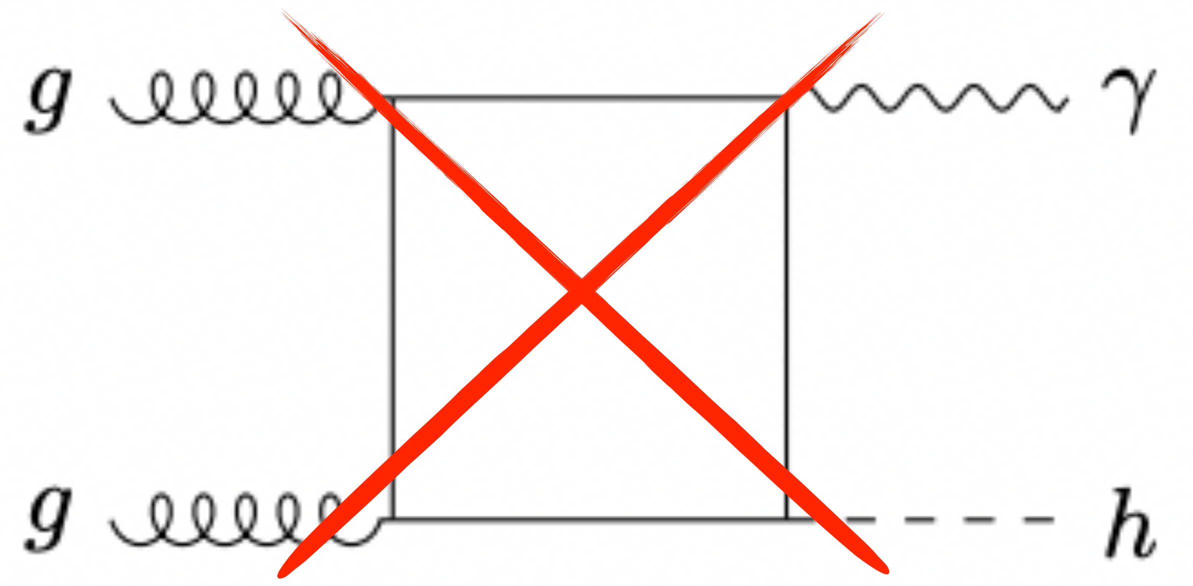
- VH(cc): the most sensitive channel
- ggH(cc): the boosted region explored in CMS

- H-s Yukawa coupling measurement is by H→ϕγ 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→ℓℓ, Z→νν, W→ℓν) [EPJC 82 (2022) 717]	$|\kappa_c| < 8.5$ (12.4)
CMS VH(cc) (Z→ℓℓ, Z→νν, W→ℓν) [arXiv:2205.05550]	**$1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$)**
CMS ggH(cc) [arXiv:2211.14181]	μ < 47 (39)

[1] https://doi.org/10.1007/JHEP07(2018)127
[2] https://doi.org/10.1103/PhysRevD.101.115005

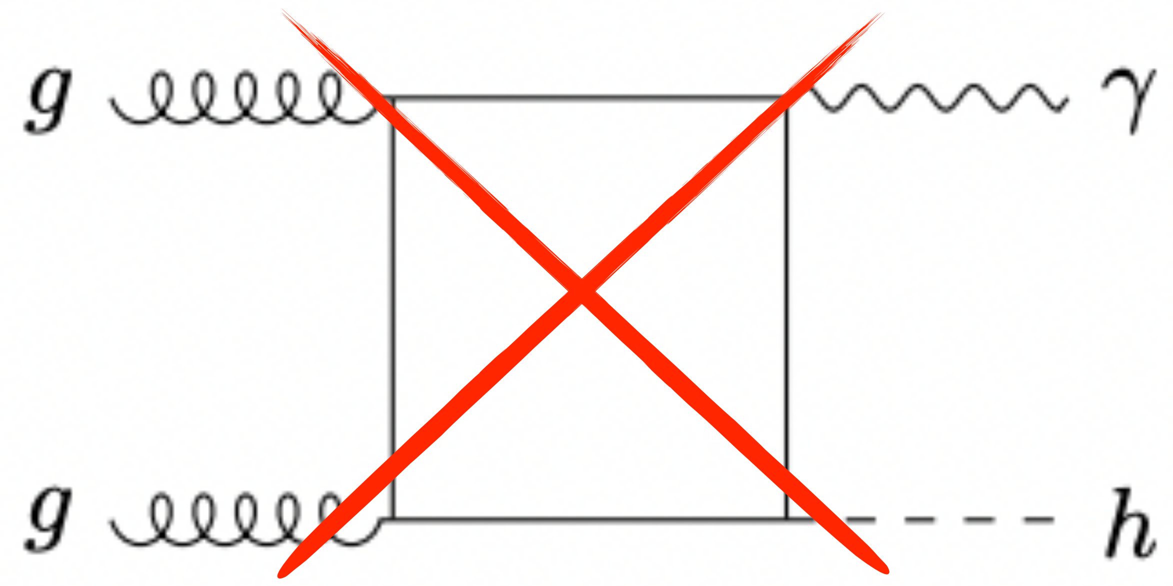
Triboson H(→WW)γ — Yukawa coupling interpretation



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

[1] https://journals.aps.org/pr/abstract/10.1103/PhysRev.51.125

Triboson H(→WW)γ — Yukawa coupling interpretation



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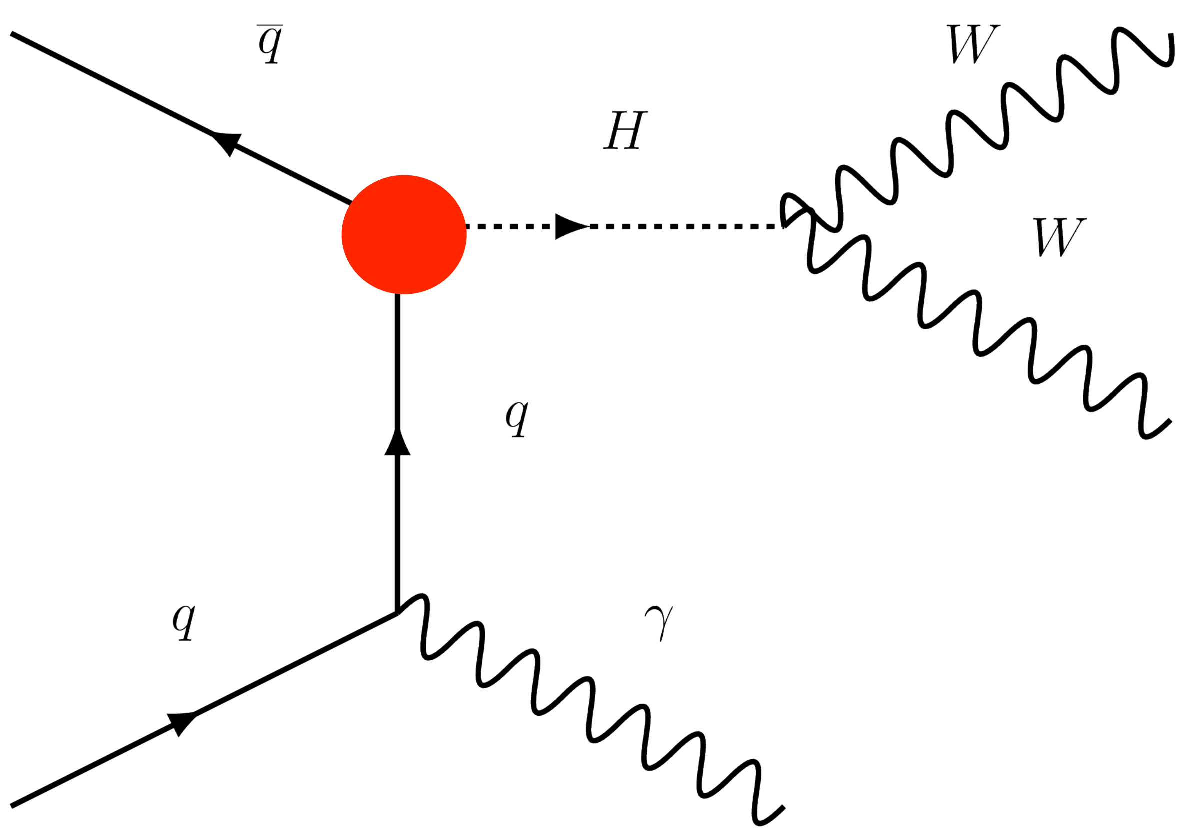

For $q = u, d, s$

1. **MadGraph**
   - Model "*Higgs effective Lagrangian*"
     - Quark masses in $\overline{\text{MS}}$ scheme from PDG are used
   - Process: $q\bar{q} \to \text{H}\gamma$
2. **JHU generator**
   - $\text{H} \to \text{W}^{+}\text{W}^{-} \to e^{\pm}\mu^{\mp}\nu_{e}\bar{\nu}_{\mu}$

For $q = c$

1. **MadGraph**
   - Model: *loop_sm_MSbar_yb_yc-yc4FS*
     - Closely following theory studies for bbH (1409.5301)
   - Process: $q\bar{q} \to \text{H}\gamma$ [QCD]
2. **JHU generator**
   - $\text{H} \to \text{W}^{+}\text{W}^{-} \to e^{\pm}\mu^{\mp}\nu_{e}\bar{\nu}_{\mu}$

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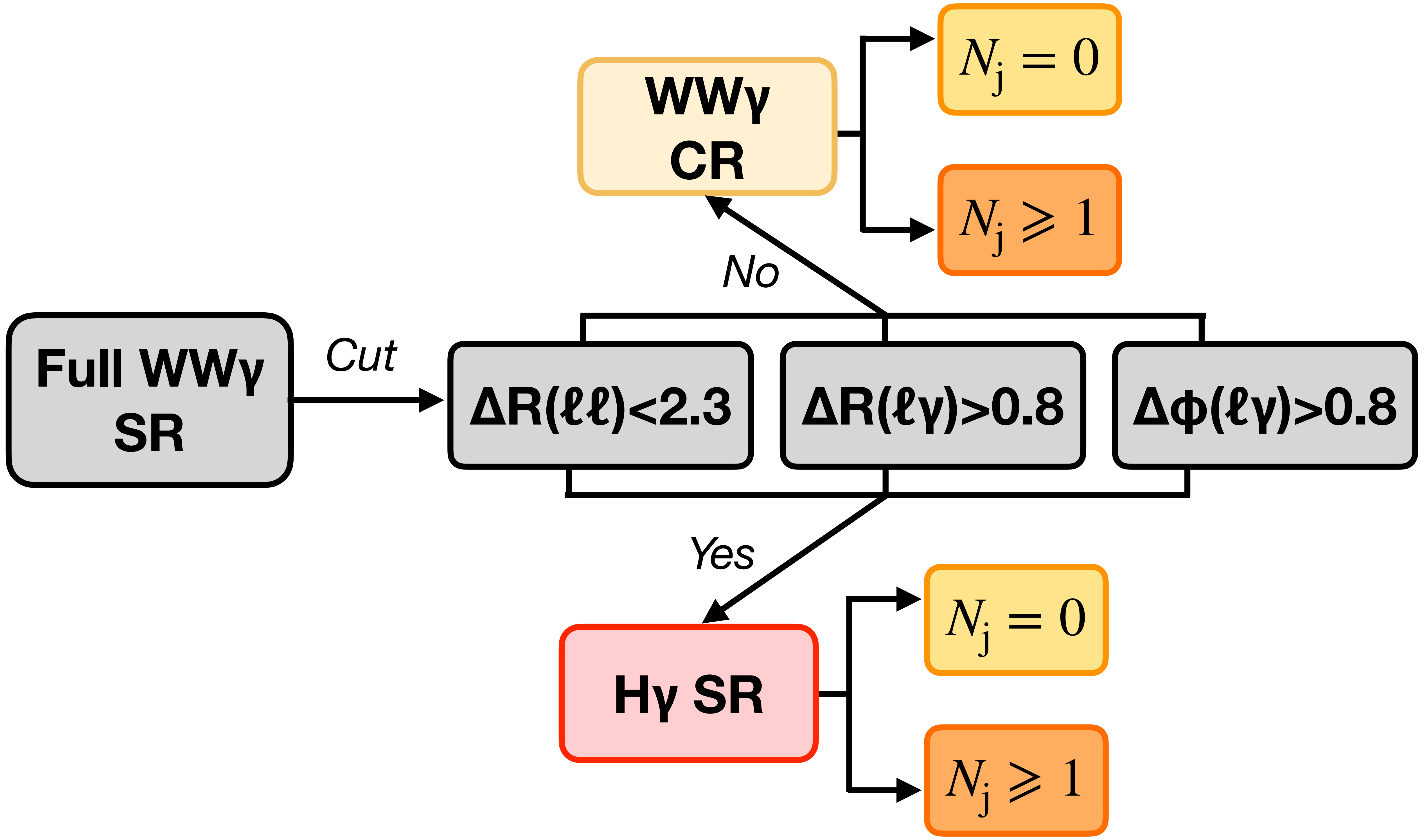
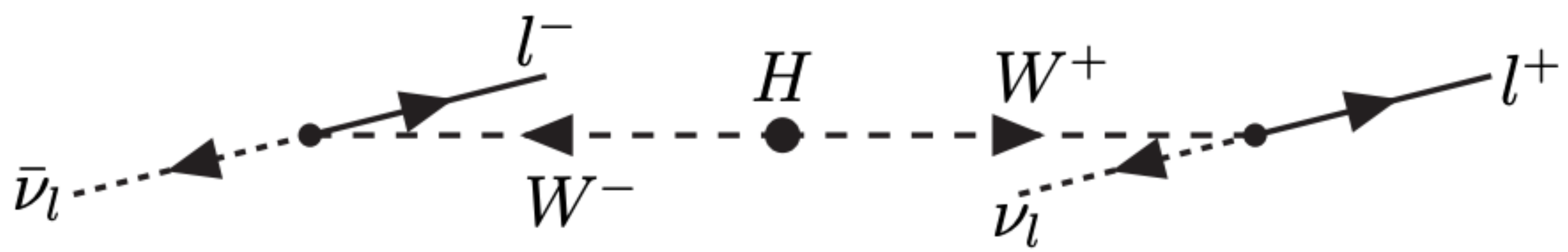
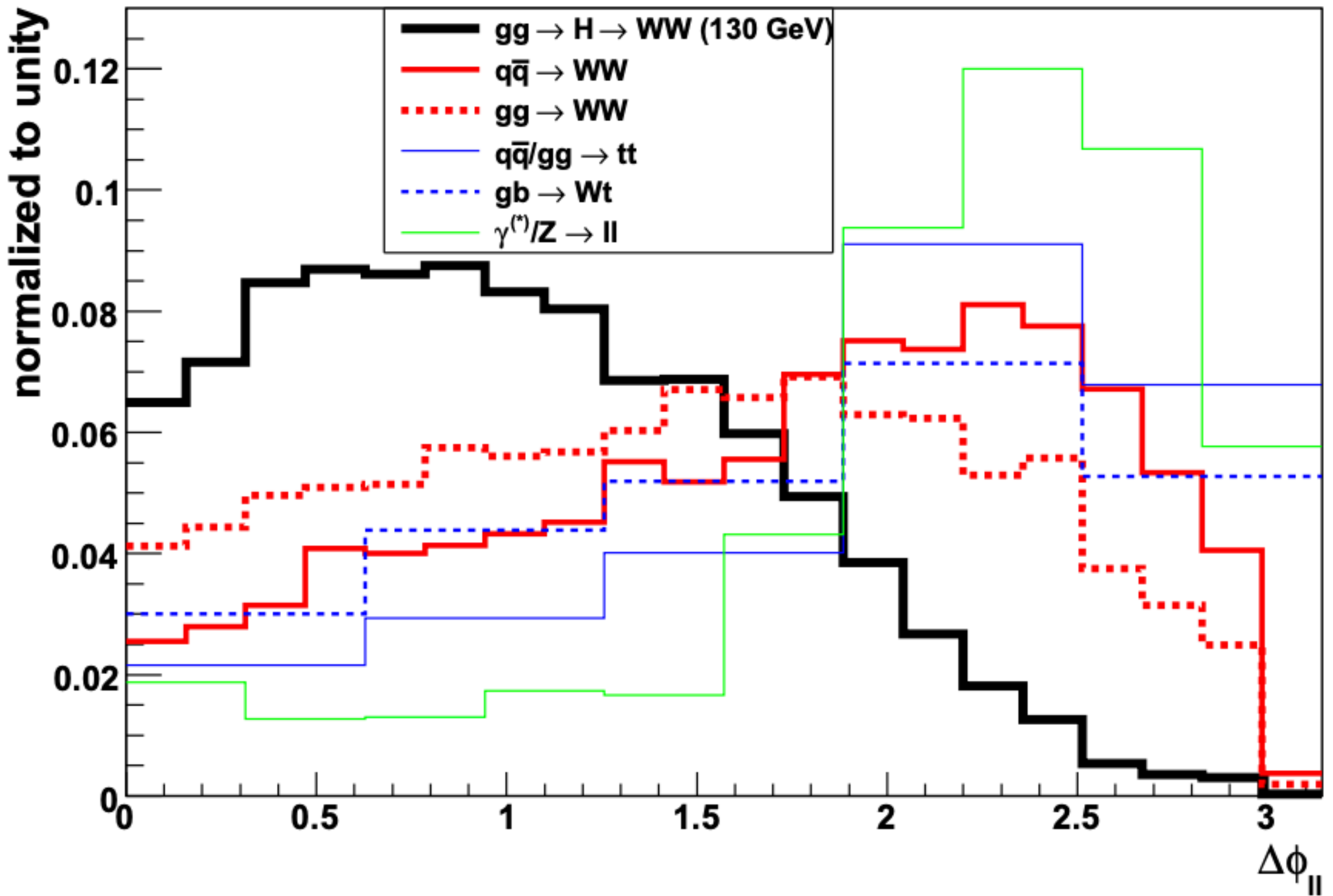
Triboson H(→WW)γ — Yukawa coupling interpretation





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(→WW)γ — Yukawa coupling interpretation

Cross section limits

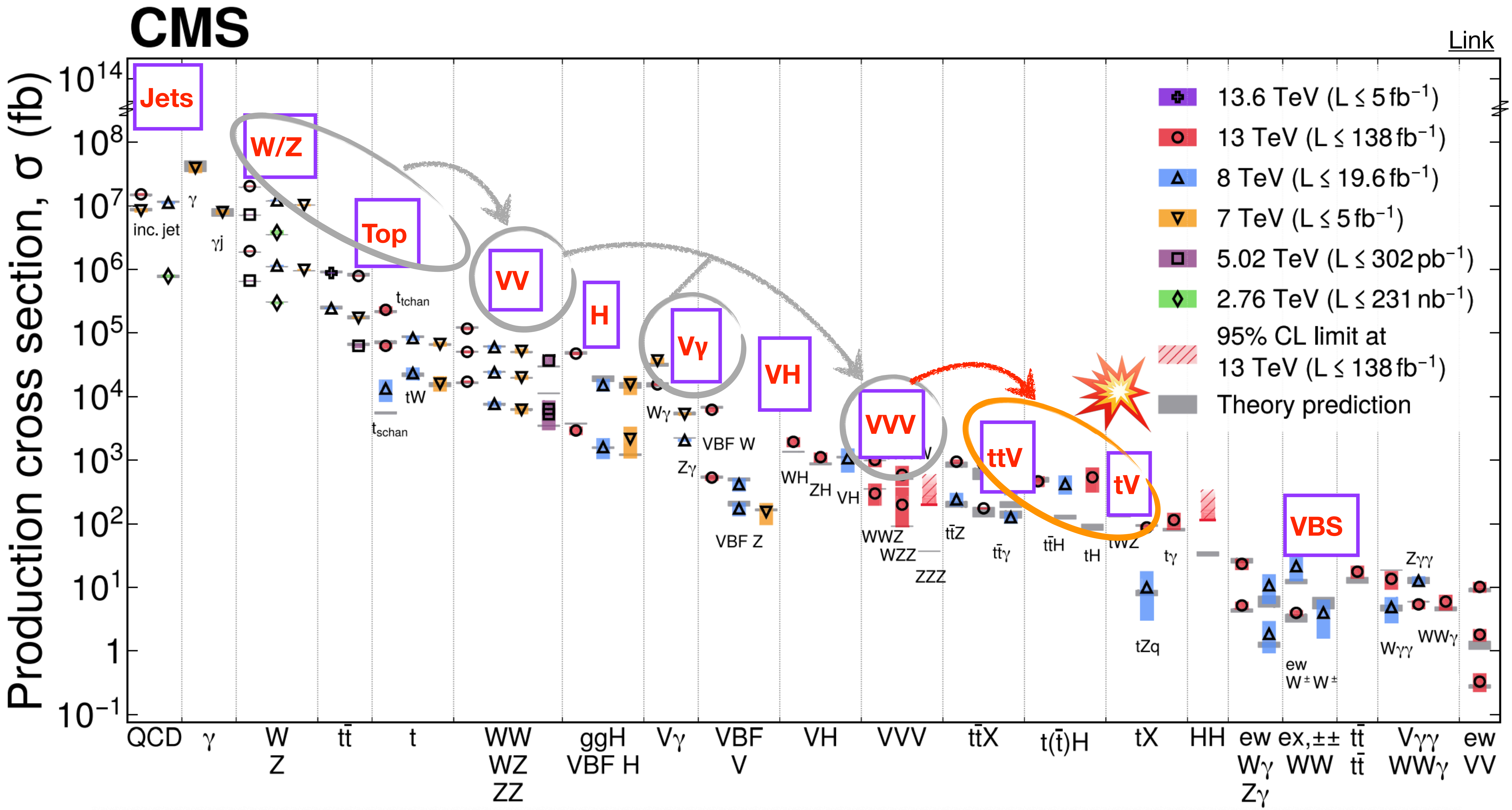
Process	σ upper limits obs. (exp.) [fb]
$\mathrm{u\bar{u}} \to \mathrm{H} + \gamma \to \mathrm{e}\mu\nu_{\mathrm{e}}\nu_{\mu}\gamma$	85 (67)
$\mathrm{d\bar{d}} \to \mathrm{H} + \gamma \to \mathrm{e}\mu\nu_{\mathrm{e}}\nu_{\mu}\gamma$	72 (58)
$\mathrm{s\bar{s}} \to \mathrm{H} + \gamma \to \mathrm{e}\mu\nu_{\mathrm{e}}\nu_{\mu}\gamma$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

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

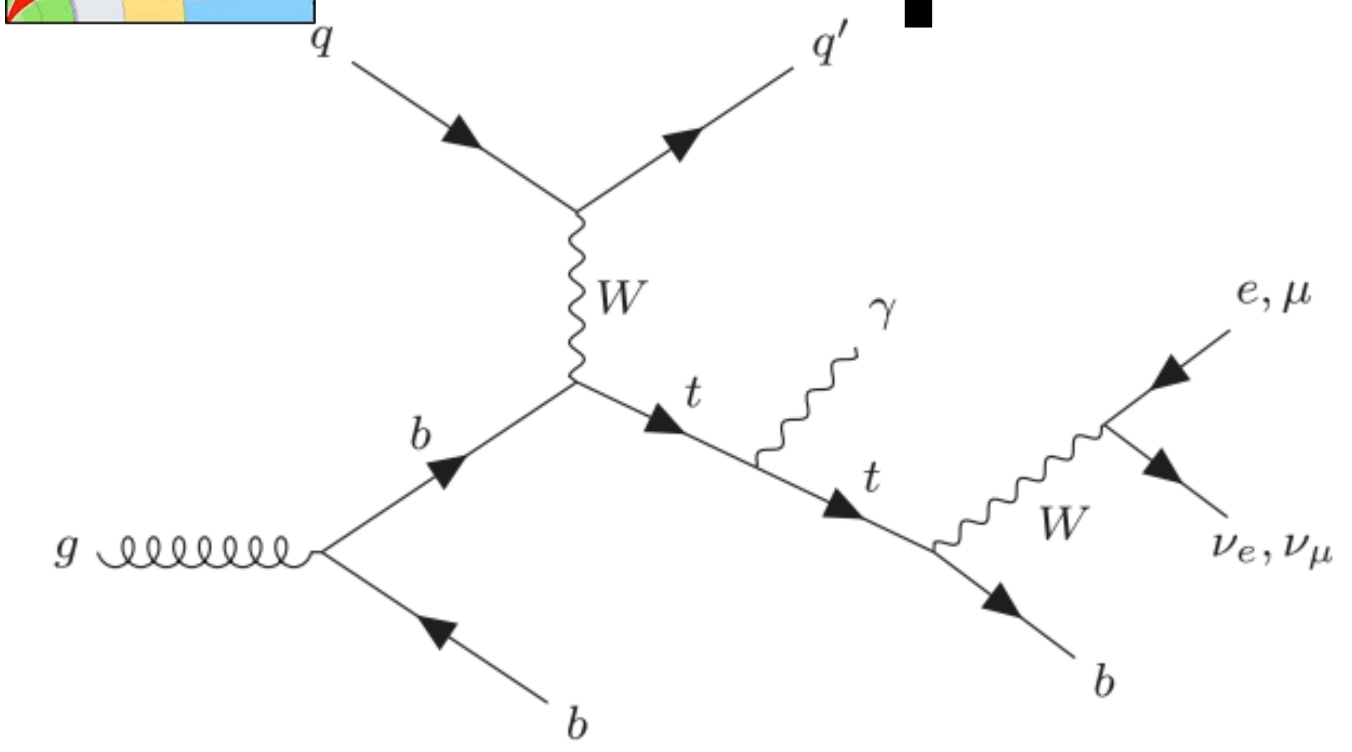
- $\kappa_{\mathrm{H}}^2 \approx \dfrac{1 - Br^{\mathrm{SM}}_{q\bar{q}}}{2} + \dfrac{\sqrt{(1 - Br^{\mathrm{SM}}_{q\bar{q}})^2 + 4Br^{\mathrm{SM}}_{q\bar{q}}\kappa_q^2}}{2}$
- Hγ rate can be scaled with $\kappa_q^2 \times \dfrac{\kappa_{\mathrm{H}}^2}{(1 - Br^{\mathrm{SM}}_{q\bar{q}})\kappa_{\mathrm{H}}^2 + Br^{\mathrm{SM}}_{q\bar{q}}\kappa_q^2}$

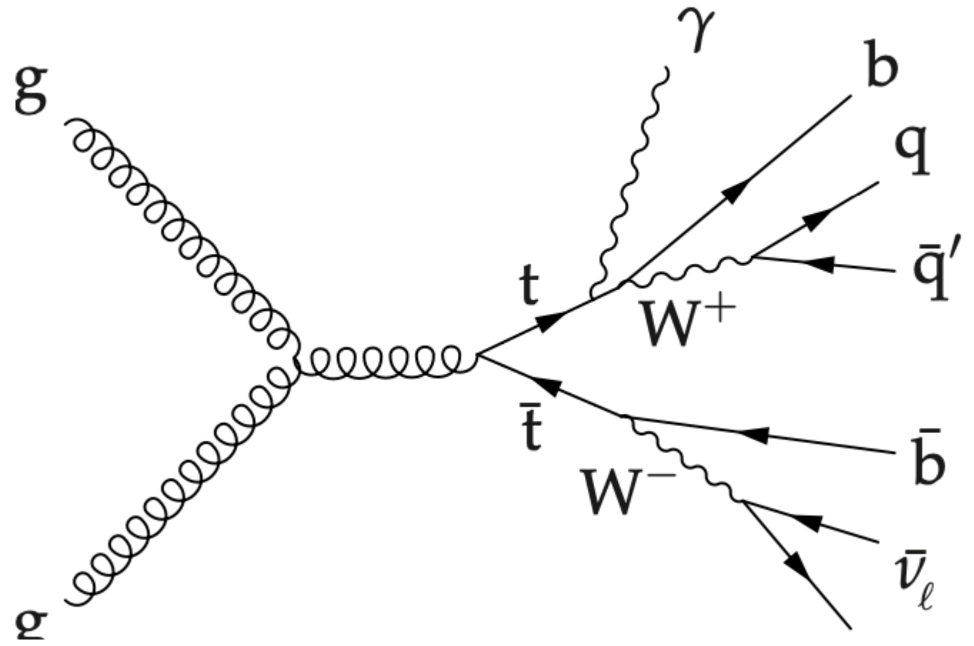
κ_{q} limits obs. (exp.) at 95% CL
$\lvert\kappa_{\mathrm{u}}\rvert \leq 16000\ (13000)$
$\lvert\kappa_{\mathrm{d}}\rvert \leq 17000\ (14000)$
$\lvert\kappa_{\mathrm{s}}\rvert \leq 1700\ (1300)$
$\lvert\kappa_{\mathrm{c}}\rvert \leq 200\ (110)$

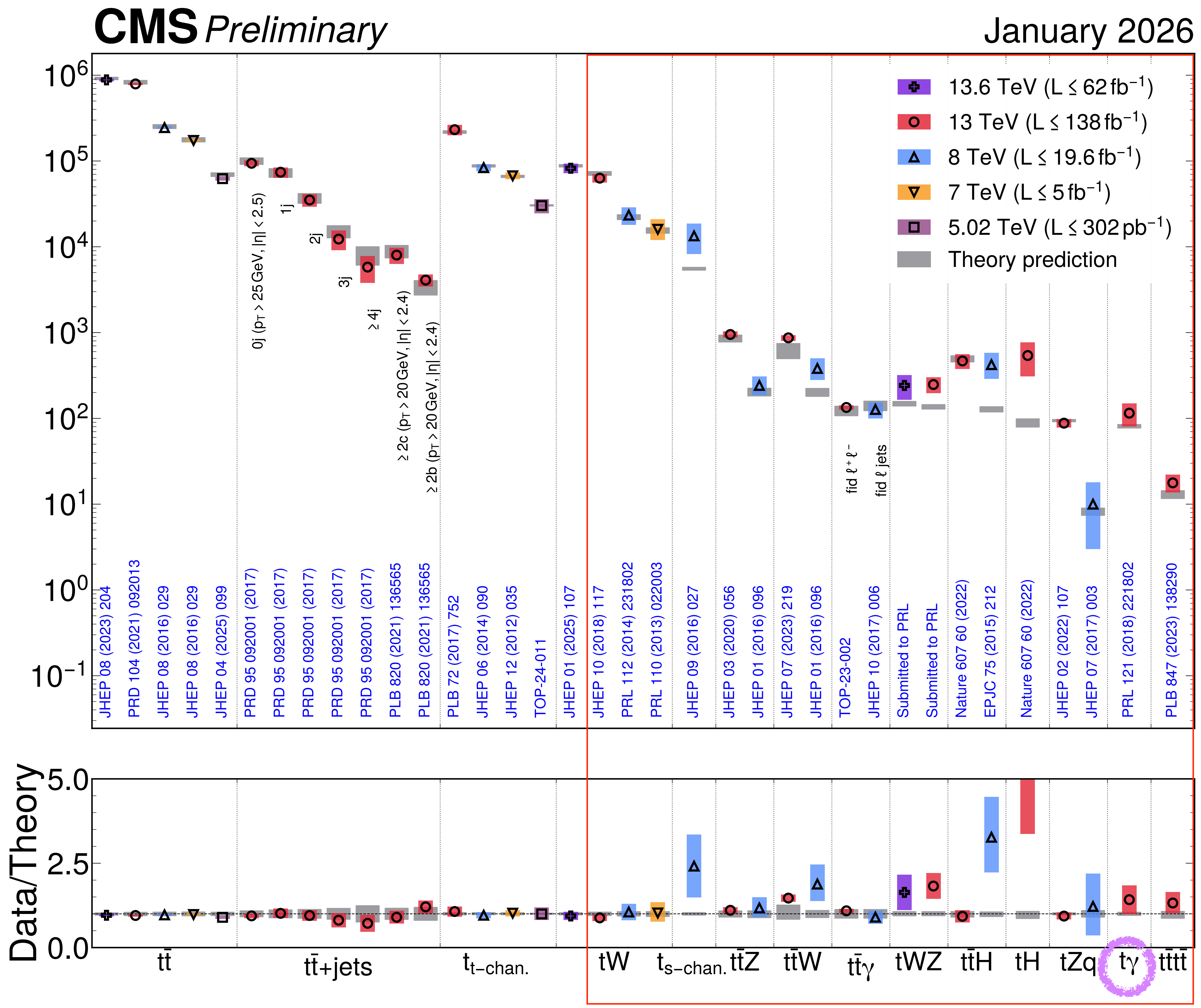
[1] https://journals.aps.org/prd/pdf/10.1103/PhysRevD.100.073013


CMS
Link
Production cross section, σ (fb)
Jets
W/Z
Top
VV
H
Vγ
VH
VVV
ttV
tV
VBS
13.6 TeV (L ≲ 5 fb⁻¹)
13 TeV (L ≲ 138 fb⁻¹)
8 TeV (L ≲ 19.6 fb⁻¹)
7 TeV (L ≲ 5 fb⁻¹)
5.02 TeV (L ≲ 302 pb⁻¹)
2.76 TeV (L ≲ 231 nb⁻¹)
95% CL limit at 13 TeV (L ≲ 138 fb⁻¹)
Theory prediction
inc. jet
γj
t_tchan
tW
t_schan
Wγ
Zγ
VBF W
VBF Z
WH
ZH
VH
WWZ
WZZ
ZZZ
tt̄Z
tt̄γ
tt̄H
tH
tWZ
tγ
tZq
ew W±W±
Zγγ
Wγγ
WWγ
QCD
γ
W
Z
tt̄
t
WW
WZ
ZZ
ggH
VBF H
Vγ
VBF
V
VH
VVV
tt̄X
t(t̄)H
tX
HH
ew
Wγ
Zγ
ex,±±
WW
tt̄
tt̄
Vγγ
WWγ
ew
VV

