Recent Standard Model Measurements at the CMS experiment

报告人：安莹 (AN Ying)

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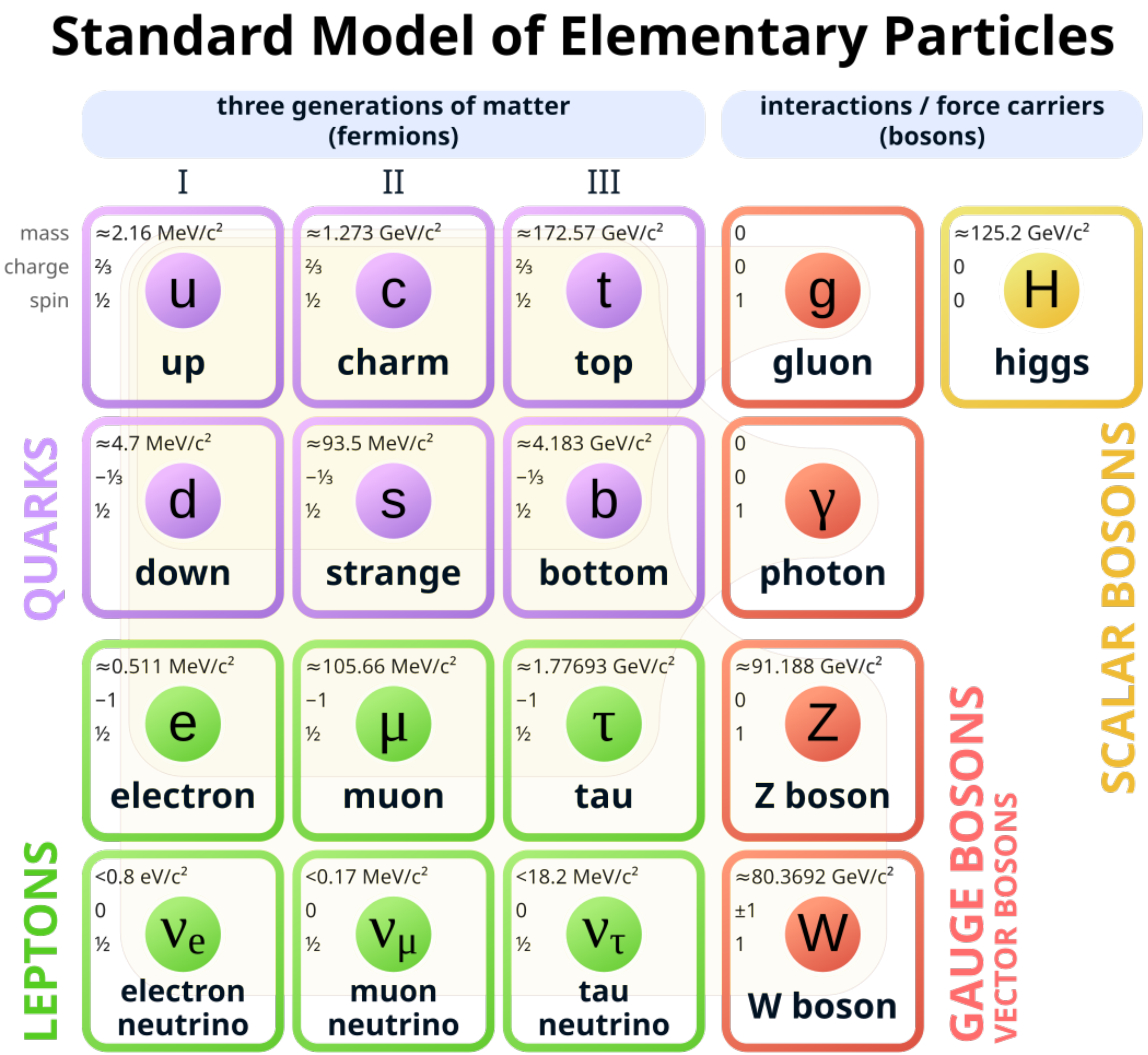
Standard Model



Standard Model of Elementary Particles

three generations of matter (fermions)

interactions / force carriers (bosons)

	I	II	III		
mass charge spin QUARKS	≈2.16 MeV/c^2 ⅔ ½ u up	≈1.273 GeV/c^2 ⅔ ½ c charm	≈172.57 GeV/c^2 ⅔ ½ t top	0 0 1 g gluon	≈125.2 GeV/c^2 0 0 H higgs
	≈4.7 MeV/c^2 −⅓ ½ d down	≈93.5 MeV/c^2 −⅓ ½ s strange	≈4.183 GeV/c^2 −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS	≈0.511 MeV/c^2 −1 ½ e electron	≈105.66 MeV/c^2 −1 ½ μ muon	≈1.77693 GeV/c^2 −1 ½ τ tau	≈91.188 GeV/c^2 0 1 Z Z boson	
	<0.8 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino	≈80.3692 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS

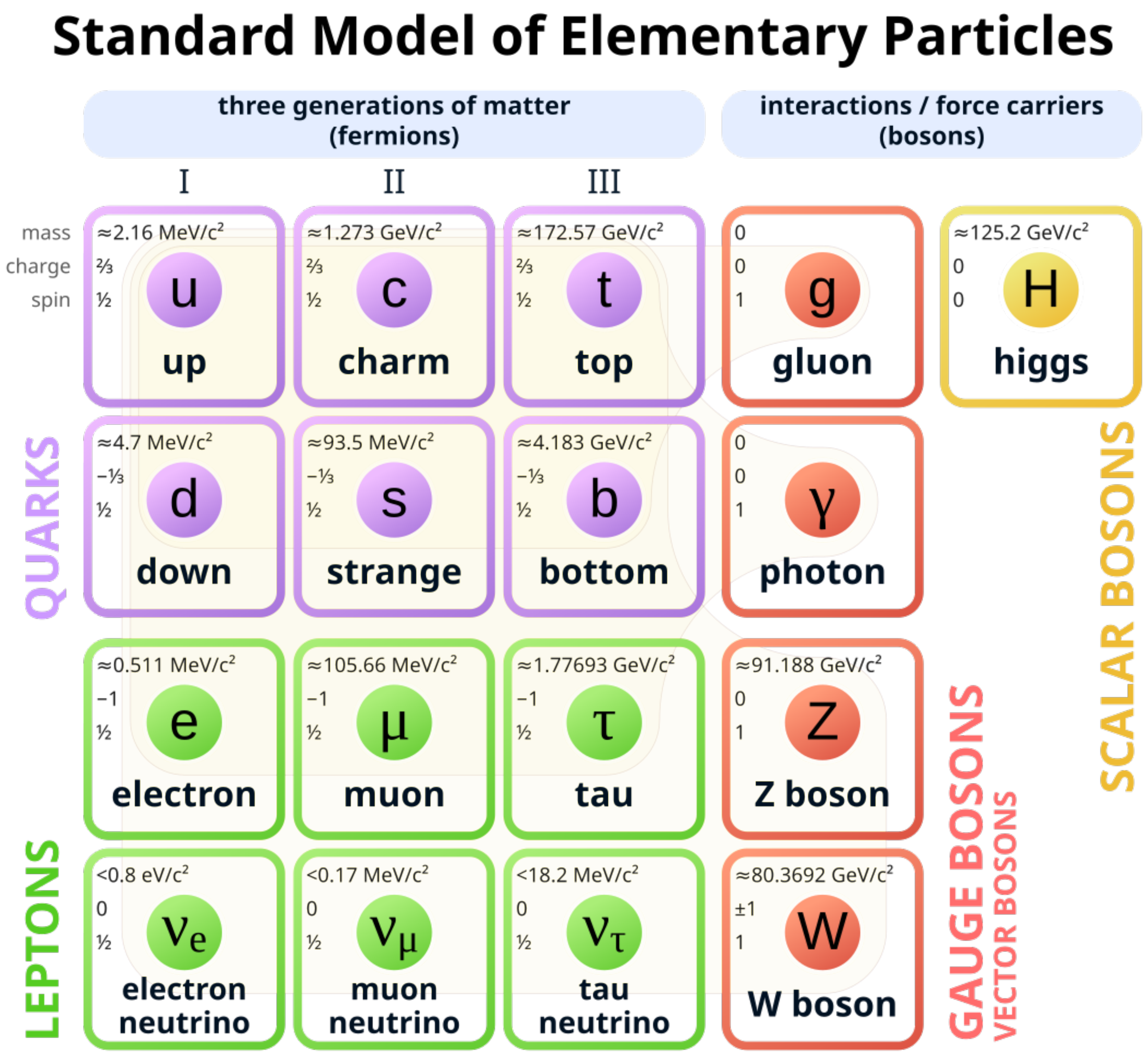
Quantum field theory based on gauge group:

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

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

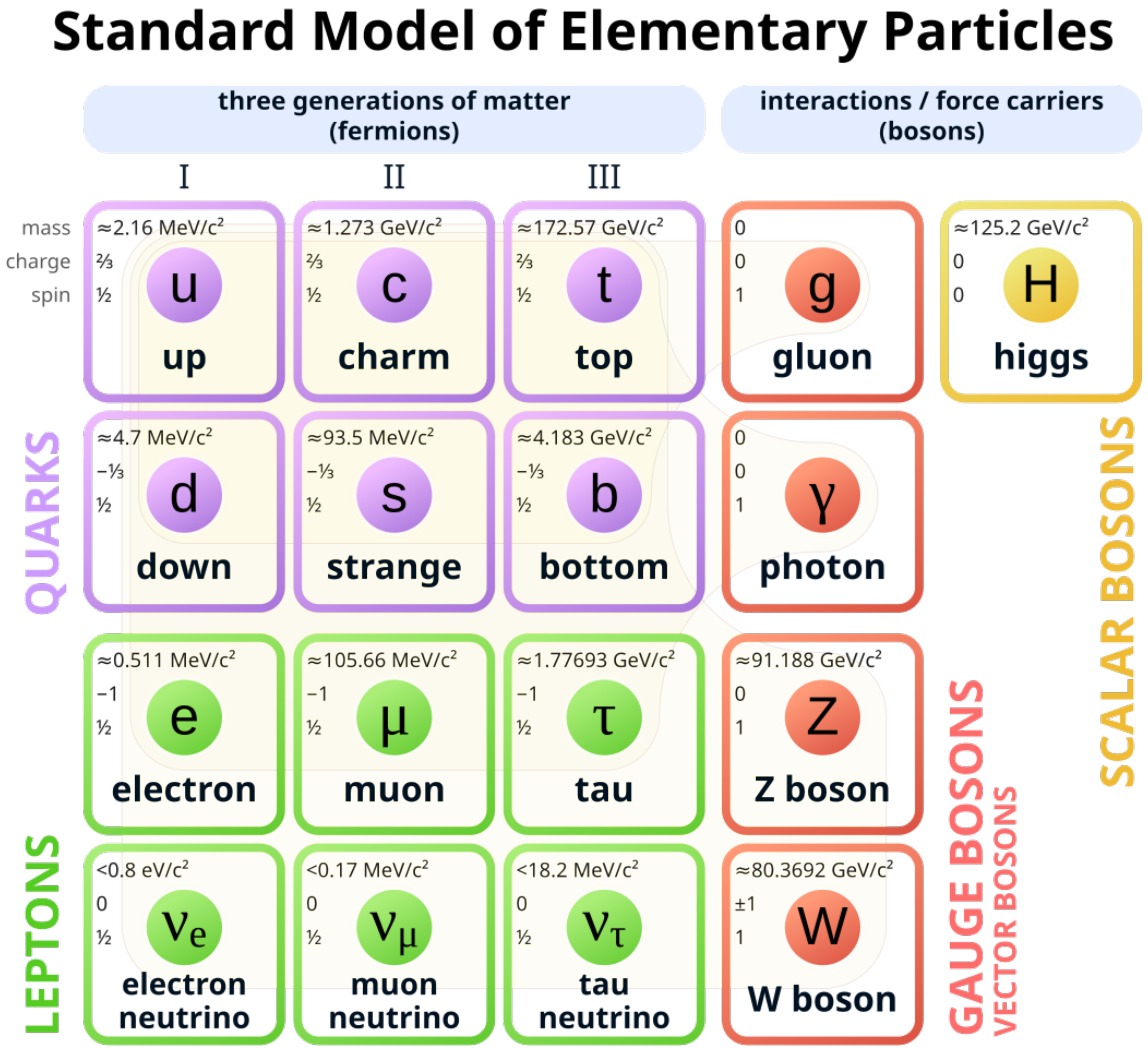
nature of dark matter

origin of neutrino masses

matter-antimatter asymmetry

…

Standard Model



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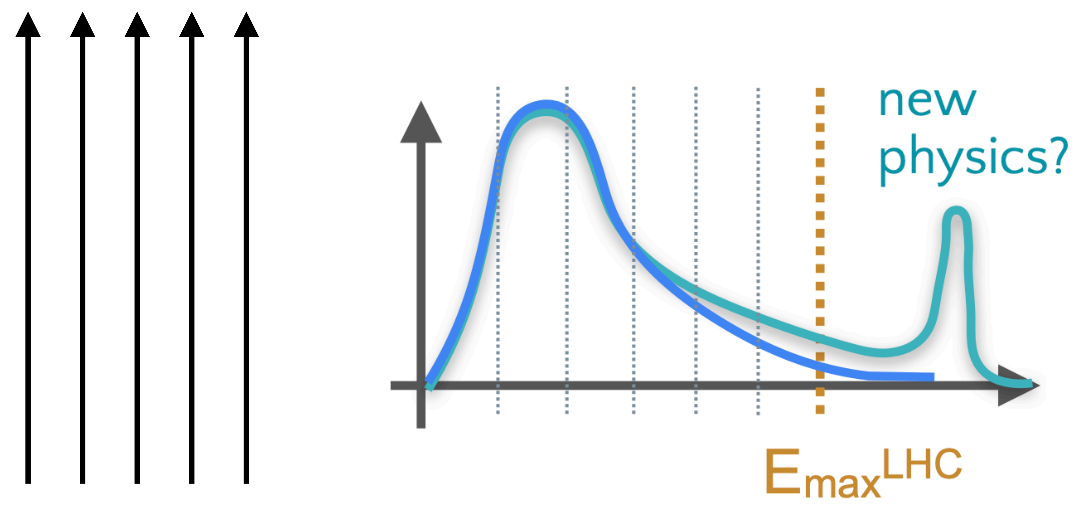
Look for new physics to answer open questions:

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

  look for deviations from predictions



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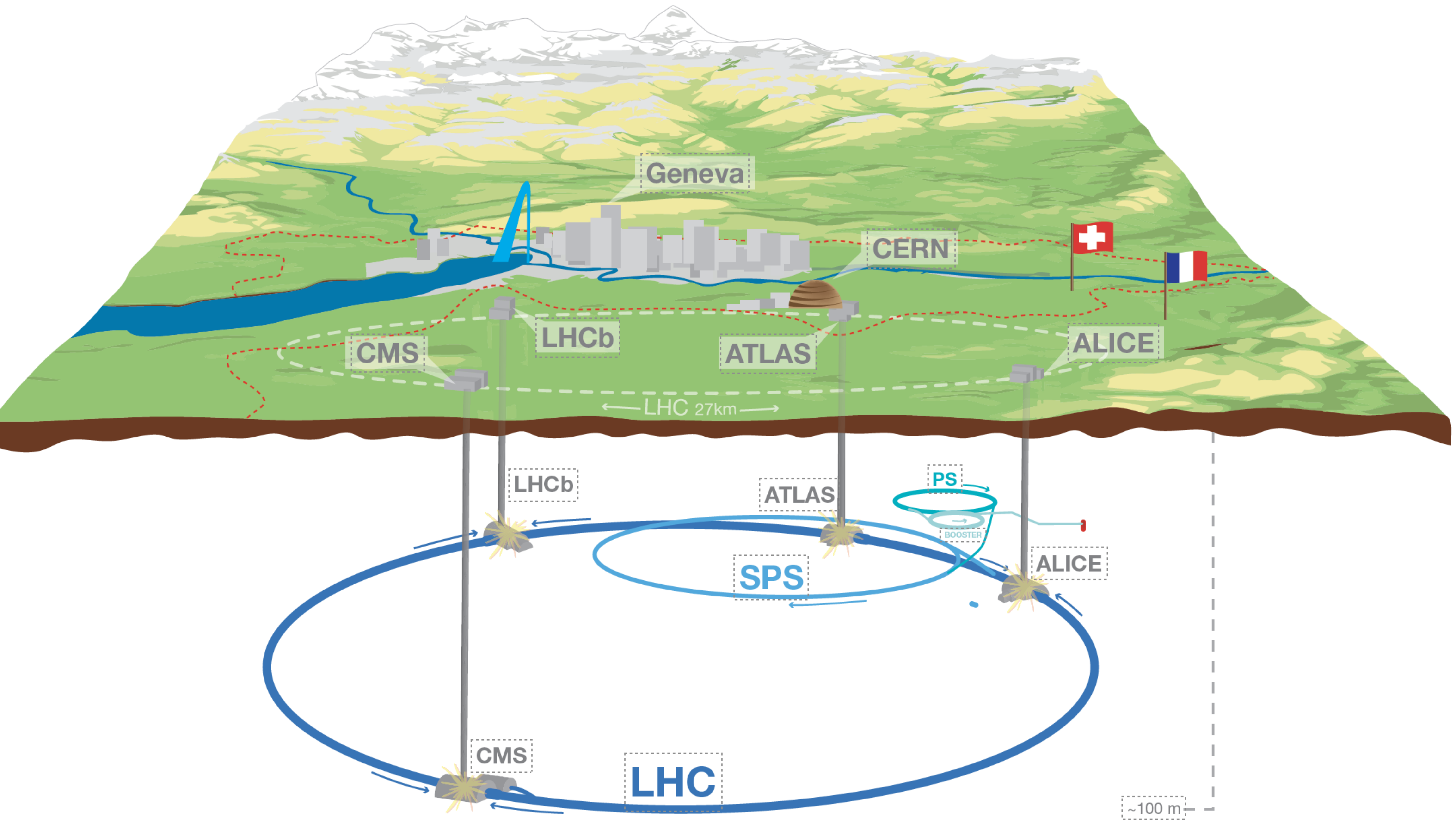
Large hardon collider (LHC)



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- 27 km circumference
- ~175m underground
- Operating since 2008
- Superconducting magnets to accelerate protons up to 7 TeV

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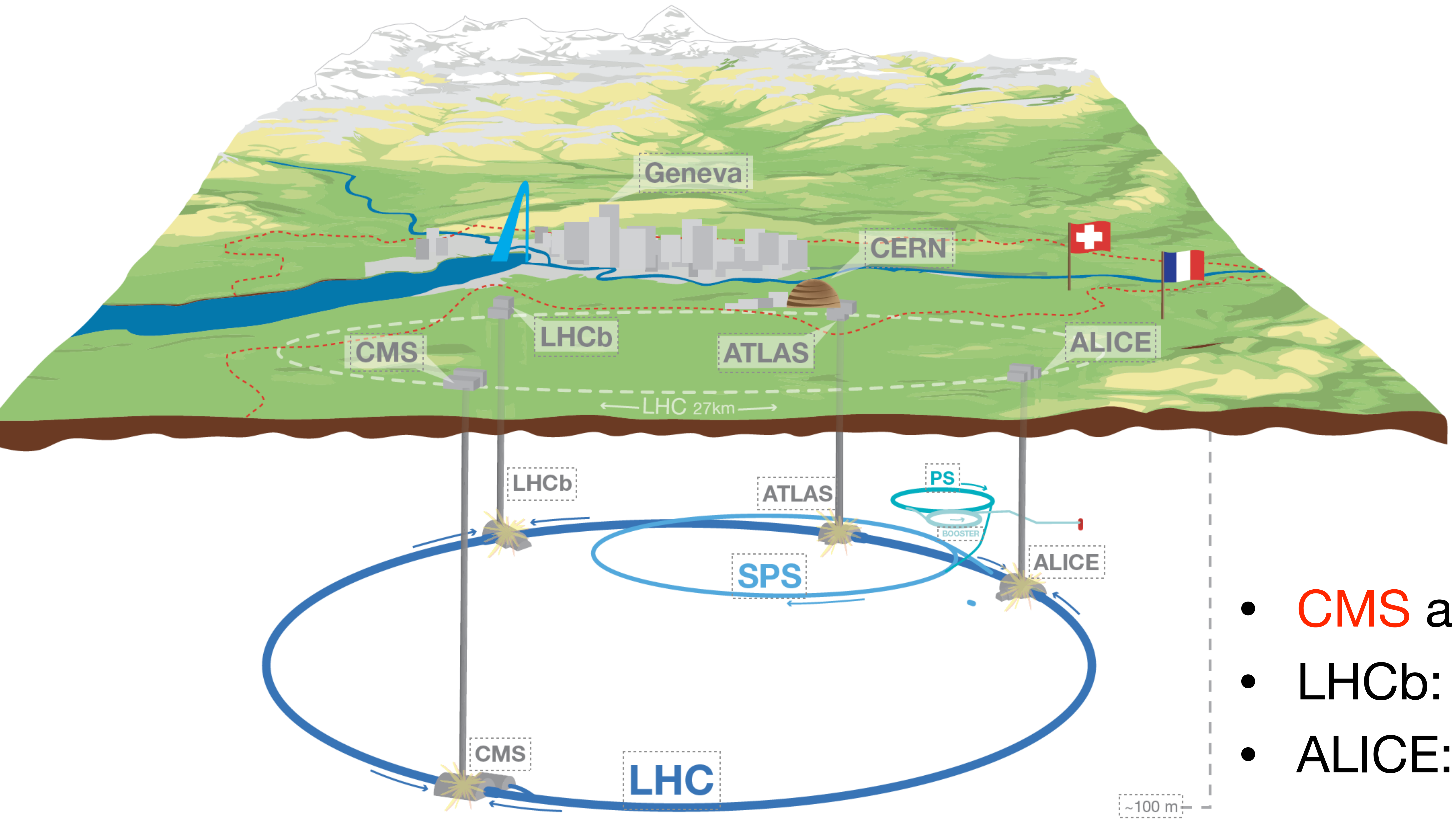

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- CMS and ATLAS: Two general purpose experiments
- LHCb: Flavour (b) physics (main interest)
- ALICE: Analysis of ion-ion collisions (main interest)

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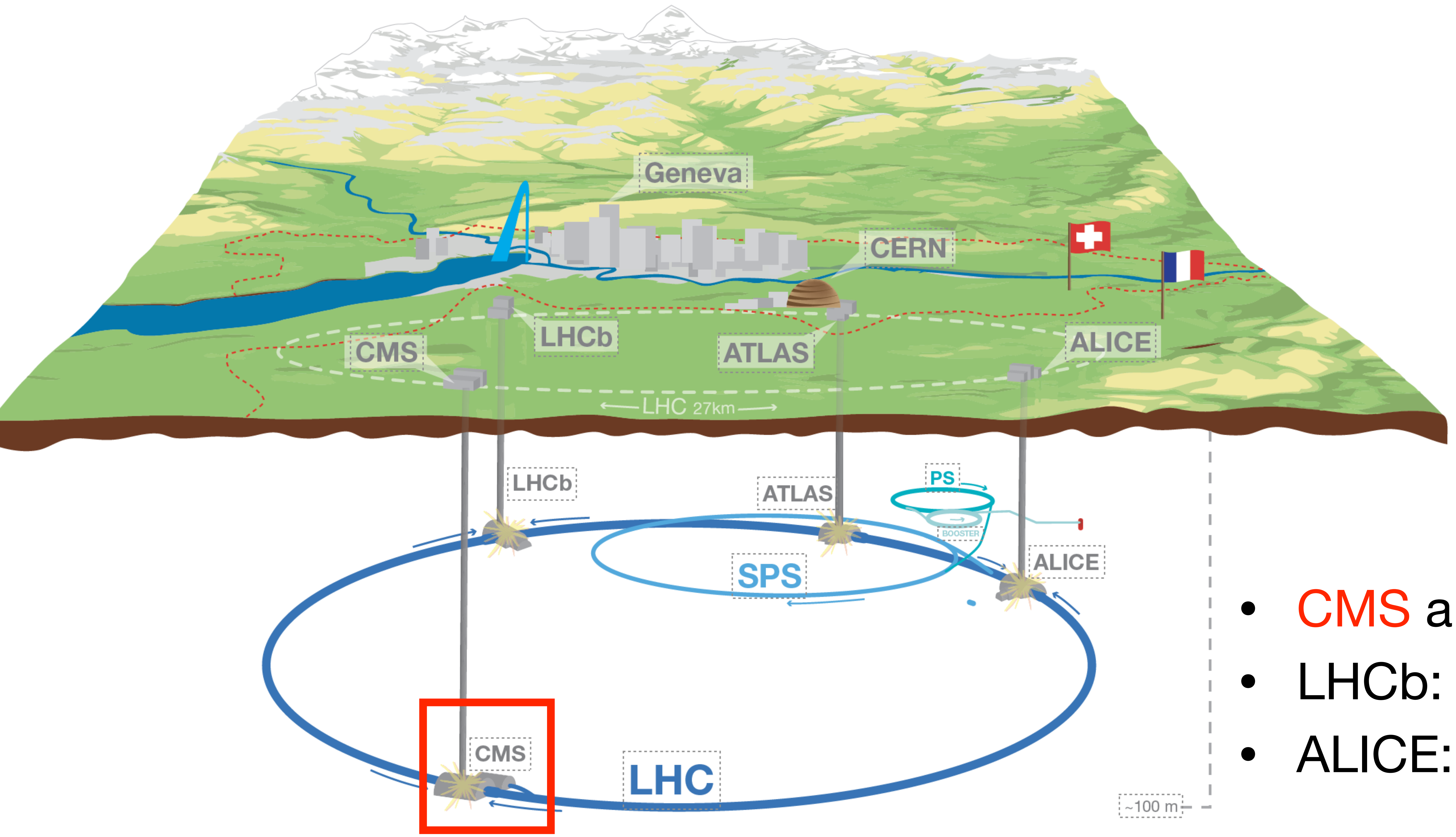

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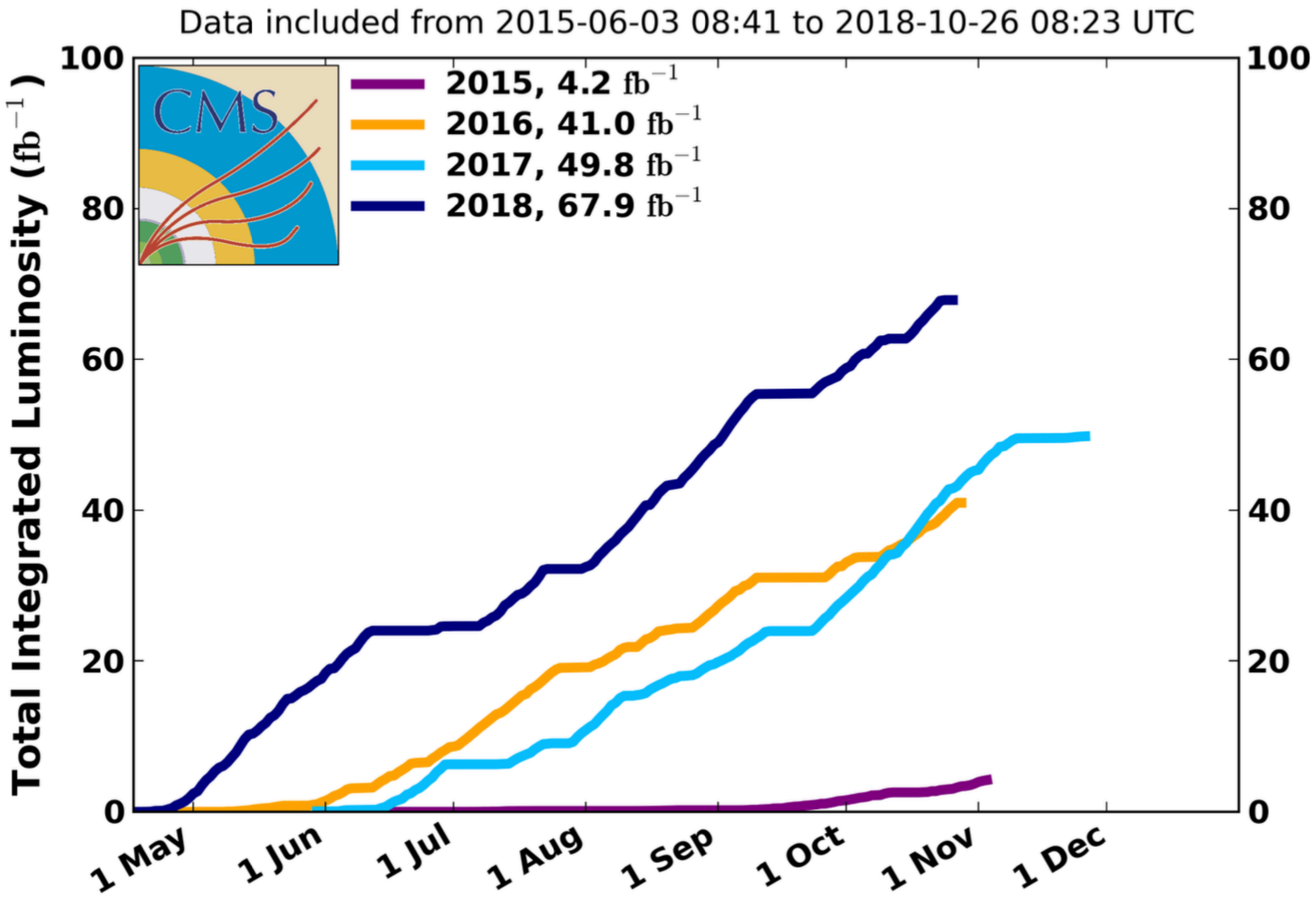
- Completed two data-taking periods Run 1 and Run 2 at $\sqrt{s}$ = 7(8) and 13 TeV
- Run 3 data-taking at $\sqrt{s}$ = 13.6 TeV is ongoing

LHC — luminosity and pileup Run 2

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

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



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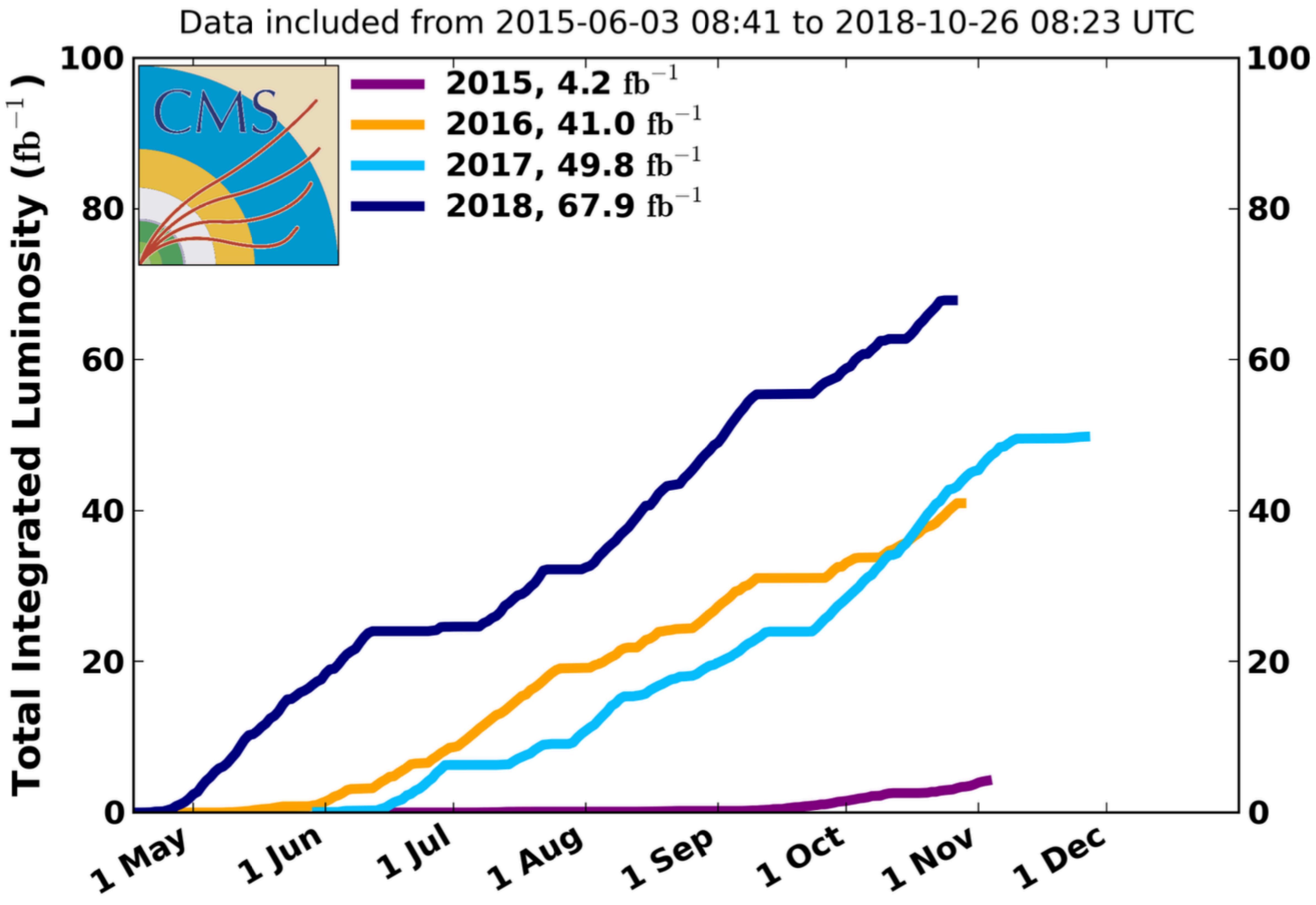
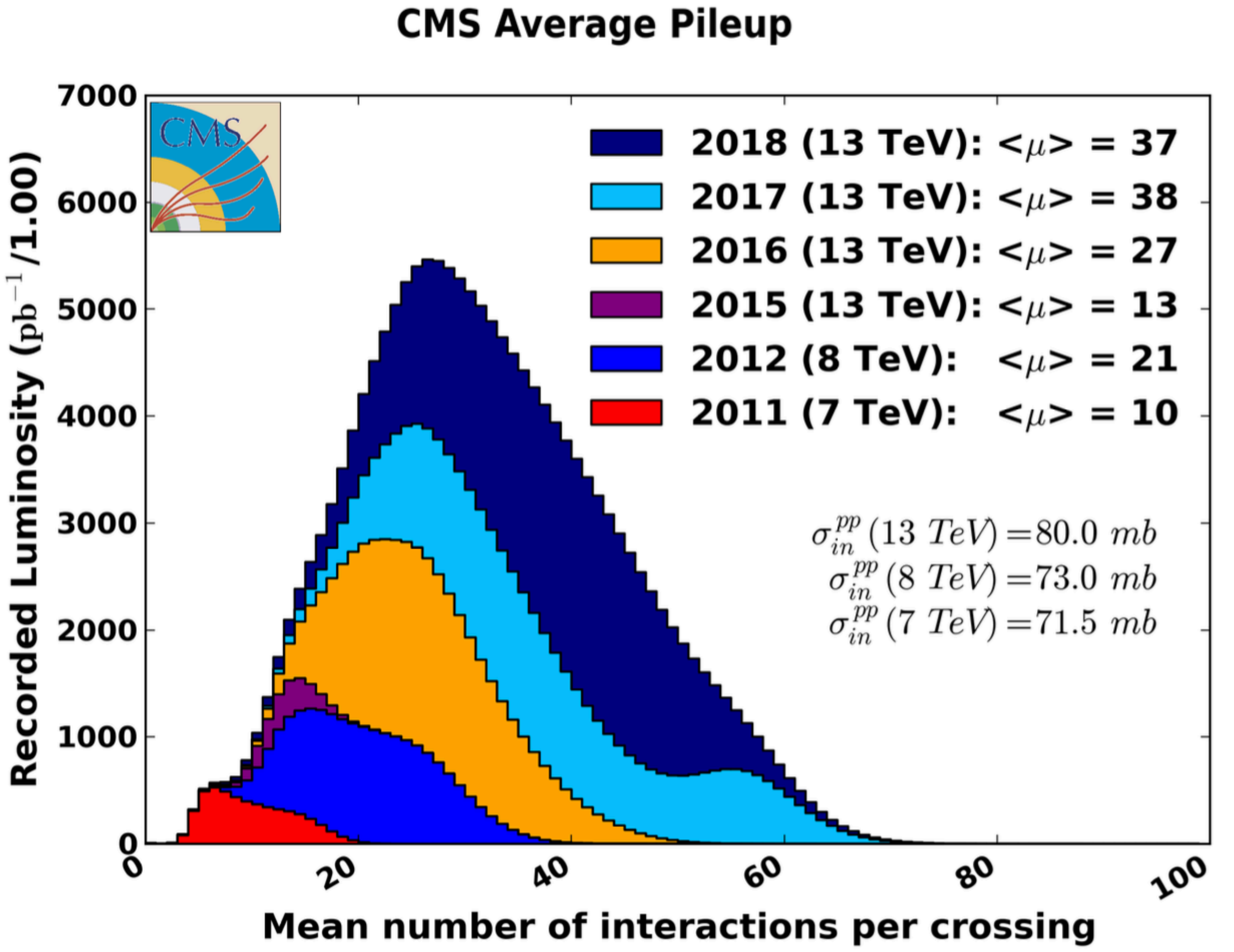
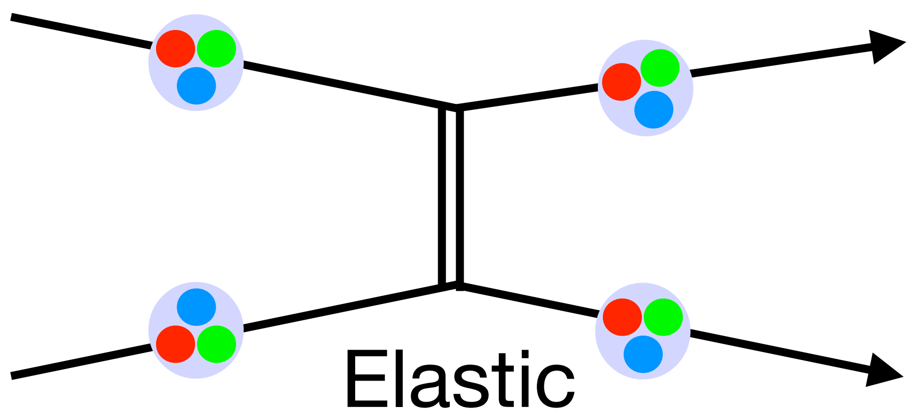
- **concurrent proton-proton interactions** in the same bunch crossing
- **number of simultaneous collisions** obeys the **Poisson** statistics at fixed instantaneous luminosity



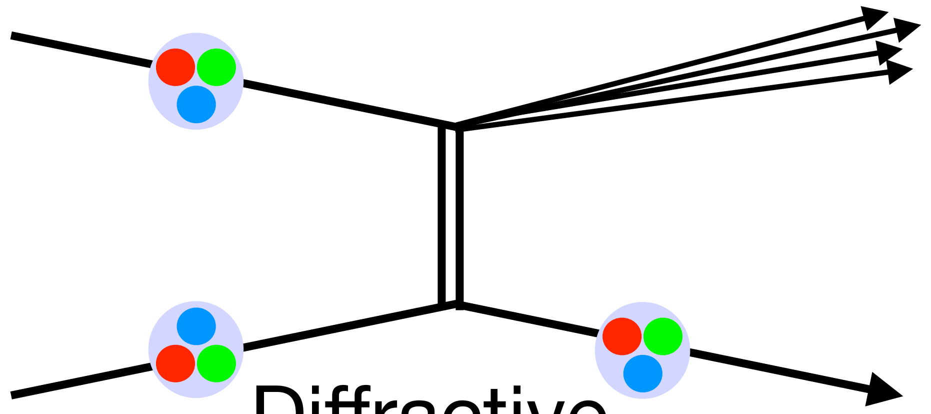


LHC — proton-proton interaction

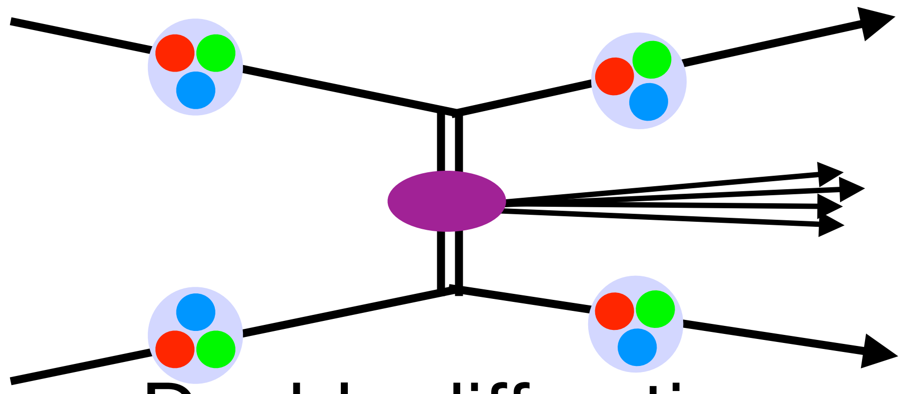
protons are not elementary objects
pp collision = collision of two “garbage cans” full of quarks and gluons (a.k.a. partons)



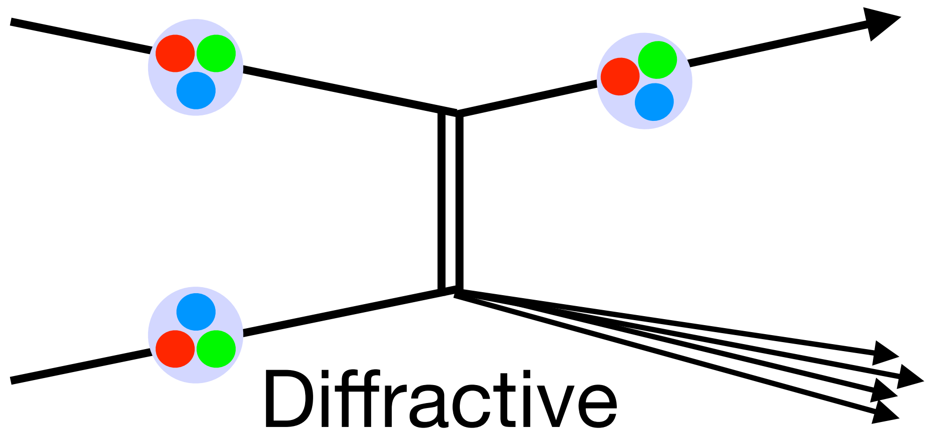
Elastic
≈10mb



Diffractive
≈10mb



Double diffractive
small



Diffractive
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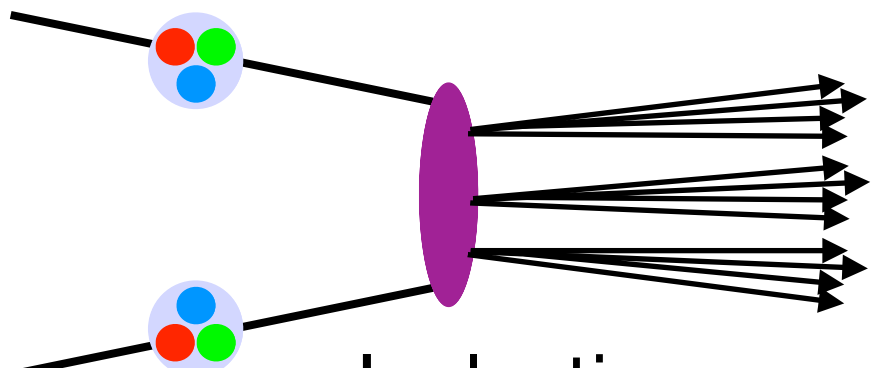
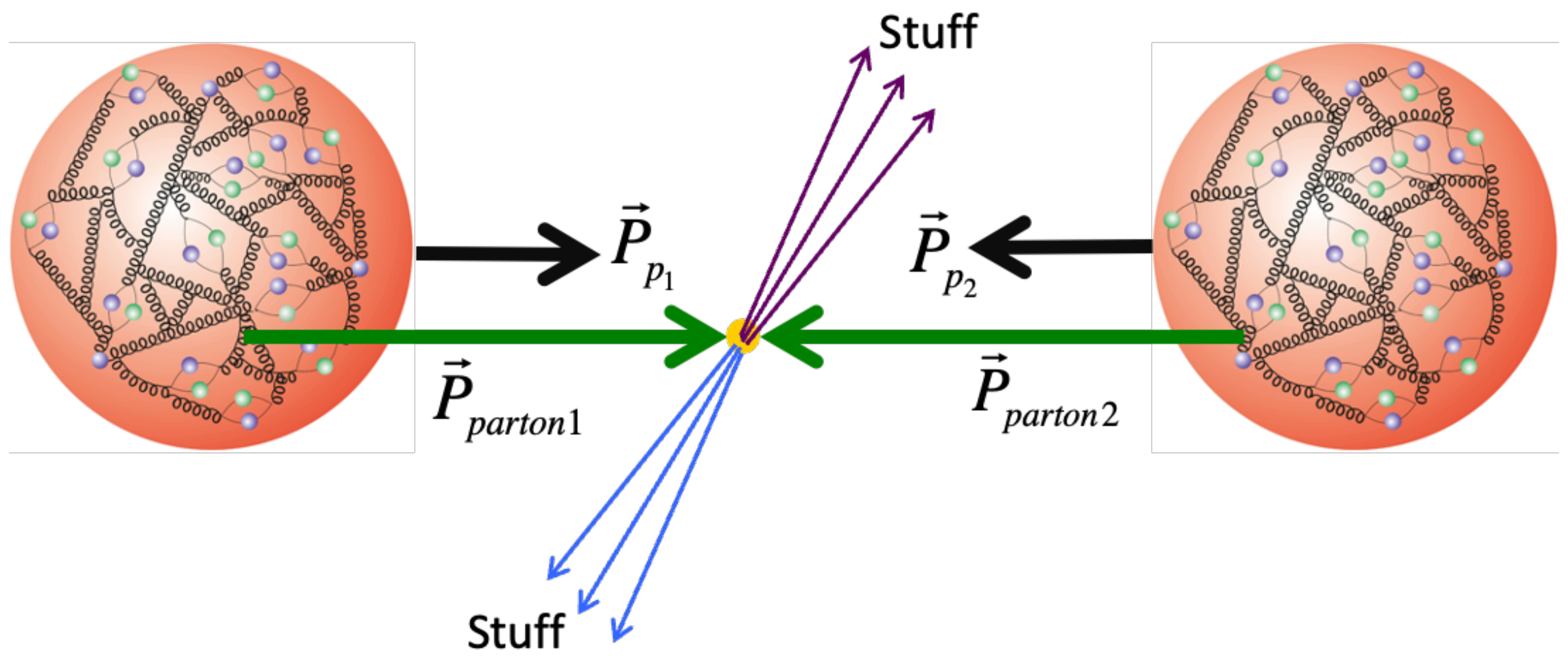


Inelastic
≈70mb

main physics studies



Hard collision:

- hard scattering of two partons
- quark/gluon showering + hadronization
- underlying event (UE) = remnants of protons
- this factorization is approximate (!)

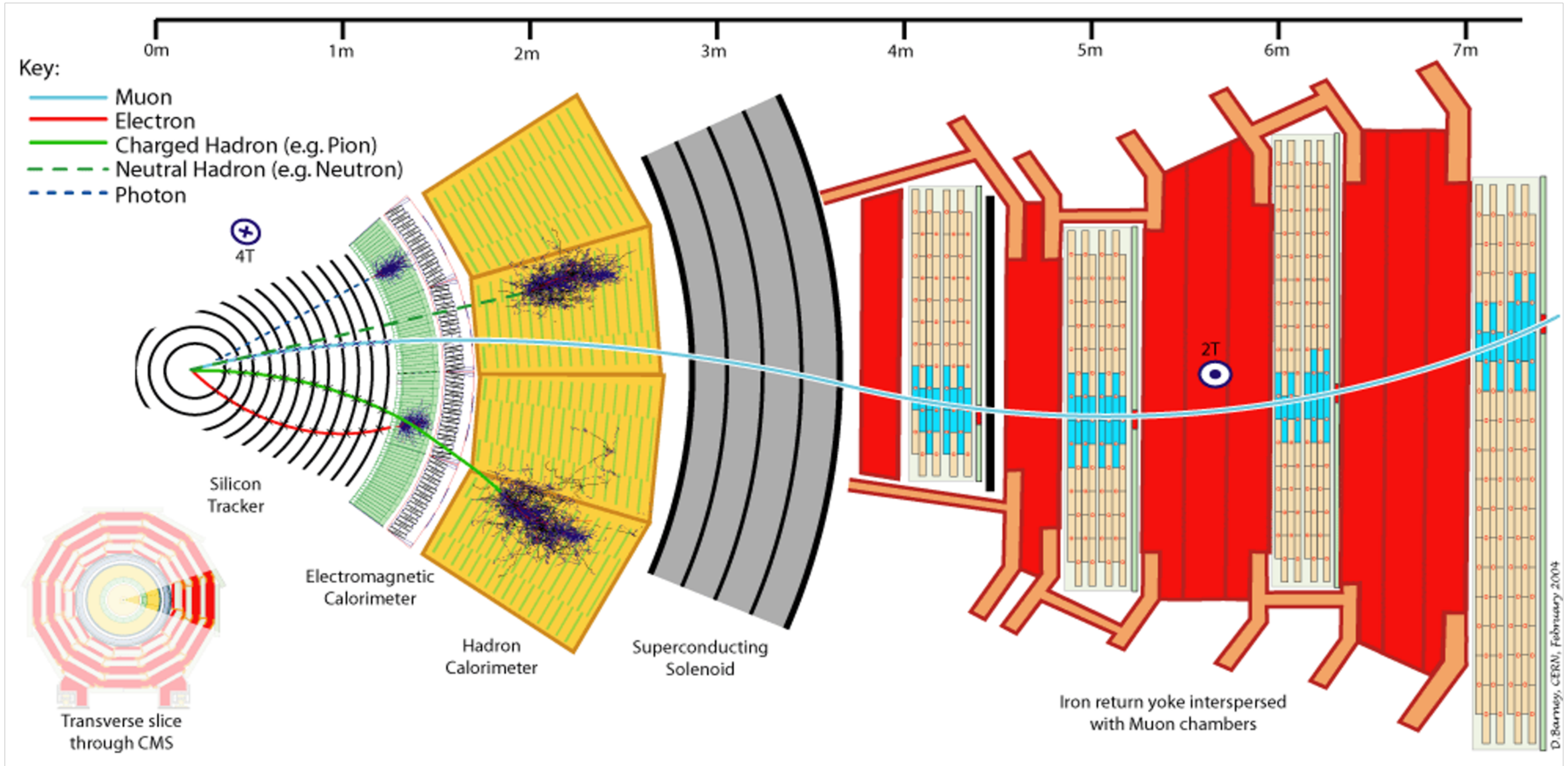
Monte Carlo Generators

Other types of scatterings:

- Double-parton scattering (two hard scatterings within a single proton-proton collision)
- Diffractive scattering (scattering induced by strong force, but with no net color transfer)

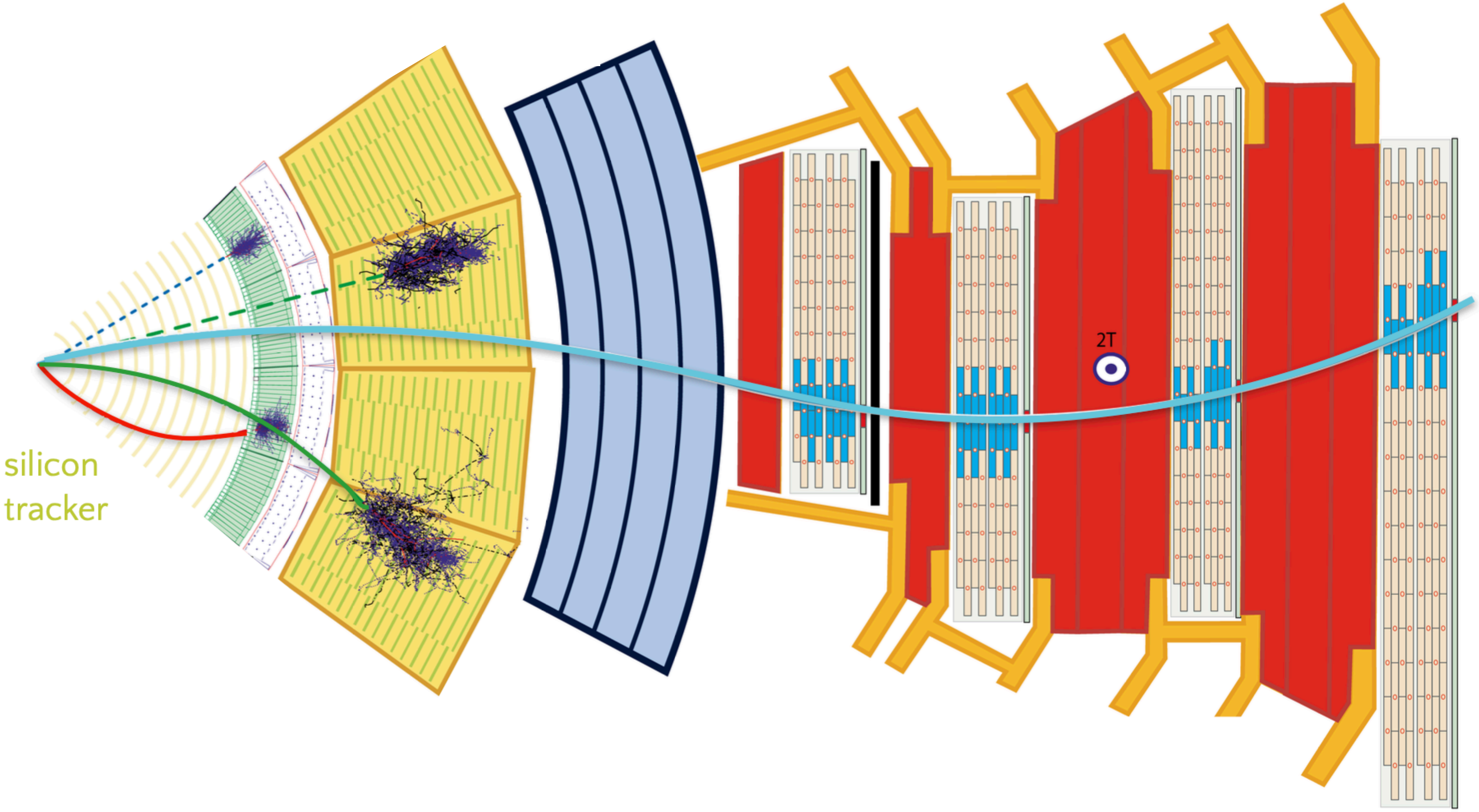
The Compact Muon Solenoid (CMS)

