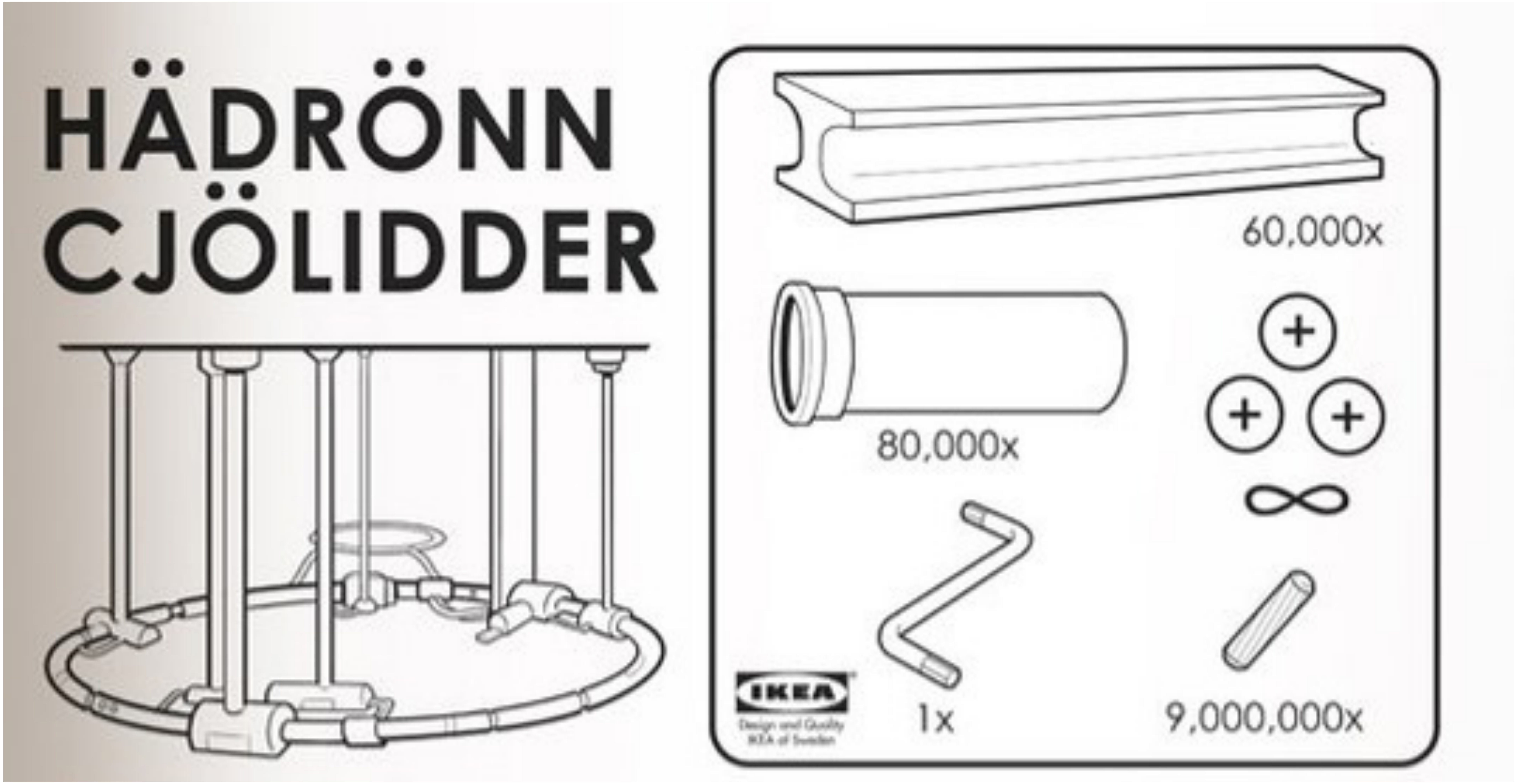
The scattering of vector bosons in proton collisions and some future developments

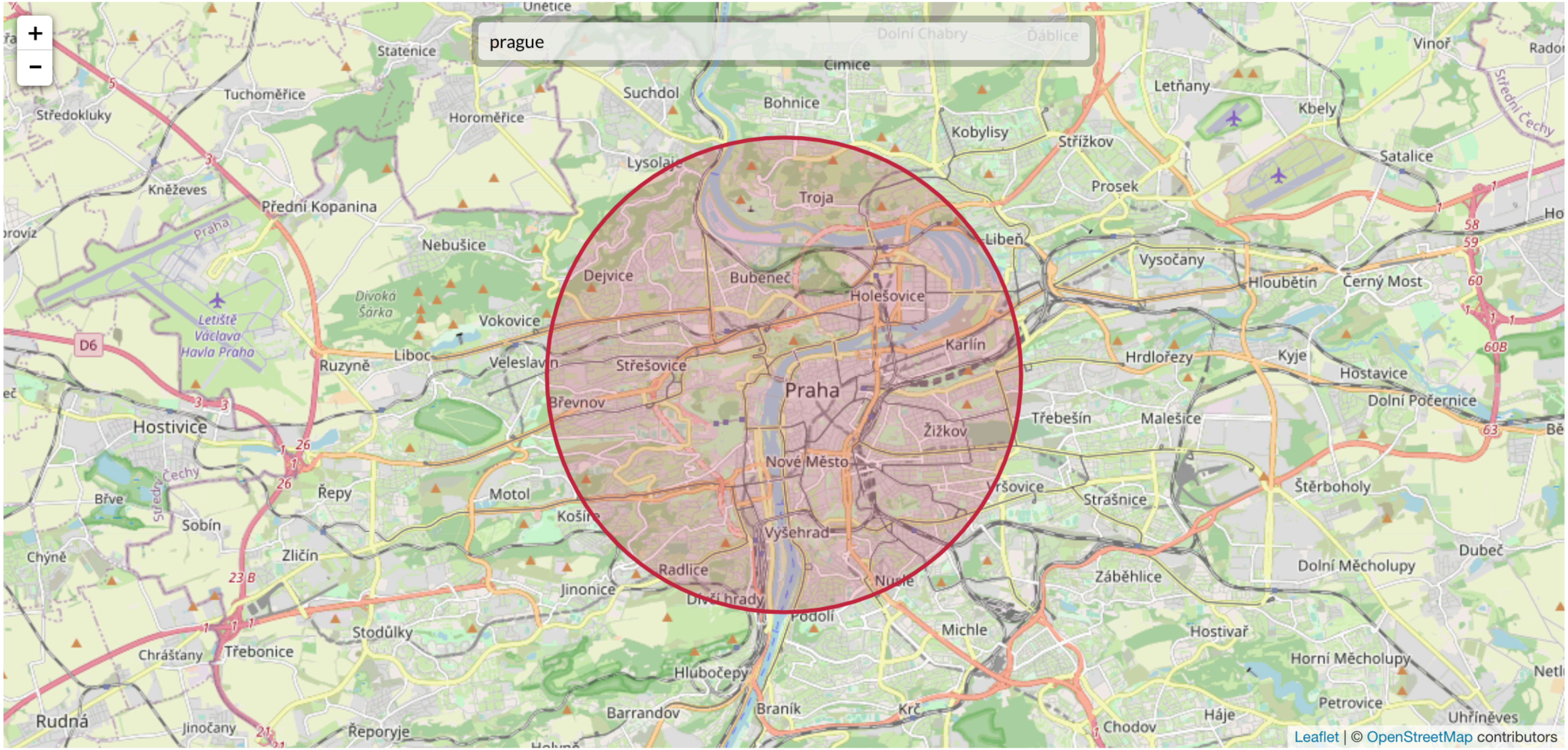
P. Govoni
University and INFN, Milano - Bicocca