Top couplings — with bosons







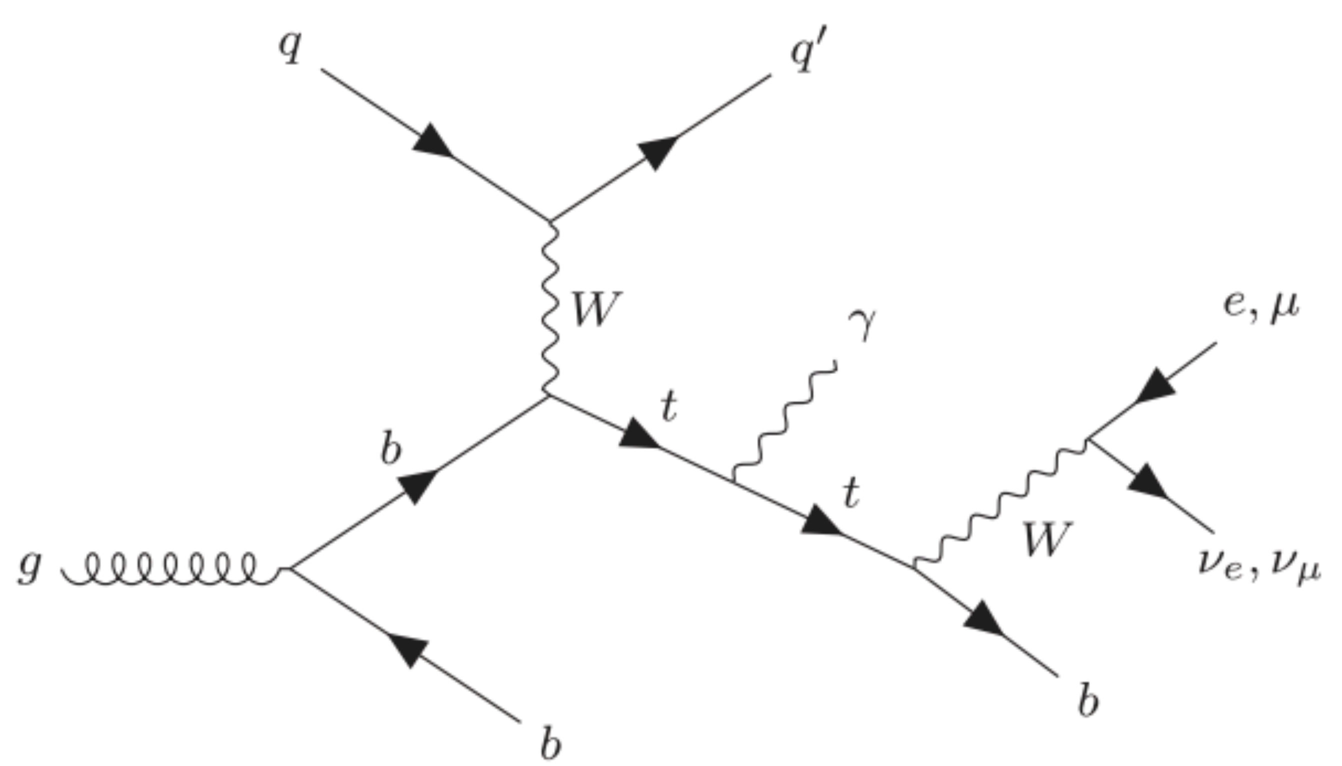
- The tγq process is observed by ATLAS. CMS so far only has evidence for tγq, **first-ever tγq differential** cross sections and **simultaneous tγq+ttγ** cross section
- These processes represent a direct probe of the top-photon coupling
  - Precise measurements provide a stringent test of SM predictions
  - Anomalous top-photon electroweak coupling via EFT fit to tγq+ttγ

Simultaneous measurement of the tγq+ttγ

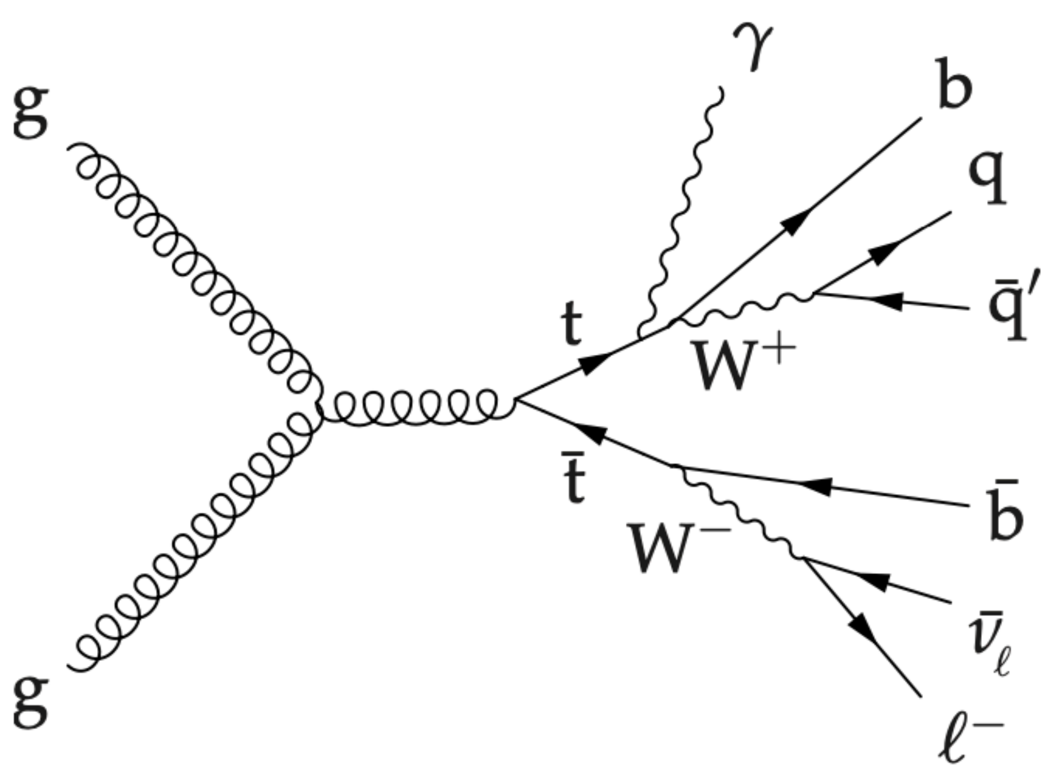
- Full set of correlations between the two processes
- Possible for a more straightforward EFT interpretation

CMS-PAS-TOP-25-003

Top couplings — Simultaneous tγq and $t\bar{t}\gamma$



Low cross section ~1 pb



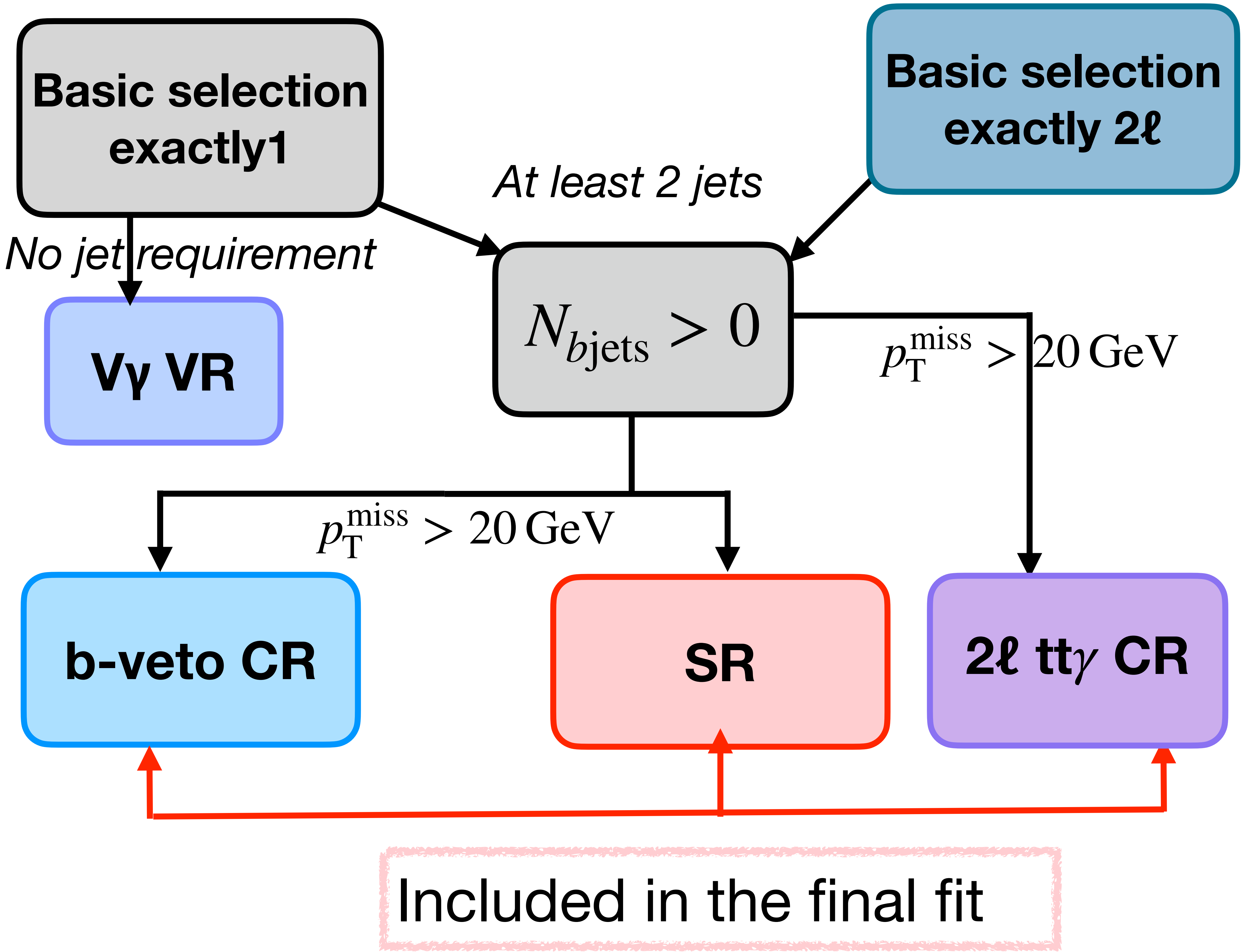
High cross section ~500 pb

Signal events (**N_ℓ=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 tγq, $t\bar{t}\gamma$ and others

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

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



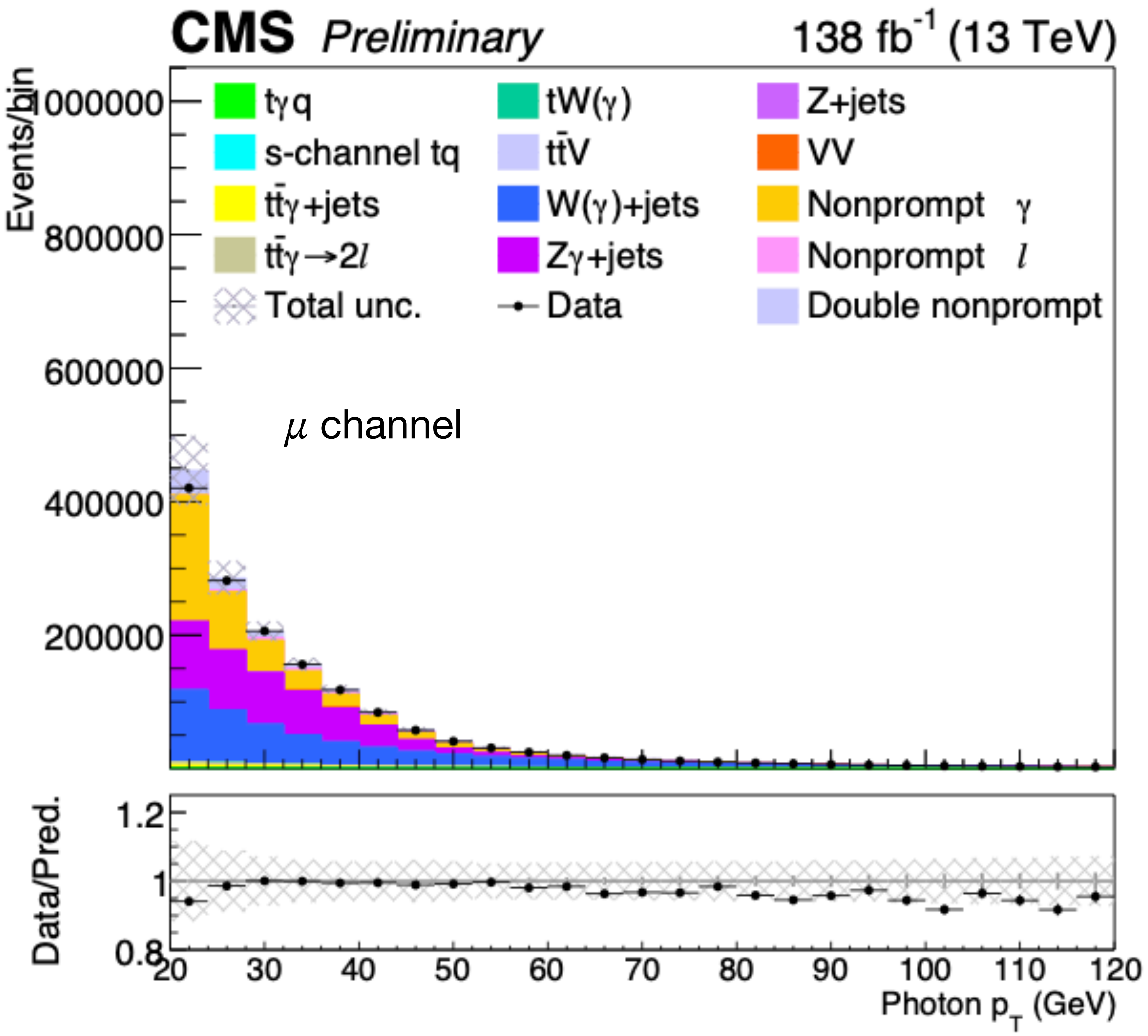
Background estimation — ele misID validation

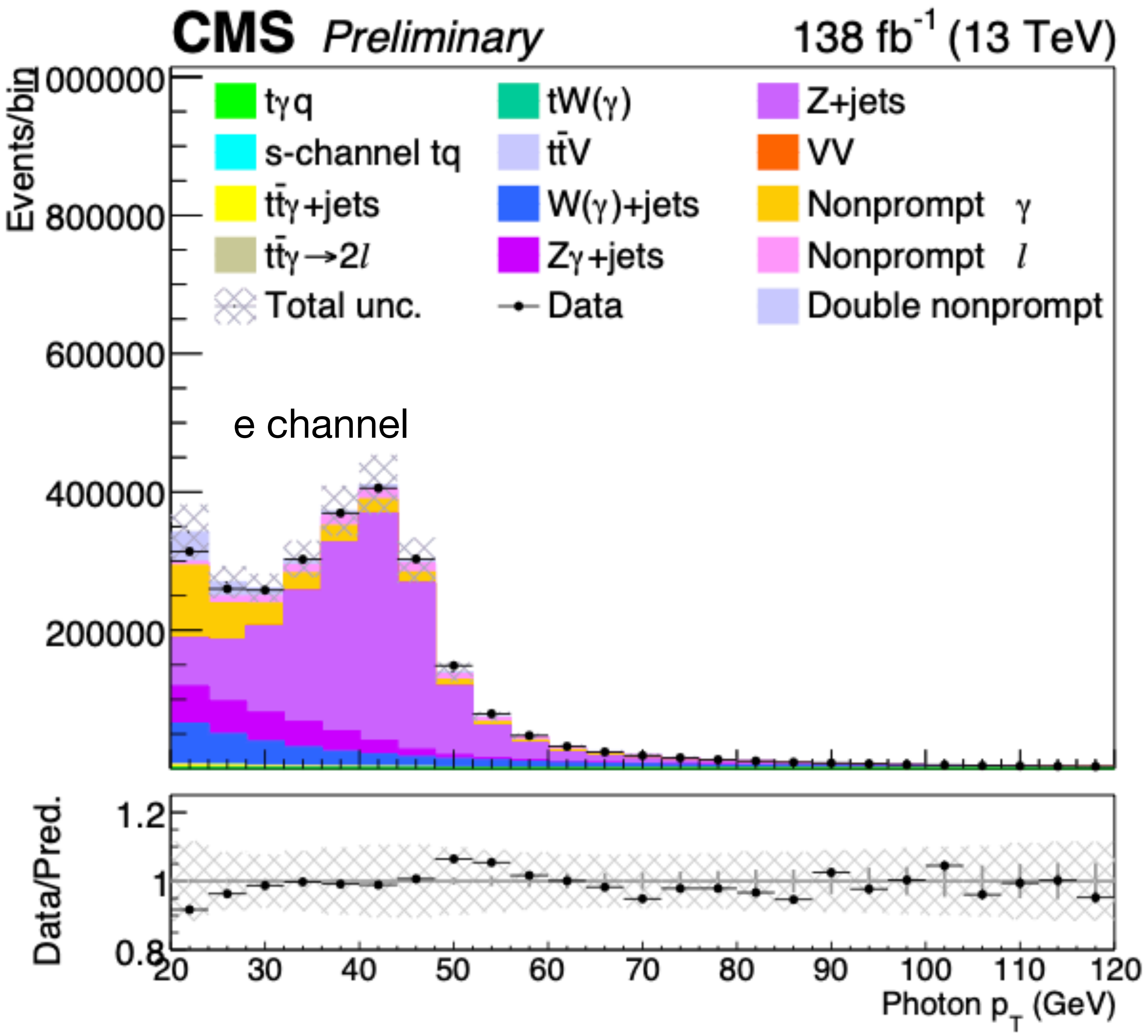
Disagreement can be cured by <u>normalisation factor</u> ***derived from $m_{l\gamma}$ distribution***

→ *Float the misID normalisation in the fit as rateParam*

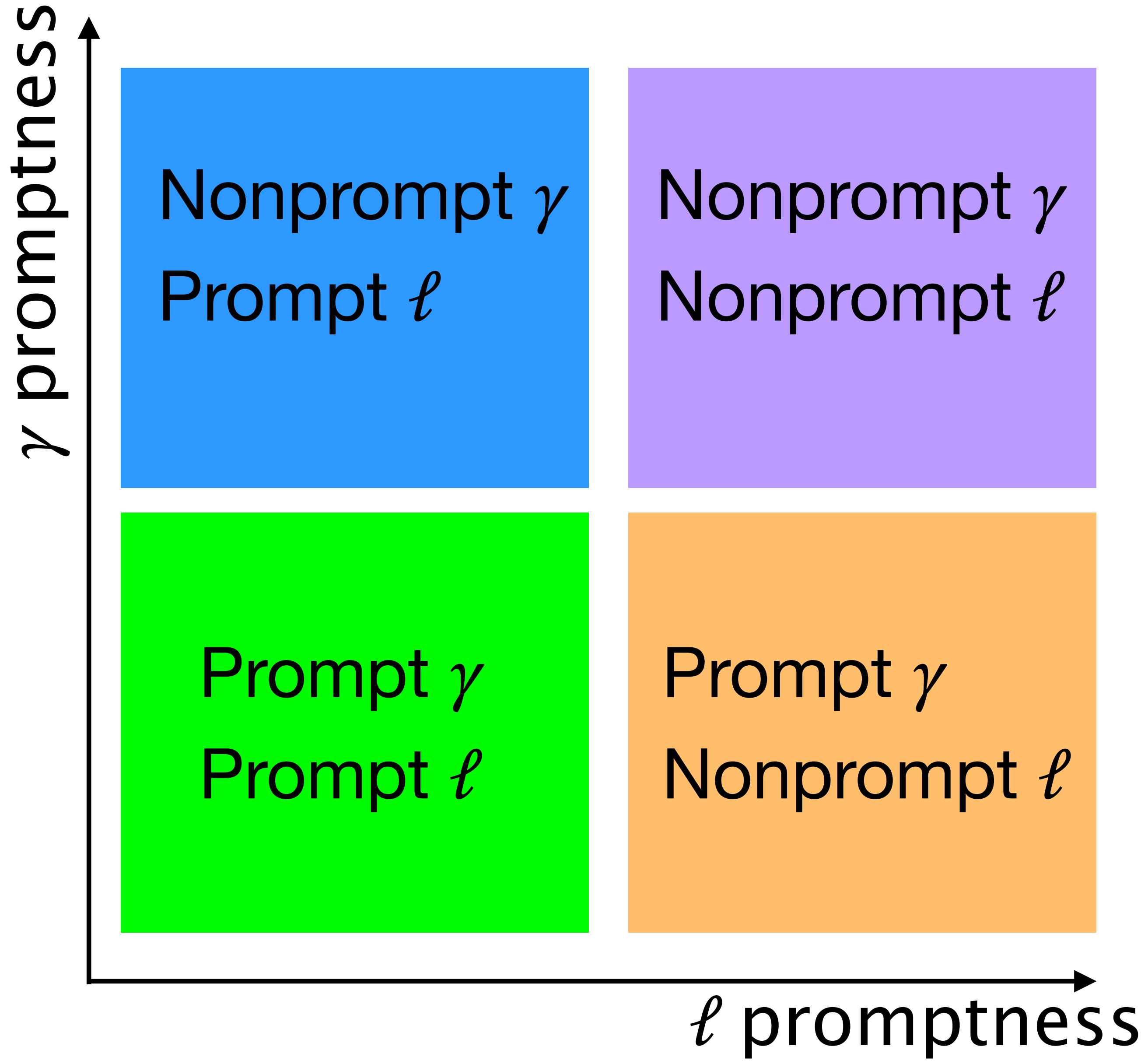
Validation by checking agreement from other kinematic distributions in Vγ VR

→ <u>No shape mismodeling, agreement can be fixed by the simple normalization factor</u>





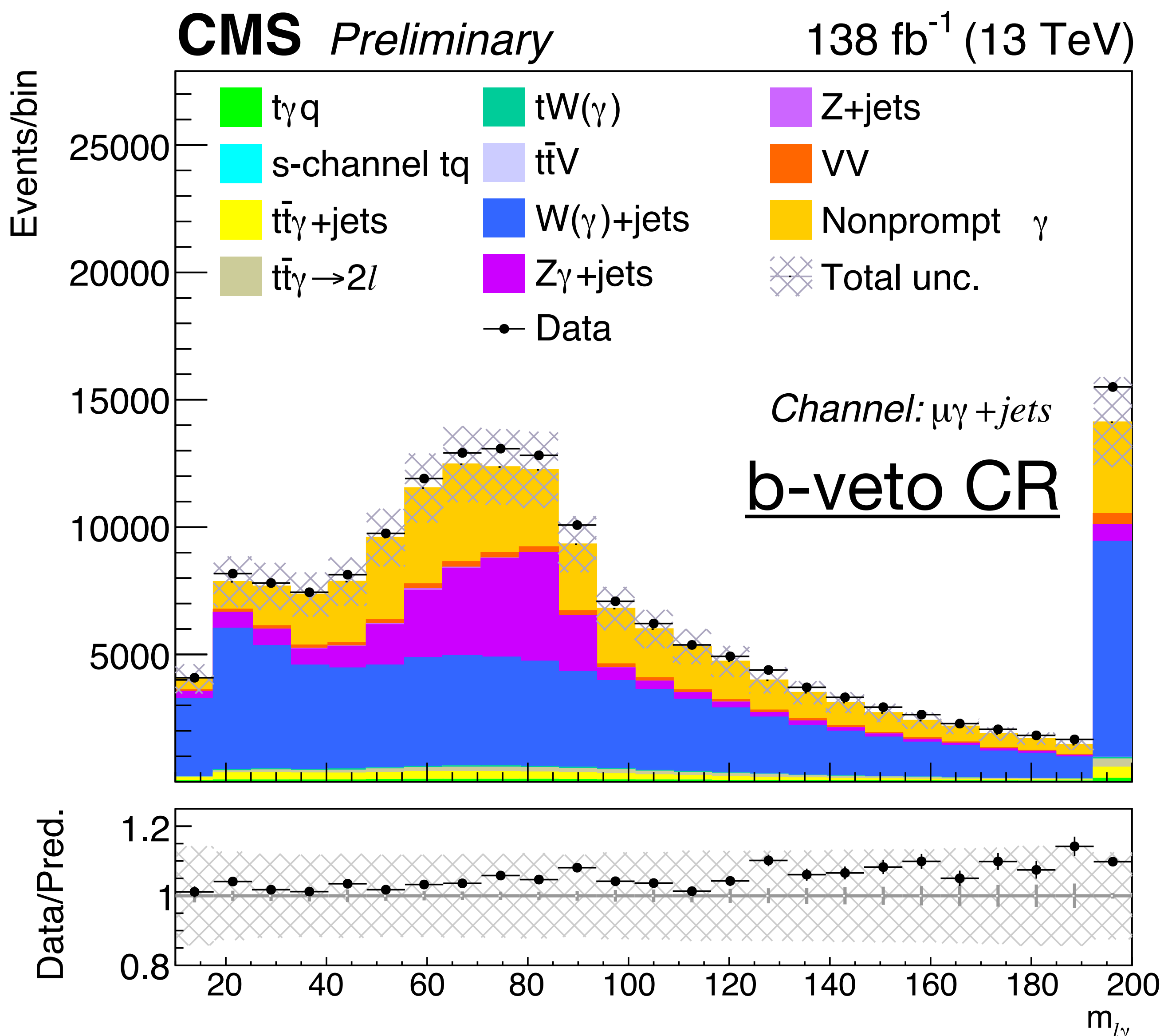
Background estimation — Double Nonprompt



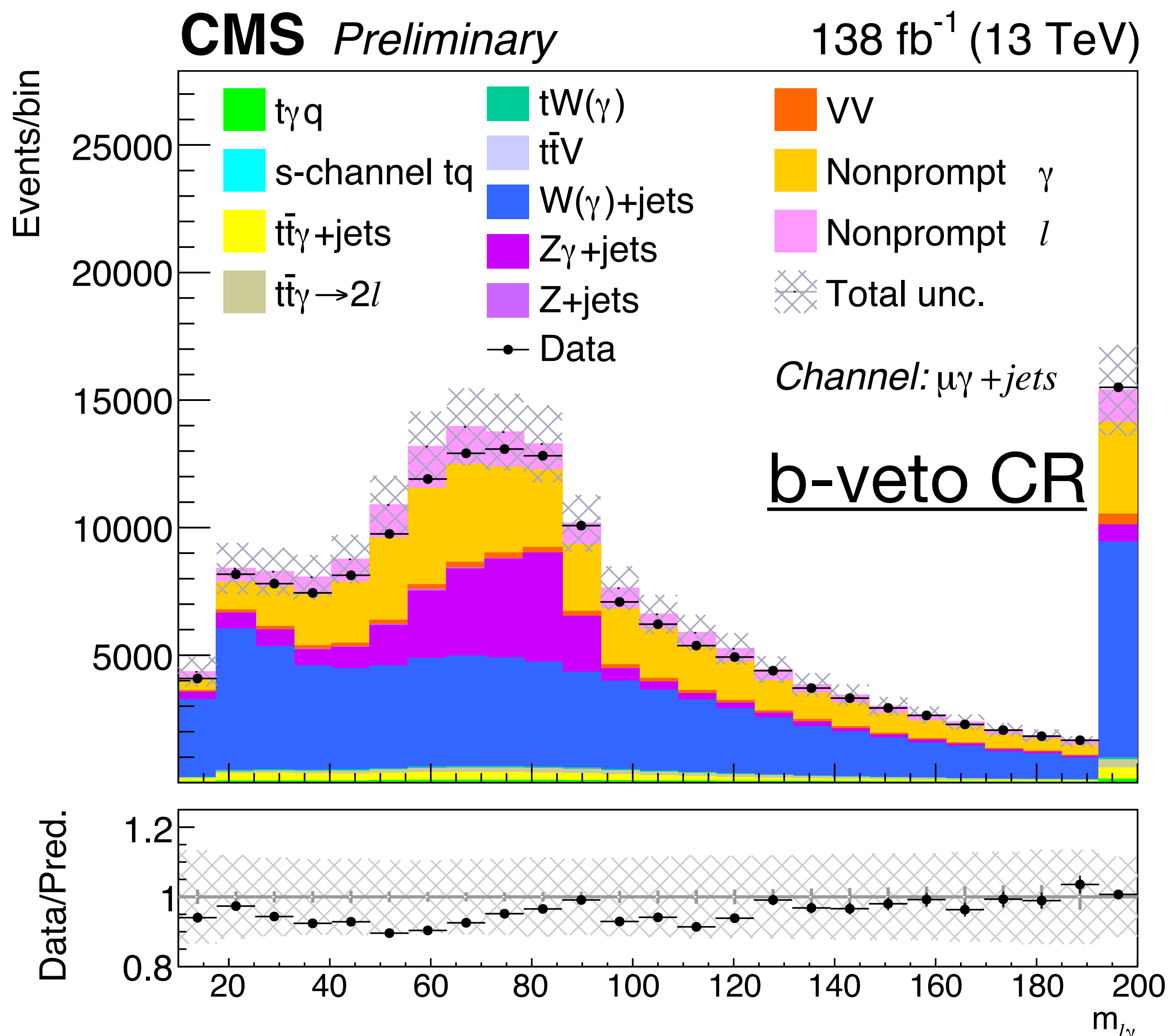
Each data-driven sample contains contributions as the left plot. If we use these two data-driven samples simultaneously, the nonprompt ℓ/γ, and double nonprompt contributions are **double counted, especially important for single lepton channel**

$$(N_{\text{nonprompt}\gamma} - N_{\text{double nonprompt}}) + (N_{\text{nonprompt}\ell} - N_{\text{double nonprompt}}) + N_{\text{double nonprompt}}$$