- 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



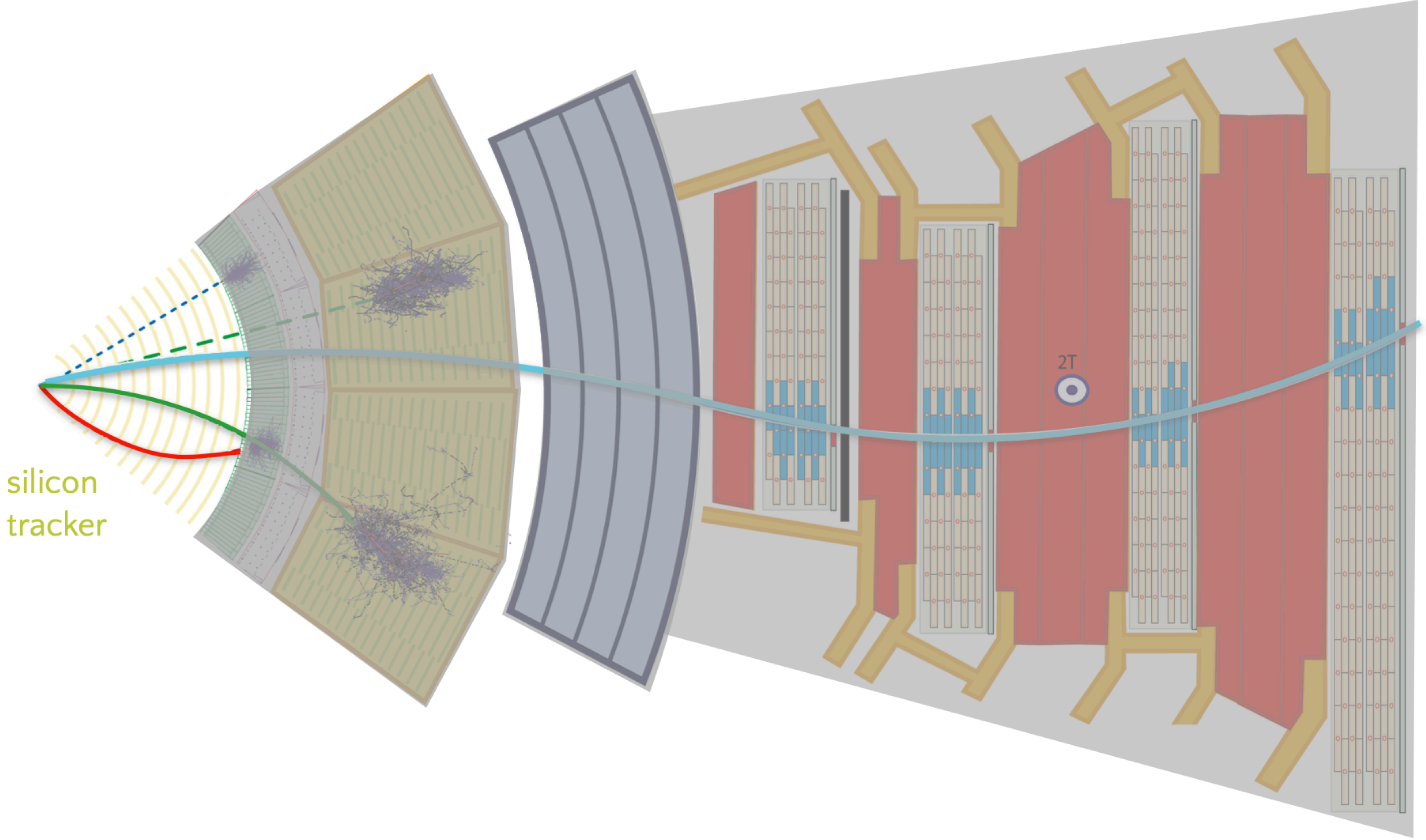
CMS detector

- Layered structure for different particle reconstruction



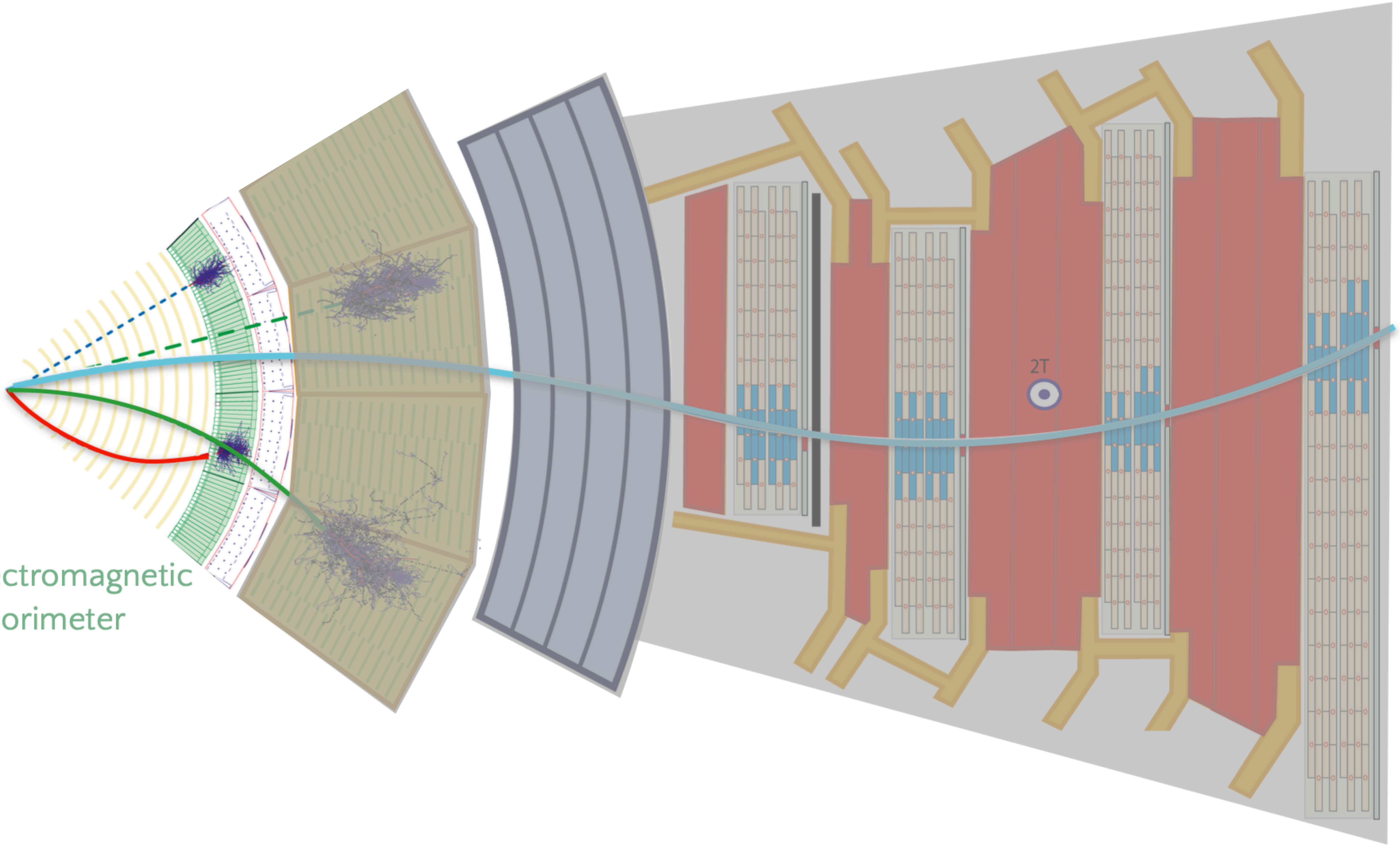
CMS detector

- 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



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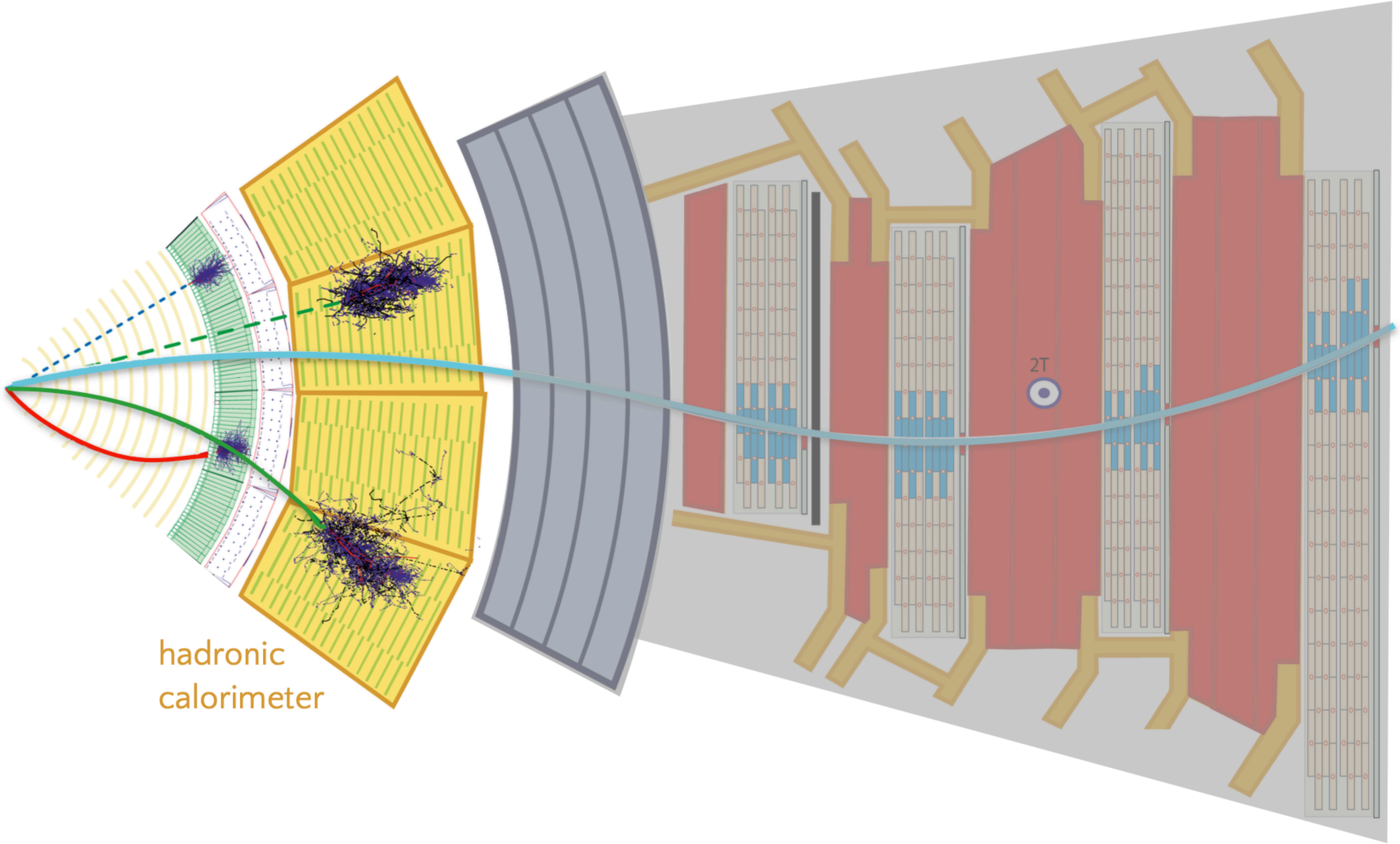

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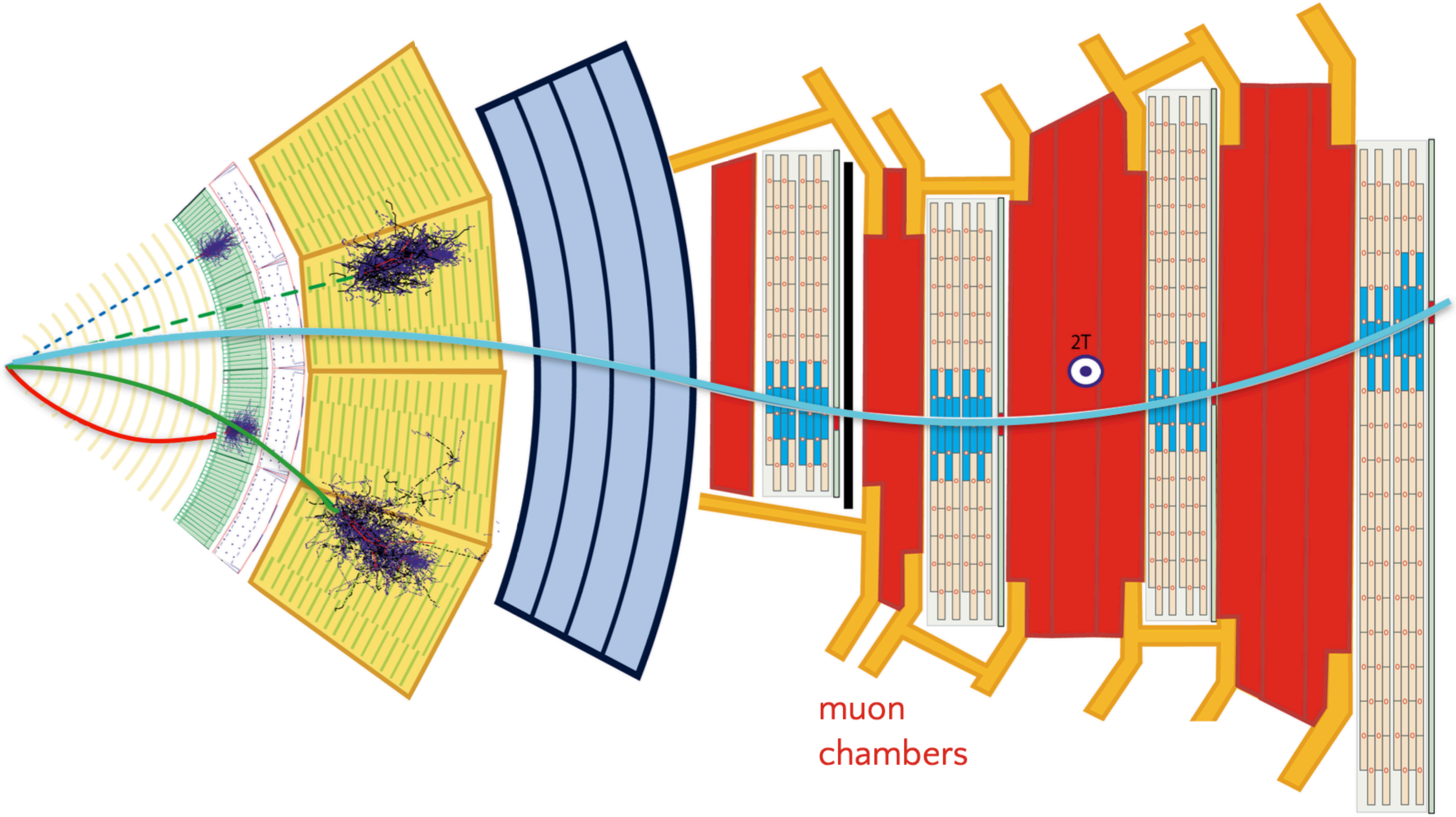
- Track muon trajectory



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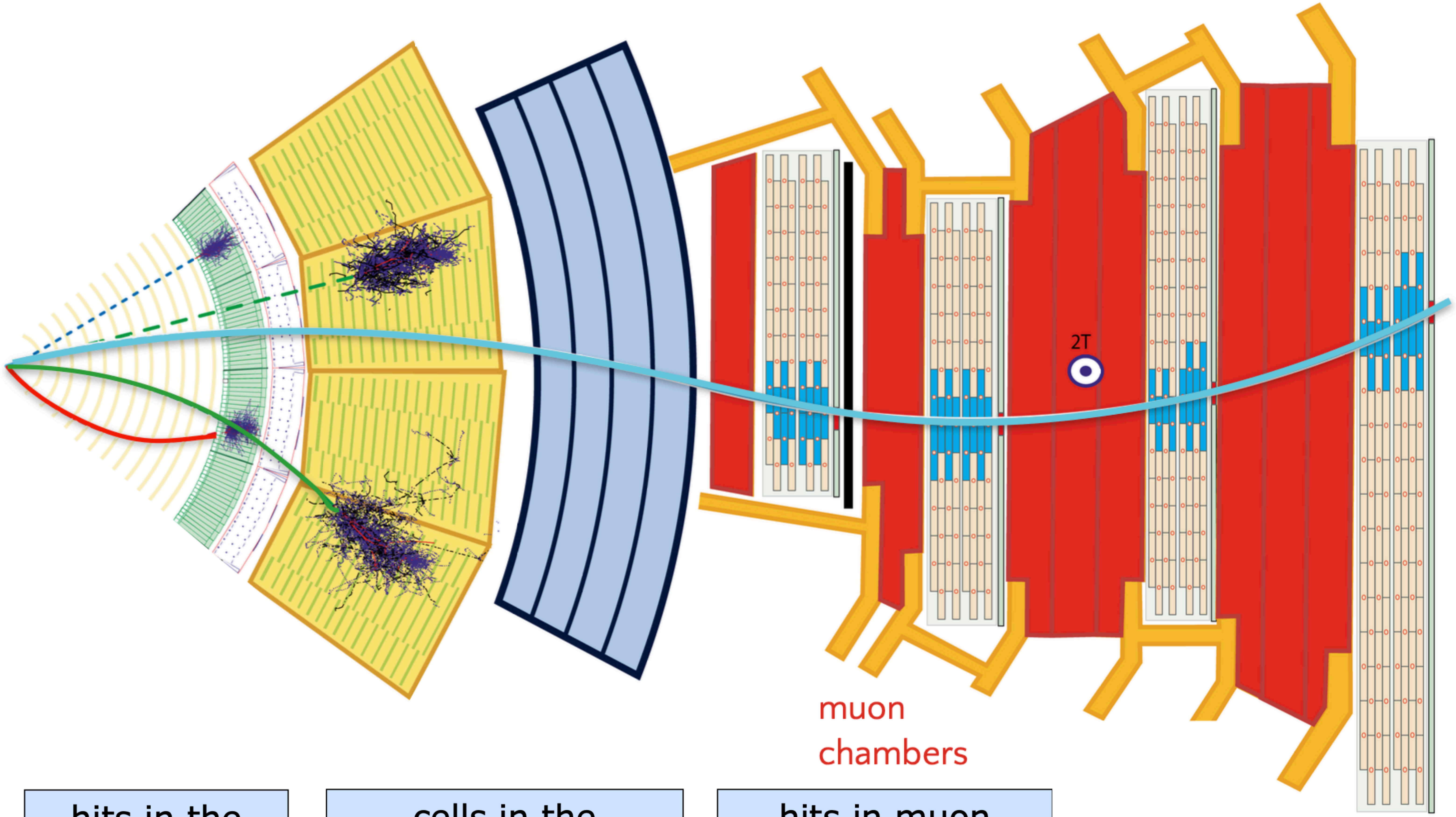


- Information from all sub-detectors combined to reconstruct particles

- 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 → tracker tracks

cells in the calorimeter → calorimetric clusters

hits in muon detectors → muon tracks

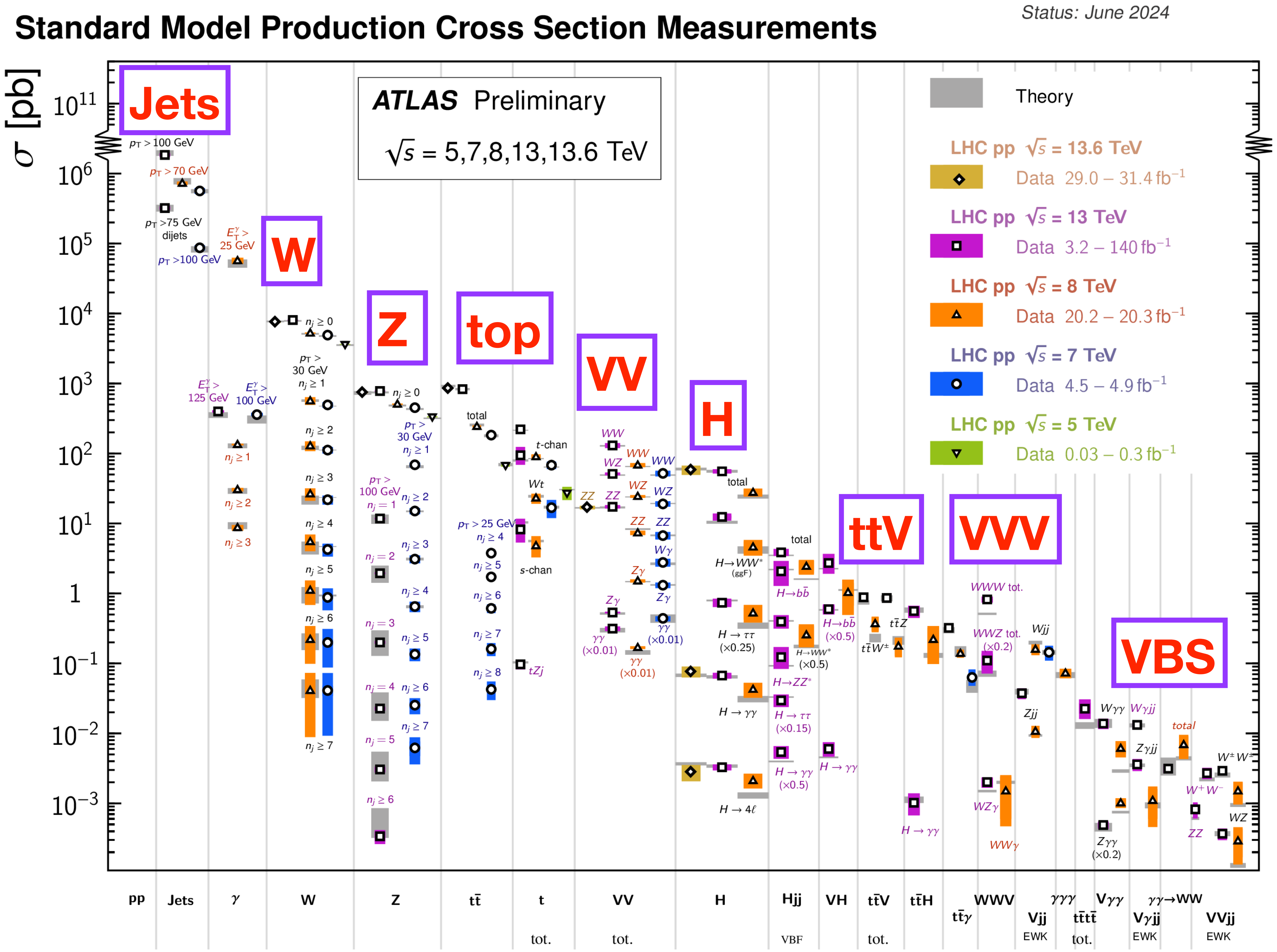
PF algorithm is the base of the physics analysis

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)



Workflow for data analysis

LHC collision → 40 MHz, Fast readout → *L1-trigger* → 100 kHz, Full readout → *High-level trigger* → ~1 kHz → *Offline data*

Workflow for data analysis


LHC collision

40 MHz → Fast readout

L1-trigger

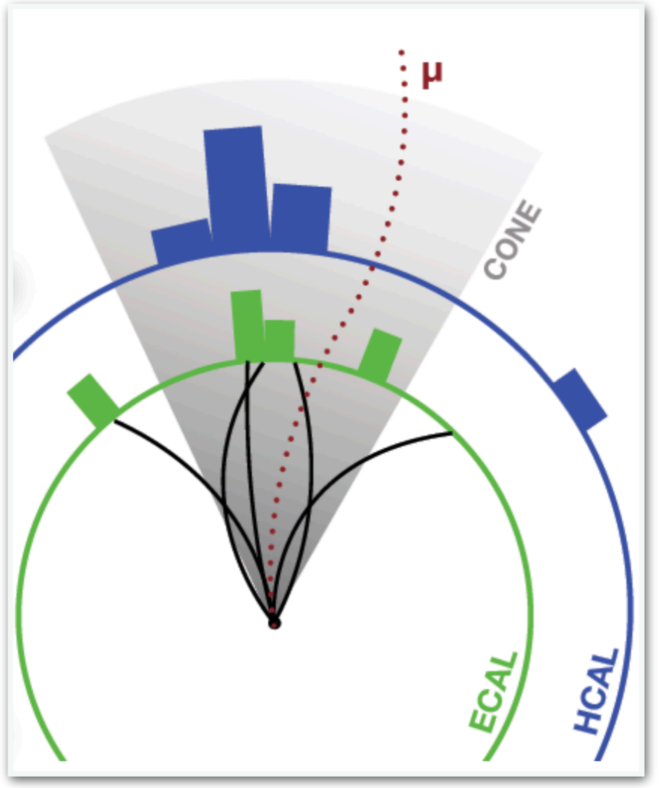
100 kHz → Full readout

High-level trigger

~1 kHz →

Offline data

- The list of “stable” particles are detected
    - $e^{\pm}$, $\mu^{\pm}$, γ; some hadrons $\pi^{\pm}$,$K^{\pm}$, K_L, n, and p



Reconstruction

- *Partice Flow algorithm*

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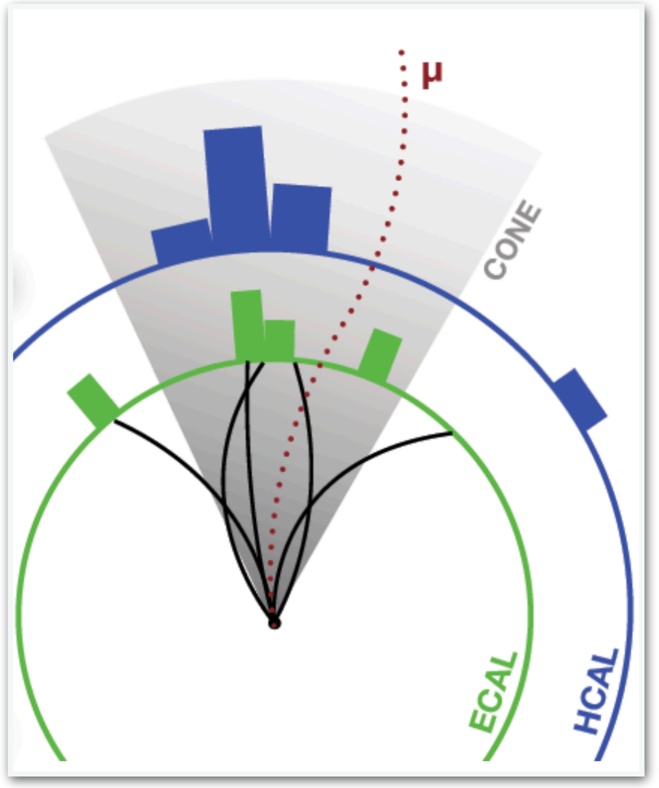

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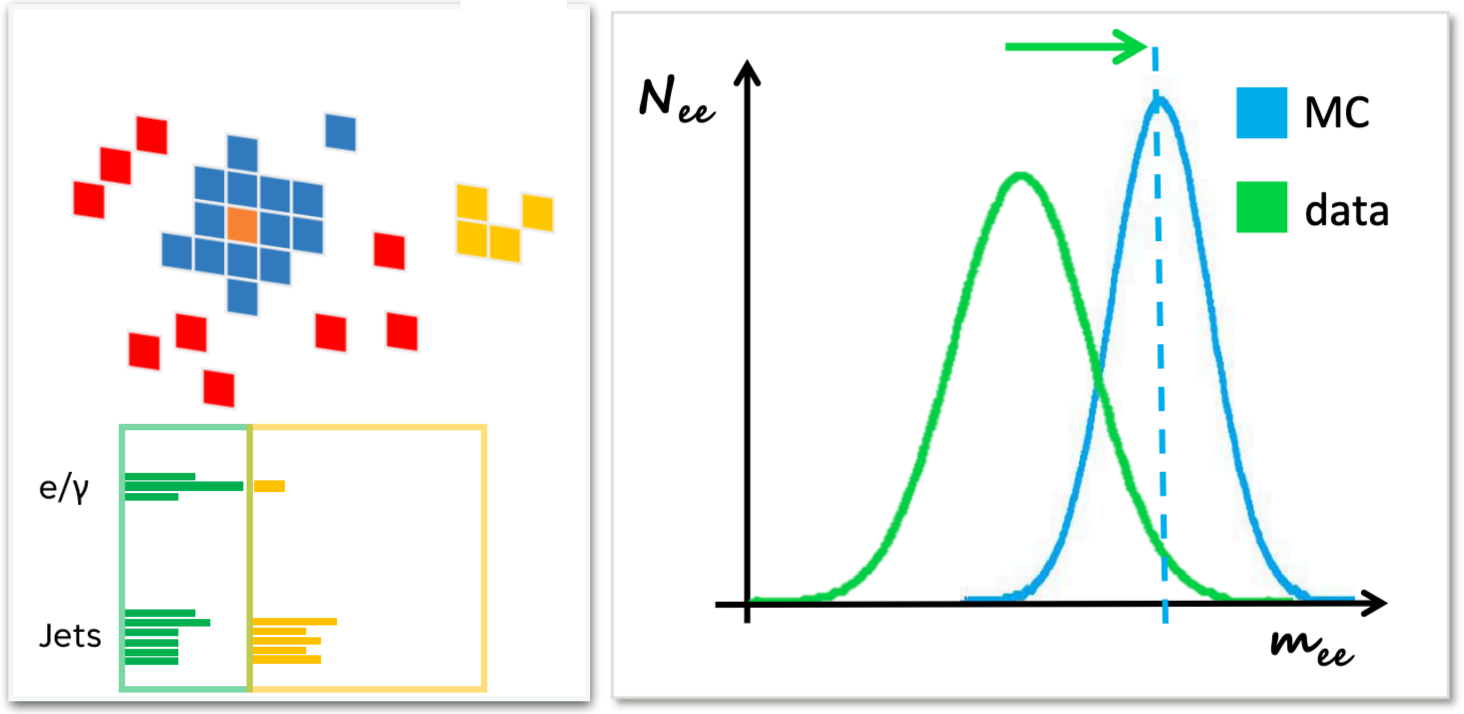

Identification & Calibration

- *Energy correction*
- *Efficiency calibration*

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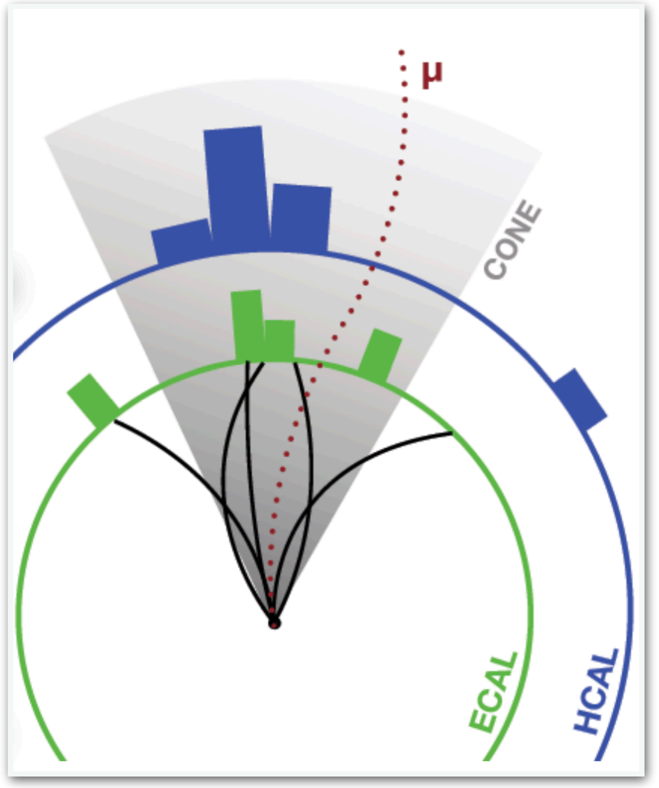

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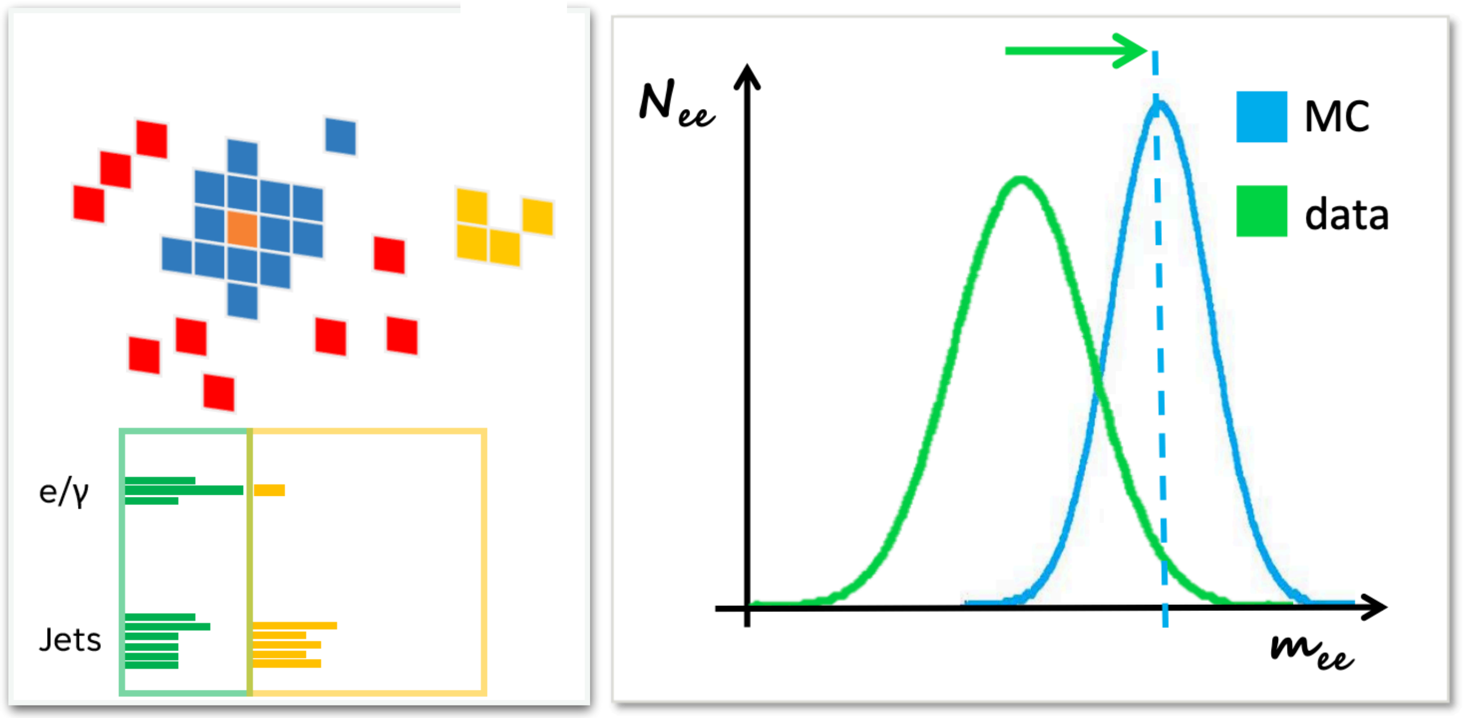

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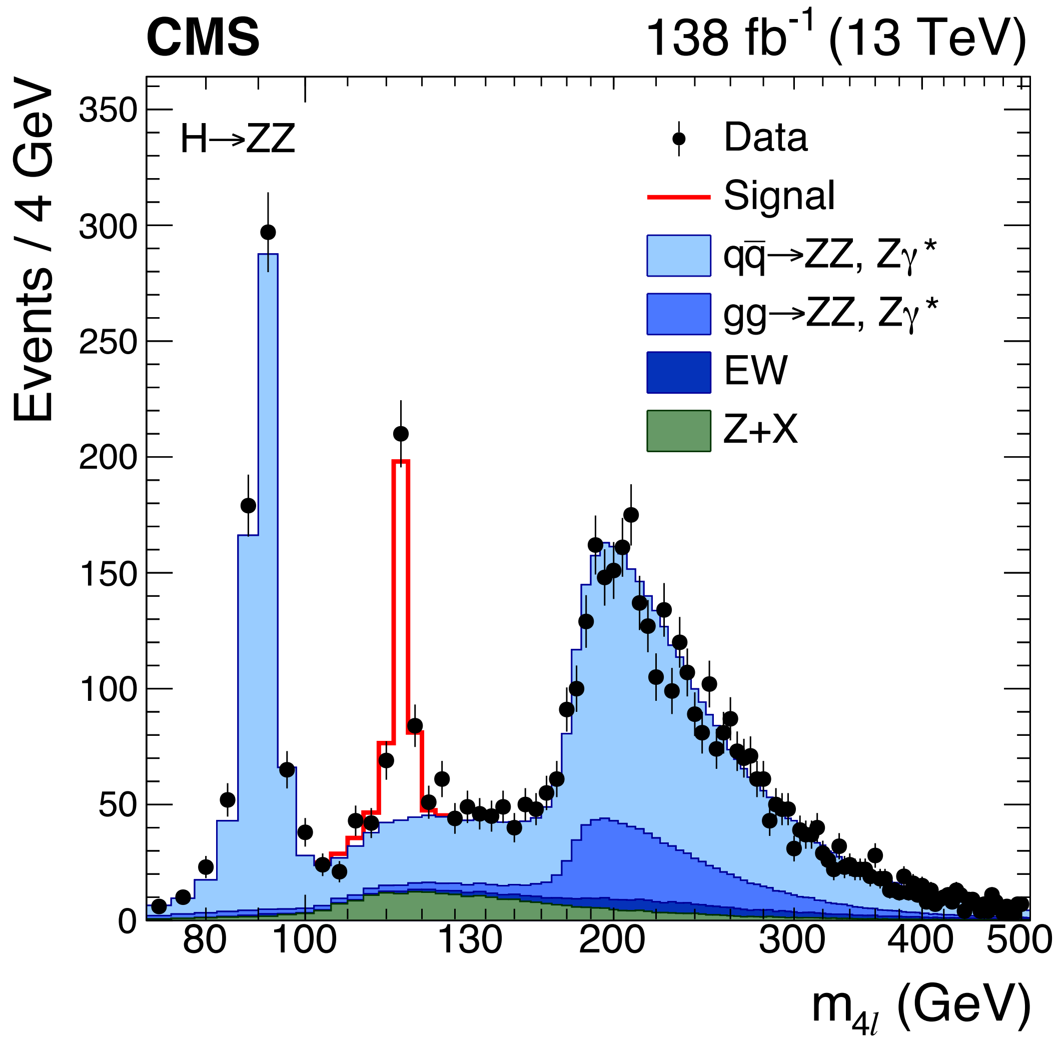
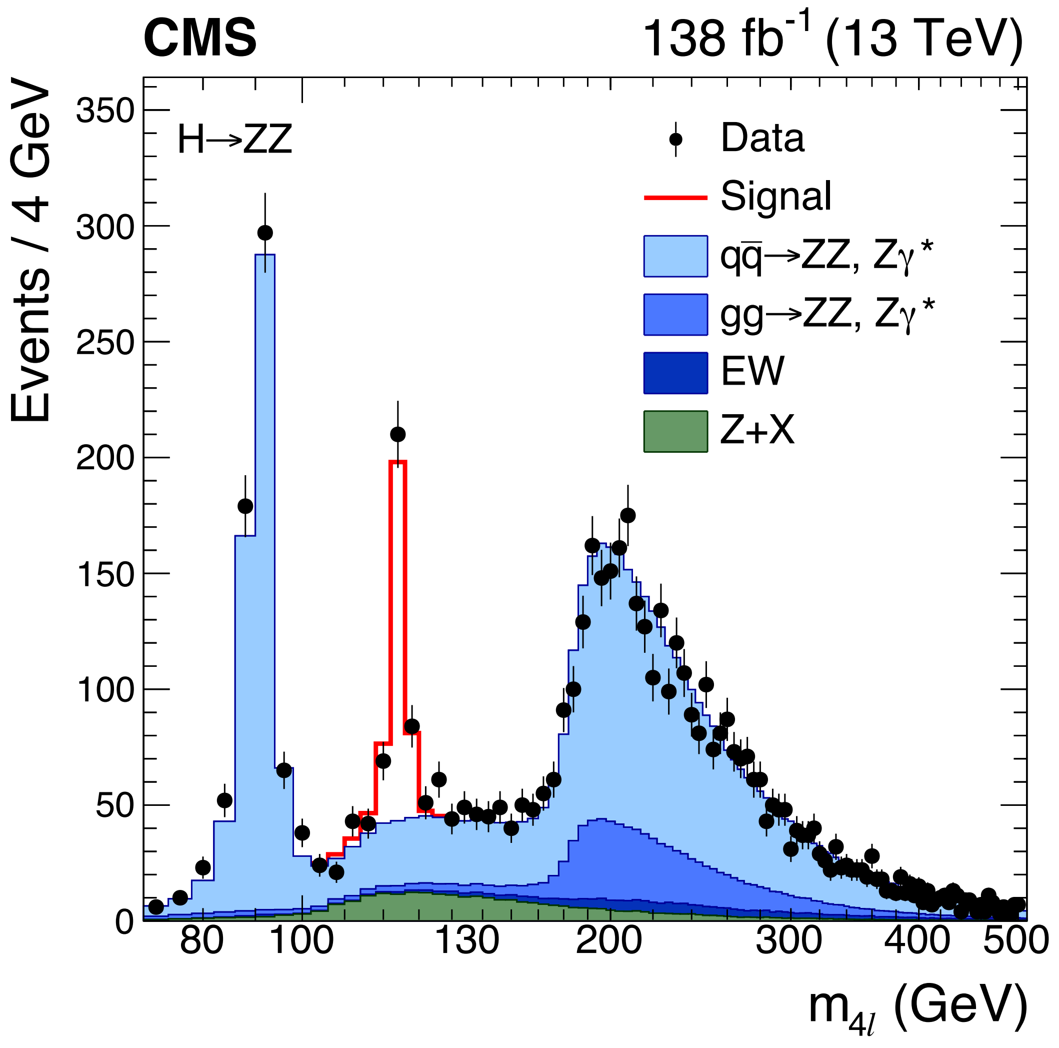


Data analysis

- *MC simulation preparation*
- *Background estimation*
- *Systematics and etc.*

Paper

Data analysis — the cross-section



Observed events (Poisson statistics)

Recorded integrated luminosity

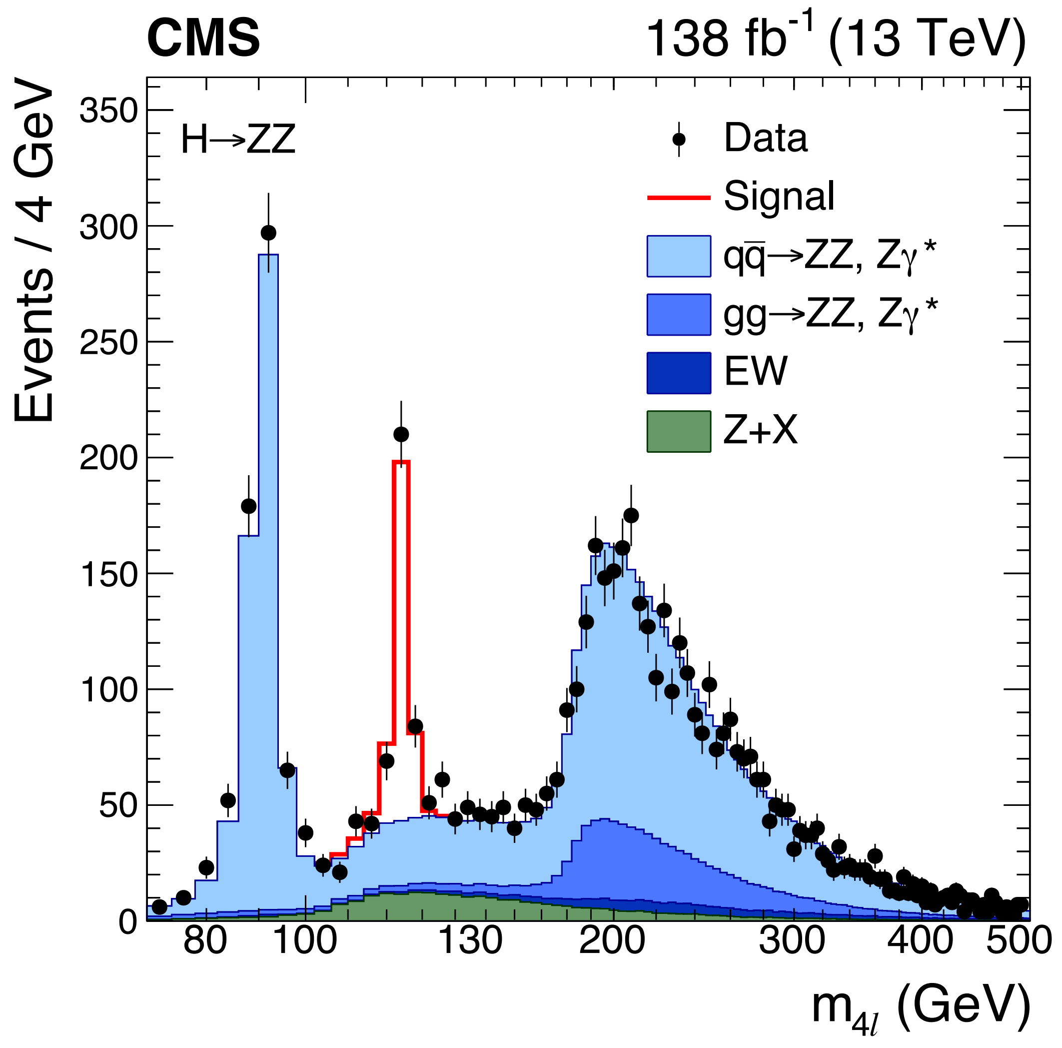
Detector acceptance

Analysis selection efficiency

$$N_{\text{sig}} = \mathscr{L}\mathscr{A}\epsilon\sigma_{\text{sig}}^{\text{exp.}}$$

Production cross section

Data analysis — the cross-section



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Production cross section

Events after selection

Estimated number of background events

$$\boxed{\sigma_{\text{sig}}^{\text{mea.}} = \frac{N_{\text{tot}} - N_{\text{bkg}}}{\mathscr{L}\mathscr{A}\epsilon}}$$

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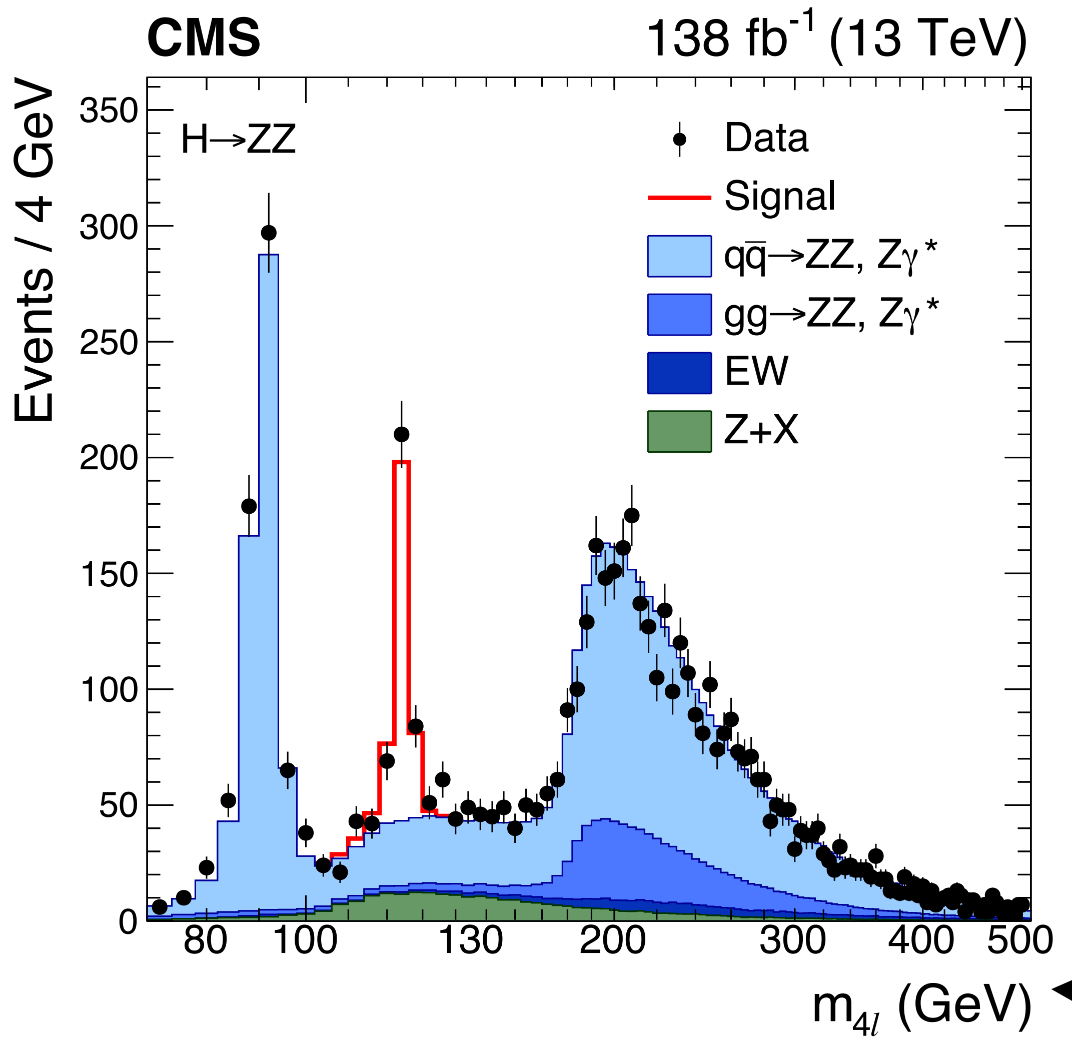
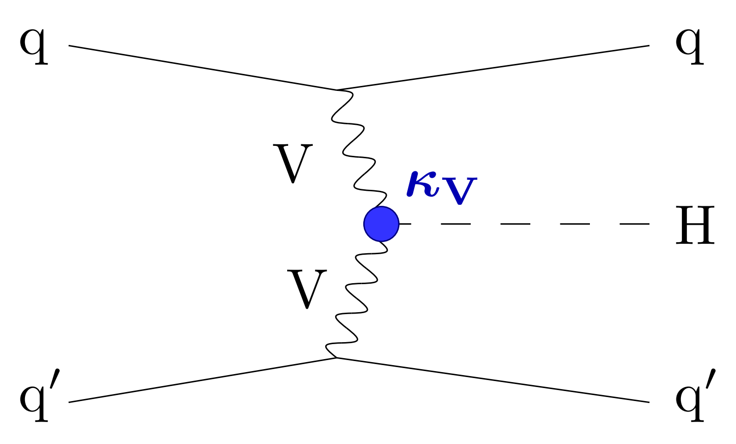
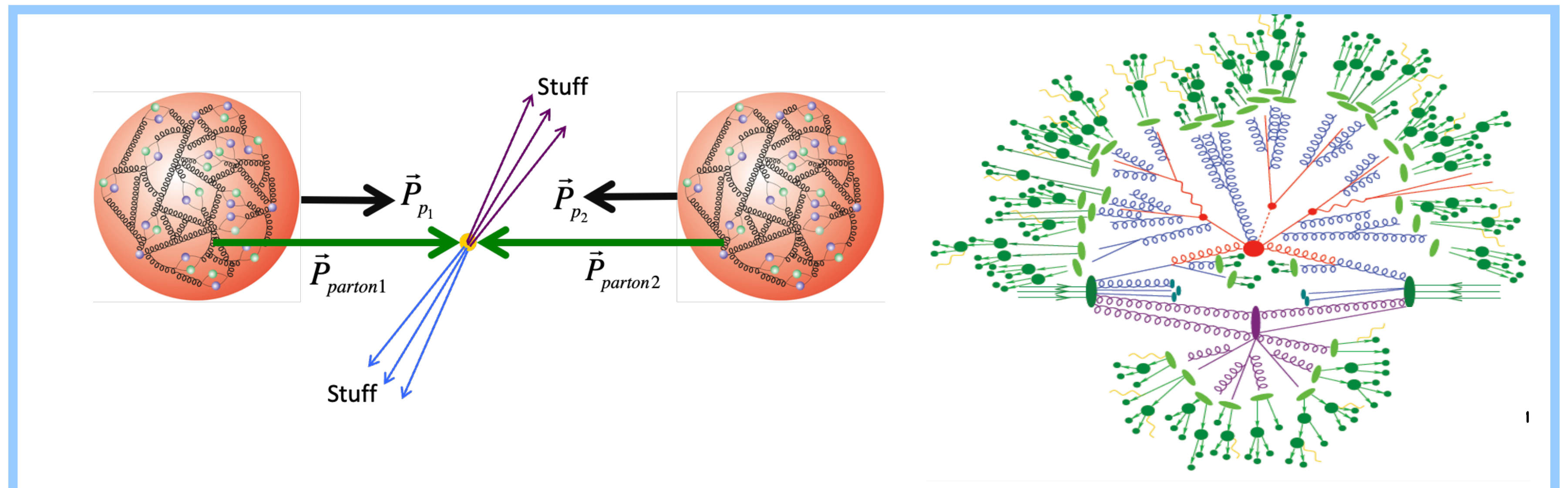
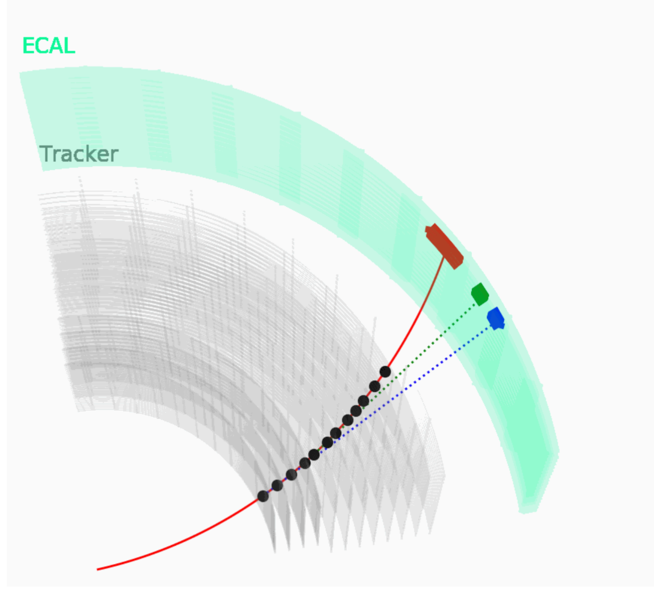




Interesting physics



Hard collision with showering + hadronization



Detector response

91
81
120
130
121
125
150
...