29/09/22, Institute for Physics at the Czech Academy of Sciences

the Large Hadron Collider



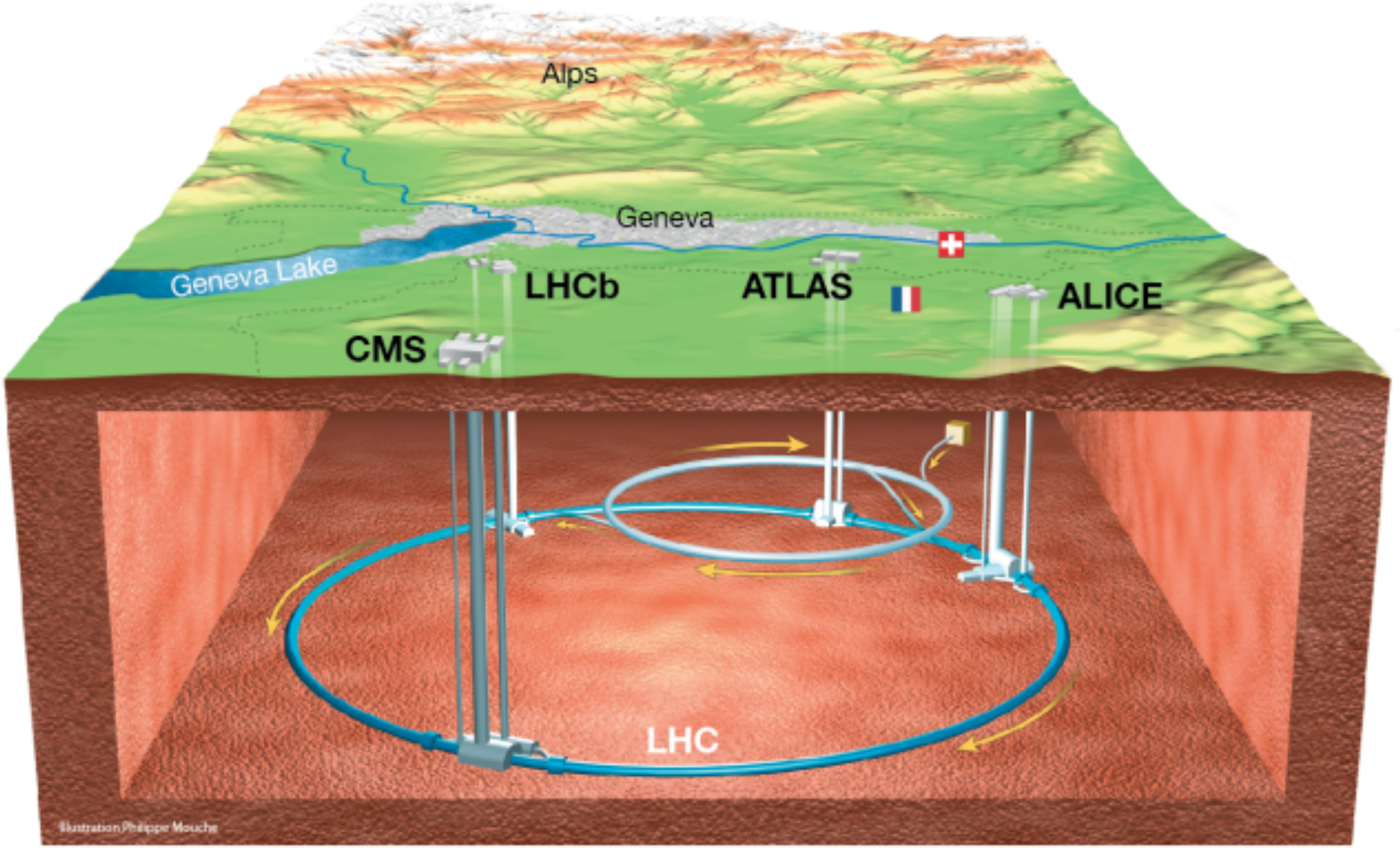
the LHC at home



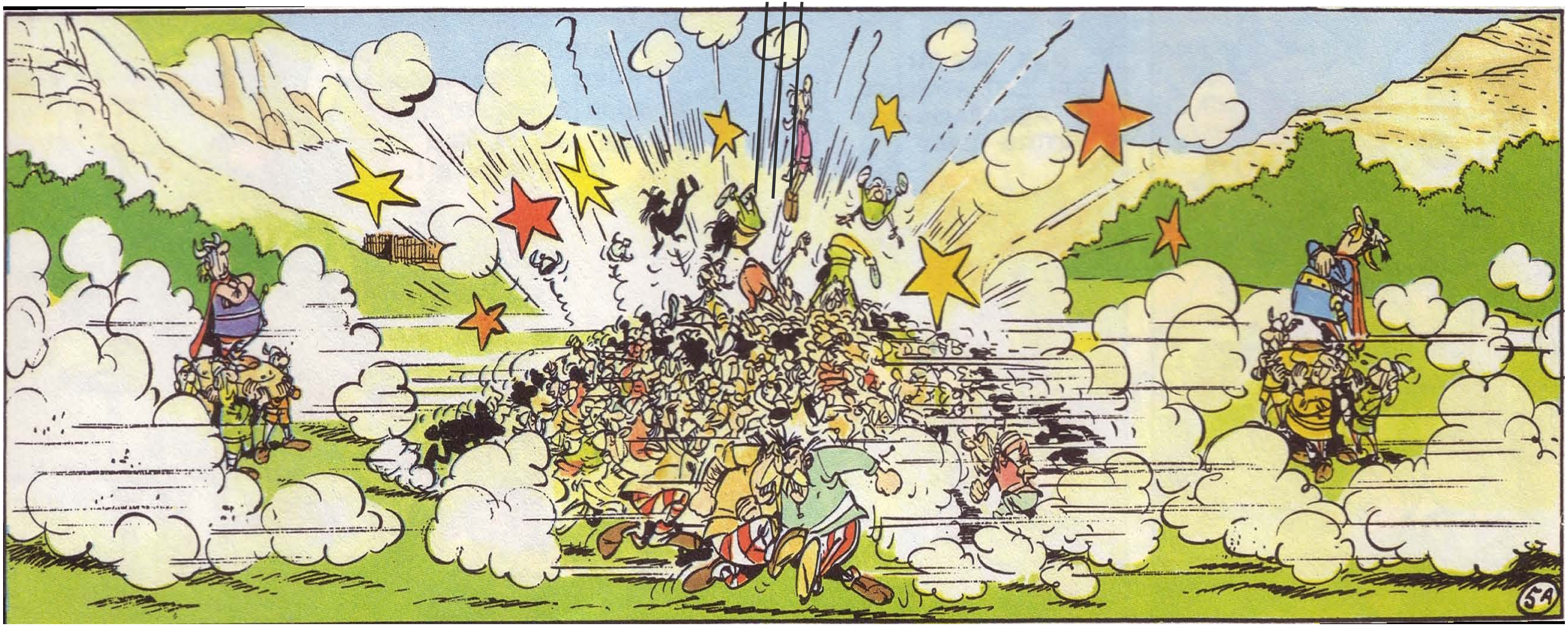
prague

https://natronics.github.io/science-hack-day-2014/lhc-map/

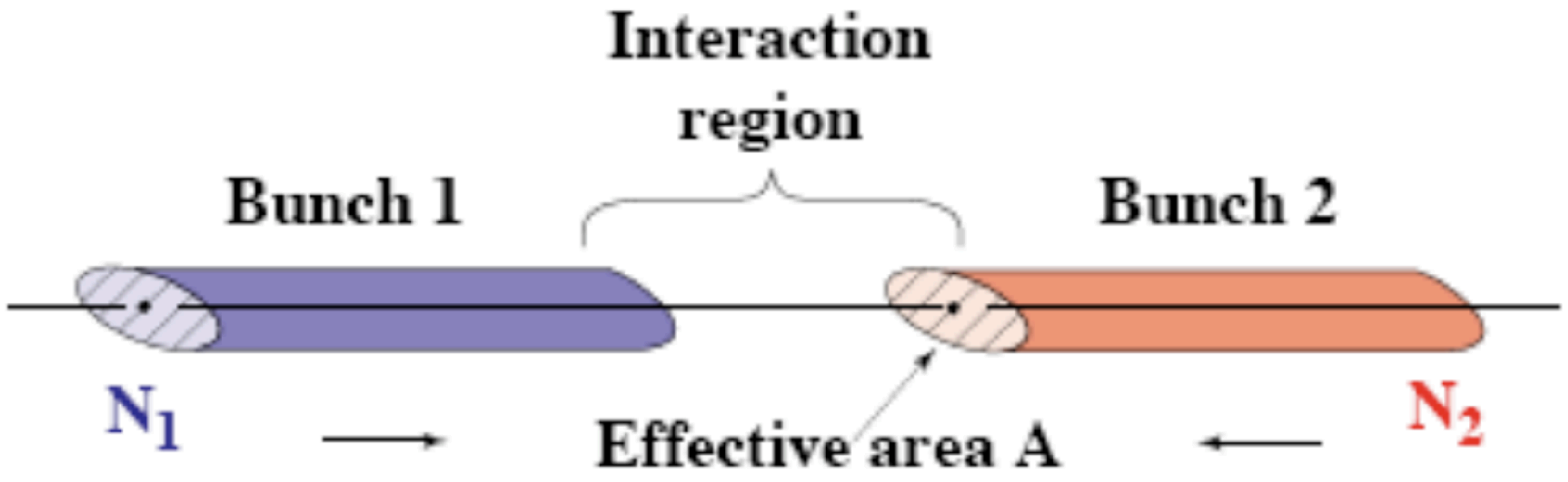
the Large Hadron Collider



the proton beam collision at the LHC

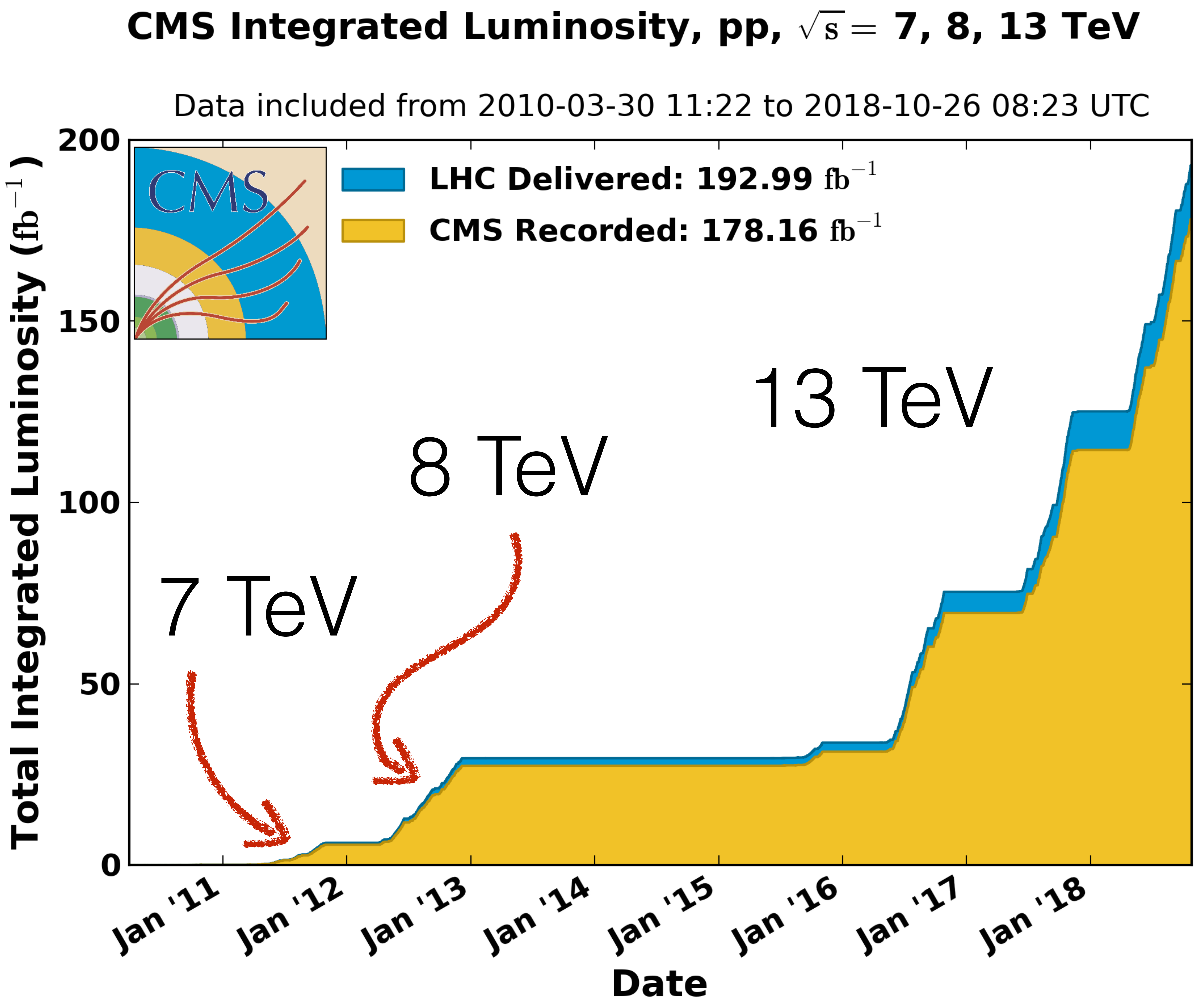


the beam collisions

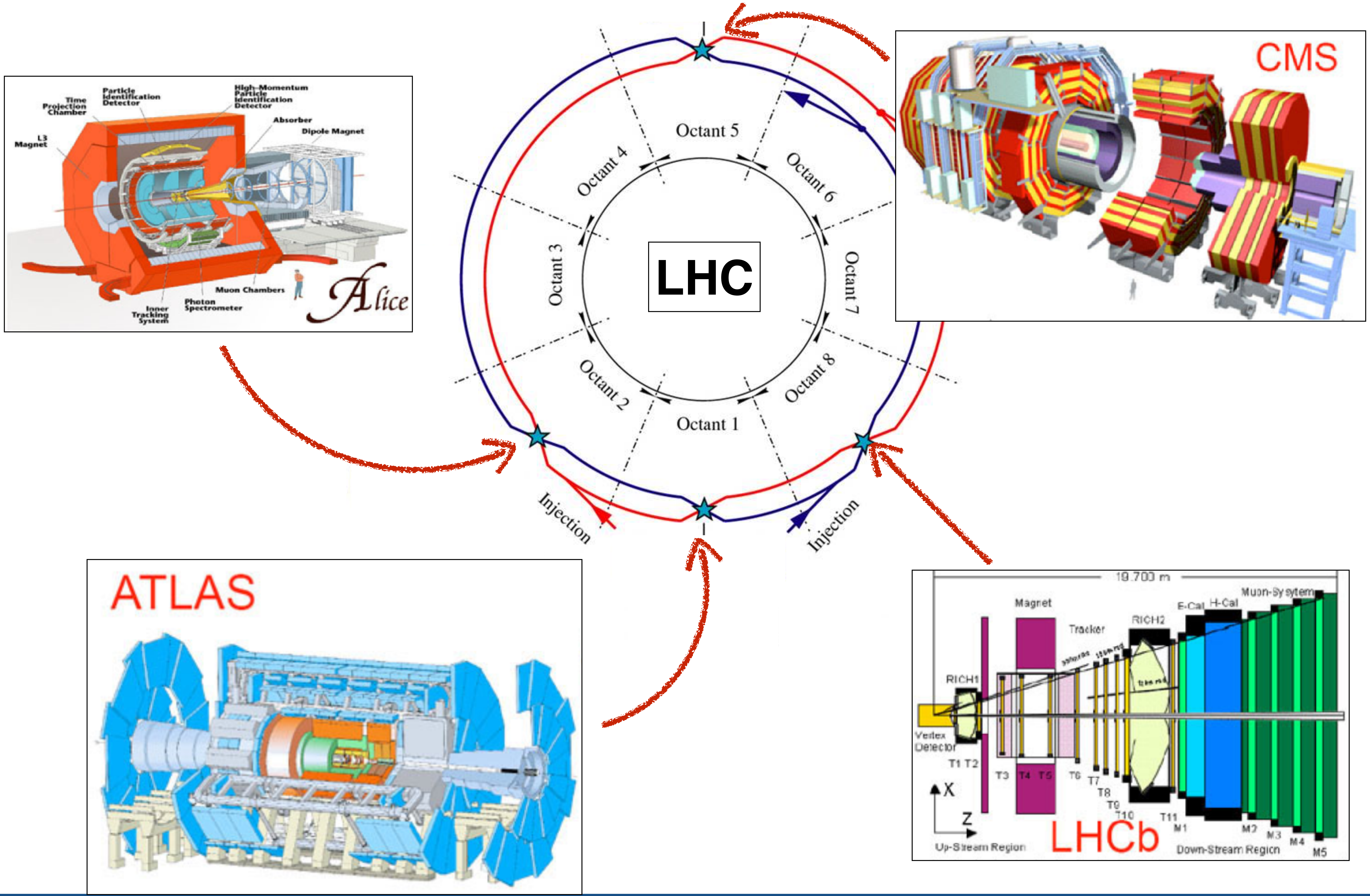


$$E_{c.m.} = \sqrt{s} = E_{p_1} + E_{p_2}$$

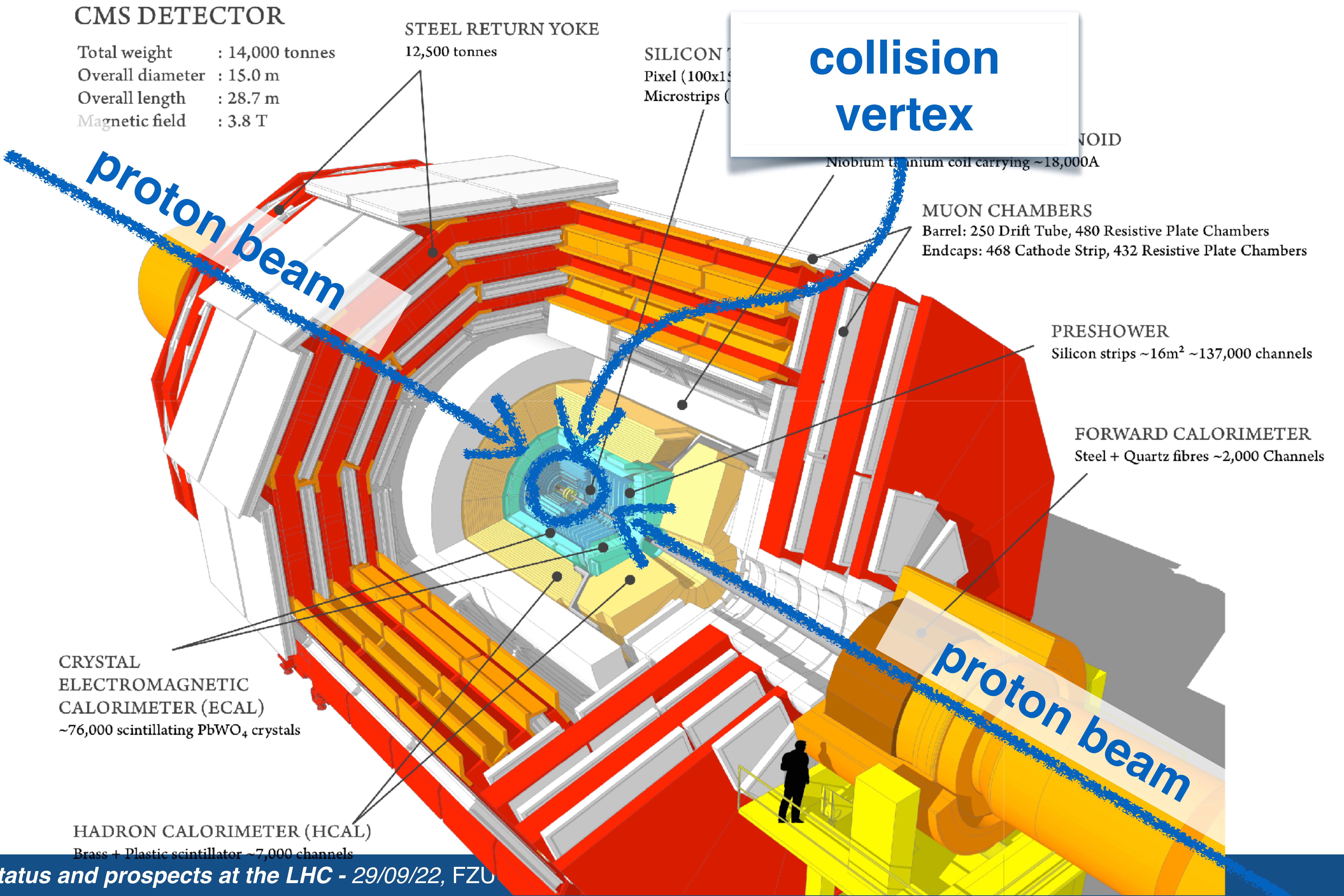
$$N = \int \mathcal{L}\, dt\ \sigma = L\sigma$$