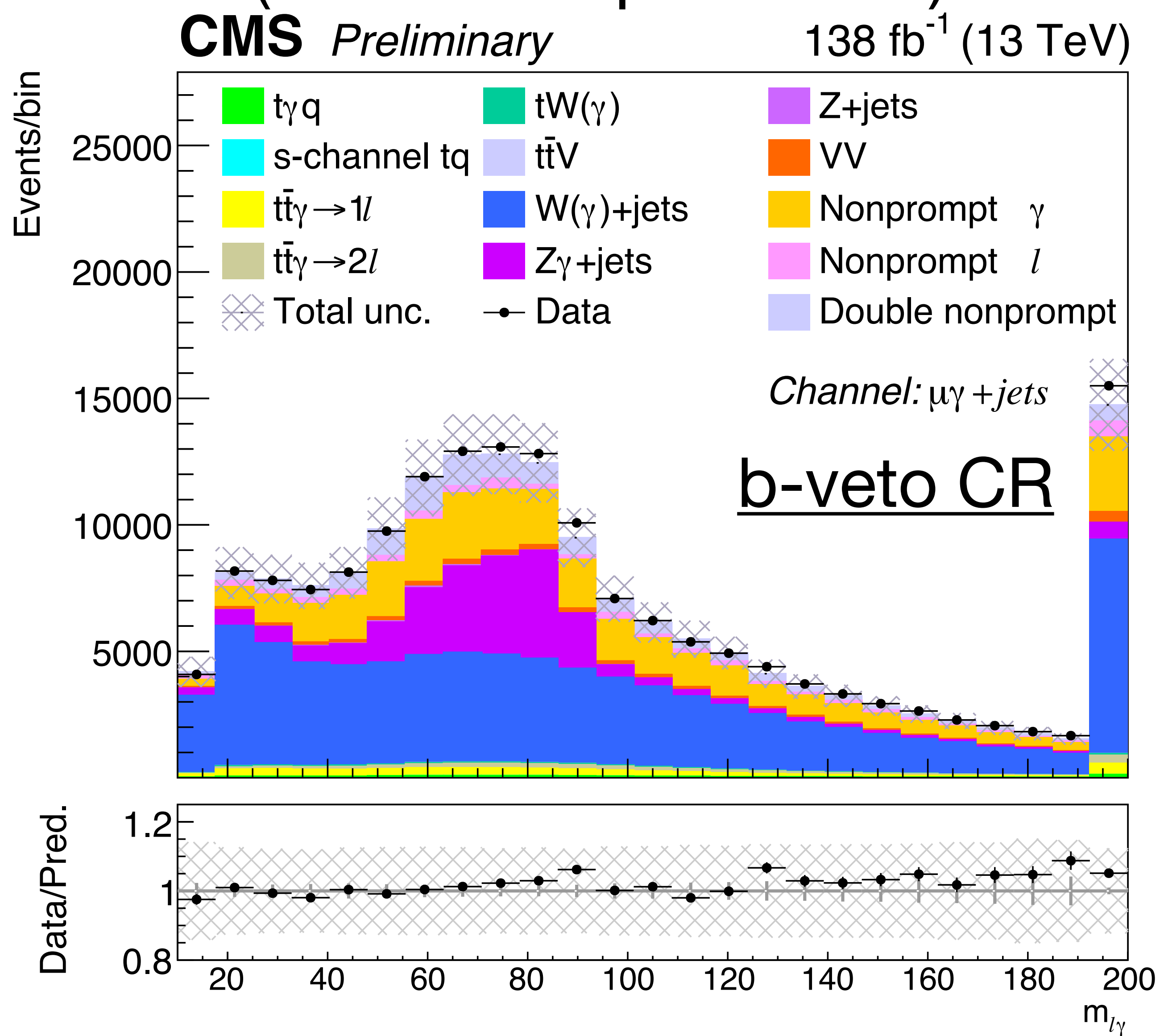
Only nonprompt γ



Nonprompt γ + Nonprompt ℓ

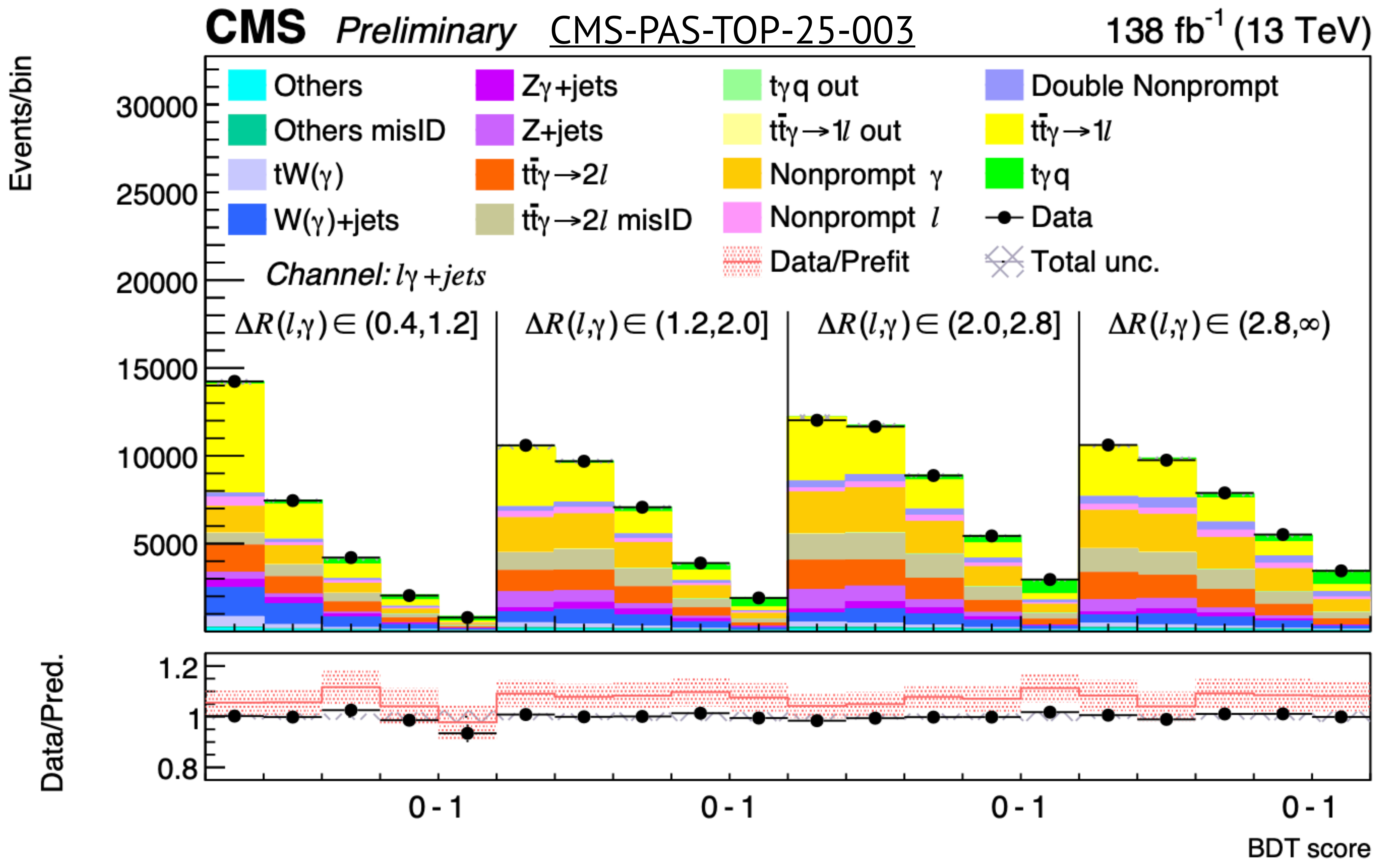


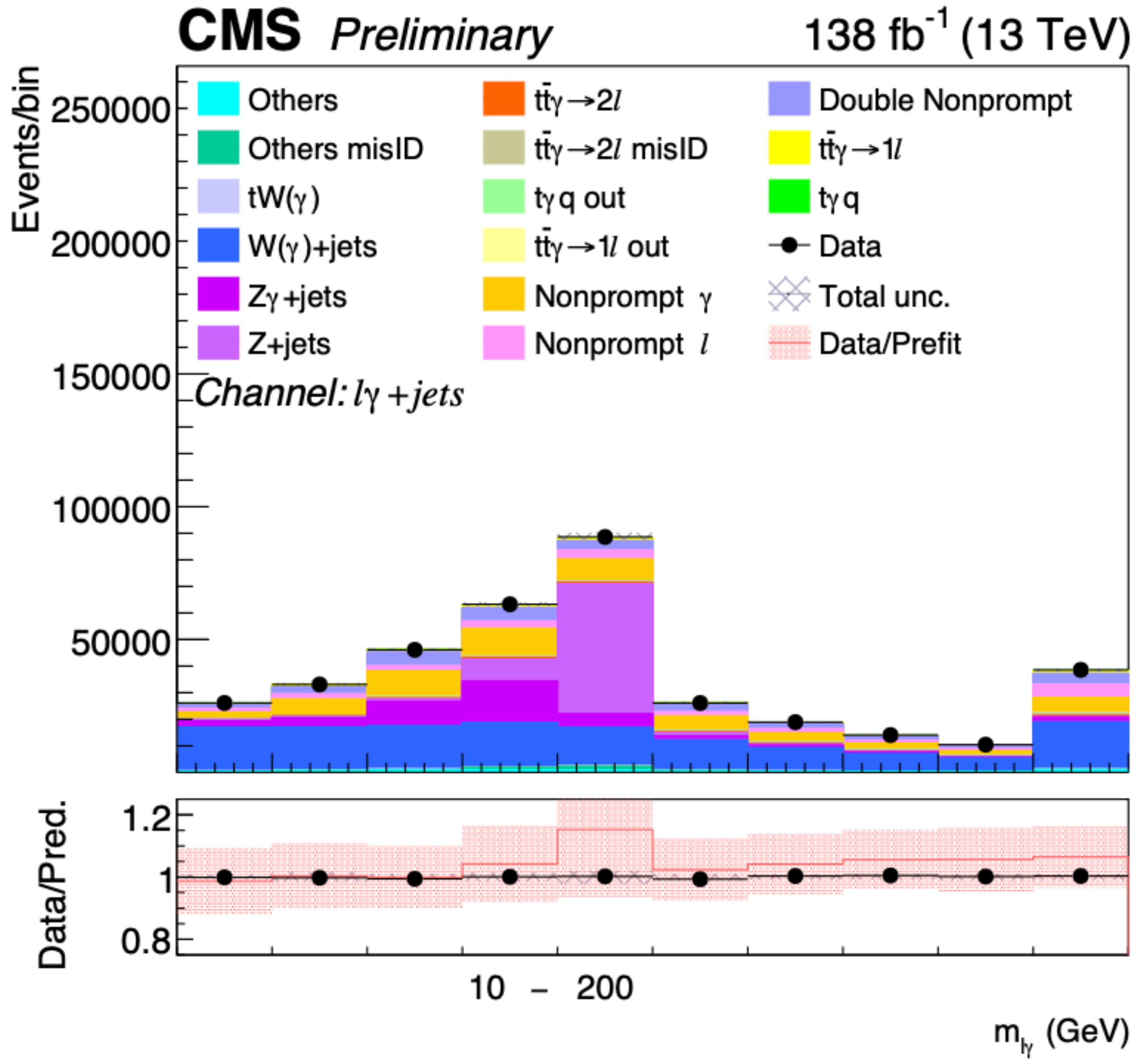
Nonprompt γ + Nonprompt ℓ + Double Nonprompt (with overlap removal)

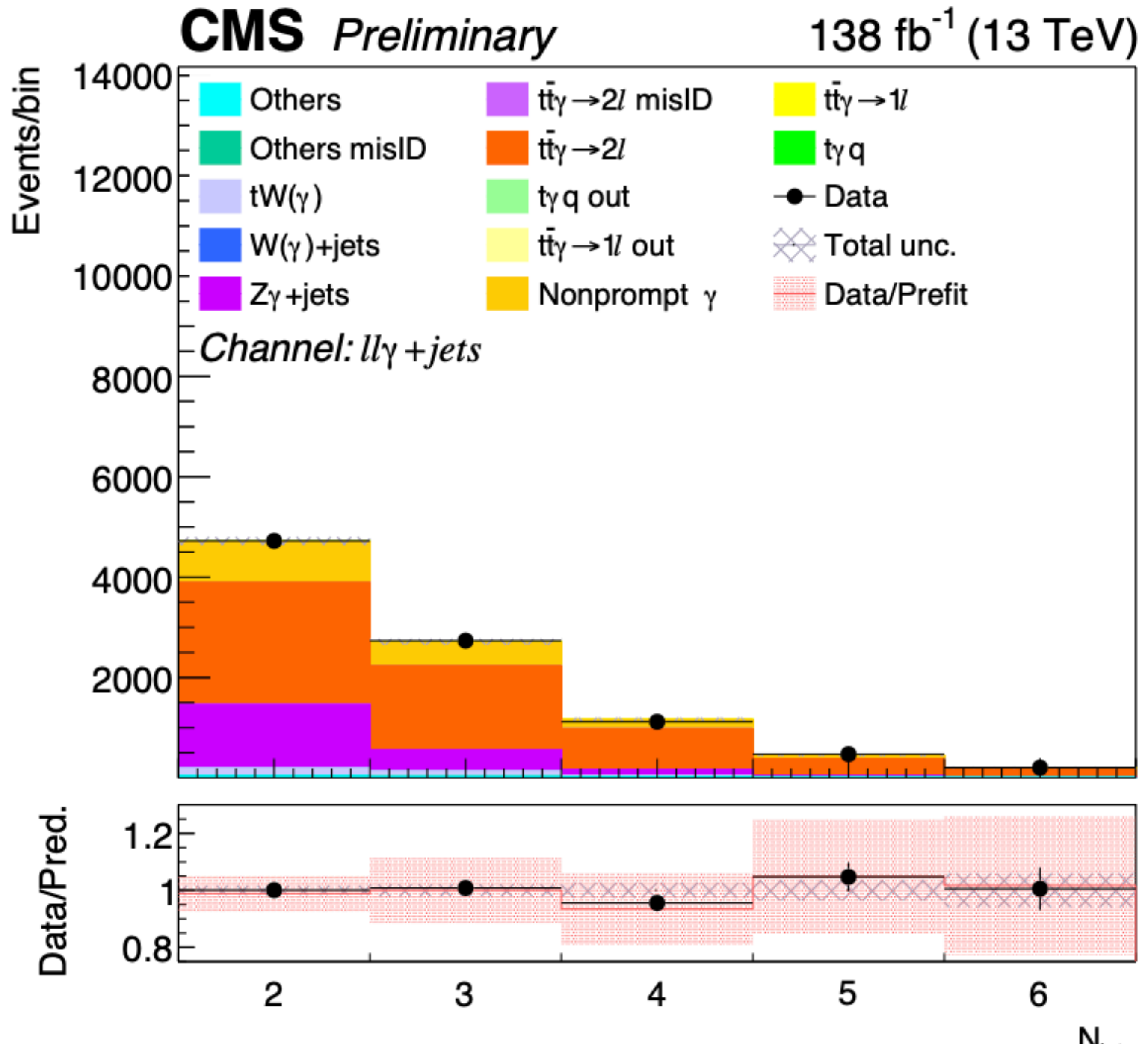


BDT training — prefit BDT score

- Simultaneous fit for events in SR and CRs
- Post-fit results: good agreement within uncertainties







Simultaneous inclusive fit

Observed results:

$$\mu_{t\gamma q} = 1.141^{+0.082}_{-0.080} = 1.141^{+0.067}_{-0.066}\,(\text{syst})\,^{+0.047}_{-0.047}\,(\text{stat}),$$
$$\mu_{t\bar{t}\gamma\to 1\ell} = 1.055^{+0.059}_{-0.059} = 1.055^{+0.055}_{-0.055}\,(\text{syst})\,^{+0.021}_{-0.021}\,(\text{stat}),$$
$$\sigma^{\text{mea.}}_{\text{tot. } t\gamma q} = 236.87^{+17.0}_{-16.6}\ \text{fb},$$
$$\sigma^{\text{mea.}}_{\text{tot. } t\bar{t}\gamma\to 1\ell} = 1445.24^{+80.8}_{-80.8}\ \text{fb}.$$

ATLAS measured fiducial cross section at stable-particle level

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

Theoretical cross sections:

$\sigma^{t\bar{t}\gamma}_{\text{theo.}} = 1369.9 \pm 22.8$ fb (decay photon from LO×1.71)

$\sigma^{t\bar{t}\gamma}_{\text{theo.}} = 1351.8 \pm 23.8$ fb (decay photon from NLO)

$\sigma^{t\gamma q}_{\text{theo.}} = 207.6 \pm 8.5$ fb

ATLAS theoretical cross sections at stable-particle level:

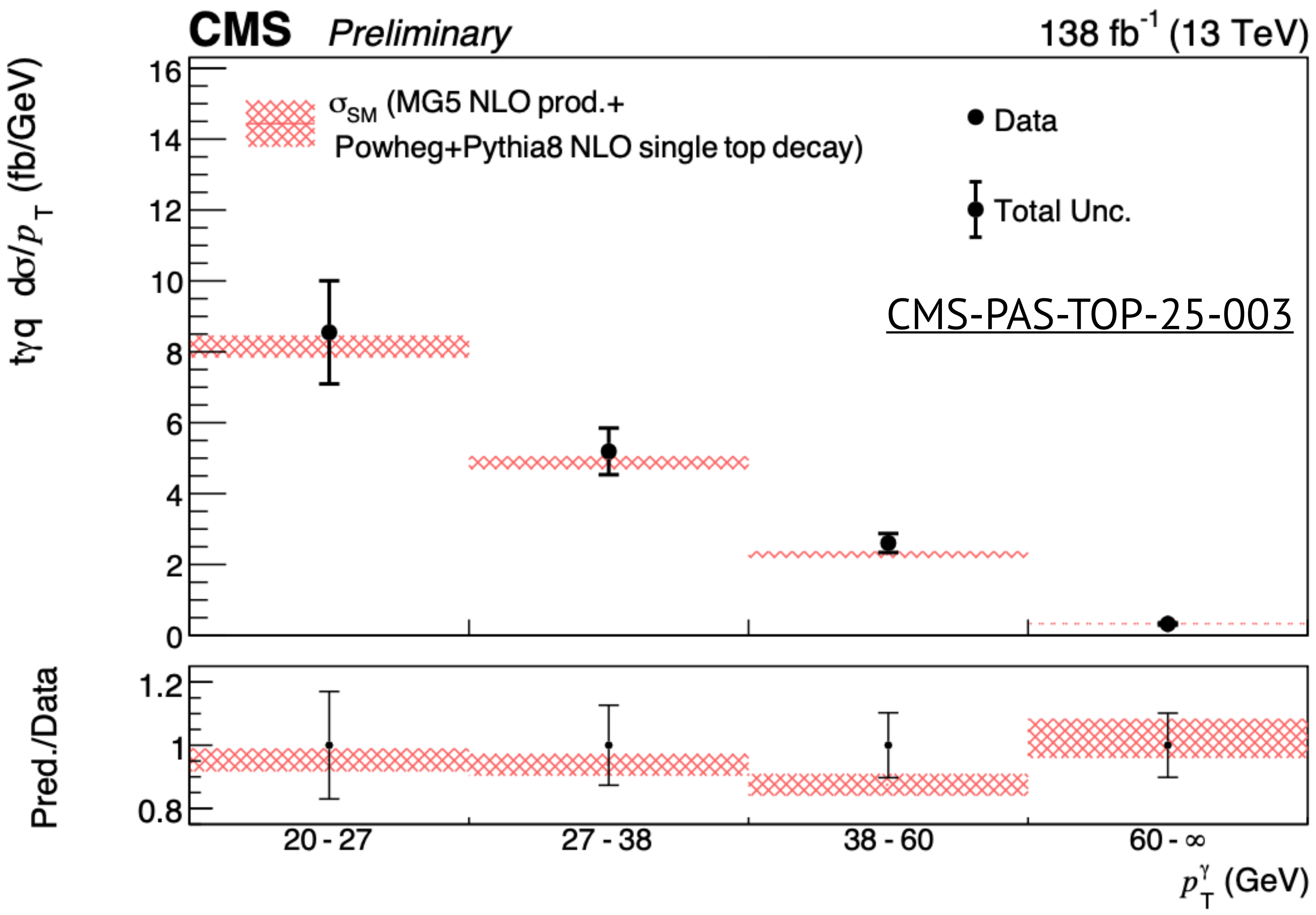
$\sigma(tq\gamma) \times B(t\to\ell\nu b) + \sigma(t\to\ell\nu b\gamma)q = 217^{+27}_{-15}$ fb

CMS-PAS-TOP-25-003

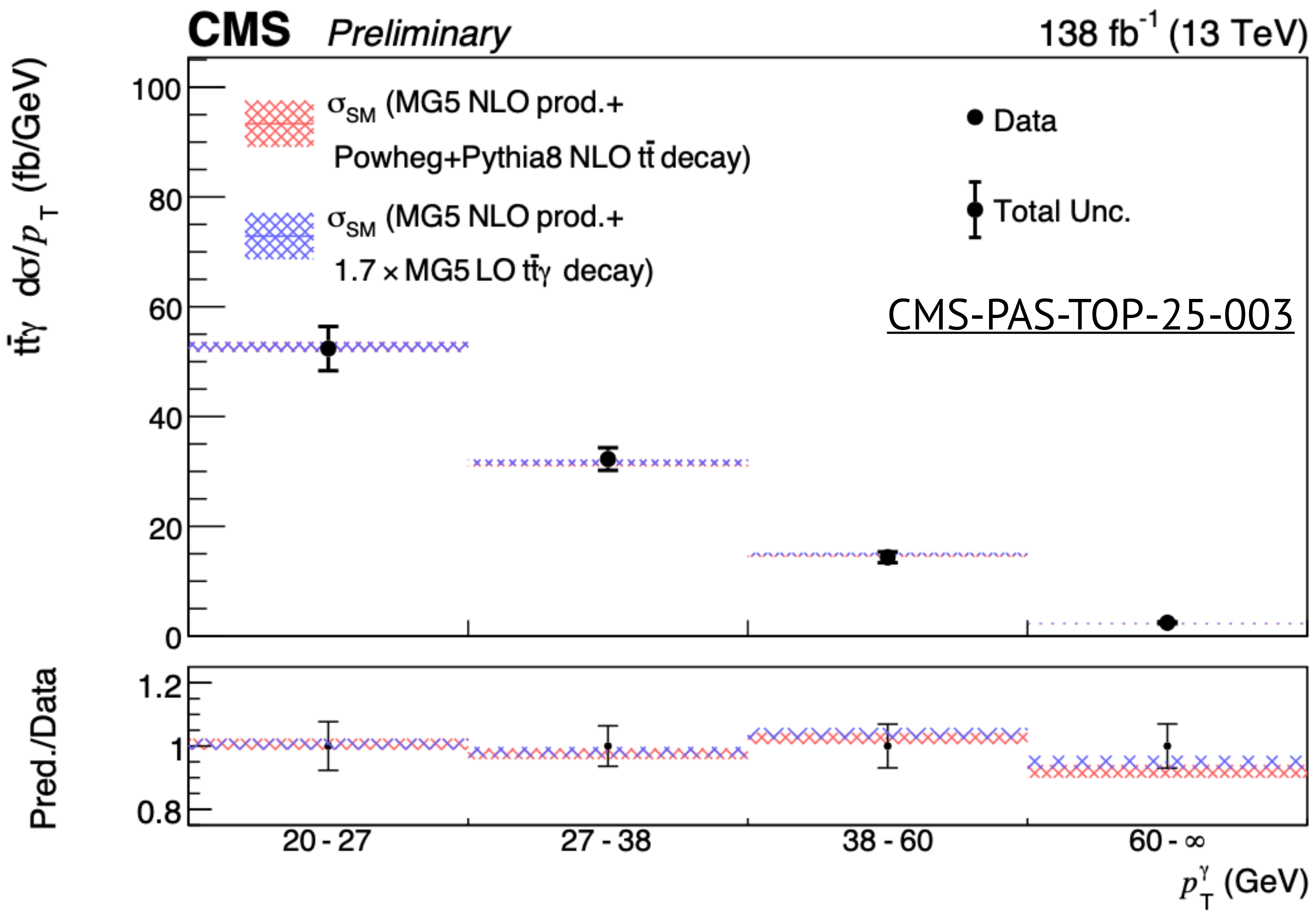
ATLAS $t\gamma q$ paper

Simultaneous 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

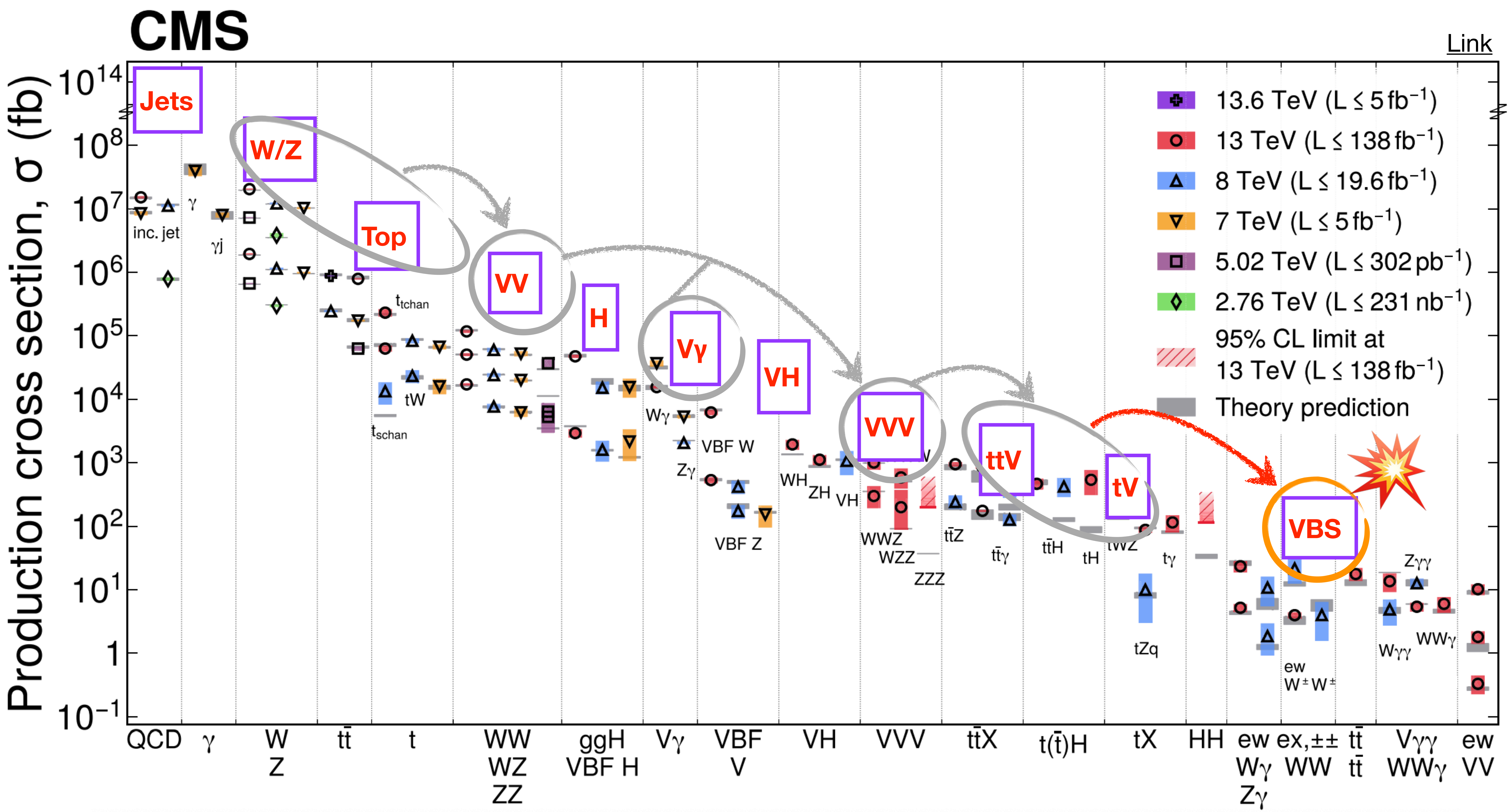


Data compared to **MG5 NLO prod.** γ + **Powheg+Pythia8 NLO decay** γ



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

Link



CMS
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W/Z
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Vγ
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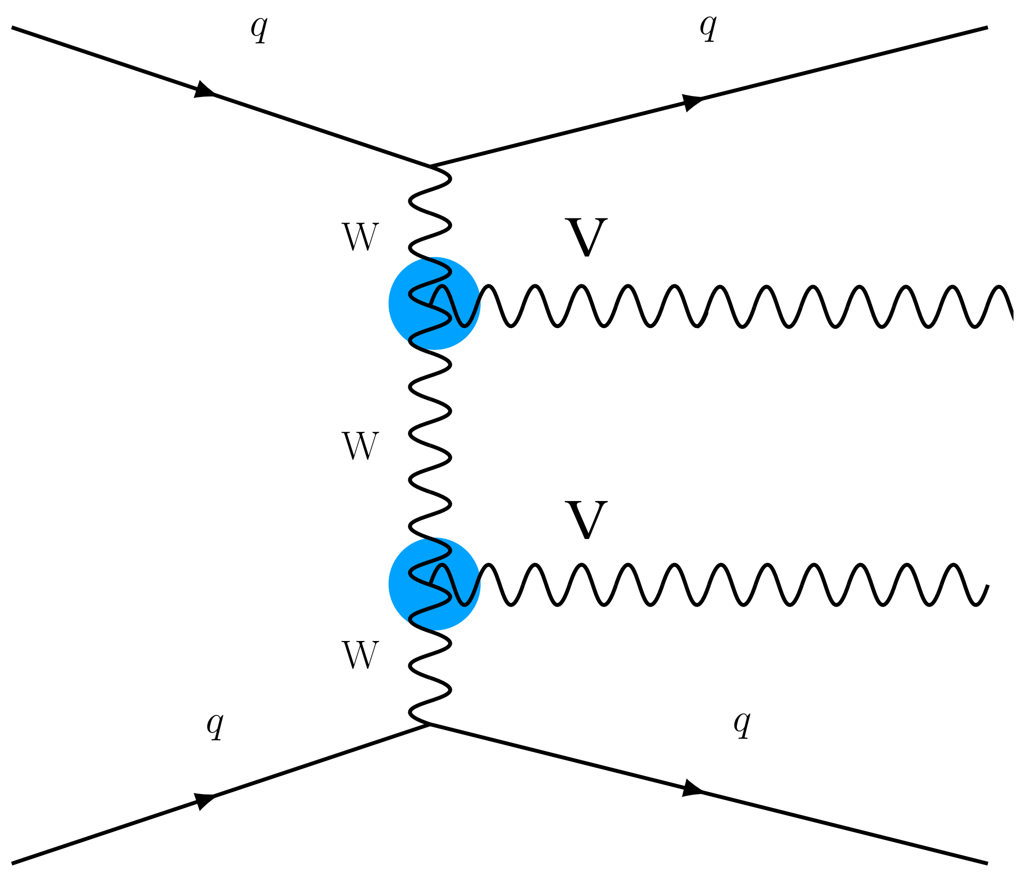
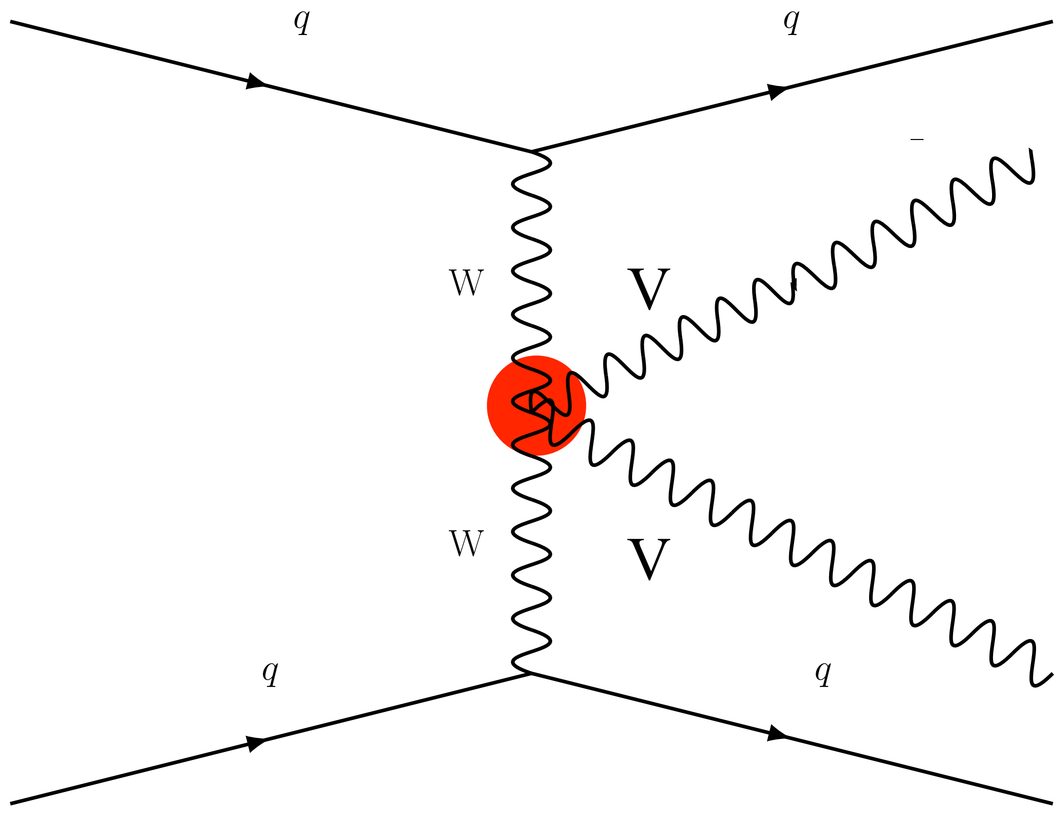
VBF Z
WH
ZH
VH
WWZ
WZZ
ZZZ
tt̄Z
tt̄γ
tt̄H
tH
tWZ
tγ
tZq
ew W±W±
Zγγ
WWγ
Wγγ
QCD
γ
W Z
tt̄
t
WW WZ ZZ
ggH VBF H
Vγ
VBF V
VH
VVV
tt̄X
t(t̄)H
tX
HH
ew Wγ Zγ
ex,±± WW
tt̄ tt̄
Vγγ WWγ
ew VV

VBS production — Motivation

TGC: Triple gauge couplings



QGC: Quartic gauge couplings



Multiboson couplings:

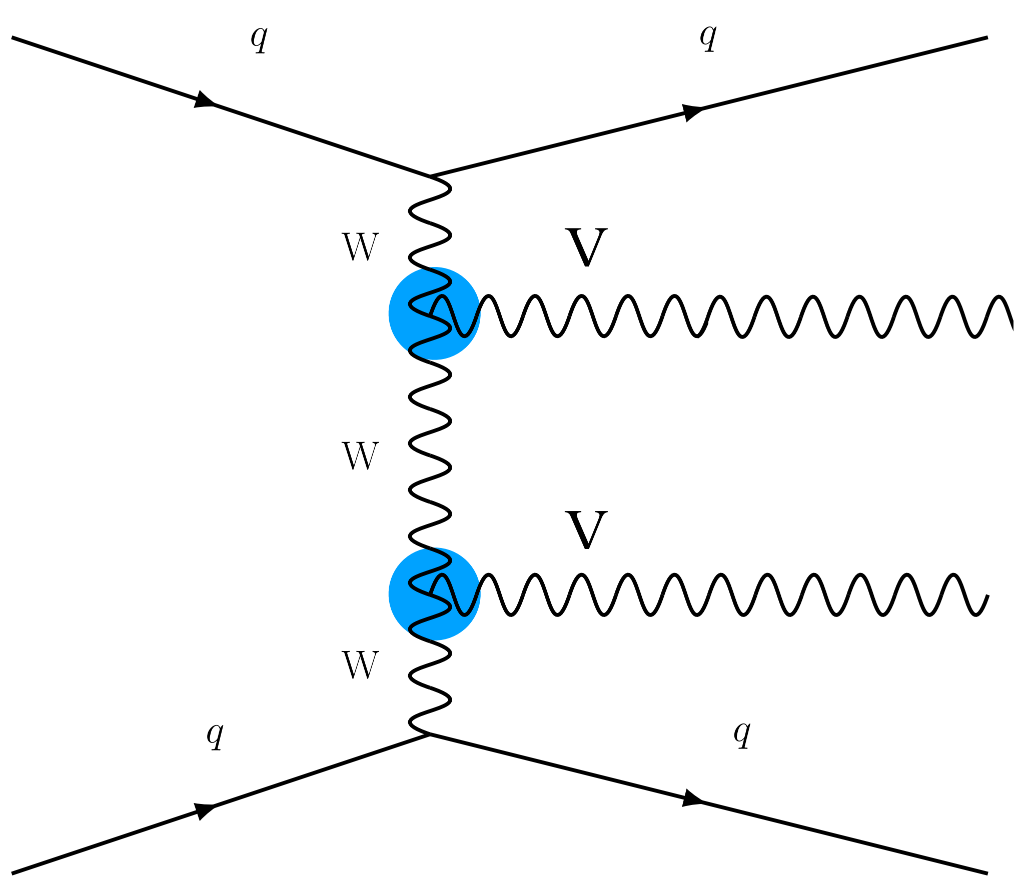
- T(Q)GC: WWZ, WWγ, WWZγ, WWγγ, etc.
- BSM TGC: ZZγ, Zγγ, etc
- BSM QGC : ZZγ, ZZZγ, Zγγγ, etc