Convert to physics quantities

Events after selection

Estimated number of background events

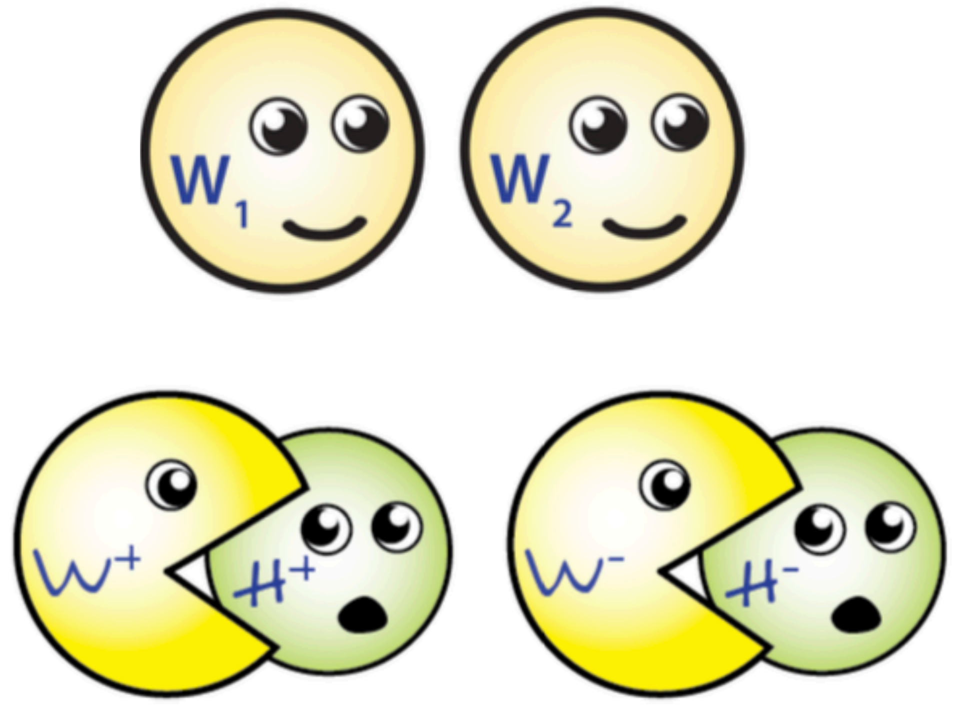
compared to the model $\sigma^{\text{exp.}}_{\text{sig}}$ ←

$$\sigma^{\text{mea.}}_{\text{sig}} = \frac{N_{\text{tot}} - N_{\text{bkg}}}{\mathscr{L}\mathscr{A}\epsilon}$$

- the analysis result is a statistical estimator: it comes with its **expectation** value, uncertainty and coverage
- **understanding all the terms on the right and the related uncertainties is the data analysis**

W mass — Motivation

Through the Higgs mechanism, electroweak symmetry breaking (EWSB) gives mass to the W± and Z bosons and provides their longitudinal polarization states

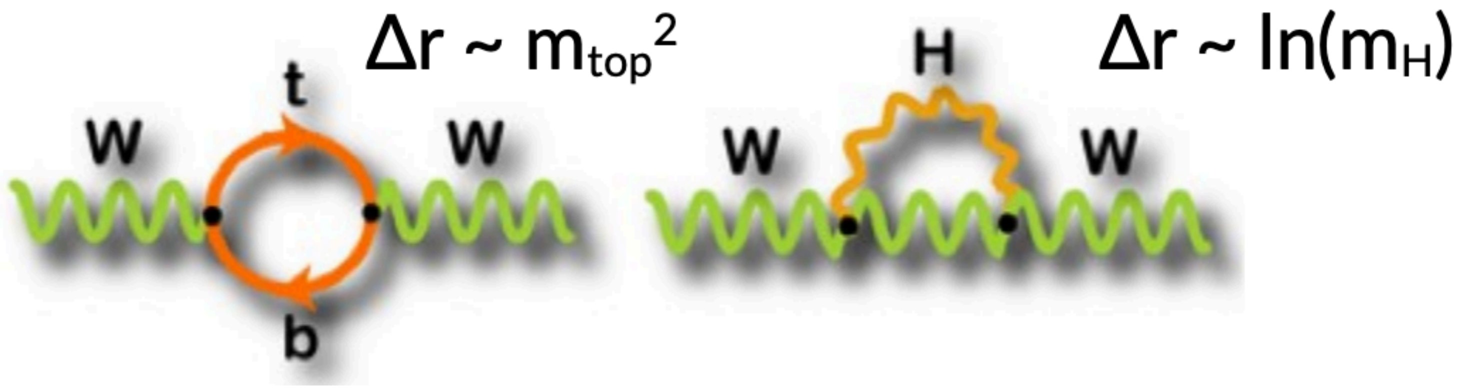


- The precise Higgs mass measurement provides the complete set of inputs needed to over-constrain the SM EW sector
- Precision measurement of the m_W boson mass provides a stringent test of EWSB and its interplay with Higgs physics

SM does not predict m_W but relationship to other parameters

- Possible BSM particles can modify relation

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}\frac{1}{1-\Delta r}$$



m_W can be determined indirectly in EW global fit

- Prediction: Δm_W SM = 6 MeV more precise than direct measurements
- Call for direct measurements to over constrain SM and find cracks

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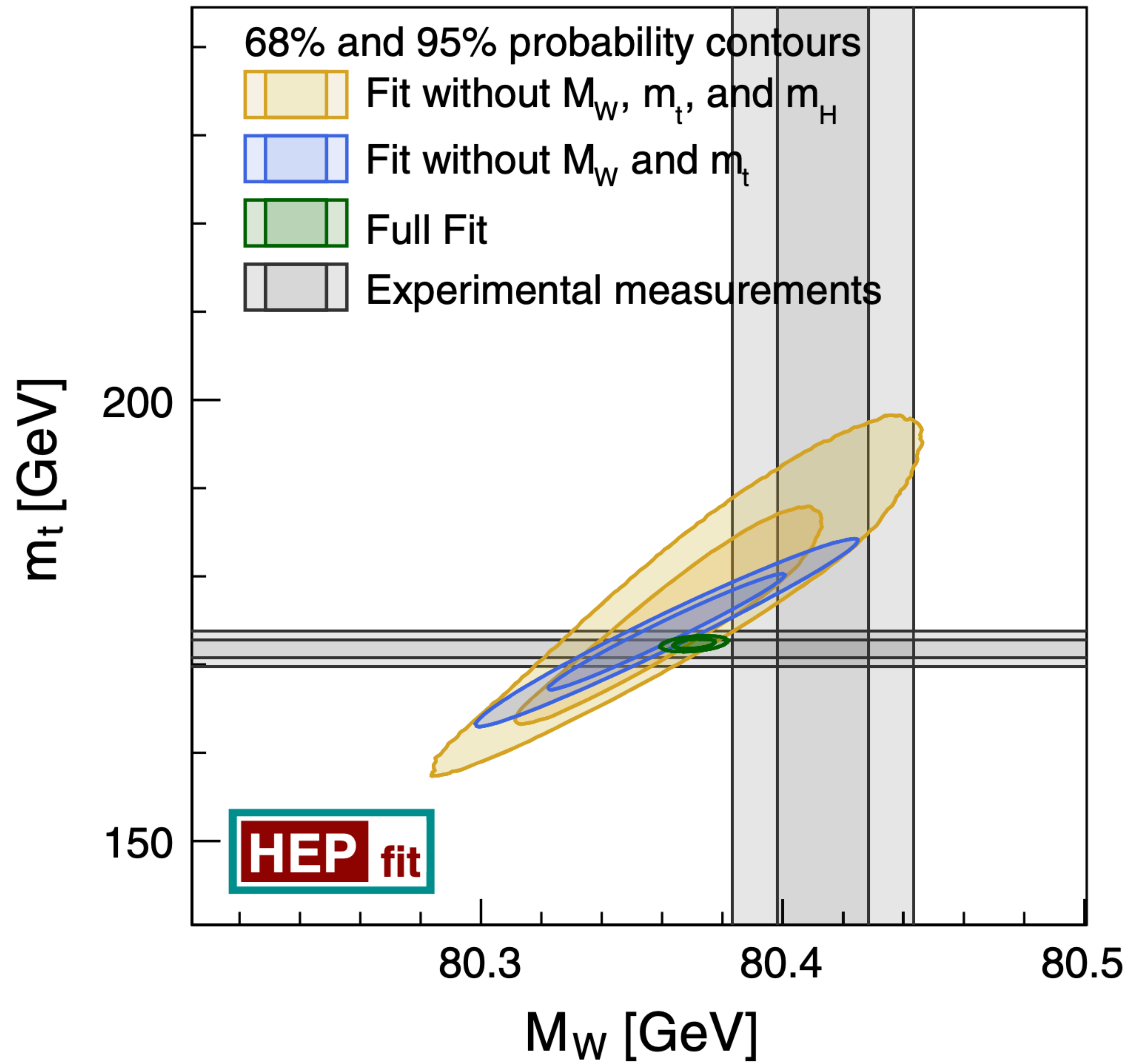


W mass — Introduction

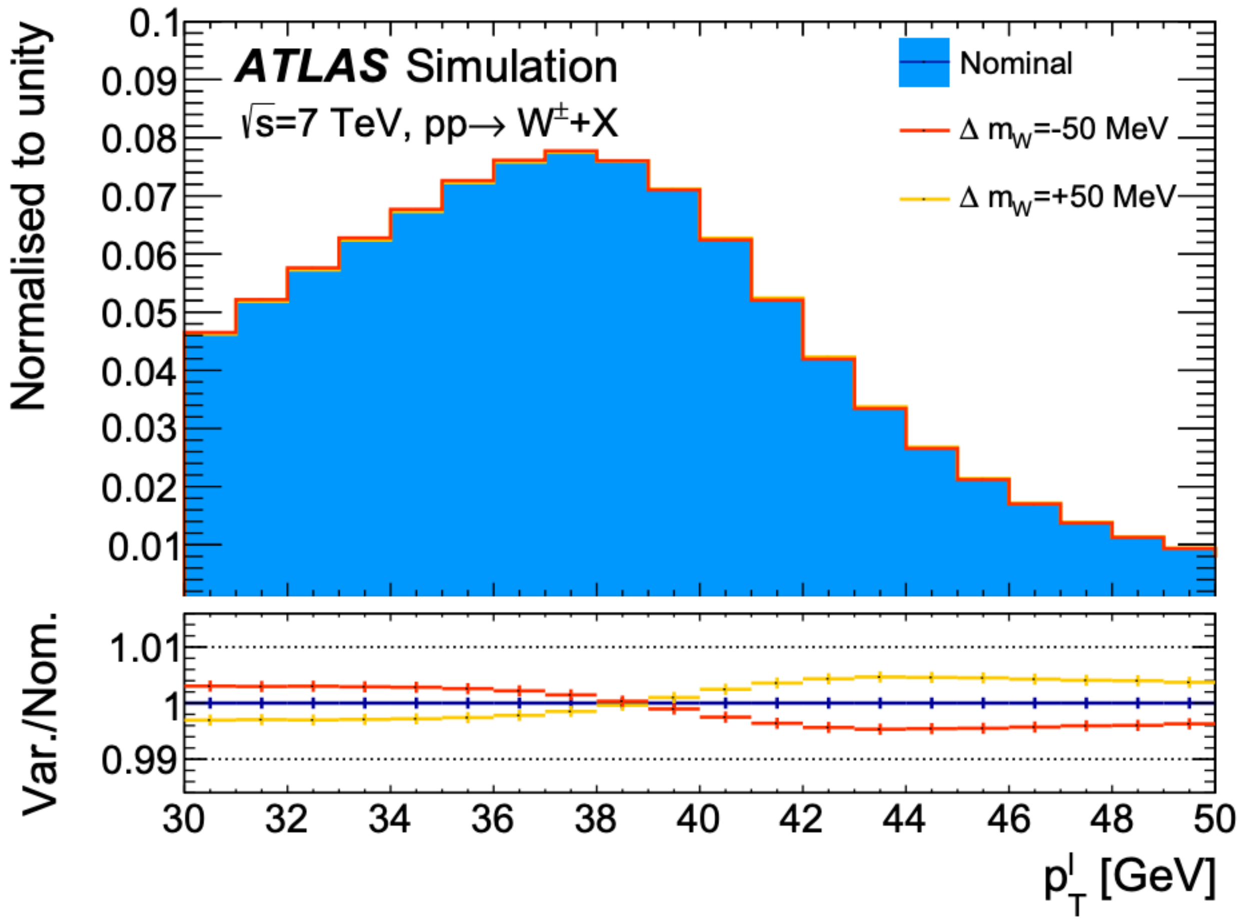
At pp colliders m_W is one of the most challenging measurements

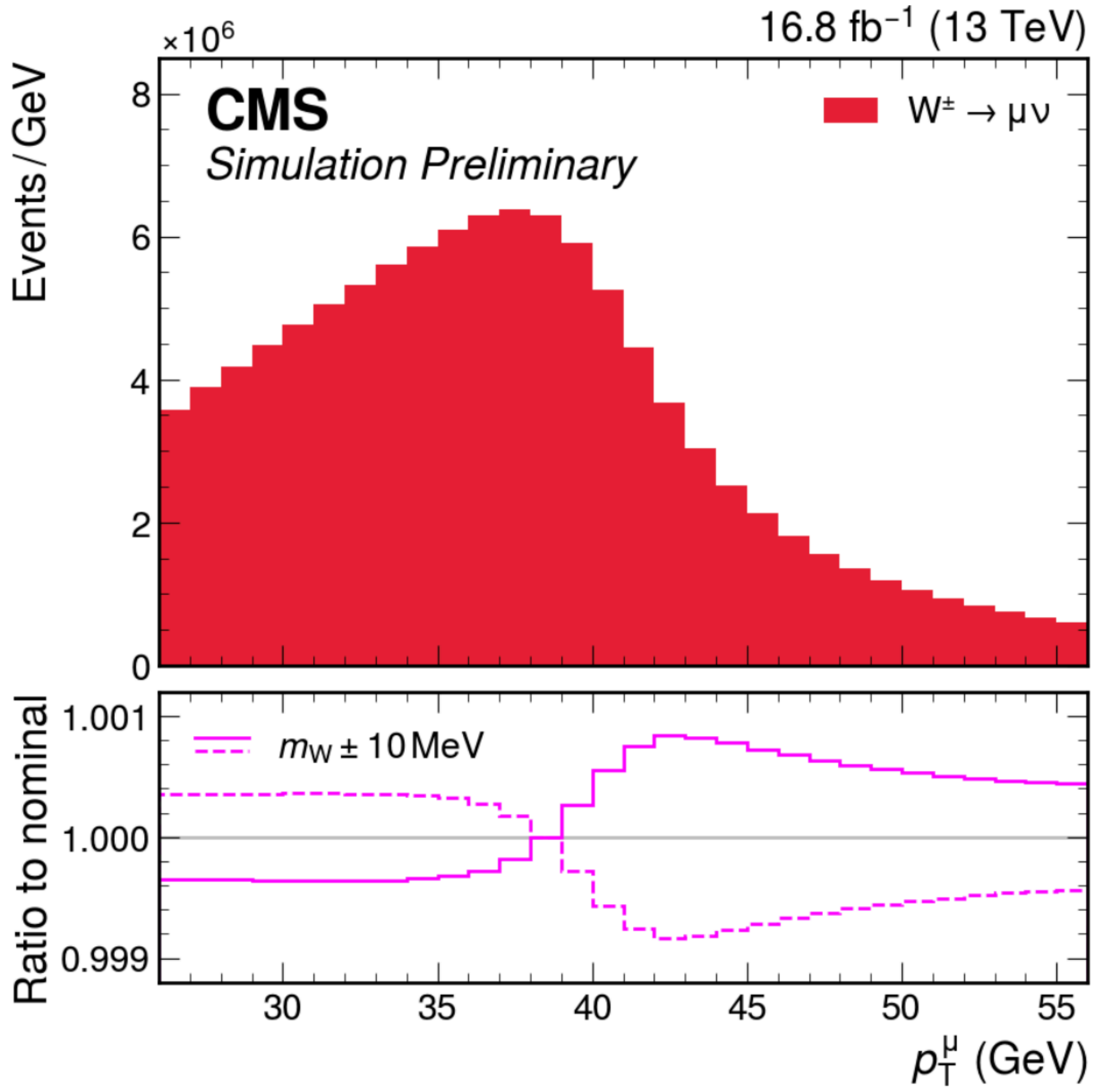
Measurement possible from partial information: m_T or $p_T(\ell)$

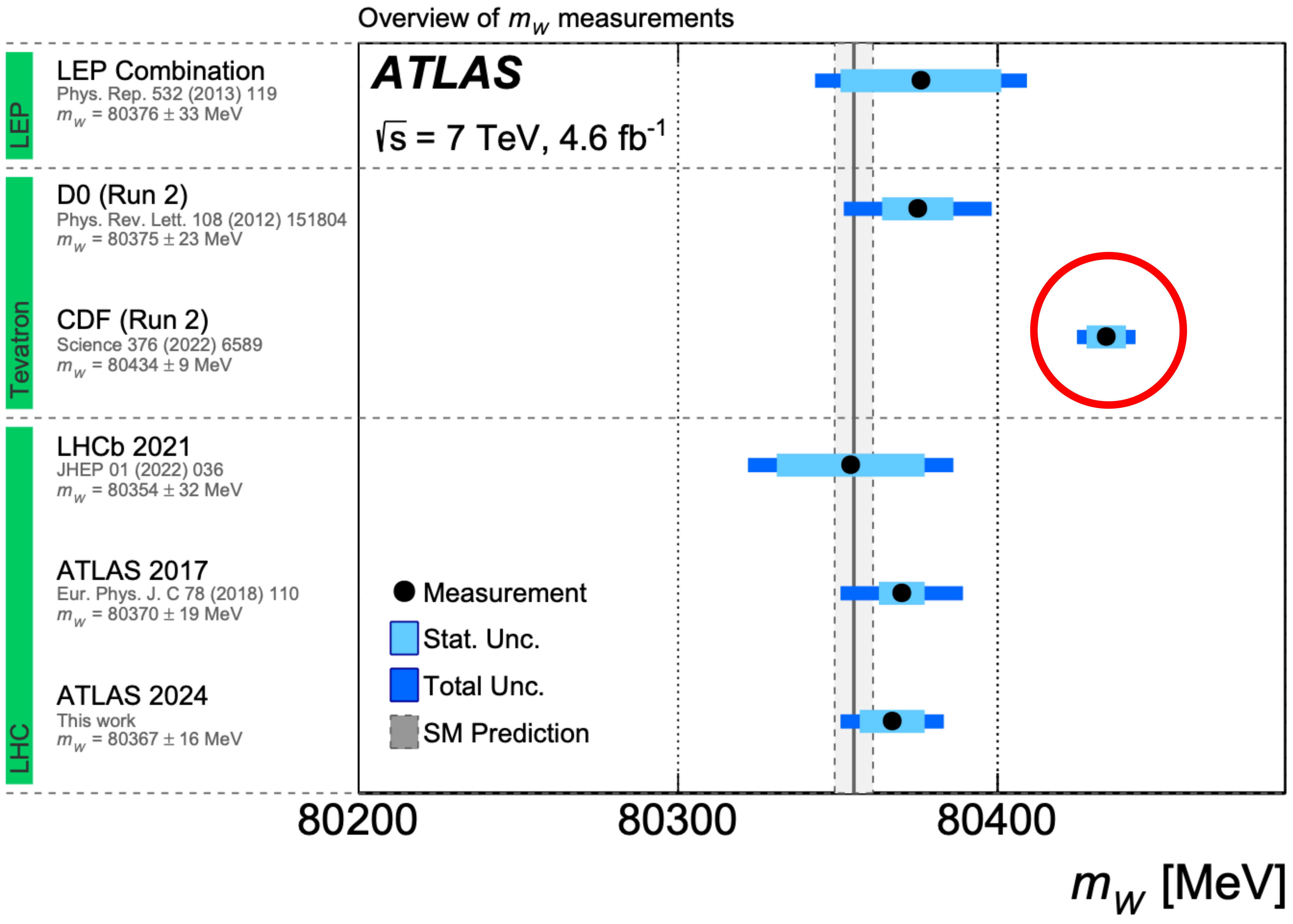
W cannot be fully reconstructed in leptonic channel due to neutrino

m_W is sensitive to 0.1% level variations in templates

Extreme control needed over all experimental and theoretical aspects







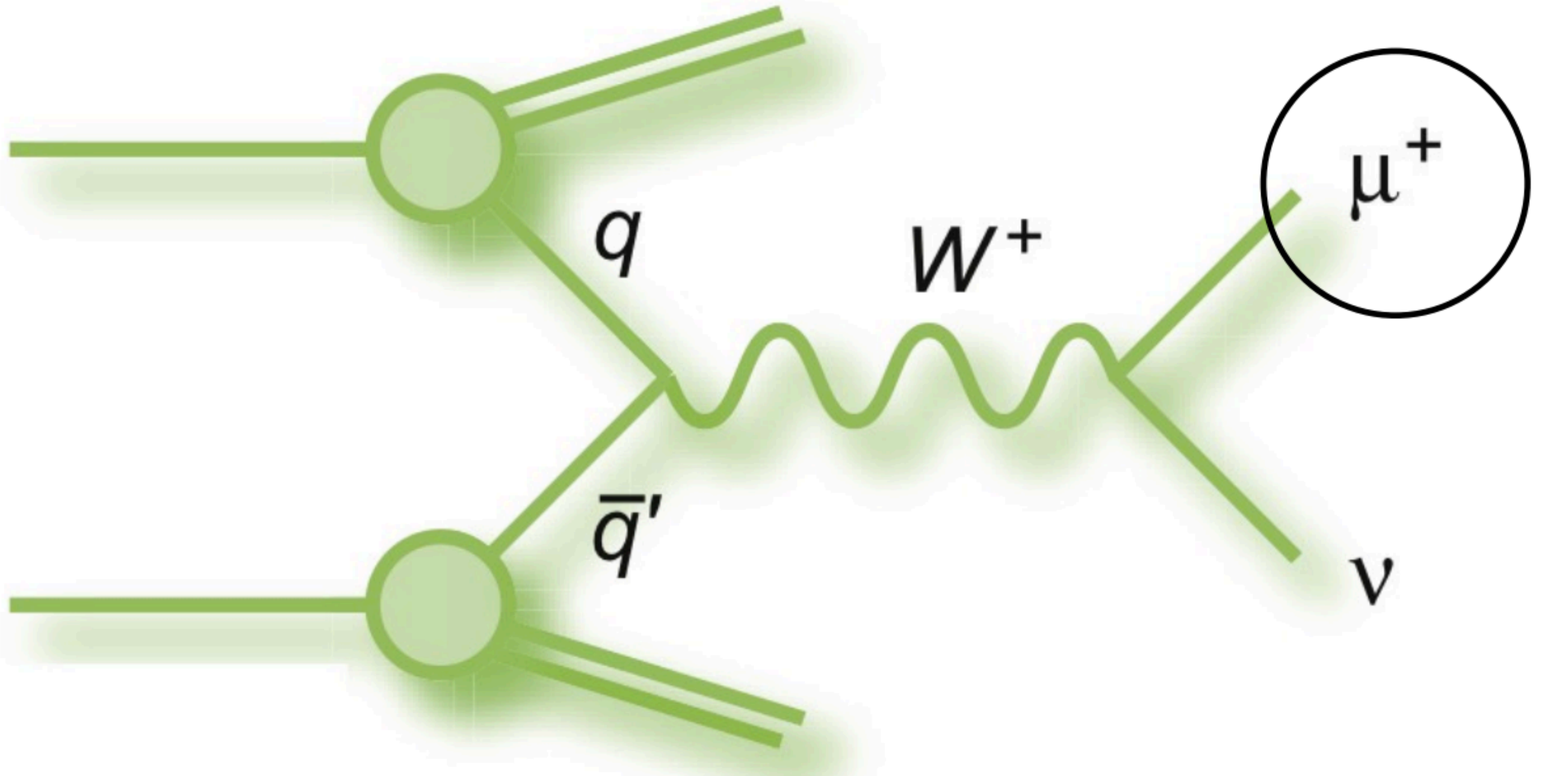
CDF Run 2 results in significant tension with SM and all other measurements

This tension highlights the importance of **independent and precise W-boson mass measurement** as stringent tests of the electroweak sector

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 → μν
- **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 → τ ν, Z → μμ (mostly with one muon out-of-acceptance), Z → τ τ , top, diboson



W mass — Measurement strategy

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

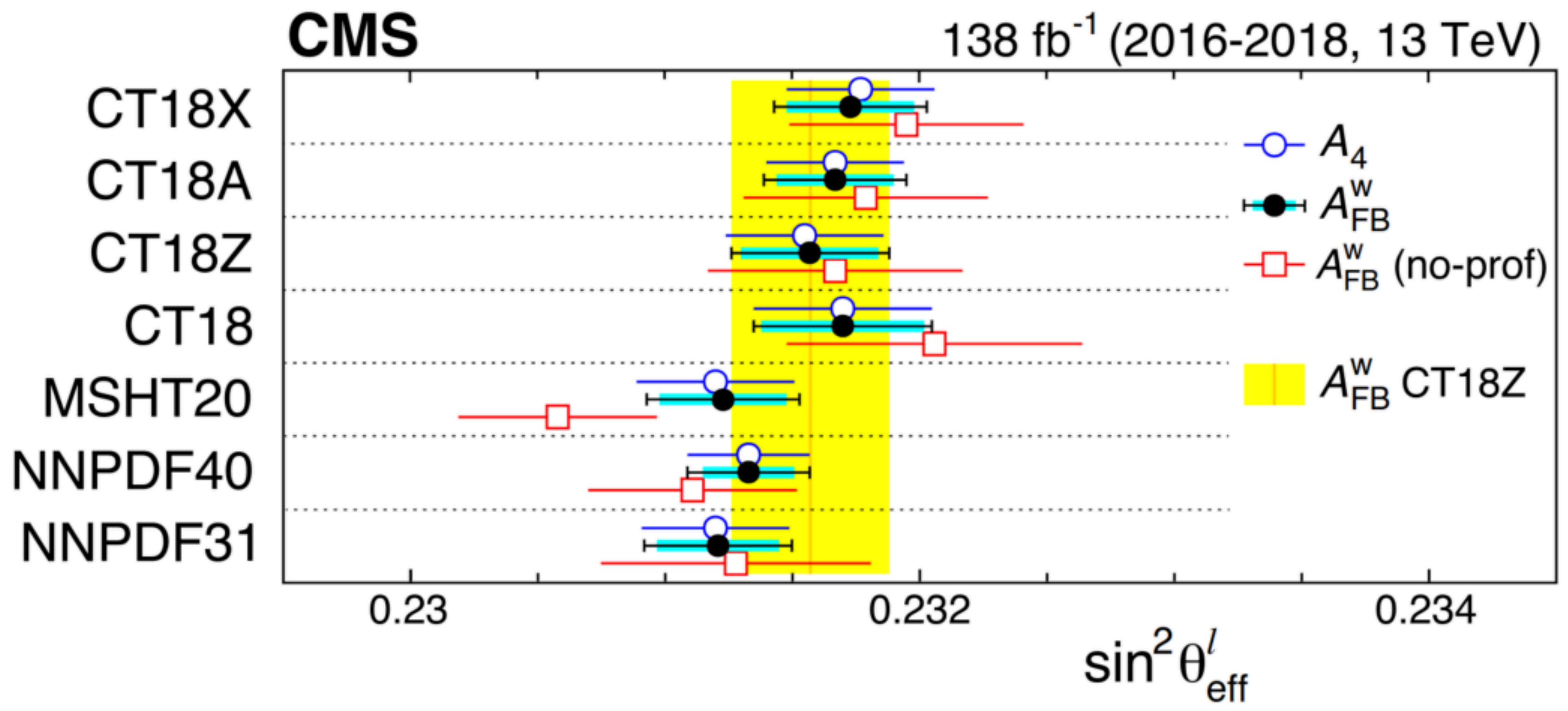
- **Straightforward single muon selection:** track quality criteria, loose transverse impact parameter cut, and isolation
- Selected events are about 90% W → μν
- **Nonprompt background** from data-driven estimate
  - Mostly from B and D decays with smaller contribution from π or K decay-in-flight
-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

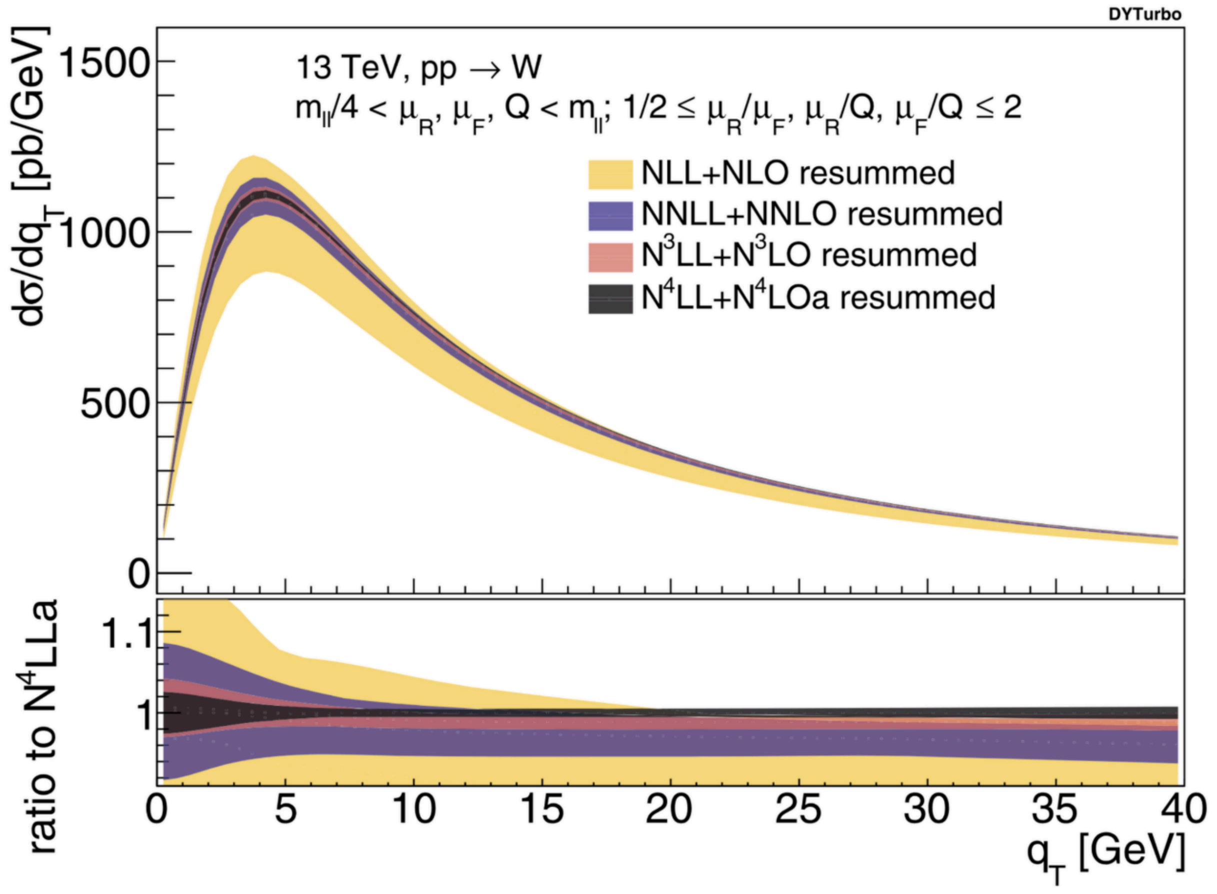
Theoretical and **experimental uncertainties** are important for extracting mass results

- 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.

$$\frac{d\sigma}{\underbrace{dp_T^2\, dm\, dy}_{\text{W differential cross section}}\ \underbrace{d\cos\theta^*\, d\phi^*}_{\text{Decay angles from muons in W rest frame}}} =$$

$$\frac{3}{16\pi}\underbrace{\frac{d\sigma_{UL}}{dp_T^2\, dm\, dy}}_{\text{Unpolarized cross section}}\left[(1+\cos^2\theta^*) + \sum_{i=0}^{7}\underbrace{A_i(p_T, m, y)}_{\text{Angular coefficients encode W polarization}}\cdot \underbrace{P_i(\cos\theta^*, \phi^*)}_{\text{Spherical harmonics encode W decay}}\right]$$

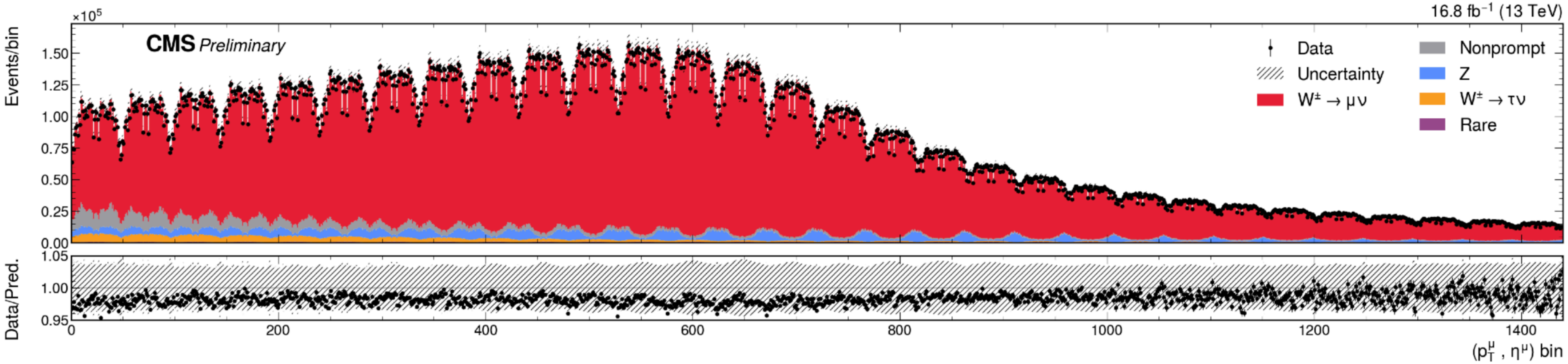




W mass — Measurement strategy

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

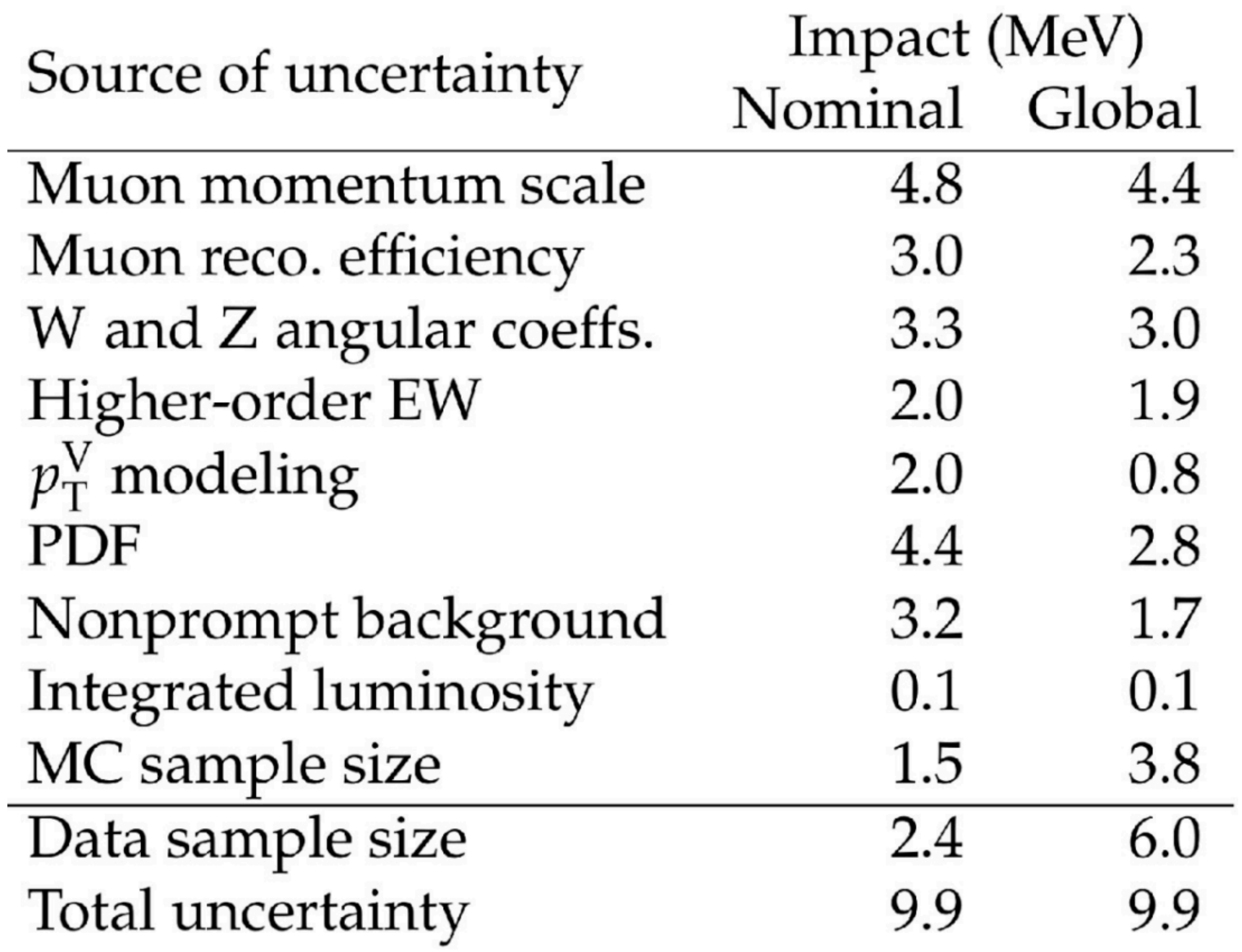


Enabling feature of the measurement: **Systematic variations** in W p_T , rapidity, decay angles from QCD uncertainties, PDFs, have a different effect on the muon kinematics as compared to a change in m_W PDF and boson p_T modeling uncertainties are strongly constrained in-situ by the data

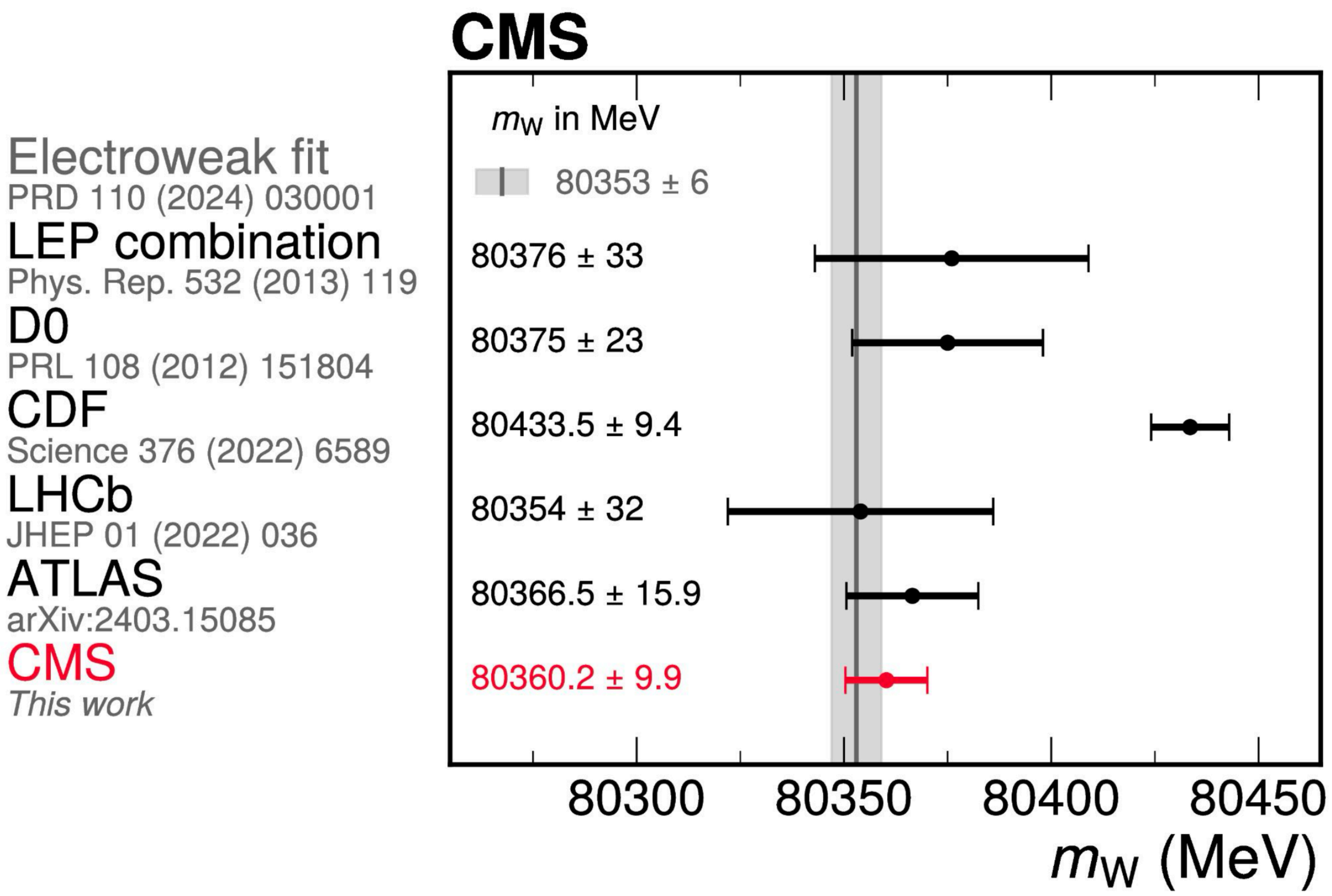
Thousand work are done here, details seen its publication

W mass — Results

$$m_{\mathrm{W}} = 80360.2 \pm 9.9\,\mathrm{MeV}$$



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
$p_{\mathrm{T}}^{\mathrm{V}}$ 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

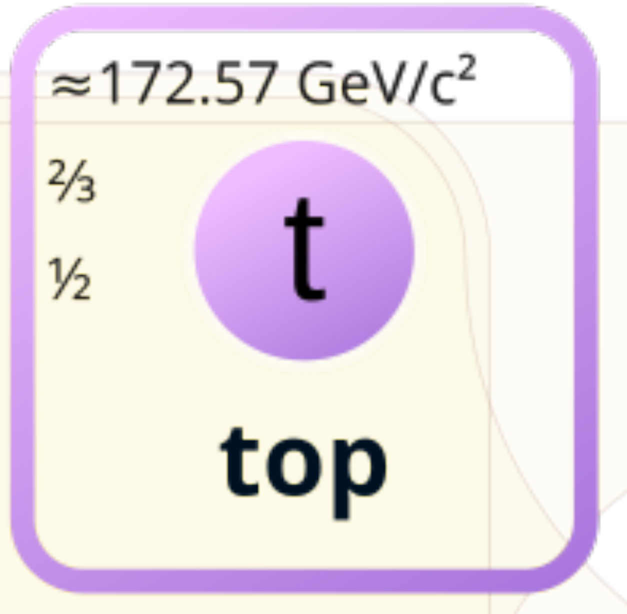


- Recent CMS measurement is the most precise at the LHC, approaching quoted CDF precision, compatible with SM prediction and other measurements
- Exploits strong in-situ constraints to reduce PDF/QCD uncertainties
- Clear tension with CDF measurement

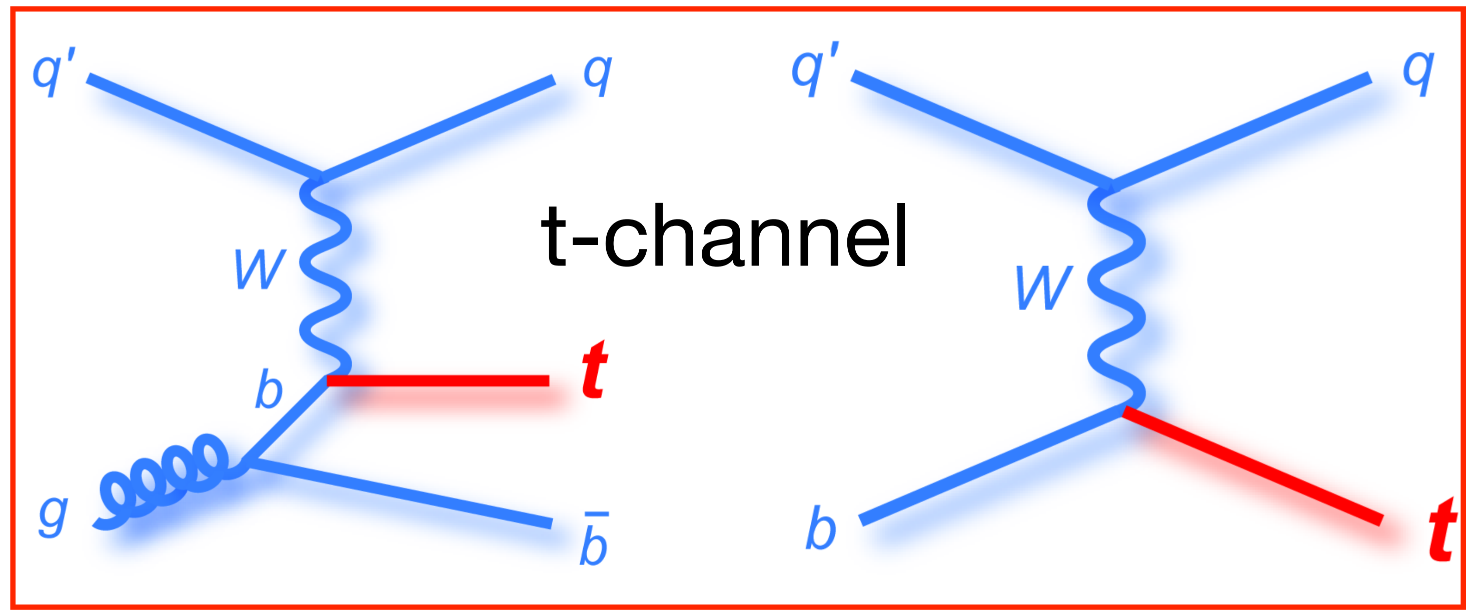
Top mass — Motivation

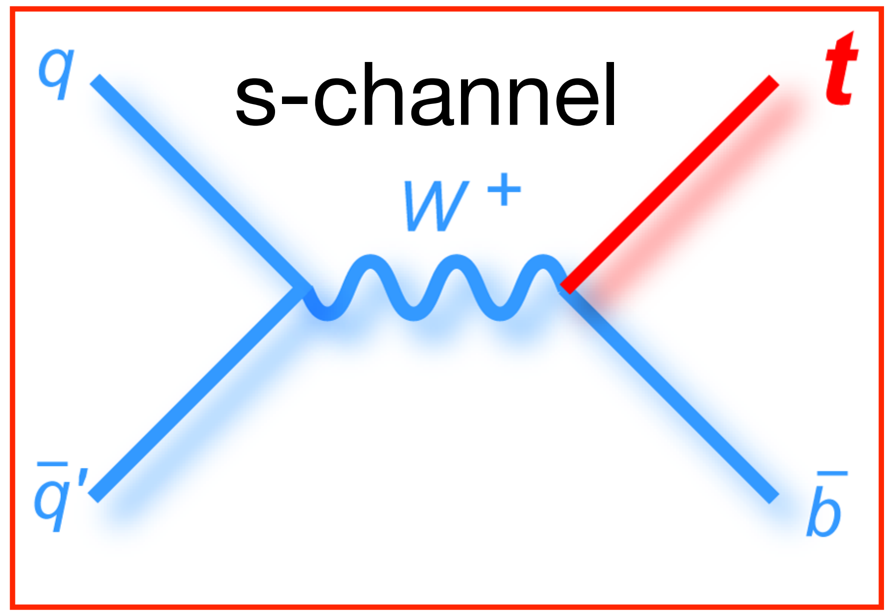
- spin 1/2, charge 2/3
- short lifetime: τ~5×10^{-25} s ≪ Λ^{-1}QCD:

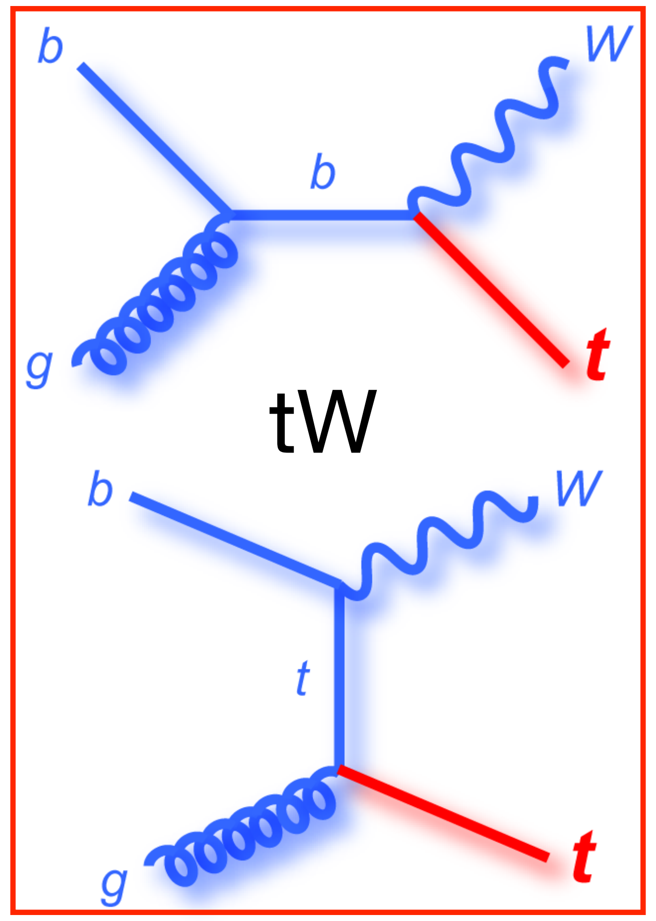
  decays before it fragments ➞ observe "naked" quark
- BR$(t \rightarrow Wb) \simeq 99.8\,\%$
- Main production mode: t-channel single top and t$\bar{t}$ productions



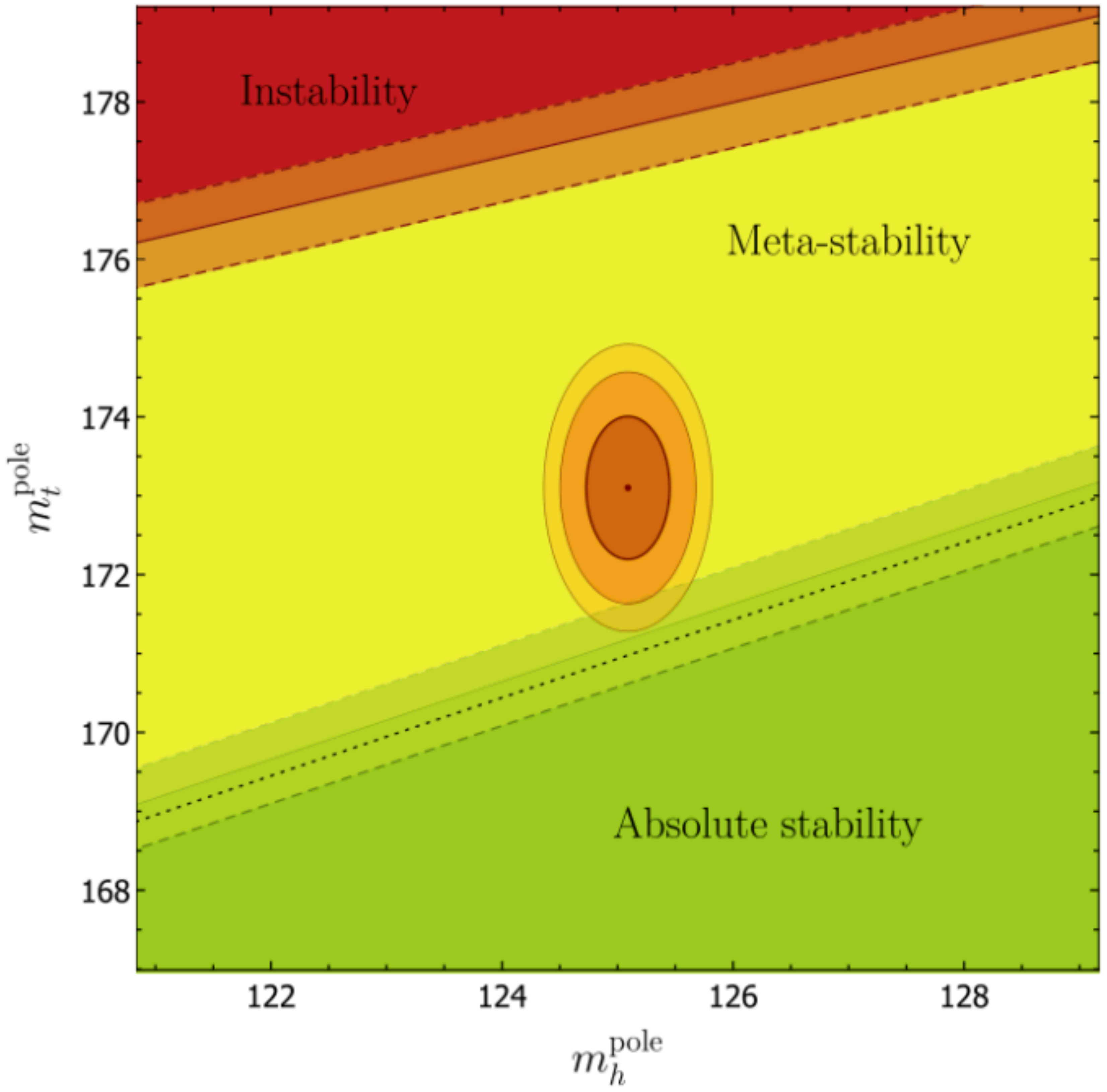
- Heaviest elementary particle in the SM
  - Used in SM consistency checks
- Special interplay with the Higgs boson
  - Yukawa coupling O(1), vacuum stability, quartic coupling
- Cosmological consequences: Universe lifetime

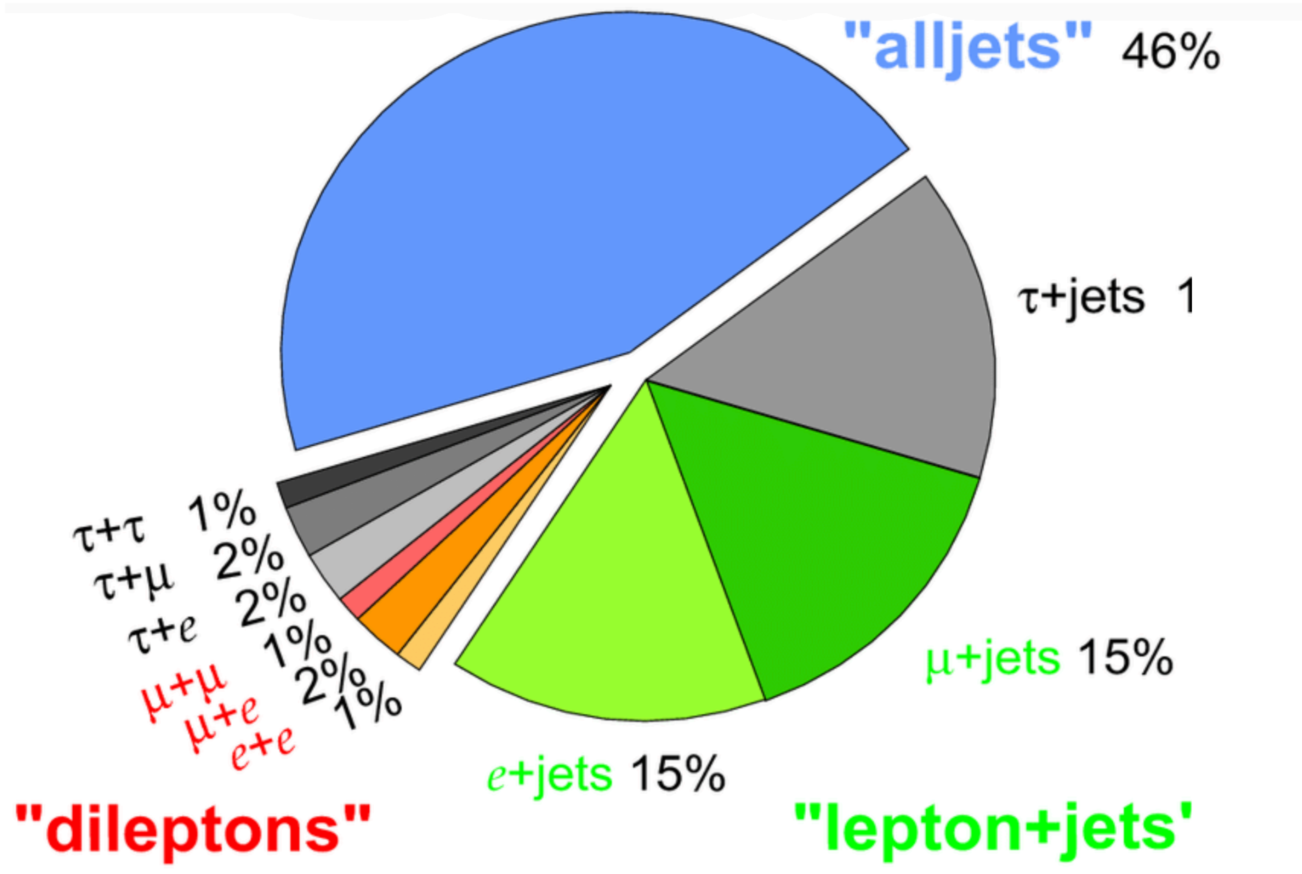


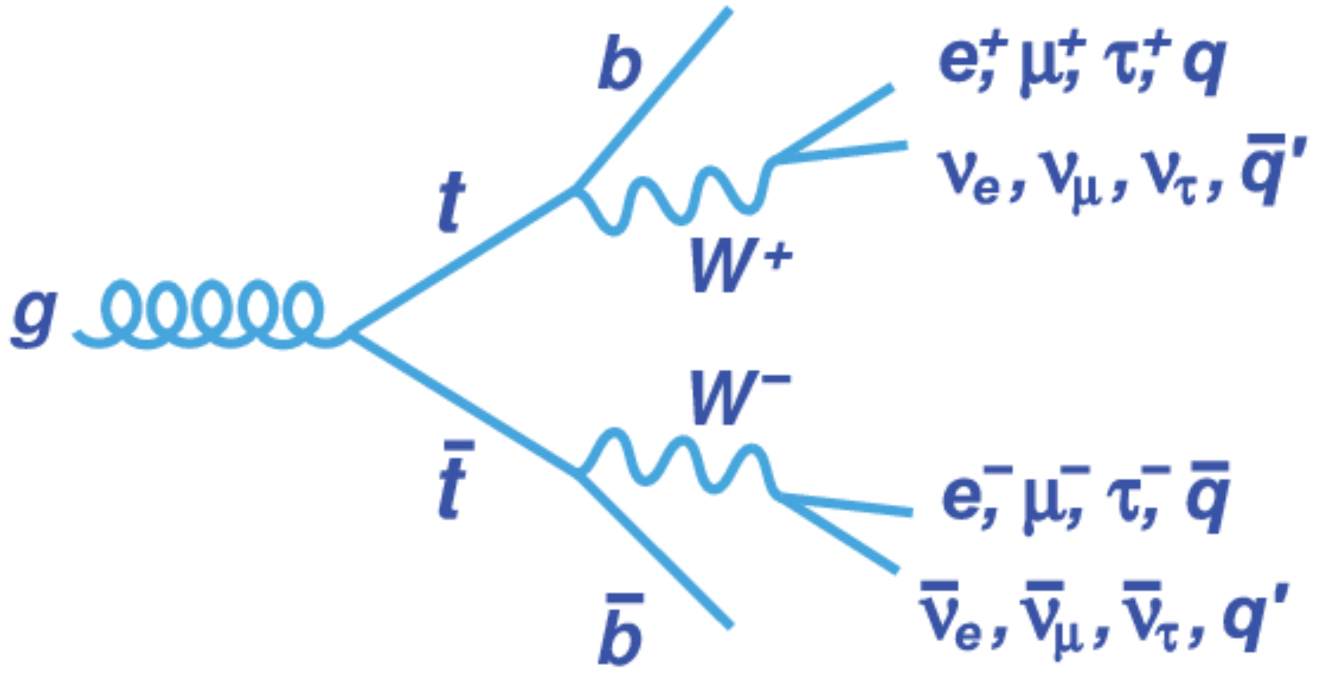




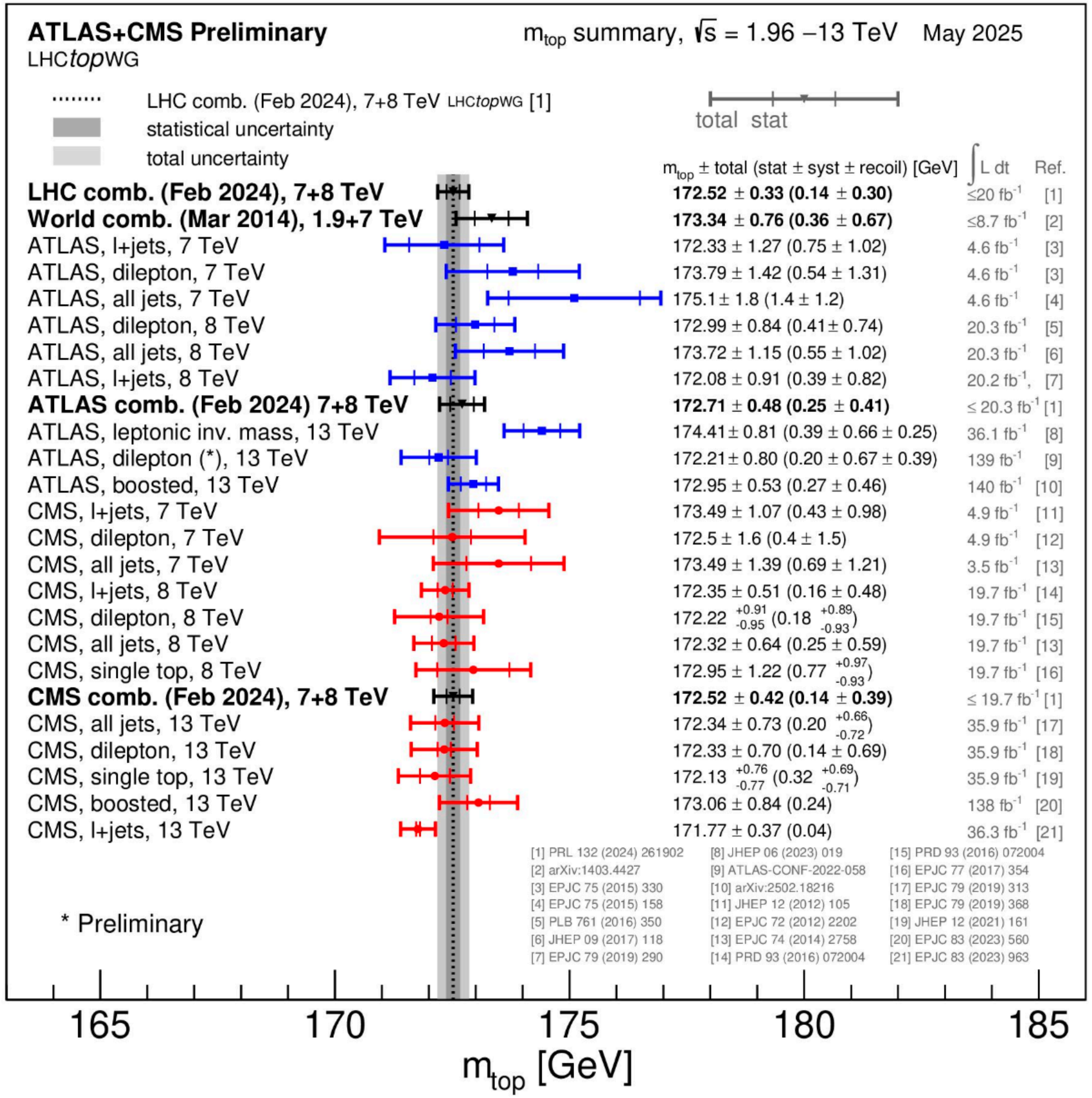
Phys. Rev. D 97, 056006 (2018)