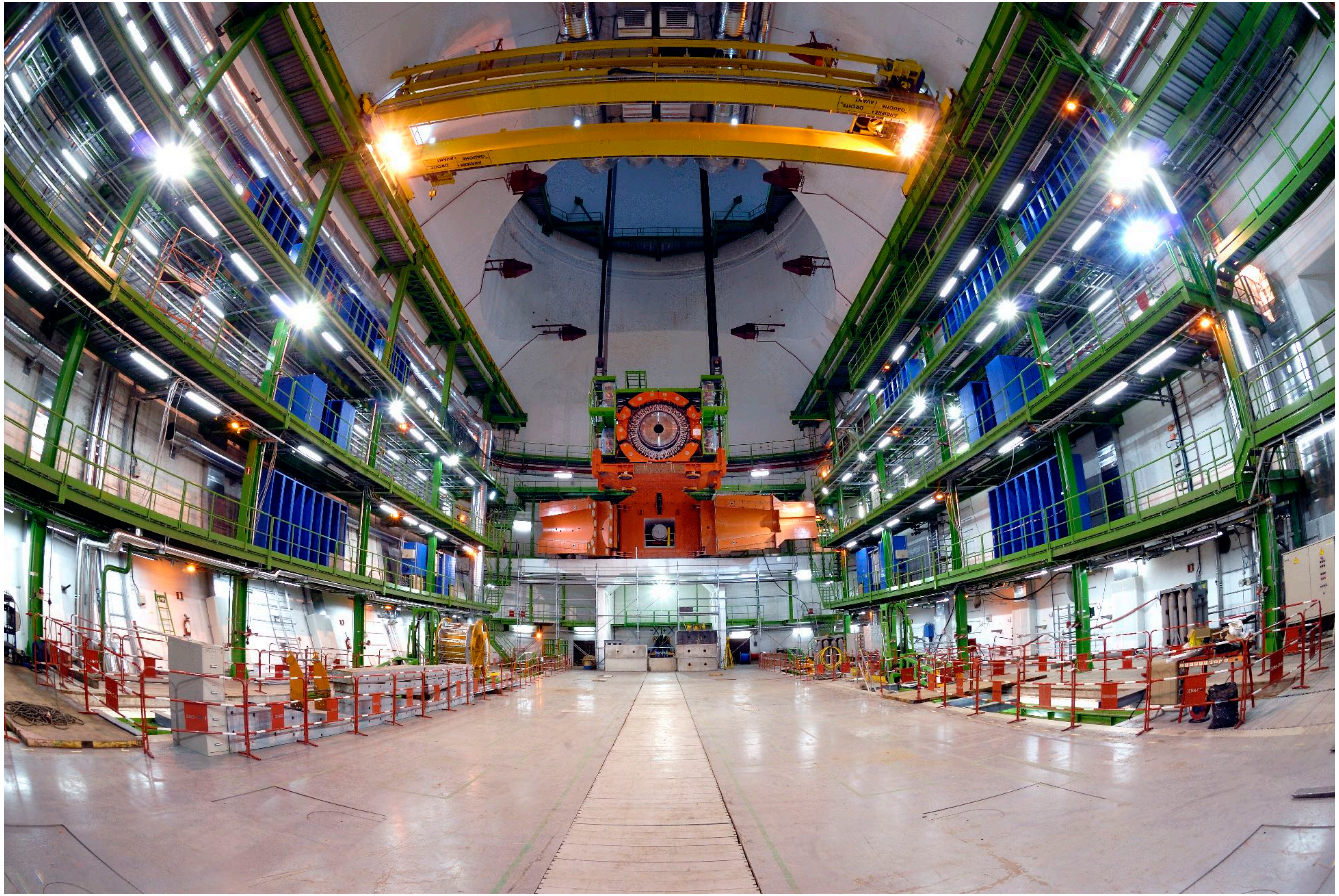
the particle detectors



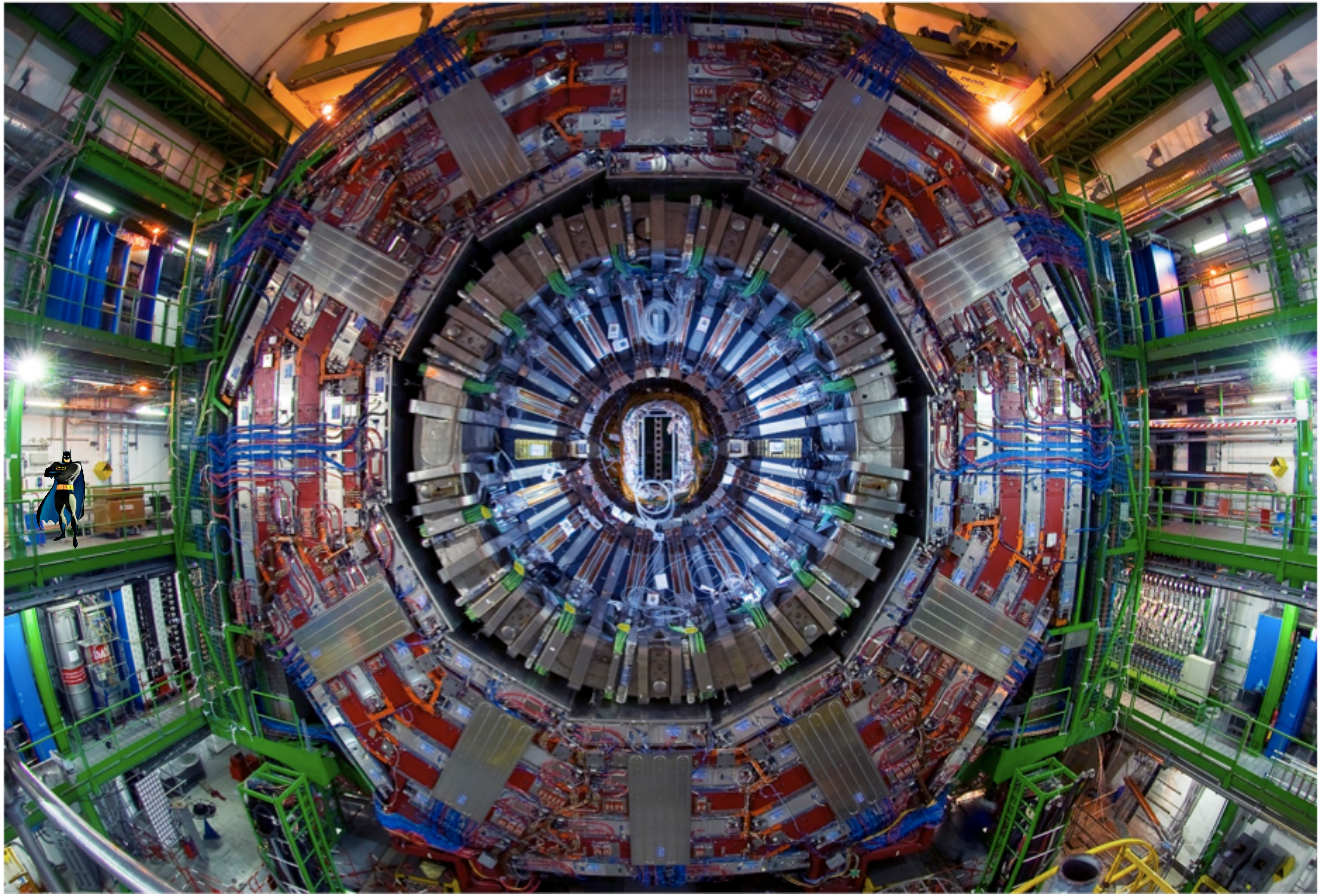
the Compact Muon Solenoid, CMS



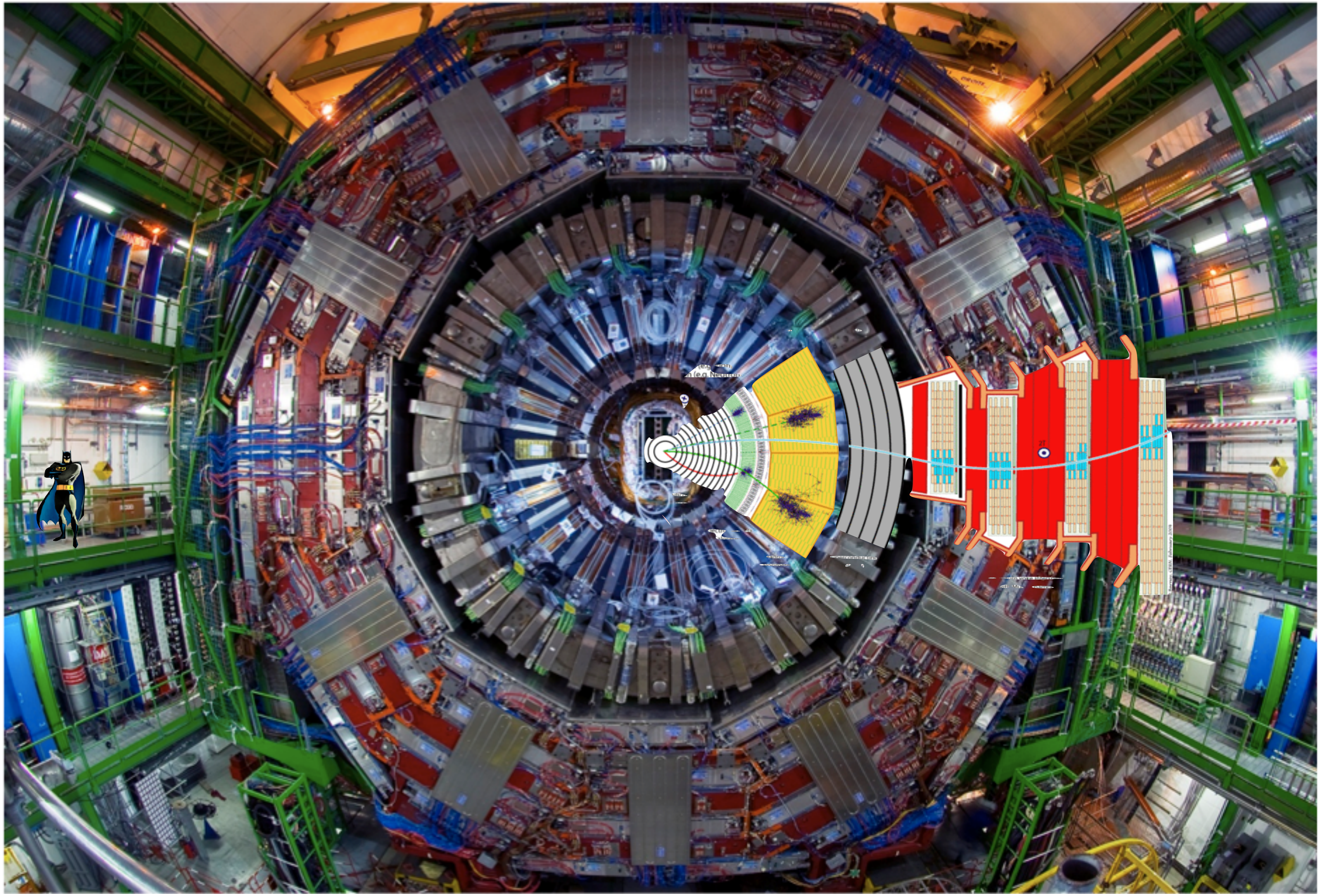
the CMS cavern



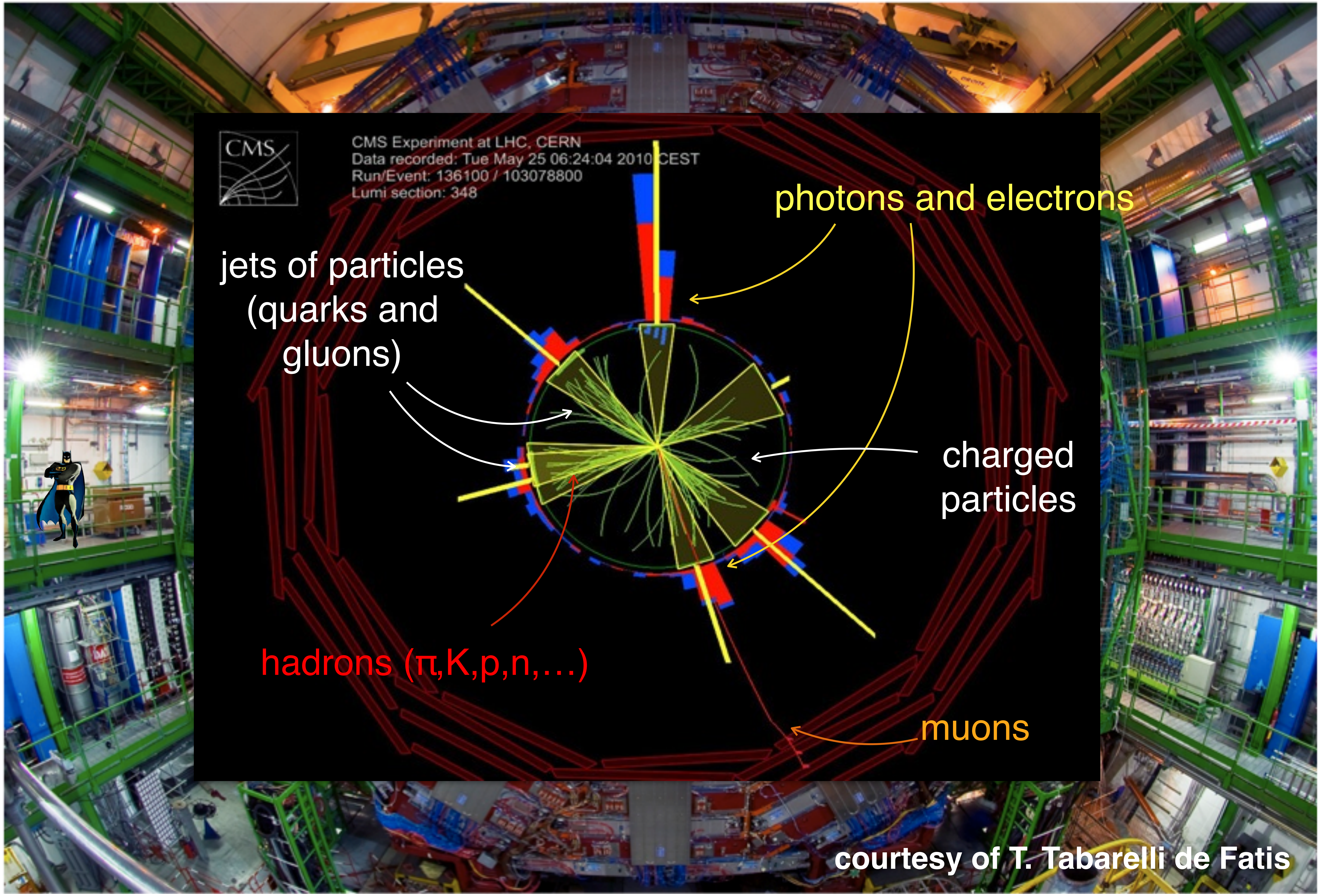
the CMS detector in it



CMS particle identification



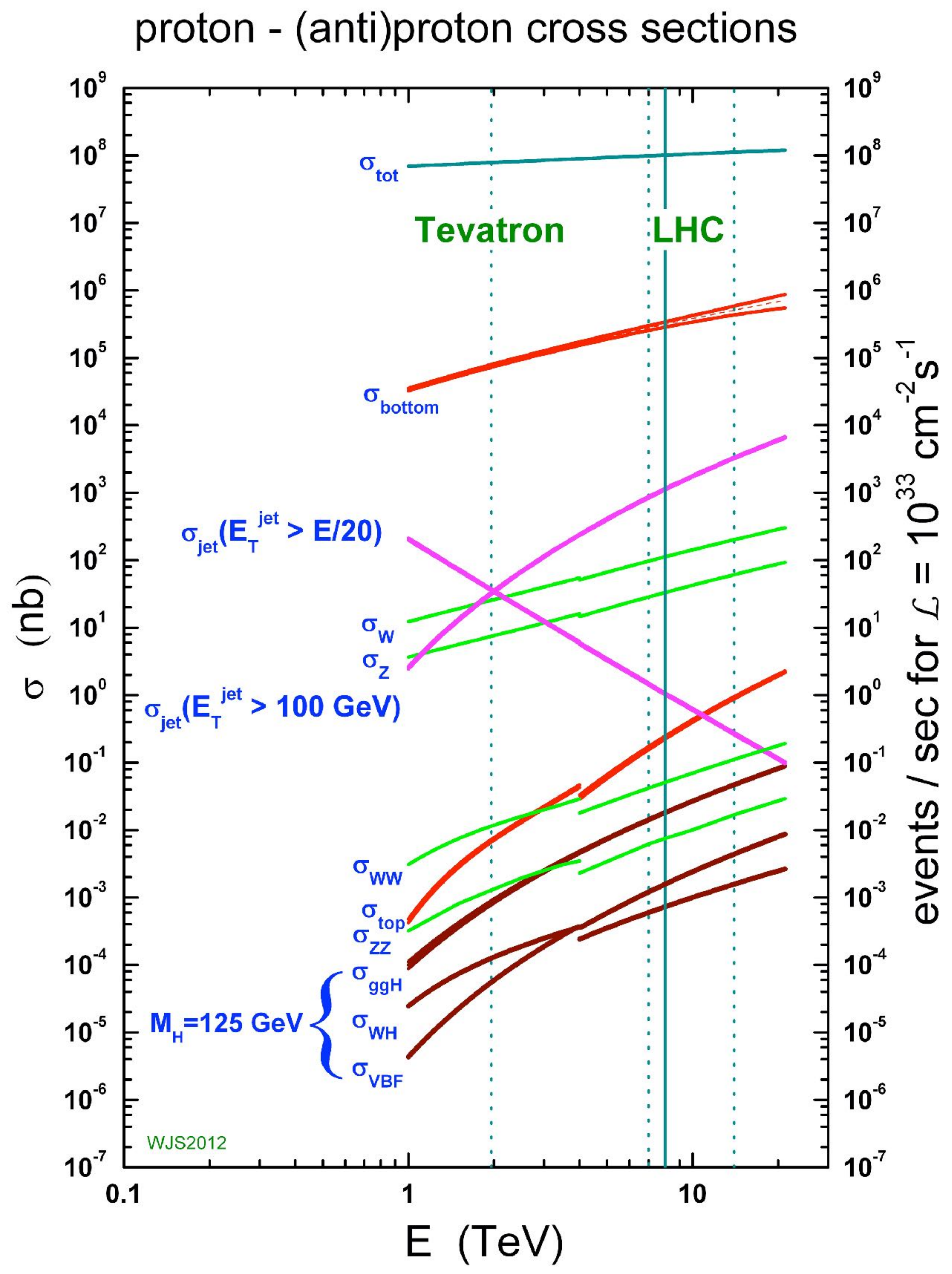
CMS event visualisation



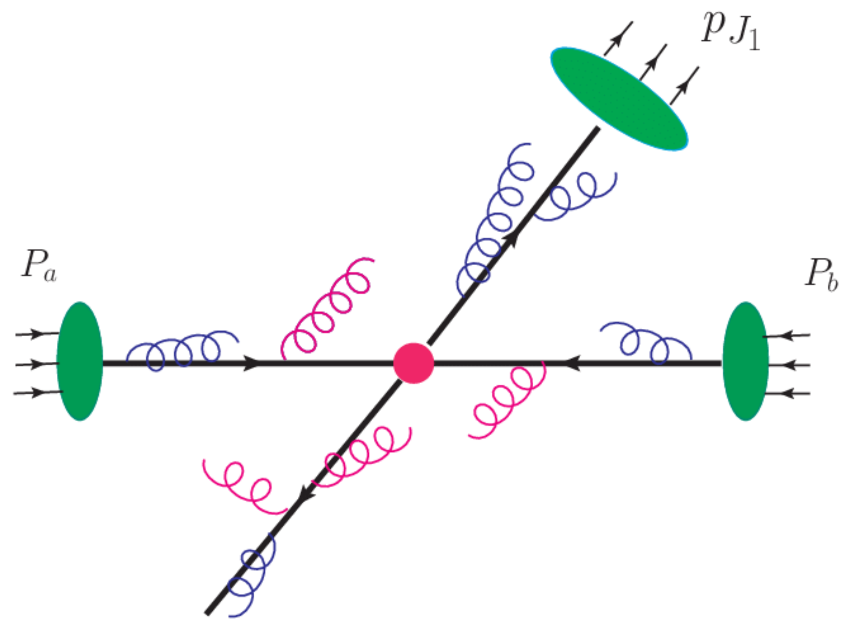
courtesy of T. Tabarelli de Fatis

expected processes at the LHC

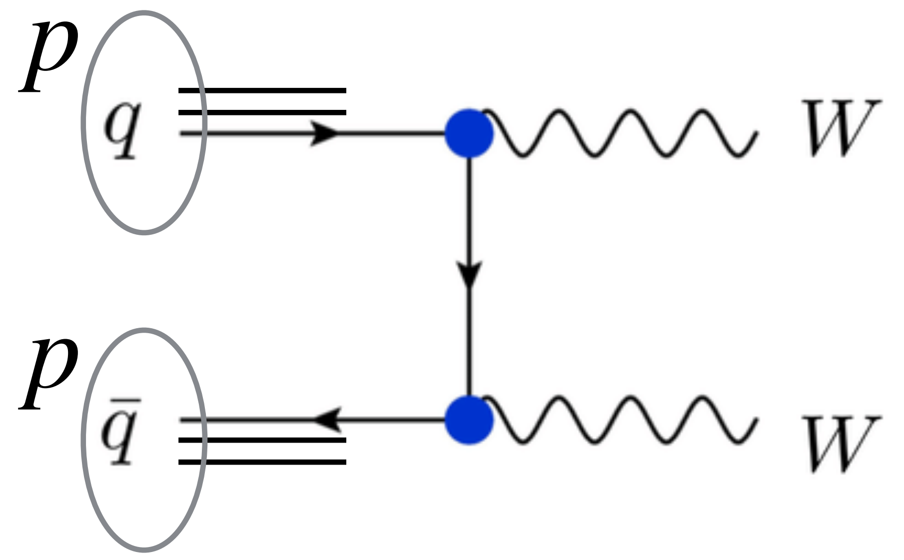
J. Stirling's plots
https://arxiv.org/abs/1412.1337