☑ Test SM for the electroweak sector

☑ Provide platform for anomalous couplings

VBS production — Motivation

TGC: Triple gauge couplings



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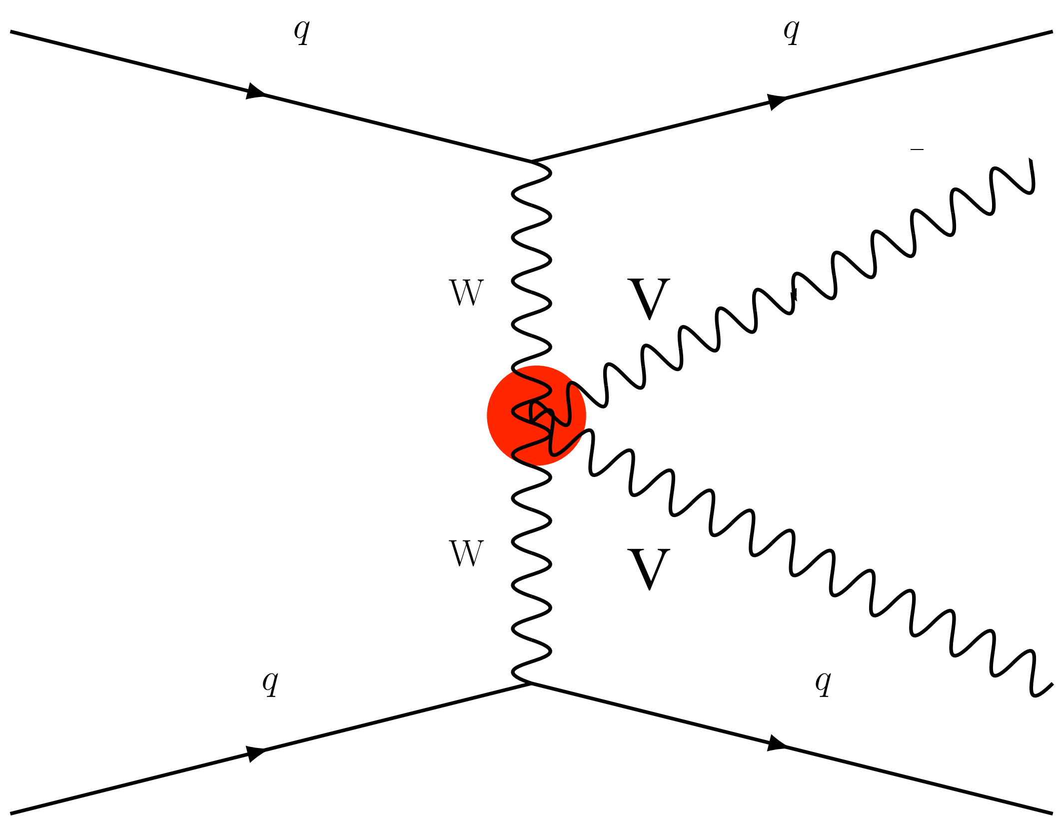

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☑ Test SM for the electroweak sector

☑ Provide platform for anomalous couplings

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

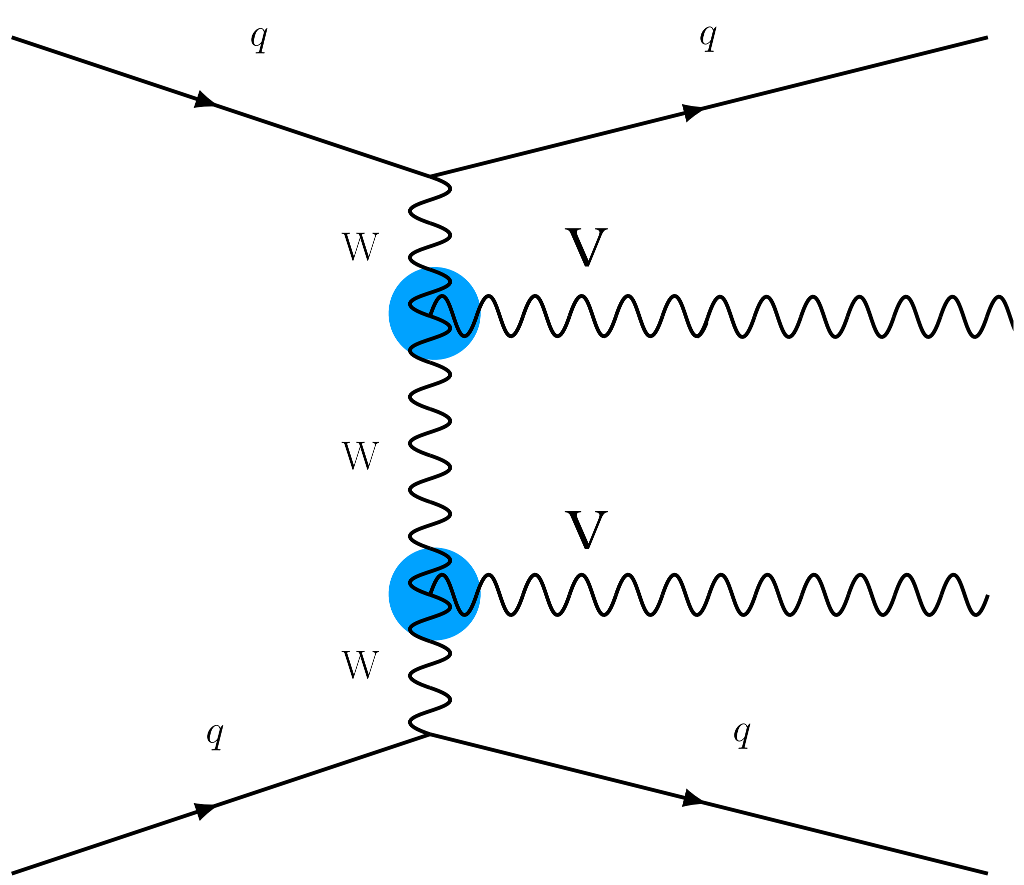
Important process to investigate **electroweak symmetry breaking (EWSB)**

☑ Unitarity preservation visible in massive $V_L V_L$ scattering

☑ Probe the nature of EW symmetry breaking

VBS production — Motivation

TGC: Triple gauge couplings



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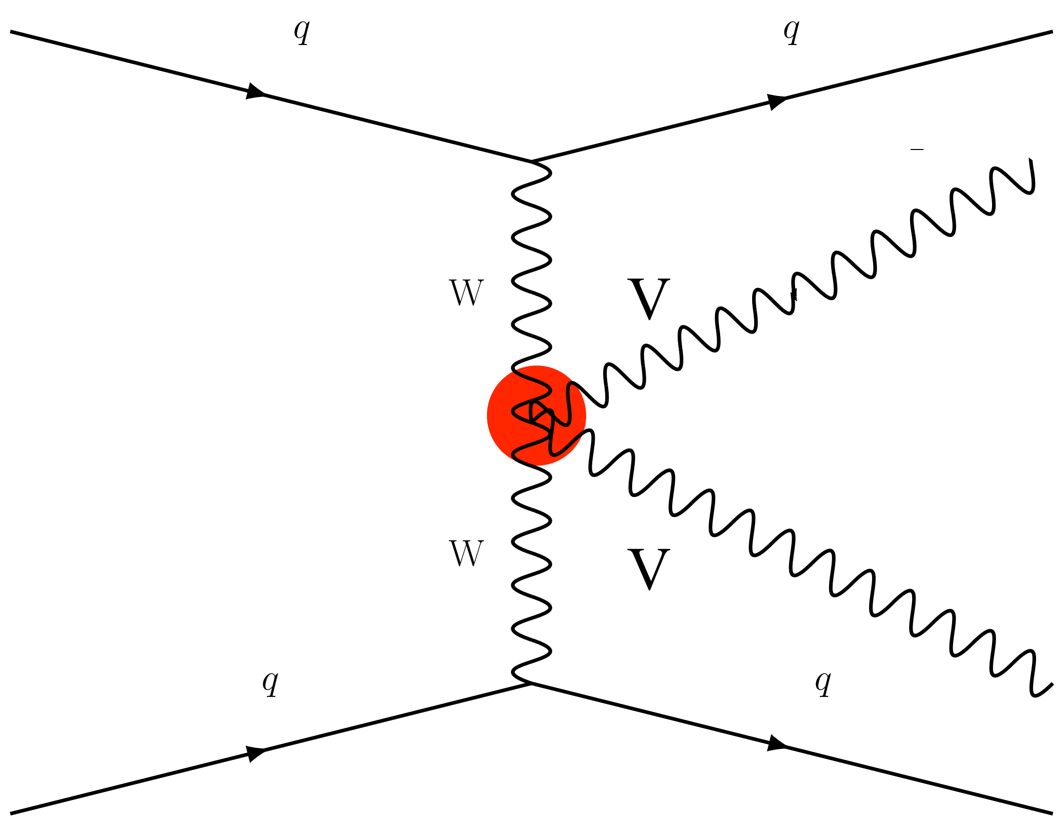

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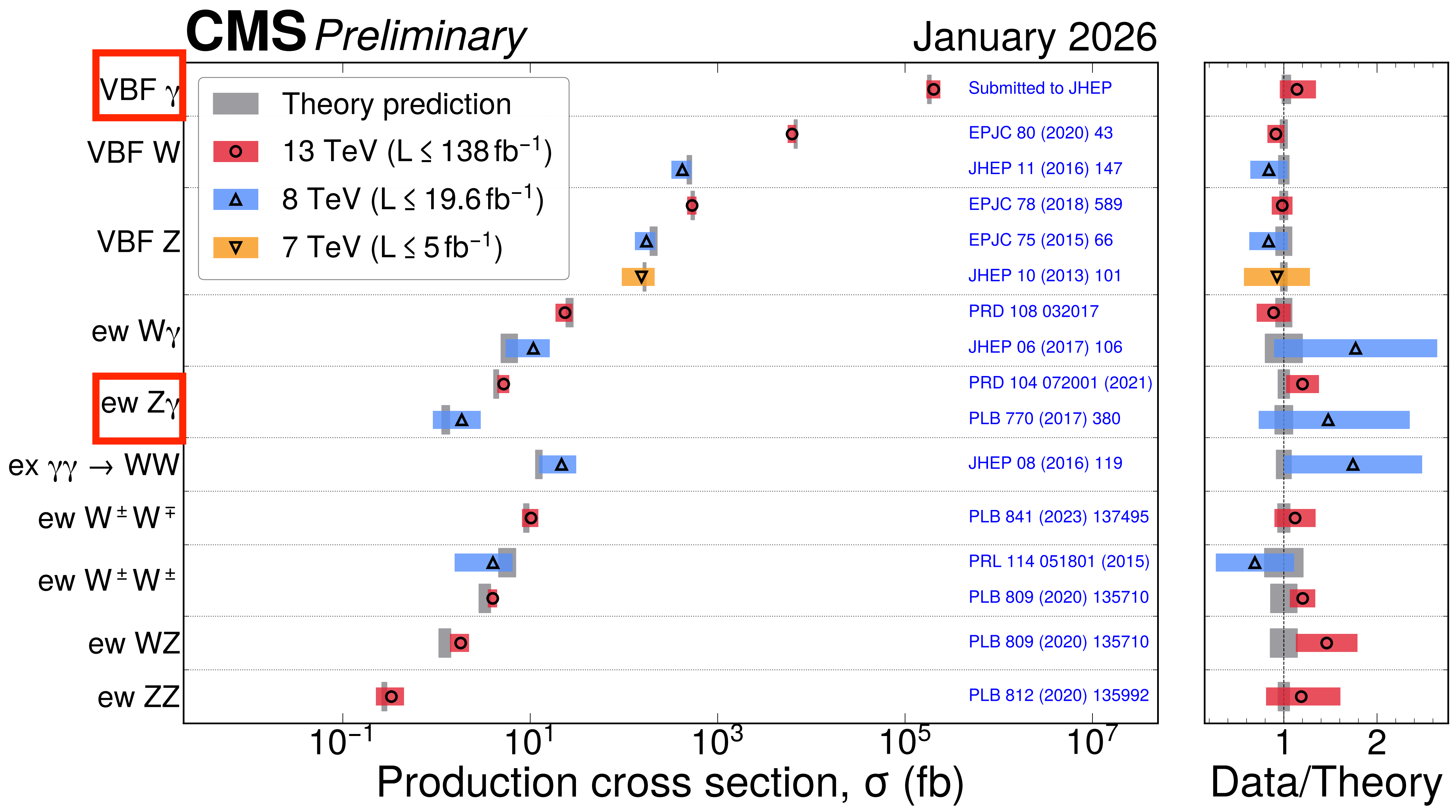

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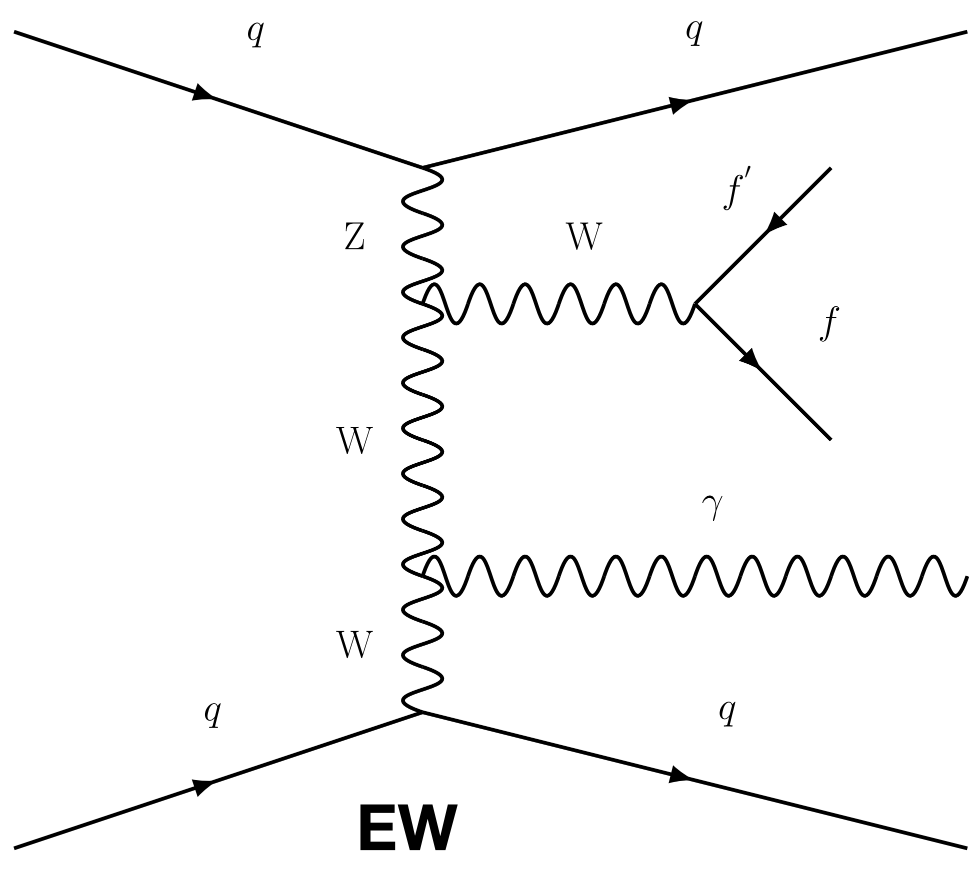
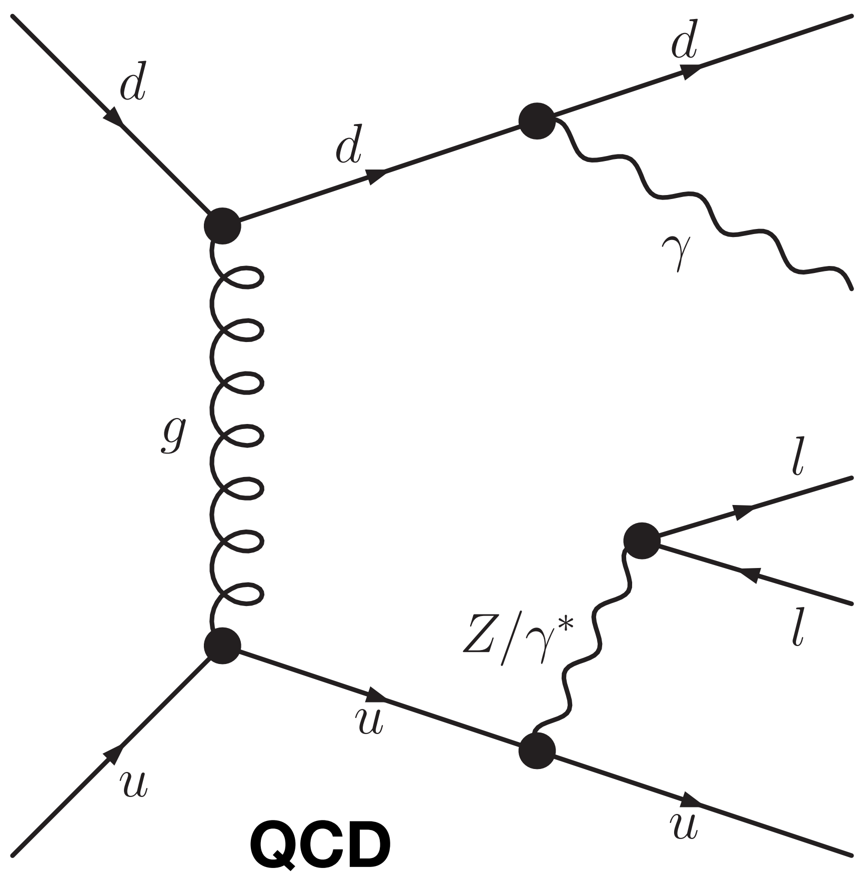
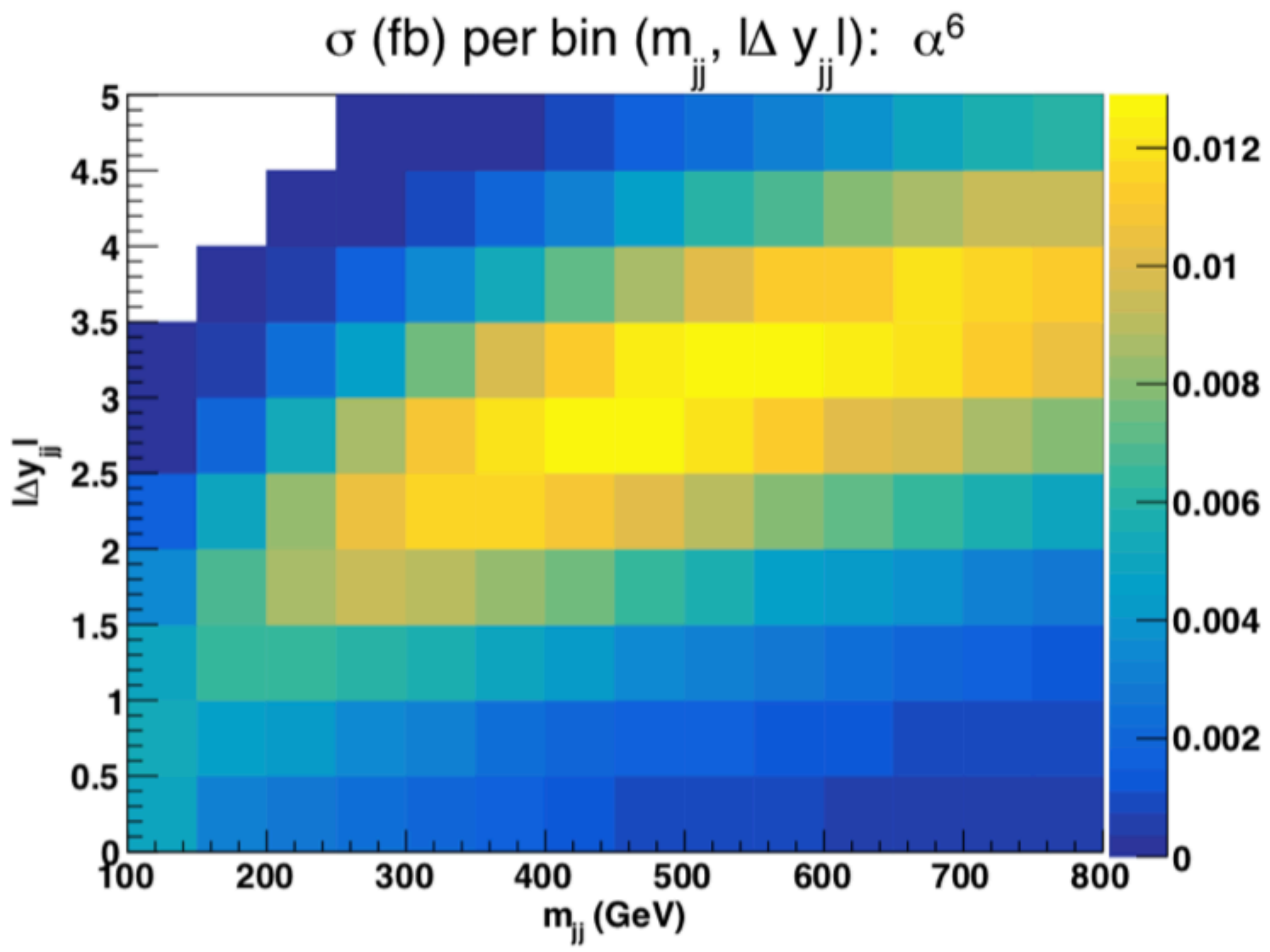
☑ Probe the nature of EW symmetry breaking

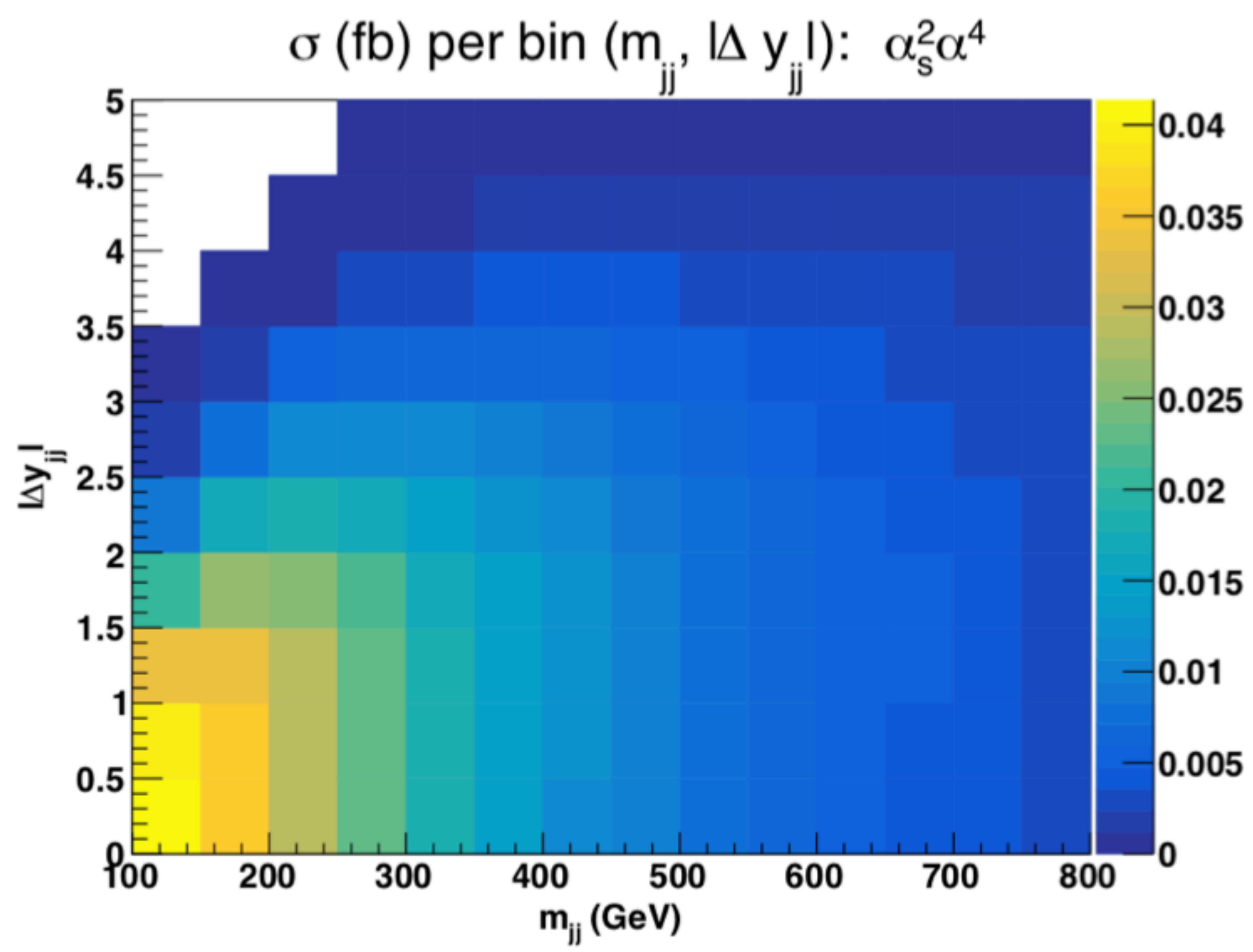
VBS Zγ analysis strategy

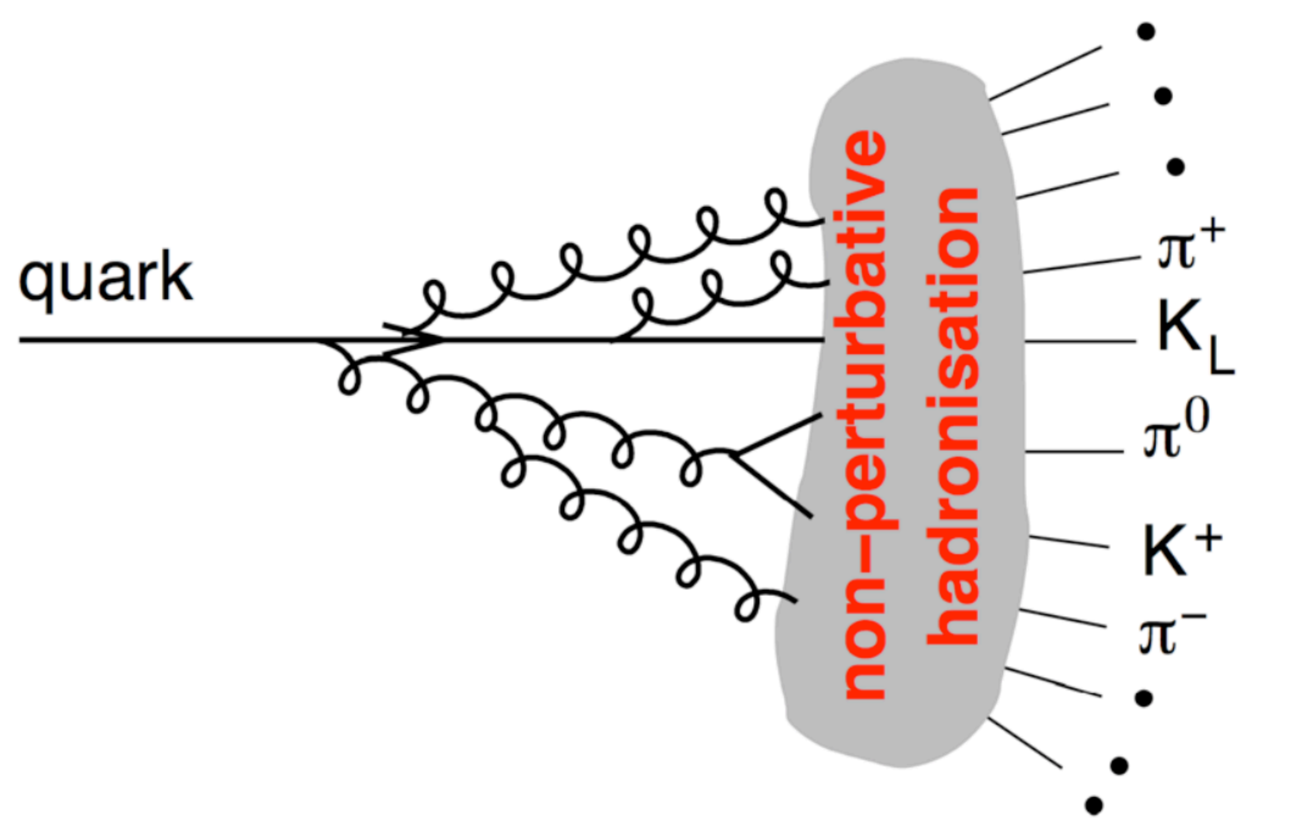




- **EW VBS:** six fermions final state at leading order $\mathcal{O}(\alpha^6)$
- **Irreducible background:**
  - QCD-induced $\mathcal{O}(\alpha^4\alpha_s^2)$ (large)
  - Interference: between EW and QCD $\mathcal{O}(\alpha^5\alpha_s)$ (small)
  - Diboson, $t\bar{t}\gamma$, tW, etc (small)
- **Reducible**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