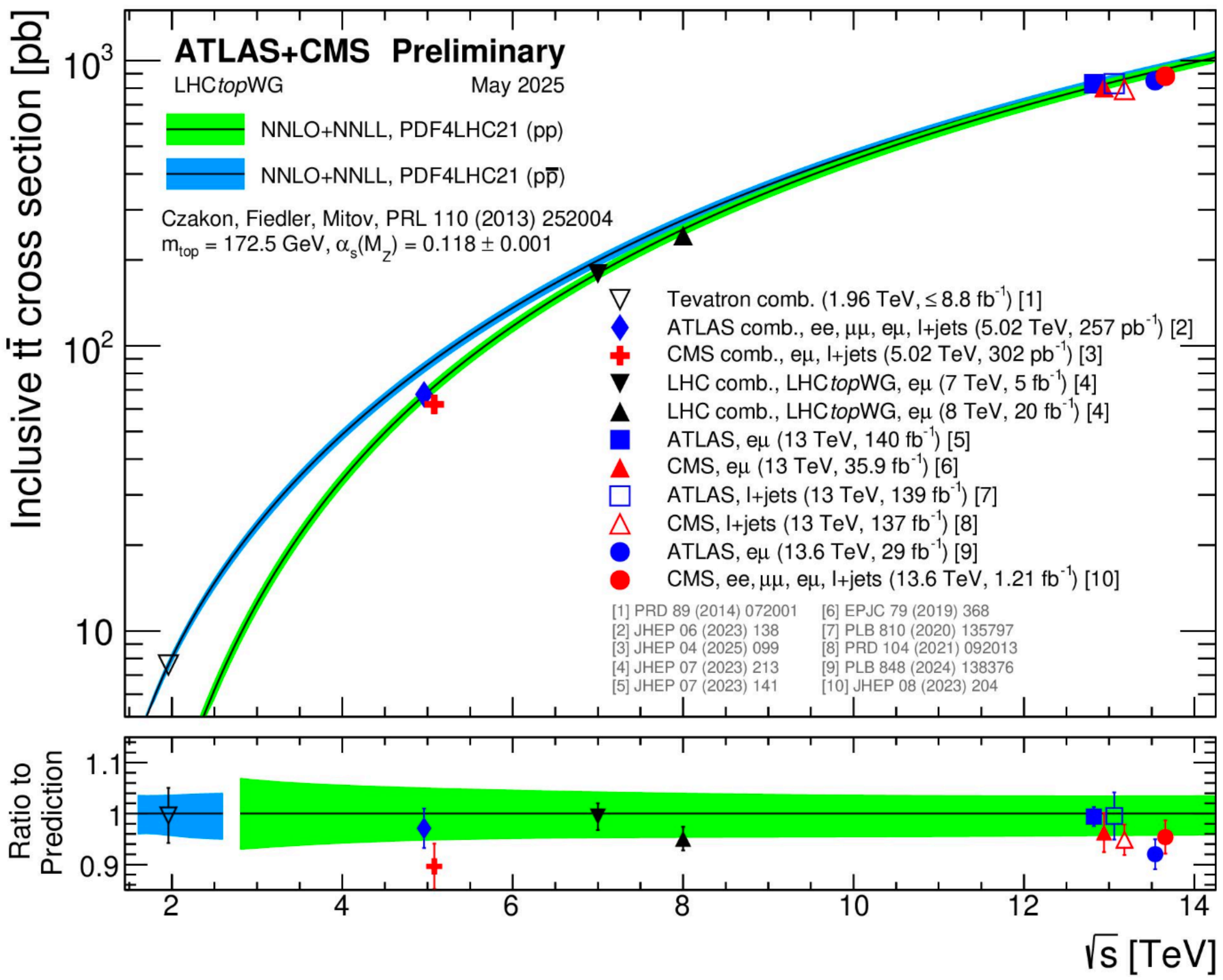






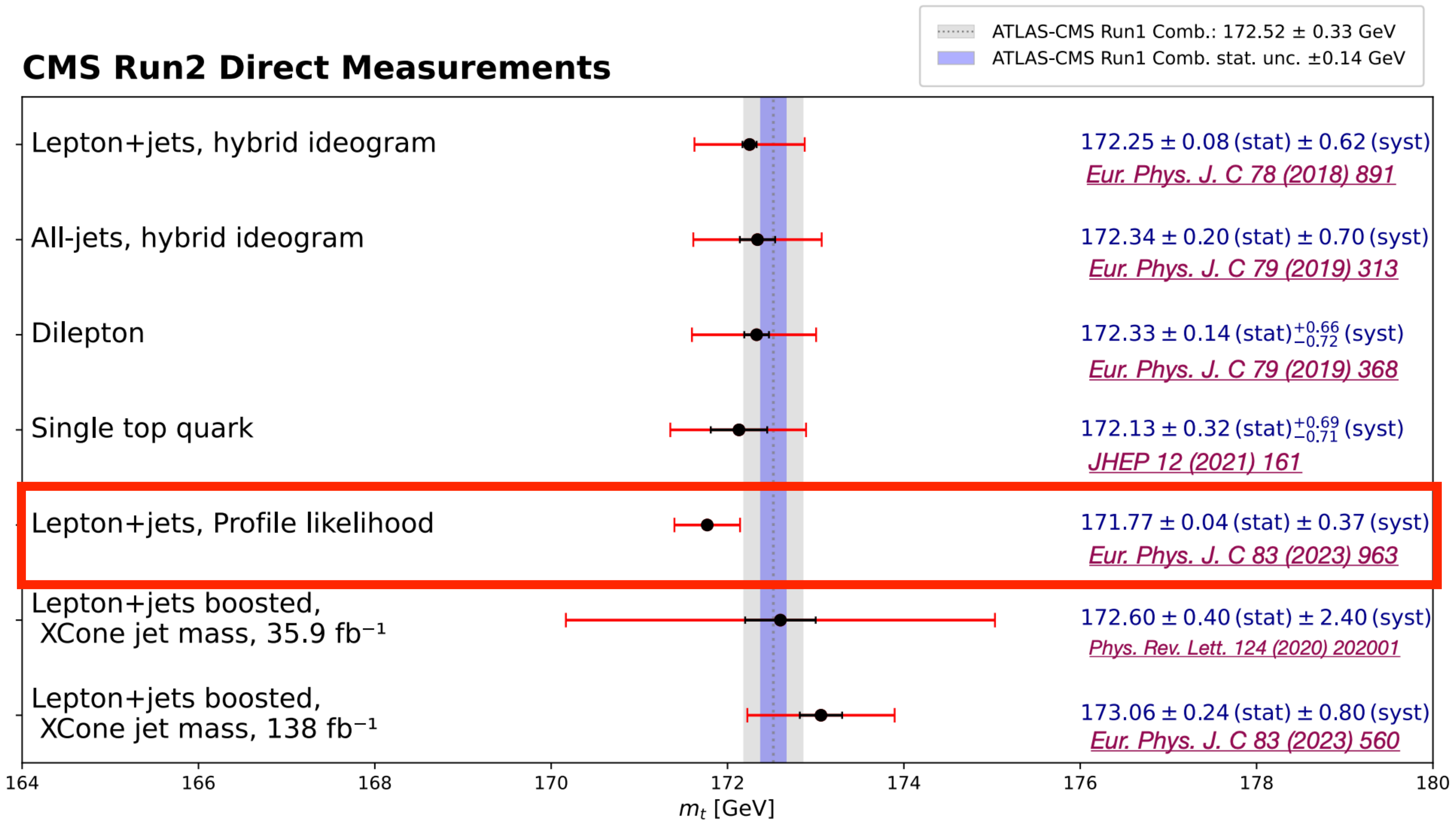
Top mass — Overview



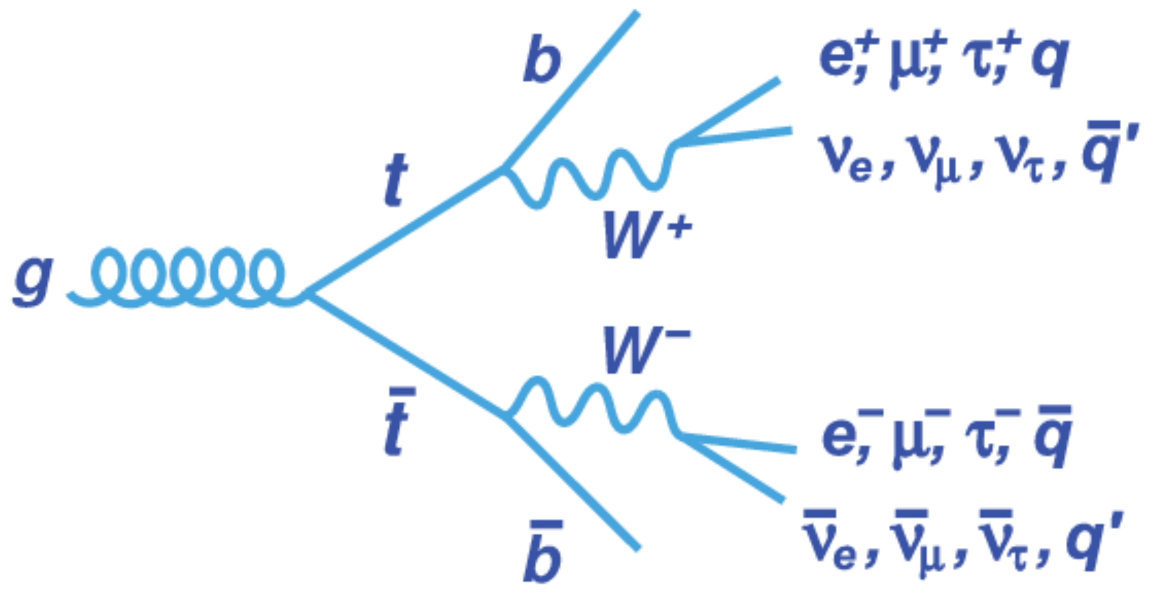


- **Direct measurement**: m_t is extracted by comparing the distribution of a reconstructed mass-sensitive observable with its Monte Carlo (MC) prediction
- **Indirect measurement**: experimental observables of production, such as the total cross-section, are compared to fixed-order calculations performed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

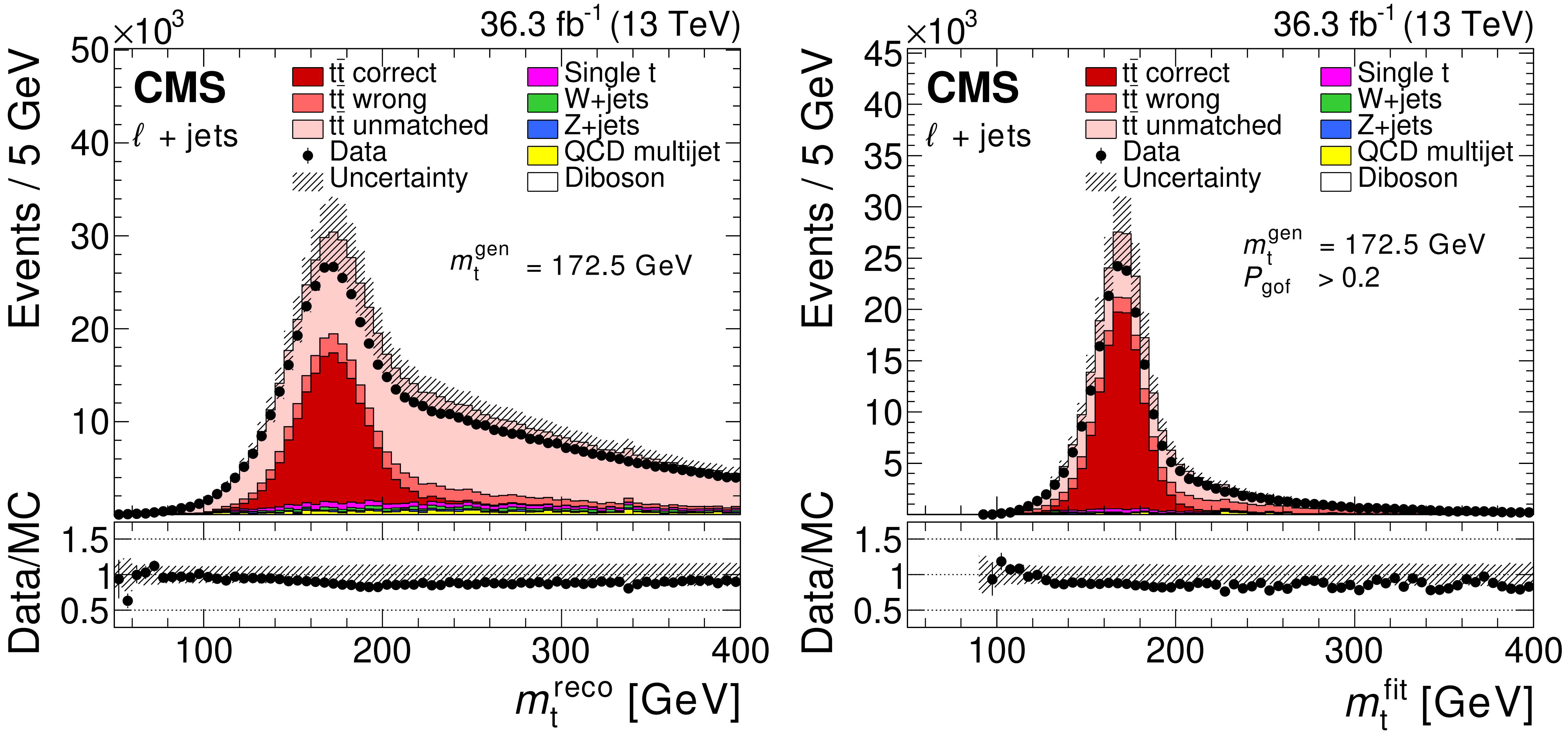
Top mass — direct measurement



Most precise measurements from direct reconstruction of top decays in ℓ+jets events



- Exactly one lepton of μ or e
- At least four AK4 jet
- At least two b-tagged jet
- ***More than 95% of events are*** $t\bar{t}$ ***signal events***



Kinematic fit is used to evaluate the compatibility of an event with the $t\bar{t}$ hypothesis

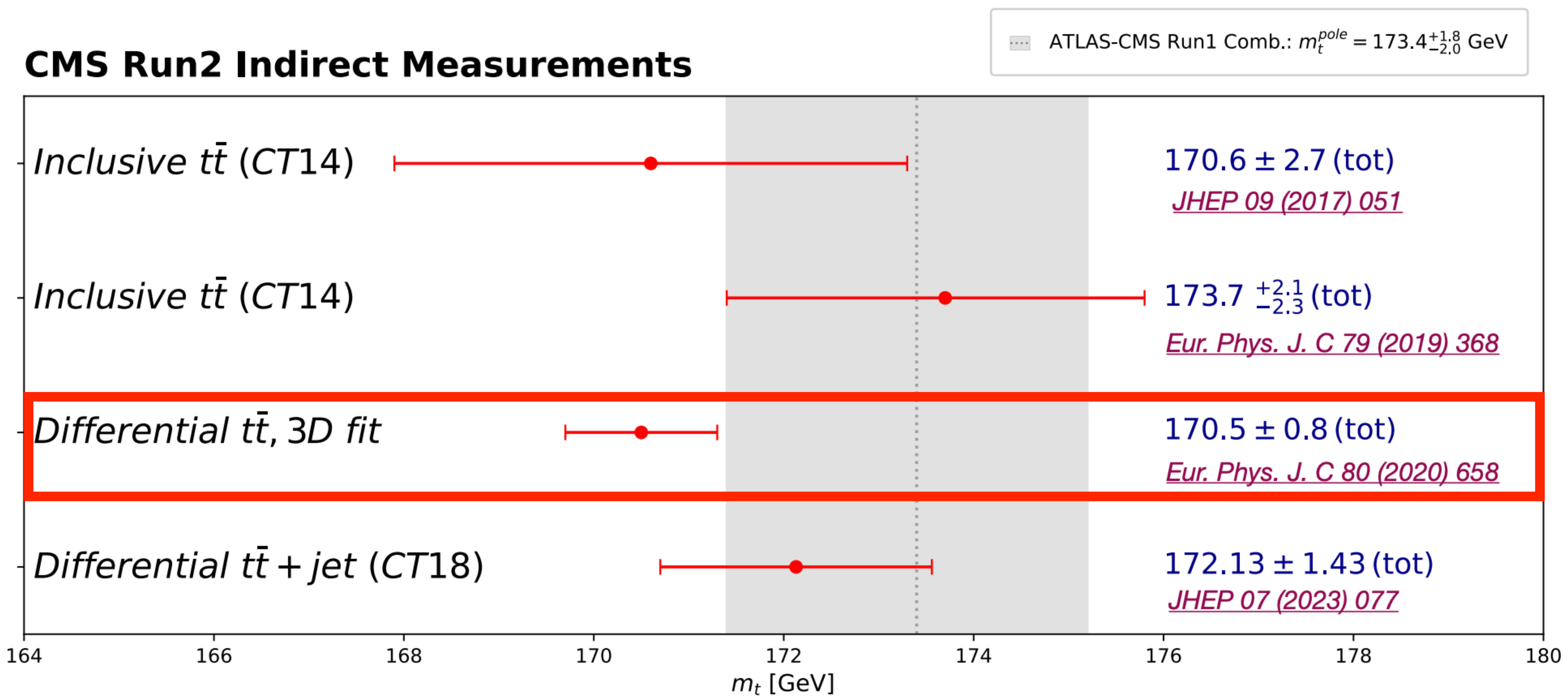
momenta of the lepton and of the four leading jets, missing E$_T$*, and the resolutions of these variables as inputs*

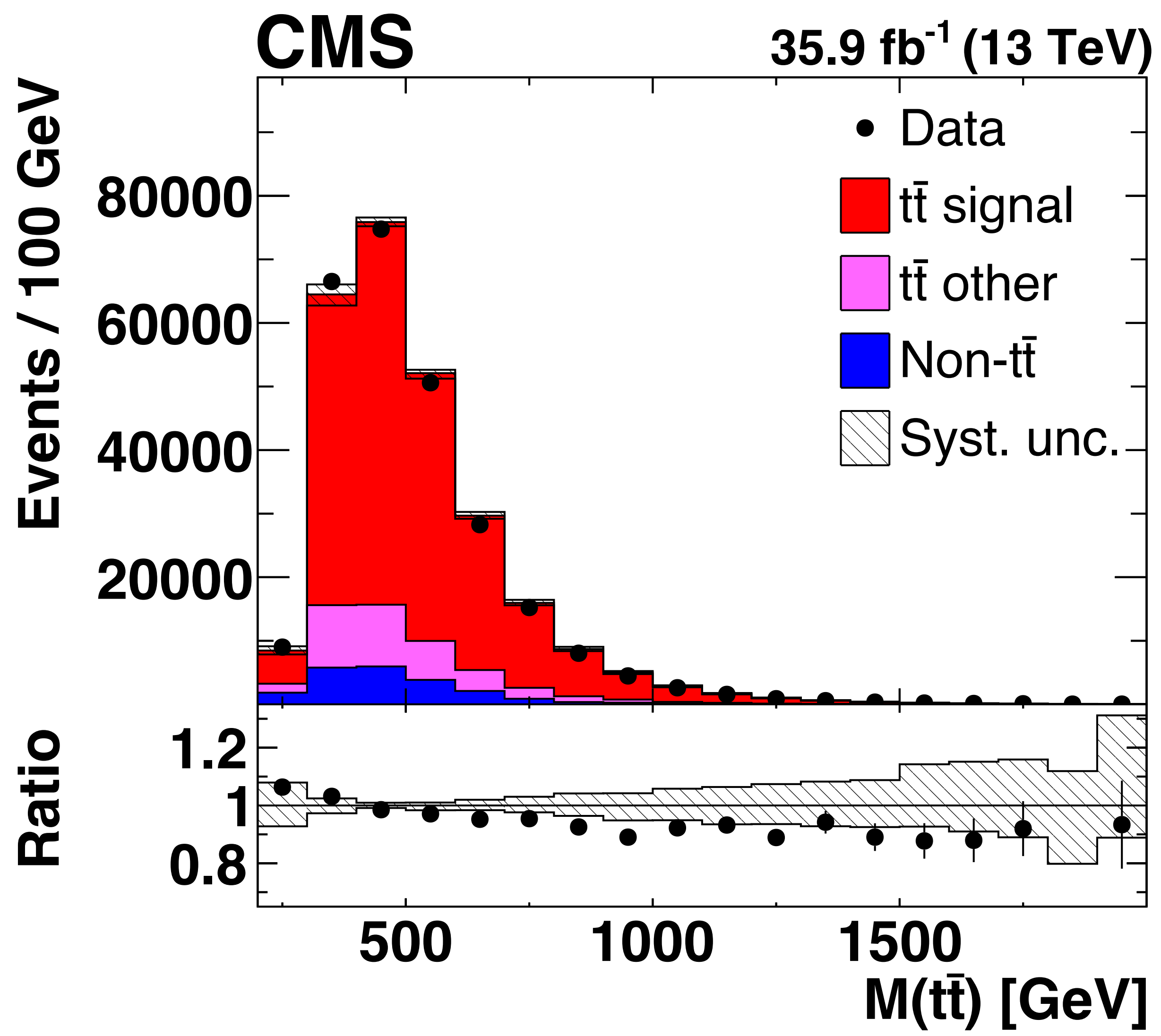
→ The mass of top quark decaying leptonically or hadronically is obtained with better resolution

The hadronically decaying top mass reconstructed from jets causes worse resolution

Both experimental and theoretical uncertainties are carefully evaluated

Top pole mass — indirect measurement

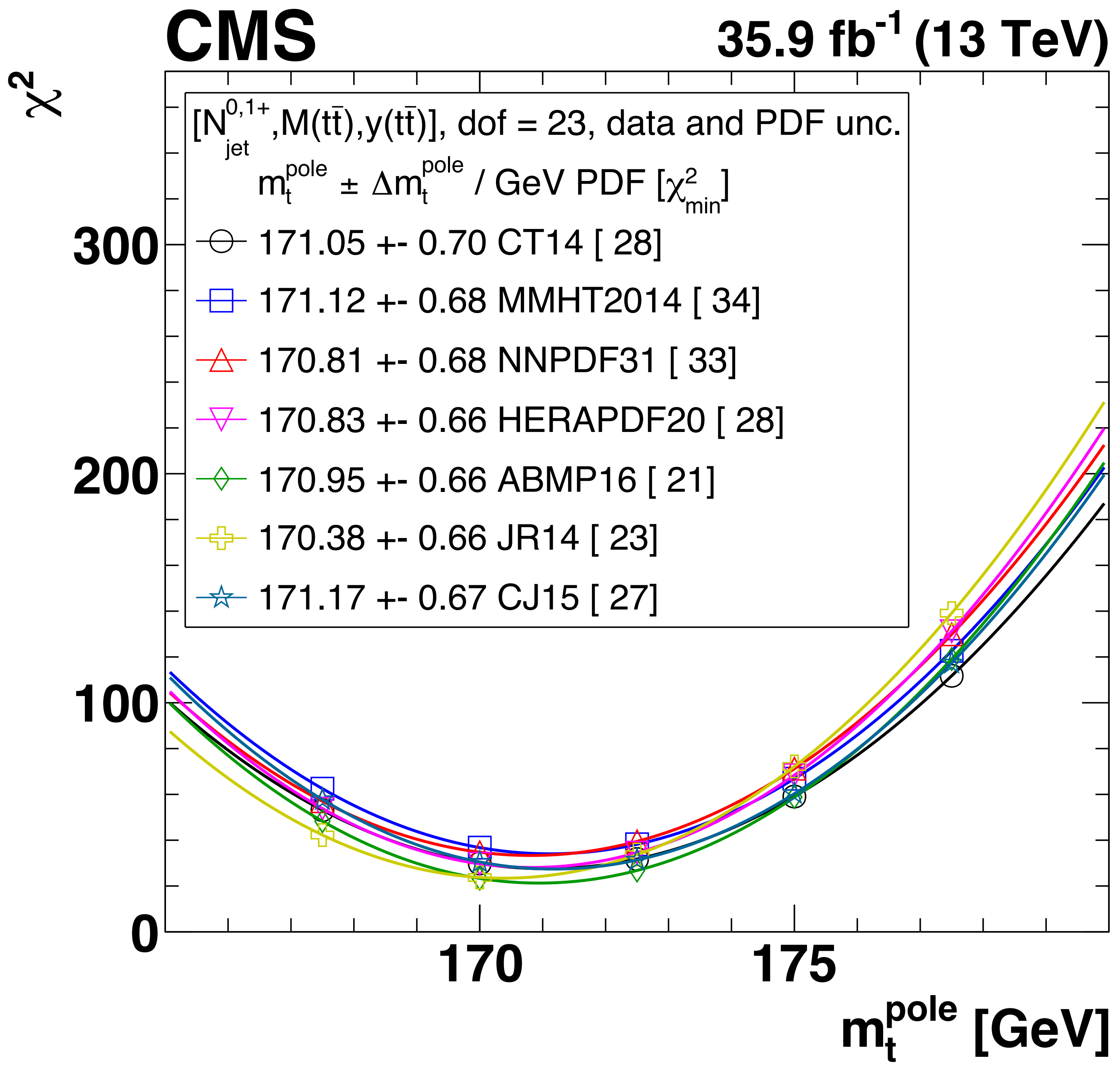


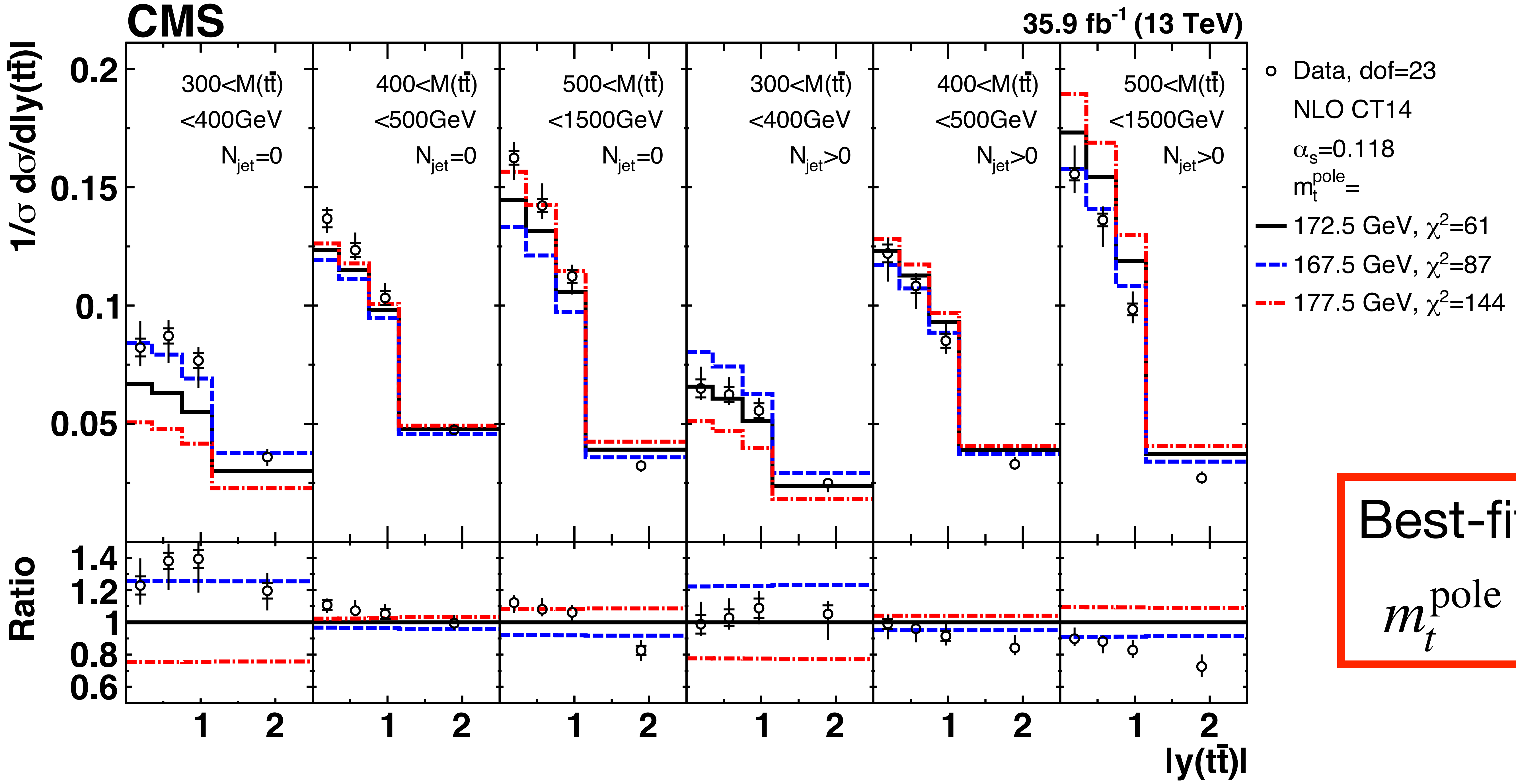


- Similar $t\bar{t}$ phase space selection

  More than 90% of events are $t\bar{t}$ signal events

- Differential cross sections are measured and compared to fixed-order predictions calculated for different values of the top-quark pole mass

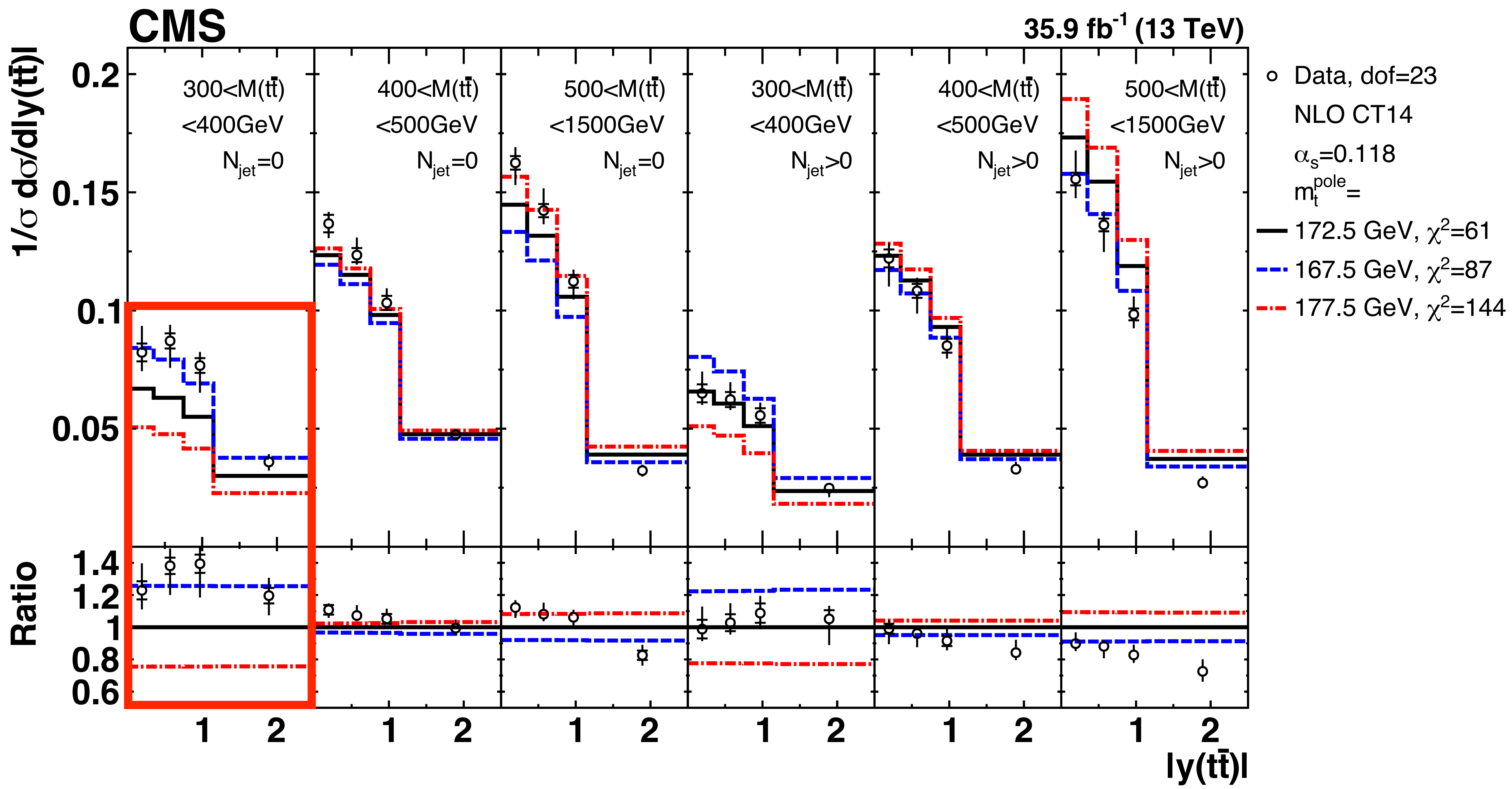




Best-fit:

$$m_t^{\rm pole} = 170.5 \pm 0.8 \text{ GeV}$$

Top Production at threshold



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

Top Production at threshold

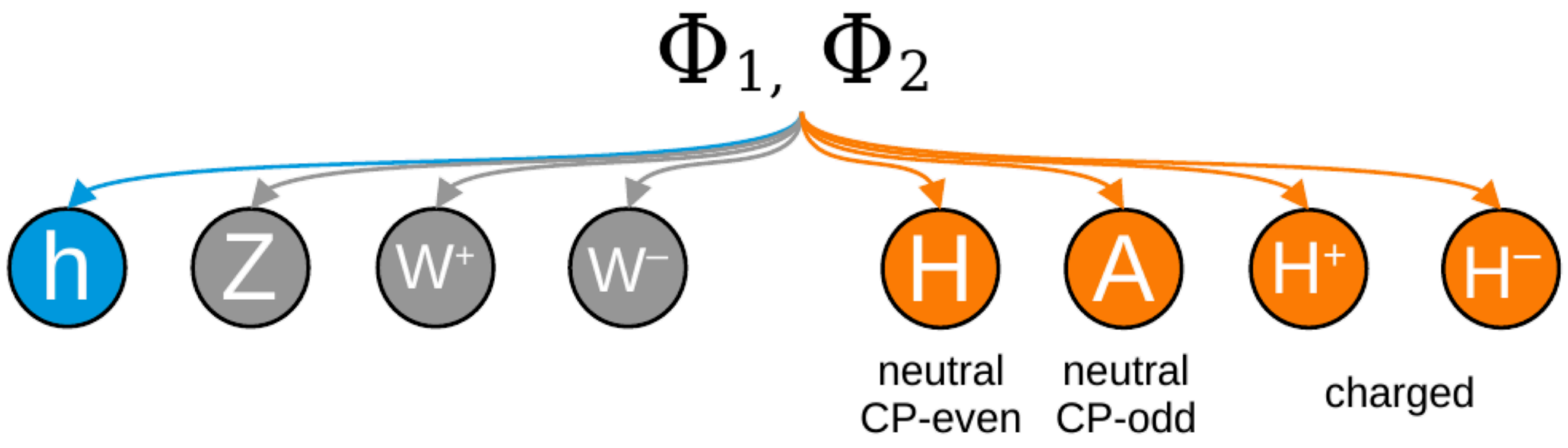
New unobserved SM phenomenon?

New physics?

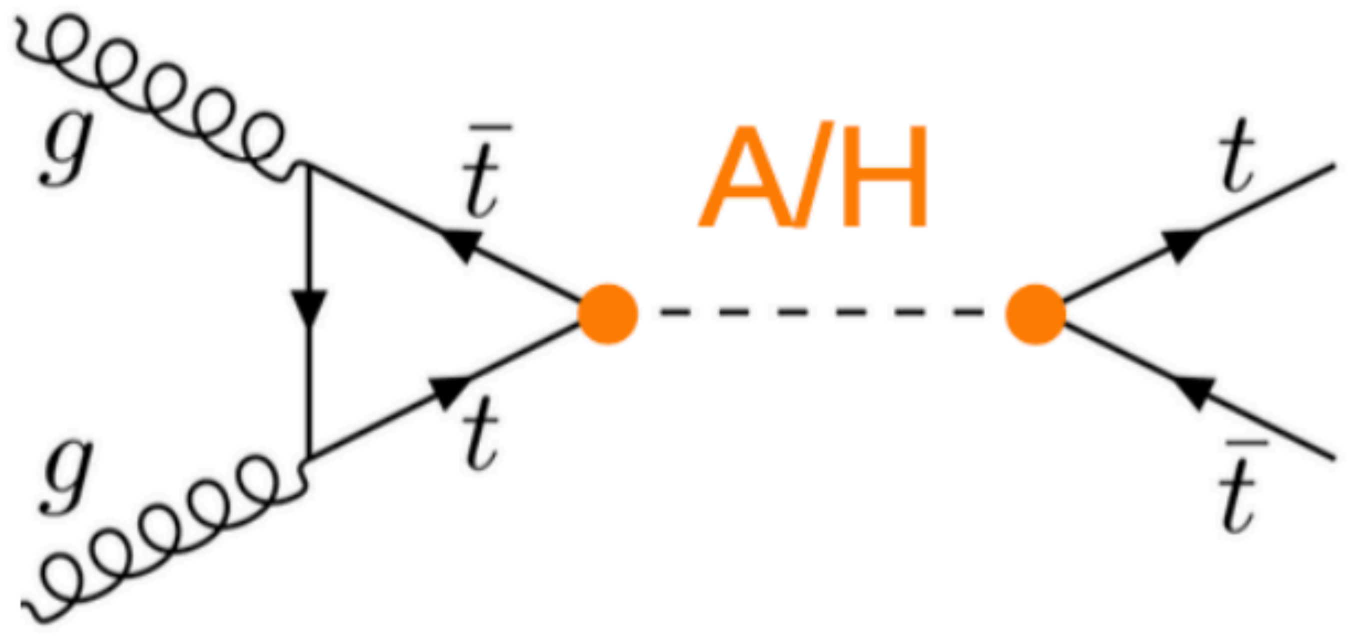
Top Production at threshold

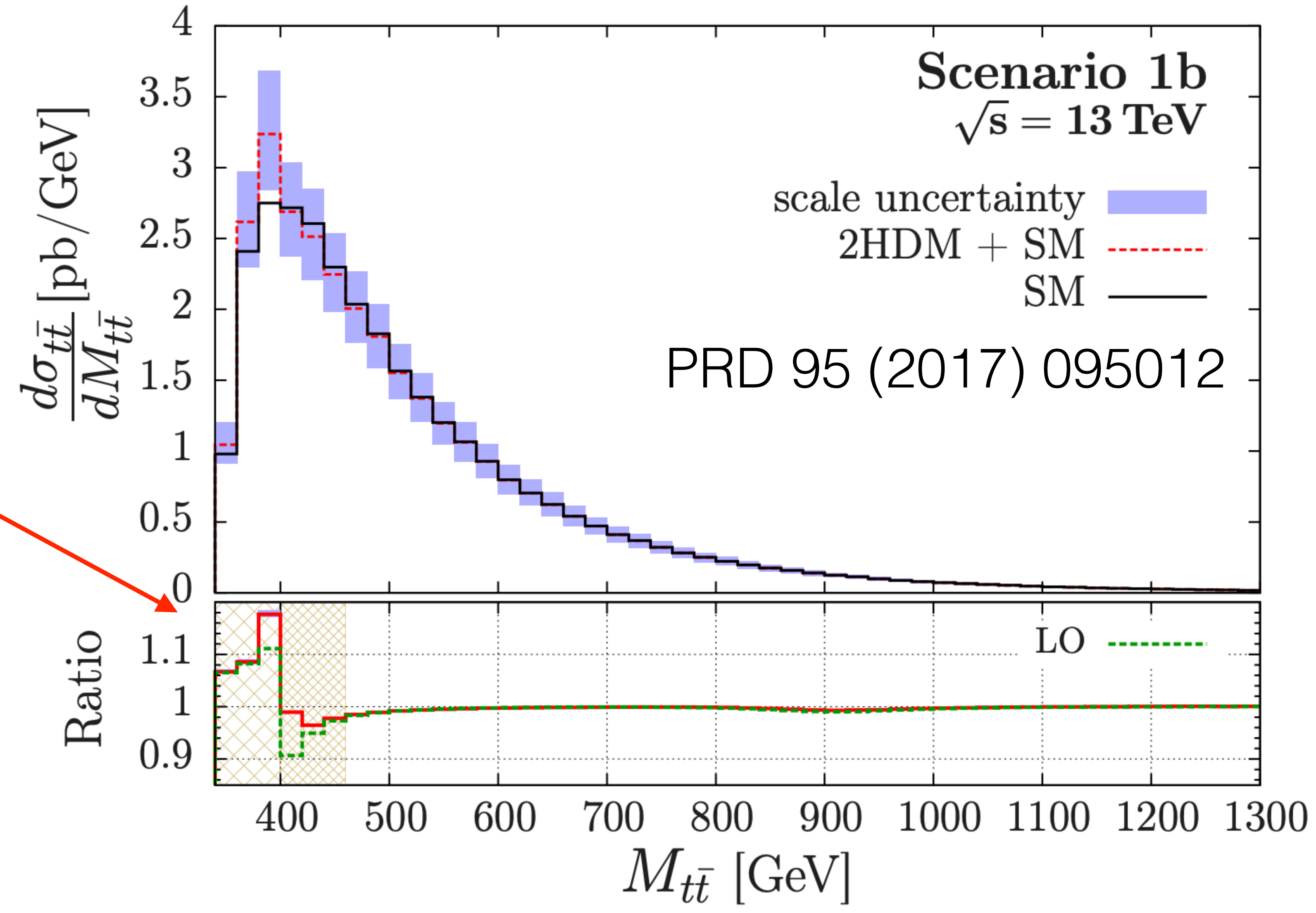
New physics?

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





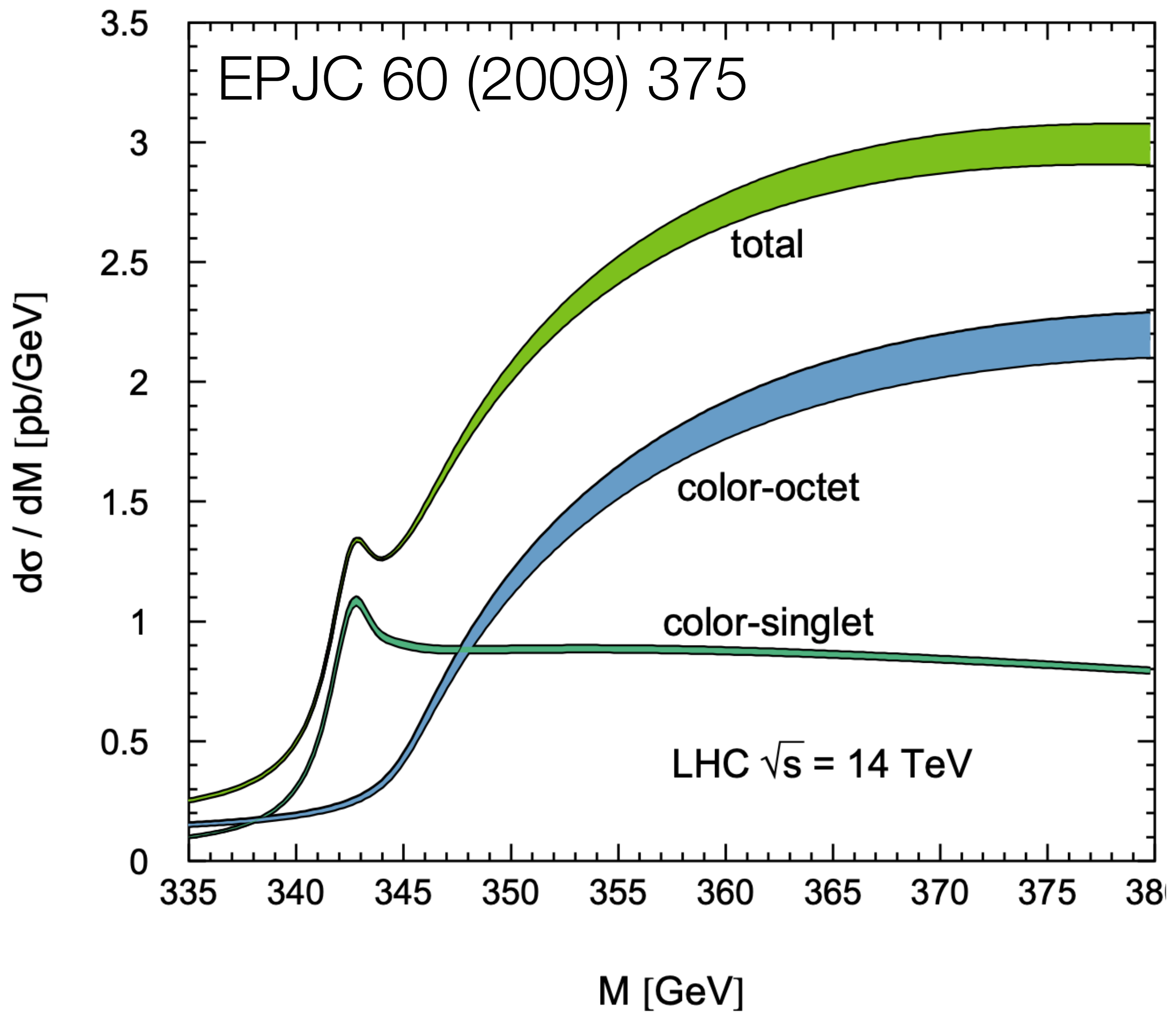
PRD 95 (2017) 095012

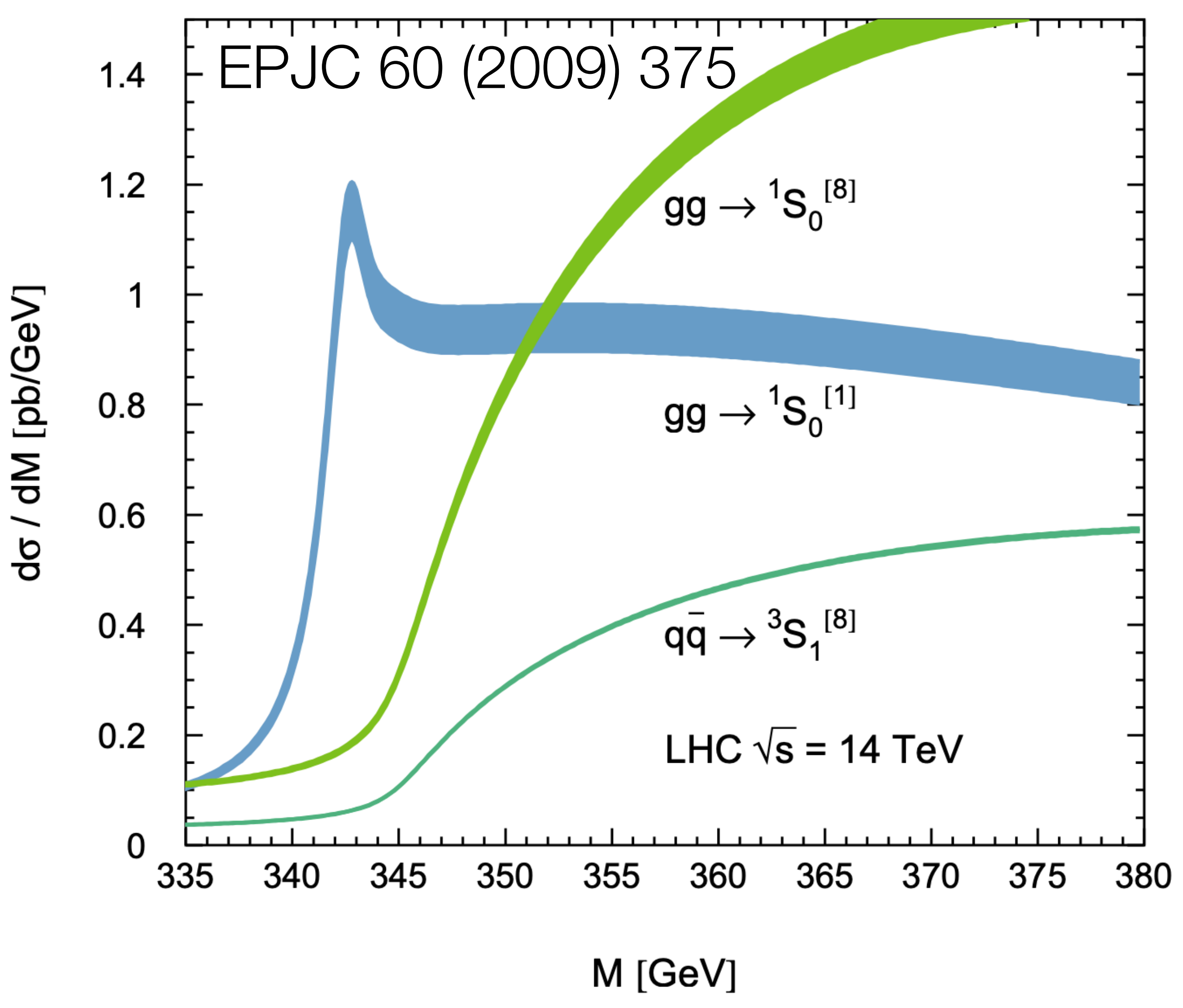
peak-dip structure

Top Production at threshold

New unobserved SM phenomenon?

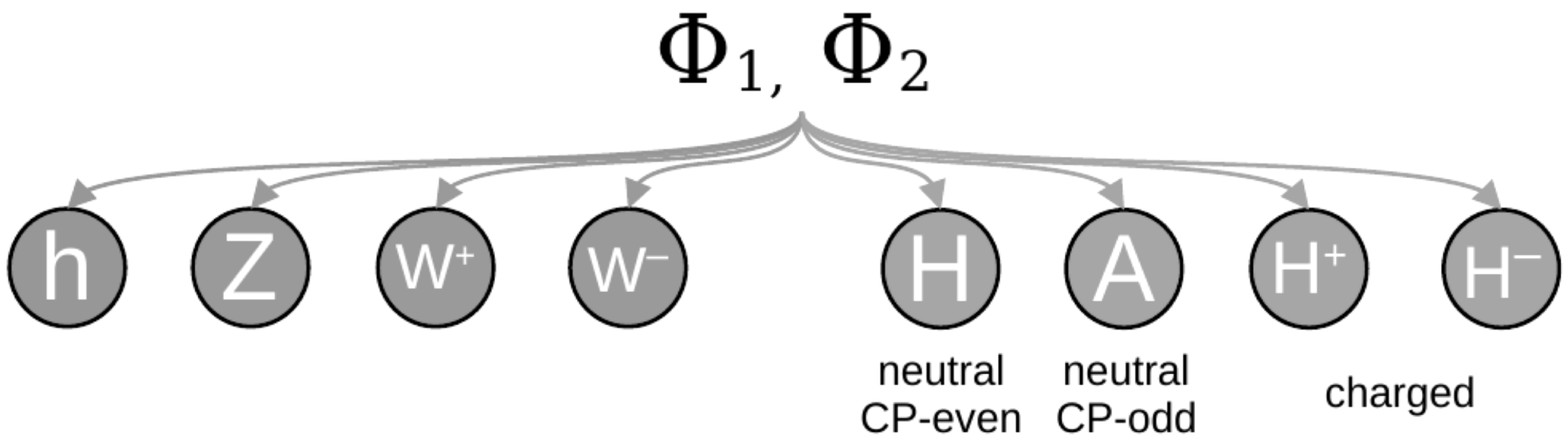
QCD predicts SM $t\bar{t}$ (quasi)bound states close to the $t\bar{t}$ threshold in **non-relativistic (NR) QCD** calculations (the prediction was made even before the top quark discovery)





New physics?

Two Higgs Doublet Model (2HDM)



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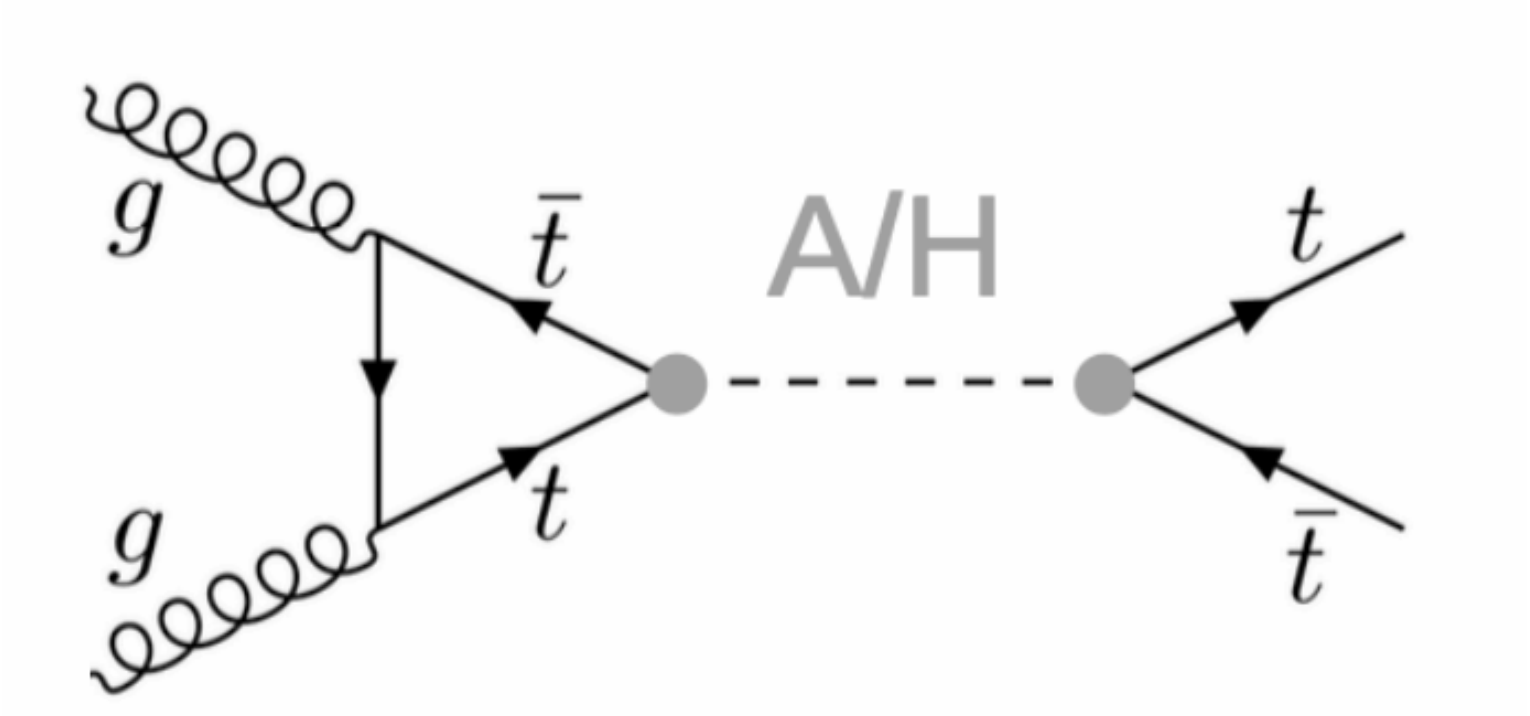

Top Production at threshold

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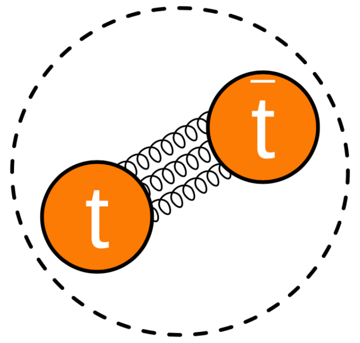
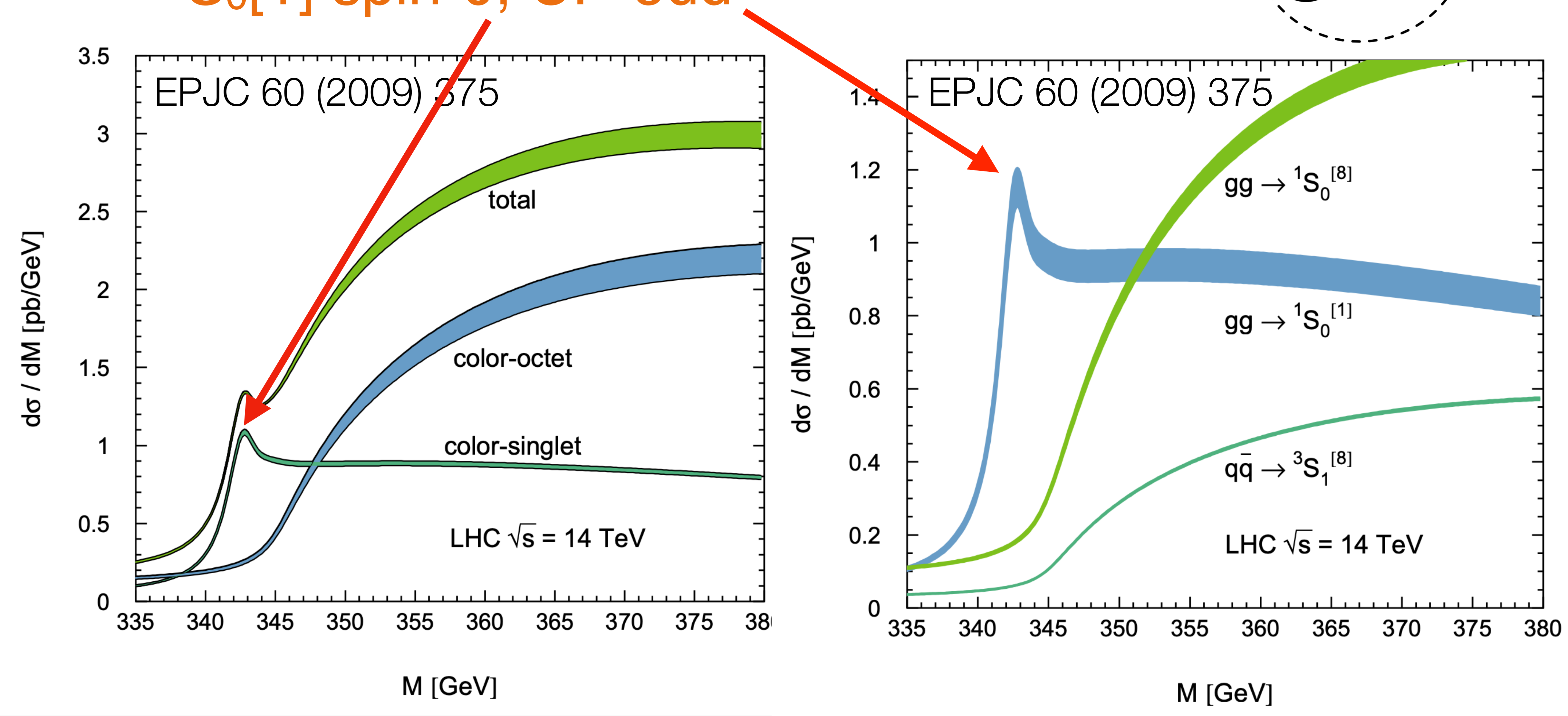
- pseudoscalar color-singlet toponium η_t: $^1S_0[1]$ spin-0, CP-odd





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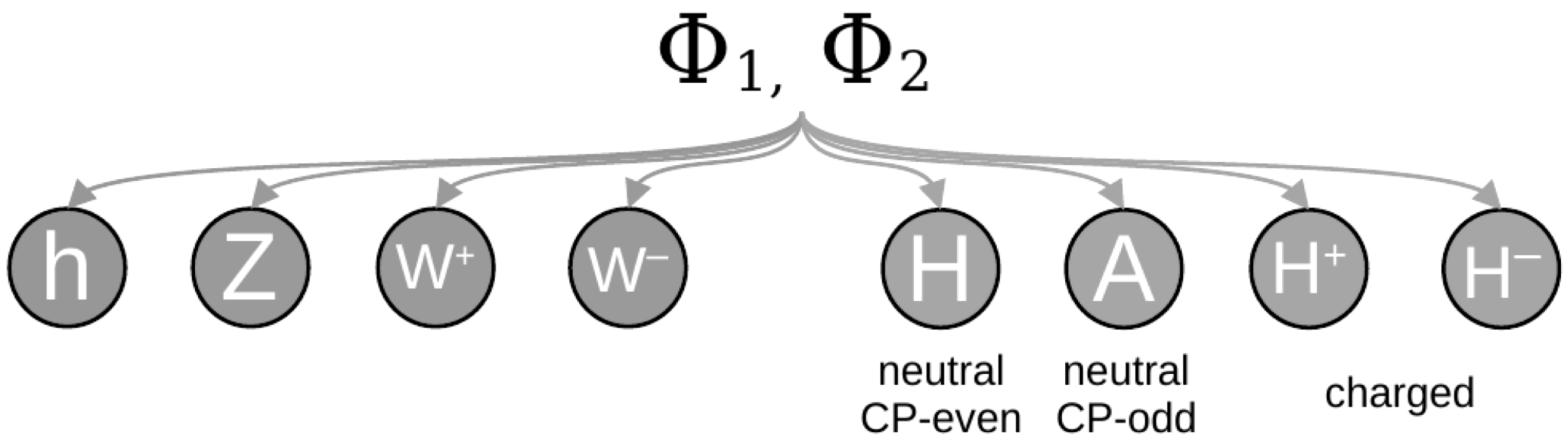

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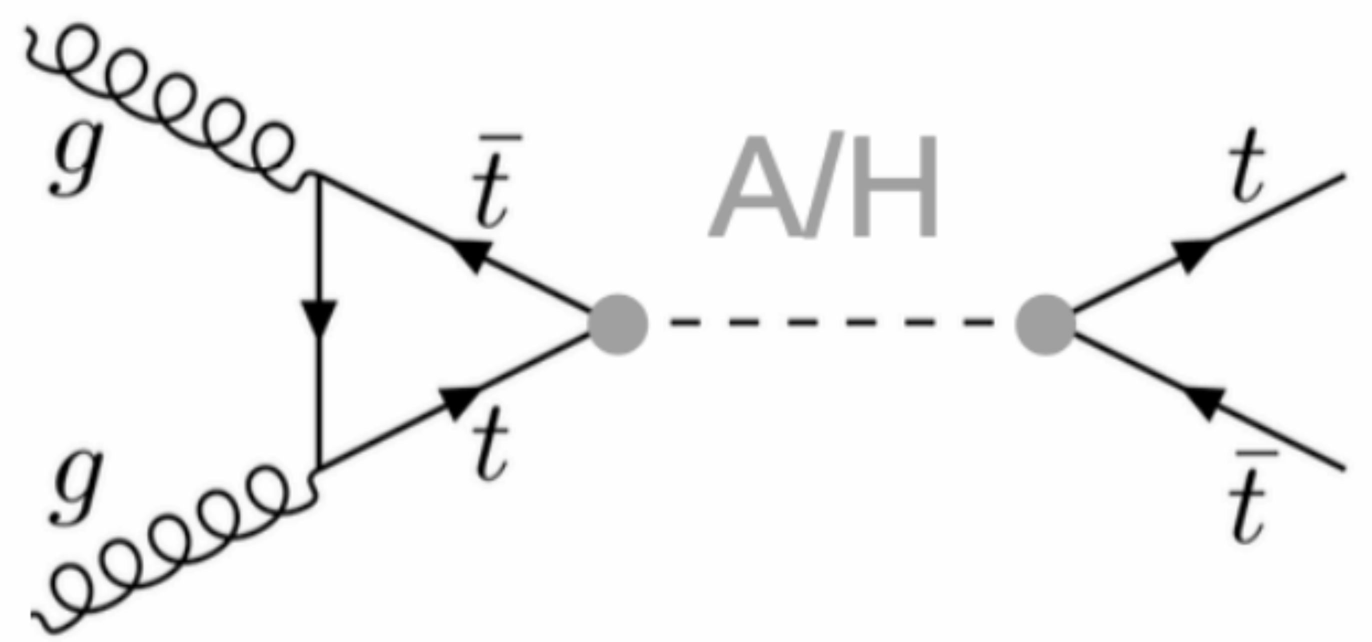

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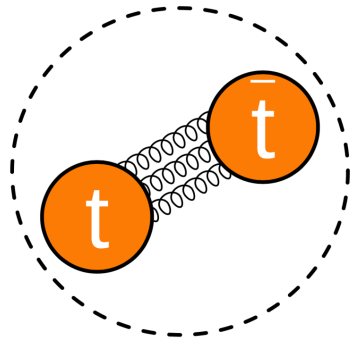
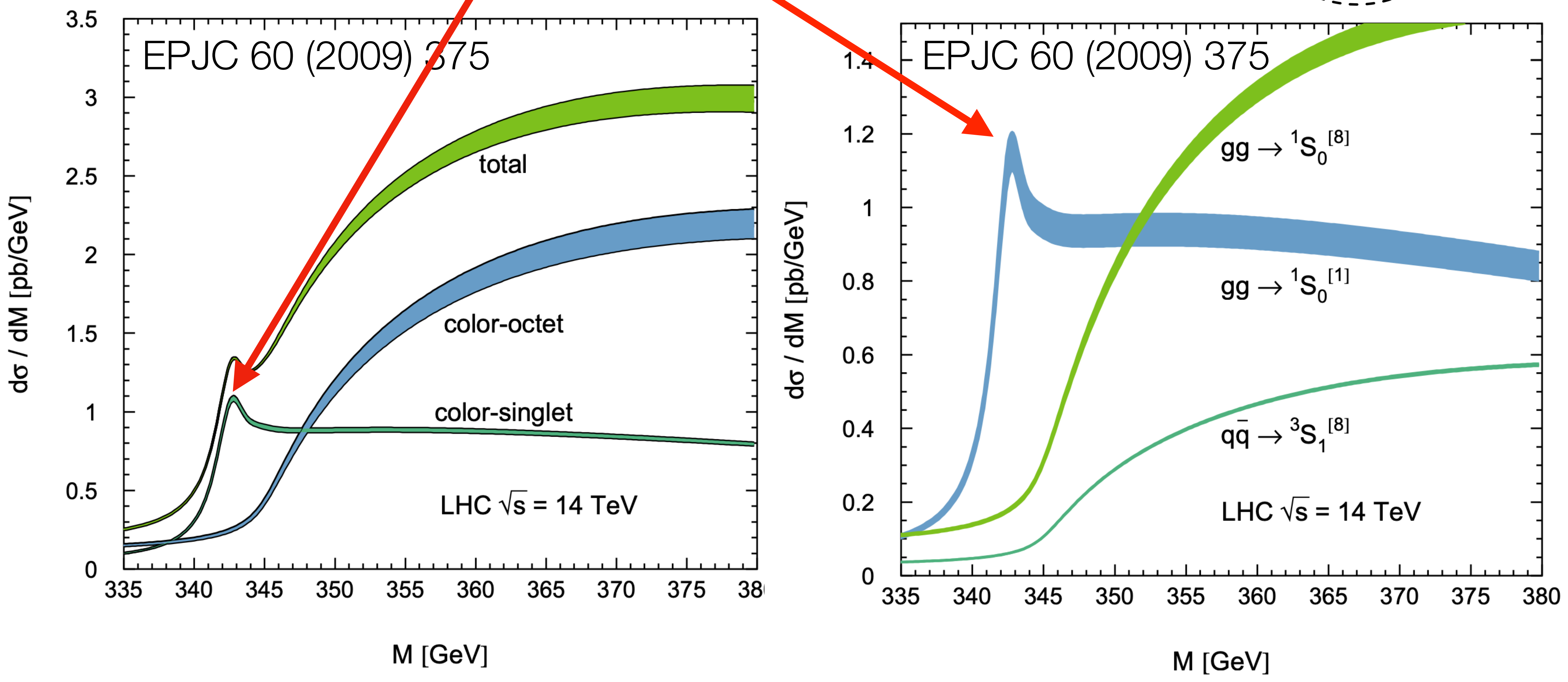




Approximating $t\bar{t}$ bound states:

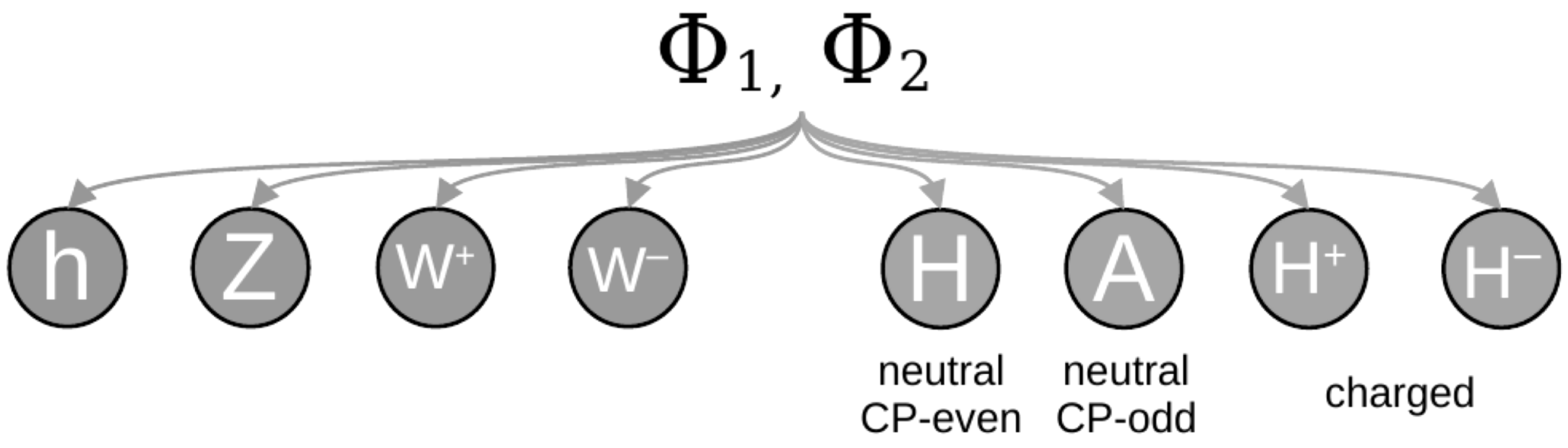
- *simplified model JHEP 03 (2024) 099*
- *generic particle with direct couplings to gluons and tops, mass and width from fit to NRQCD*

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

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

New physics?