purely-QCD processes

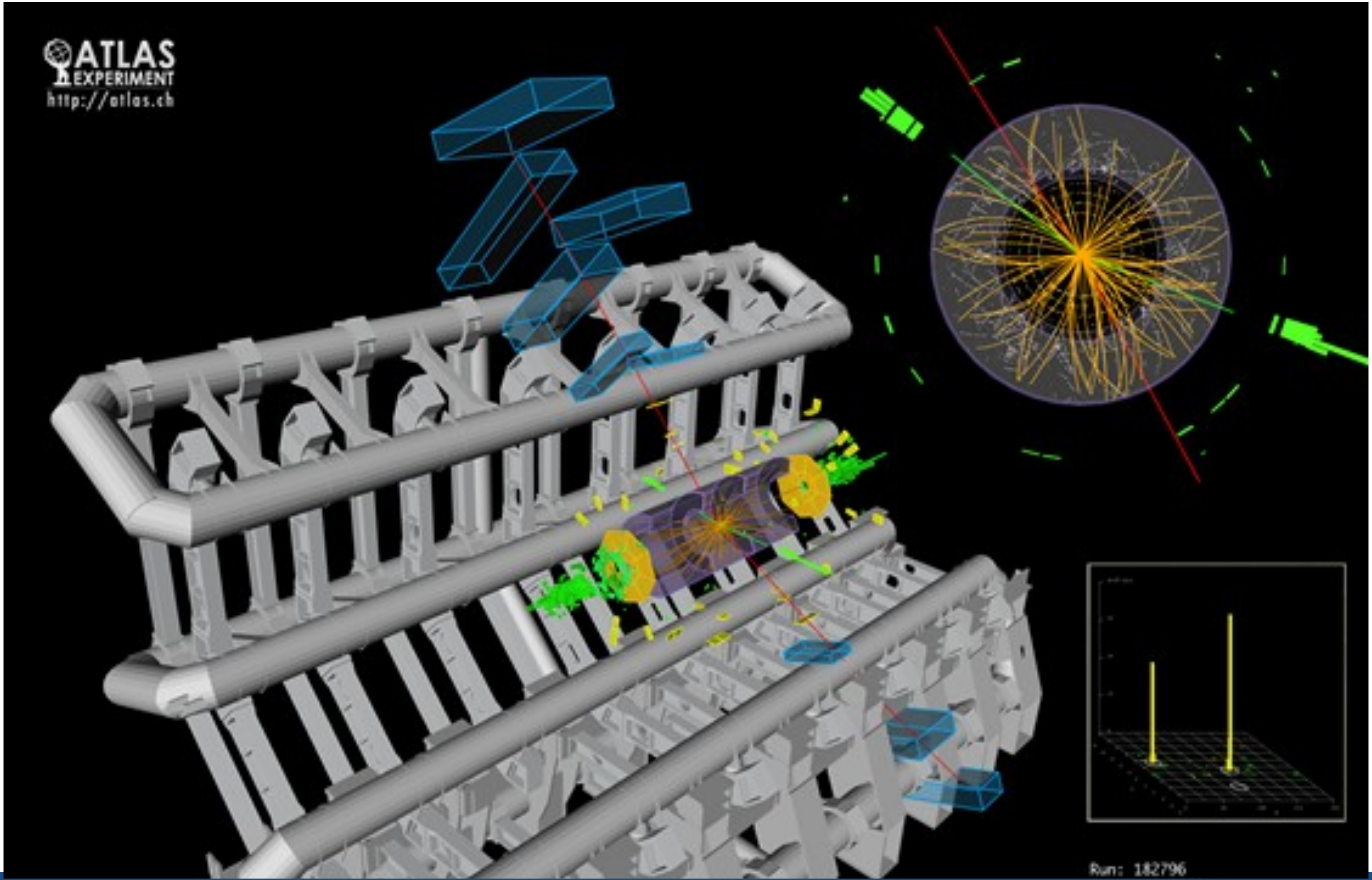


electroweak processes

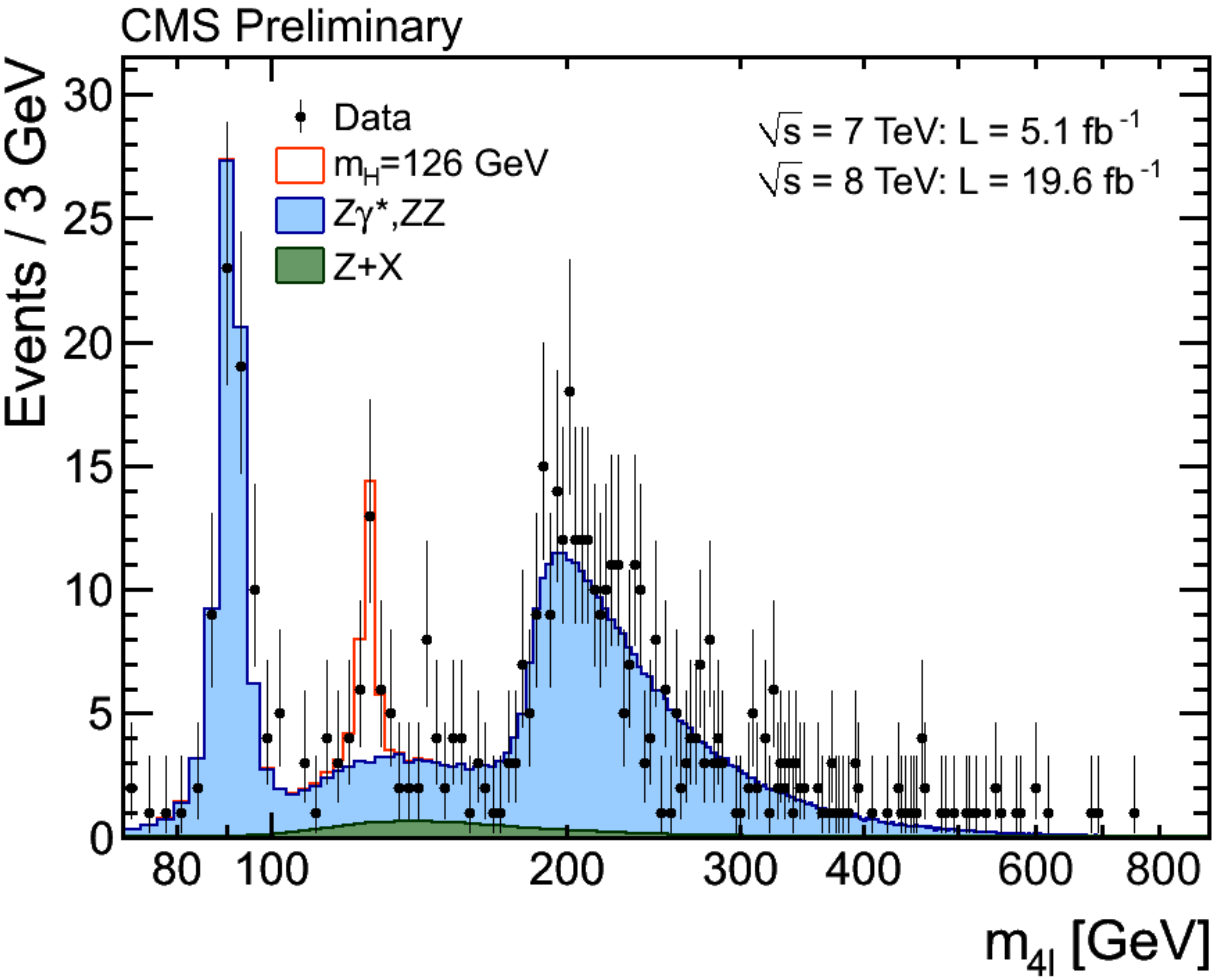


$$\sigma = \int dx_1 dx_2 \underbrace{f_1^{(P1)}(x_1,\mu^2)\; f_2^{(P2)}(x_2,\mu^2)}_{protons}\; \underbrace{\hat{\sigma}(x_1 x_2 s,\mu^2)}_{partons}$$

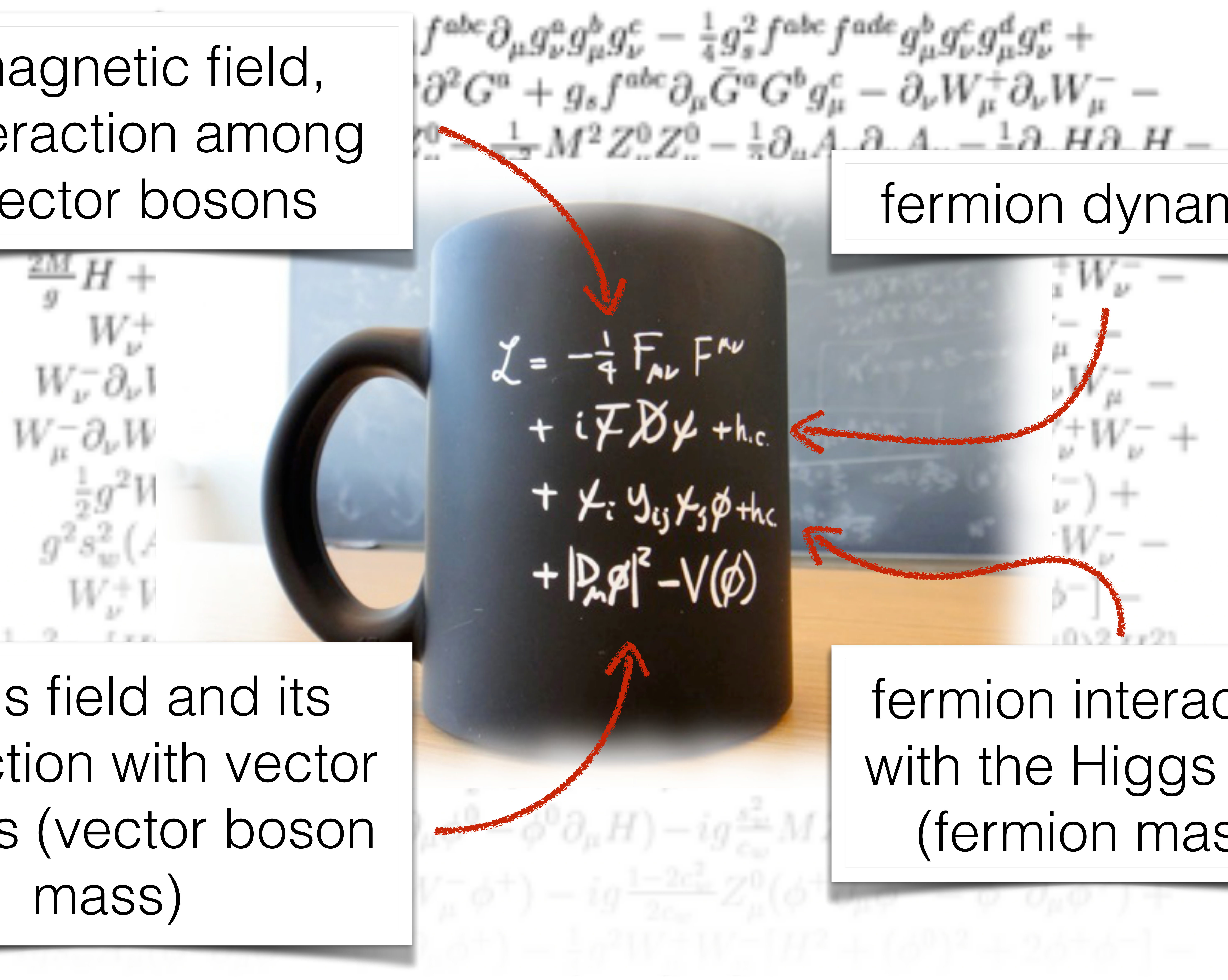
a relevant example: $h \to ZZ \to e^+e^- \mu^+\mu^-$



the Higgs boson discovery



the standard model of elementary interactions



magnetic field, interaction among vector bosons

fermion dynamics

Higgs field and its interaction with vector bosons (vector boson mass)

fermion interaction with the Higgs field (fermion mass)

S. Weinberg, a model of leptons

Phys. Rev. Lett. 19, 1264

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[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).

[13] The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L \equiv [\tfrac12(1+\gamma_5)]\begin{pmatrix}\nu_e\\ e\end{pmatrix} \qquad (1)$$

and on a right-handed singlet

$$R \equiv [\tfrac12(1-\gamma_5)]e. \qquad (2)$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L - \bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q = T_3 - N_R - \tfrac12 N_L$, and the electron number $N = N_R + N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y \equiv N_R + \tfrac12 N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero doublet

$$\varphi = \begin{pmatrix}\varphi^0\\ \varphi^-\end{pmatrix} \qquad (3)$$

whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and Y gauge transformations is

$$\mathfrak{L} = -\tfrac14(\partial_\mu\vec{A}_\nu - \partial_\nu\vec{A}_\mu + g\vec{A}_\mu\times\vec{A}_\nu)^2 - \tfrac14(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu - i\tfrac12 g'B_\mu)L$$
$$-\tfrac12|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\varphi + i\tfrac12 g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) - M_1{}^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2. \qquad (4)$$

We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda \equiv \langle\varphi^0\rangle$ real. The "physical" φ fields are then φ^-

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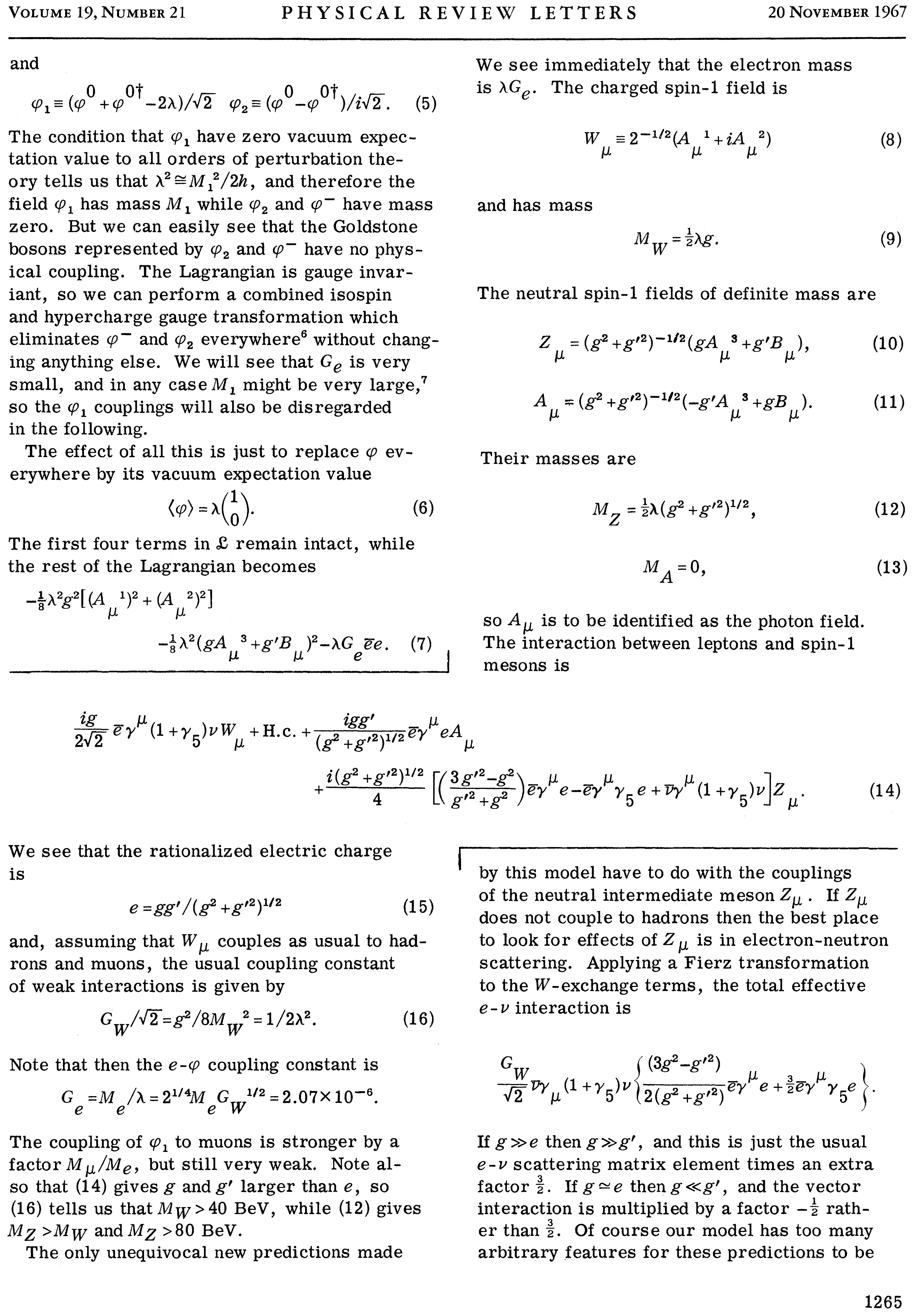

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and

$$\varphi_1 \equiv (\varphi^0 + \varphi^{0\dagger} - 2\lambda)/\sqrt{2} \quad \varphi_2 \equiv (\varphi^0 - \varphi^{0\dagger})/i\sqrt{2}. \qquad (5)$$

The condition that φ_1 have zero vacuum expectation value to all orders of perturbation theory tells us that $\lambda^2 \cong M_1{}^2/2h$, and therefore the field φ_1 has mass M_1 while φ_2 and φ^- have mass zero. But we can easily see that the Goldstone bosons represented by φ_2 and φ^- have no physical coupling. The Lagrangian is gauge invariant, so we can perform a combined isospin and hypercharge gauge transformation which eliminates φ^- and φ_2 everywhere[6] without changing anything else. We will see that G_e is very small, and in any case M_1 might be very large,[7] so the φ_1 couplings will also be disregarded in the following.

The effect of all this is just to replace φ everywhere by its vacuum expectation value

$$\langle\varphi\rangle = \lambda\begin{pmatrix}1\\0\end{pmatrix}. \qquad (6)$$

The first four terms in $\mathfrak{L}$ remain intact, while the rest of the Lagrangian becomes

$$-\tfrac18\lambda^2 g^2[(A_\mu{}^1)^2 + (A_\mu{}^2)^2]$$
$$-\tfrac18\lambda^2(gA_\mu{}^3 + g'B_\mu)^2 - \lambda G_e\bar{e}e. \qquad (7)$$

We see immediately that the electron mass is λG_e. The charged spin-1 field is

$$W_\mu \equiv 2^{-1/2}(A_\mu{}^1 + iA_\mu{}^2) \qquad (8)$$

and has mass

$$M_W = \tfrac12\lambda g. \qquad (9)$$

The neutral spin-1 fields of definite mass are

$$Z_\mu = (g^2+g'^2)^{-1/2}(gA_\mu{}^3 + g'B_\mu), \qquad (10)$$

$$A_\mu = (g^2+g'^2)^{-1/2}(-g'A_\mu{}^3 + gB_\mu). \qquad (11)$$

Their masses are

$$M_Z = \tfrac12\lambda(g^2+g'^2)^{1/2}, \qquad (12)$$

$$M_A = 0, \qquad (13)$$

so A_μ is to be identified as the photon field. The interaction between leptons and spin-1 mesons is

$$\frac{ig}{2\sqrt2}\bar{e}\gamma^\mu(1+\gamma_5)\nu W_\mu + \text{H.c.} + \frac{igg'}{(g^2+g'^2)^{1/2}}\bar{e}\gamma^\mu eA_\mu$$
$$+\frac{i(g^2+g'^2)^{1/2}}{4}\left[\left(\frac{3g'^2-g^2}{g'^2+g^2}\right)\bar{e}\gamma^\mu e - \bar{e}\gamma^\mu\gamma_5 e + \bar{\nu}\gamma^\mu(1+\gamma_5)\nu\right]Z_\mu. \qquad (14)$$

We see that the rationalized electric charge is

$$e = gg'/(g^2+g'^2)^{1/2} \qquad (15)$$

and, assuming that W_μ couples as usual to hadrons and muons, the usual coupling constant of weak interactions is given by

$$G_W/\sqrt2 = g^2/8M_W{}^2 = 1/2\lambda^2. \qquad (16)$$

Note that then the e-φ coupling constant is

$$G_e = M_e/\lambda = 2^{1/4}M_e G_W{}^{1/2} = 2.07\times10^{-6}.$$

The coupling of φ_1 to muons is stronger by a factor M_μ/M_e, but still very weak. Note also that (14) gives g and g' larger than e, so (16) tells us that $M_W > 40$ BeV, while (12) gives $M_Z > M_W$ and $M_Z > 80$ BeV.

The only unequivocal new predictions made by this model have to do with the couplings of the neutral intermediate meson Z_μ. If Z_μ does not couple to hadrons then the best place to look for effects of Z_μ is in electron-neutron scattering. Applying a Fierz transformation to the W-exchange terms, the total effective e-ν interaction is

$$\frac{G_W}{\sqrt2}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu\left\{\frac{(3g^2-g'^2)}{2(g^2+g'^2)}\bar{e}\gamma^\mu e + \tfrac32\bar{e}\gamma^\mu\gamma_5 e\right\}.$$

If $g \gg e$ then $g \gg g'$, and this is just the usual e-ν scattering matrix element times an extra factor $\tfrac32$. If $g \simeq e$ then $g \ll g'$, and the vector interaction is multiplied by a factor $-\tfrac12$ rather than $\tfrac32$. Of course our model has too many arbitrary features for these predictions to be

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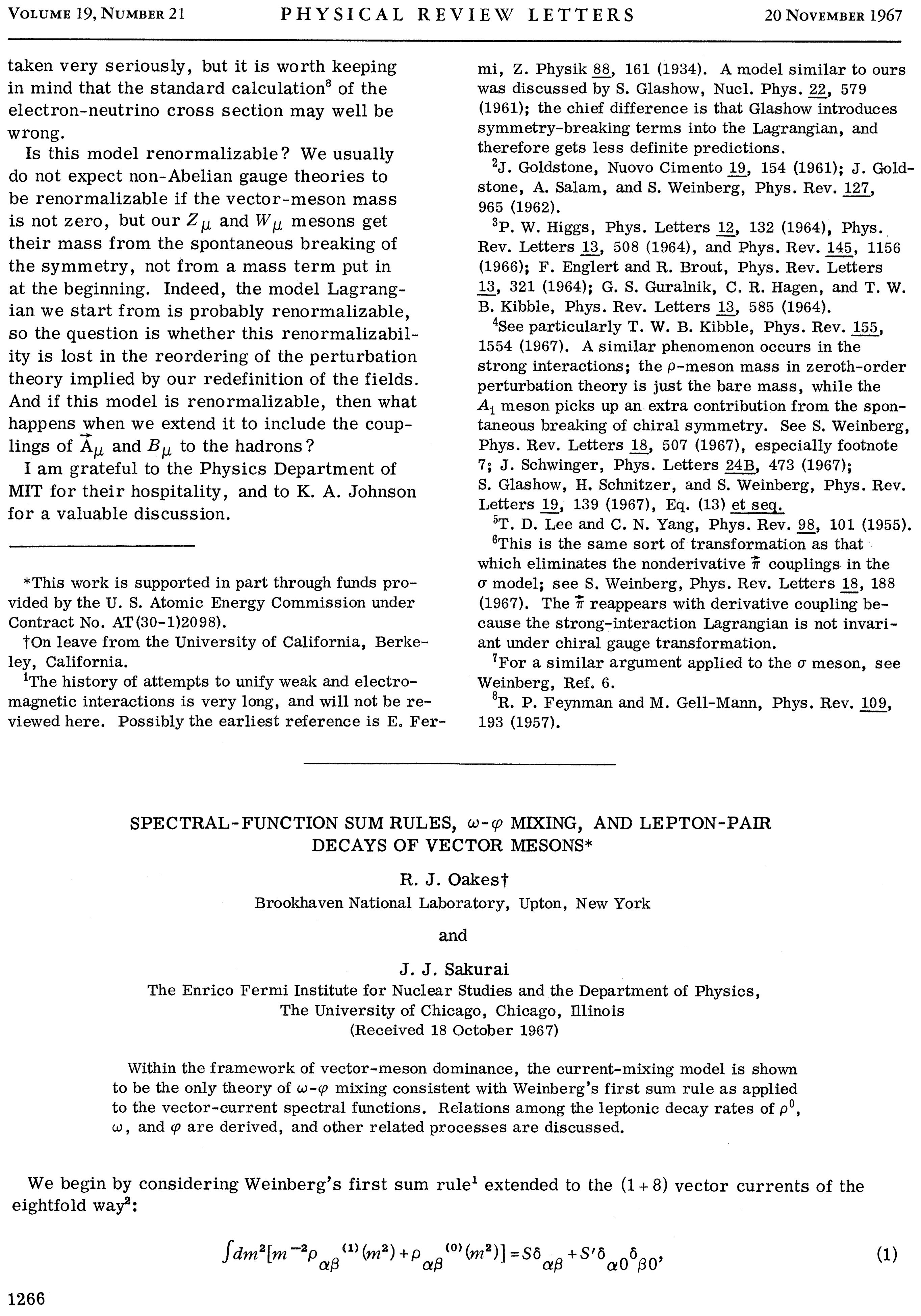

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taken very seriously, but it is worth keeping in mind that the standard calculation[8] of the electron-neutrino cross section may well be wrong.