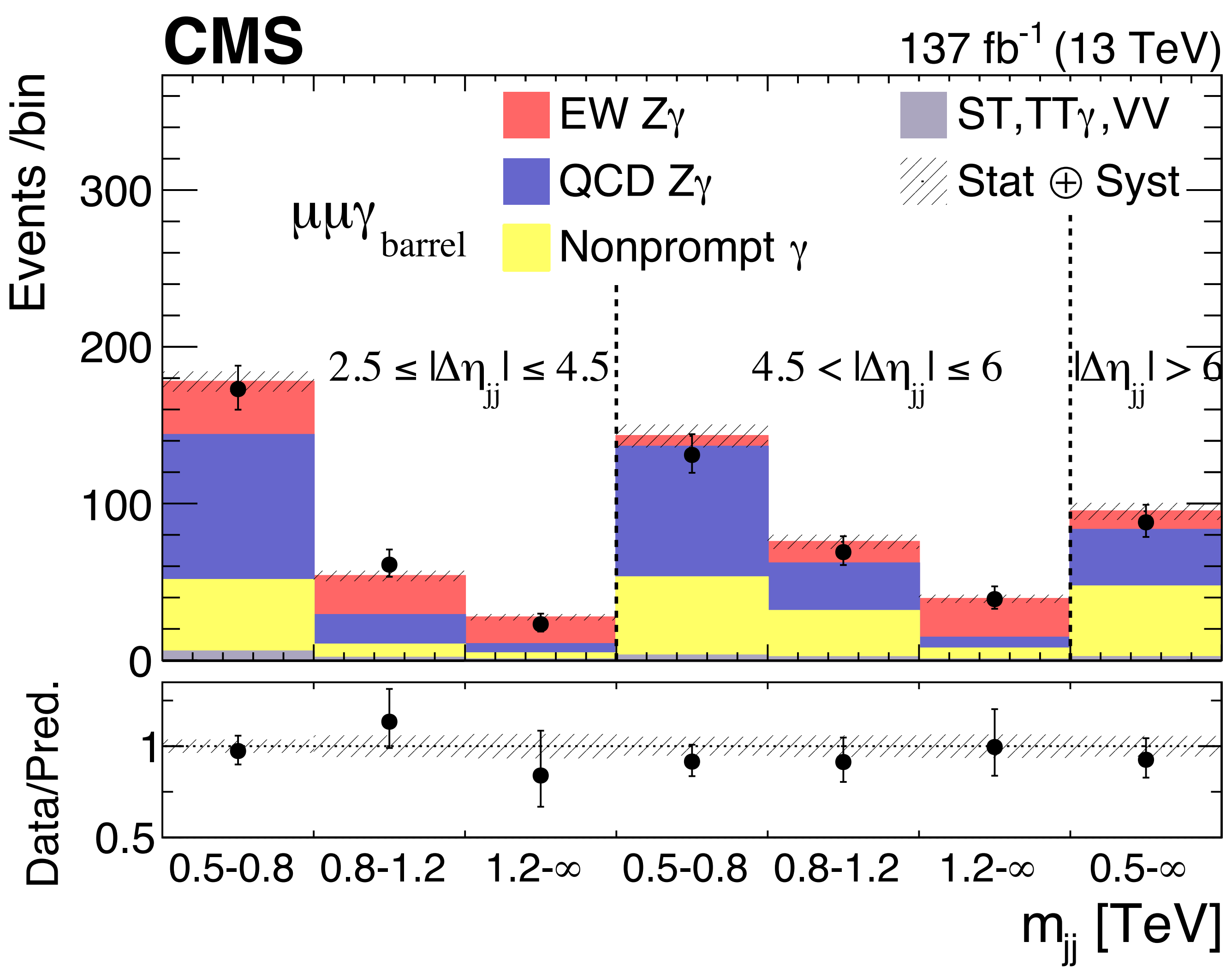




Nonprompt γ background

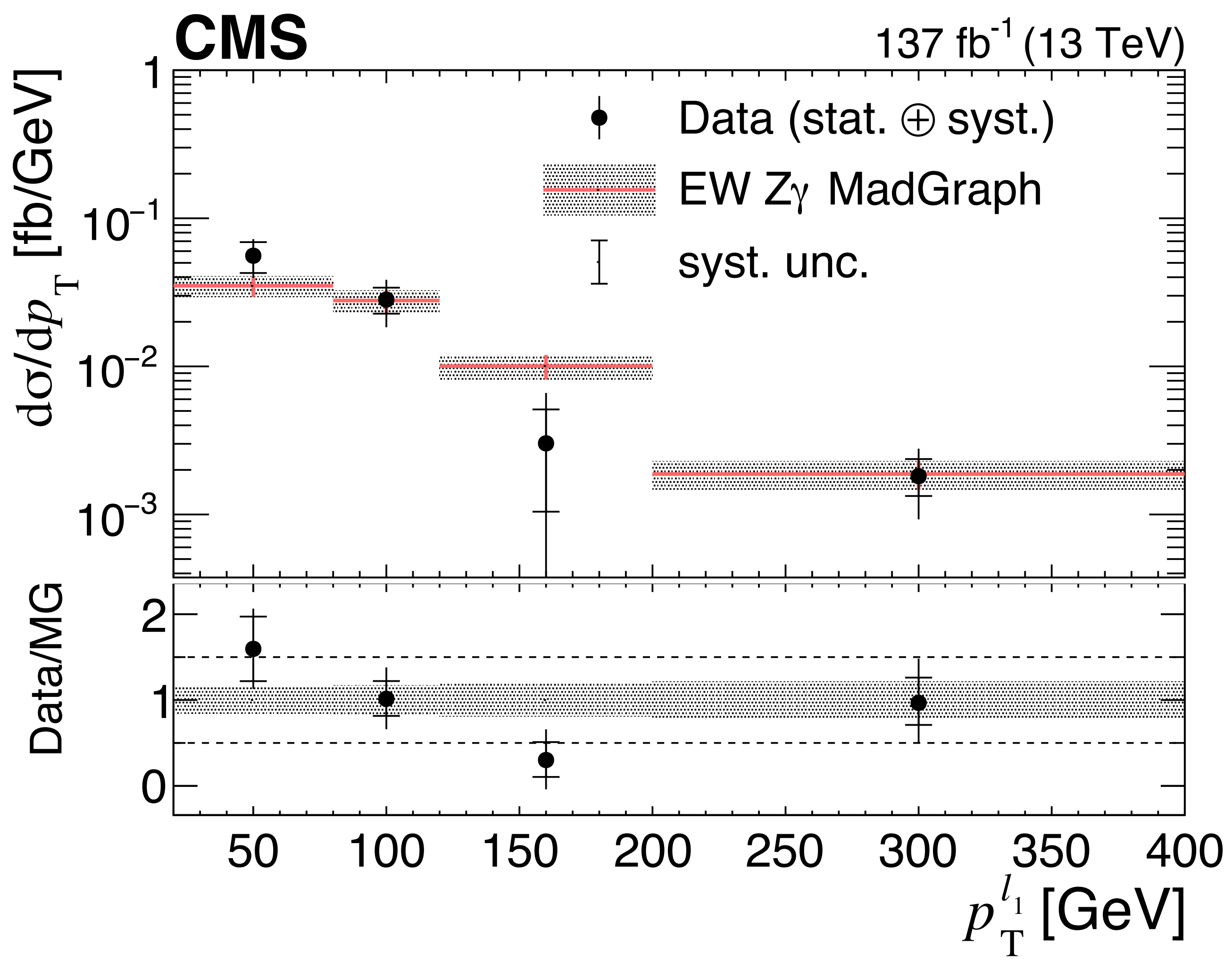
Main background is from corresponding QCD production which can be suppressed by the VBS kinematic variables like m_{jj}>500, $\Delta\eta_{jj}$>2.5, so the cut-based ID is mainly used to identify leptons and photon

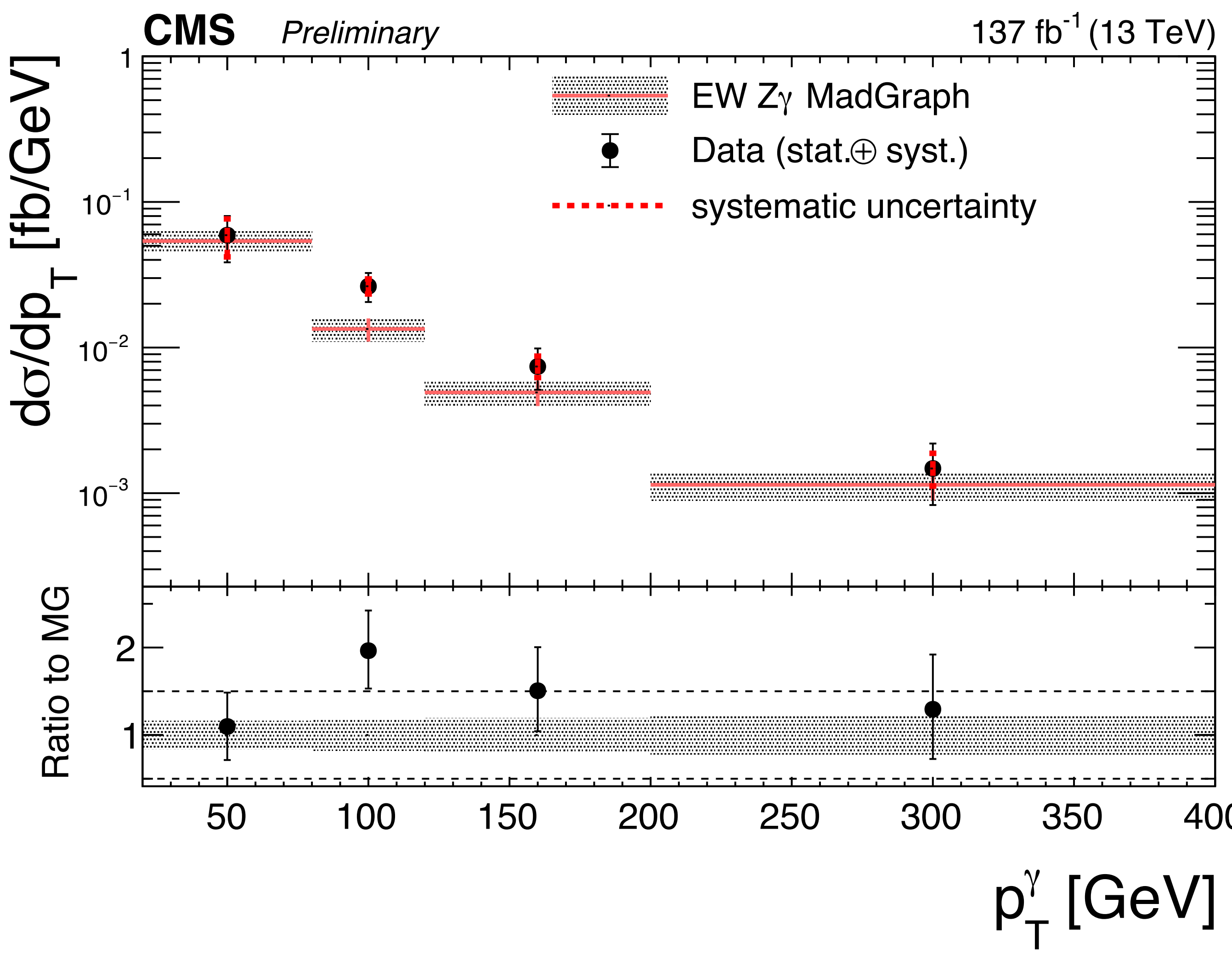
VBS Zγ results



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

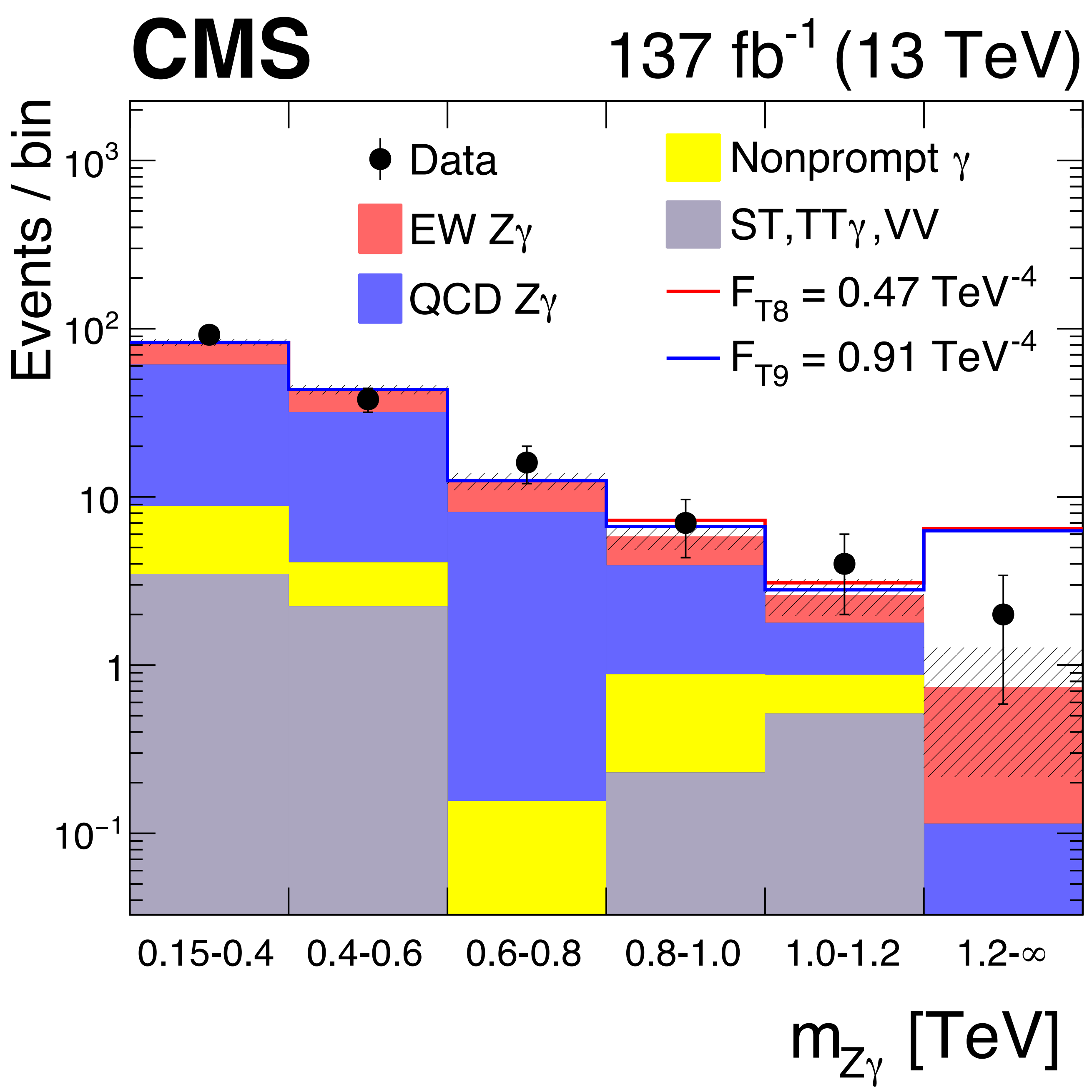
- $\sigma_{\mathrm{EW}}^{\mathrm{SM\ pred.}} = 4.34 \pm 0.26\,(\mathrm{scale}) \pm 0.06\,(\mathrm{PDF})\ \mathrm{fb}$
- $\mu = 1.20^{+0.12}_{-0.12}\,(\mathrm{stat})\,^{+0.14}_{-0.12}\,(\mathrm{syst})$
- $\sigma_{\mathrm{mea.}} = 5.21 \pm 0.52\,(\mathrm{stat}) \pm 0.56\,(\mathrm{syst})\ \mathrm{fb}$



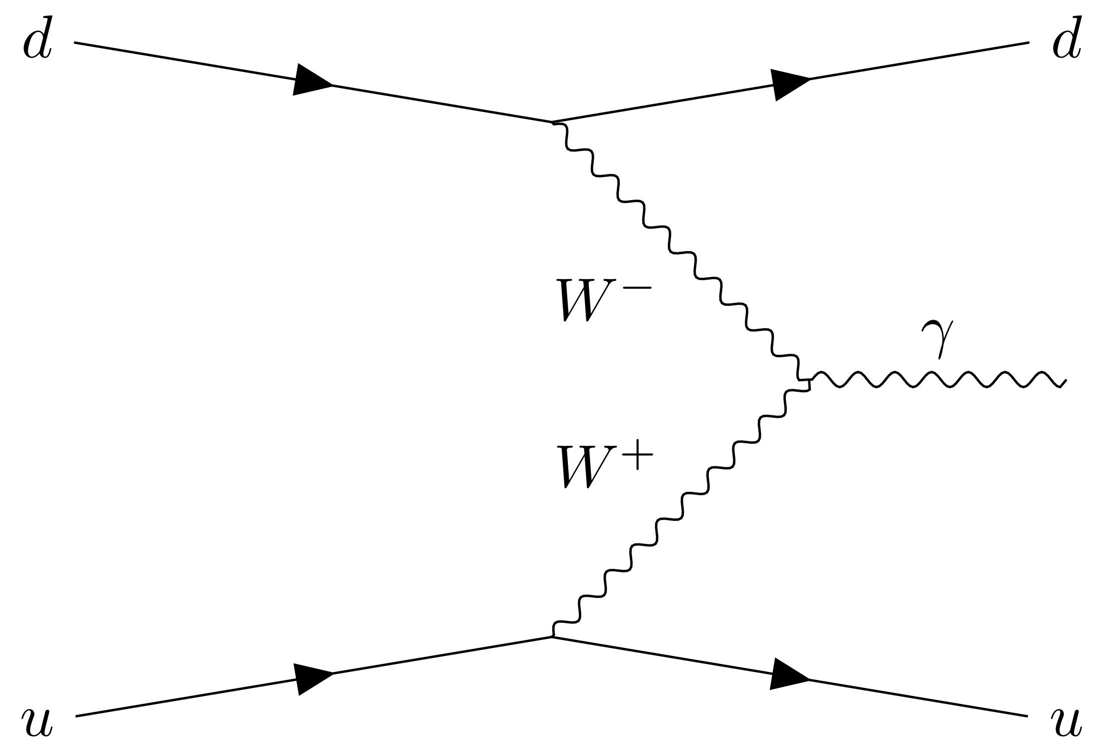


- Extended the SM Lagrangian with higher dimensional operators maintaining SU(2)×U(1) gauge symmetry:

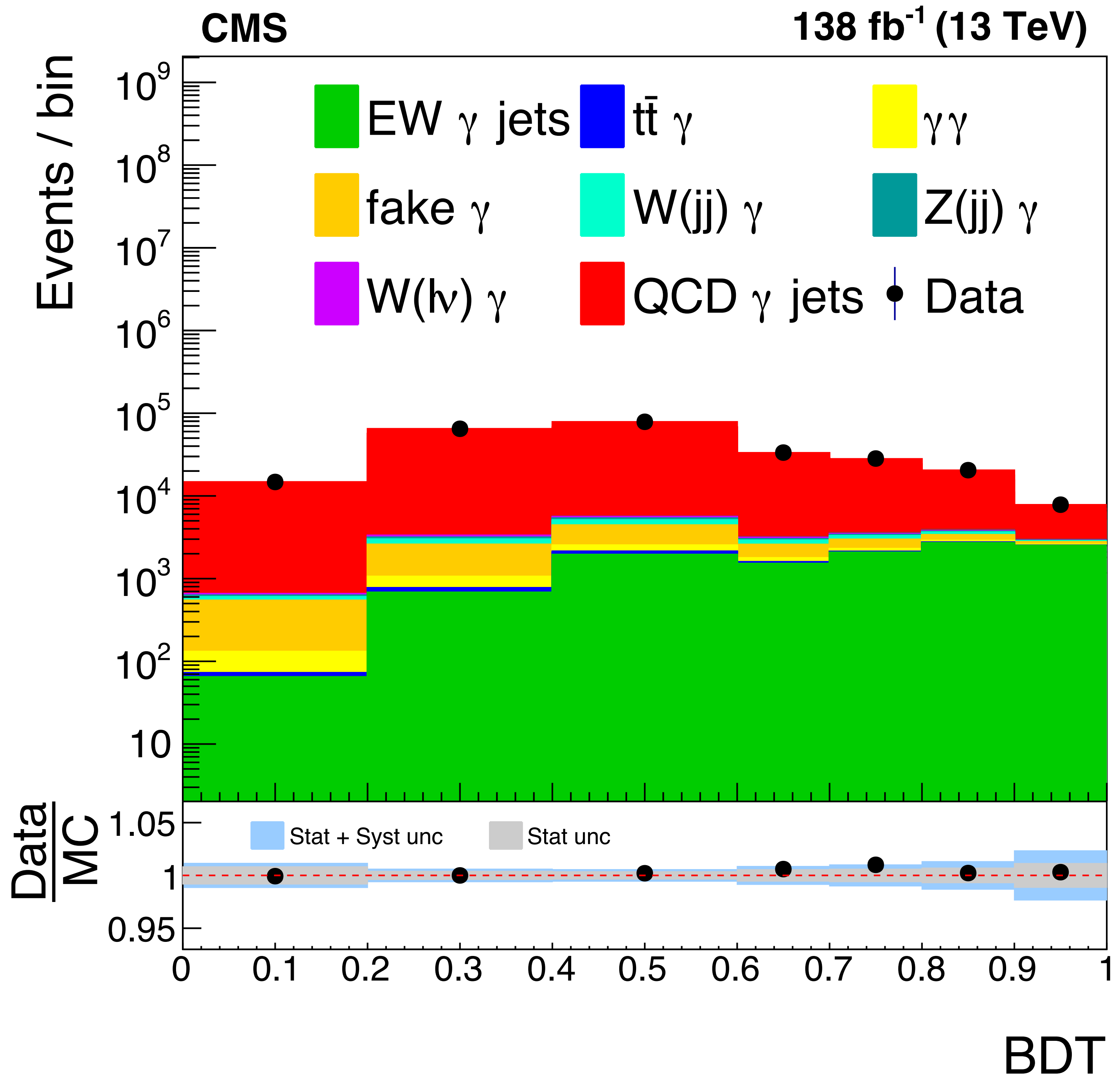
$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathscr{O}^{(6)} + \frac{c_i^{(8)}}{\Lambda^4}\mathscr{O}^{(8)} + \ldots.$$

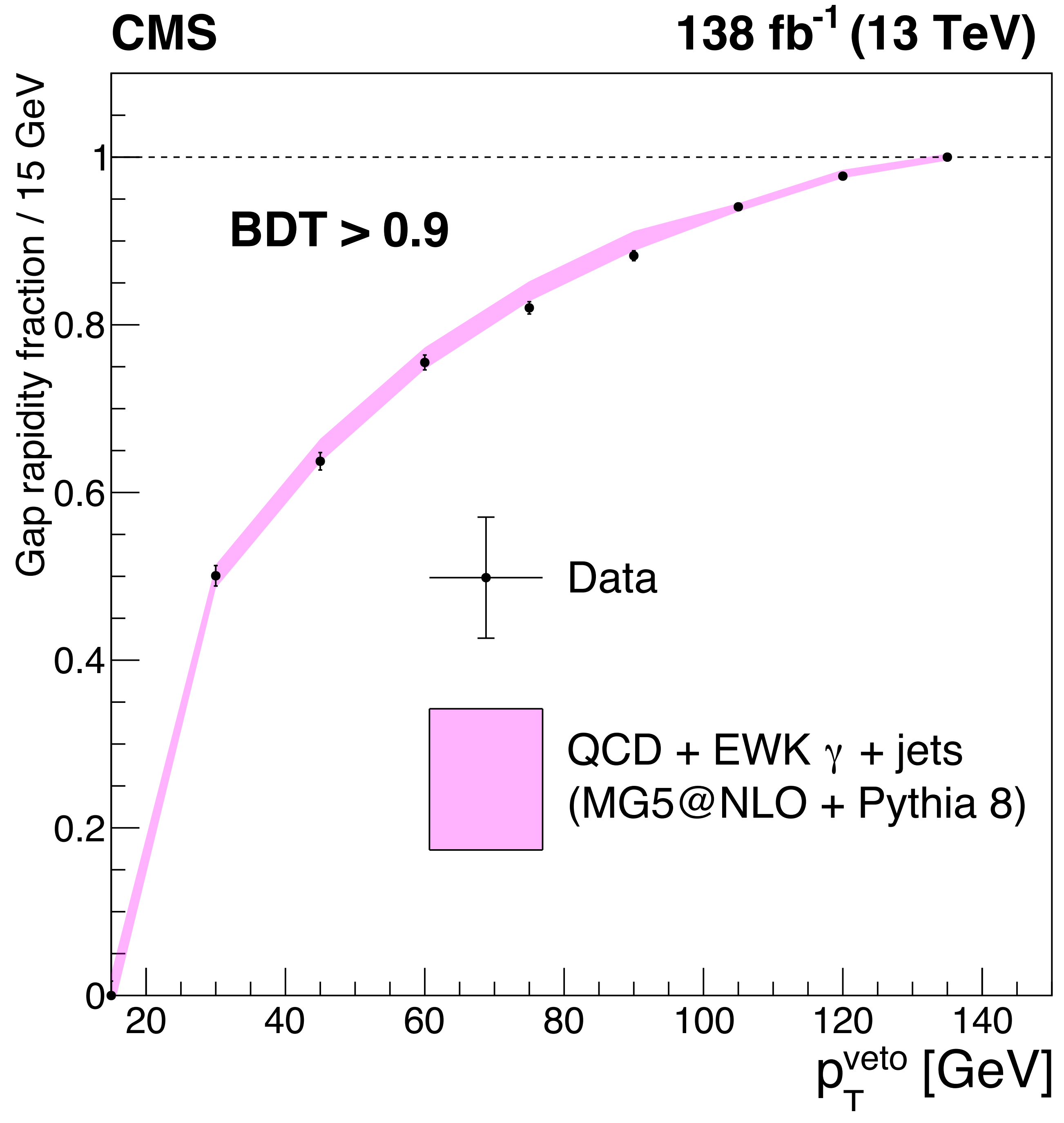


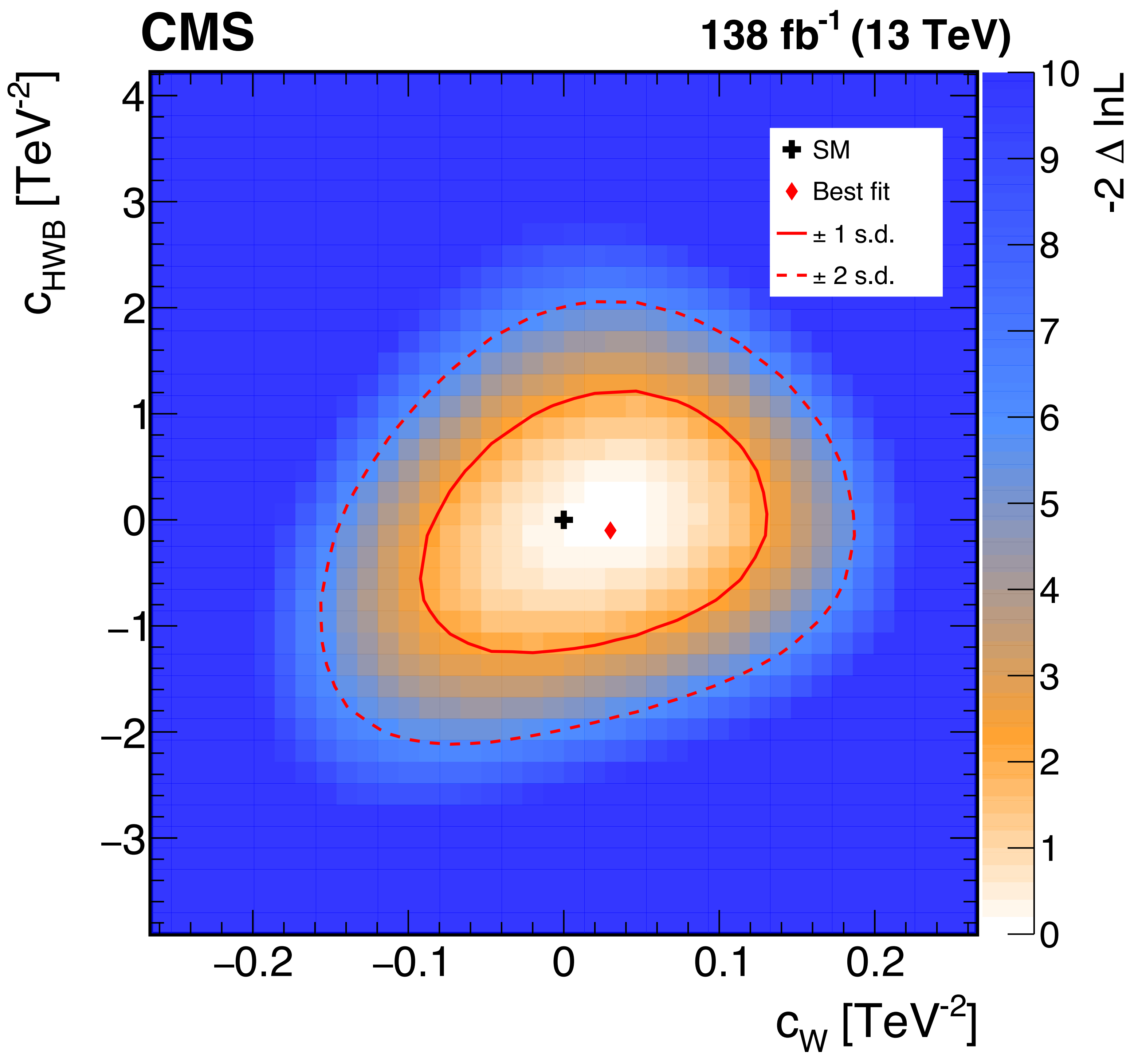
VBF γ results



- 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}

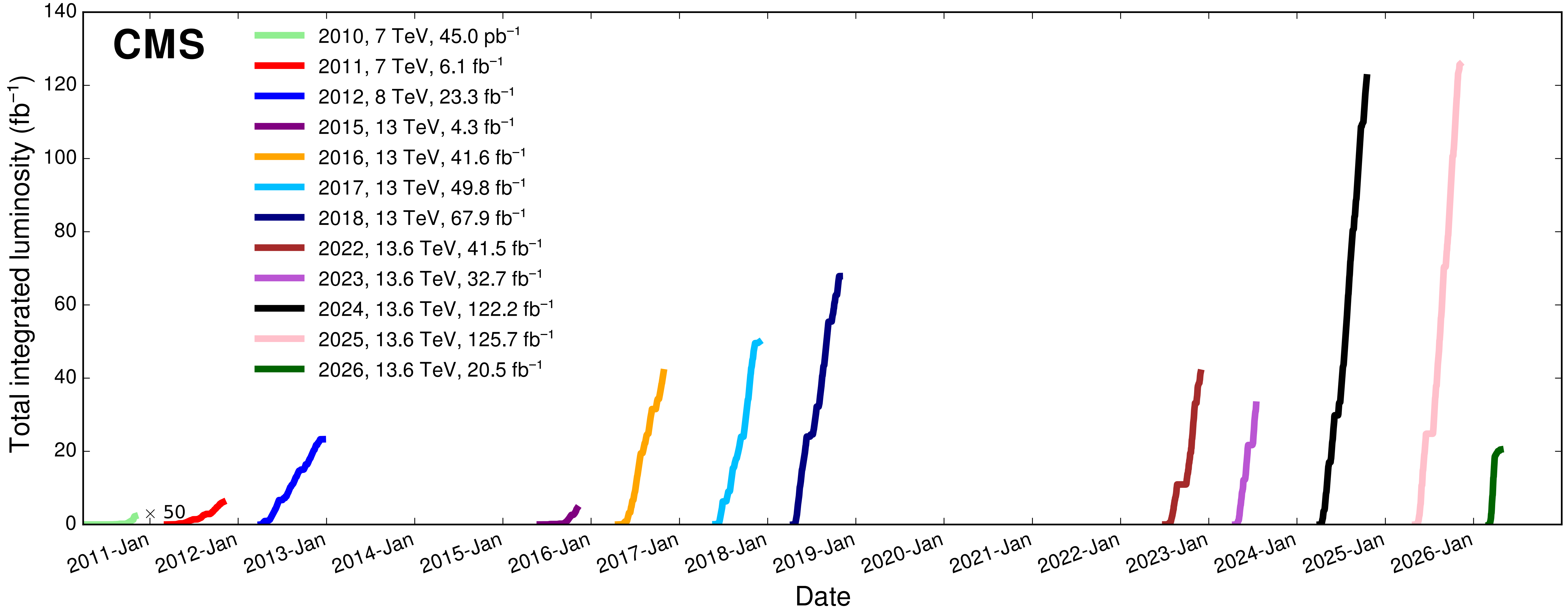


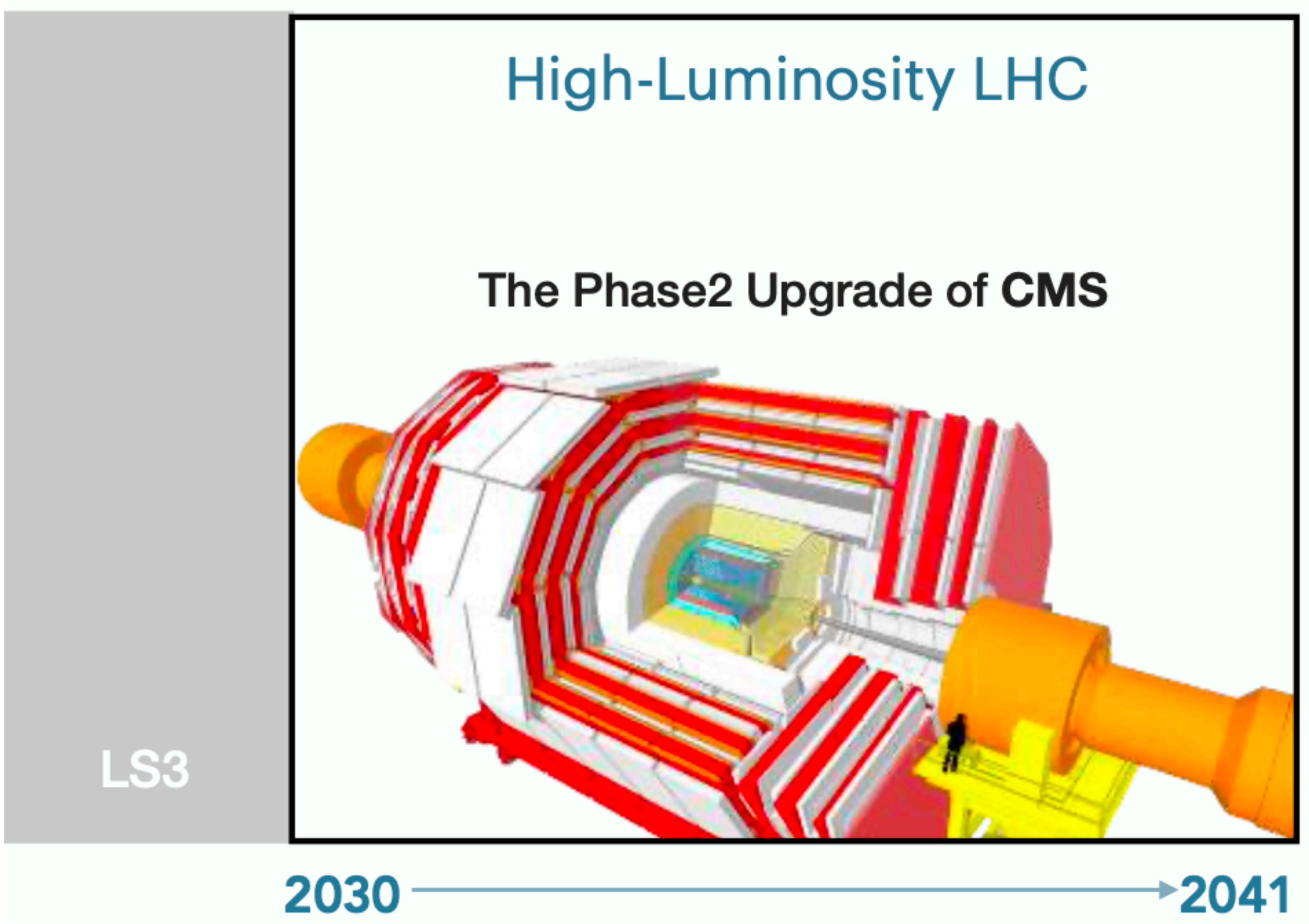




https://arxiv.org/abs/2512.00502

LHC status and prospect





A remarkable breadth of physics results

Run-1

Higgs boson discovering

Natural SUSY searches
- Exclude large part of parameter space

Probing QGP

Run-2

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 $B_s \to \mu^+\mu^-$

Recent highlights

Run-2 Run-3

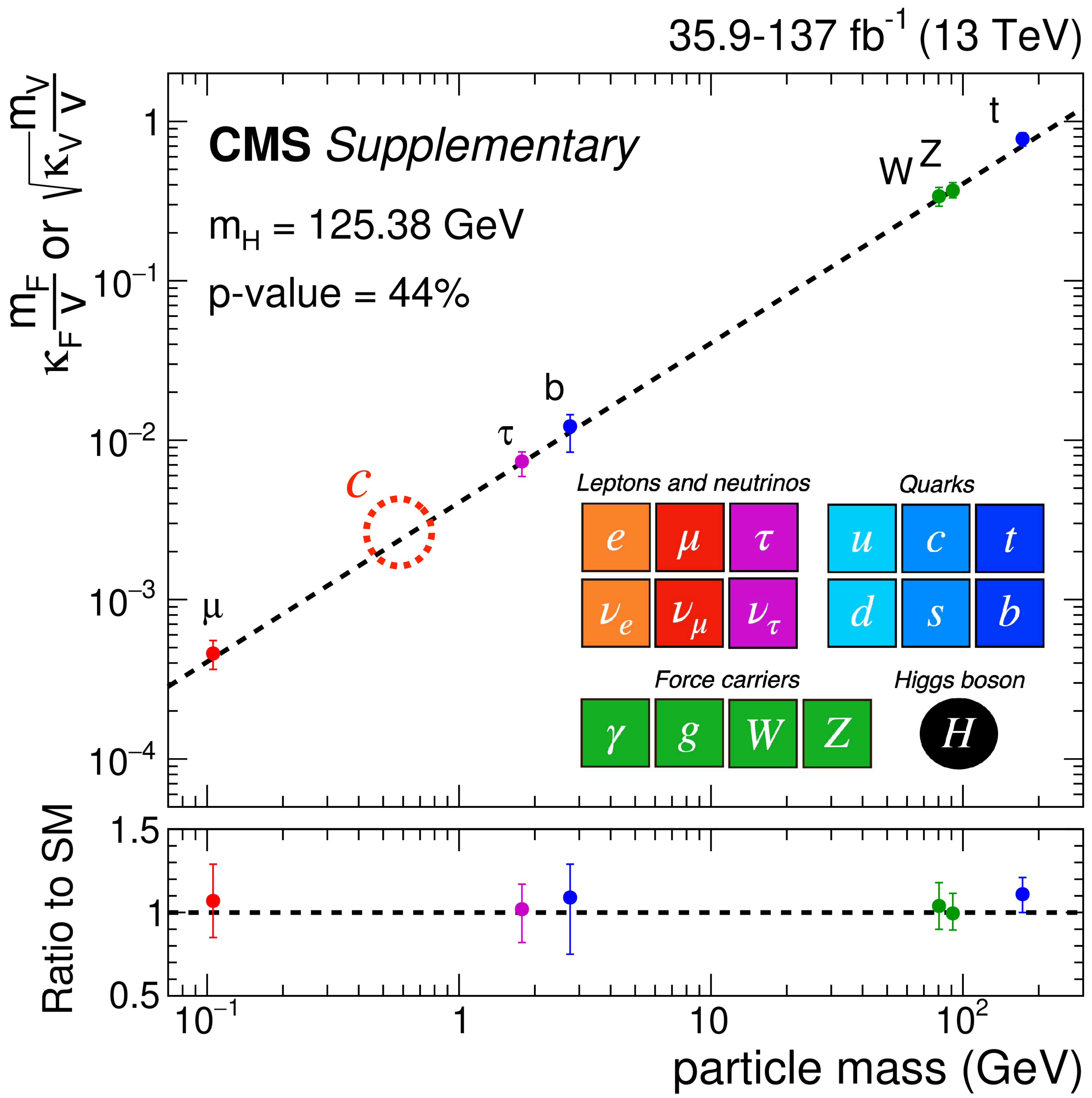
Precision physics
- Higgs boson physics
- top quark physics
- Searches
- Flavour physics
- Heavy Ions physics