Two Higgs Doublet Model (2HDM)



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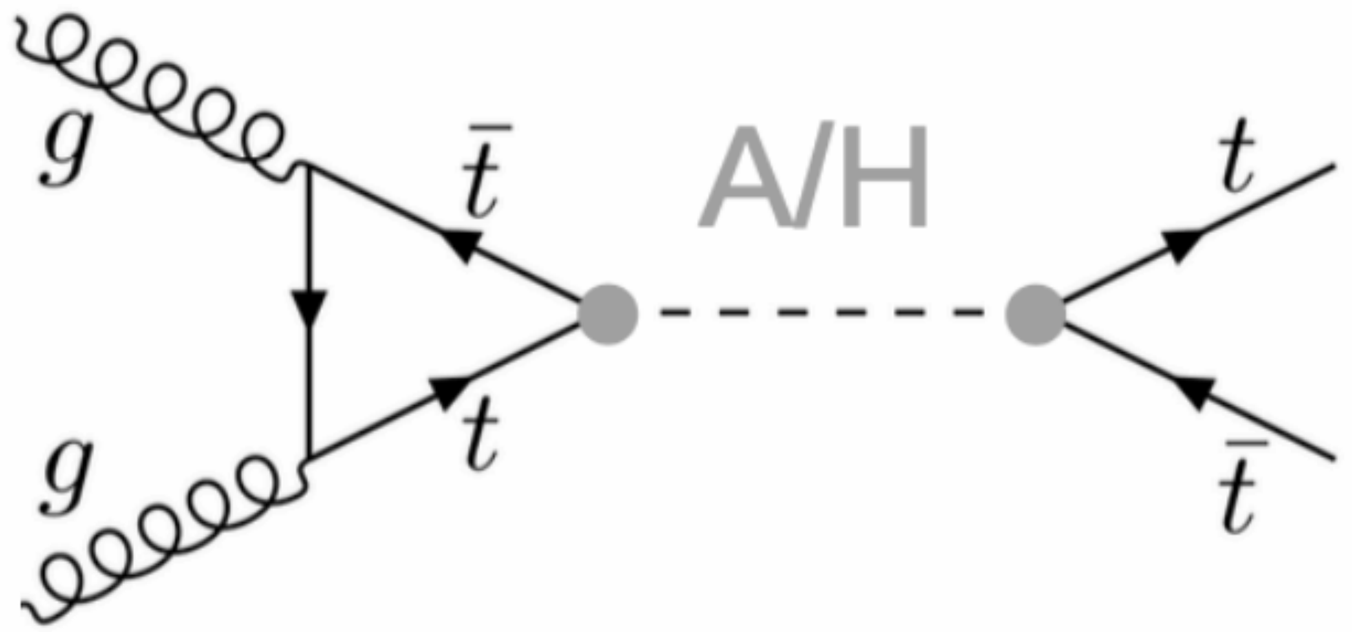
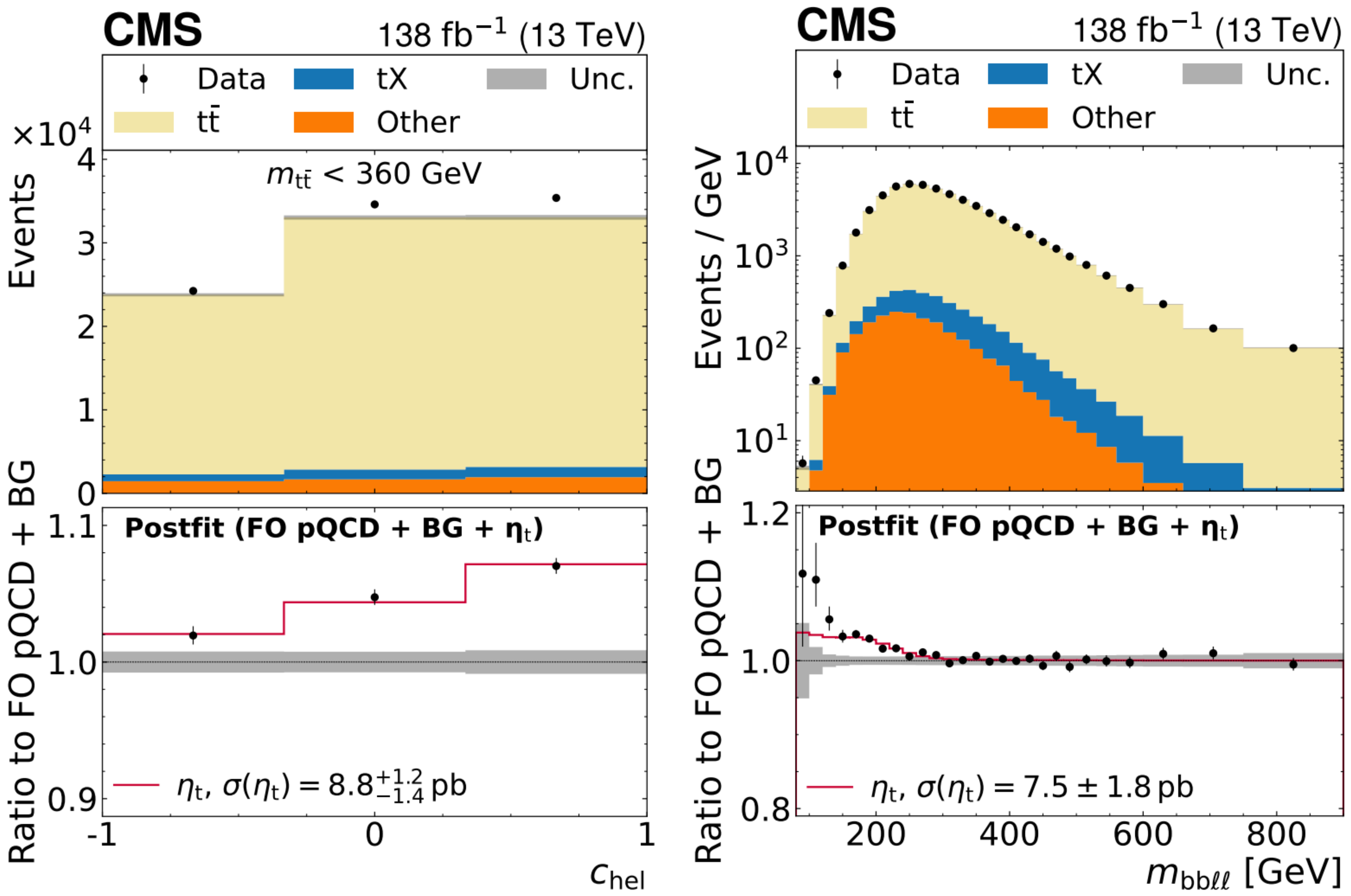


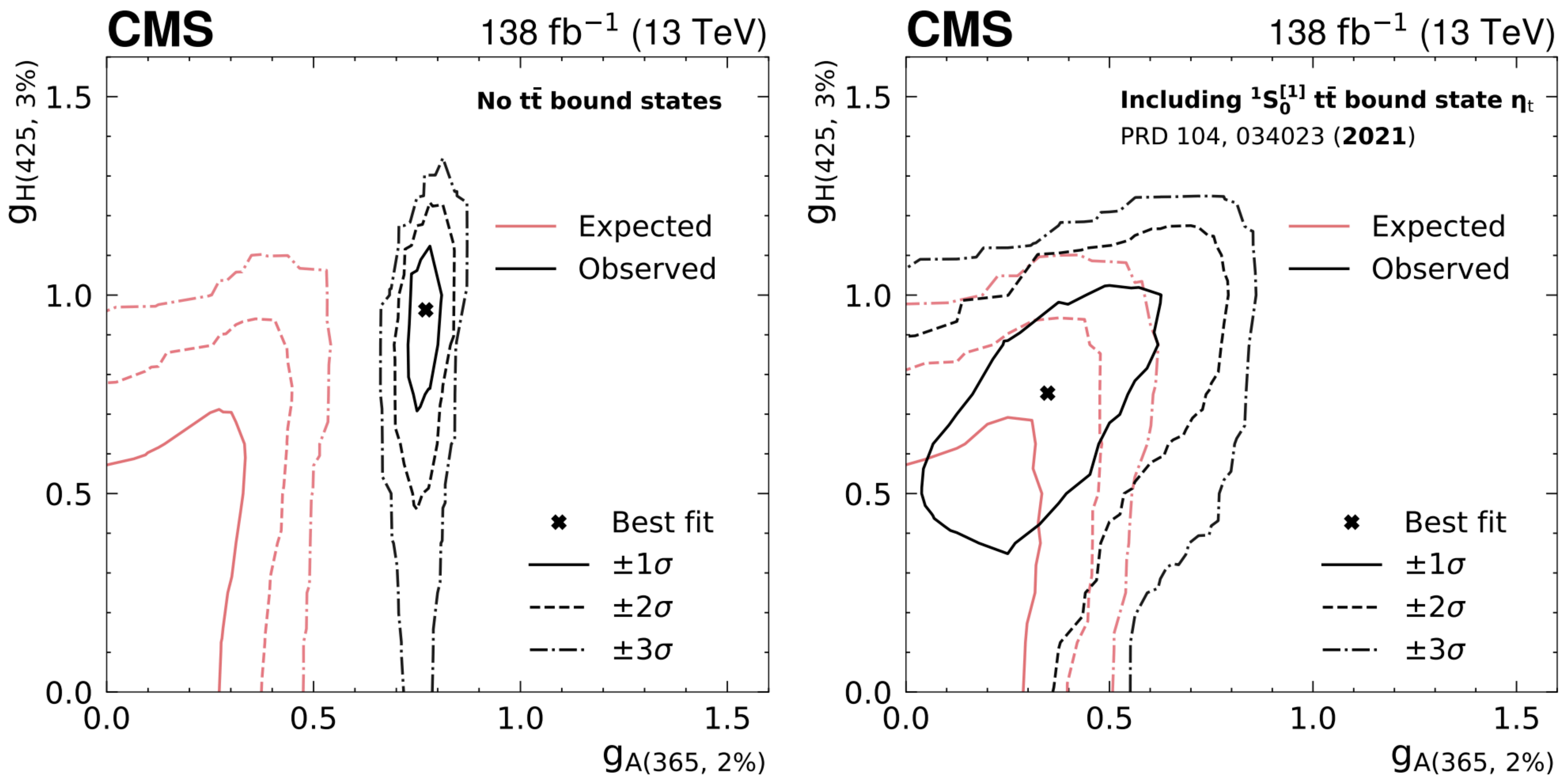
Top Production at threshold

New unobserved SM phenomenon



- An excess is observed (>5σ) 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

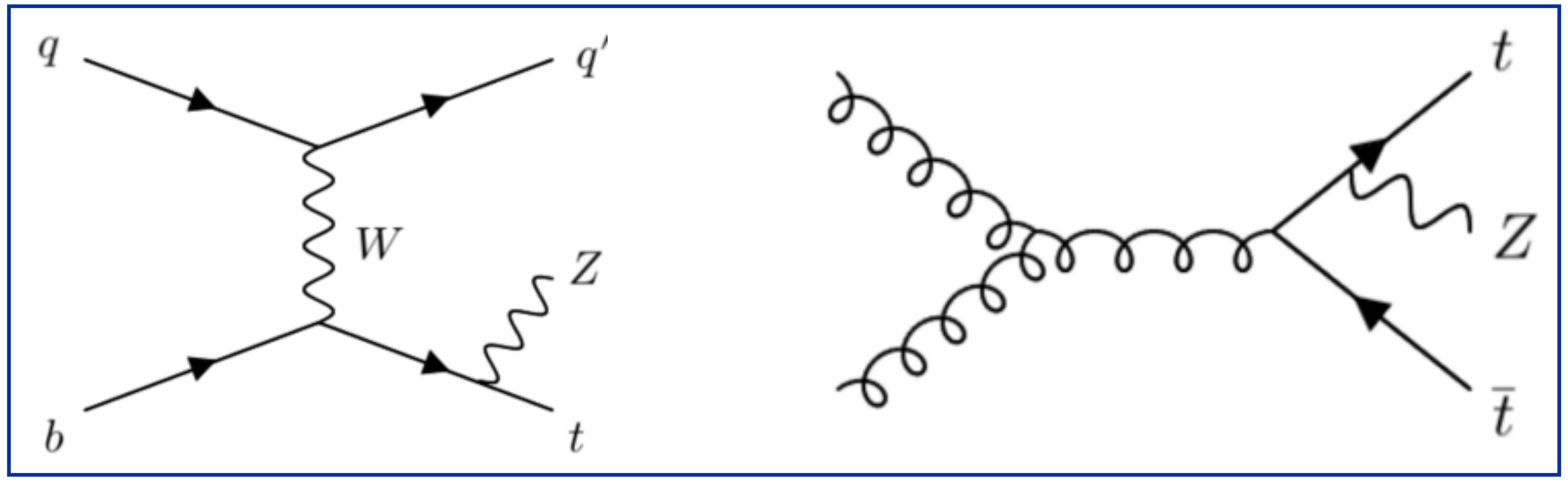
New physics?

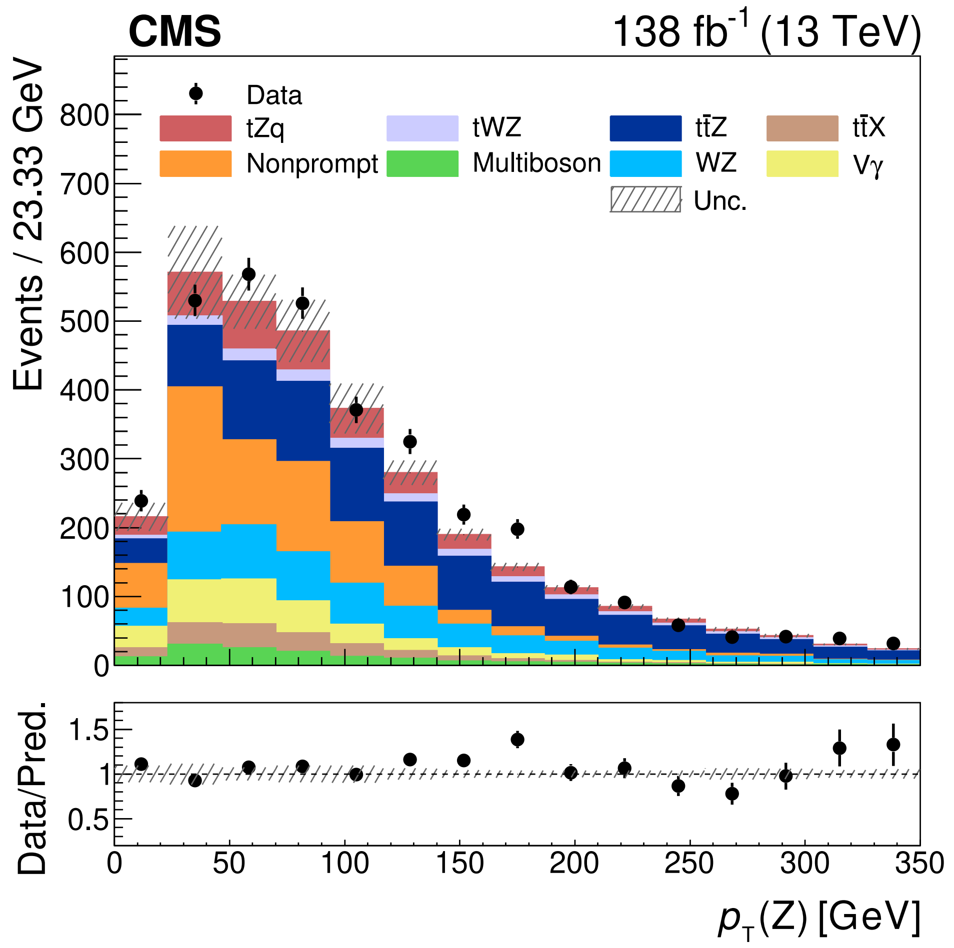


- Incorporating quasi-bound state η_t, eliminating the need for additional exotic pseudoscalar or scalar boson
- Exclusion limits at the 95% CL are set on the coupling strength between top quarks and new bosons, covering mass ranges of 365–1000 GeV
  - Coupling values as low as 0.4 (0.6) are excluded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

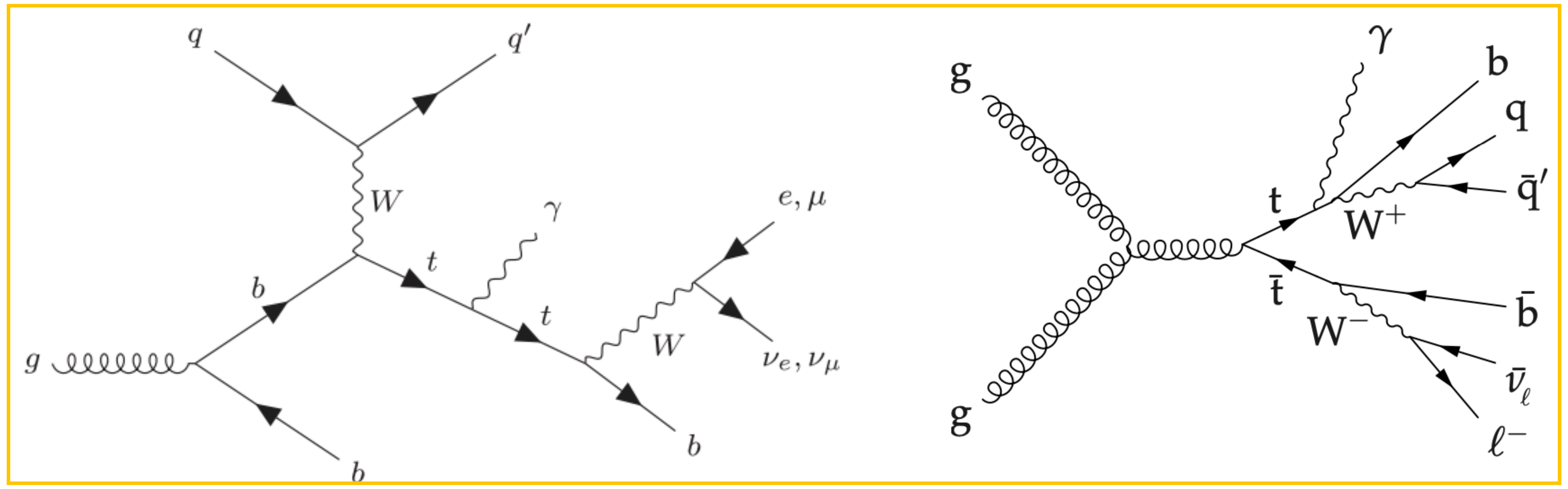
Top couplings — with bosons

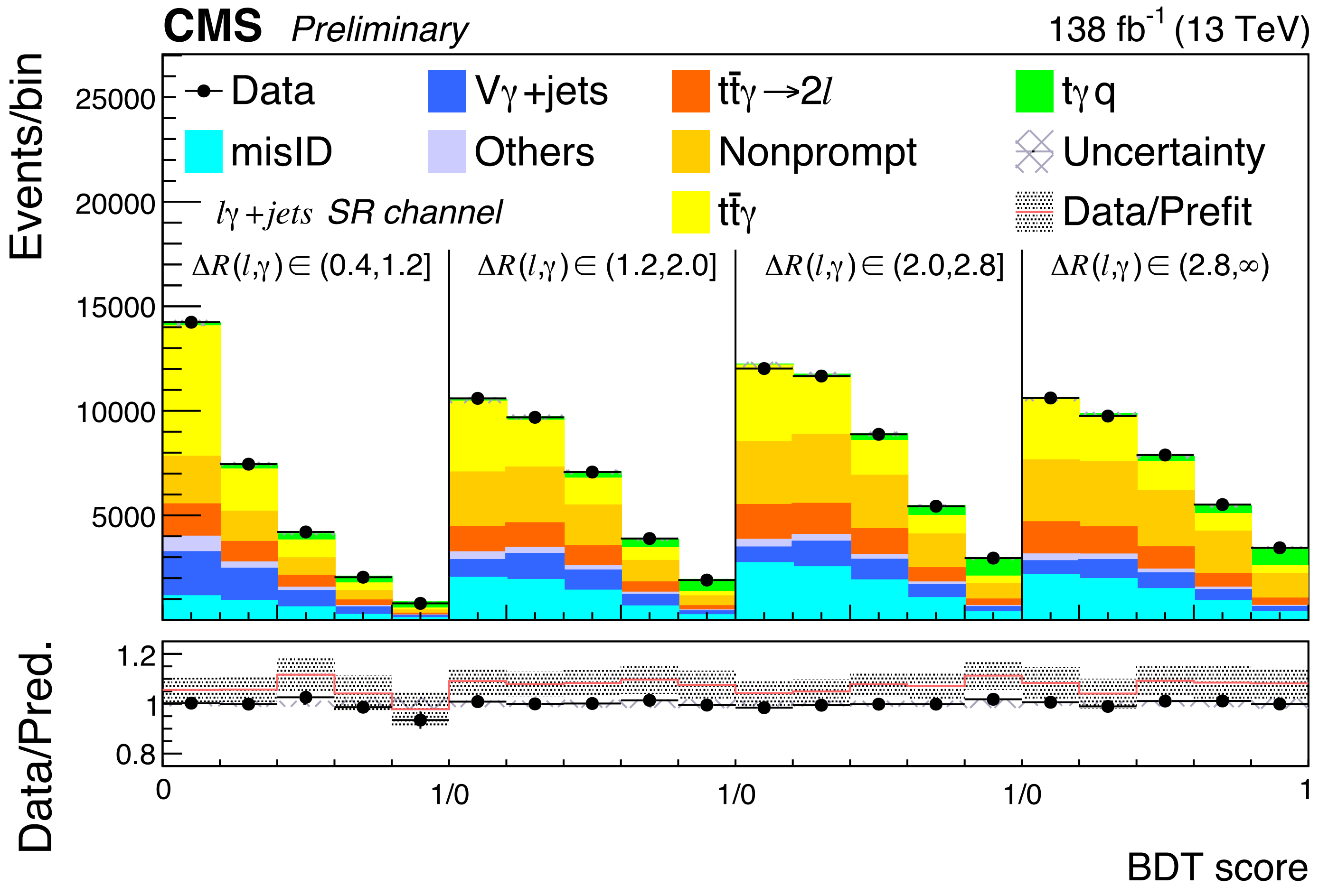
t-Z coupling in tZq and $t\bar{t}Z$



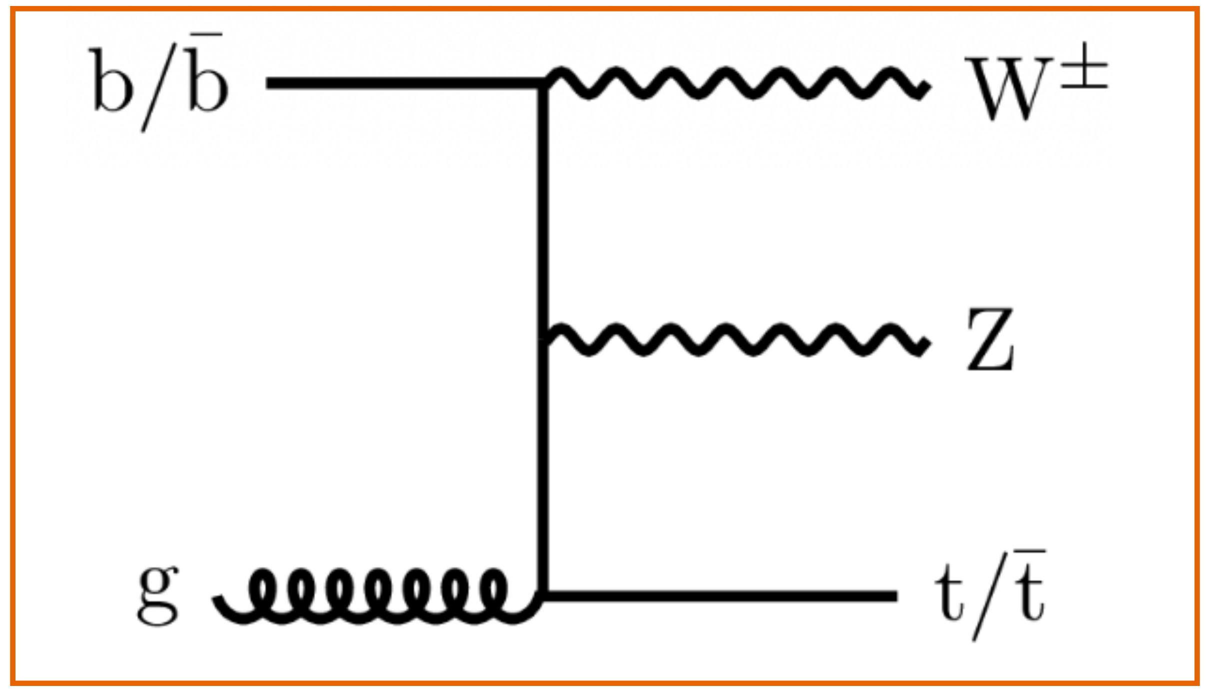


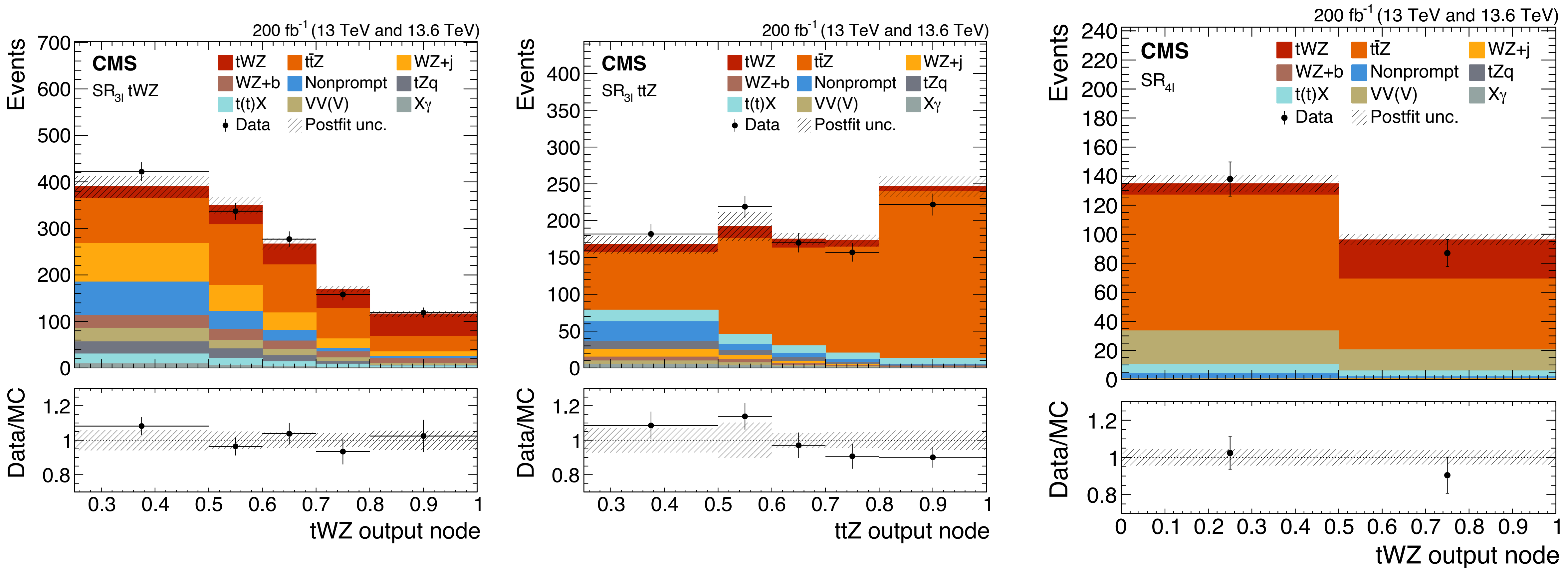
t-γ coupling in tγq and $t\bar{t}\gamma$



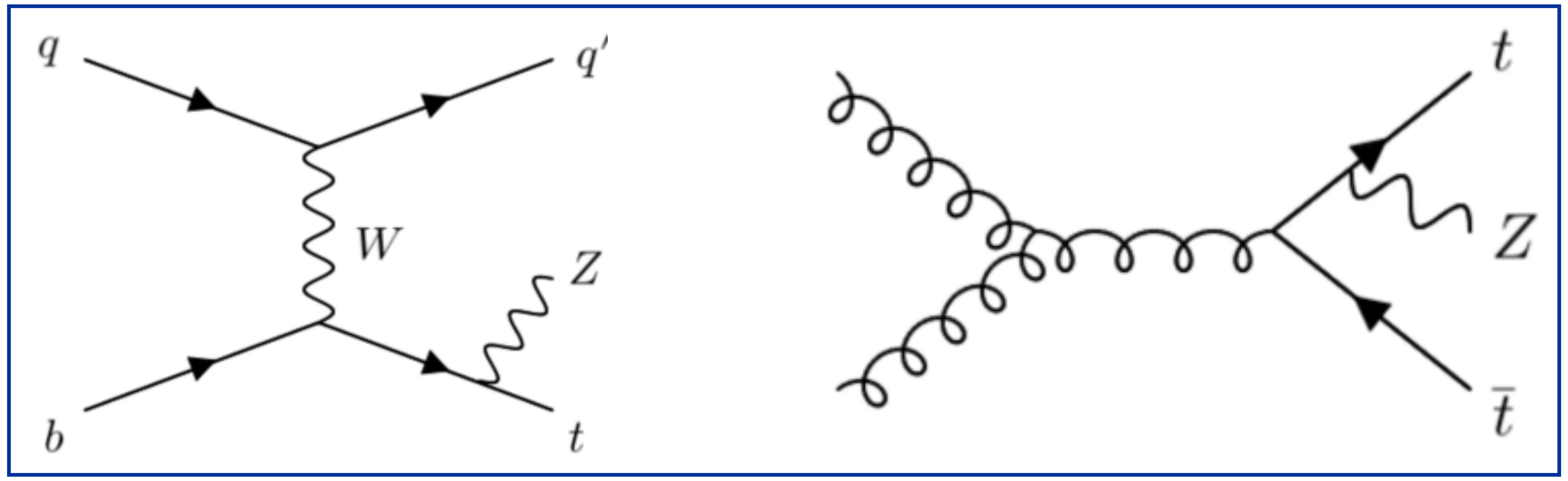


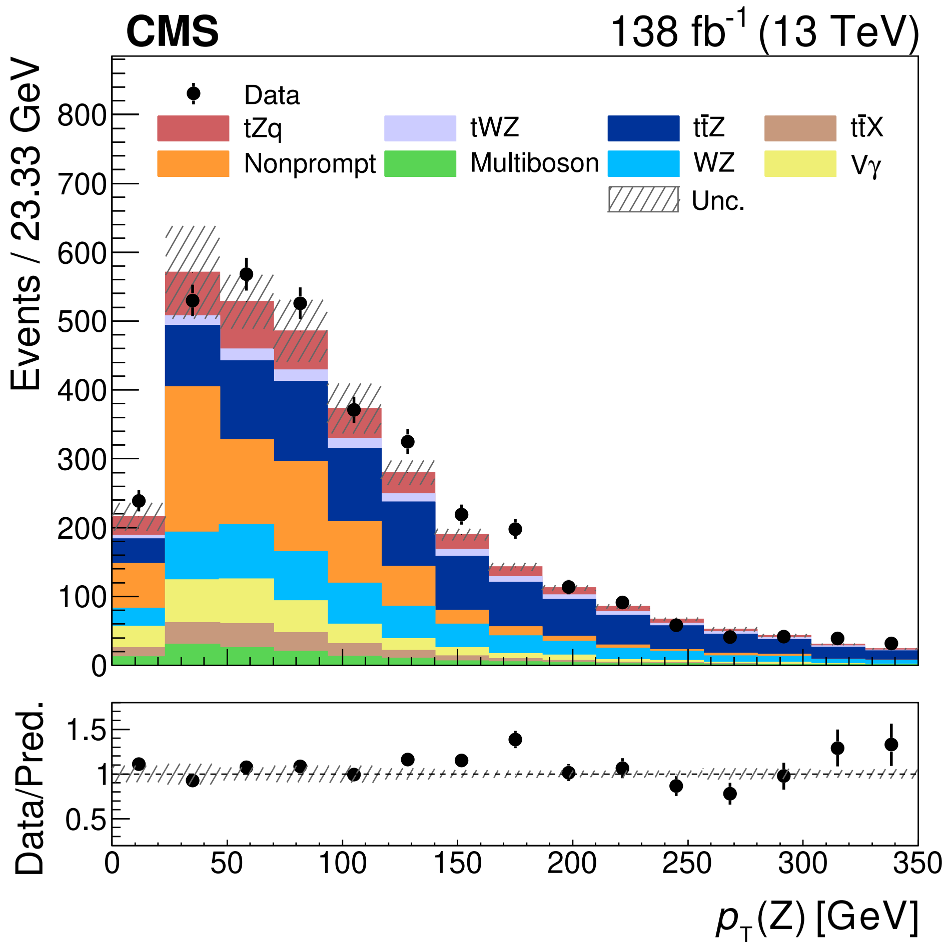
Rare process tWZ





Top couplings — with bosons

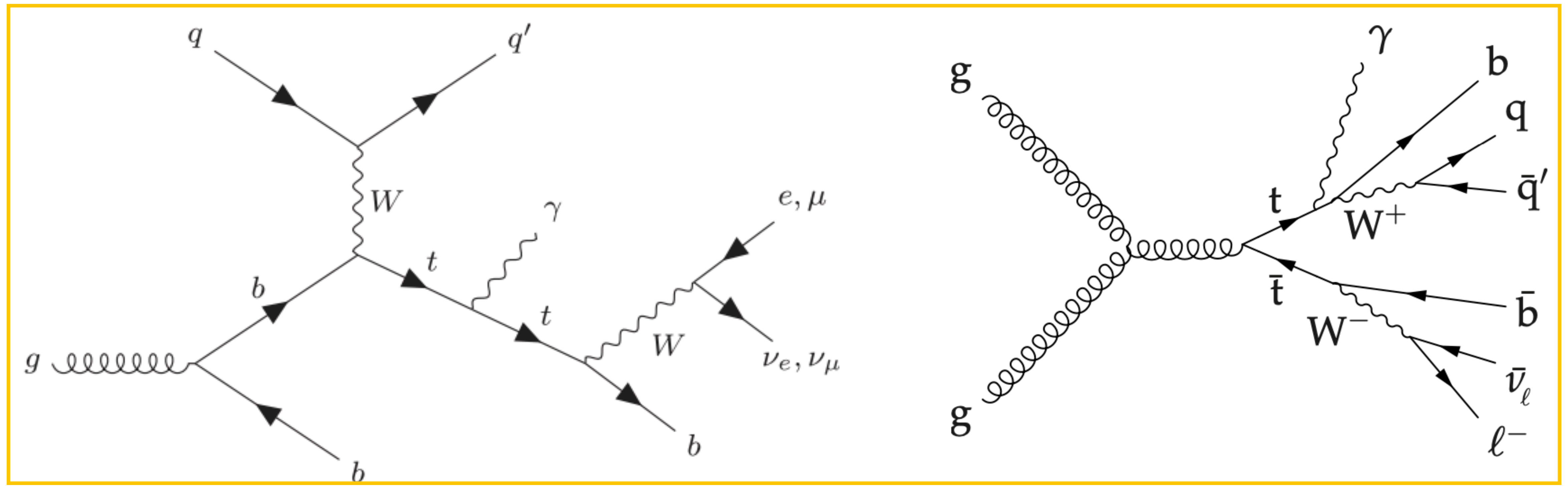




t-Z coupling in tZq and tt̄Z

Backgrounds are:

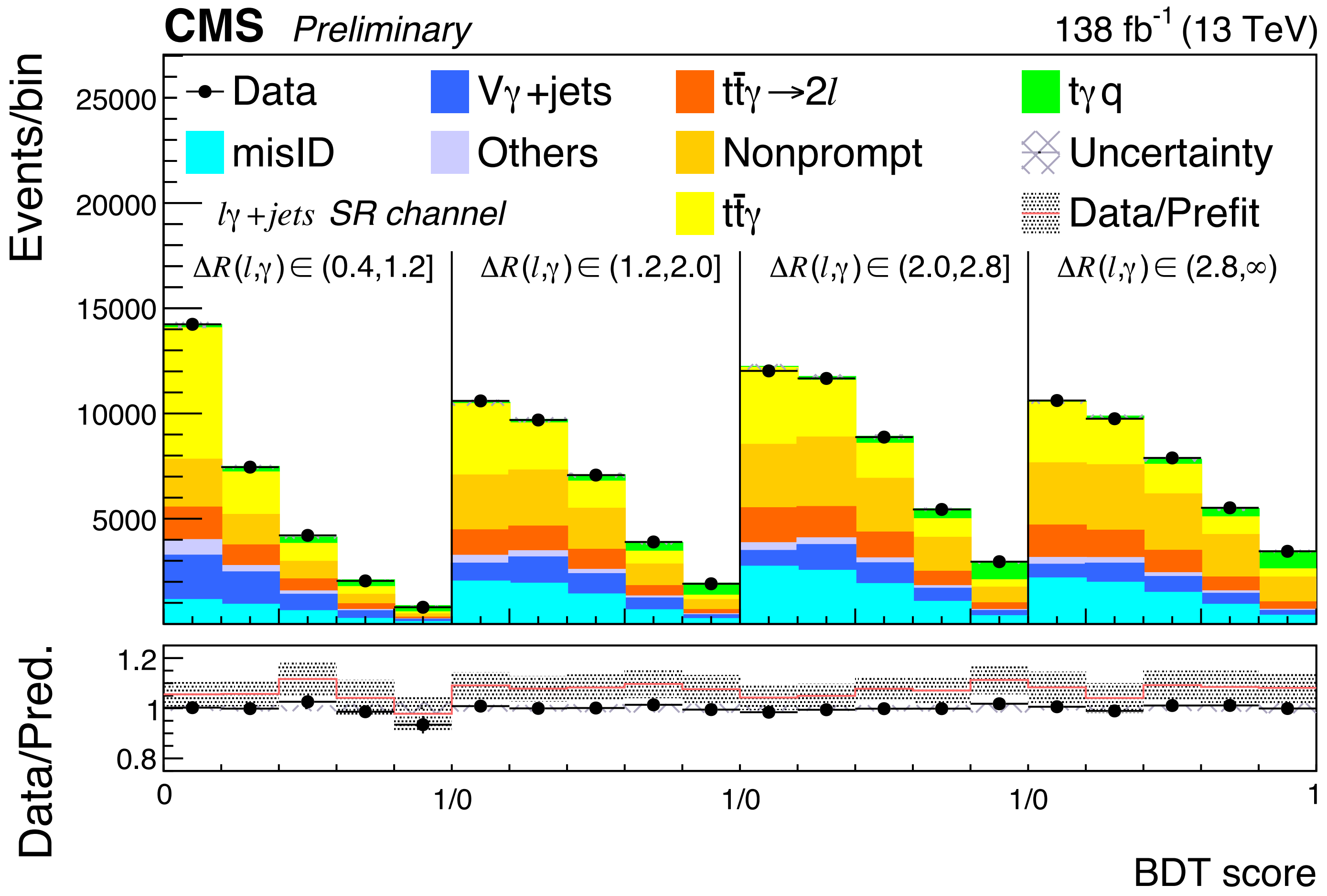
- Nonprompt ℓ (jet → ℓ)
- tWZ, WZ
- tt̄W, multiboson, Vγ

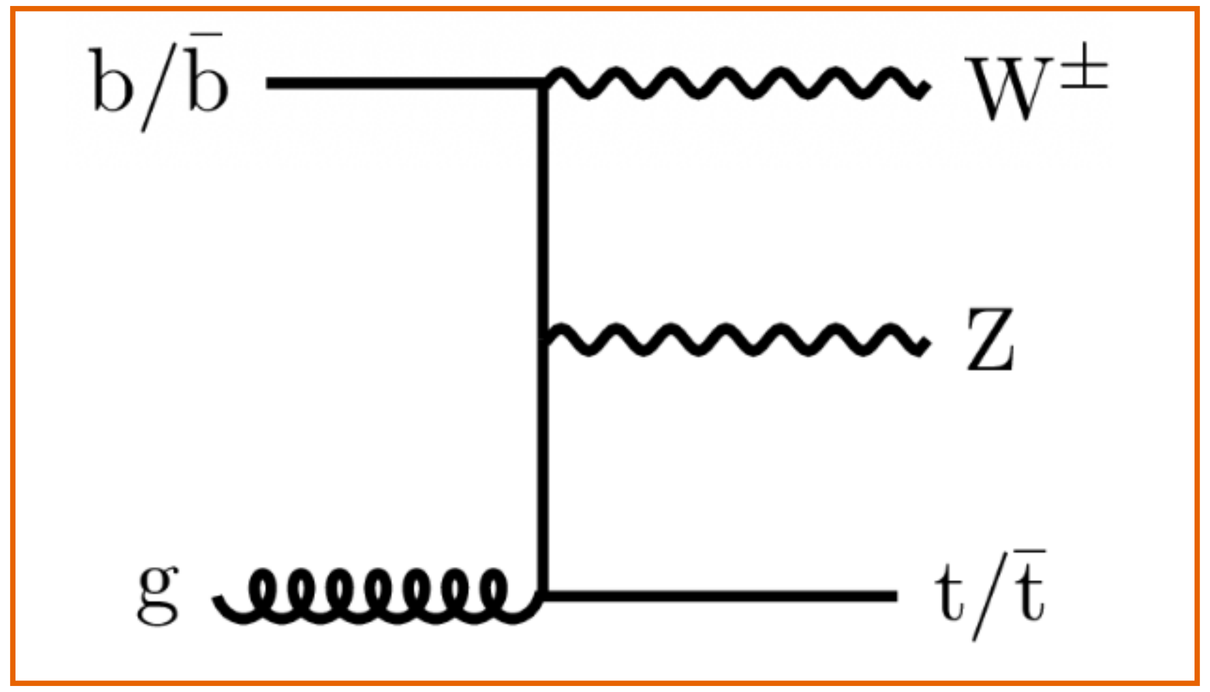


t-γ coupling in tγq and tt̄γ

Backgrounds are:

- Nonprompt ℓ/γ (jet → ℓ/γ)
- Double nonprompt
- tWγ, Wγ
- Zγ, Z+jets

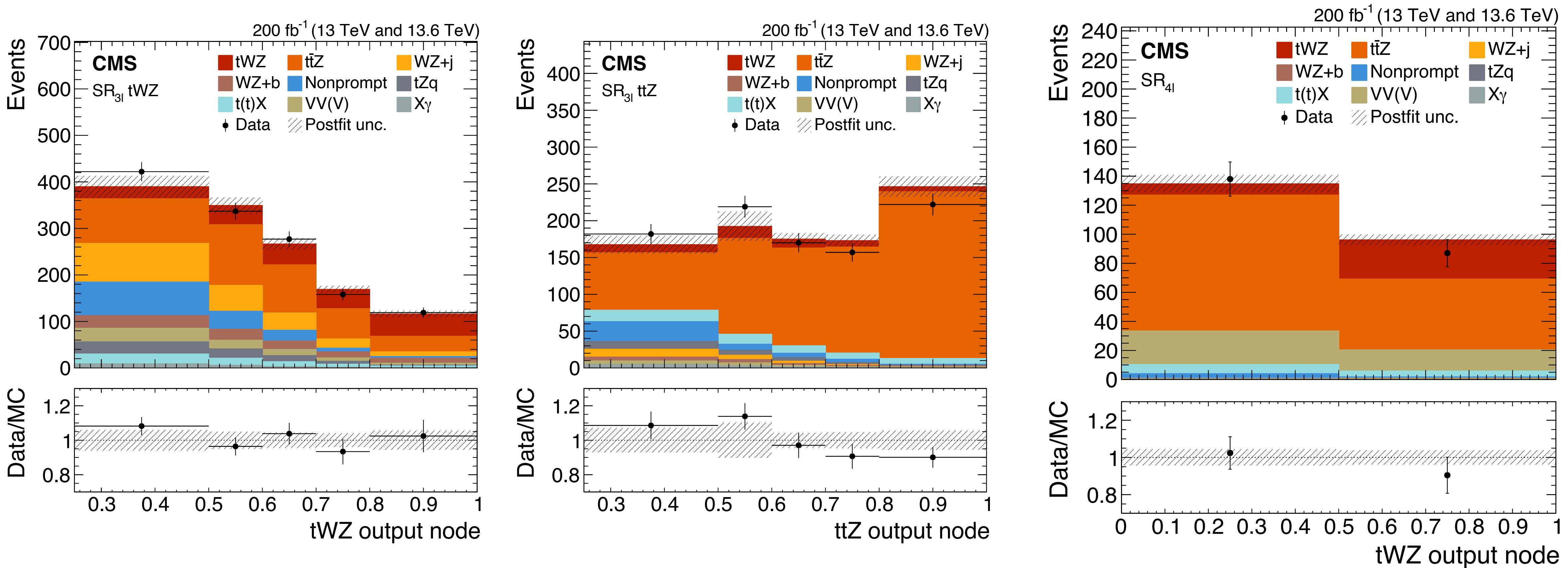




Rare process tWZ

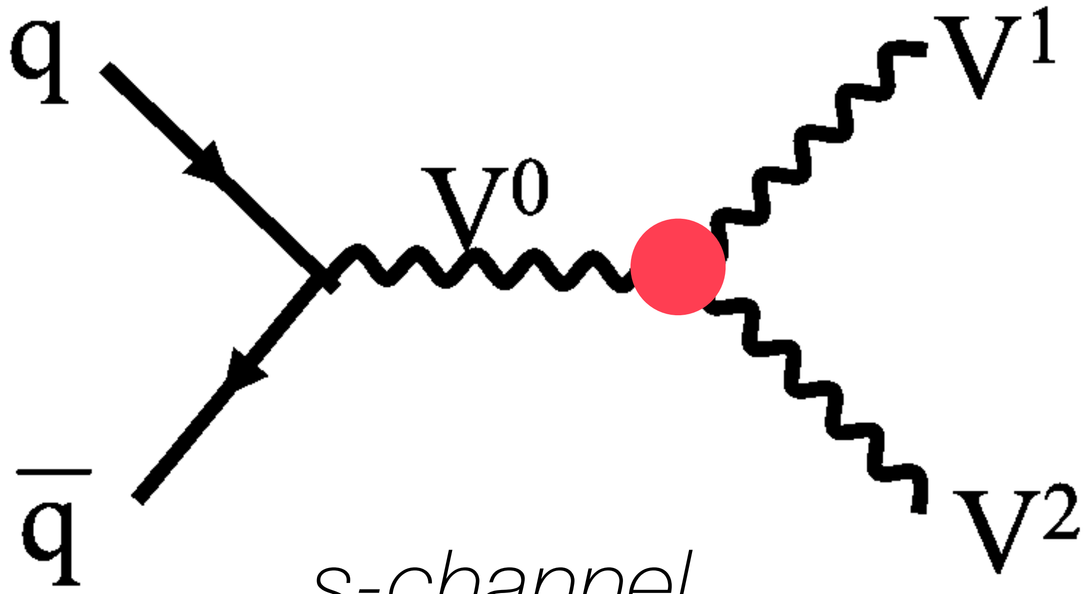
Backgrounds are:

- Nonprompt ℓ (jet → ℓ)
- tt̄Z, tZq
- WZ, VV(V)
- Xγ, t(t̄)X

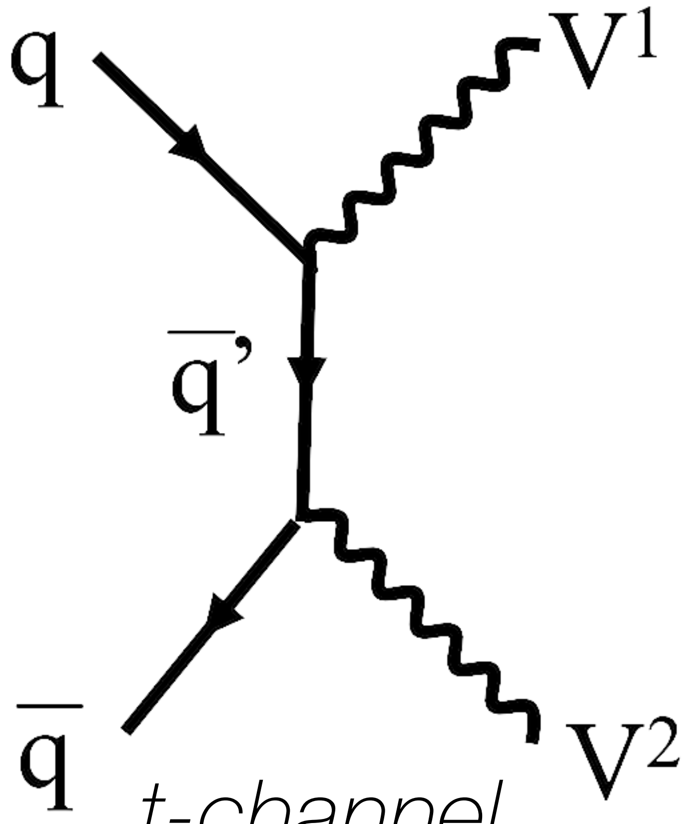


Diboson production — Motivation

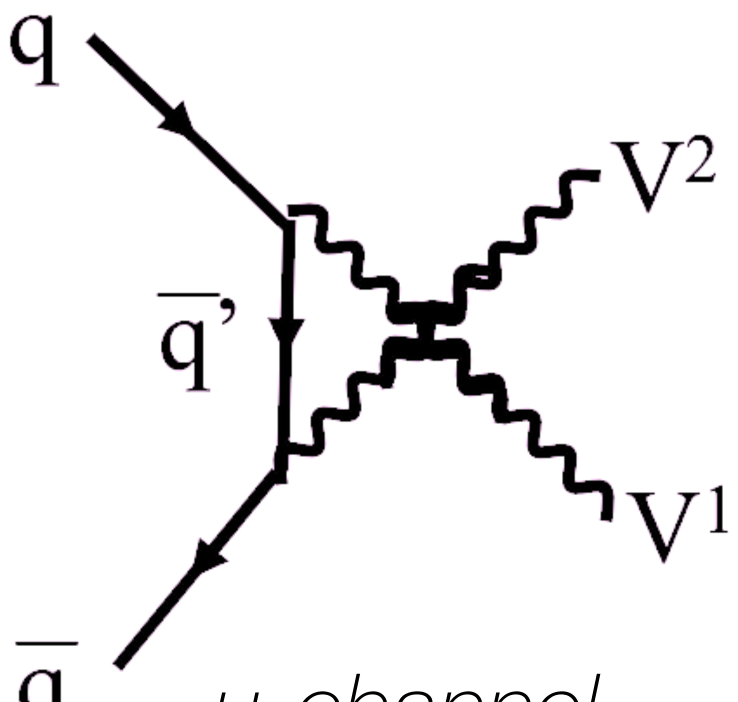
Manifestation of gauge boson couplings at the LHC: production of final states with boson pairs (W,Z,γ)



s-channel



t-channel



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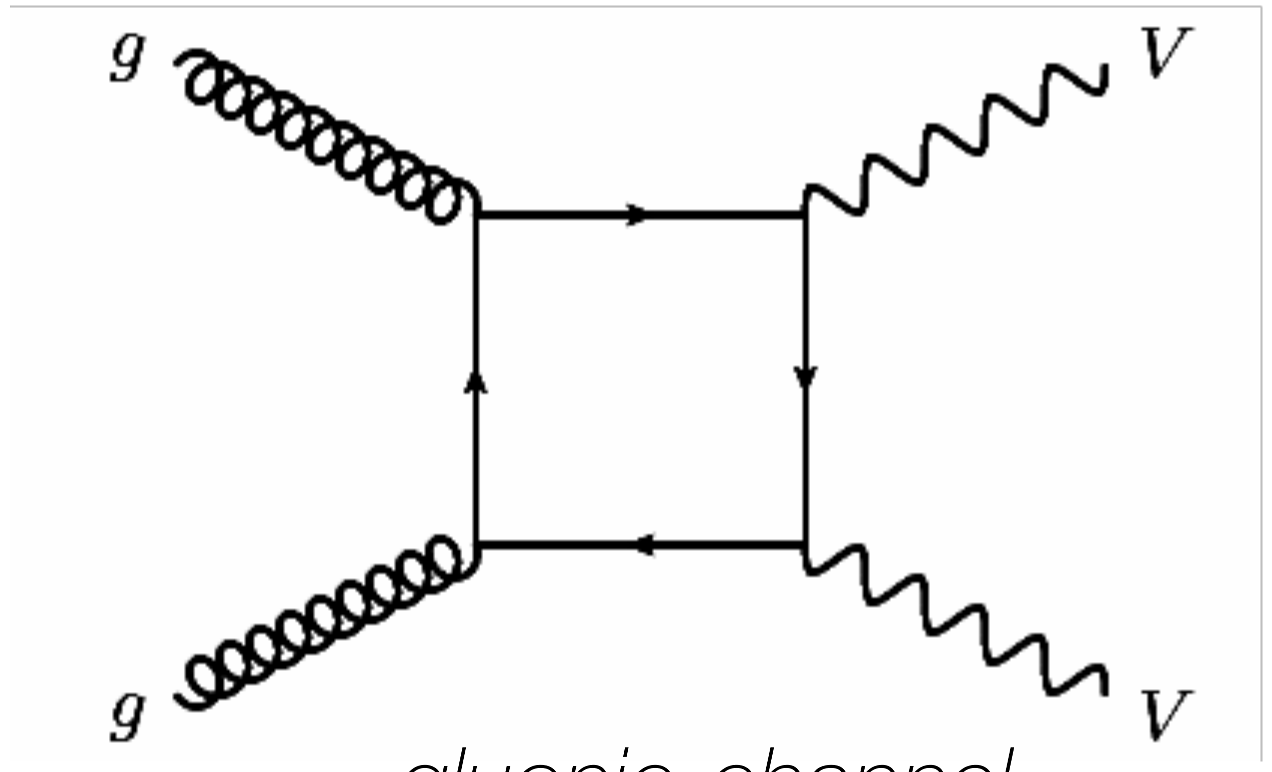


gluonic-channel

Prediction of the non-abelian SM gauge structure:

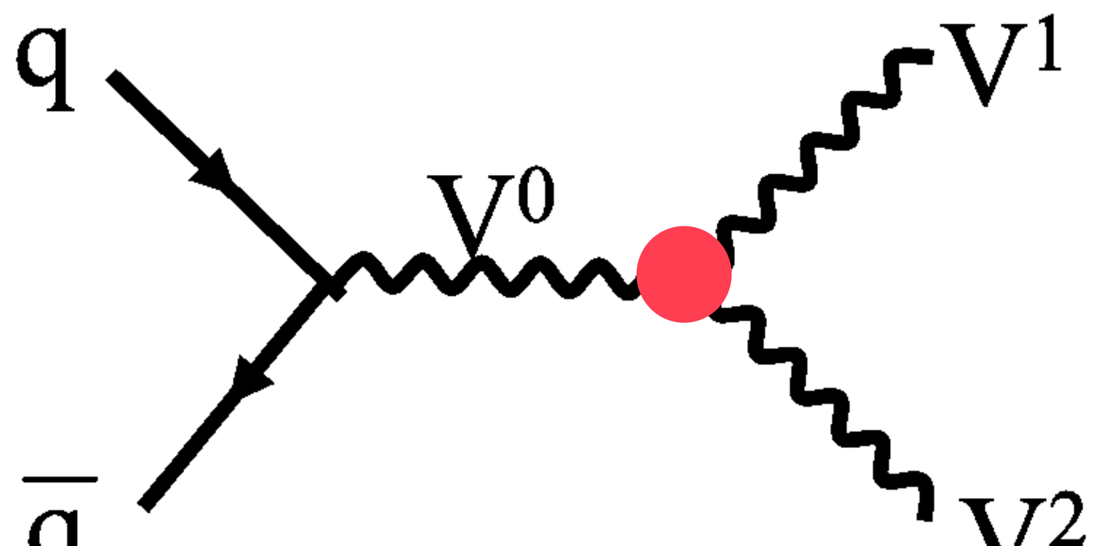
- Couplings between gauge bosons

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

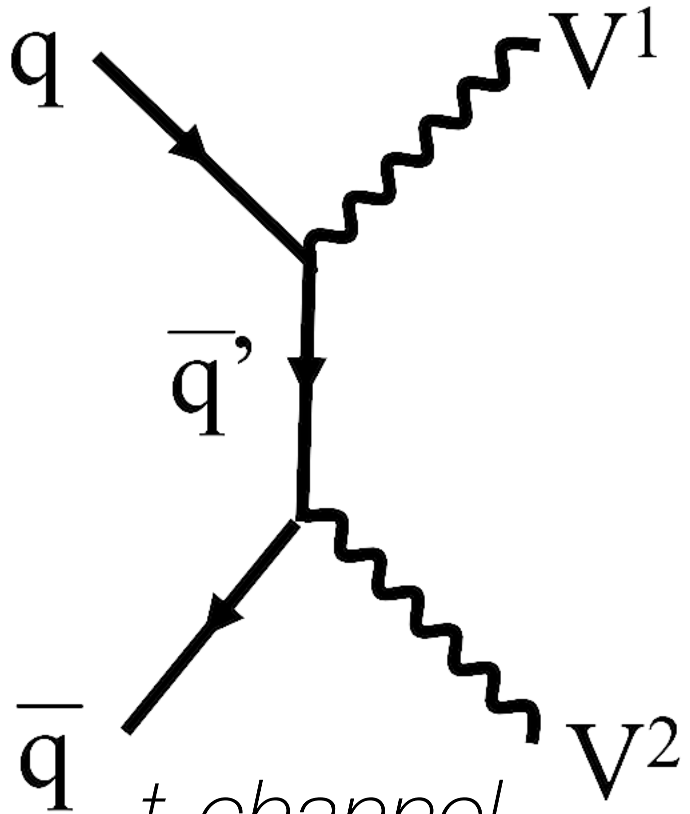
- *Deviations could hint to new physics*
- *Complementary to direct search for new physics*

Diboson production — Introduction

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



s-channel



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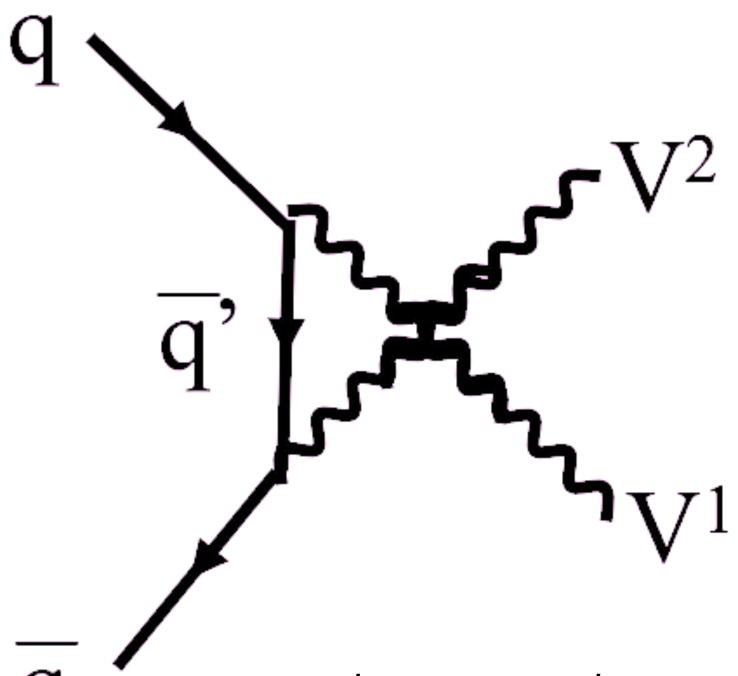

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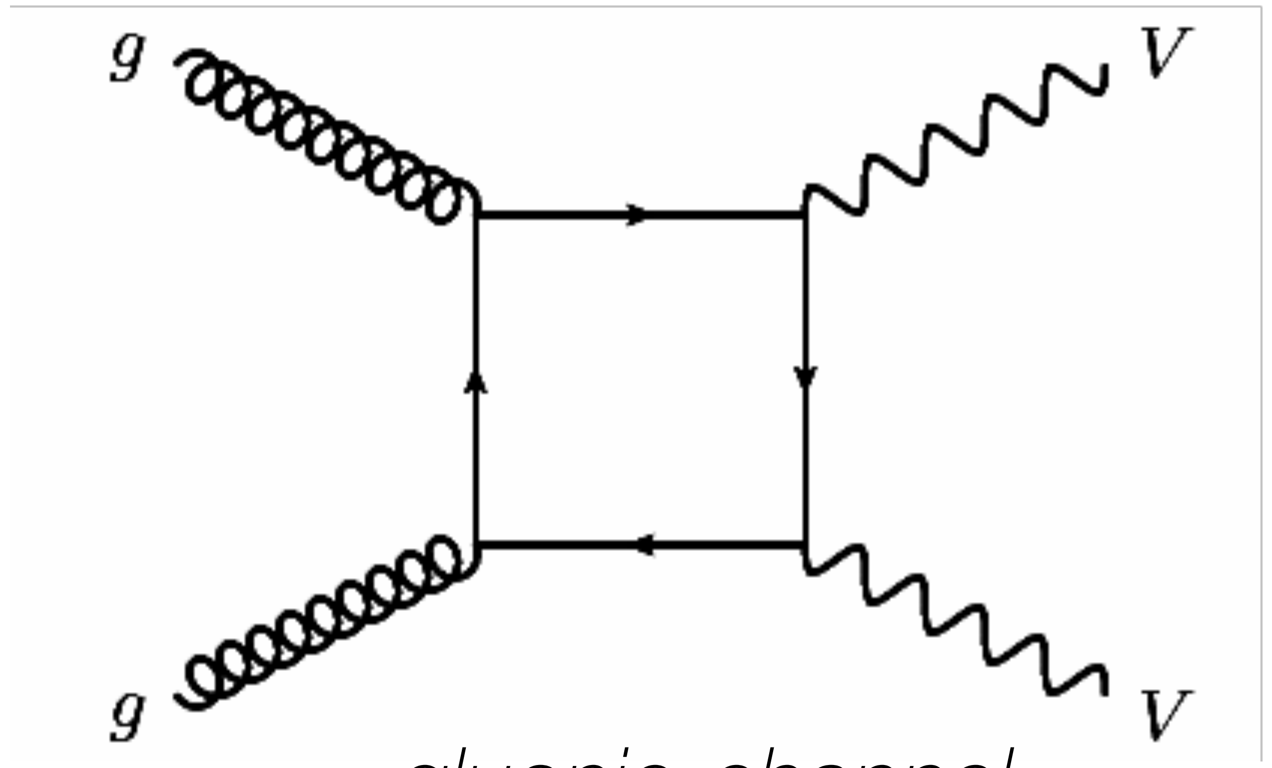


gluonic-channel

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*

Three-boson-vertex from s-channel

- *Charged couplings WWZ and WWγ allowed in the SM*
- *Neutral couplings ZZZ, ZZγ forbidden in the SM*

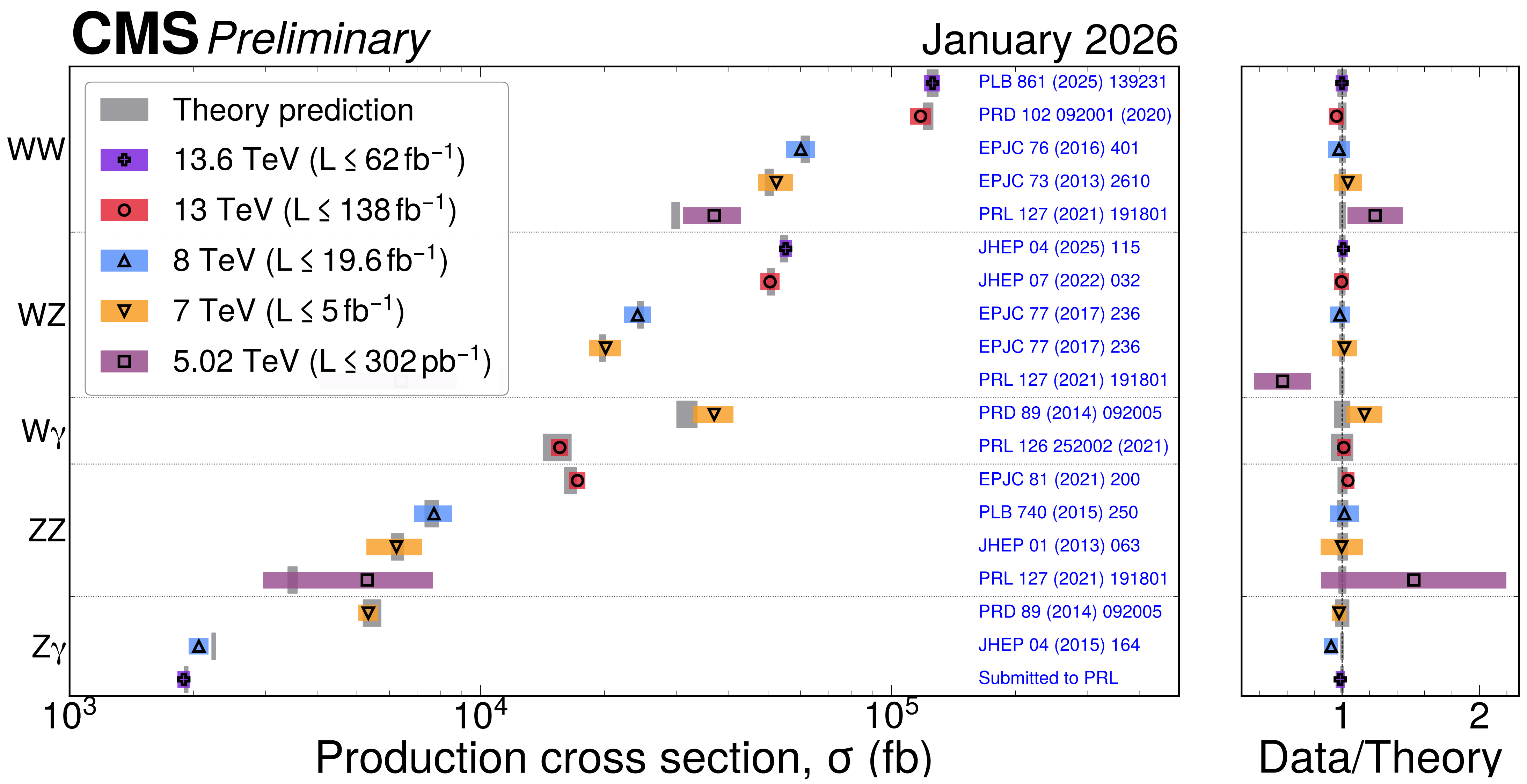
Gluonic-chanel from neutral diboson (W^+W^-,ZZ,Zγ, γγ)

- *Important NLO QCD correction*

Anomalous couplings tend to manifest in:

- *Cross section enhancement*
- *Enhancement at high p_T of two vector bosons*
- *Production angle*

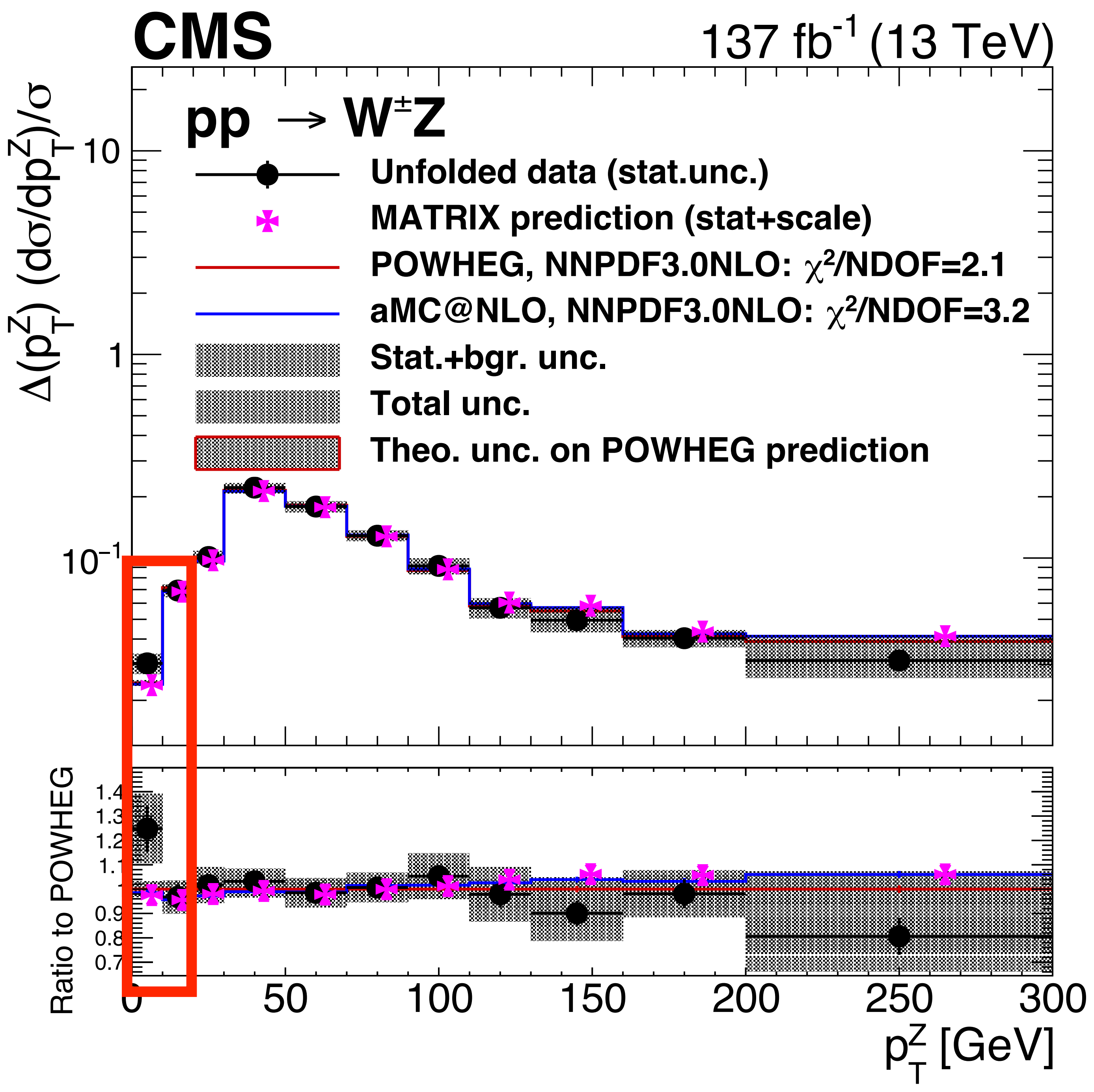
Diboson production - Results

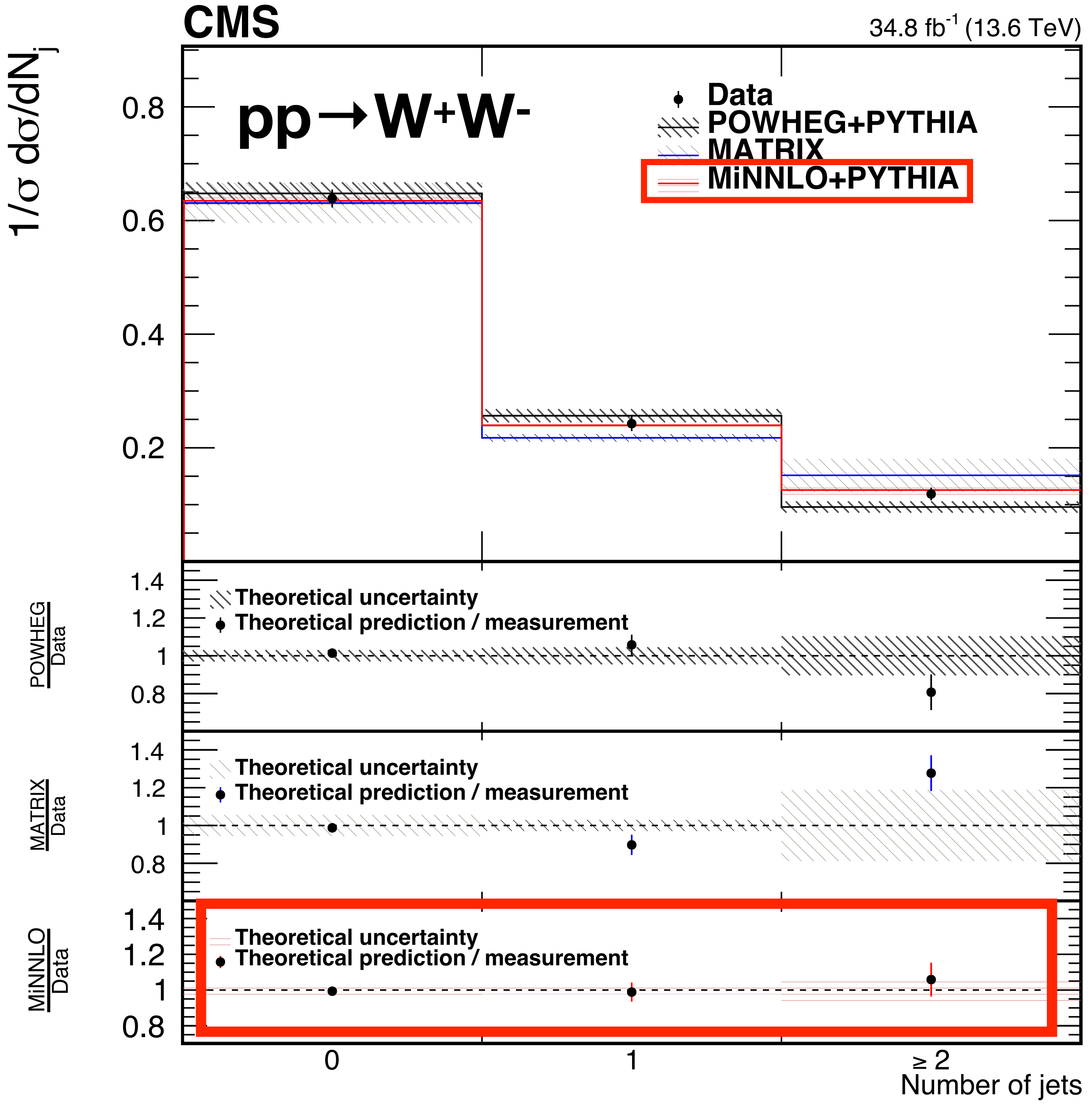


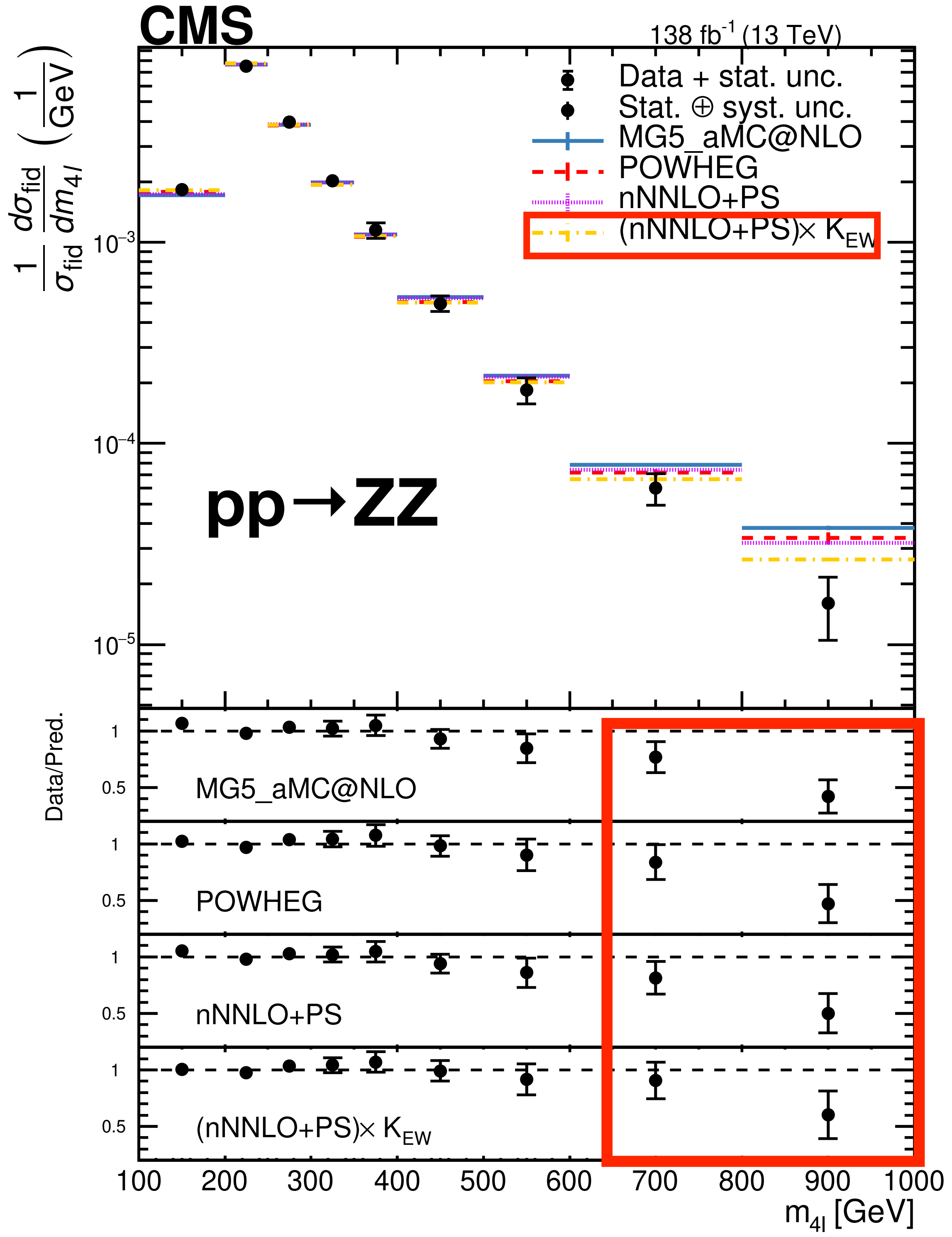
Diboson production has been widely measured at the LHC by CMS and ATLAS ver a wide range of center-of-mass energy up to 13.6 TeV

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*

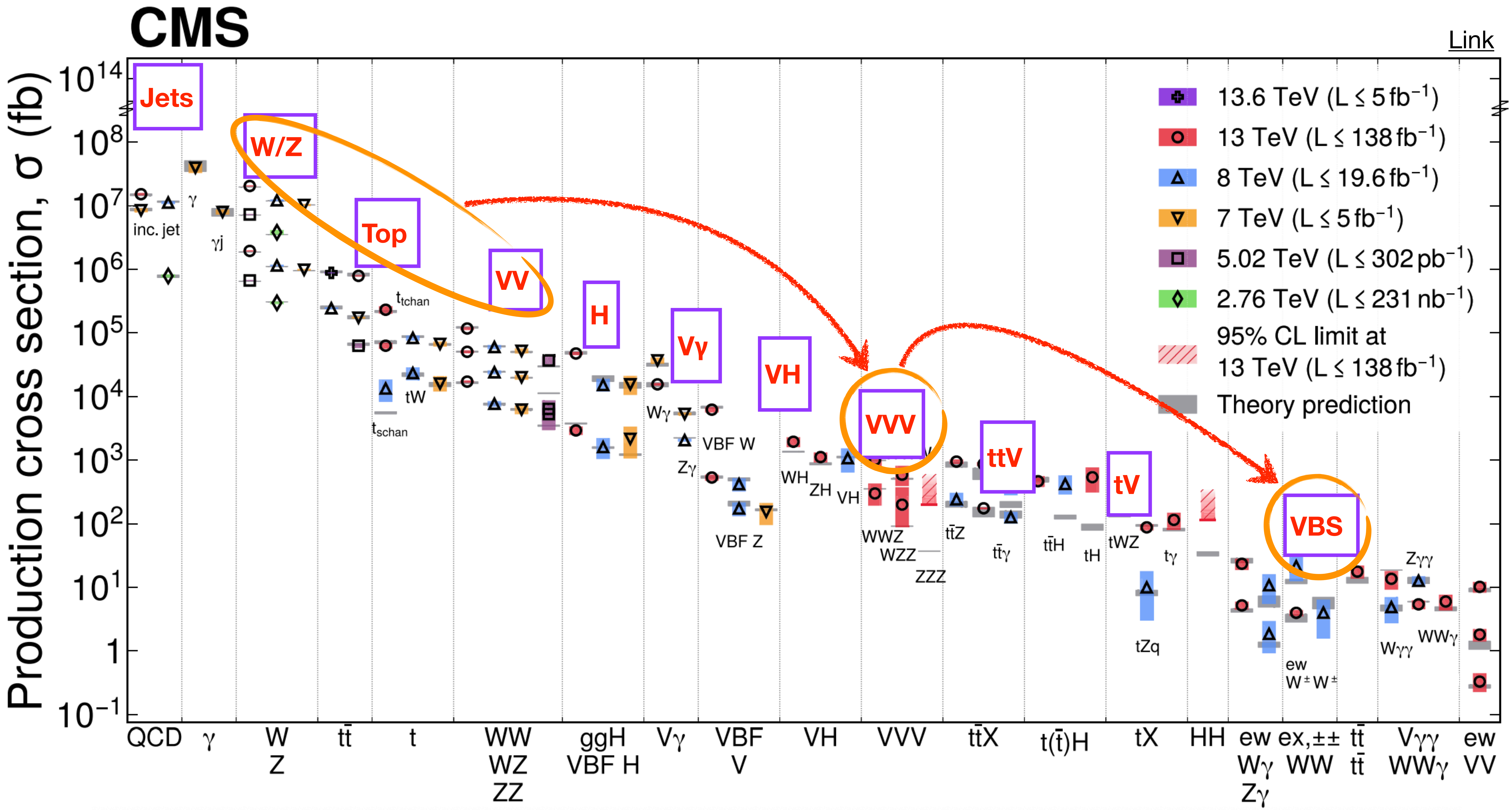






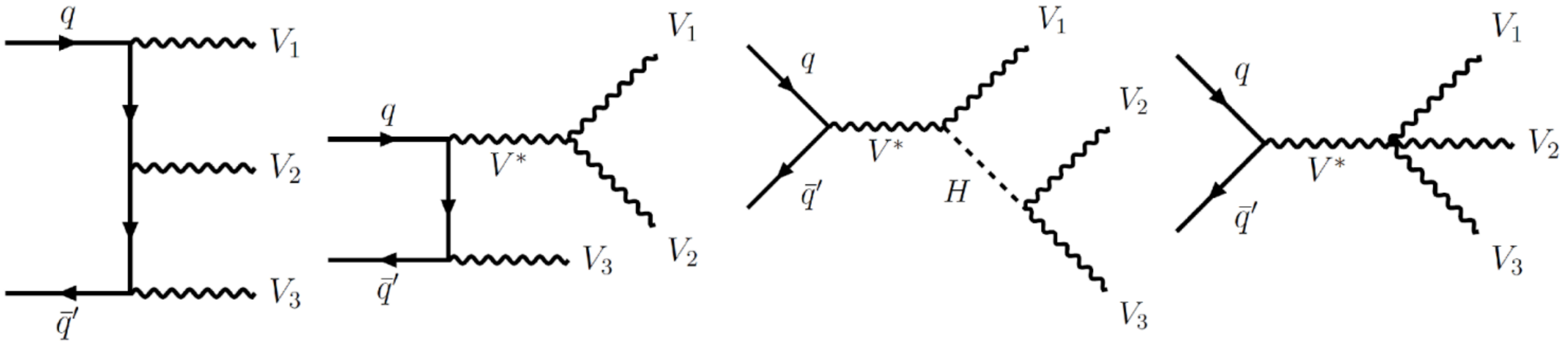
- low p_T^V for WZ from soft and collinear QCD radiations not well described
- Differential jet multiplicity in WW is best described by Powheg MiNNLO v2+Pythia (NNLO in QCD)
- Discrepancies towards higher $m_{4\ell}$ in ZZ due to missing higher order EW corrections

Link


CMS
Production cross section, σ (fb)
10^{14}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
1
10^{-1}
Jets
W/Z
Top
VV
H
Vγ
VH
VVV
ttV
tV
VBS
inc. jet
γ
γj
t_{tchan}
tW
t_{schan}
Wγ
Zγ
VBF W
VBF Z
WH
ZH
VH
WWZ
WZZ
ZZZ
$t\bar{t}Z$
$t\bar{t}\gamma$
$t\bar{t}H$
tH
tWZ
tγ
tZq
ew $W^{\pm}W^{\pm}$
Zγγ
Wγγ
WWγ
QCD
γ
W Z
$t\bar{t}$
t
WW WZ ZZ
ggH VBF H
Vγ
VBF V
VH
VVV
$t\bar{t}X$
$t(\bar{t})H$
tX
HH
ew Wγ Zγ
ex,±± WW
$t\bar{t}$ $t\bar{t}$
Vγγ WWγ
ew VV
13.6 TeV ($L \lesssim 5\,\mathrm{fb}^{-1}$)
13 TeV ($L \lesssim 138\,\mathrm{fb}^{-1}$)
8 TeV ($L \lesssim 19.6\,\mathrm{fb}^{-1}$)
7 TeV ($L \lesssim 5\,\mathrm{fb}^{-1}$)
5.02 TeV ($L \lesssim 302\,\mathrm{pb}^{-1}$)
2.76 TeV ($L \lesssim 231\,\mathrm{nb}^{-1}$)
95% CL limit at 13 TeV ($L \lesssim 138\,\mathrm{fb}^{-1}$)
Theory prediction

Triboson production — Motivation

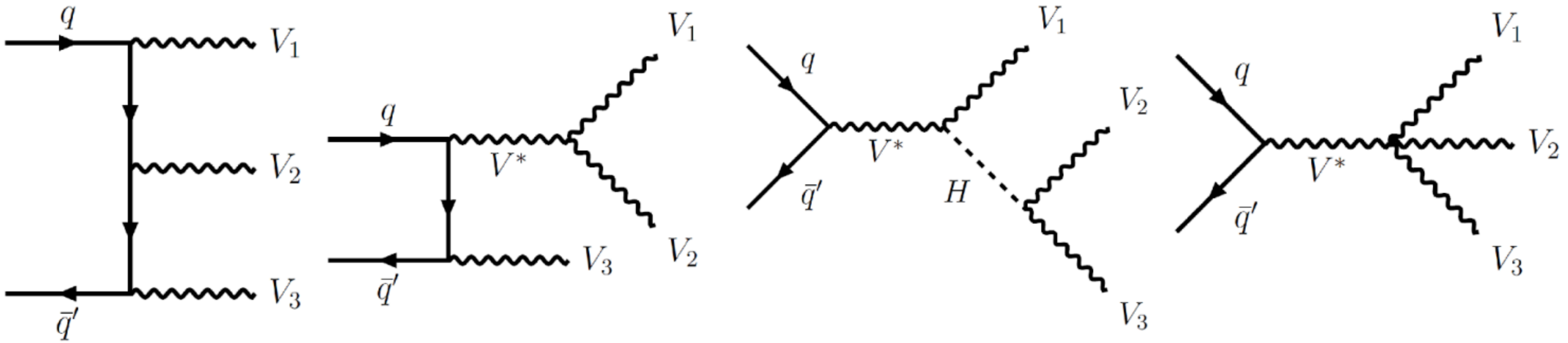
- **Direct measurement of gauge boson self-coupling and precision test of SM**



- 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**

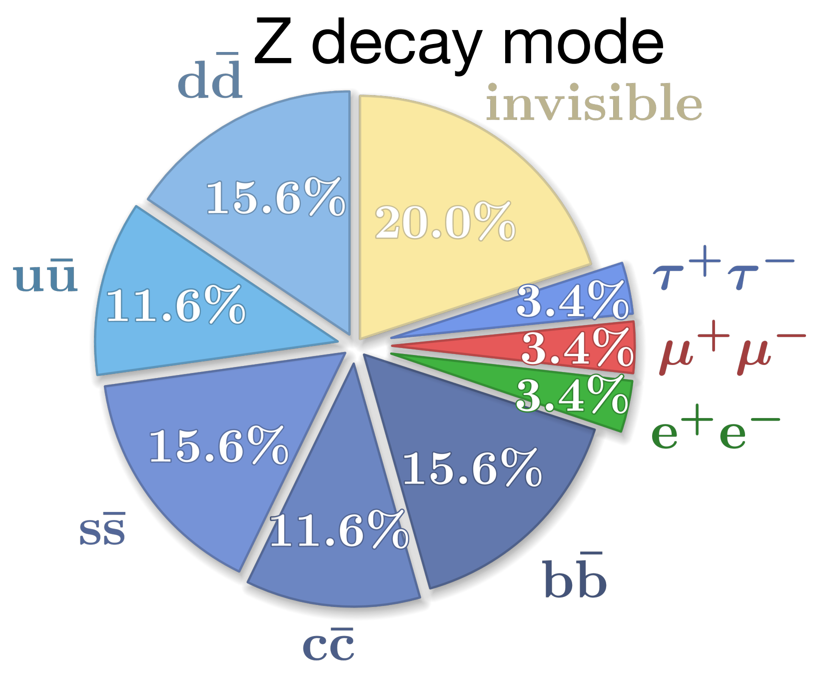


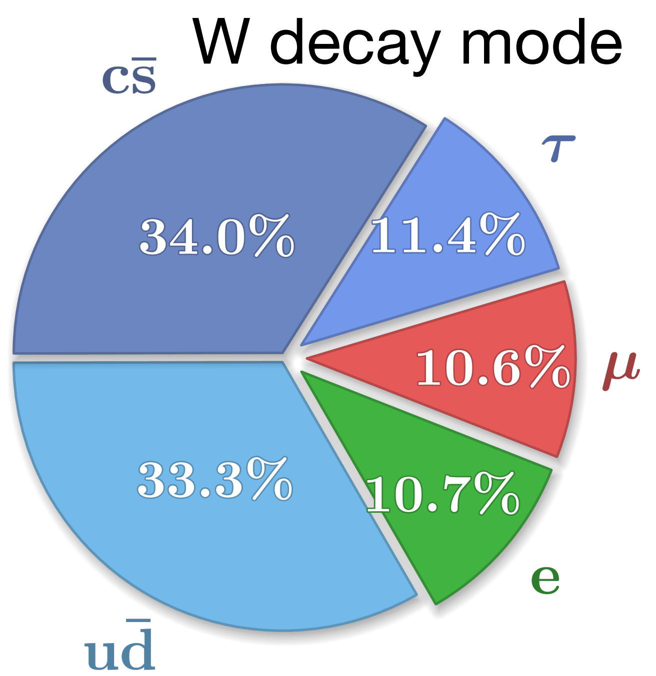
Leptonic final states are proper channels considering background components and reconstruction efficiency/resolution but with **limited statistics**

1. SM process that produce multi-leptons but one is lost
    - WZ, ZZ where a lepton is not detected
    - WZ, ZZ where Z→ττ
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

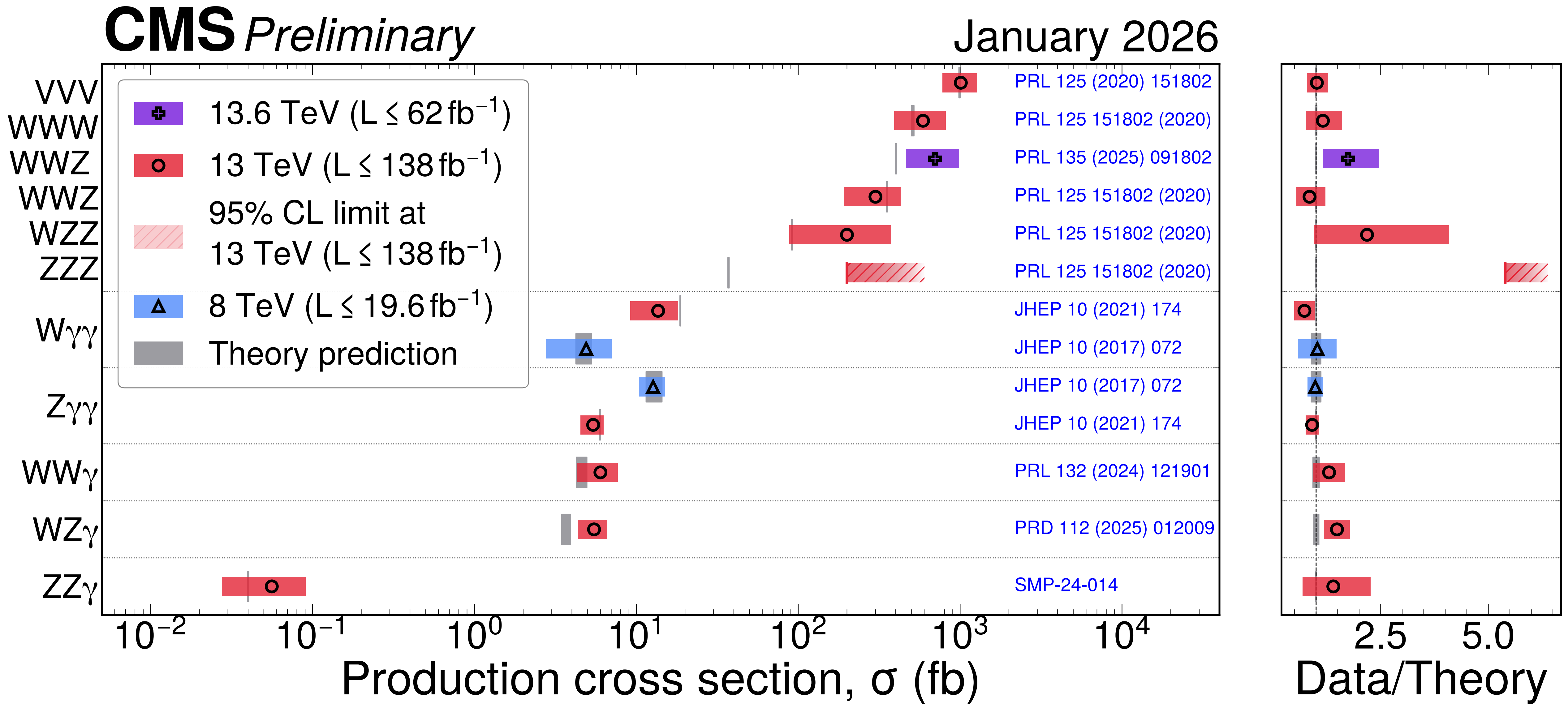
(1) estimated by normalizing MC to data

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

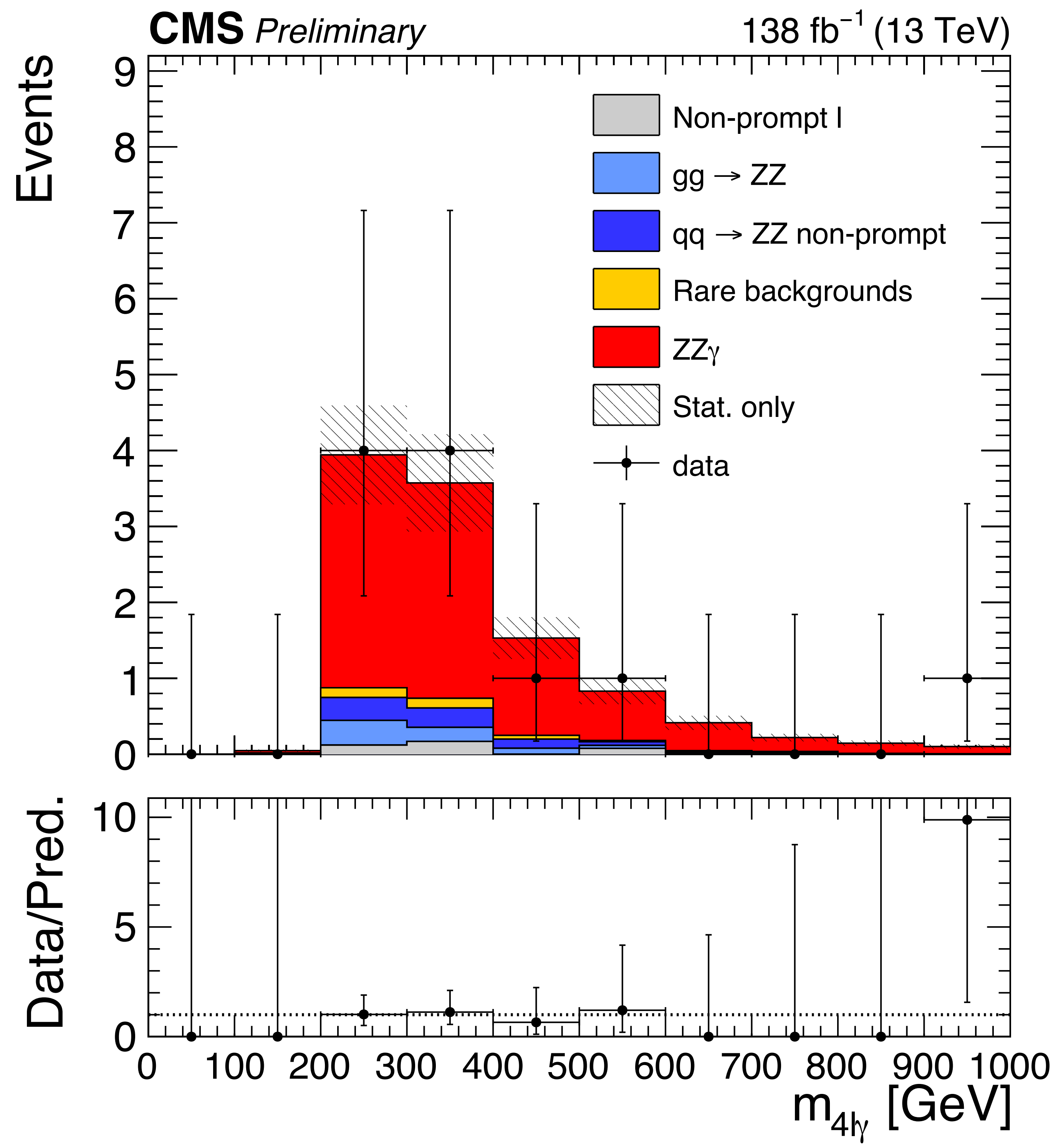

Z decay mode

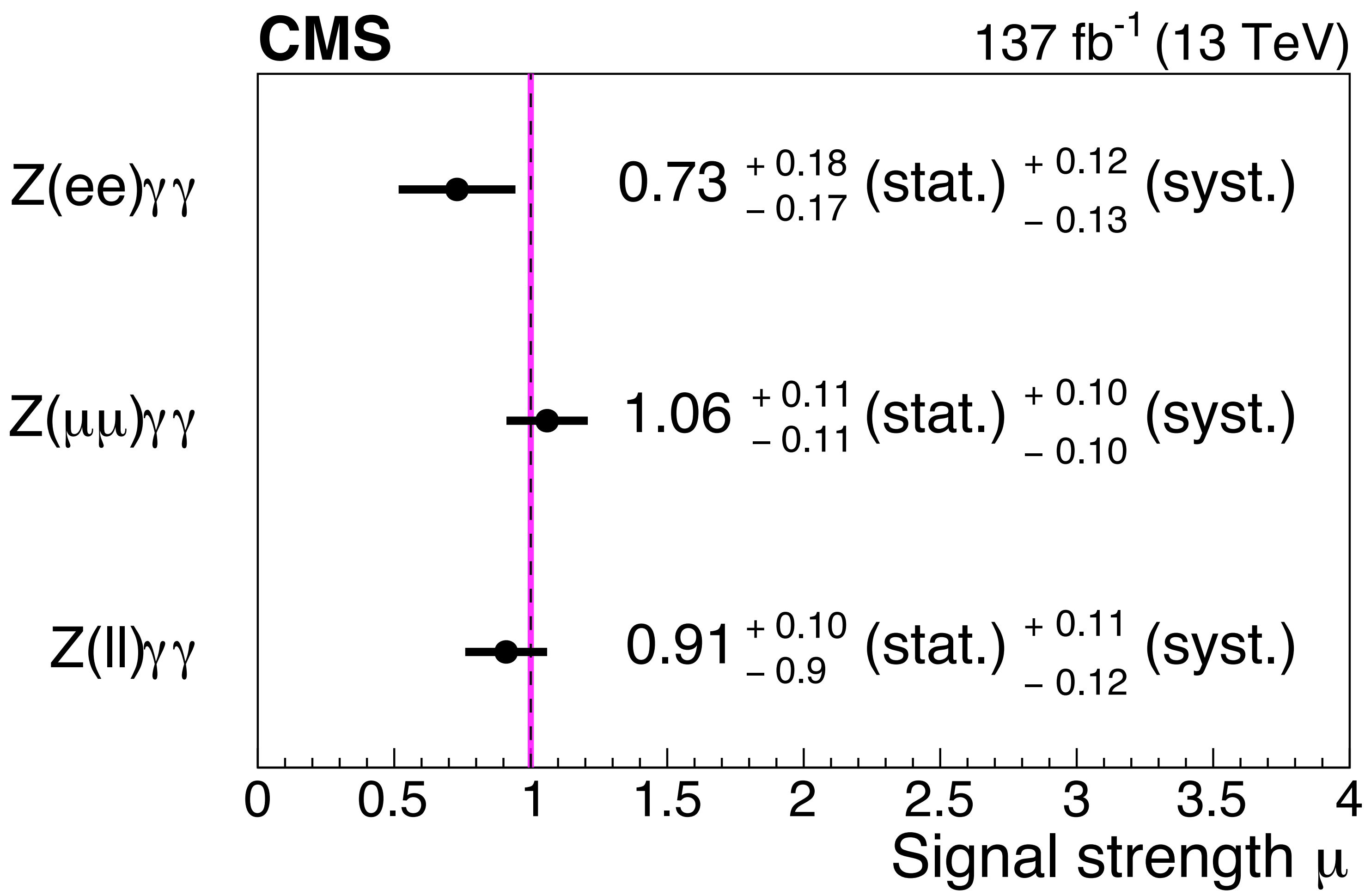

W decay mode

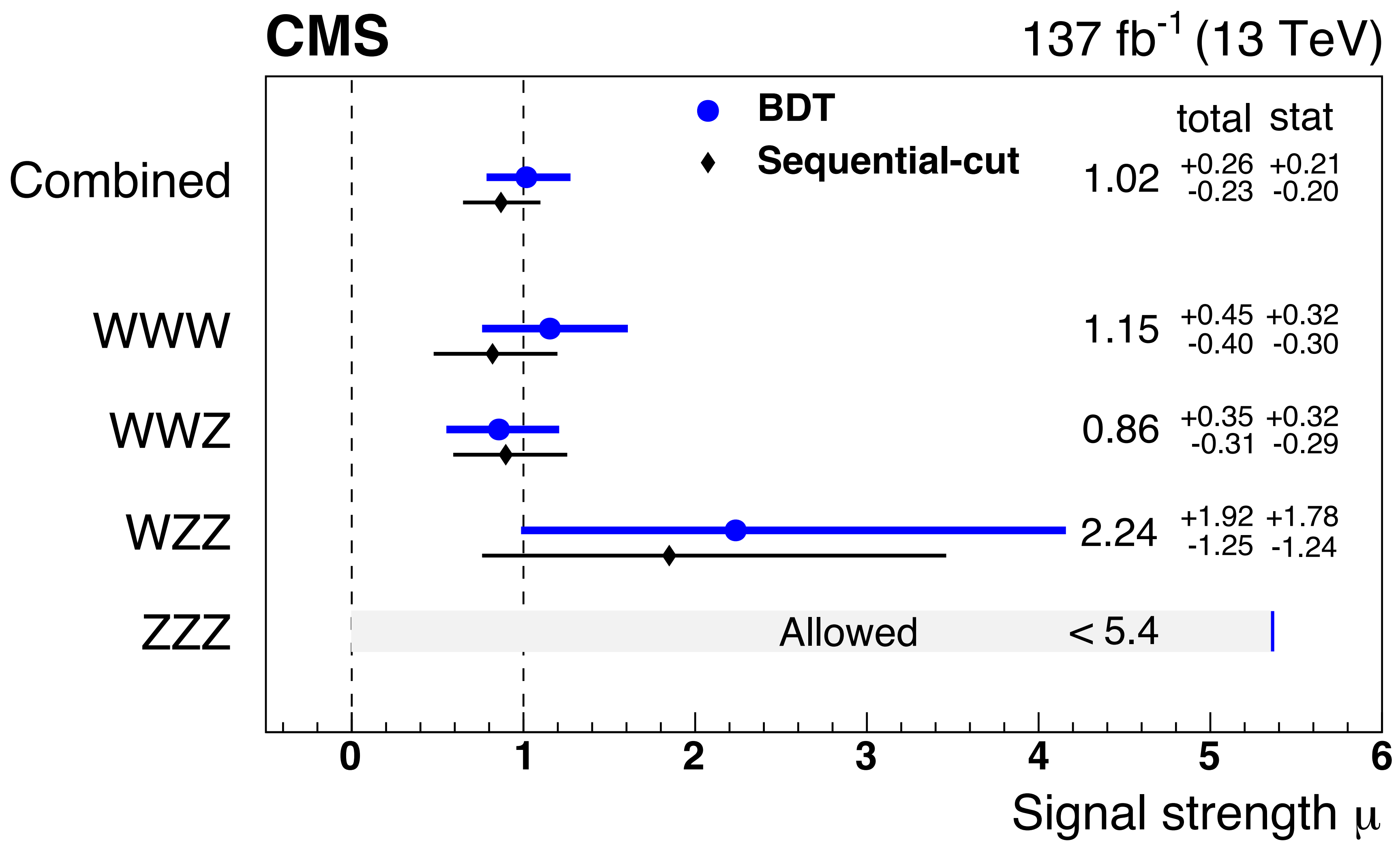
Triboson production — Results



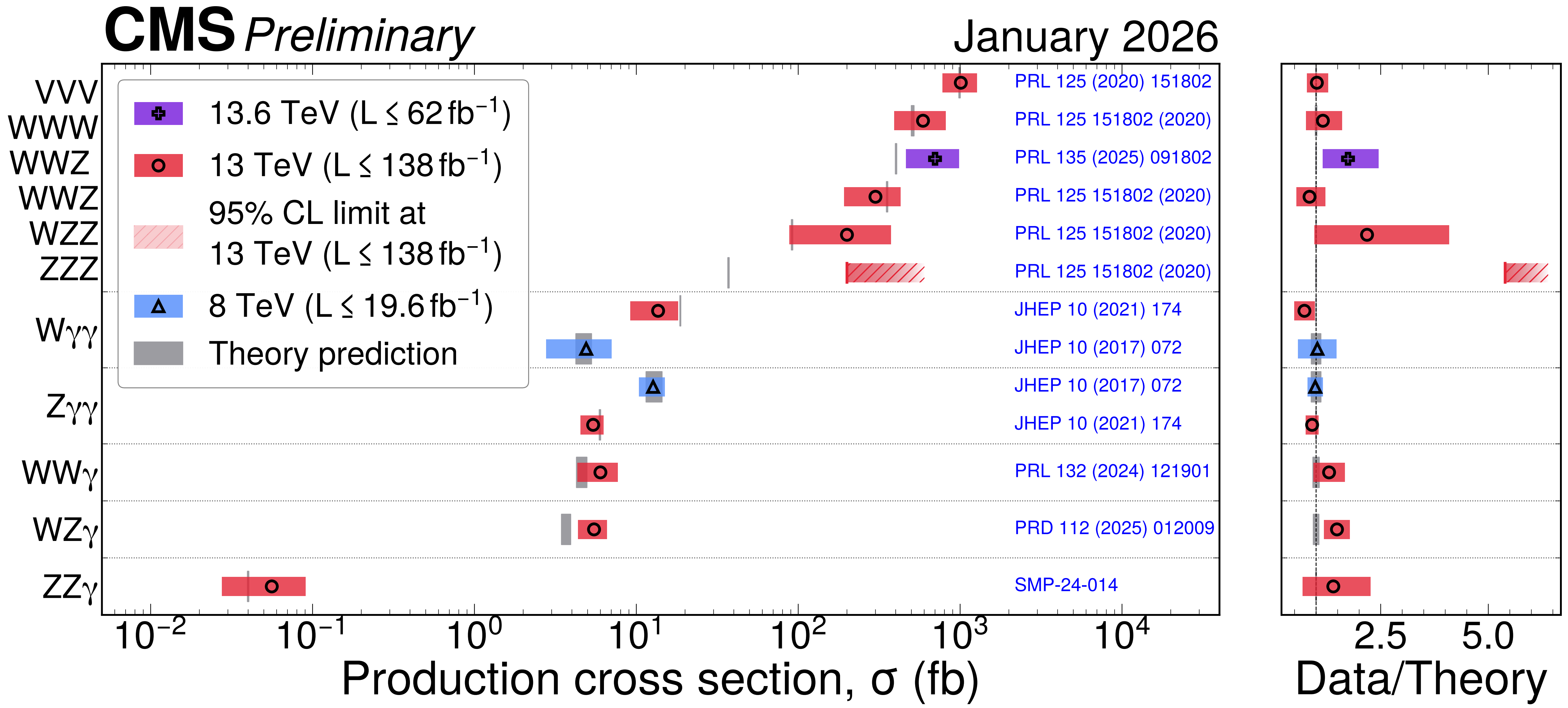
- Full Run 2 VVV (WWW, WWZ, WZZ, ZZZ) Observed: VVV 5.7σ, WWW 3.3
- Full Run 2 Wγγ (3.1σ) and Zγγ (4.8σ)
- **Full Run 2 ZZγ (3.7σ)**