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our Z_μ and W_μ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable, so the question is whether this renormalizability is lost in the reordering of the perturbation theory implied by our redefinition of the fields. And if this model is renormalizable, then what happens when we extend it to include the couplings of $\vec{A}_\mu$ and B_μ to the hadrons?

I am grateful to the Physics Department of MIT for their hospitality, and to K. A. Johnson for a valuable discussion.

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†On leave from the University of California, Berkeley, California.

[1] The history of attempts to unify weak and electromagnetic interactions is very long, and will not be reviewed here. Possibly the earliest reference is E. Fermi, Z. Physik 88, 161 (1934). A model similar to ours was discussed by S. Glashow, Nucl. Phys. 22, 579 (1961); the chief difference is that Glashow introduces symmetry-breaking terms into the Lagrangian, and therefore gets less definite predictions.

[2] J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).

[3] P. W. Higgs, Phys. Letters 12, 132 (1964), Phys. Rev. Letters 13, 508 (1964), and Phys. Rev. 145, 1156 (1966); F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964); G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Phys. Rev. Letters 13, 585 (1964).

[4] See particularly T. W. B. Kibble, Phys. Rev. 155, 1554 (1967). A similar phenomenon occurs in the strong interactions; the ρ-meson mass in zeroth-order perturbation theory is just the bare mass, while the A_1 meson picks up an extra contribution from the spontaneous breaking of chiral symmetry. See S. Weinberg, Phys. Rev. Letters 18, 507 (1967), especially footnote 7; J. Schwinger, Phys. Letters 24B, 473 (1967); S. Glashow, H. Schnitzer, and S. Weinberg, Phys. Rev. Letters 19, 139 (1967), Eq. (13) et seq.

[5] T. D. Lee and C. N. Yang, Phys. Rev. 98, 101 (1955).

[6] This is the same sort of transformation as that which eliminates the nonderivative $\vec{\pi}$ couplings in the σ model; see S. Weinberg, Phys. Rev. Letters 18, 188 (1967). The $\vec{\pi}$ reappears with derivative coupling because the strong-interaction Lagrangian is not invariant under chiral gauge transformation.

[7] For a similar argument applied to the σ meson, see Weinberg, Ref. 6.

[8] R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1957).

SPECTRAL-FUNCTION SUM RULES, ω-φ MIXING, AND LEPTON-PAIR DECAYS OF VECTOR MESONS*

R. J. Oakes†
Brookhaven National Laboratory, Upton, New York

and

J. J. Sakurai
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics,
The University of Chicago, Chicago, Illinois
(Received 18 October 1967)

Within the framework of vector-meson dominance, the current-mixing model is shown to be the only theory of ω-φ mixing consistent with Weinberg's first sum rule as applied to the vector-current spectral functions. Relations among the leptonic decay rates of ρ^0, ω, and φ are derived, and other related processes are discussed.

We begin by considering Weinberg's first sum rule[1] extended to the $(1+8)$ vector currents of the eightfold way[2]:

$$\int dm^2[m^{-2}\rho_{\alpha\beta}{}^{(1)}(m^2) + \rho_{\alpha\beta}{}^{(0)}(m^2)] = S\delta_{\alpha\beta} + S'\delta_{\alpha0}\delta_{\beta0}, \qquad (1)$$

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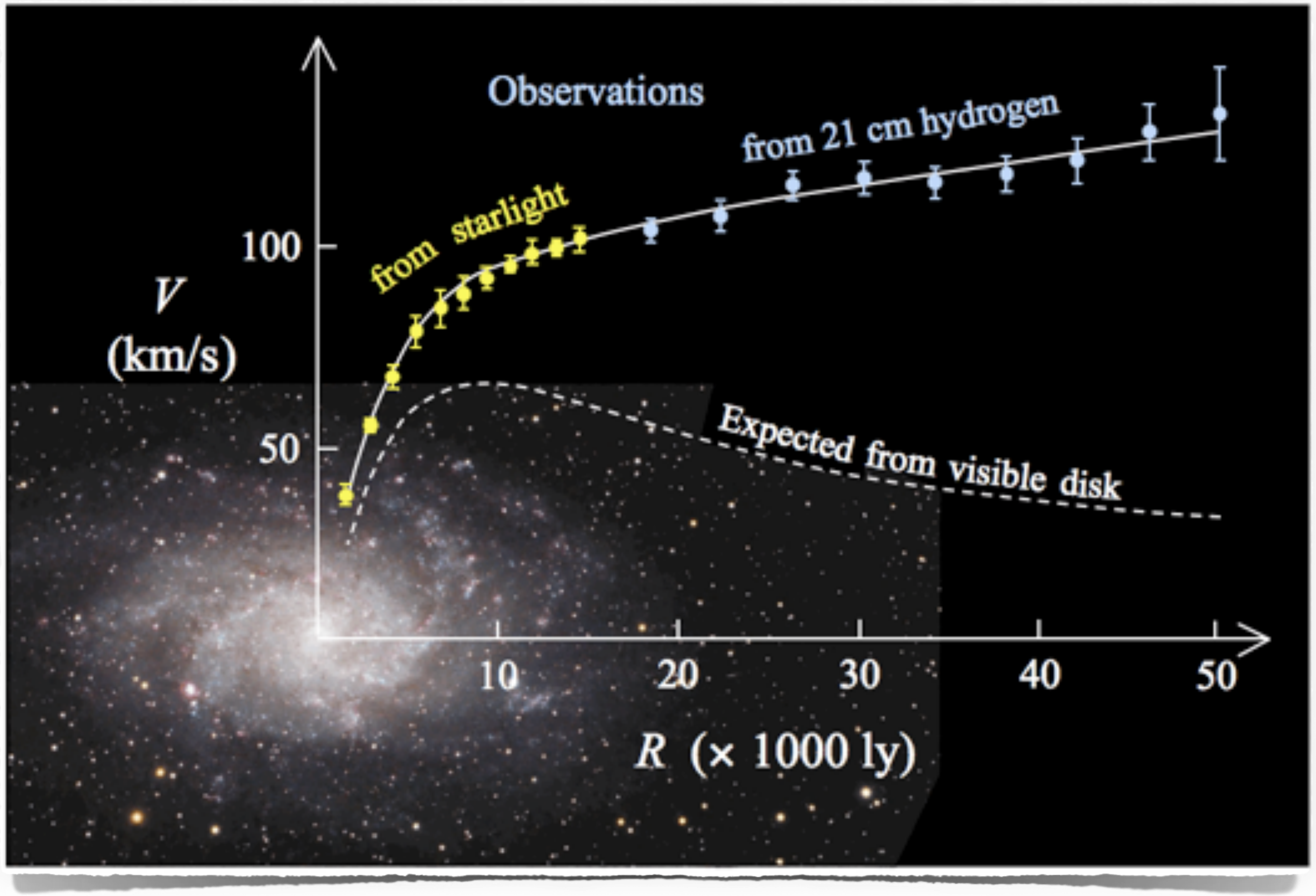
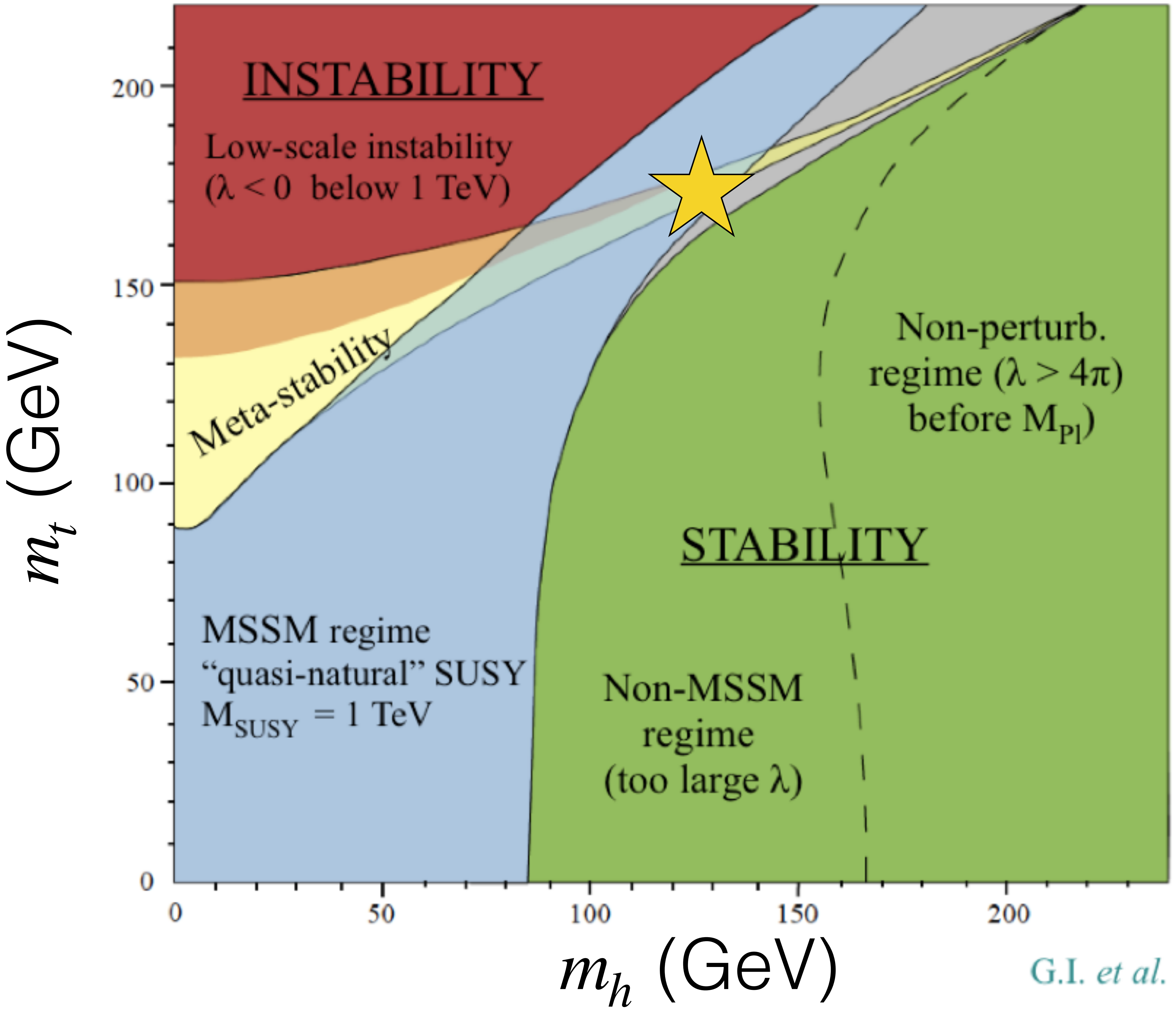
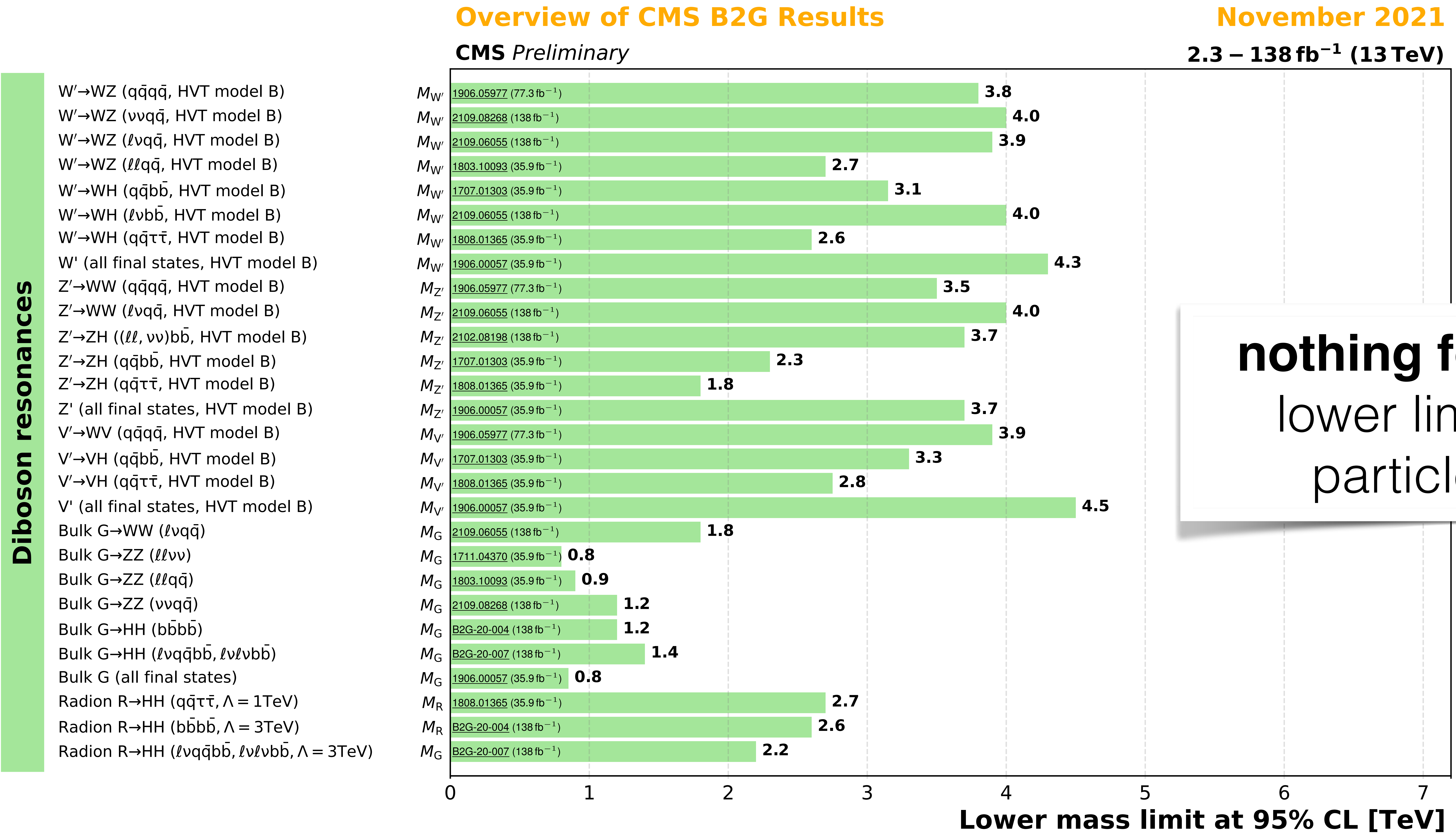
is the story over?