Performance in 2025

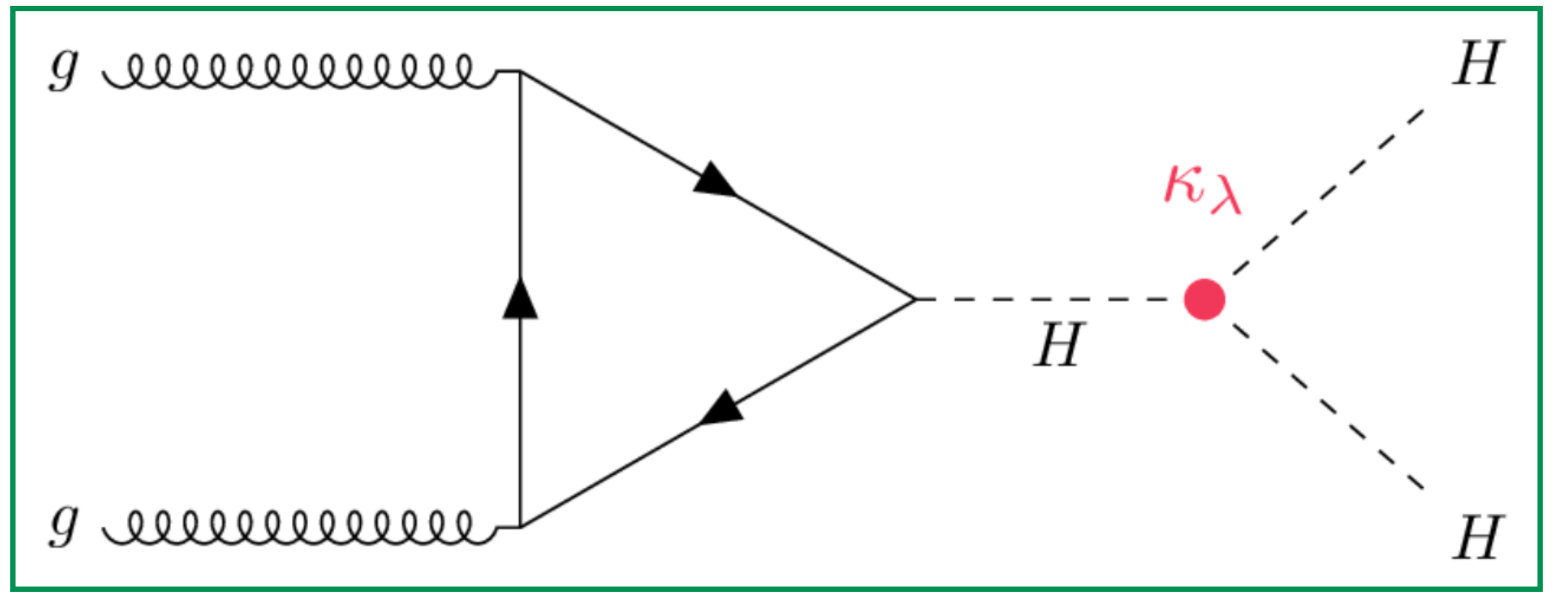
Run-3

Towards the HL-LHC

LHC status and prospect

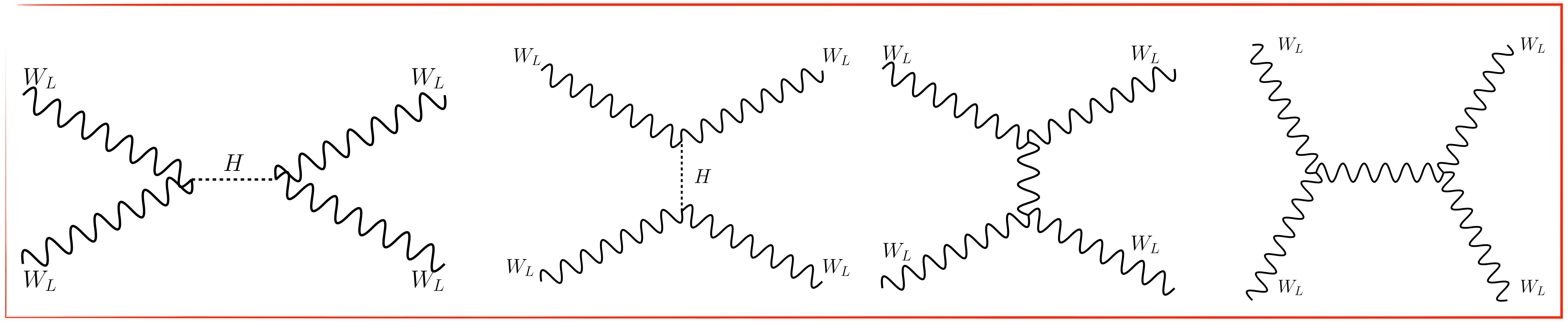


Higgs boson to the 2rd fermions couplings

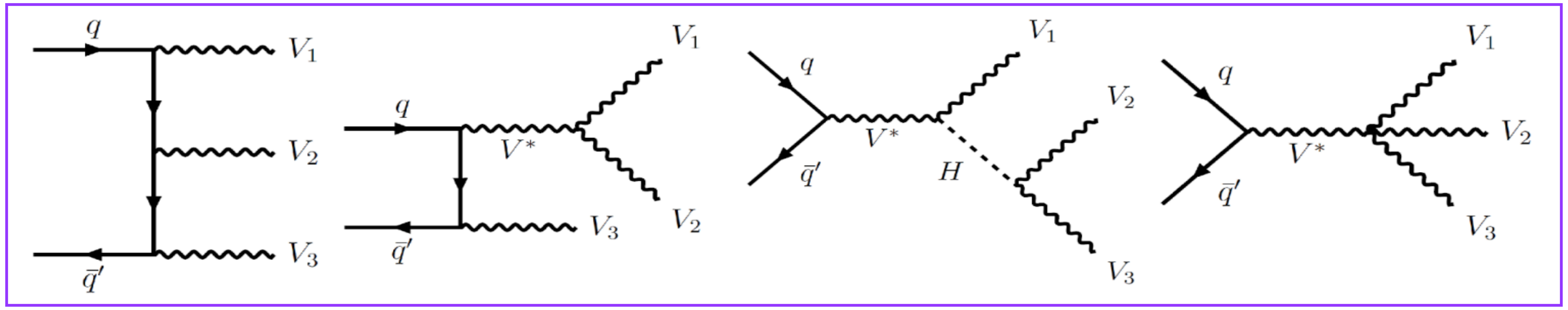


Higgs boson self-coupling

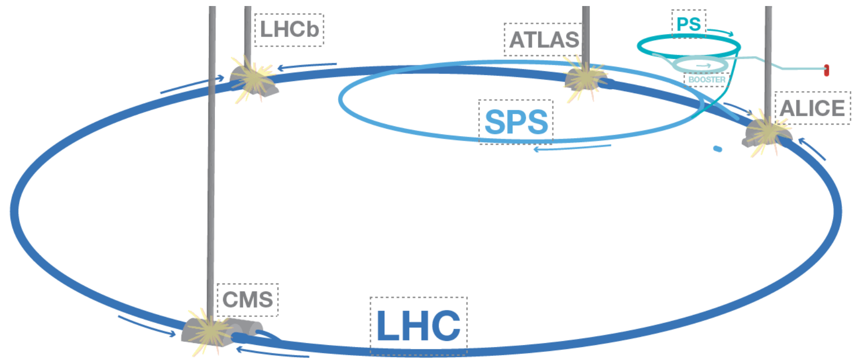
polarised VBS $V_LV_L \to V_LV_L$

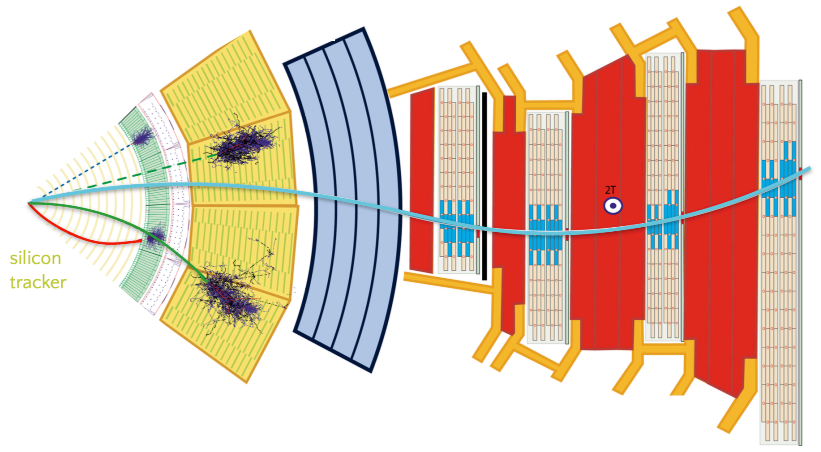


precision rare process measurement in high energy regime



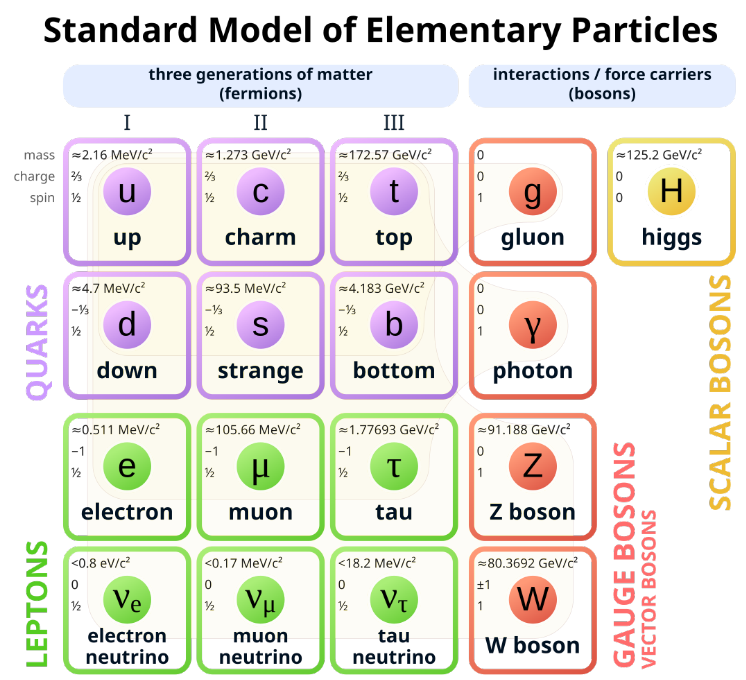
Summary

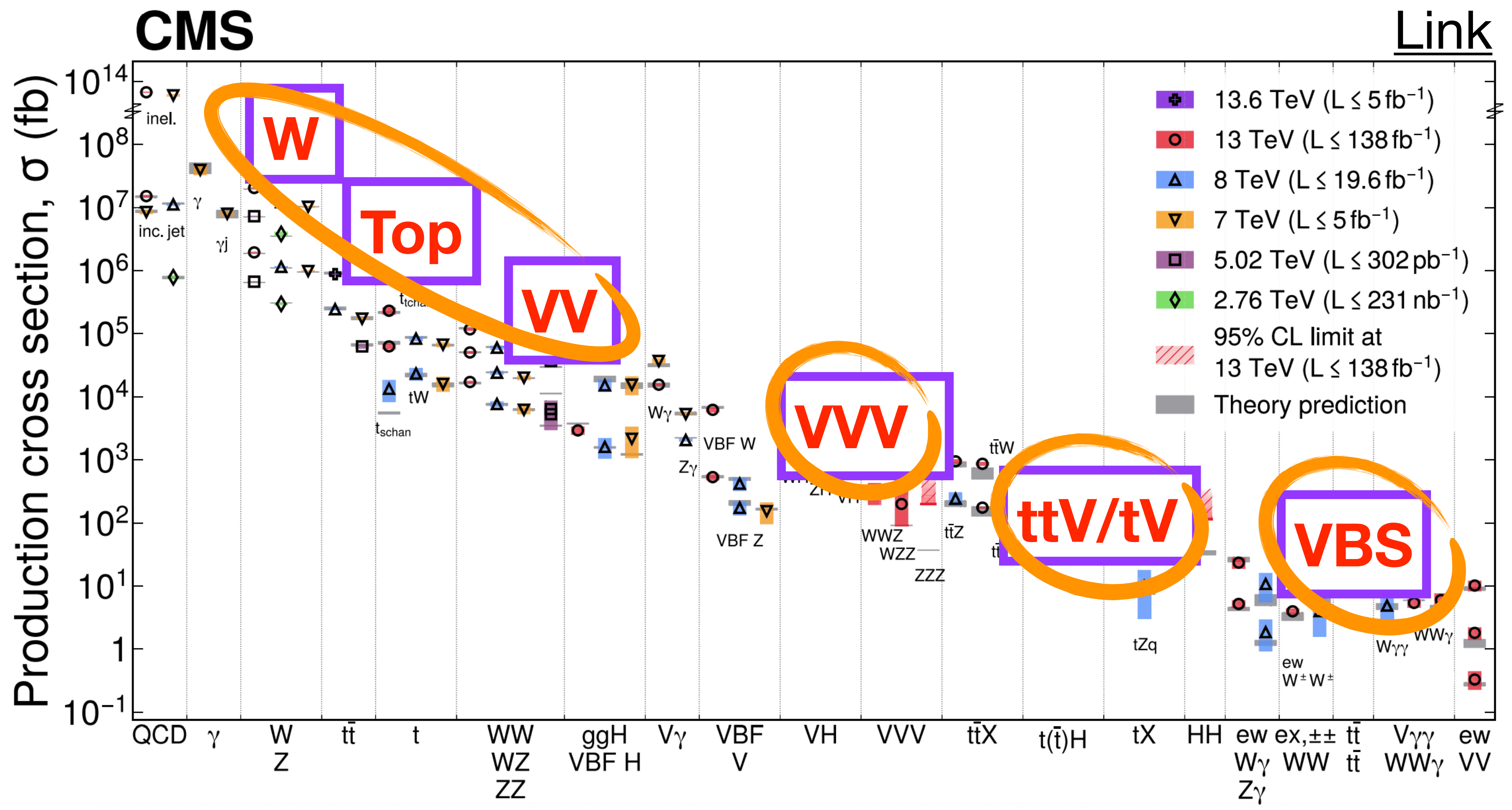




- The SM theory overview
- The recent CMS SM results
  - Fundamental mass results summary
  - Diboson and triboson productions
  - Top-gauge boson coupling production
  - VBS production
- The status and prospects of physics from LHC collisions

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

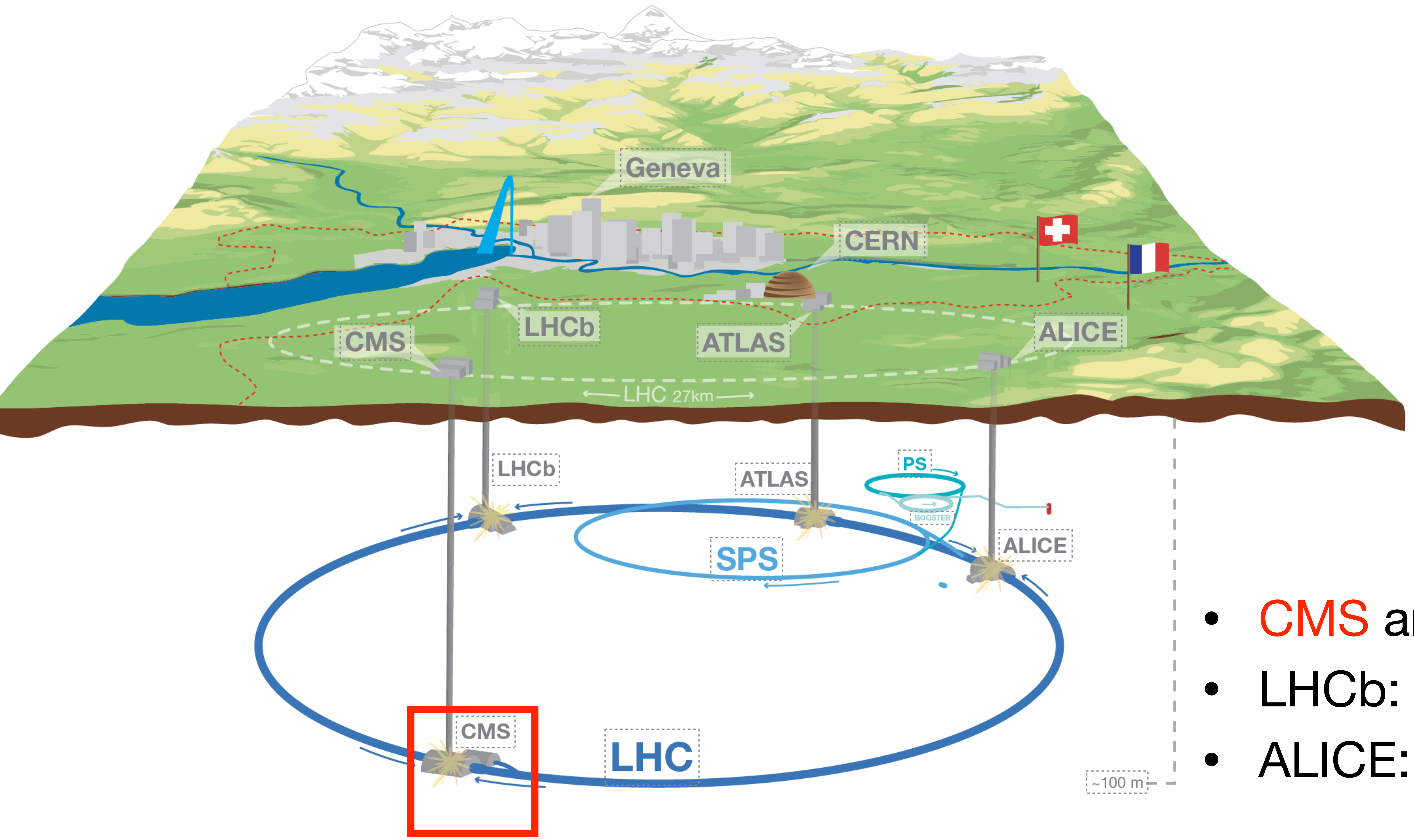




With the ongoing Run 3 and the future HL-LHC, we are entering an era where ***precision and rare-process measurements*** *will play an increasingly* ***central role in particle physics****, and where we expect to* ***achieve a new generation of representative results***

Backup

Large hardon collider (LHC)



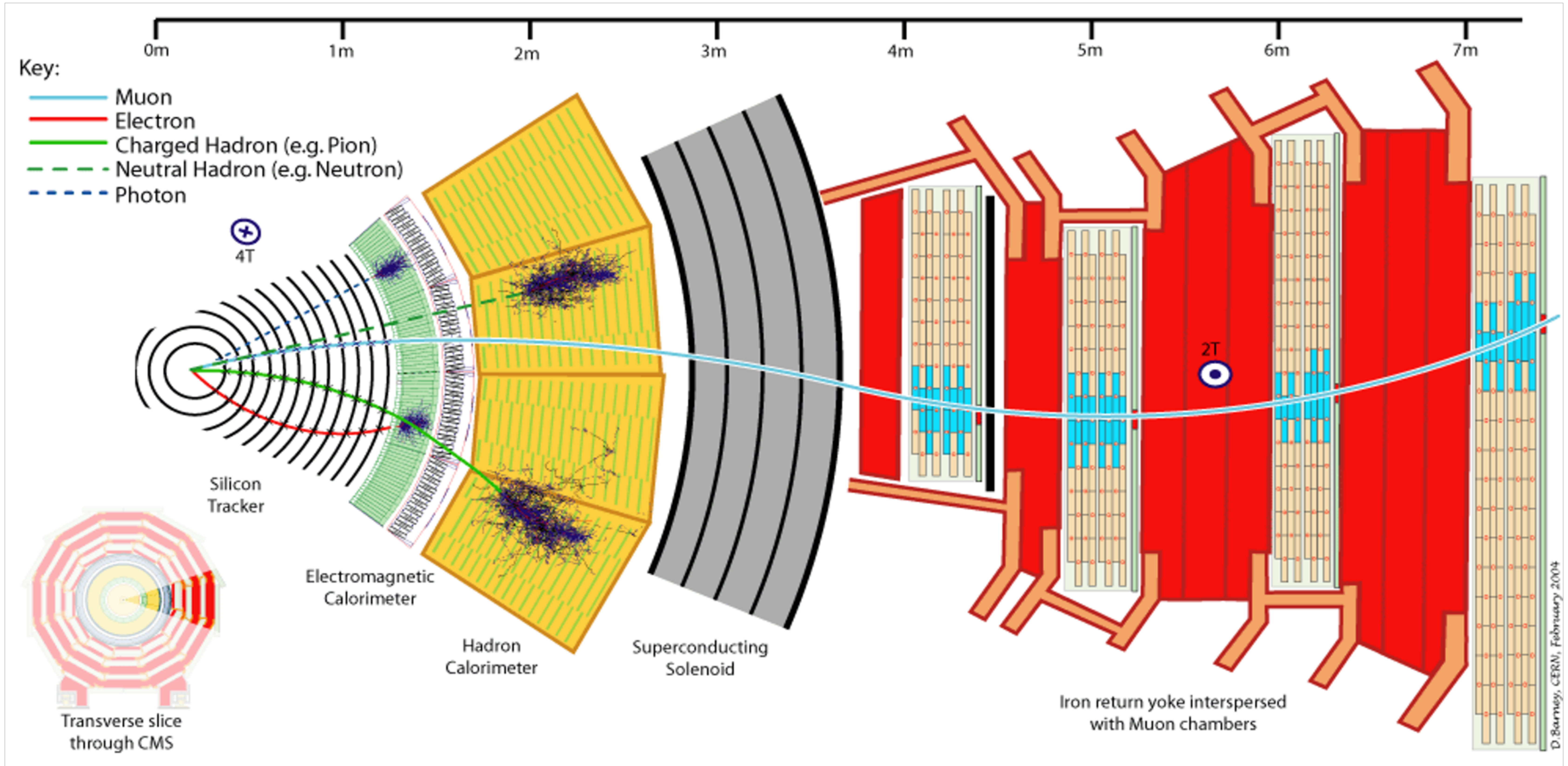
- Located in the French-Swiss border
- 27 km circumference
- ~175m underground
- Operating since 2008
- Superconducting magnets to accelerate protons up to 7 TeV

- 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

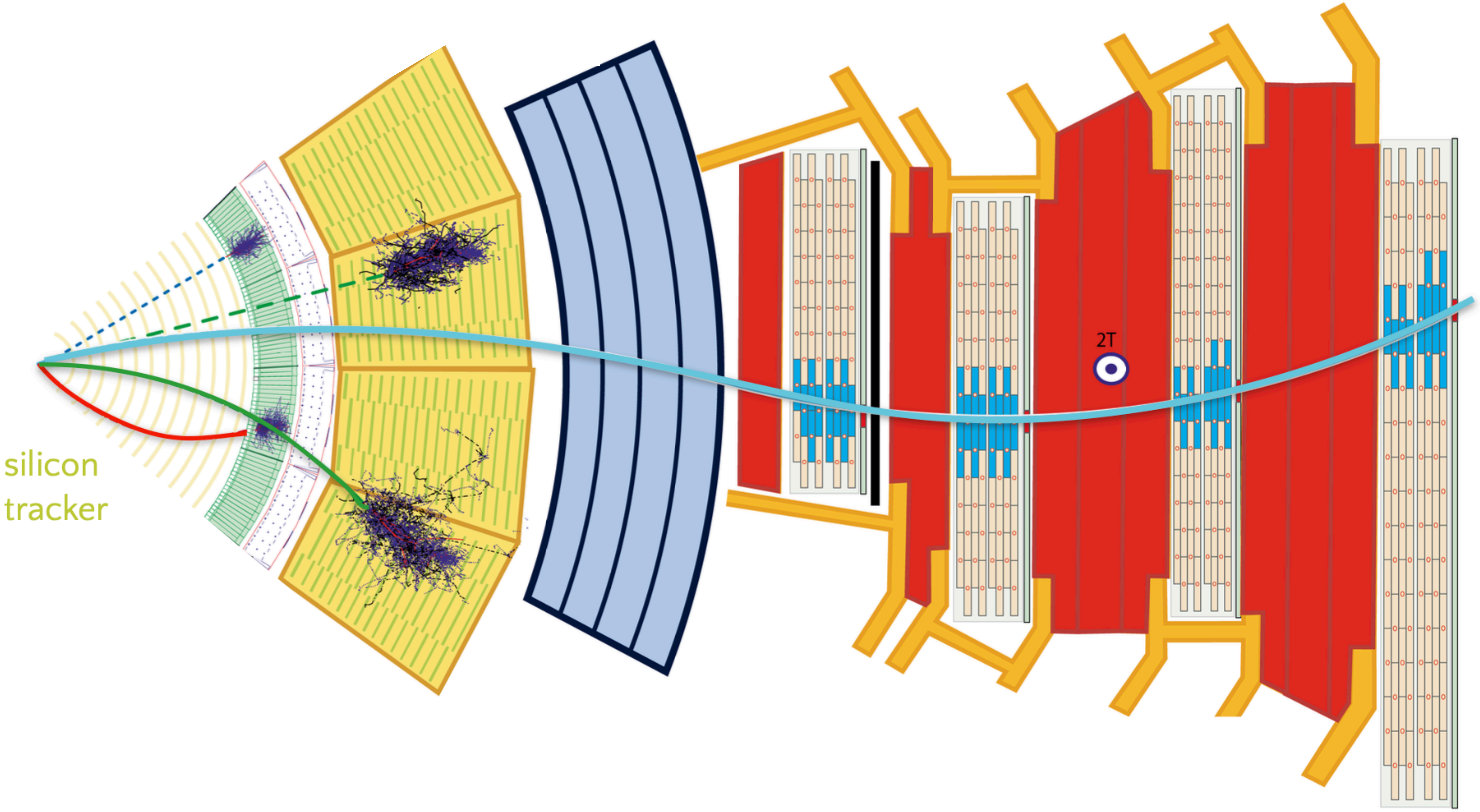
The Compact Muon Solenoid (CMS)

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



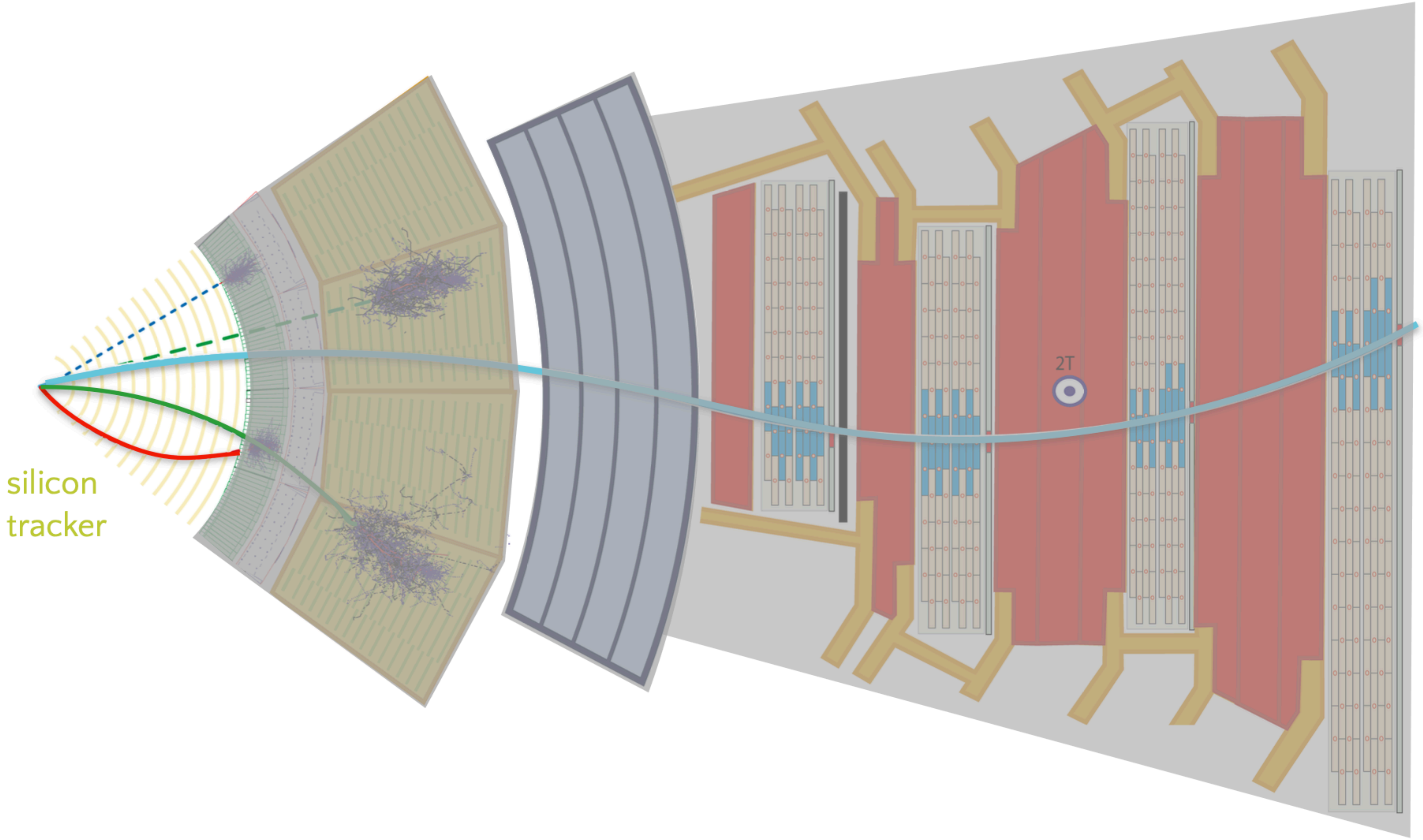
CMS detector

- Layered structure for different particle reconstruction



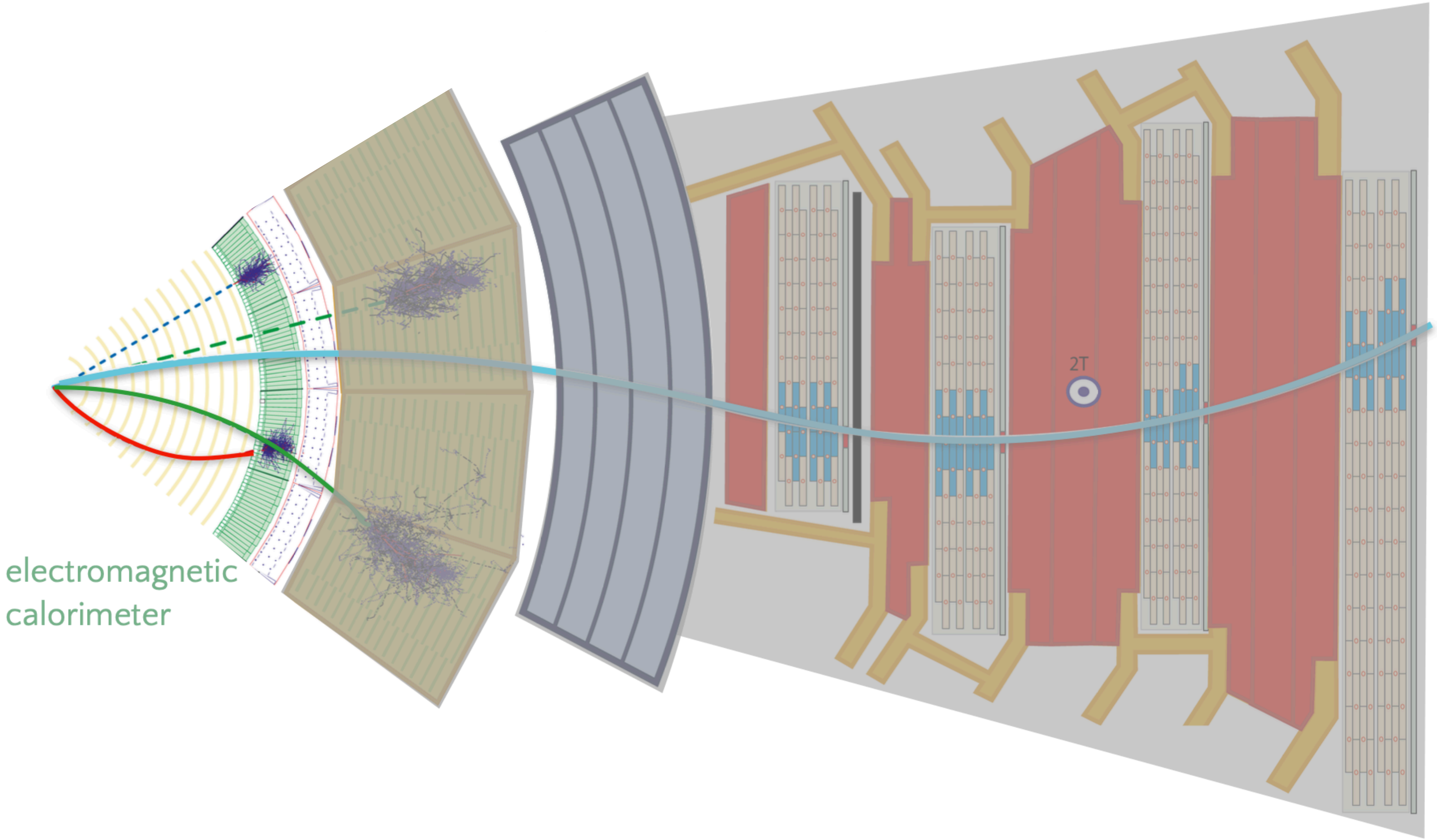
CMS detector

- Layered structure for different particle reconstruction
- Measure momentum and charge of charged particles