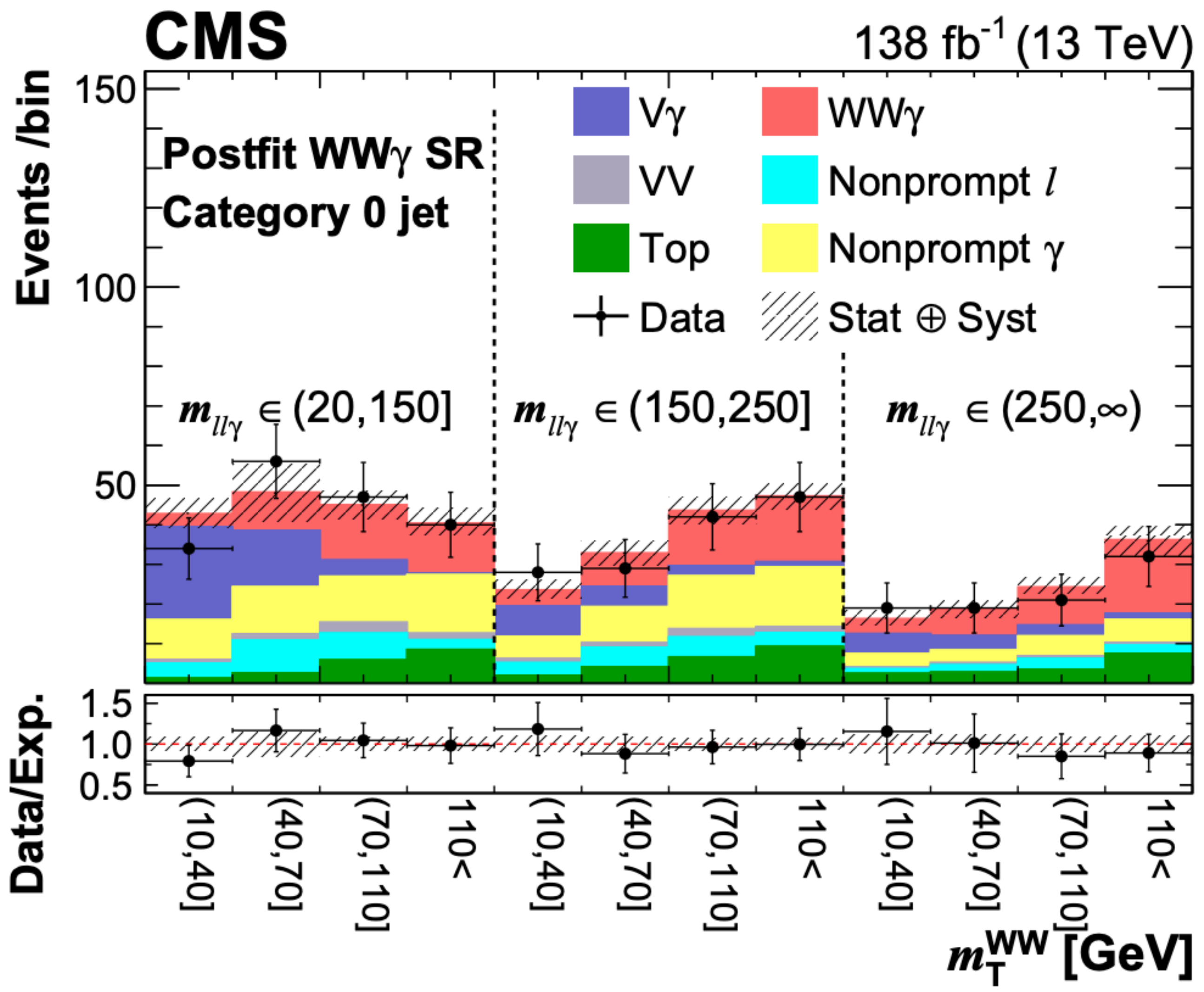


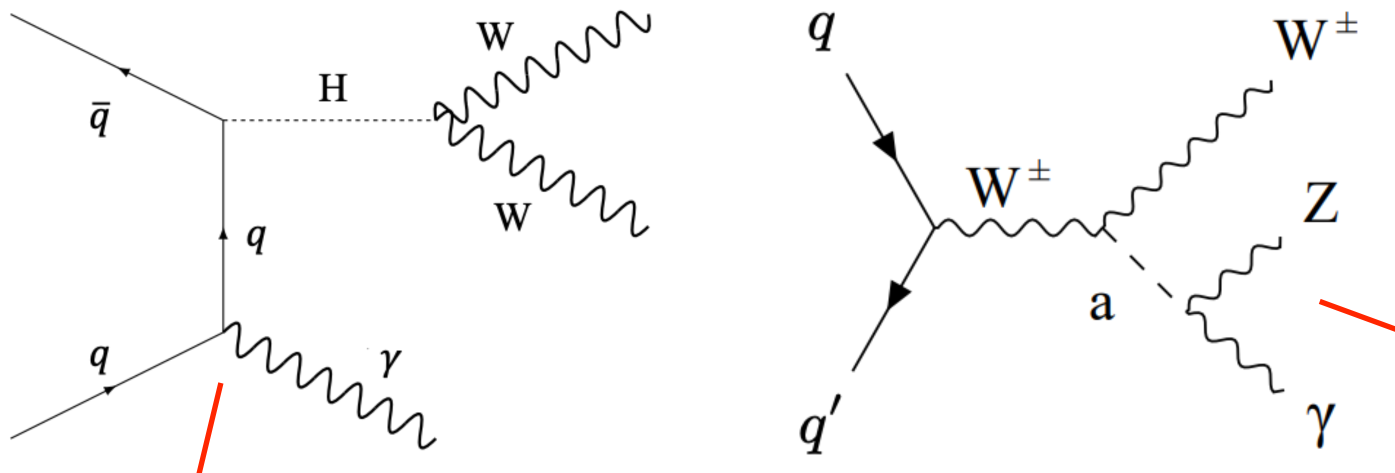


Triboson production — Results

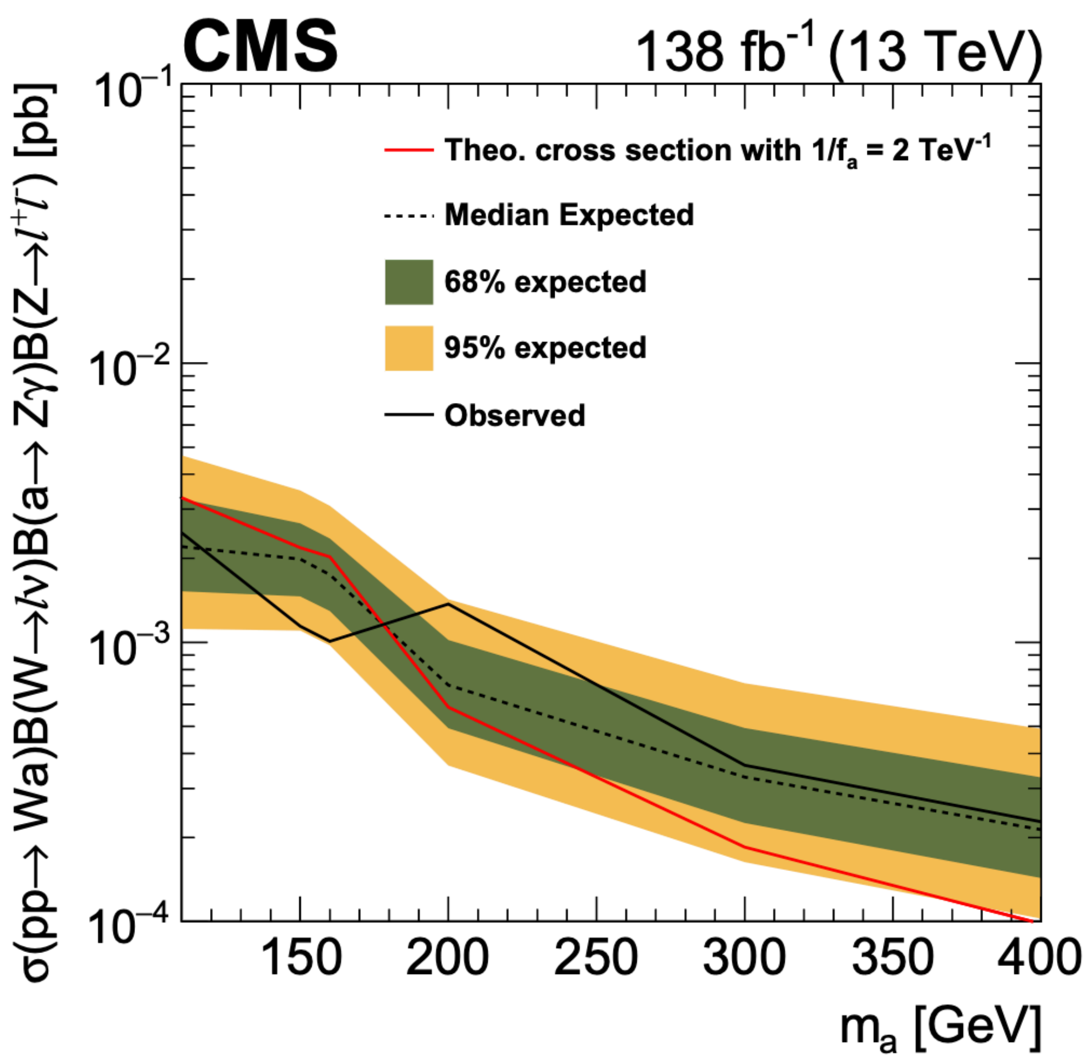


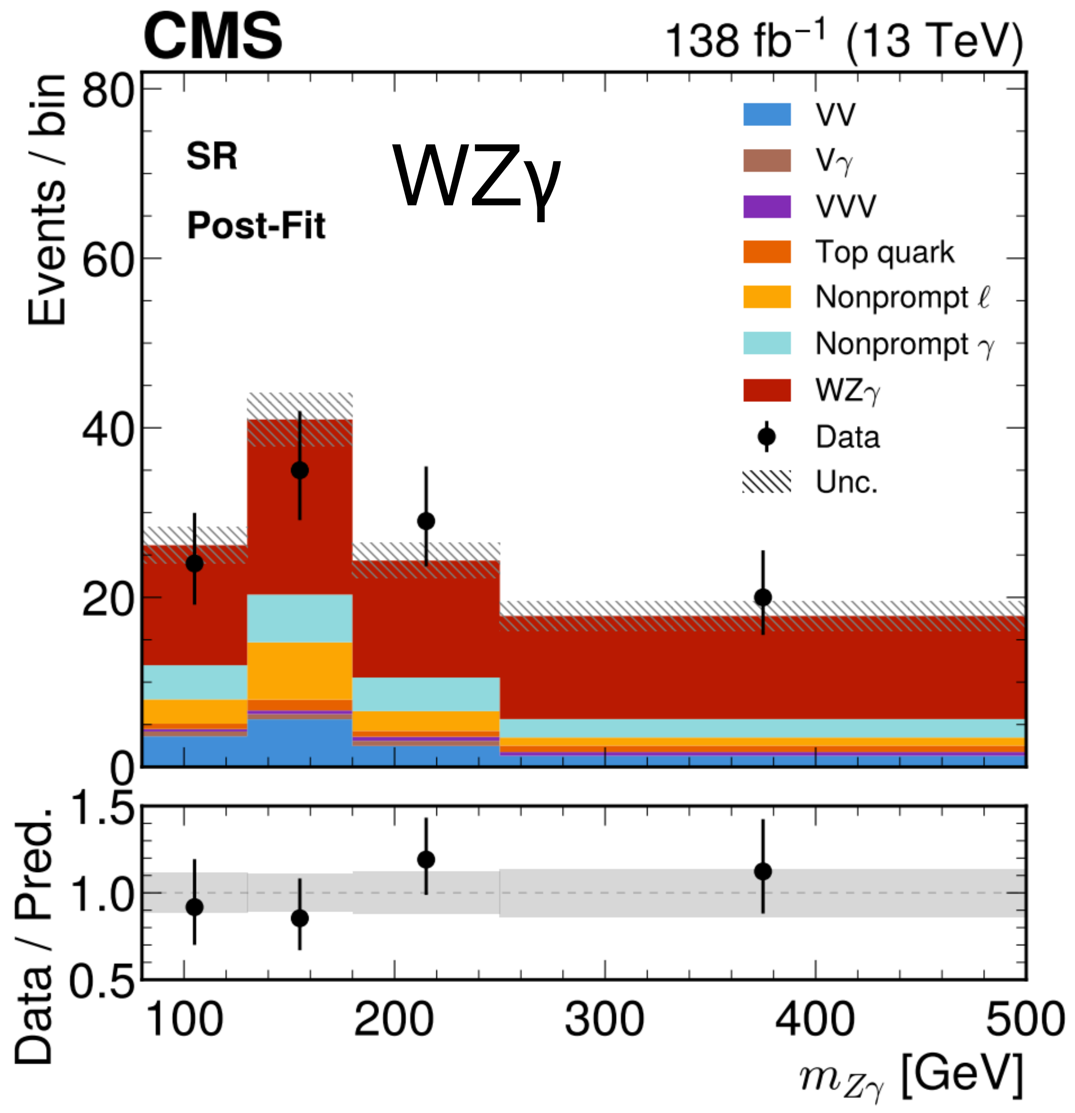
- Full Run 2 VVV (WWW, WWZ, WZZ, ZZZ)
  Observed: VVV 5.7σ, WWW 3.3
- Full Run 2 Wγγ (3.1σ) and Zγγ (4.8σ)
- **Full Run 2 ZZγ (3.7σ)**
- **Full Run 2 WWγ (>5σ) and WZγ (>5σ)**
- **Run 3 WWZ and ZH (4.5 σ)**





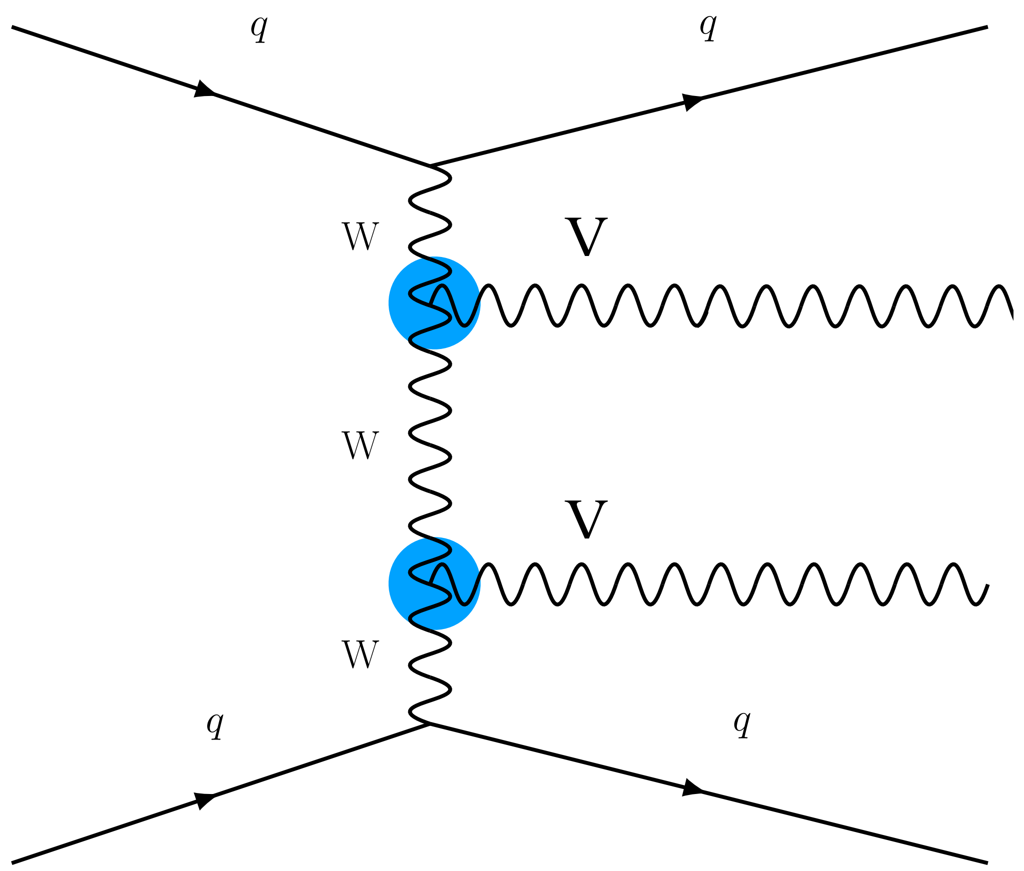
κ_q limits obs. (exp.) at 95% C.L.
$\lvert\kappa_u\rvert \le 16000\ (13000)$
$\lvert\kappa_d\rvert \le 17000\ (14000)$
$\lvert\kappa_s\rvert \le 1700\ (1300)$
$\lvert\kappa_c\rvert \le 190\ (110)$



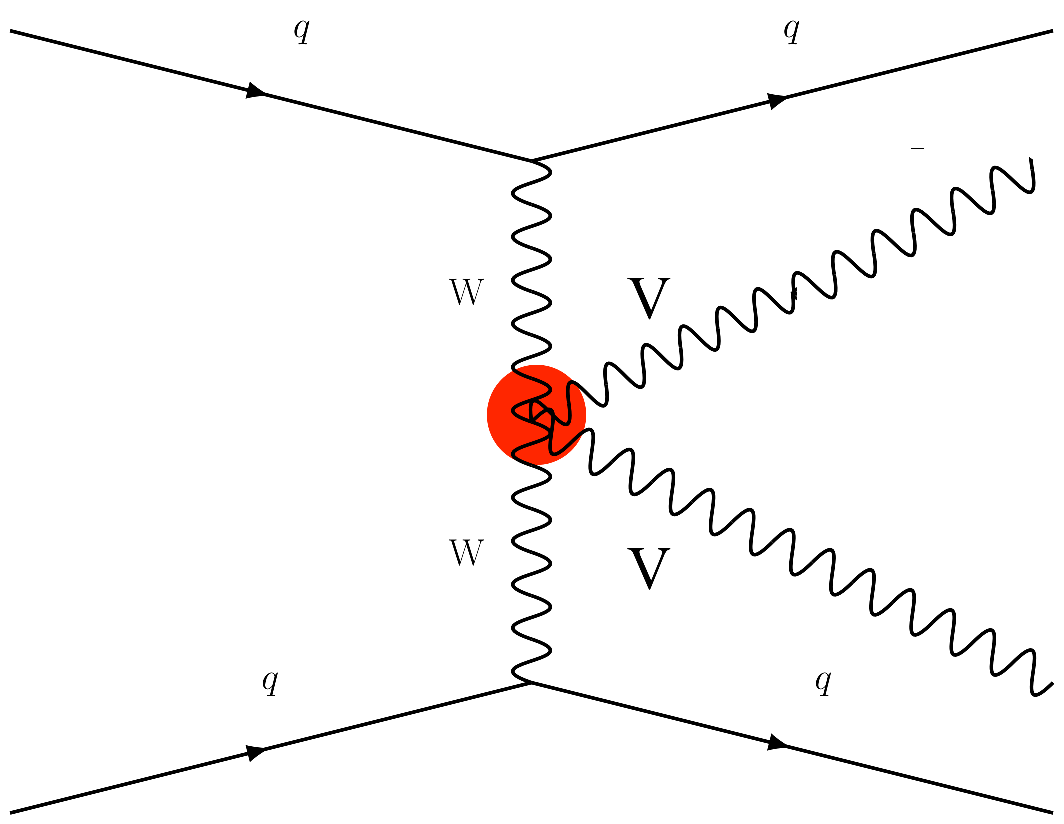


VBS production — Motivation

TGC: Triple gauge couplings



QGC: Quartic gauge couplings



Multiboson couplings:

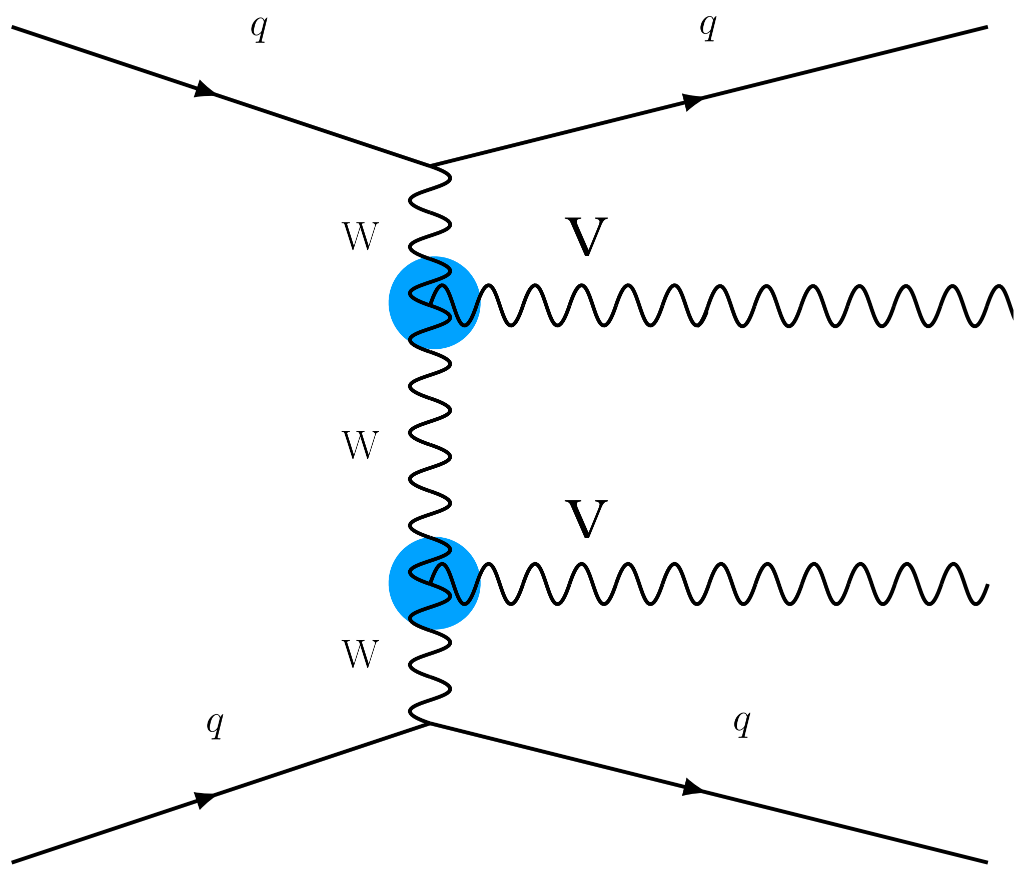
- T(Q)GC: WWZ, WWγ, WWZγ, WWγγ, etc.
- BSM TGC: ZZγ, Zγγ, etc
- BSM QGC : ZZγ, ZZZγ, Zγγγ, etc

☑ Test SM for the electroweak sector

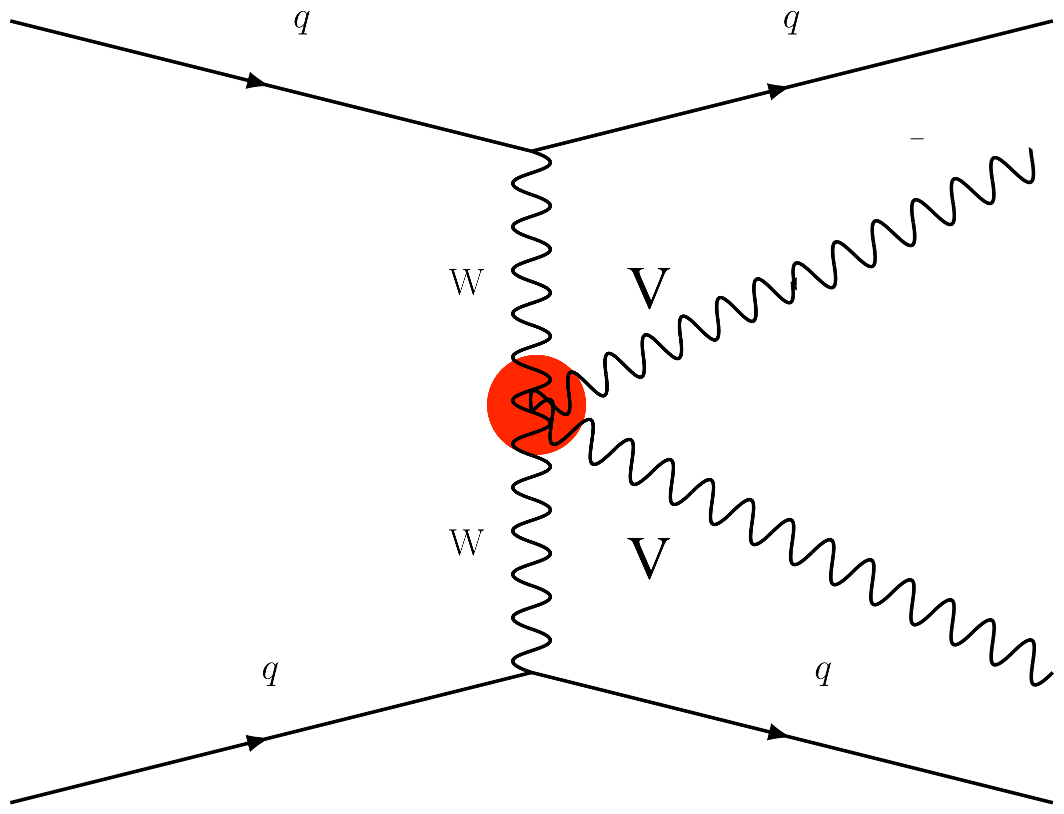
☑ Provide platform for anomalous couplings

VBS production — Motivation

TGC: Triple gauge couplings



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

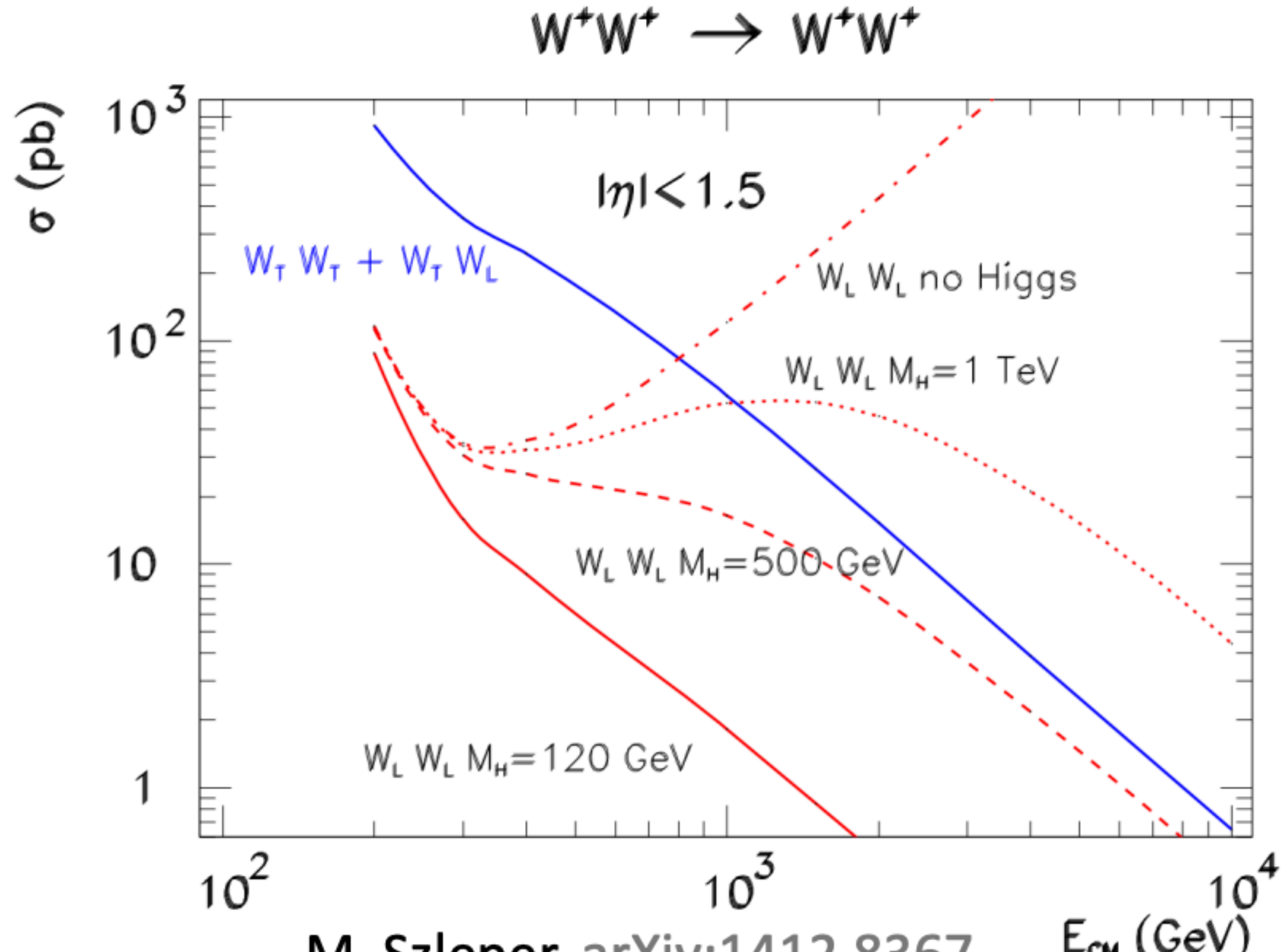
☑ Provide platform for anomalous couplings

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

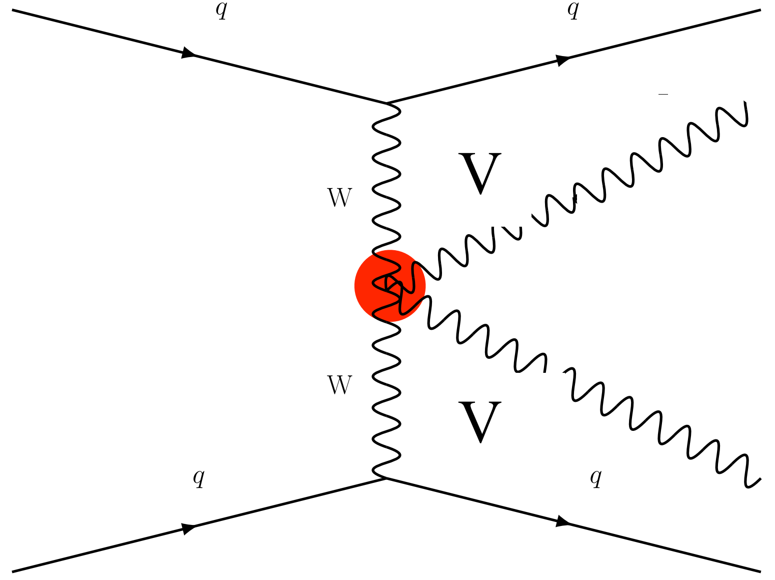
☑ Probe the nature of EW symmetry breaking



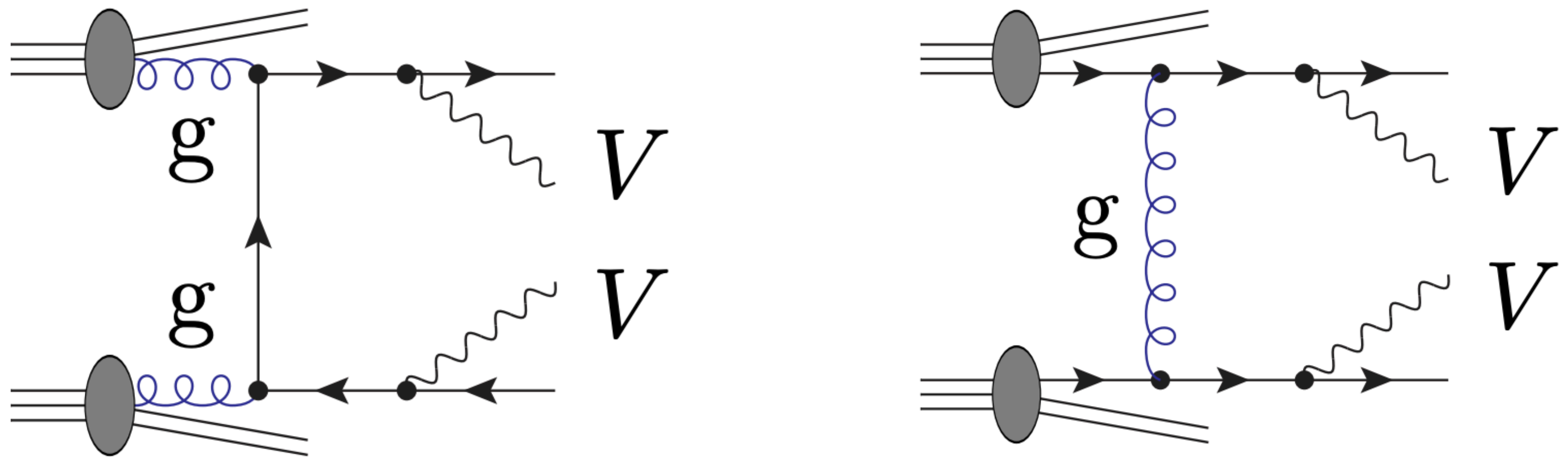
M. Szleper, arXiv:1412.8367

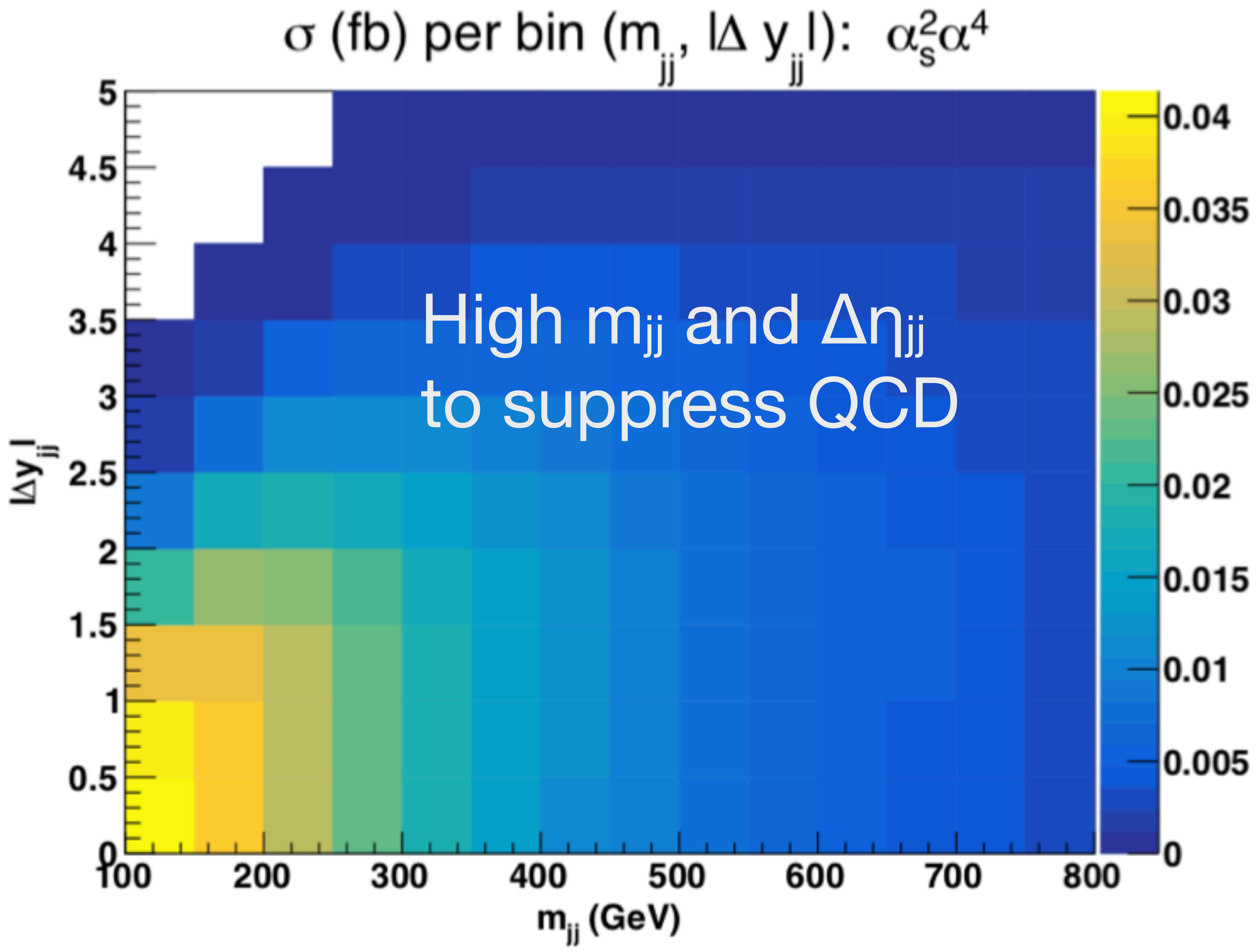
VBS production — Introduction

VBS signal



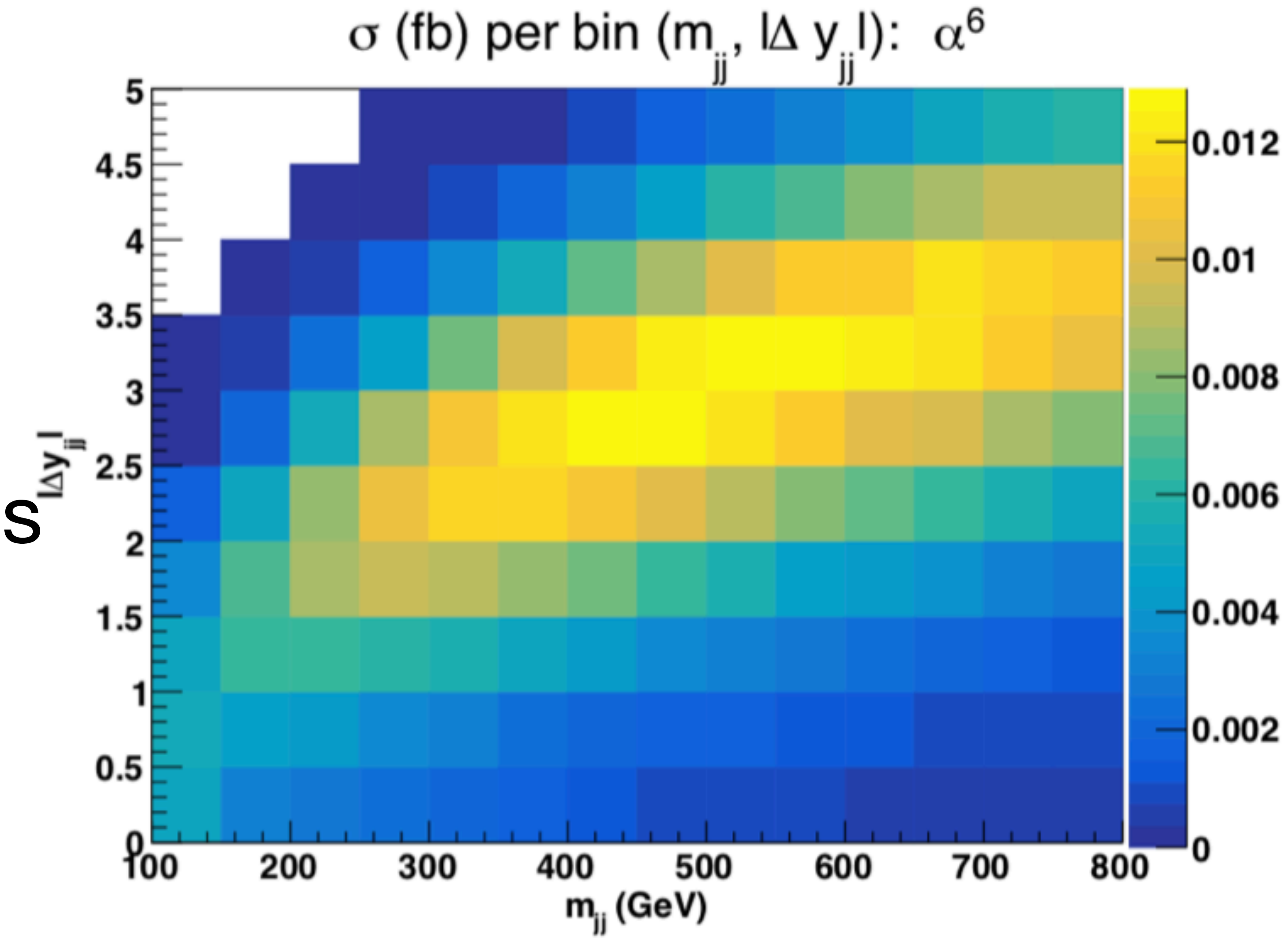
Irreducible background

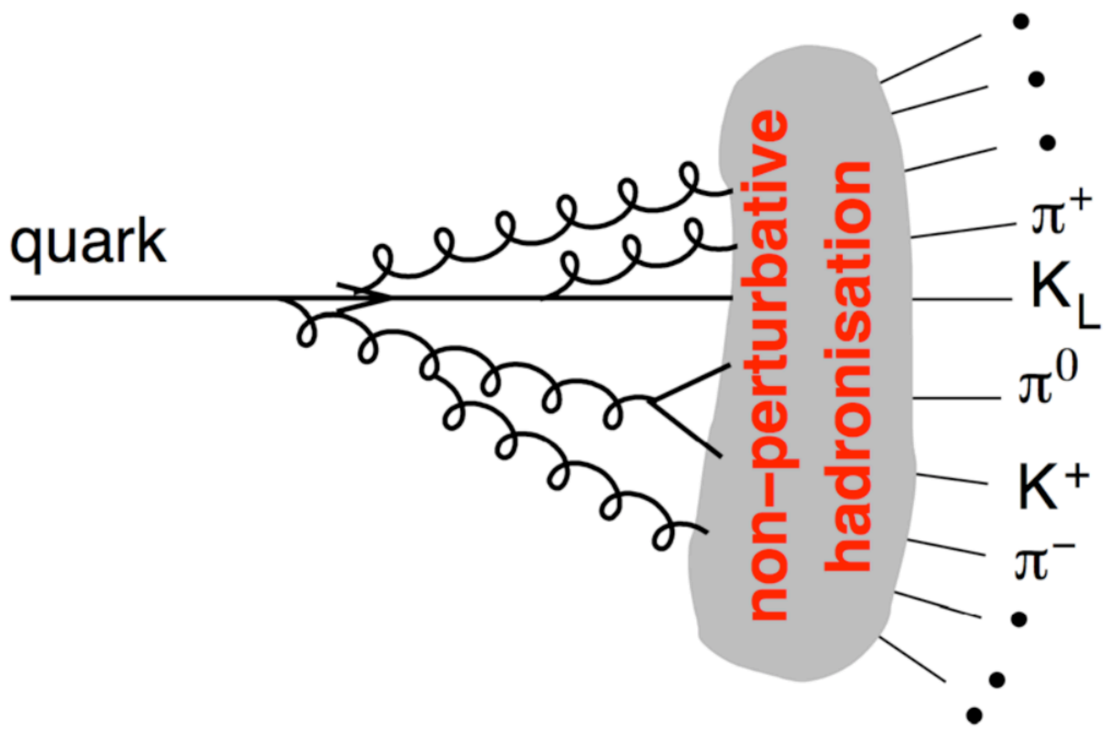



σ (fb) per bin (m_{jj}, $|\Delta y_{jj}|$): $\alpha_s^2\alpha^4$

High m_{jj} and $\Delta\eta_{jj}$ to suppress QCD

- EW process: $O(\alpha^4)$ for stable V, $O(\alpha^6)$ with decays
- QCD process $O(\alpha_s^2\alpha^2)$ for stable V, $O(\alpha_s^2\alpha^4)$ with decays
- Non-vanishing interferences between EW and QCD contributions $O(\alpha_s\alpha^3)$ for stable V, $O(\alpha_s\alpha^5)$ with decays
- Gluonic channels for neutral final states

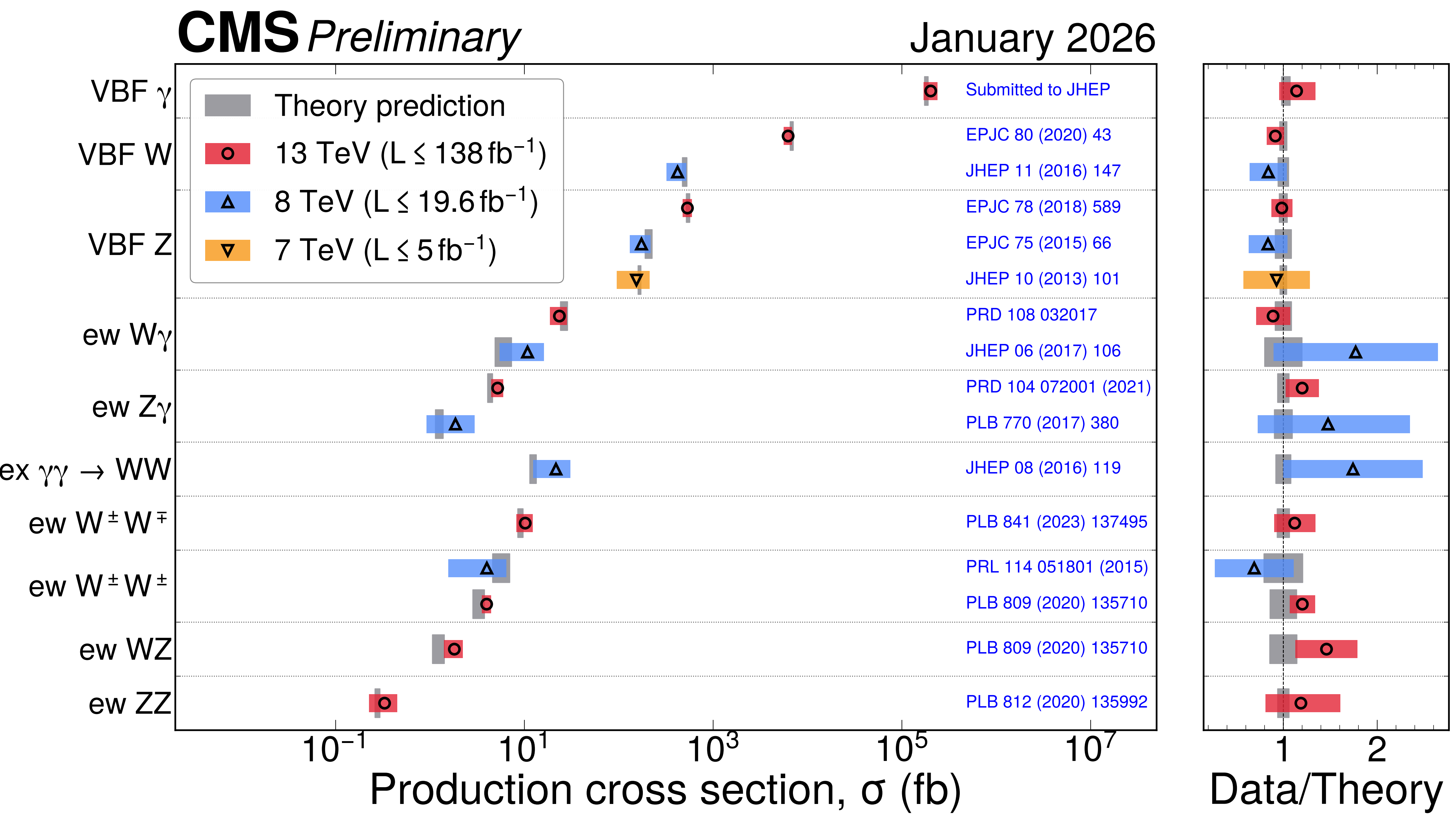

σ (fb) per bin (m_{jj}, $|\Delta y_{jj}|$): α^6



Reducible background due to mis-ID of final state particles

- Nonprompt γ in Vγ+jets
- Nonprompt ℓ in VV+jets or Vγ+jets
- Electron misidentified photon

VBS production — Results

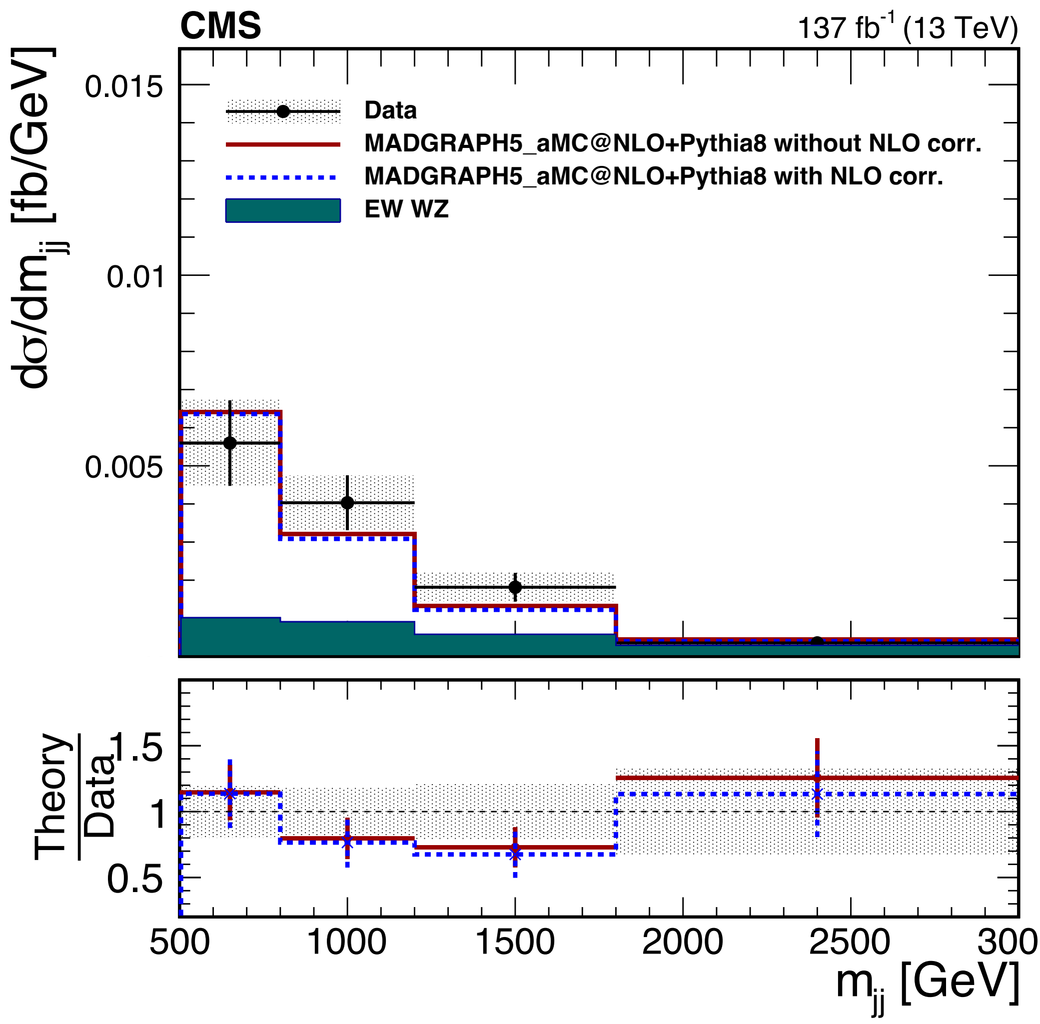


LHC has obtained observation of VBS VV and Vγ (leptonic channel, V = W, or Z)

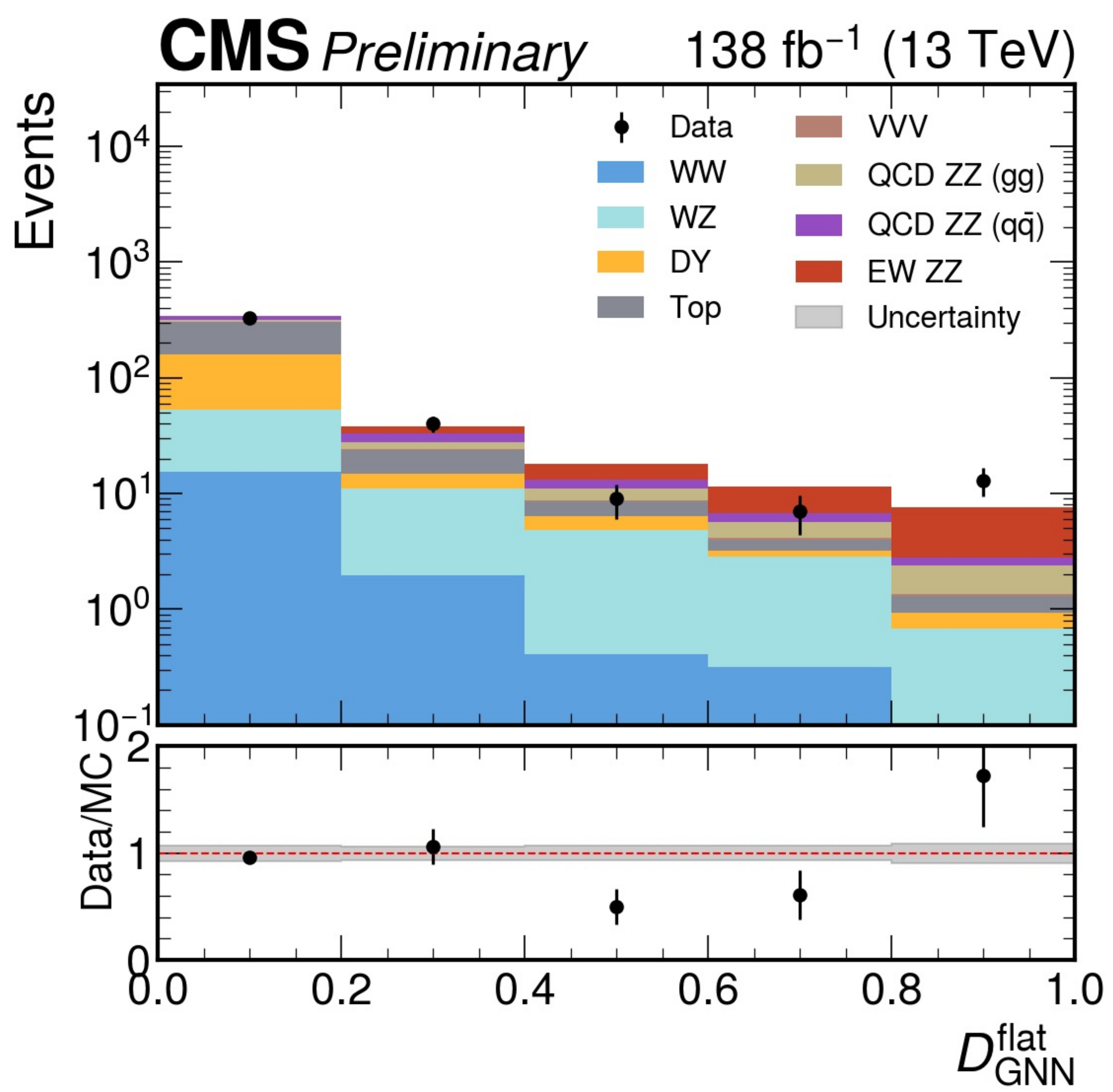
- **CMS VBS ZZ has reached the observation from the combination of ZZ(4ℓ) and ZZ(2ℓ2ν)**
- Differential cross sections provided as functions of interesting observables

The QCD cross section is usually measured together with the VBS signal

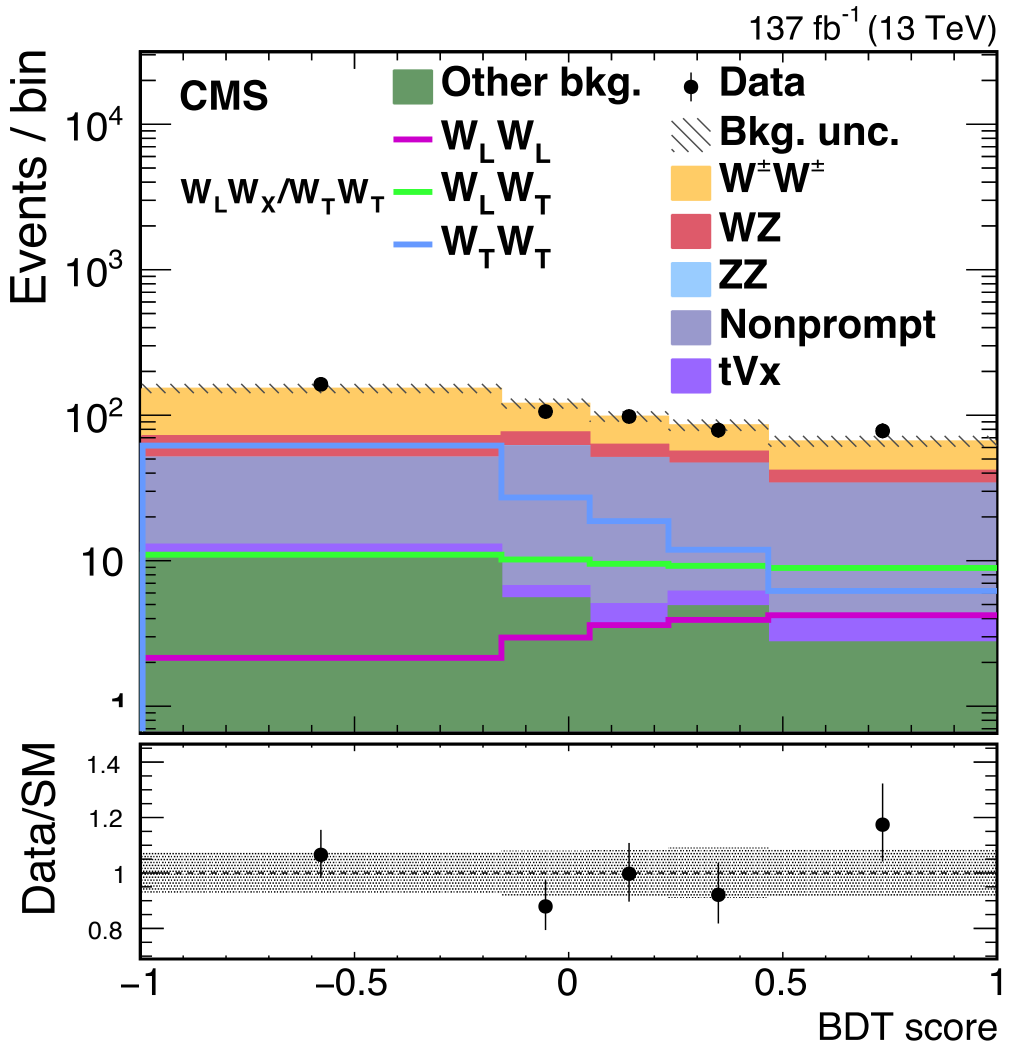
- Better control of the main background normalization
- New constraints on QCD modeling in extreme phase space