G.I. *et al.*

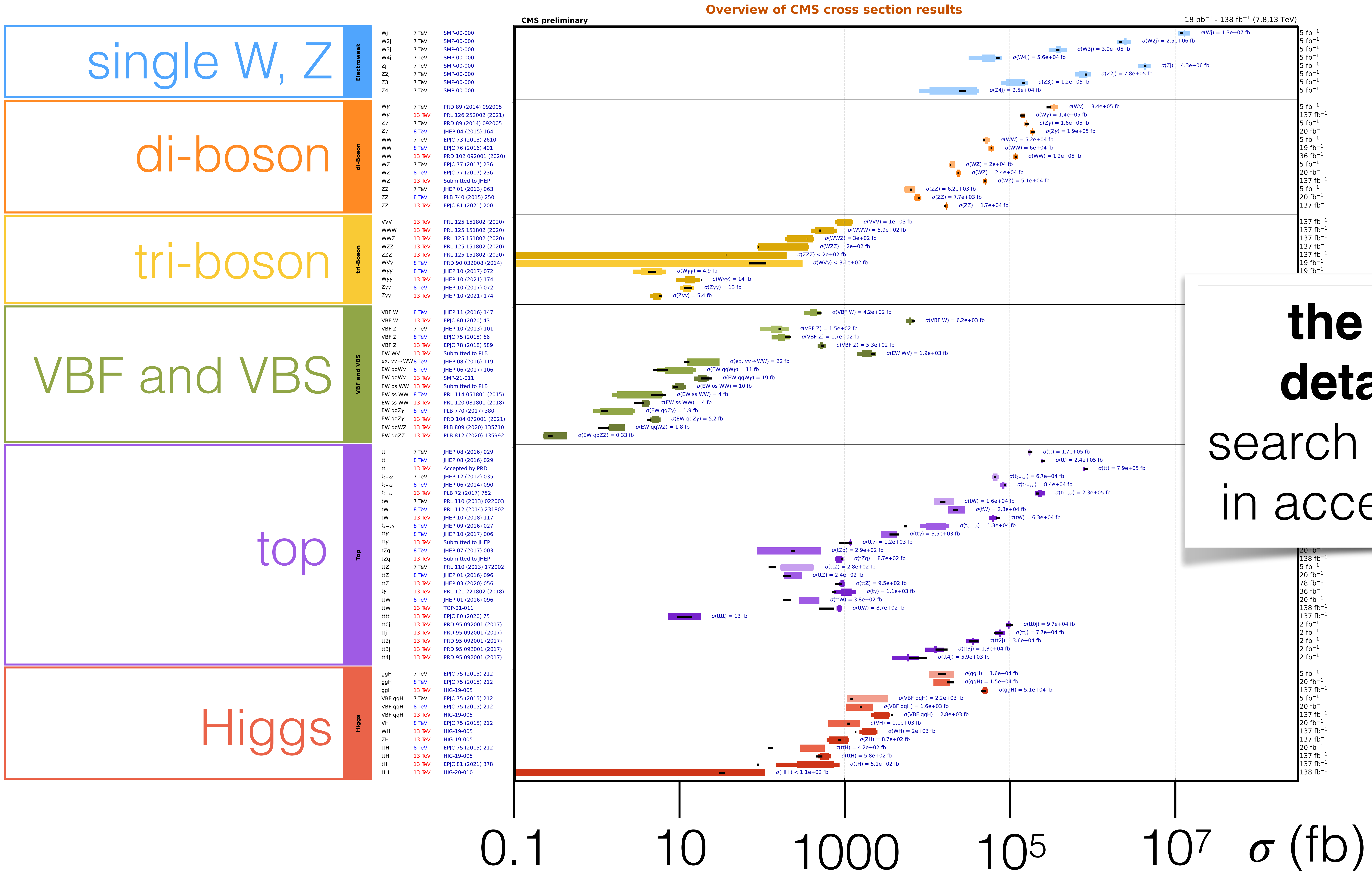
what now? new physics searches



nothing found so far:
lower limits on new
particle masses

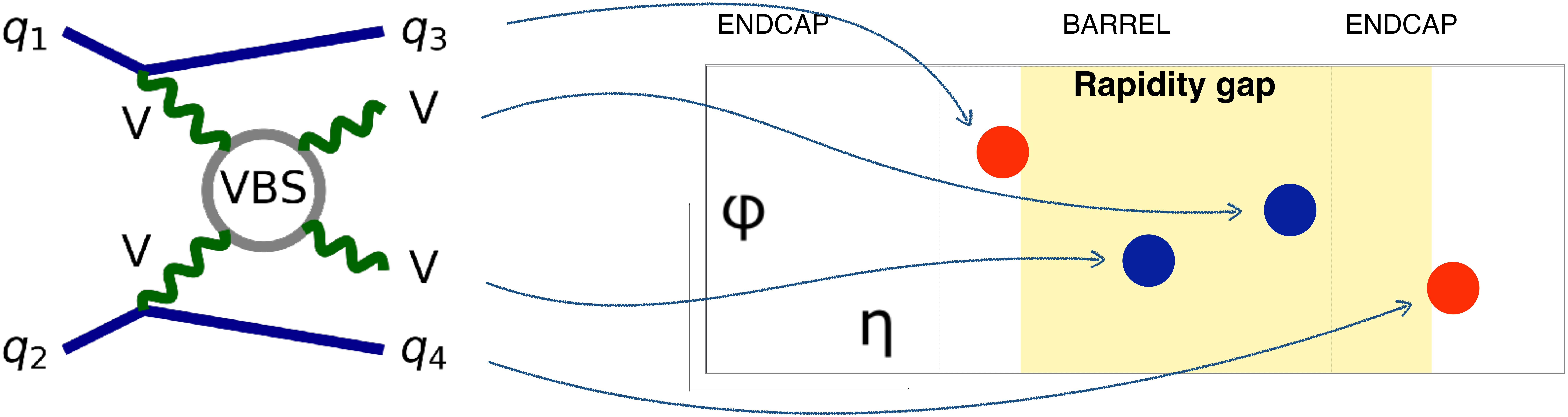
precision measurements

http://go.web.cern.ch/go/7LSN



the devil is in the details (hopefully):
search for indirect effects
in accessible processes

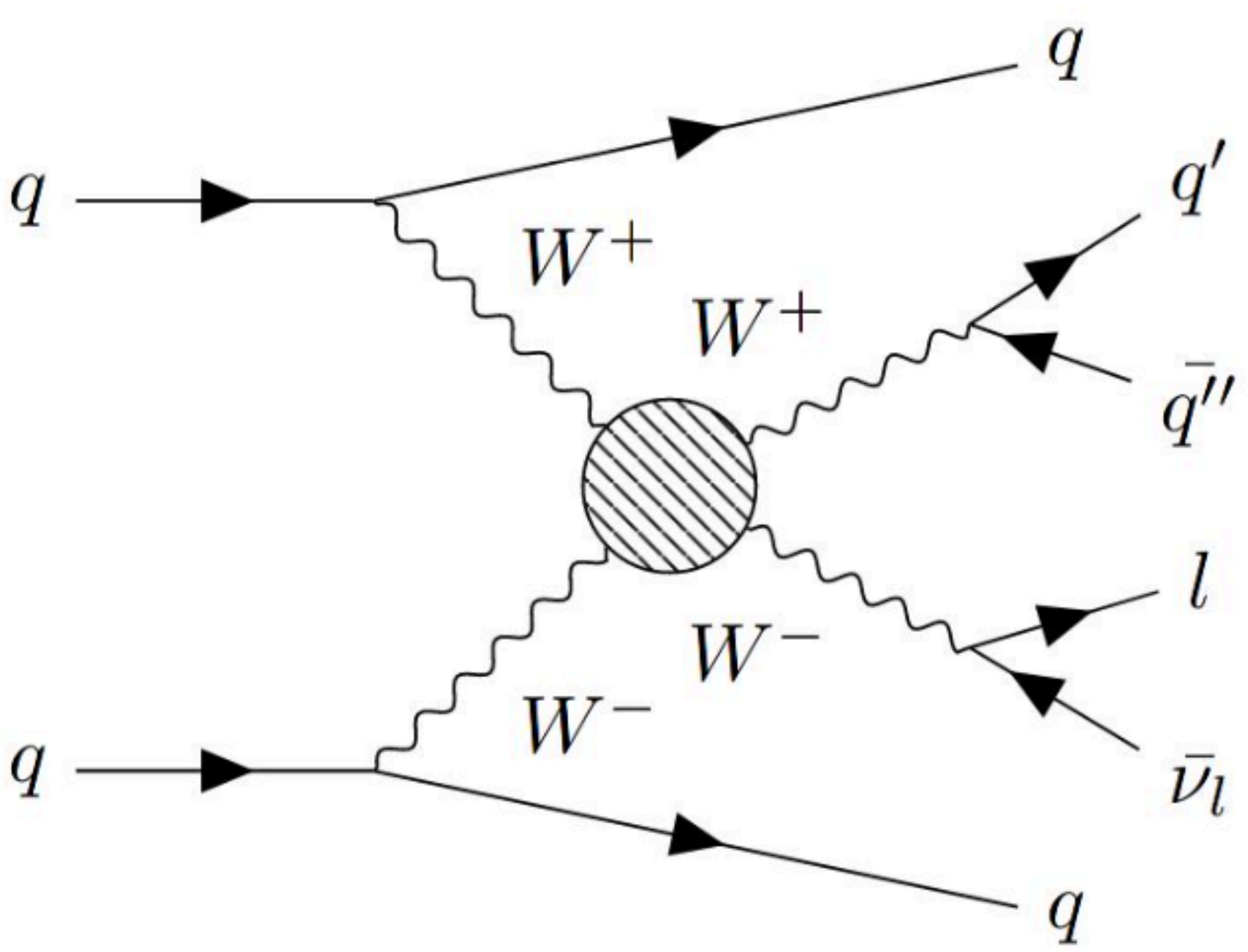
vector boson scattering

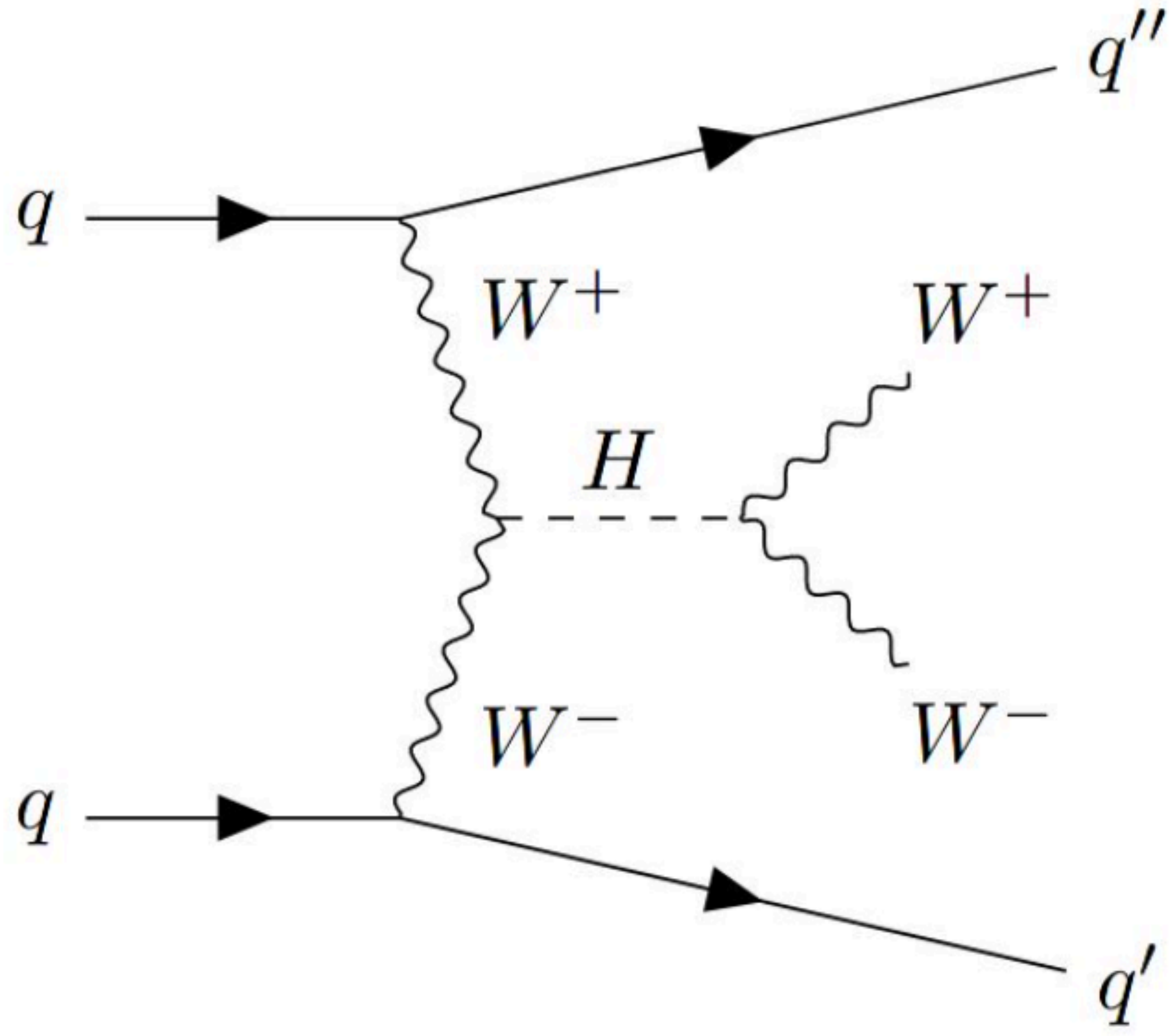


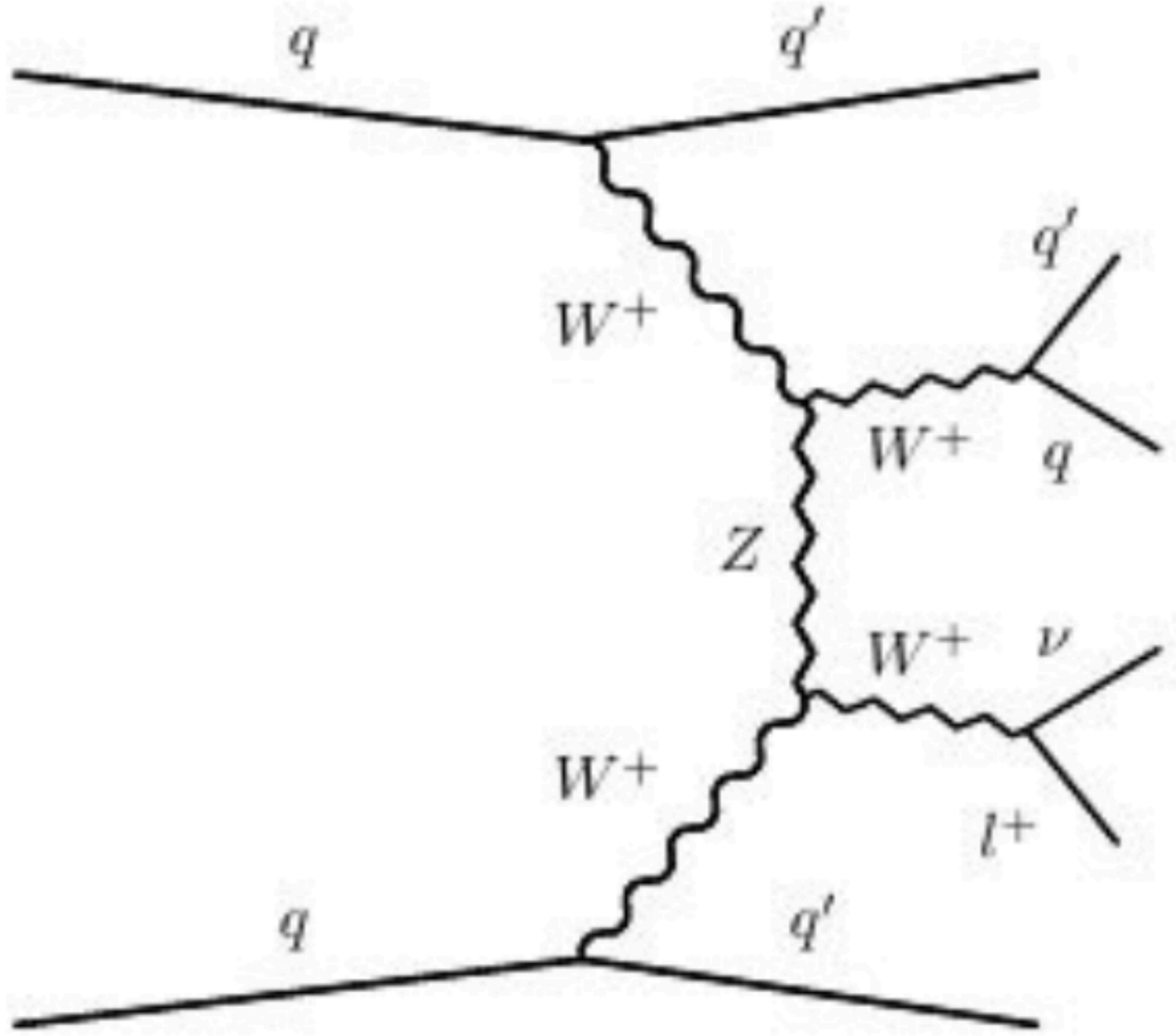
- interaction **between vector bosons**
- which are **irradiated from quarks in the proton beams**
- **final state** composed of the vector boson decay products + two jets due to the irradiating quarks

the signal

- **several different Feynman diagrams** contribute to the interaction
- at leading order (LO) in perturbation theory, **the interactions are electroweak**