CMS detector

- Layered structure for different particle reconstruction
- Measure momentum and charge of charged particles
- Collect and measure photon and electron



CMS detector

- Layered structure for different particle reconstruction
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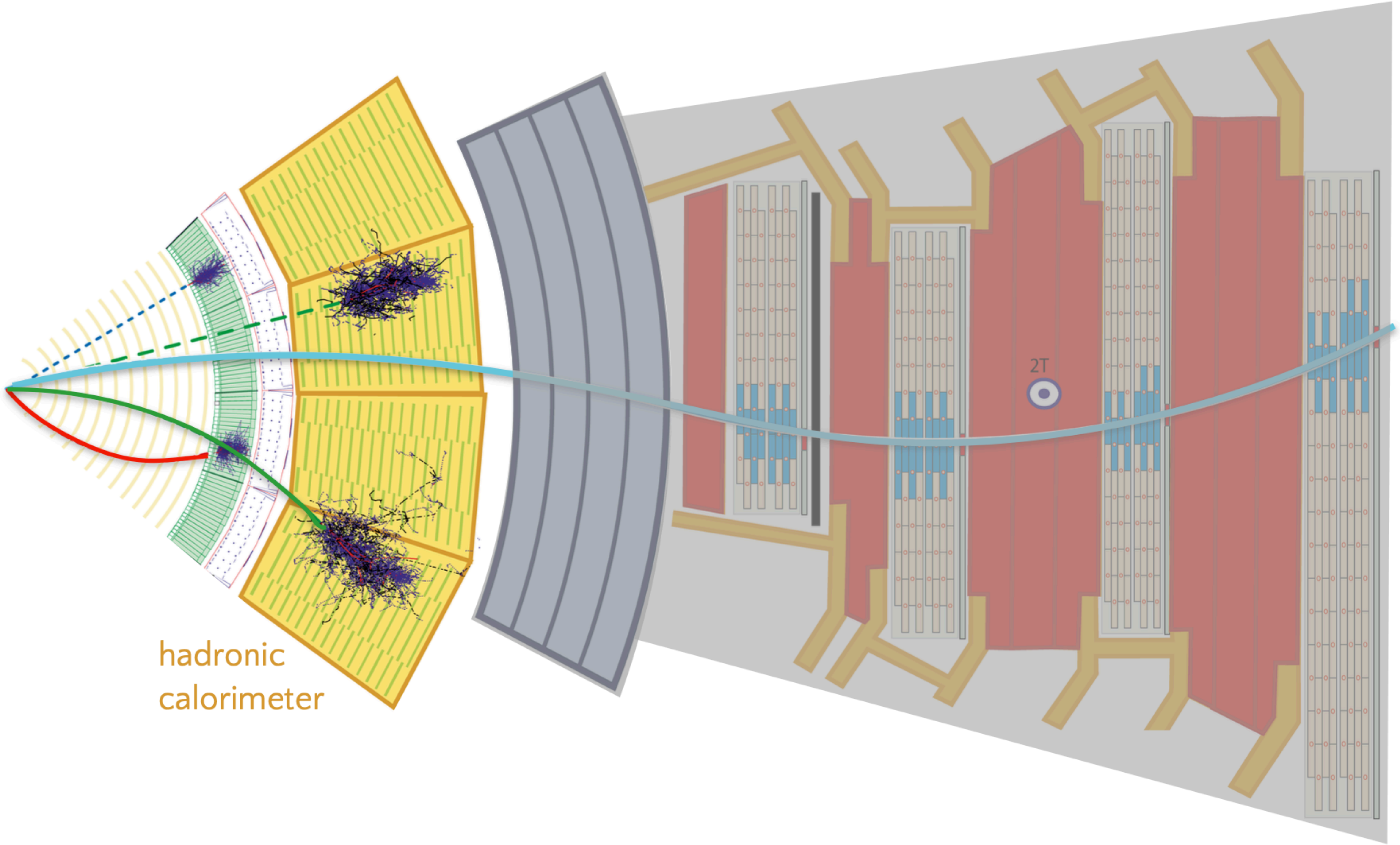
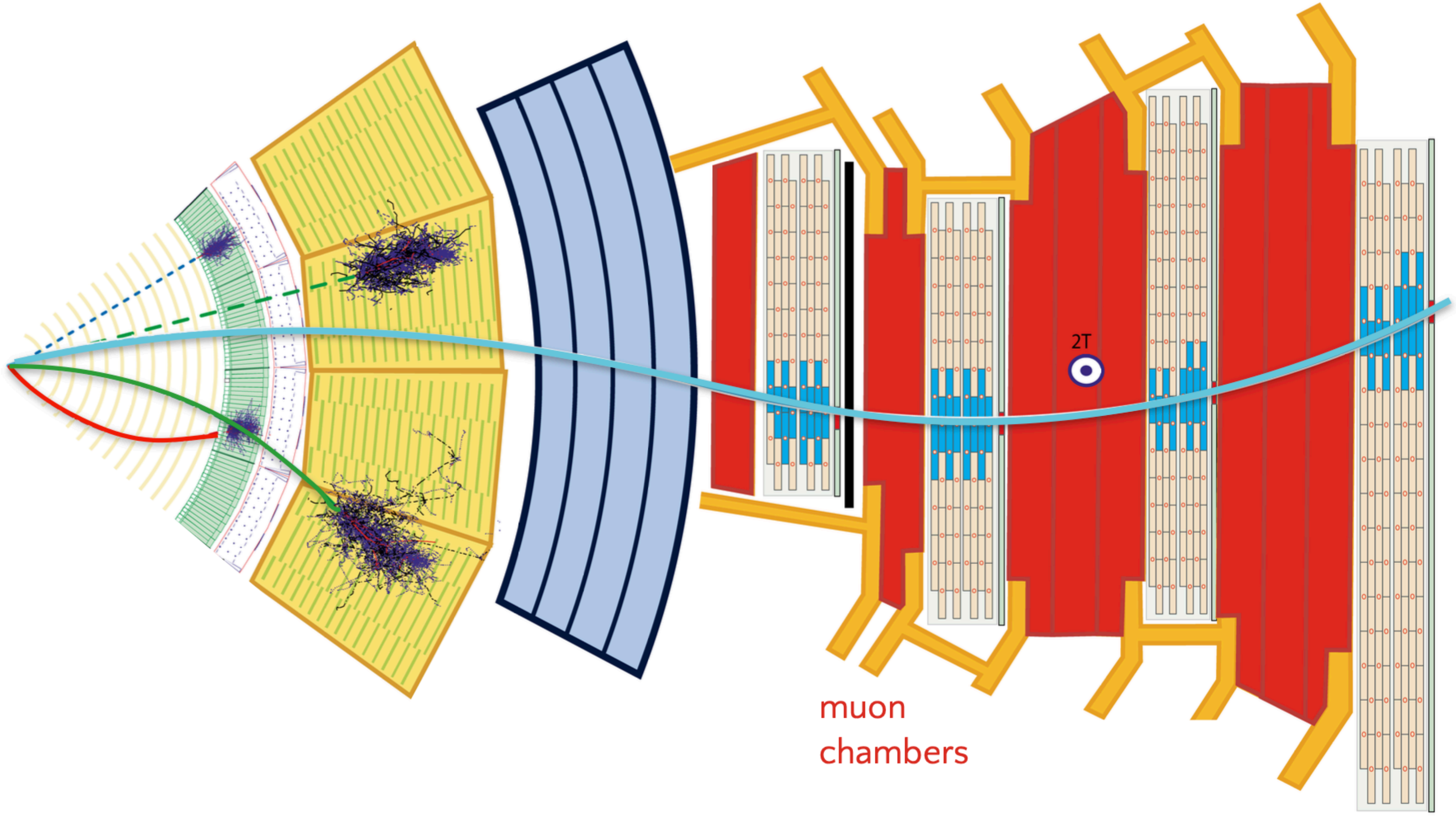
- Collect energy of hadrons



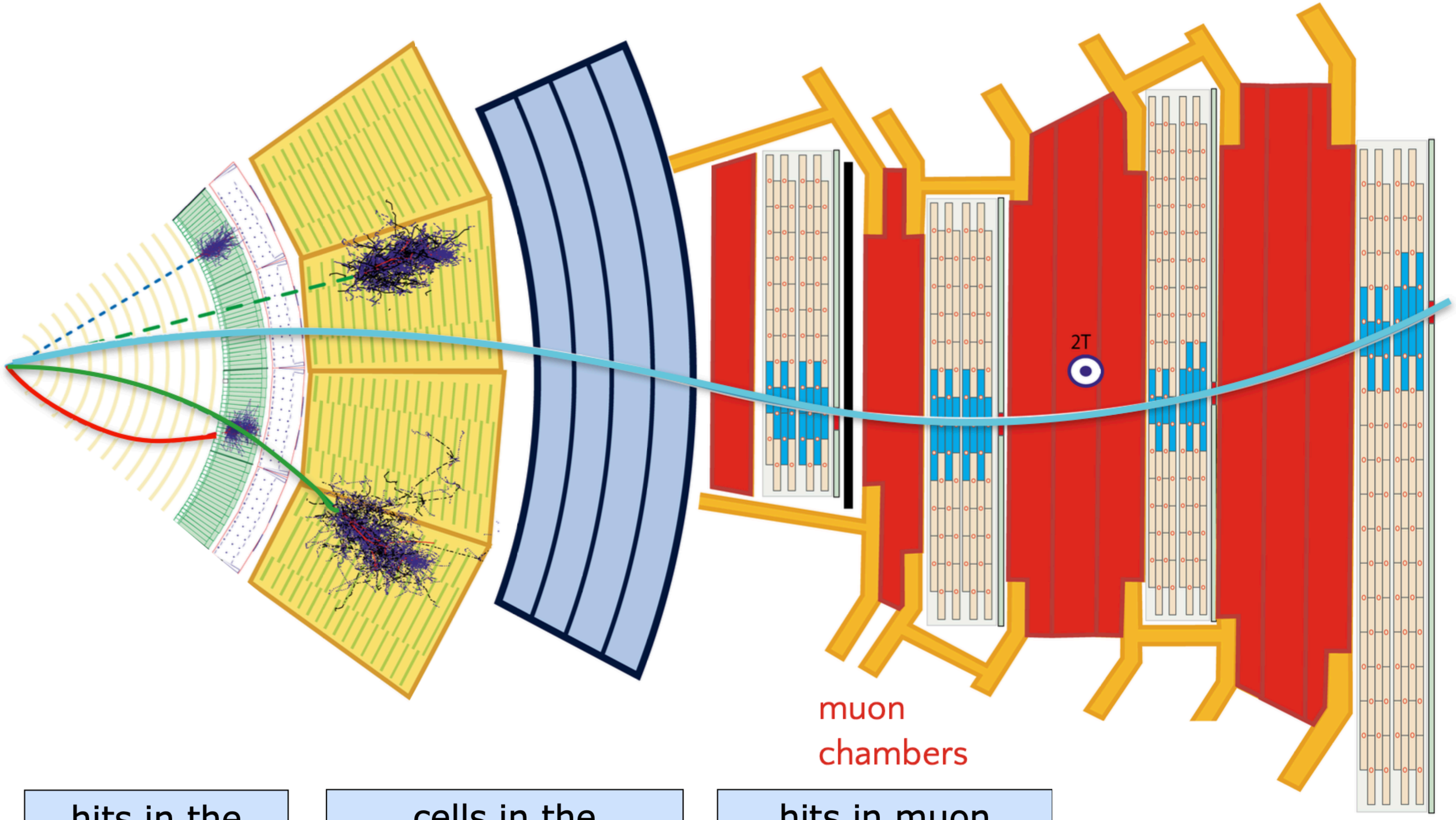
CMS detector

- 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



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



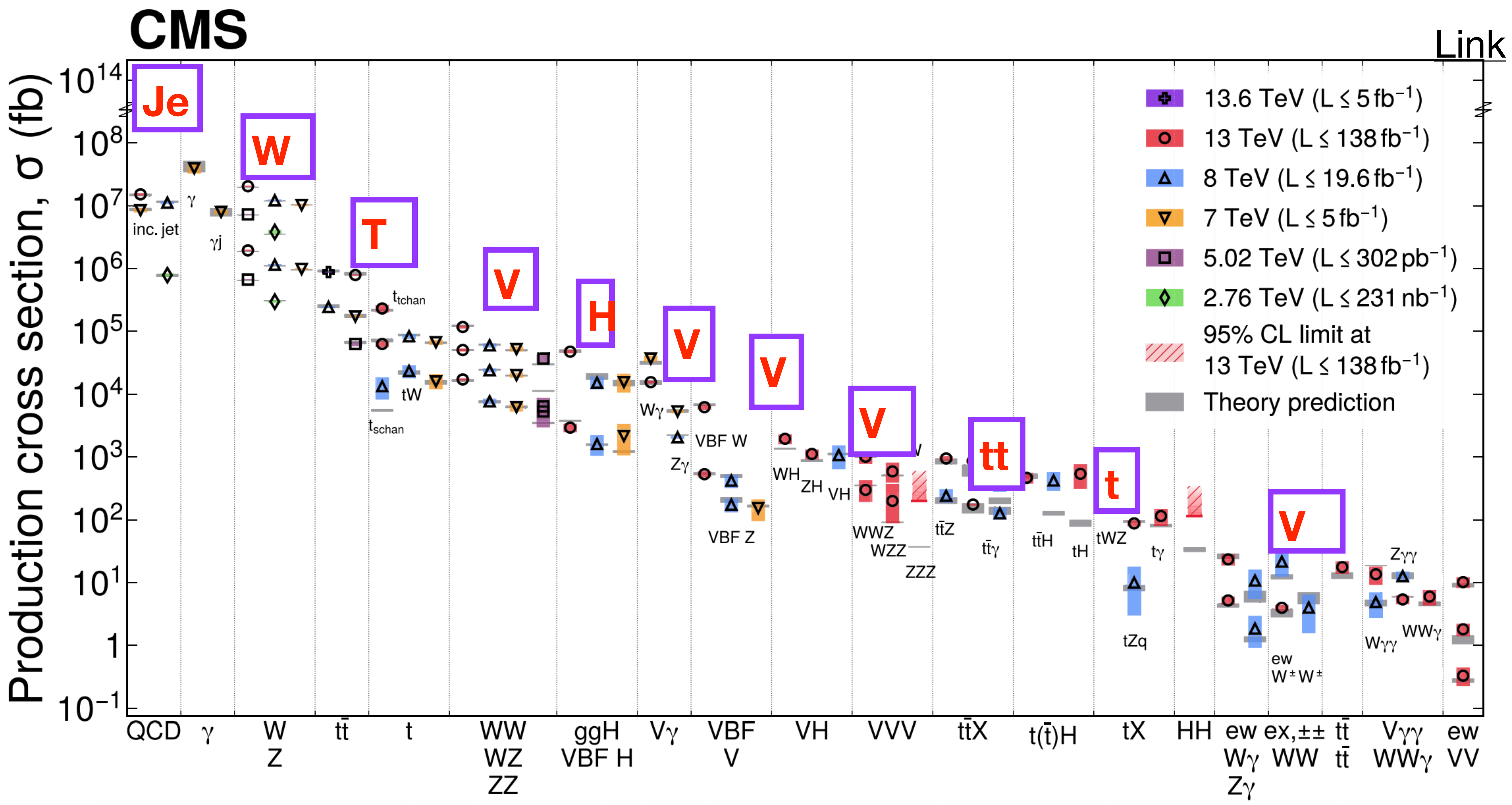
- Information from all sub-detectors combined to reconstruct particles

- 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*

hits in the tracker	cells in the calorimeter	hits in muon detectors
↓	↓	↓
tracker tracks	calorimetric clusters	muon tracks

PF algorithm is the base of the physics analysis

SM measurements

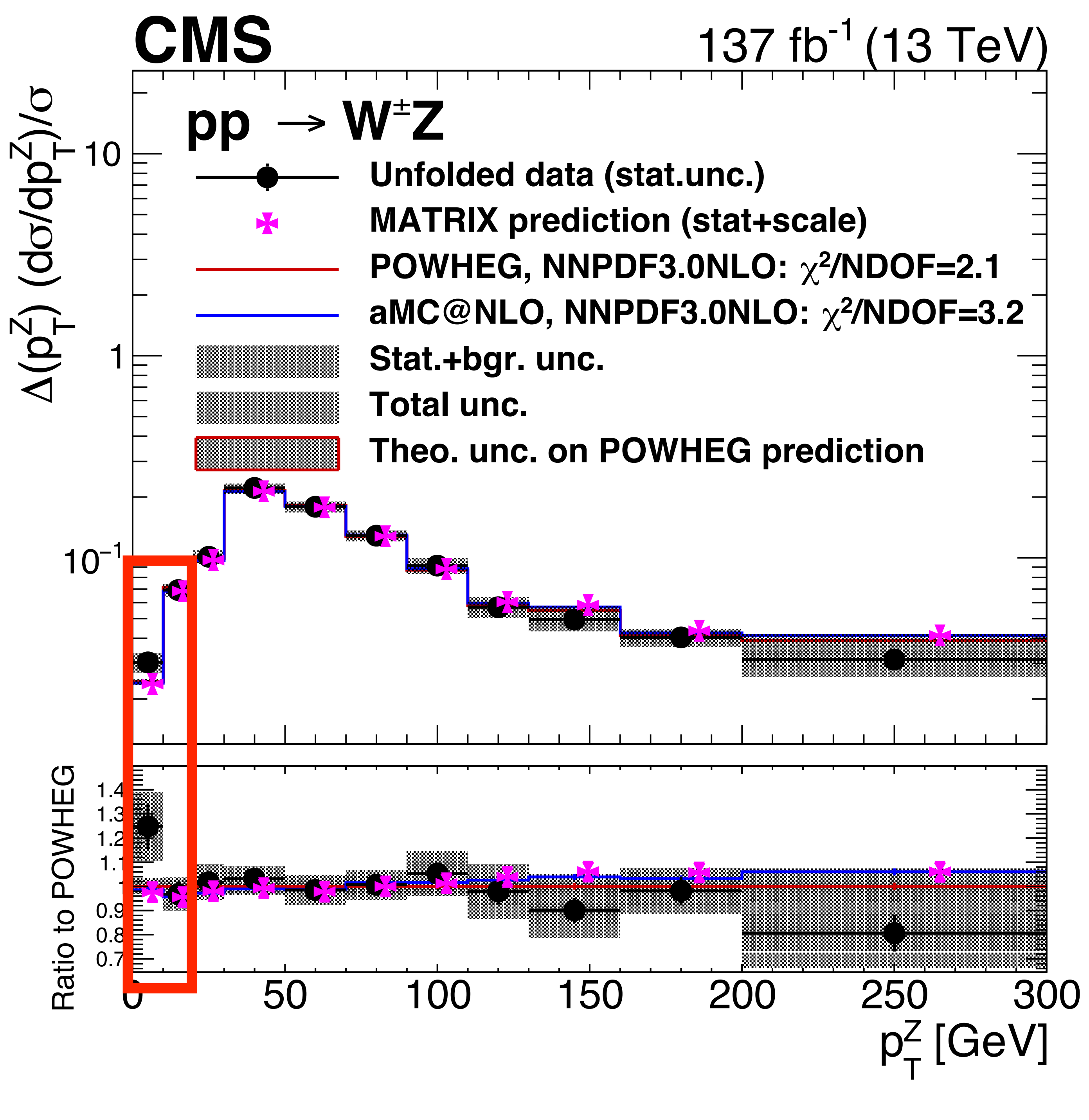


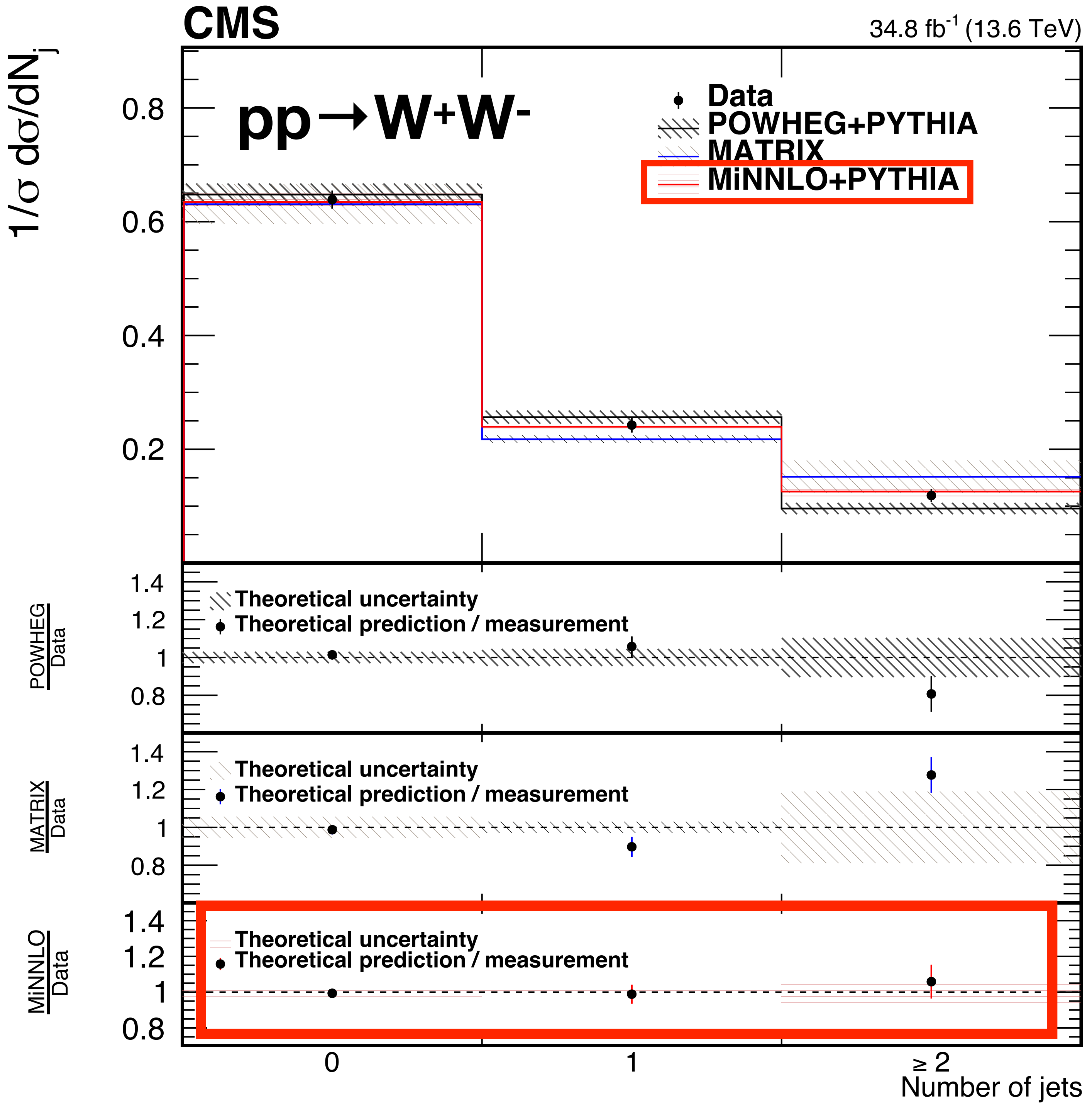
Diboson production - Results

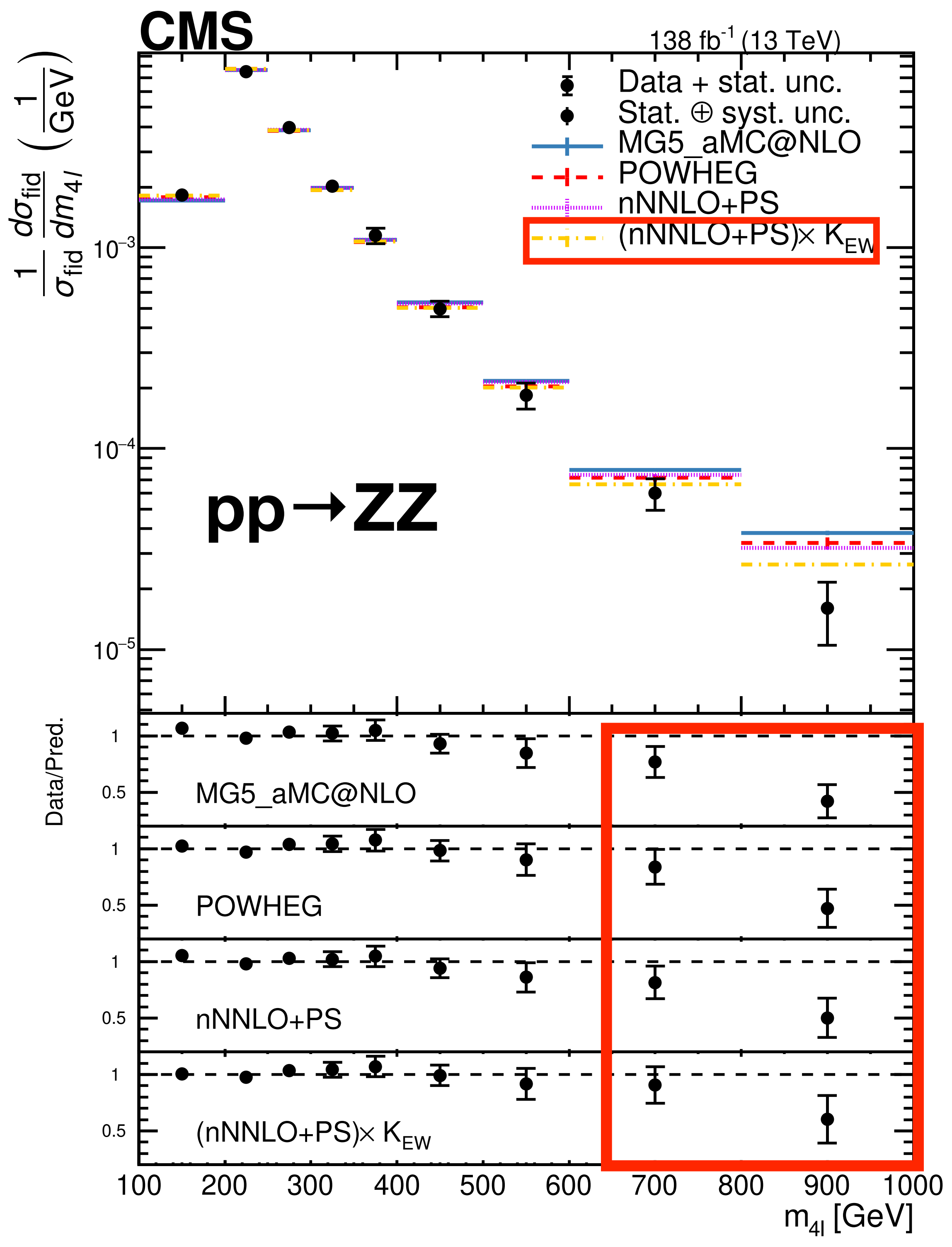
Diboson production has been widely measured at the LHC by CMS and ATLAS over a wide range of center-of-mass energy up to 13.6 TeV