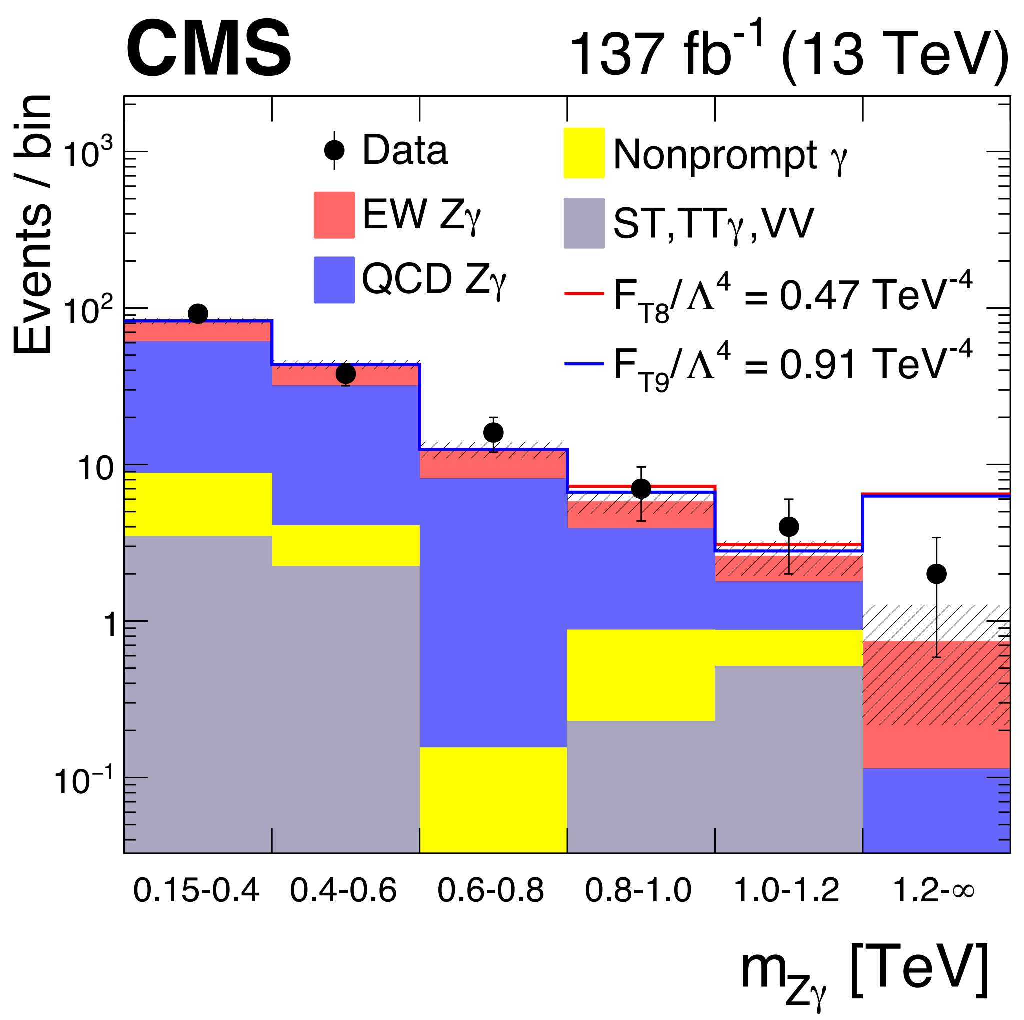
VBS WZ: m_{jj} differential cross section



VBS ZZ(2ℓ2ν): GNN output

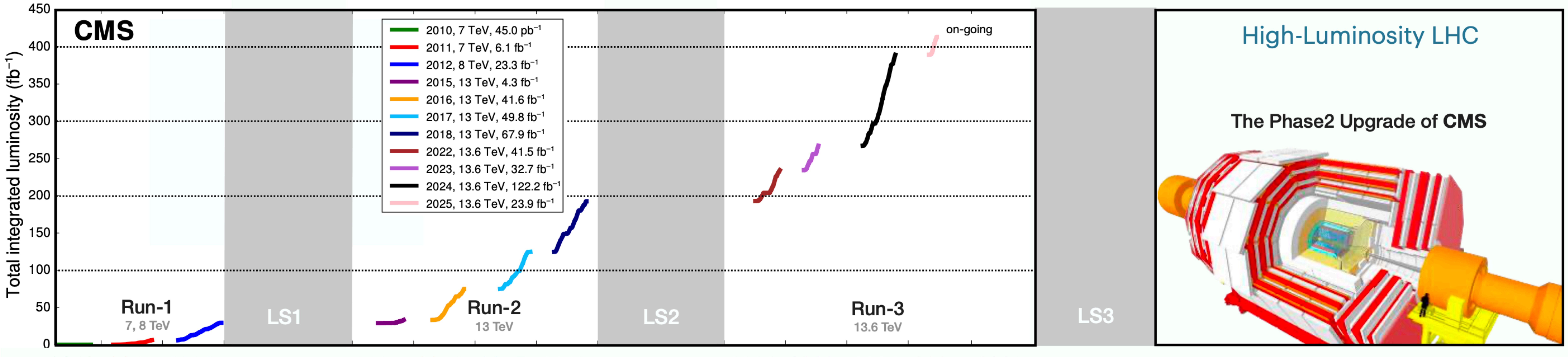


VBS longitudinally polarized same-sig WW: significance 2.3σ for $W_L^\pm W_X^\pm$



VBS Zγ: aQGC for dim-8 operators

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

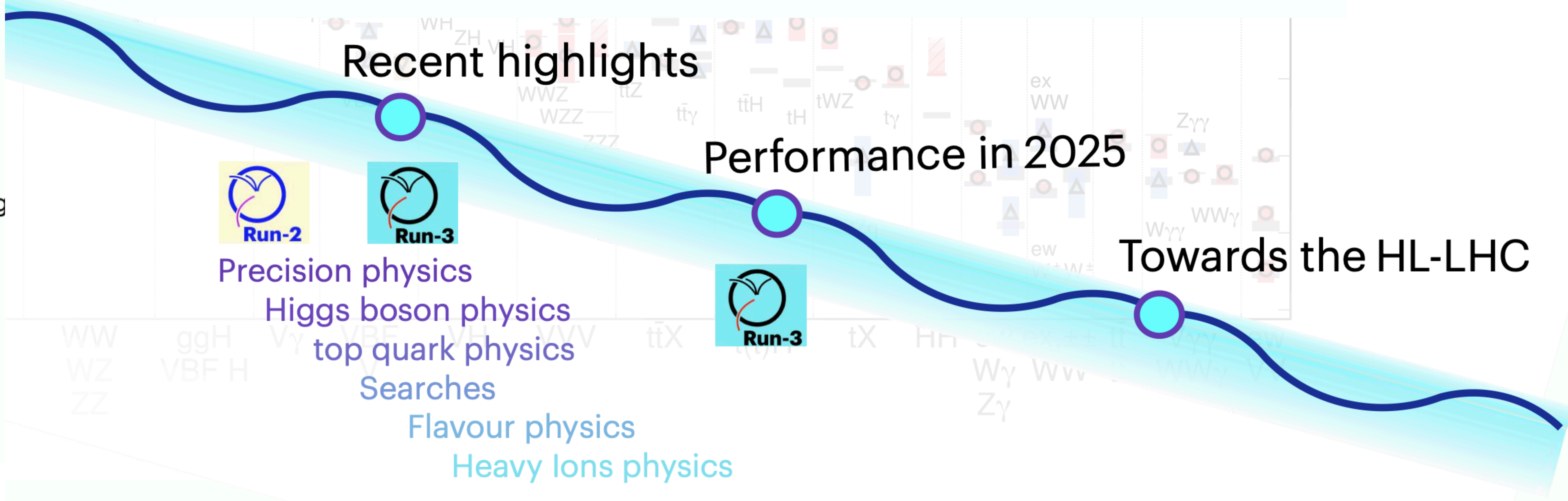
Run-2

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

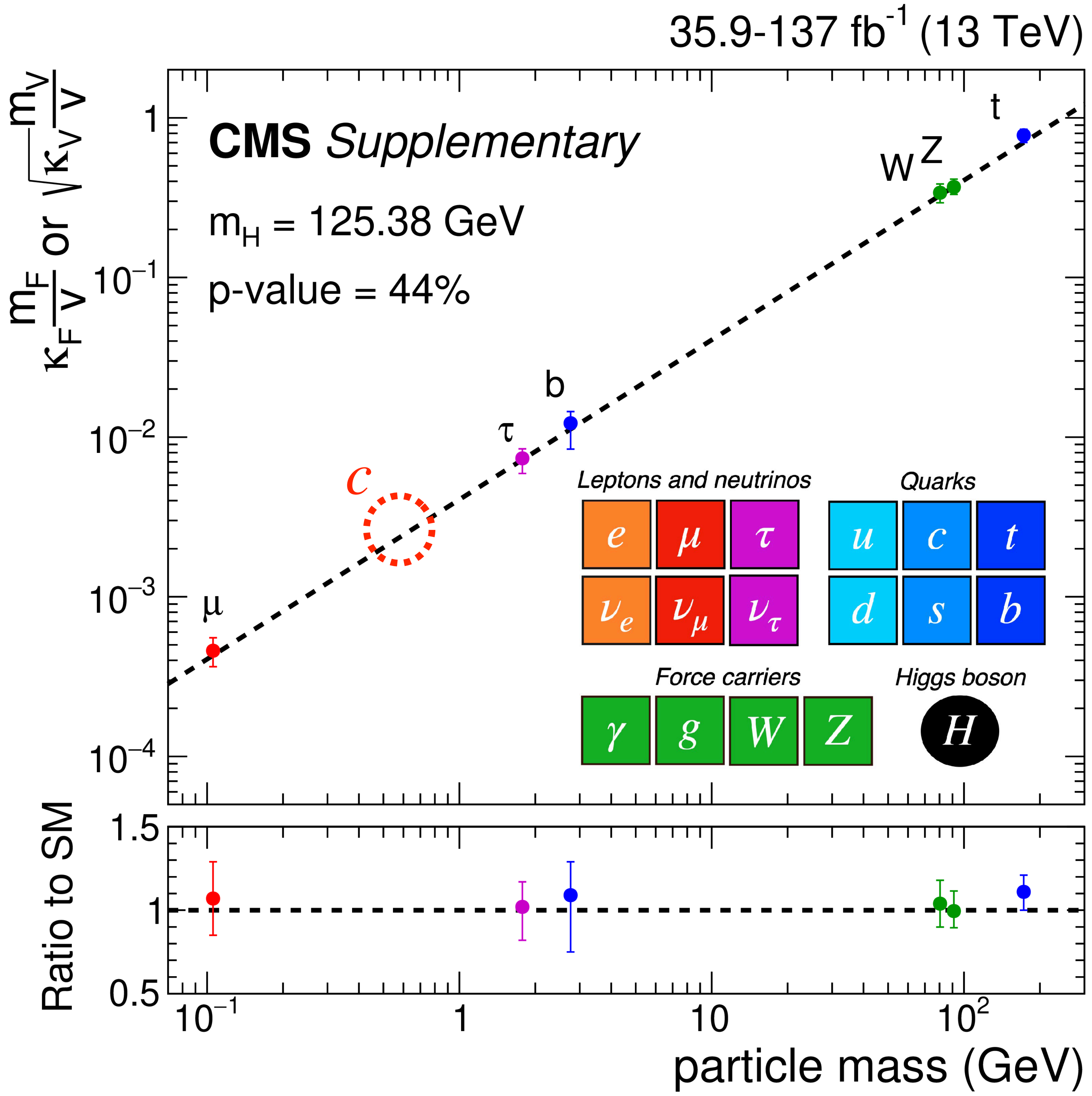
Precision physics
Higgs boson physics
top quark physics
Searches
Flavour physics
Heavy Ions physics

Performance in 2025

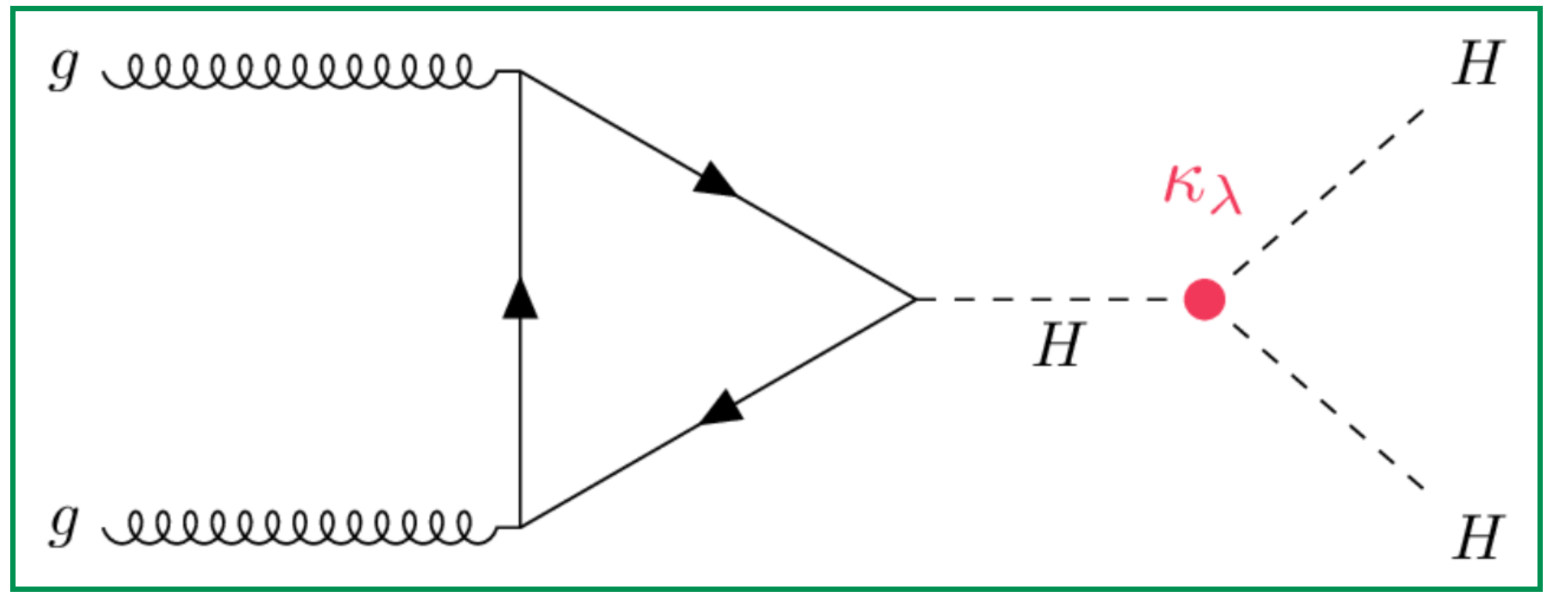
Run-3

Towards the HL-LHC

LHC status and prospect

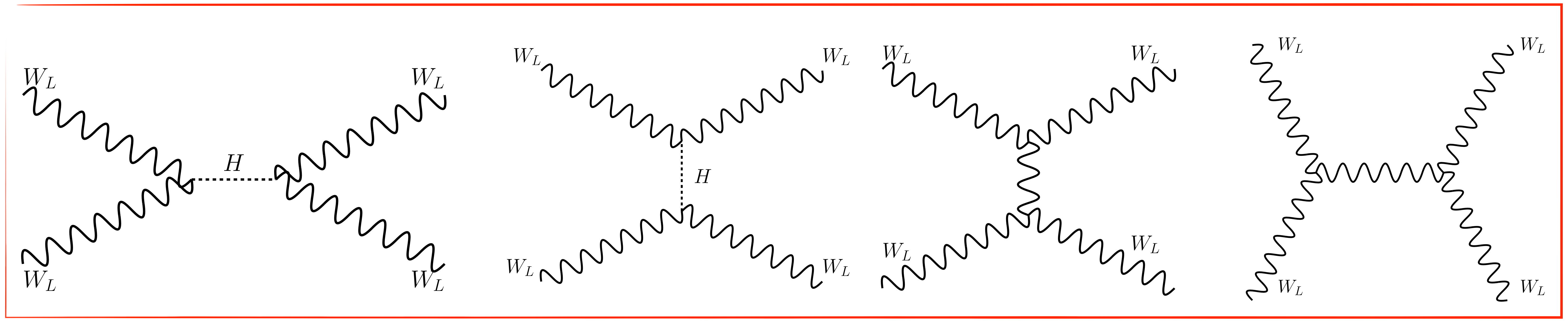


Higgs boson to 1st/2rd fermions couplings

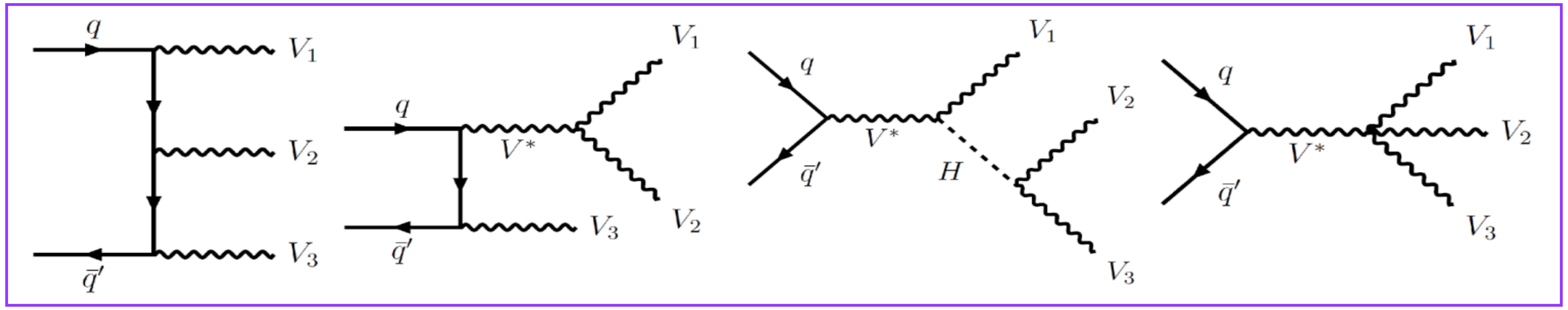


Higgs boson self-coupling

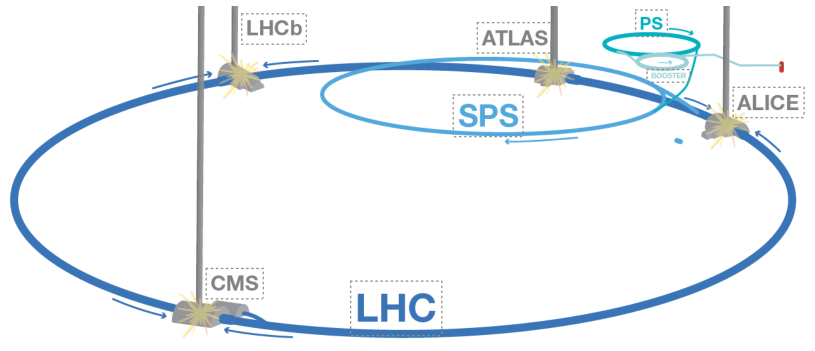
polarised VBS $V_LV_L \rightarrow V_LV_L$

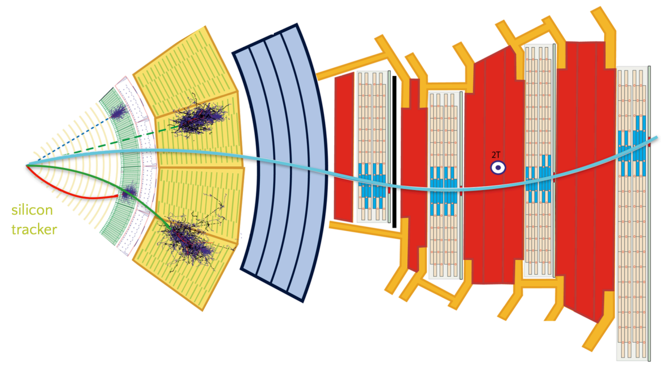


precision rare process measurement in high energy regime



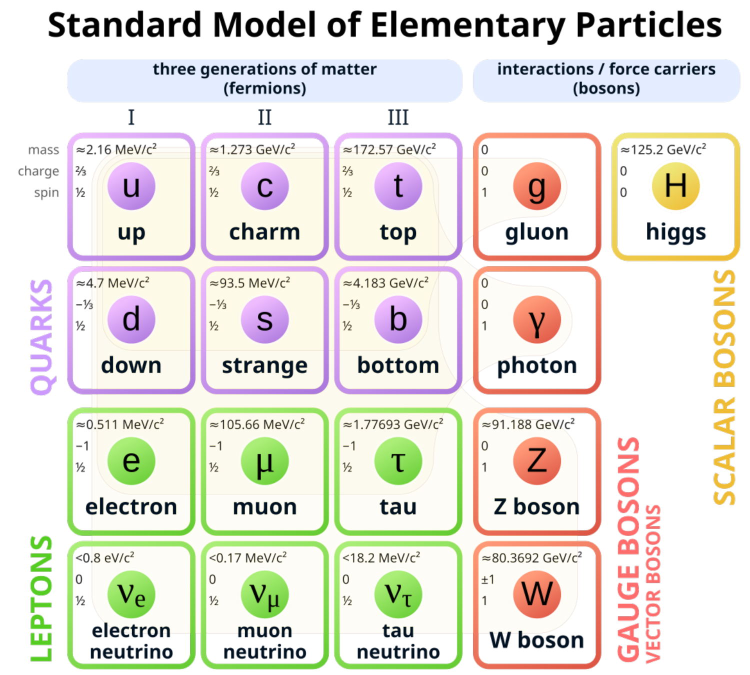
Summary

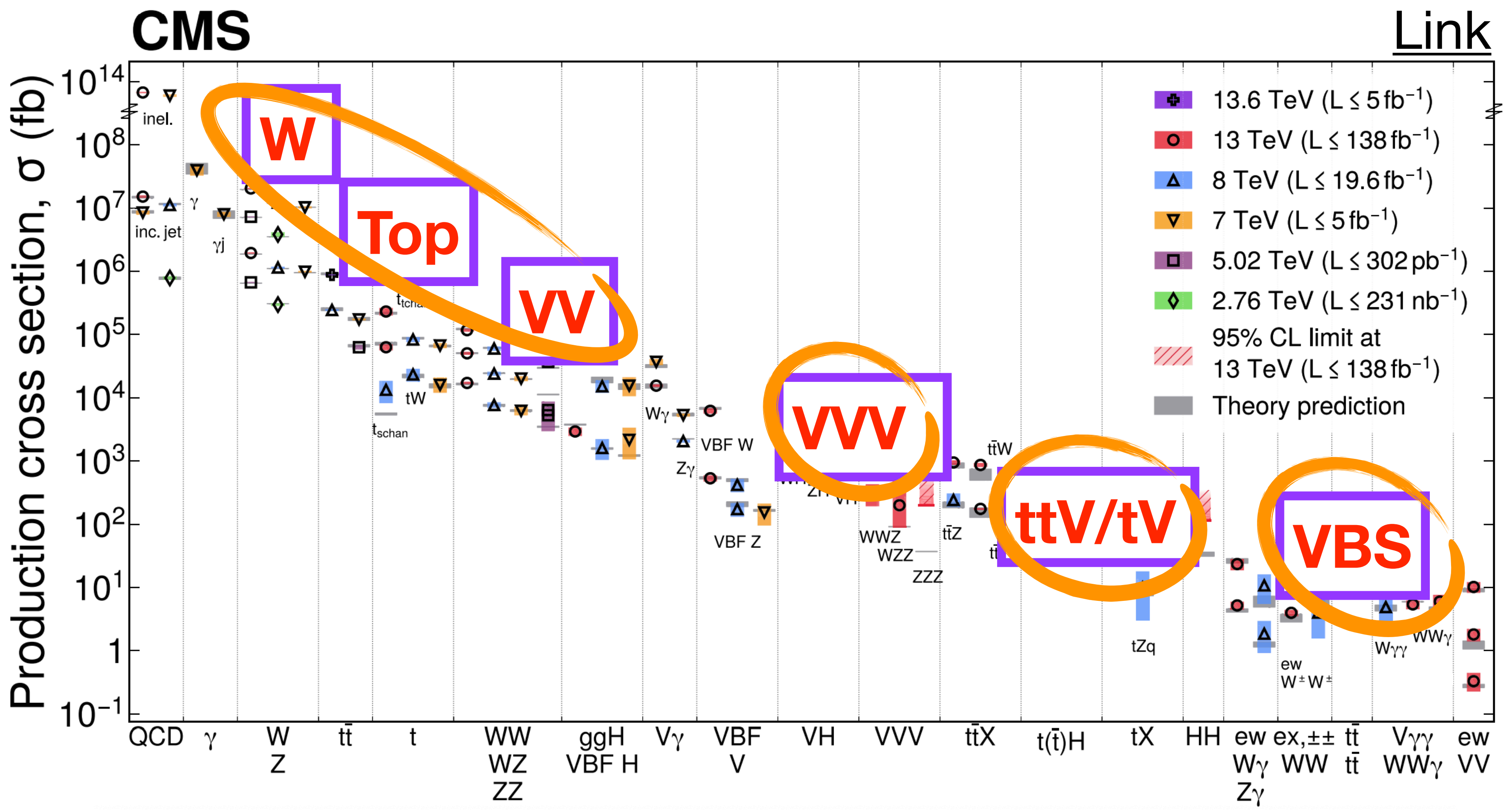




- The SM theory overview
- The introduction of the LHC and CMS
- The workflow of the CMS physics analysis
- The recent highlight of CMS SM results
- W boson and top quark mass
  - Top-gauge boson coupling production
  - Diboson and triboson productions
  - VBS production
- The status and prospects of physics from LHC collisions

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



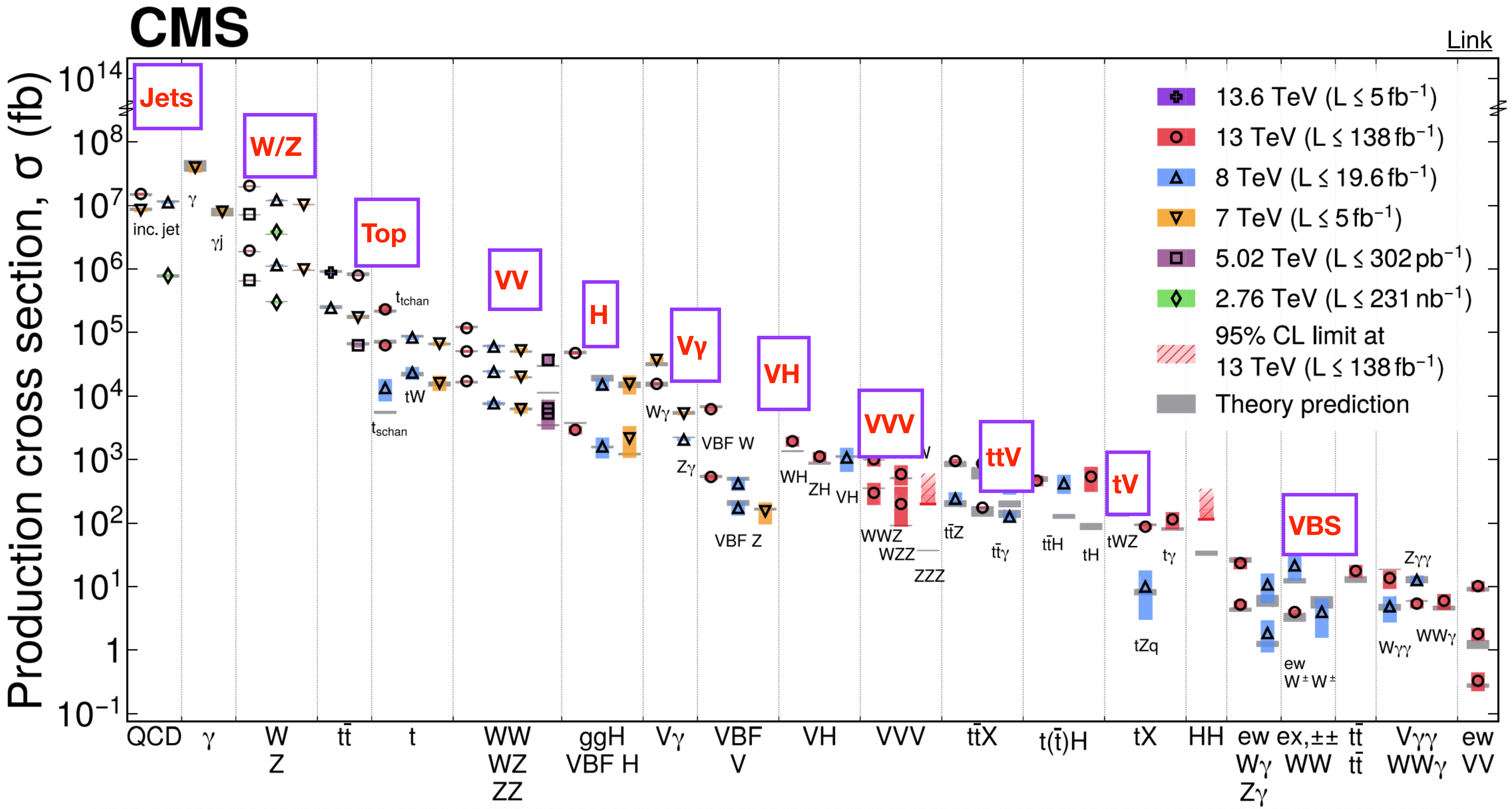


> *With the ongoing Run 3 and the future HL-LHC, we are entering an era where **precision and rare-process measurements** will play an increasingly **central role in particle physics**, and where we expect to **achieve a new generation of representative results***

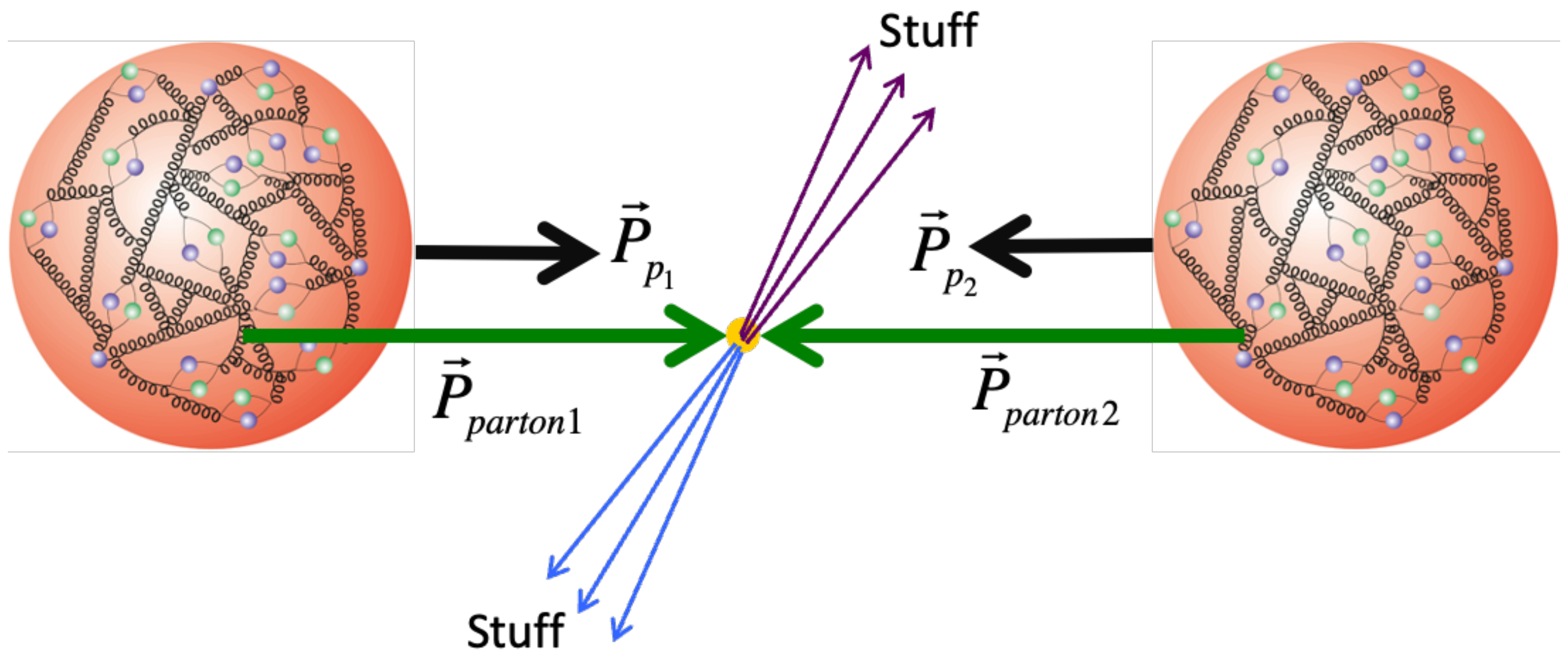
Backup

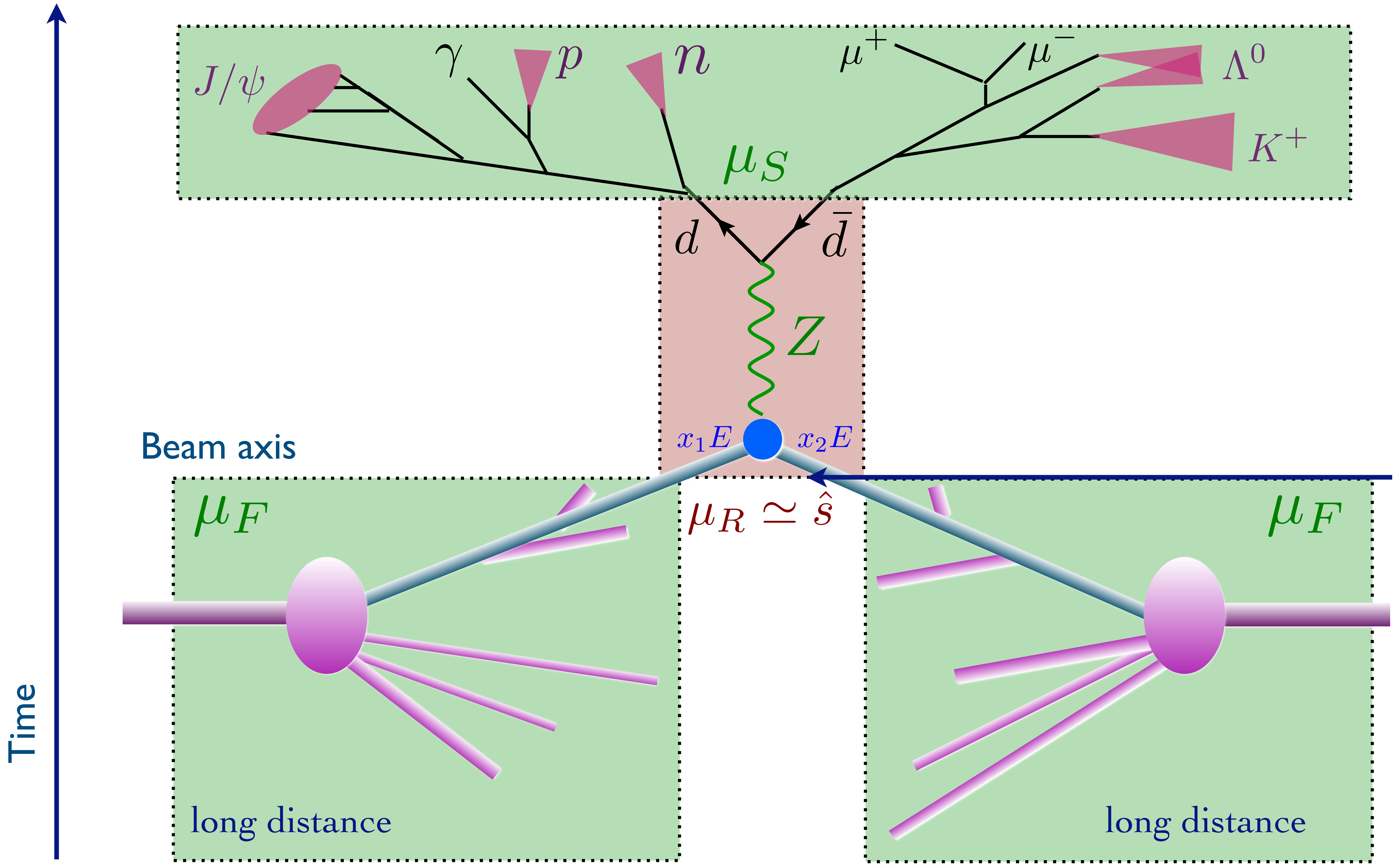
SM measurements

Link



LHC — the production cross-section





$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\rm FS}\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat{\sigma}_{pp\to\{P\}}(\mu_F,\mu_R,\mu_S)\, \mathcal{S}_{\{P\}\to\{H\}}(\mu_S)$$

Phase-space integral

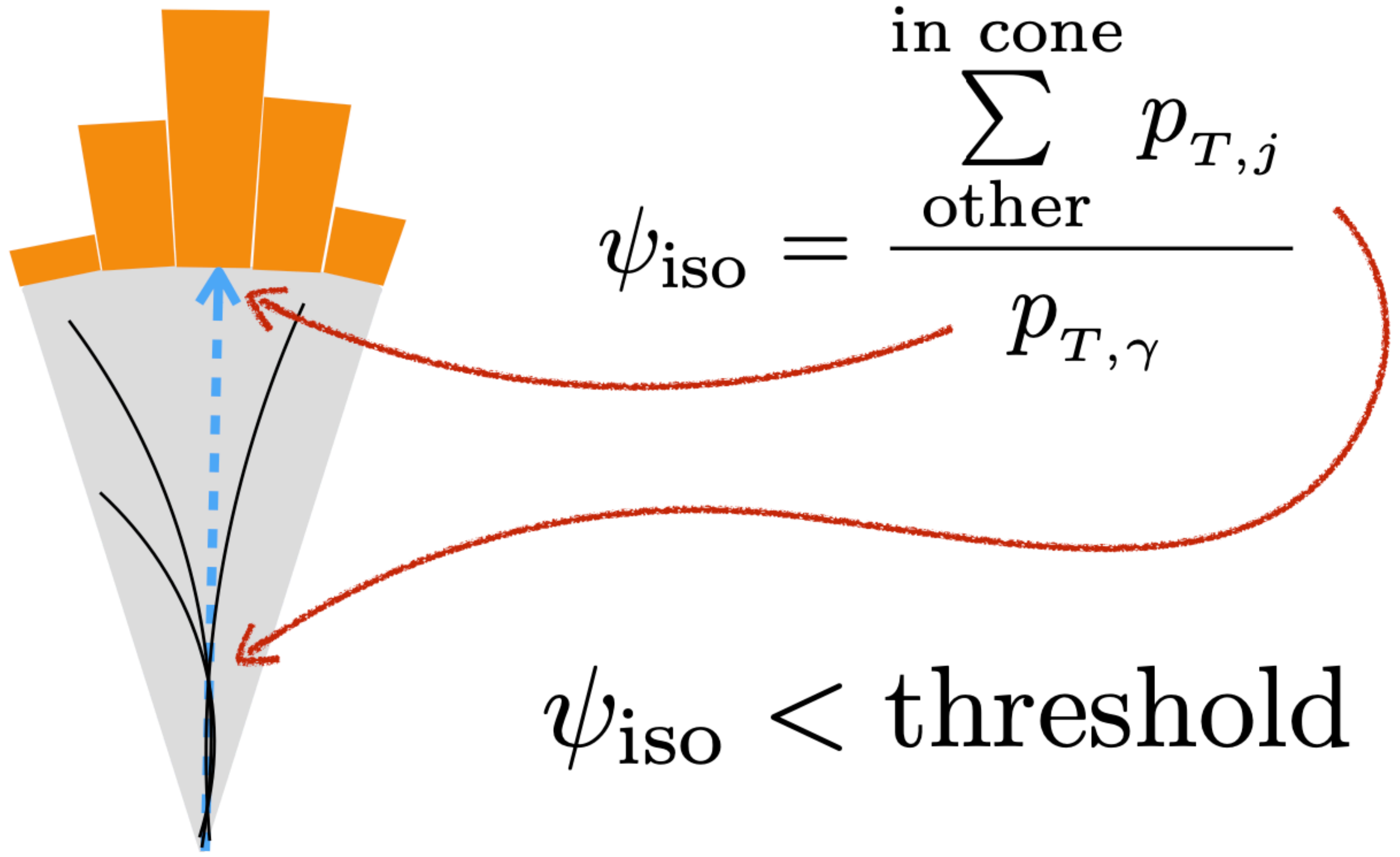
Parton density functions

Parton-level differential cross section

Parton evolution operator

$\mathcal{S} \equiv \mathbb{1}$	Inclusive observables
$\mathcal{S} \equiv$ {parton shower}	All observables

Identification selection

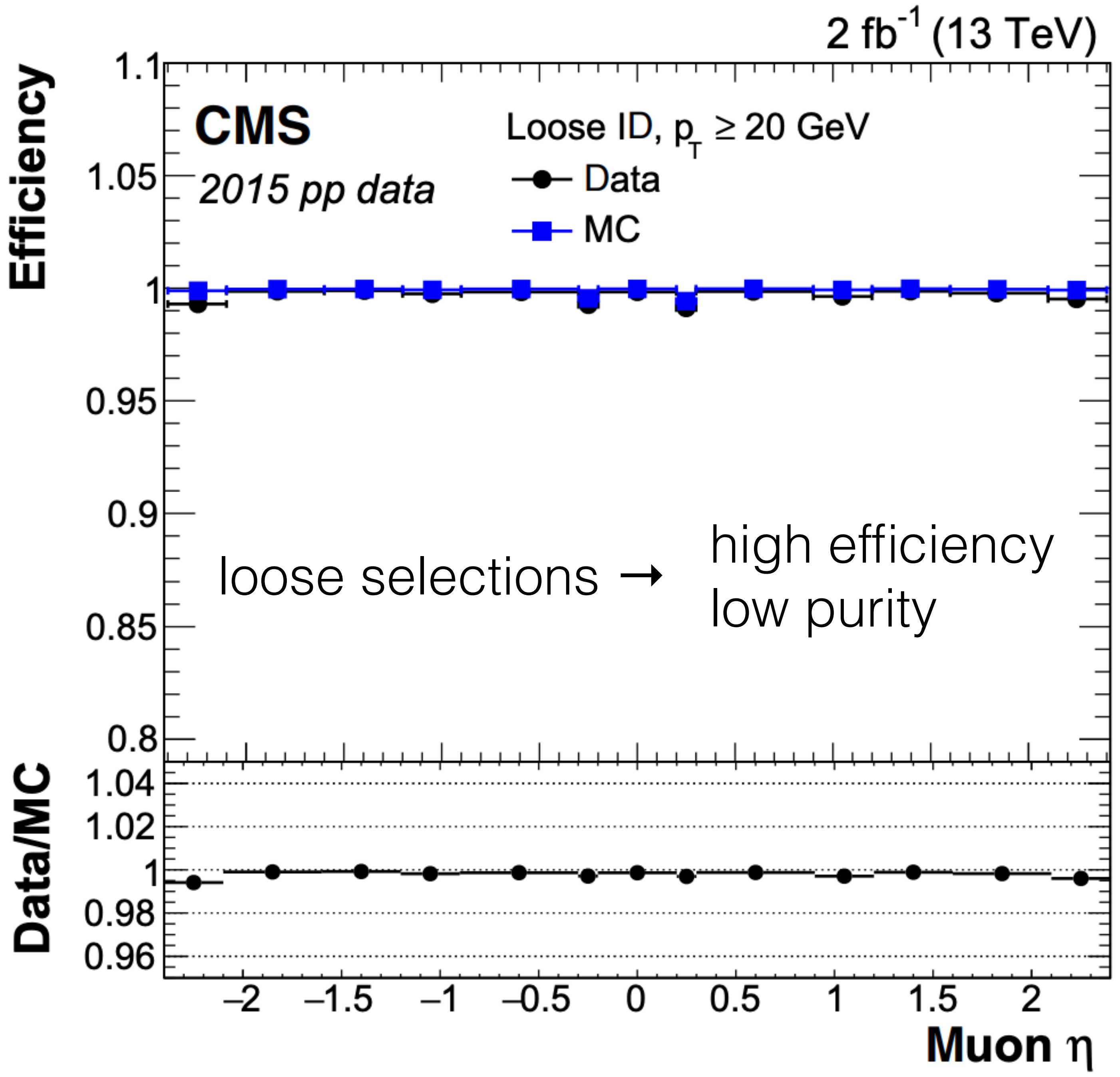


$$\psi_{\text{iso}} = \frac{\sum_{\text{other}}^{\text{in cone}} p_{T,j}}{p_{T,\gamma}}$$

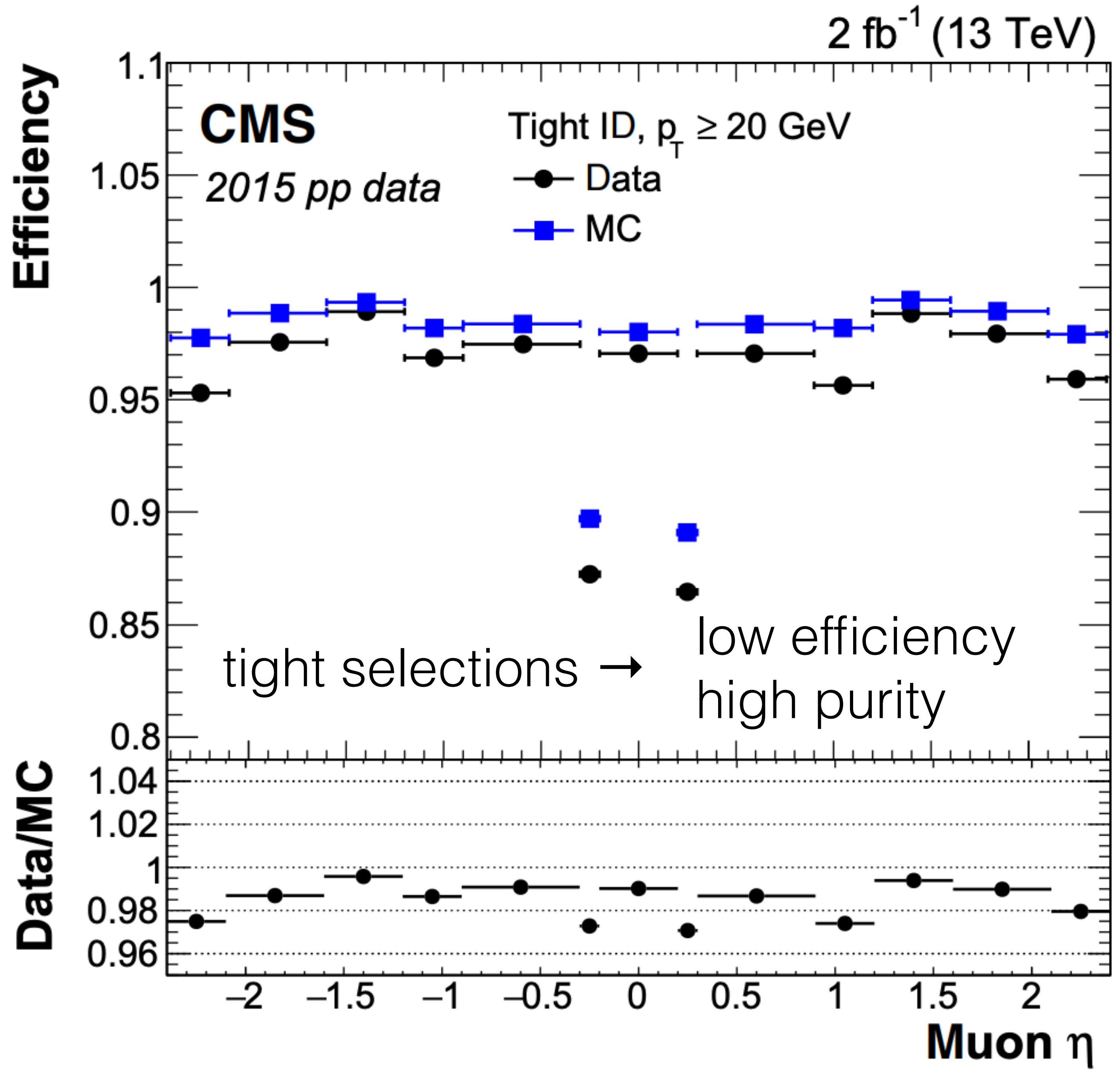
$$\psi_{\text{iso}} < \text{threshold}$$

Cut-based photon identification requirements for the tight working point

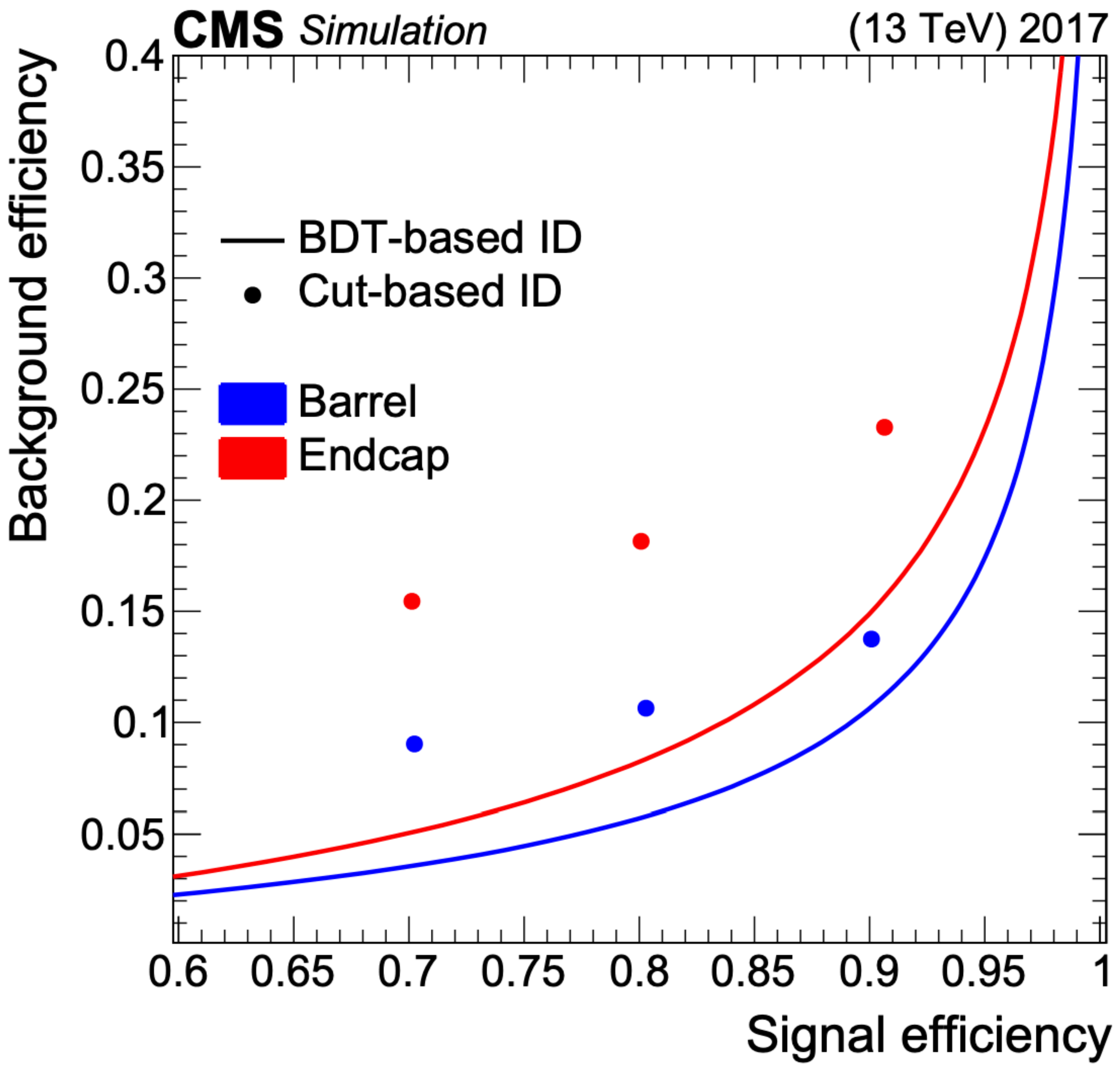
Variable	Barrel (tight WP)	Endcap (tight WP)
H/E	<0.021	<0.032
$\sigma_{i\eta i\eta}$	<0.0099	<0.027
I_{ch}	$<0.65\,\text{GeV}$	$<0.52\,\text{GeV}$
I_{n}	$<0.32\,\text{GeV} + 0.015E_{\text{T}} +$ $2.26\times10^{-5}E_{\text{T}}^2/\text{GeV}$	$<2.72\,\text{GeV} + 0.012E_{\text{T}} +$ $2.3\times10^{-5}E_{\text{T}}^2/\text{GeV}$
I_γ	$<2.04\,\text{GeV} + 0.0040E_{\text{T}}$	$<3.03\,\text{GeV} + 0.0037E_{\text{T}}$



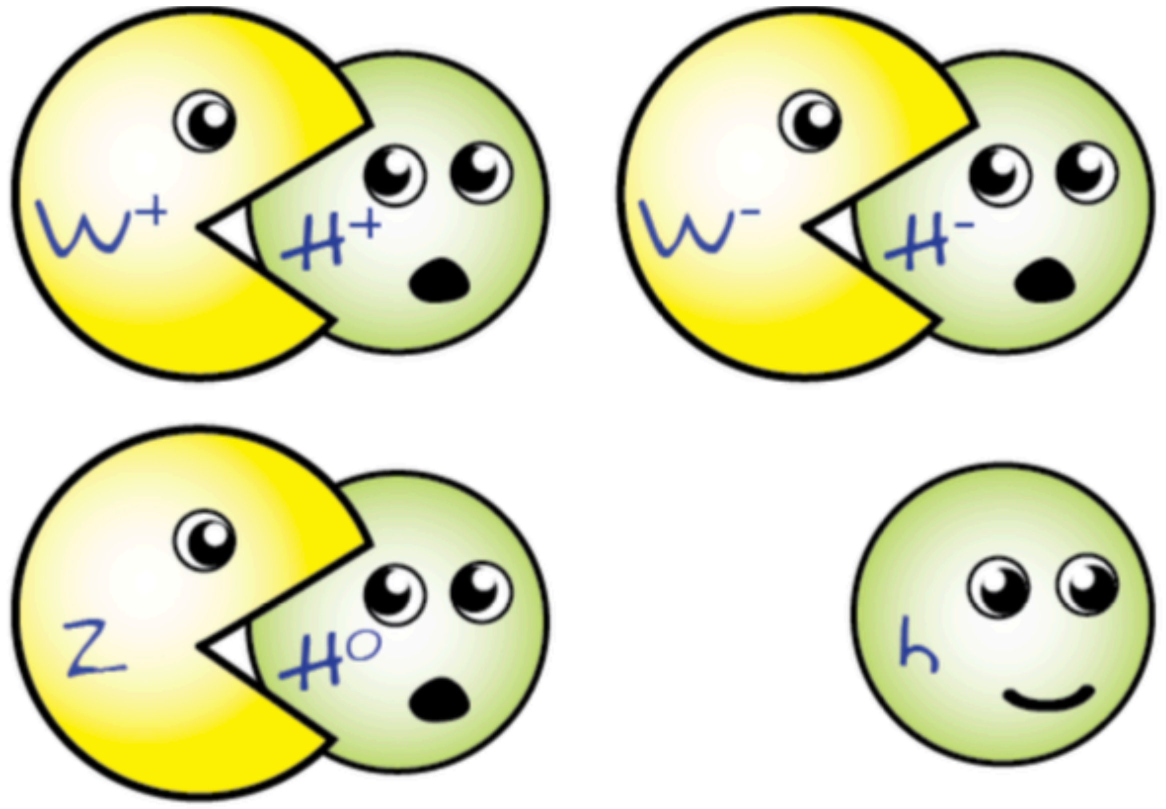
loose selections → high efficiency low purity



tight selections → low efficiency high purity



Diboson production - polarization



Higgs mechanism

⇩

W and Z boson massive

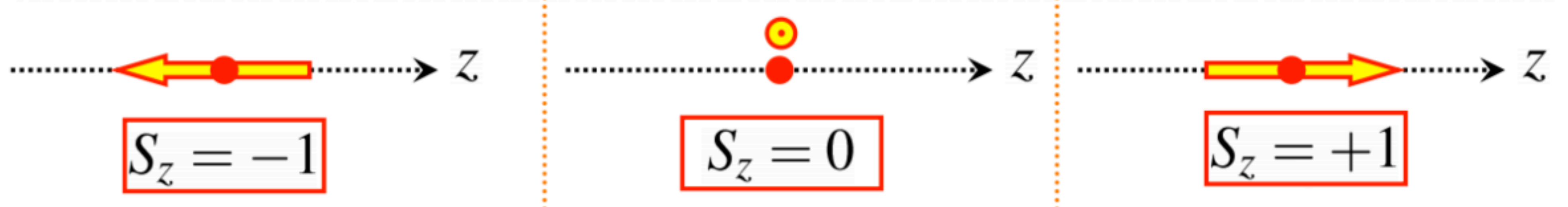
⇩

Longitudinal polarization

- The longitudinally polarization measurement of massive W and Z bosons is a direct way to probe the EWSB mechanism
- Goldstone boson theorem: “At high energy, longitudinal vector bosons are analogous to goldstone bosons”
- Helicity: $h = \frac{\vec{S}\cdot\vec{p}}{|\vec{p}|}$ (spin $\vec{S}$, momentum $\vec{p}$)
  - Transversal (T): left-/right-handed ($h = -/+1$)
  - Longitudinal (L): spin orthogonal to the momenta ($h = 0$)
- Polarization vectors in the helicity basis:

★ **For a spin-1 boson travelling along the z-axis, the polarization four vectors are:**

$$\varepsilon^{\mu}_{-} = \frac{1}{\sqrt{2}}(0,1,-i,0); \quad \varepsilon_L = \frac{1}{m}(p_z,0,0,E) \quad \varepsilon^{\mu}_{+} = -\frac{1}{\sqrt{2}}(0,1,i,0)$$



$S_z = -1$ $S_z = 0$ $S_z = +1$

transverse **longitudinal** **transverse**

Longitudinal polarization isn’t present for on-shell massless particles, the photon can exist in two helicity states $h = \pm 1$ (LH and RH circularly polarized light)