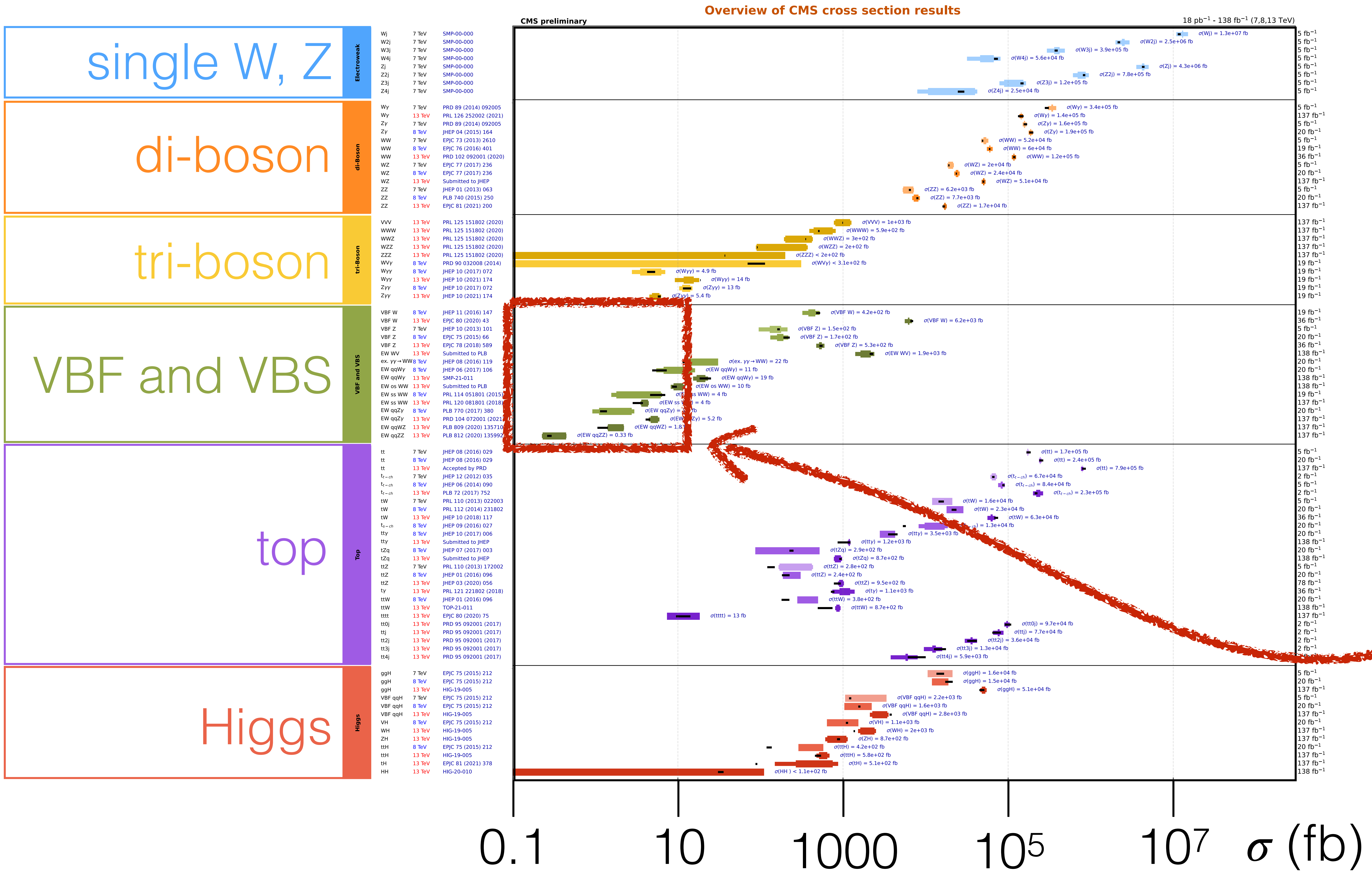






the process cross-section

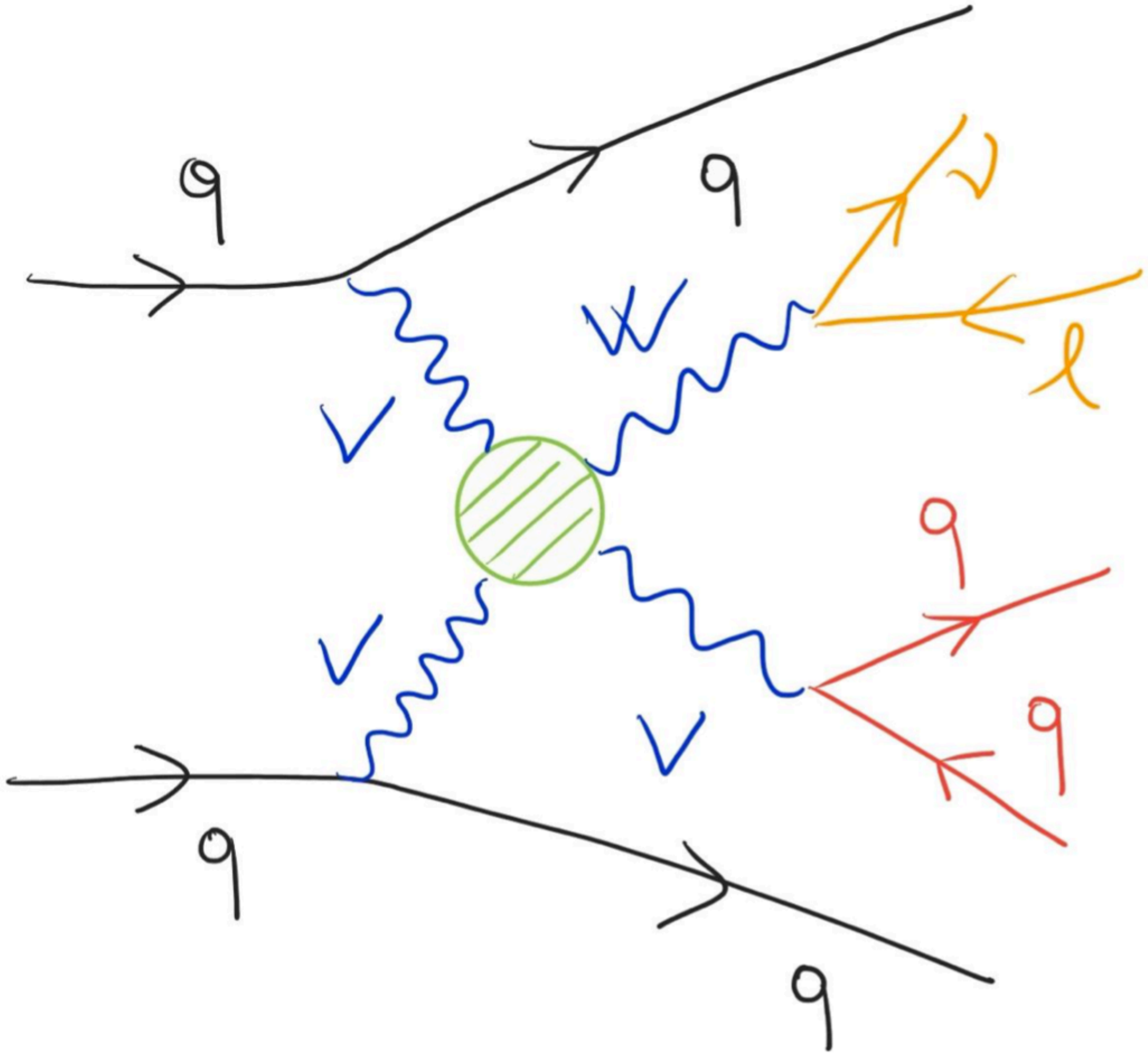
http://go.web.cern.ch/go/7LSN



among **the smallest ever measured** at the LHC

a semi-leptonic final state

10.1016/j.physletb.2022.137438



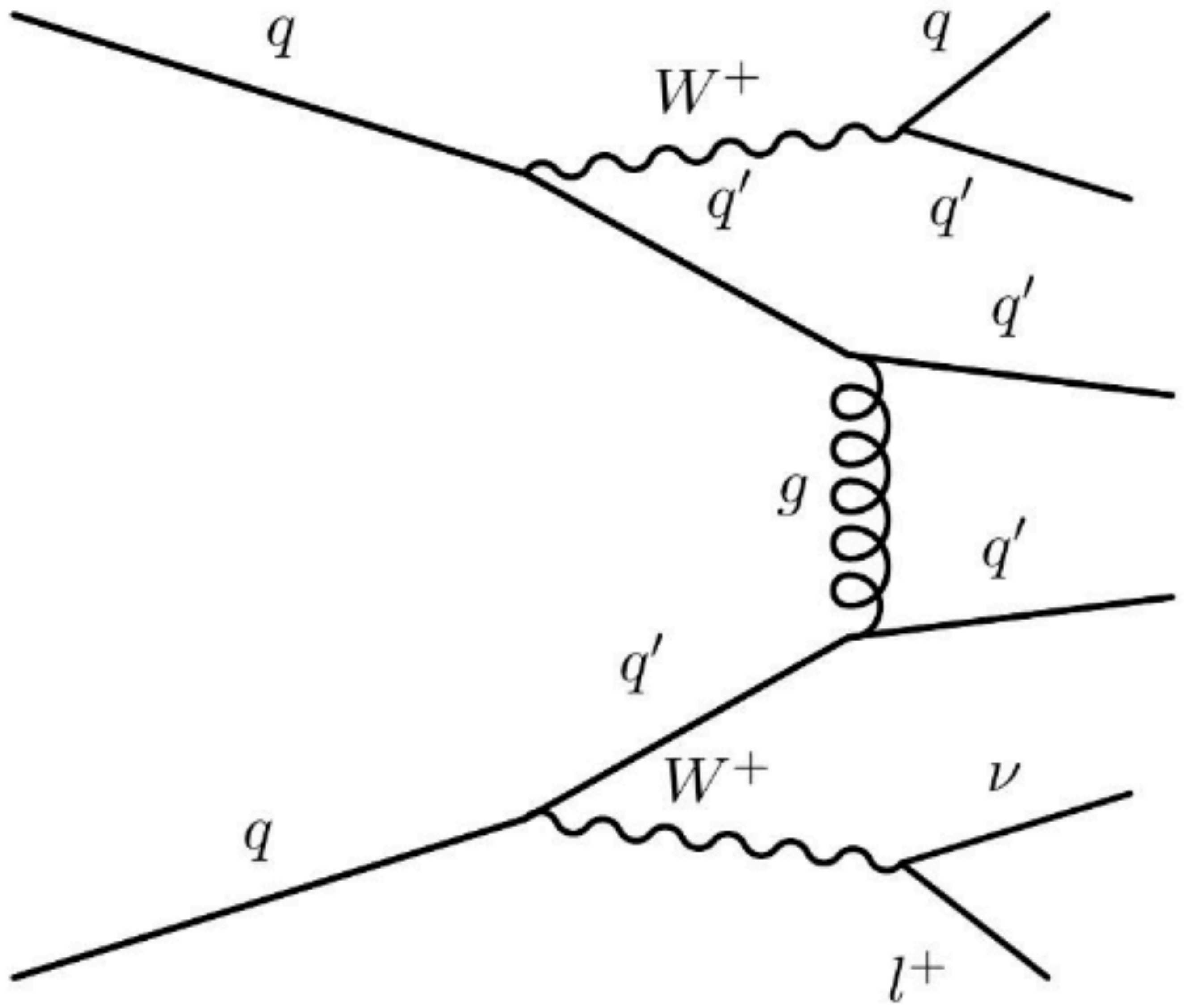
- out of the two vector bosons, **one decays into quarks and the other one into a charged lepton + neutrino pair**

- large V branching ratio into quarks means **large statistics** with respect to fully leptonic channels
- **large backgrounds**, as only one charged lepton is present in the final state

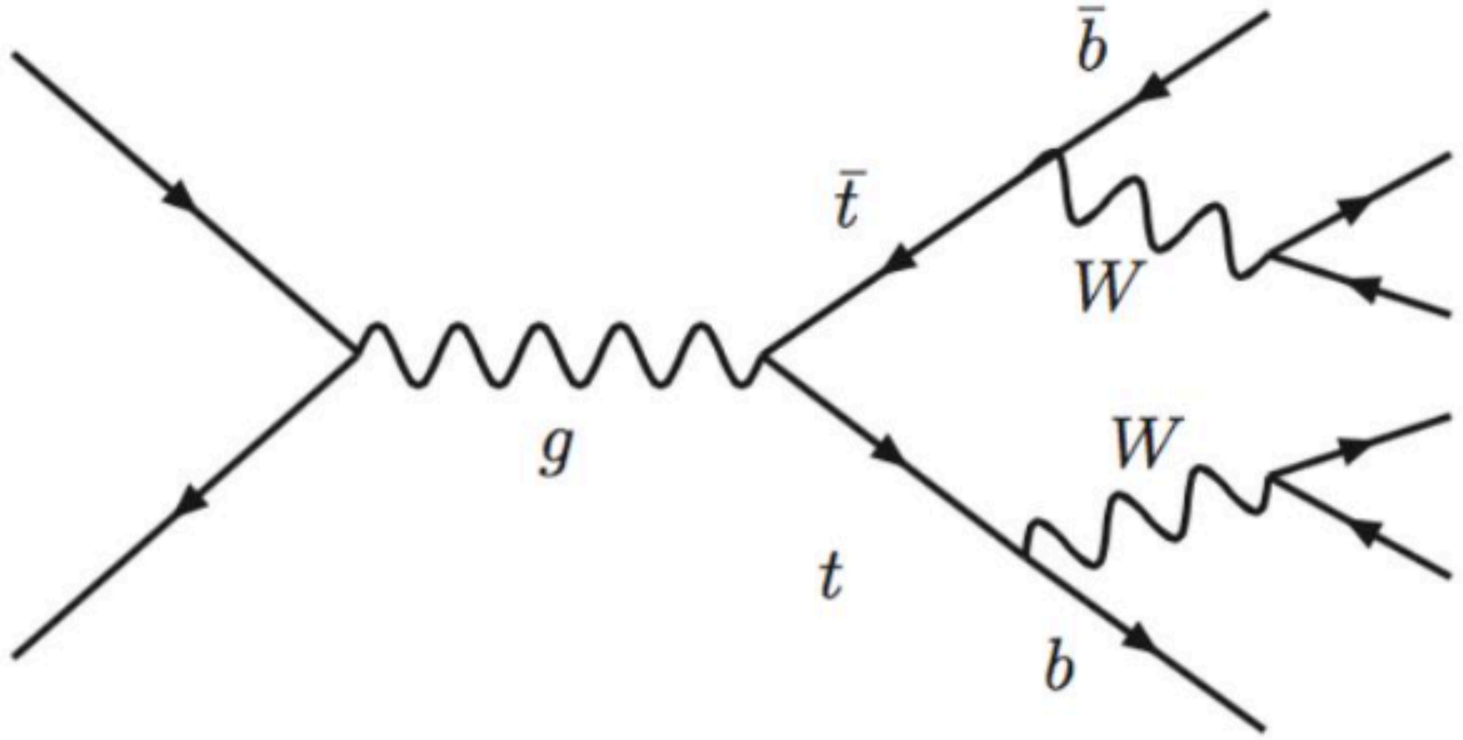
courtesy of
D. Valsecchi

the main backgrounds to this process

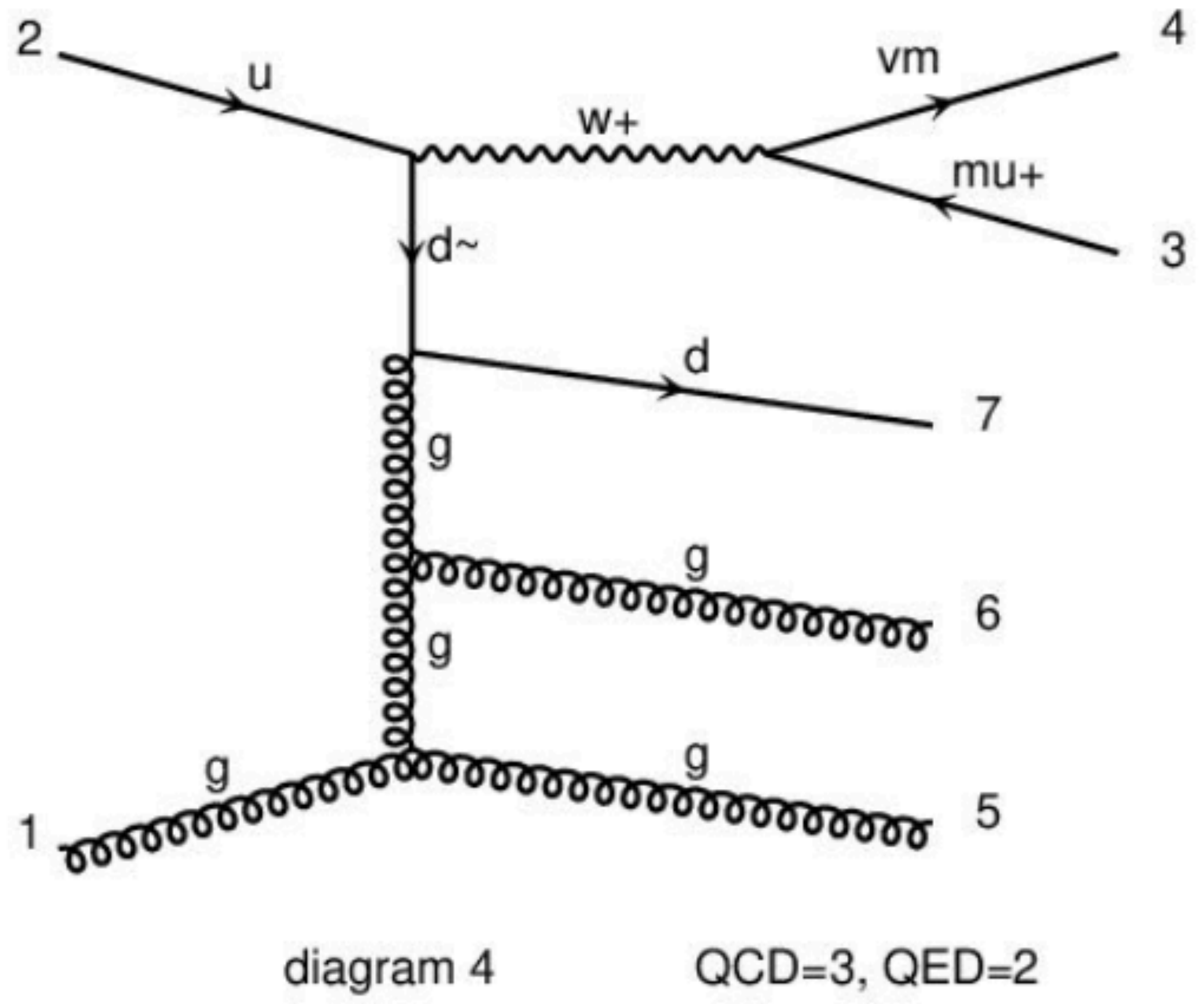
- at LO in perturbation theory, due to **processes which produce the same final state** with different processes
- due to **mistakes in the particle reconstruction** with the event information