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*





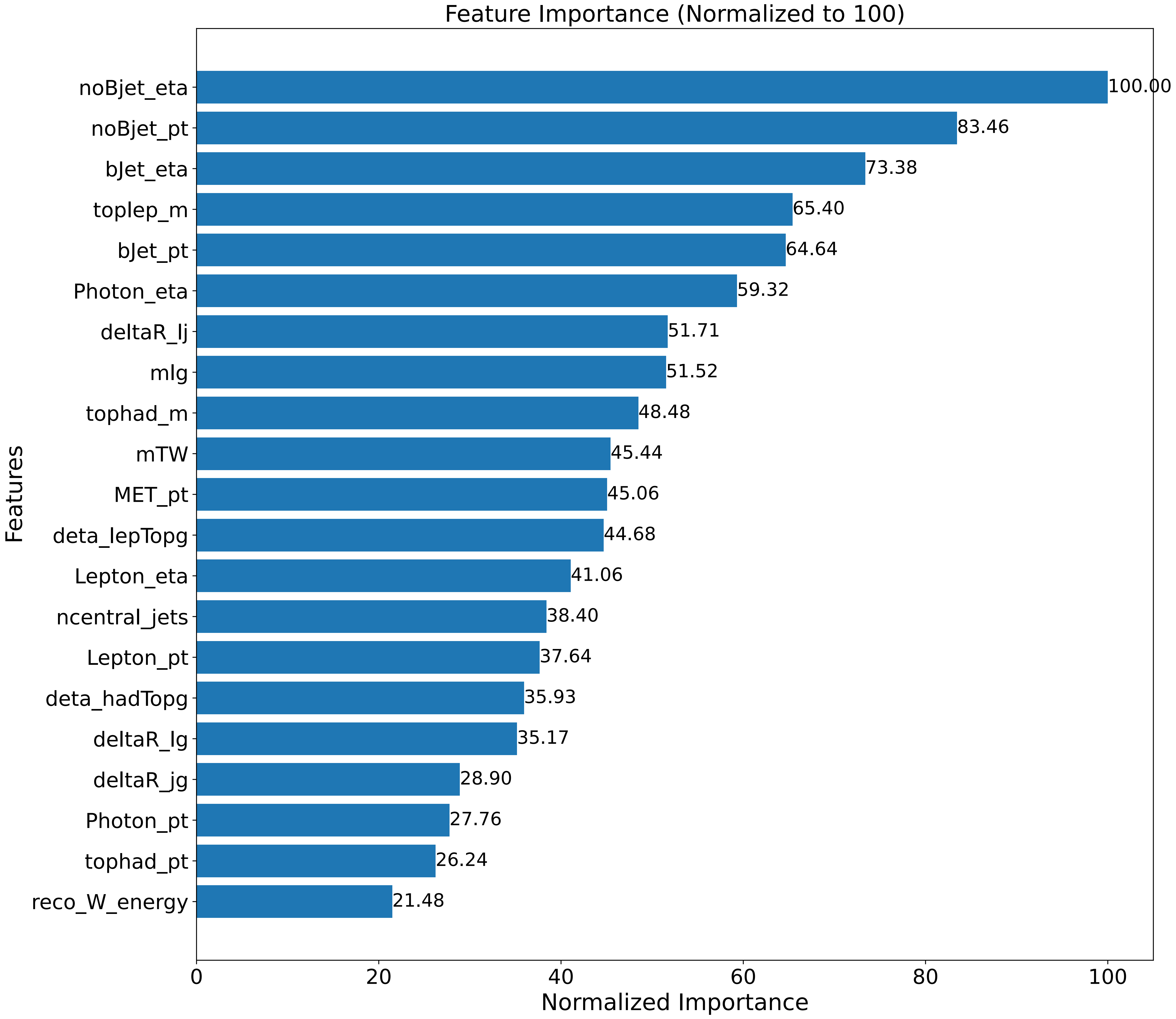


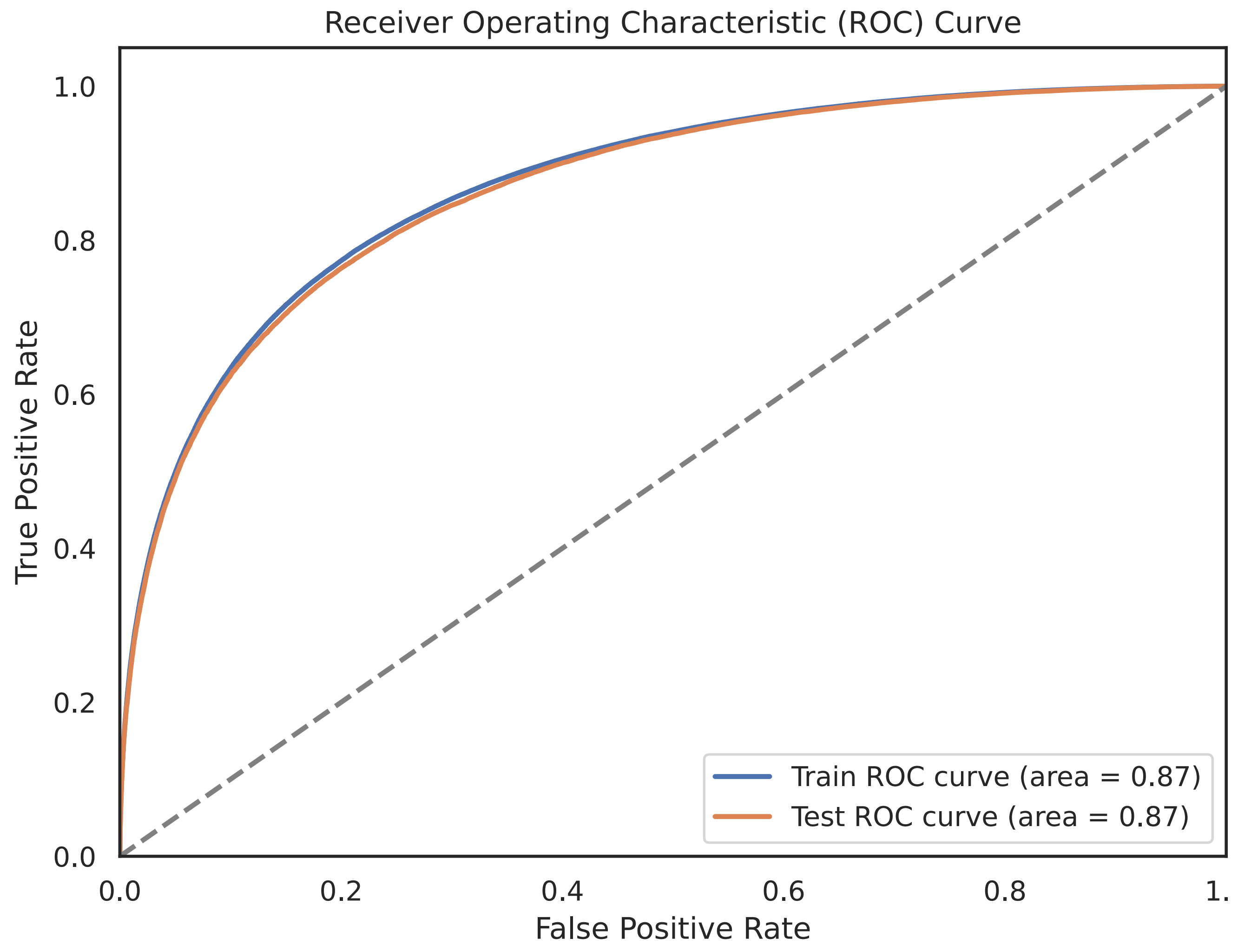
- low p_T^V for WZ from soft and collinear QCD radiations not well described
- Differential jet multiplicity in WW is best described by Powheg MiNNLO v2+Pythia (NNLO in QCD)
- Discrepancies towards higher $m_{4\ell}$ in ZZ due to missing higher order EW corrections

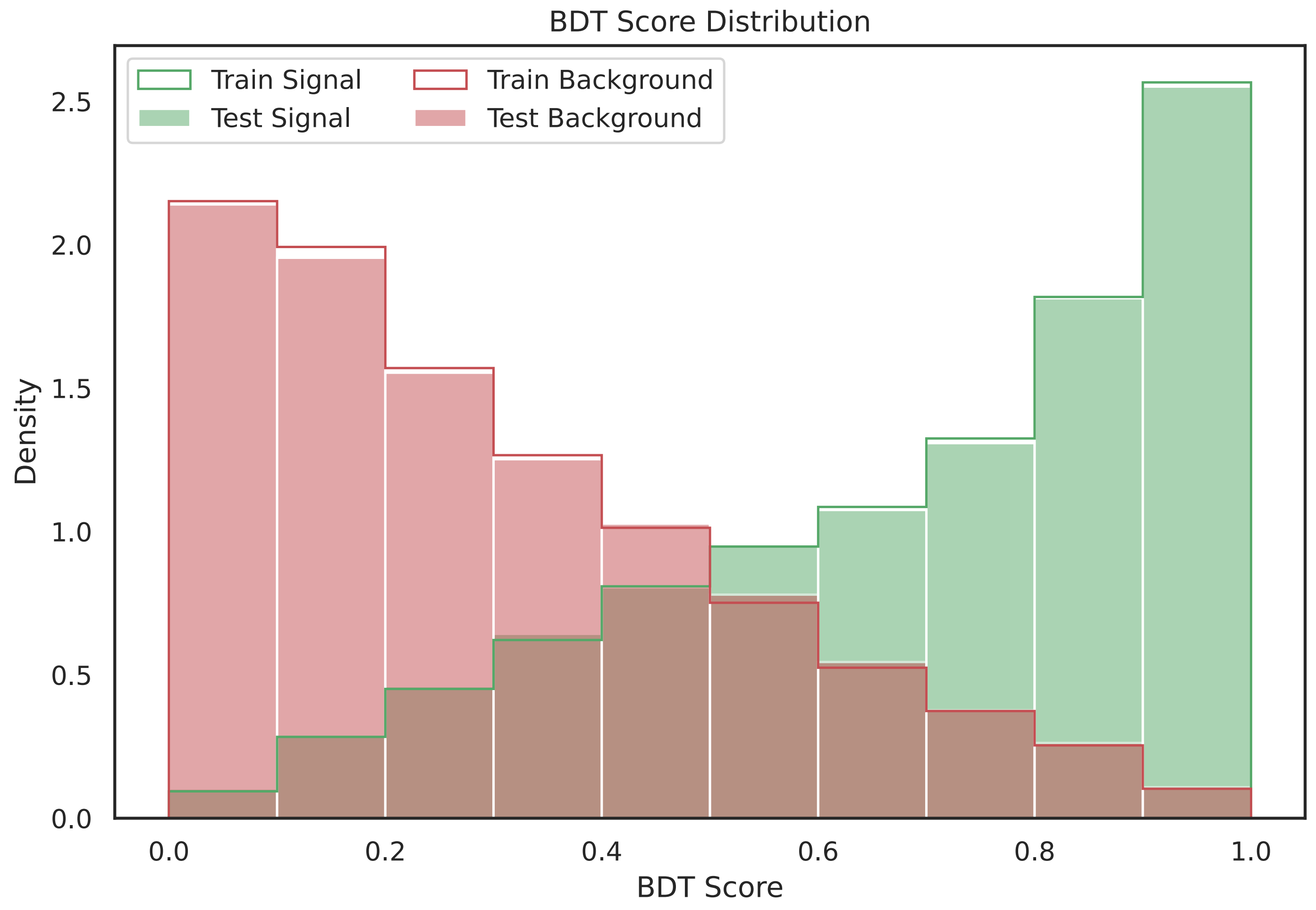
BDT training

A BDT is trained in the signal region with tγq production photon as signal and others as backgrounds

- Using simulation events
- Train one model for different lepton channels and years



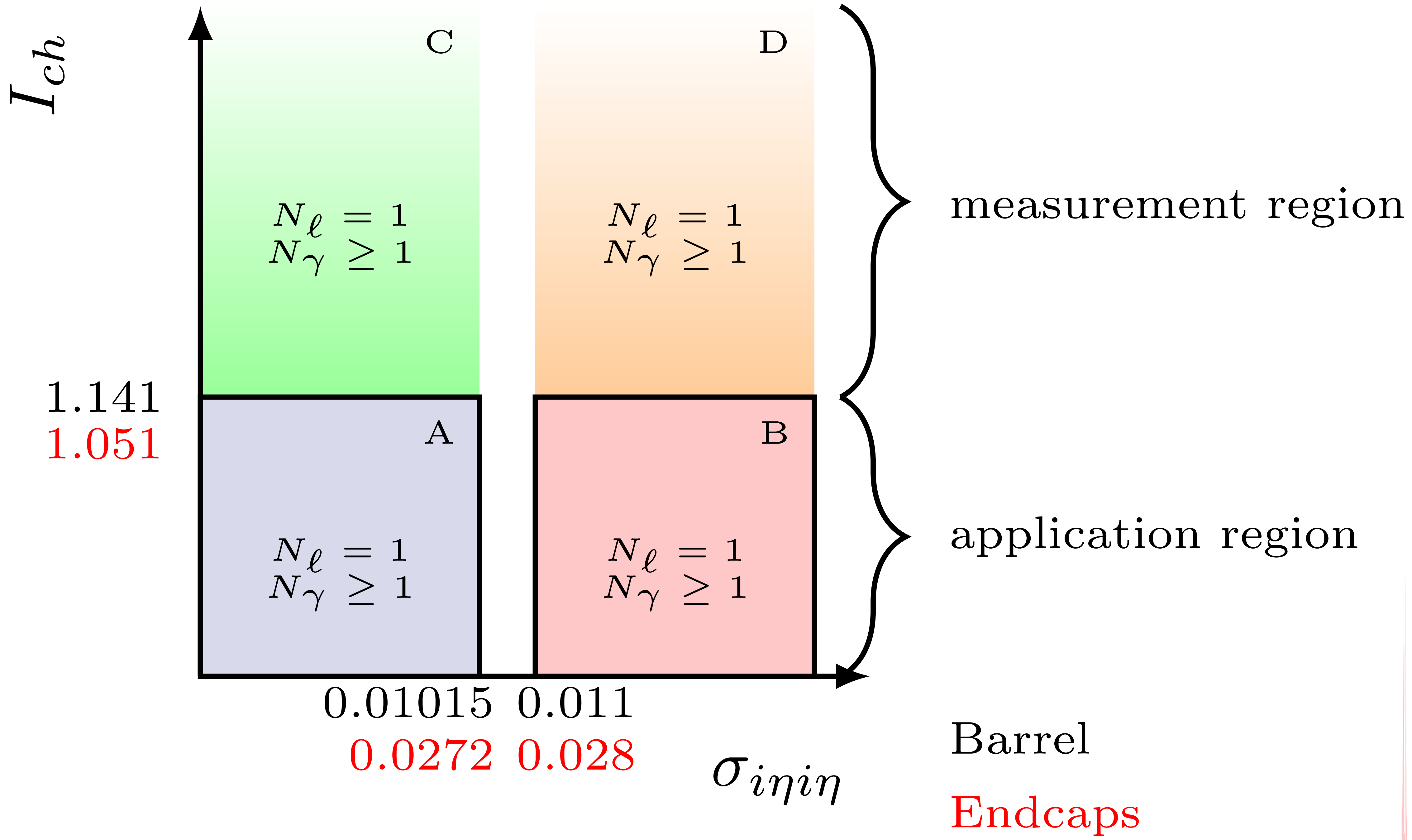




- Hyper-parameters tuned by HYPEROPT package
- Total 21 input features checked in partial SR of BDT<0.5 (before unblinding seen backup)
- Train and test matched well with ROC ~ 87%

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



$$\text{fake rate}^{ij} = \frac{\text{Data}^{ij}_{C} - (\text{prompt} + \text{ele mis.})\,\text{MC}^{ij}_{C}}{\text{Data}^{ij}_{D} - (\text{prompt} + \text{ele mis.})\,\text{MC}^{ij}_{D}}$$

$$k^{ij}_{MC} = \frac{\text{nonprompt MC}^{ij}_{A}}{\text{nonprompt MC}^{ij}_{B}} \div \frac{\text{nonprompt MC}^{ij}_{C}}{\text{nonprompt MC}^{ij}_{D}}$$

$$\text{nonprompt contribution} = \sum_{ij} (\text{data}^{ij}_{B} \times \text{fake rate}^{ij} \times k^{ij}_{MC}) - \sum_{ij} ((\text{prompt} + \text{ele mis.})\,\text{MC}^{ij}_{B} \times \text{fake rate}^{ij} \times k^{ij}_{MC})$$

Theoretical systematics

1. Renormalisation and factorisation
2. PDF → splited
3. PDF α_s (if provided)
4. Parton shower (FSR, ISR)

(Items 1–3 → *Normalization effect removed*)

5. Uncertainty on fraction of production and decay photons for tγq and ttγ signals

$$\sigma_{t\gamma q} + \sigma_{t(\to \ell\gamma b\gamma)q} = \sigma_{t(\to \ell\gamma b\gamma)q}(1 \pm X\%) + \sigma_{t\gamma q}(1 \mp Y\%).$$

New after pre-approval

- The X% is determined by calculating their total scale variations and the largest deviation among all bins is selected. Y% is then solved from the equation

6. Cross sections for minor backgrounds → VV, ttV, etc.
   - When the lnN XS uncertainty considered, the above theoretical uncertainty is not applied

Experimental systematics

- Luminosity
- PU
- L1 pre-firing (2016 and 2017) → split to Muon and ECAL parts
- Lepton ID/ISO/reco/HLT
- Photon ID/veto scale factors → photon ID split to syst. (rate+shape) and stat. parts
- Pileup Jet ID/Btagging SFs
- Jet energy scale and resolution → split JES (LOWESS smooth for some of them)
- Uncluster MET energy
- Nonprompt photon → *introduce next slide*
- Nonprompt lepton → *introduce next slide*
- Shape uncertainty on jet multiplicity → *introduce next slide*
- rateParam for ele misID

New after pre-approval

New after pre-approval

Simultaneous inclusive fit

- Simultaneous fit for events in SR, b-veto and 2ℓ ttγ CRs
  - **SR:** unrolled 2D of BDT score and ΔR(ℓ, γ)
  - **b-veto CR:** $m_{\ell\gamma}$ distribution
  - <u>**2ℓ ttγ CR:** N_{jets} distribution</u>
- POIs are signal strengths of tγq and $t\bar{t}$γ
  - *Signal events out of fiducial are regarded as backgrounds but have same uncertainties as the real signal events*
- All systematic uncertainties are considered

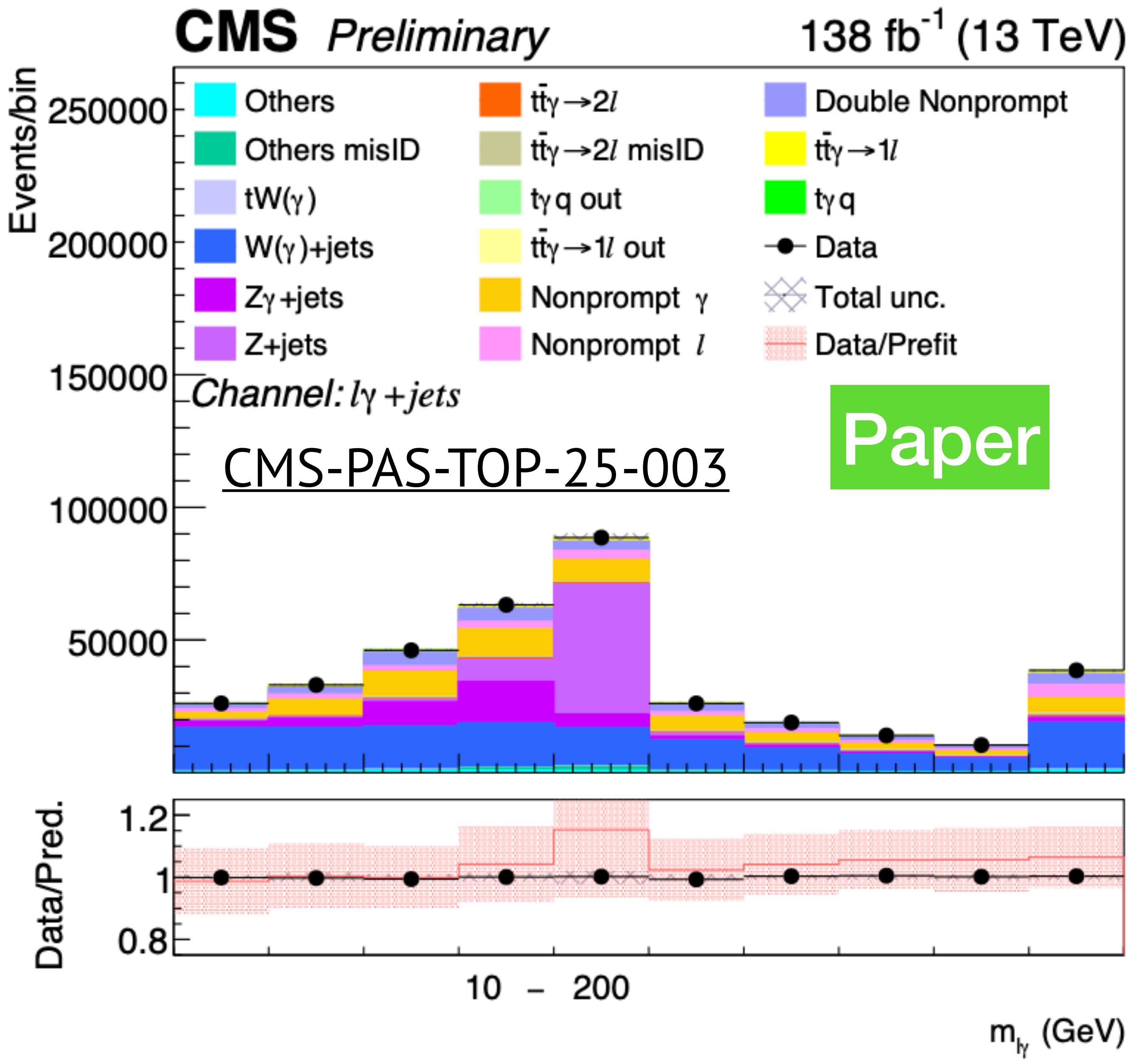
Table 1: A summary of the selection used in different regions.

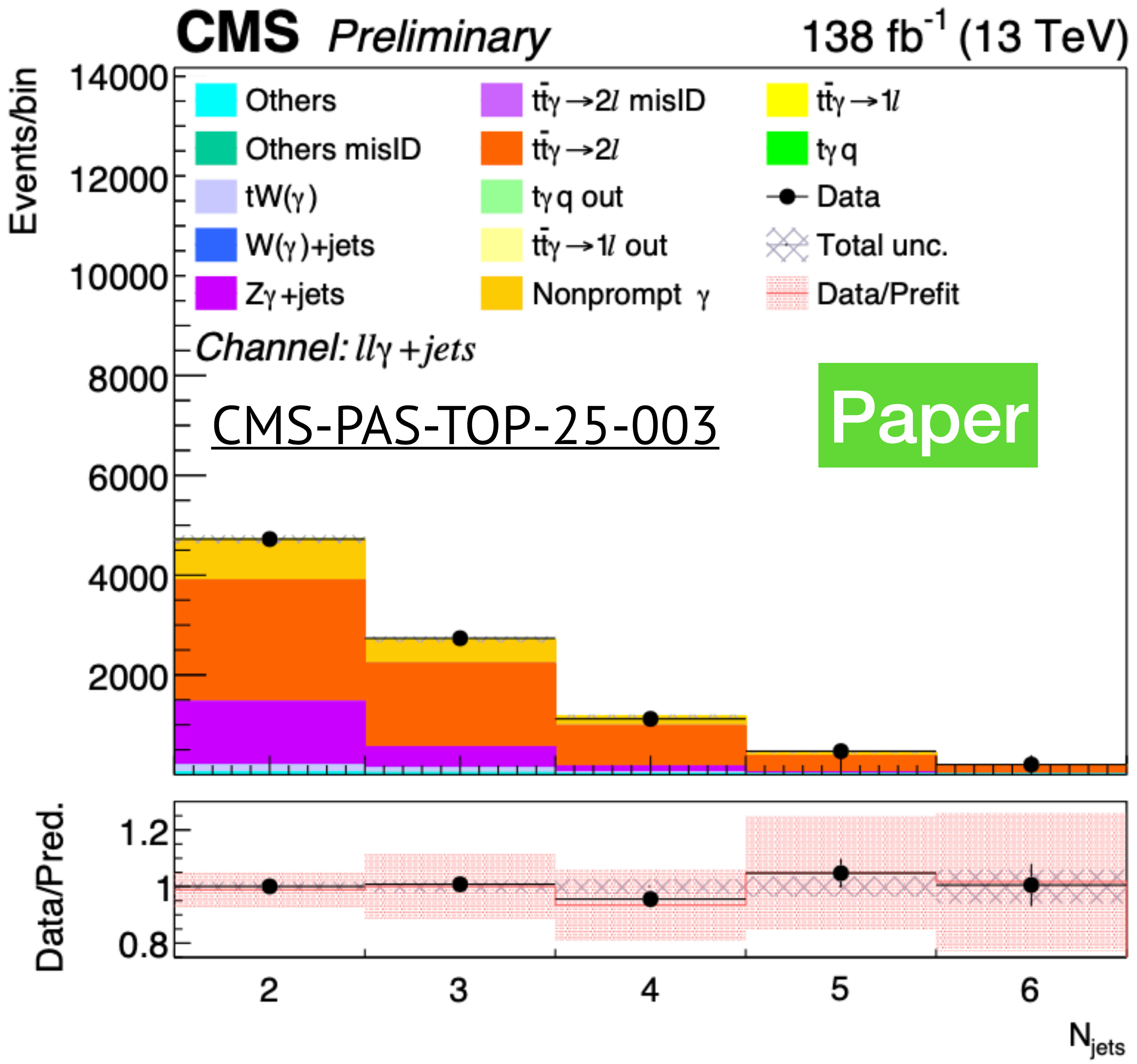
Particle-level

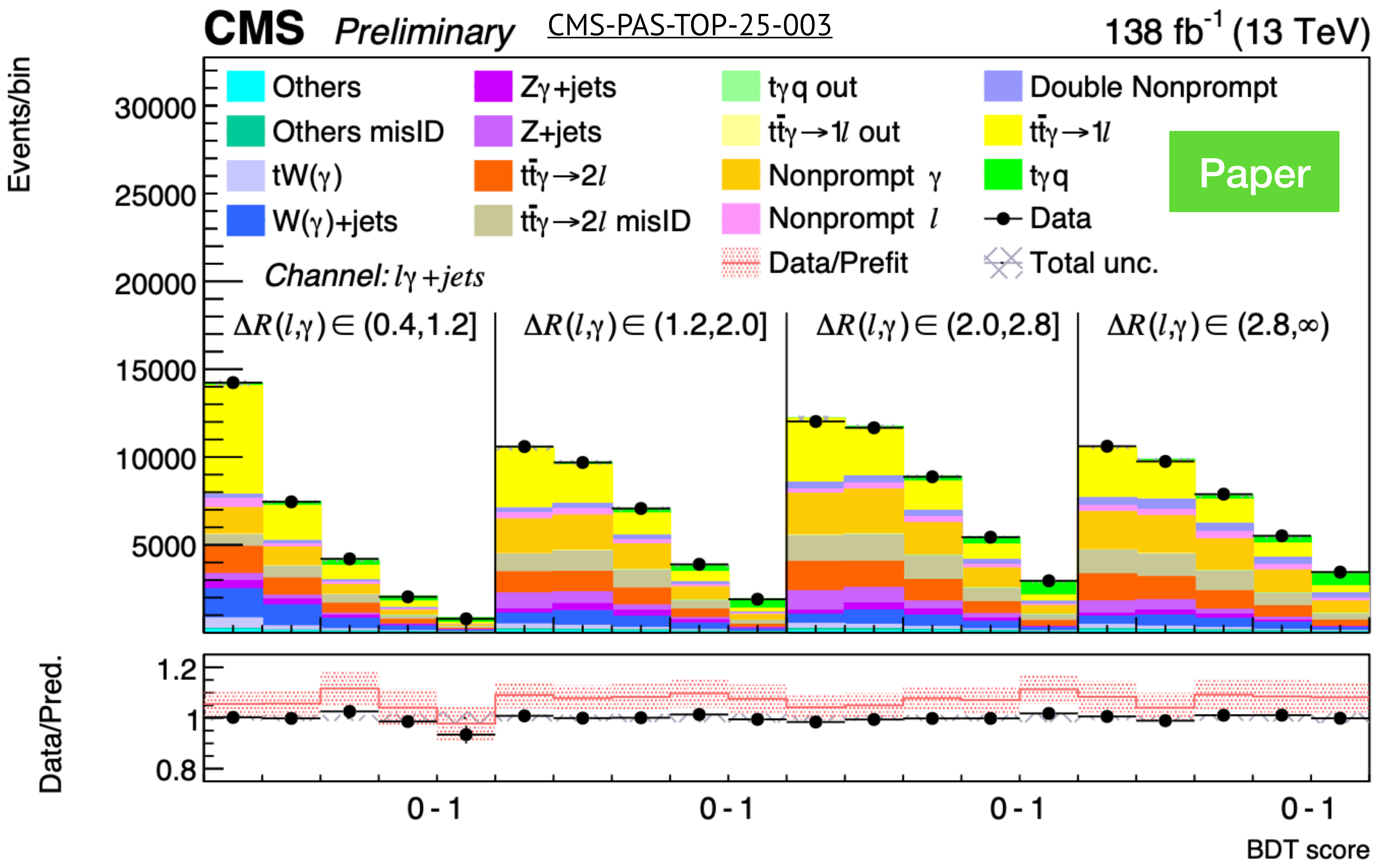
2ℓ CR	b-veto CR	SR	Fiducial region
Pass the single lepton HLT			X
At least one good PV			X
$N^{\text{reco}}_{\text{loose}\,\ell} = 2$ (opposite-sign)	$N^{\text{reco}}_{\text{loose}\,\ell} = 1$		$N^{\text{gen}}_{\ell} = 1$
$N^{\text{reco}}_{\gamma} \geq 1$			$N^{\text{gen}}_{\gamma} = 1$
$N^{\text{reco}}_{\text{jets}} \geq 2$			$N^{\text{gen}}_{\text{jets}} \geq 2$
$p_{\text{T}}^{\ell} > 30\,(35)$ GeV and $\lvert\eta\rvert < 2.4\,(2.5)$			
$p_{\text{T}}^{\gamma} > 20$ GeV and $\lvert\eta\rvert < 2.5$			
$p_{\text{T}}^{\text{j}} > 30$ GeV and $\lvert\eta\rvert < 4.7$			
$\Delta R(\ell,\gamma) > 0.4$, $\Delta R(\ell,\text{jets}) > 0.4$			
$\Delta R(\gamma,\text{jets}) > 0.4$			$\Delta R(\gamma,\text{jets}) > 0.1$
subleading $p_{\text{T}}^{\ell} > 15$ GeV	X	X	X
$N_{\text{bjets}} \geq 1$	$N_{\text{bjets}} = 0$	$N_{\text{bjets}} \geq 1$	X
$p_{\text{T}}^{\text{miss}} > 20$ GeV			X

The requirements at parton level are minimal, demanding the particle promptness and the number of objects matches the number of generated objects.

Simultaneous inclusive fit —Post-fit plots



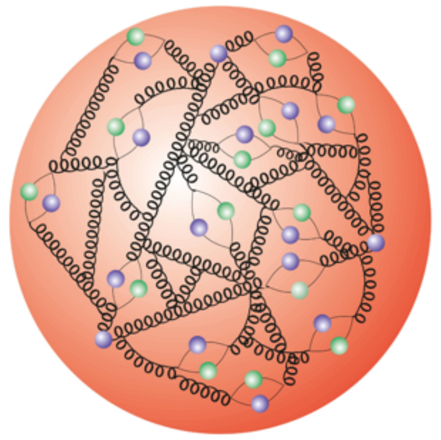




VBS Zγ systematics and results

Theoretical uncertainties:

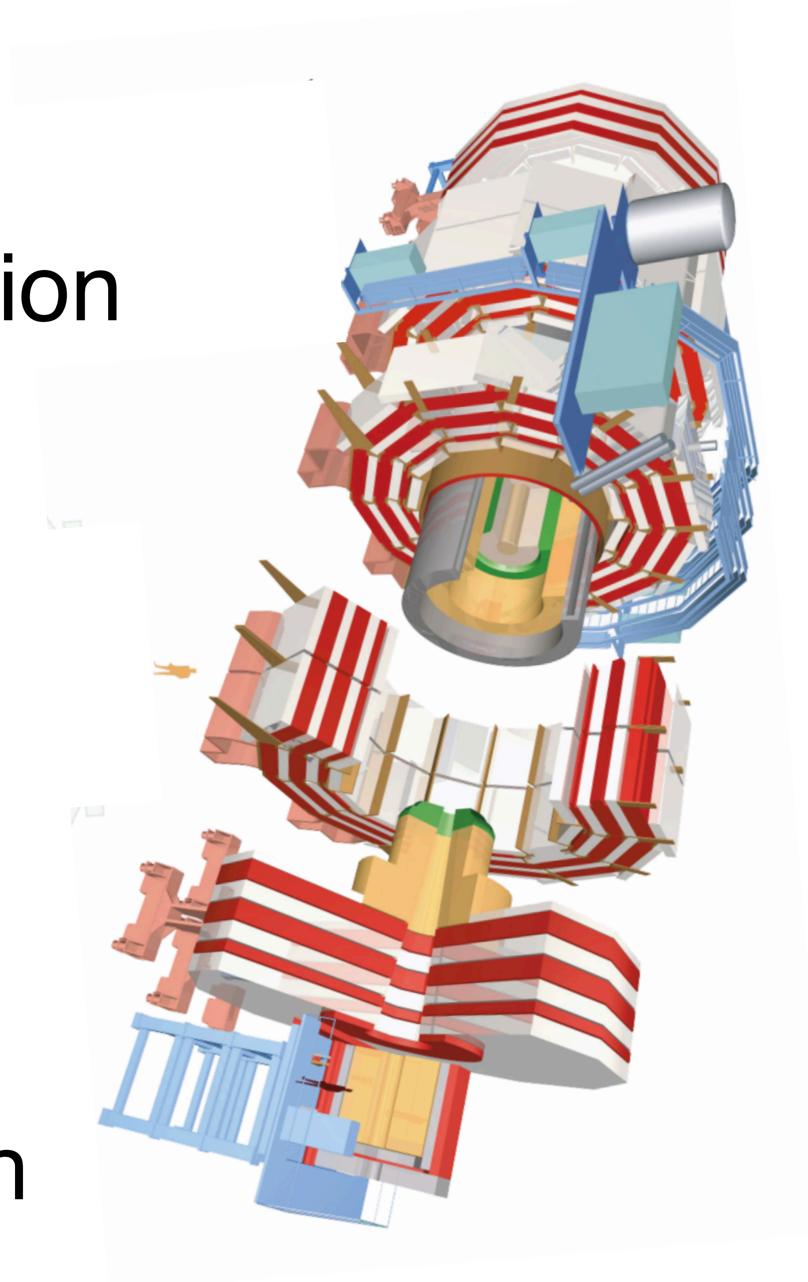
- PDF and α_S
- Factorization and renormalization scale
- Parton shower



$$\sigma_{tot}^{pp\to X}(\mu_F,\mu_R) = \sum_{i,j}\int dx_1 dx_2 f_{i,p}(x_1,\mu_F) f_{j,p}(x_2,\mu_F)\hat{\sigma}_{ij}^{ij\to X}(x_1x_2S,\mu_F,\mu_R)$$

Experimental uncertainties:

- Particle energy correction and identification efficiency
  - Jet and e/γ energy correction
  - Lepton ID, isolation efficiency
  - Etc.
- Luminosity, pileup, L1prefiring and etc.
- **Background modelling**
  - Nonprompt γ (ℓ) data-driven estimation



Gaussian constrained pdf

$$\mathscr{L}(\vec{\mu};\vec{\theta}) = \prod_{j}^{N} \textbf{Poisson}(n_j \,|\, \mu\cdot s_j(\vec{\theta}) + b_j(\vec{\theta})\,)\cdot p(\tilde{\vec{\theta}}\,|\,\vec{\theta})$$

- 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