QCD-WV

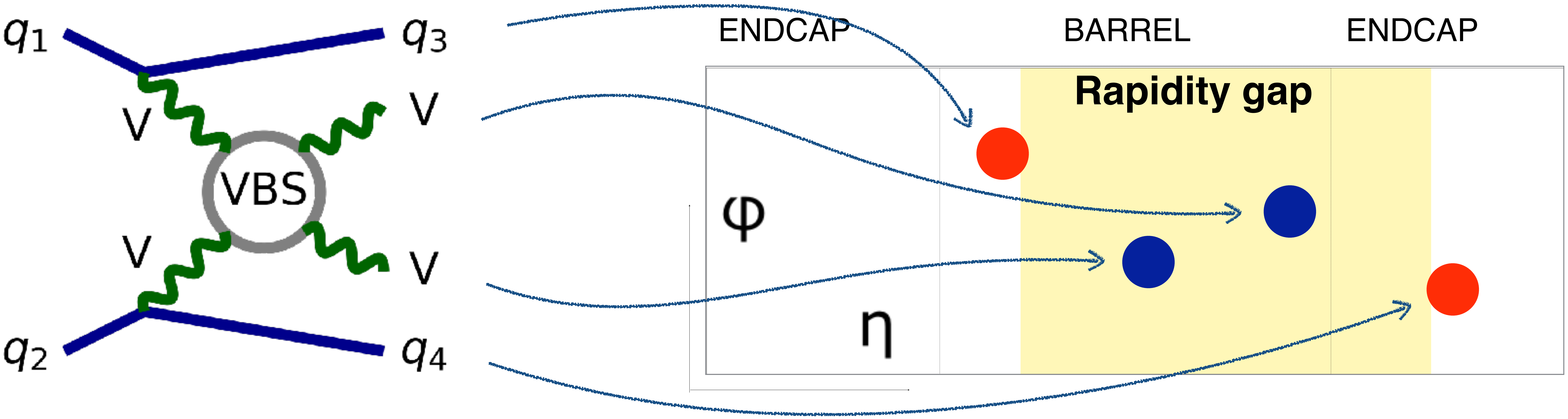


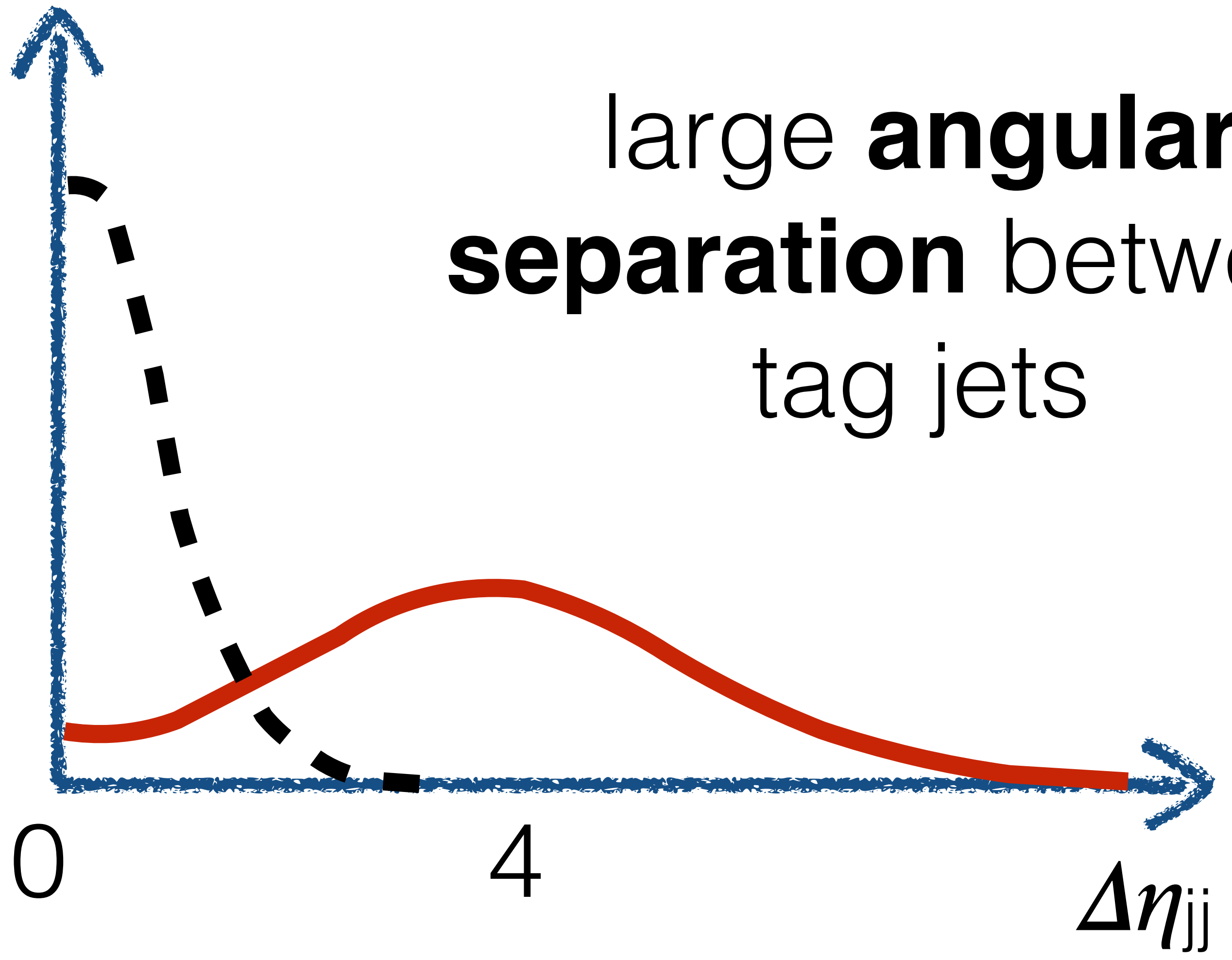
QCD ttbar



W+ jets

background reduction





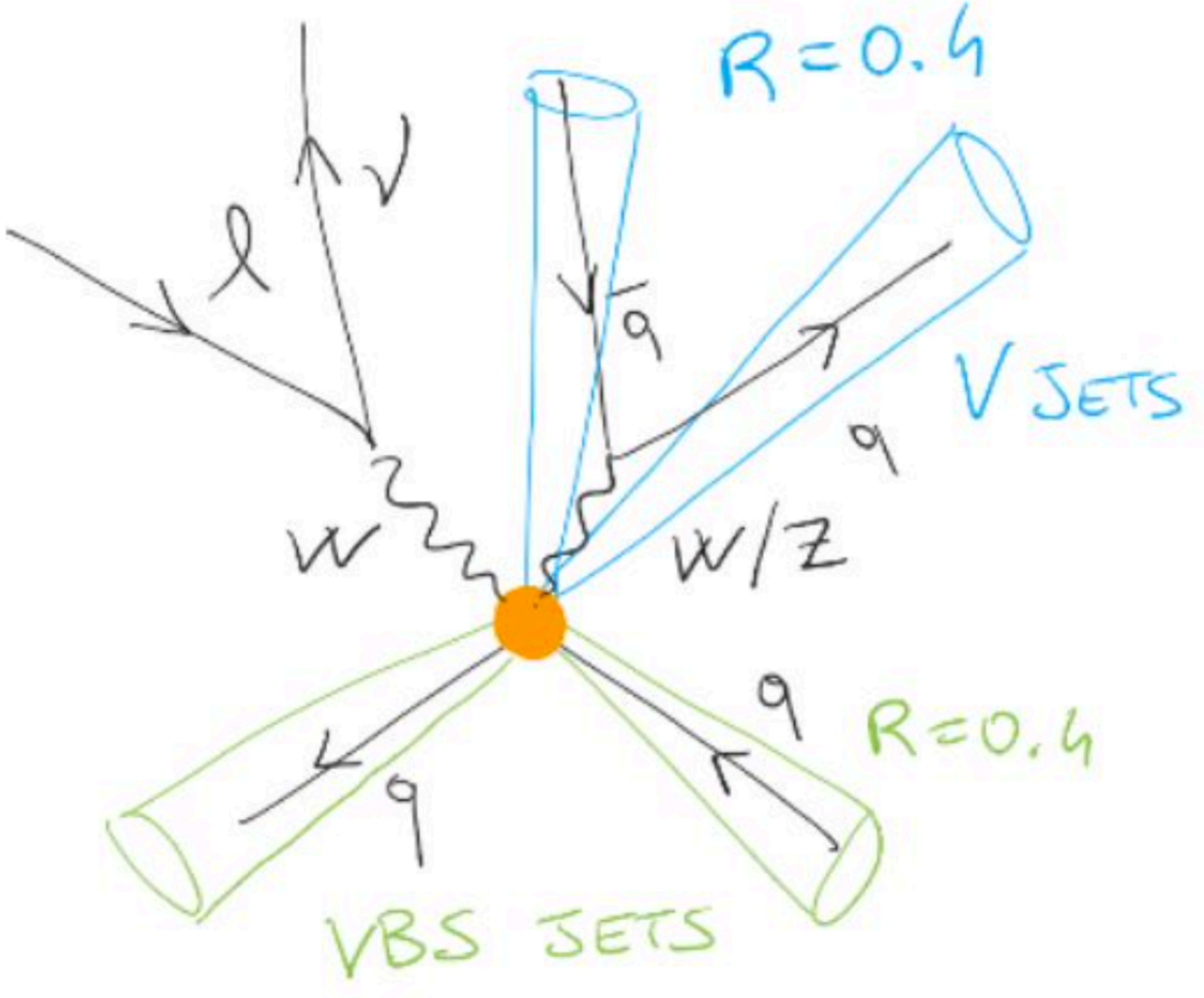
large **angular separation** between tag jets

low QCD activity between tag jets, since there's no color flow between the two protons

vector boson identification

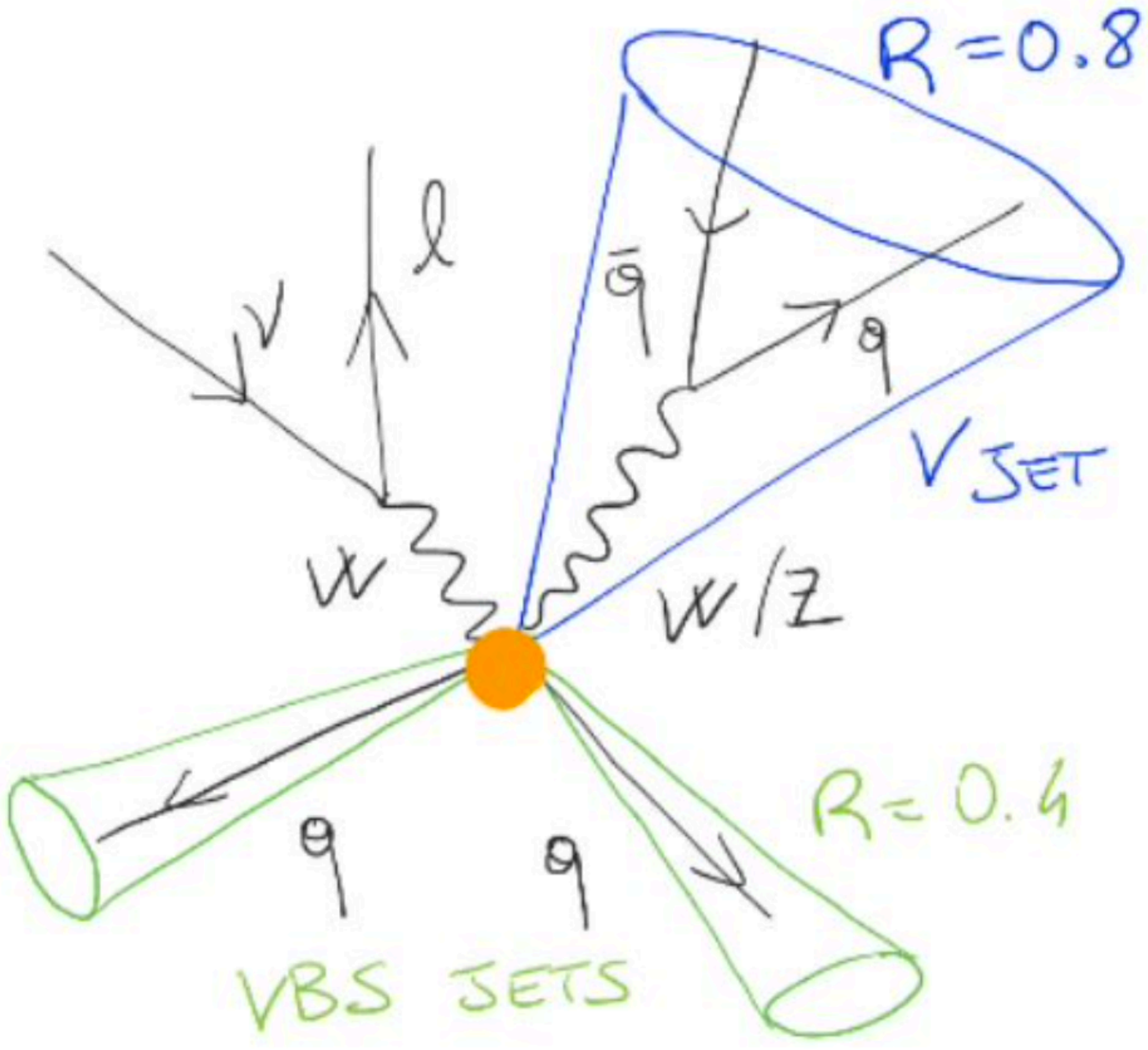
courtesy of
D. Valsecchi

RESOLVED CASE



the quarks due to the V decay originate **two jets**

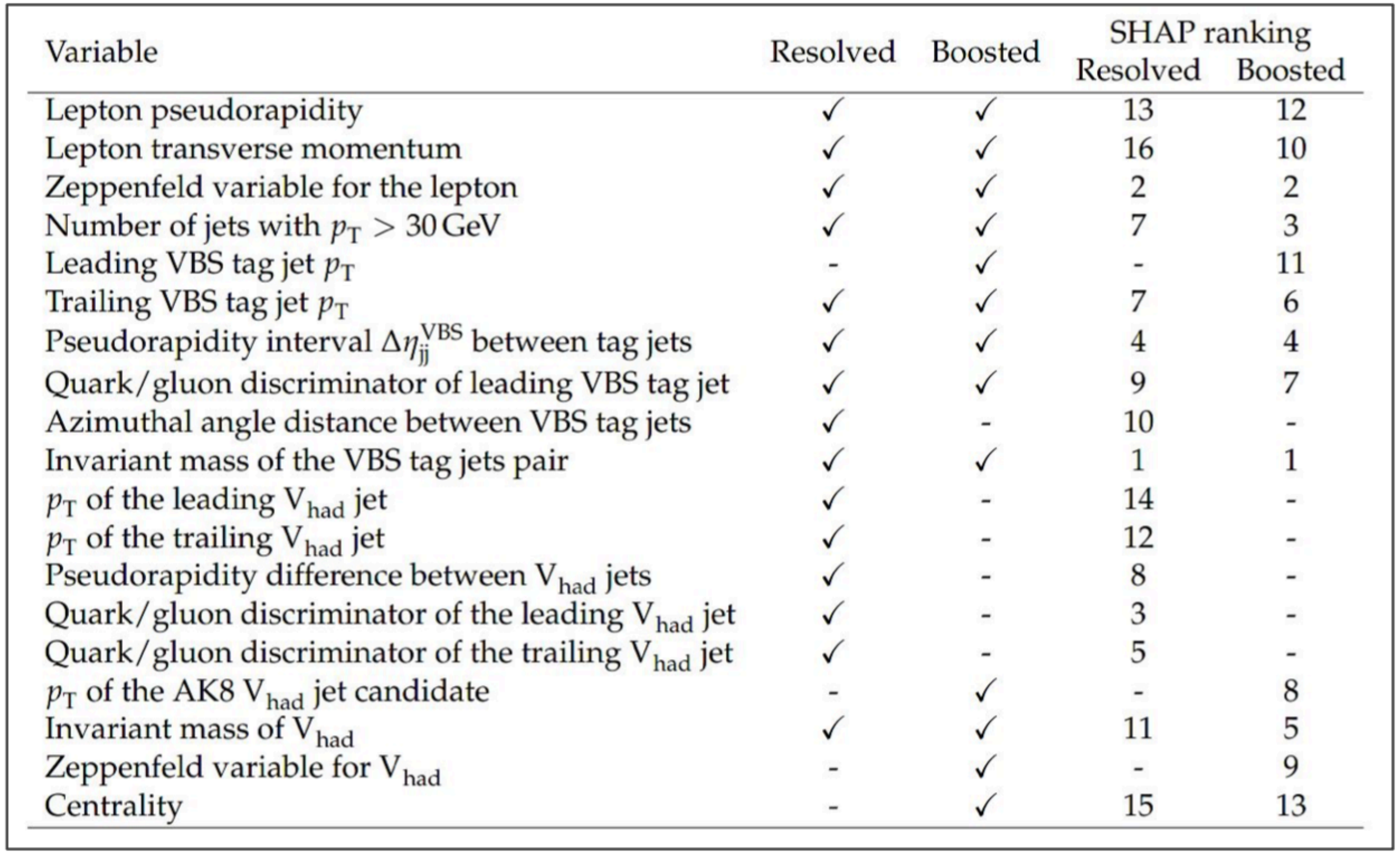
MERGED CASE



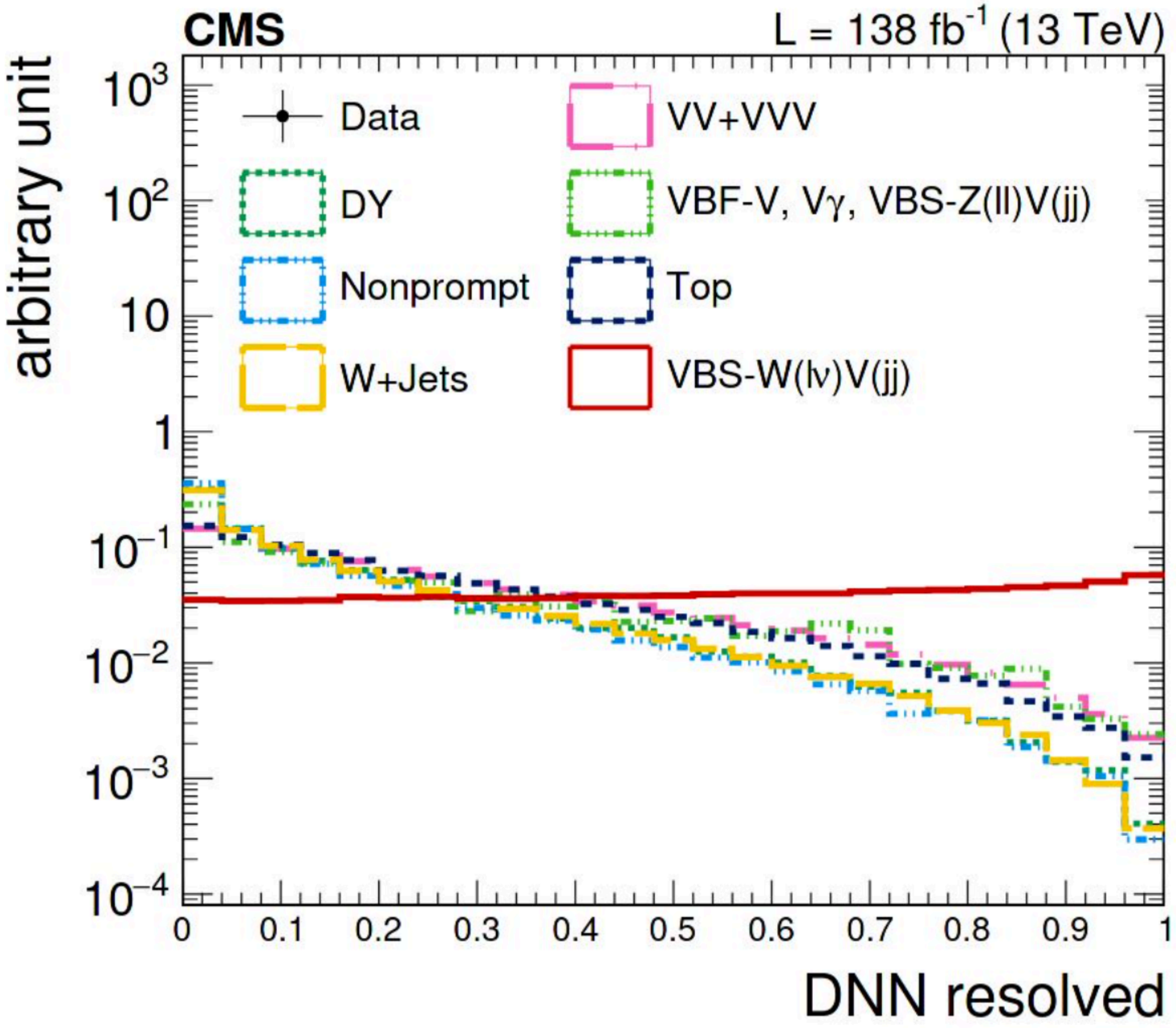
the quarks due to the V decay are close enough to originate **one single large jet**

signal extraction: a deep neural network

- many variables that characterise the signal **combined into a single discriminant**
- choose variables according to their importance (explainable AI)

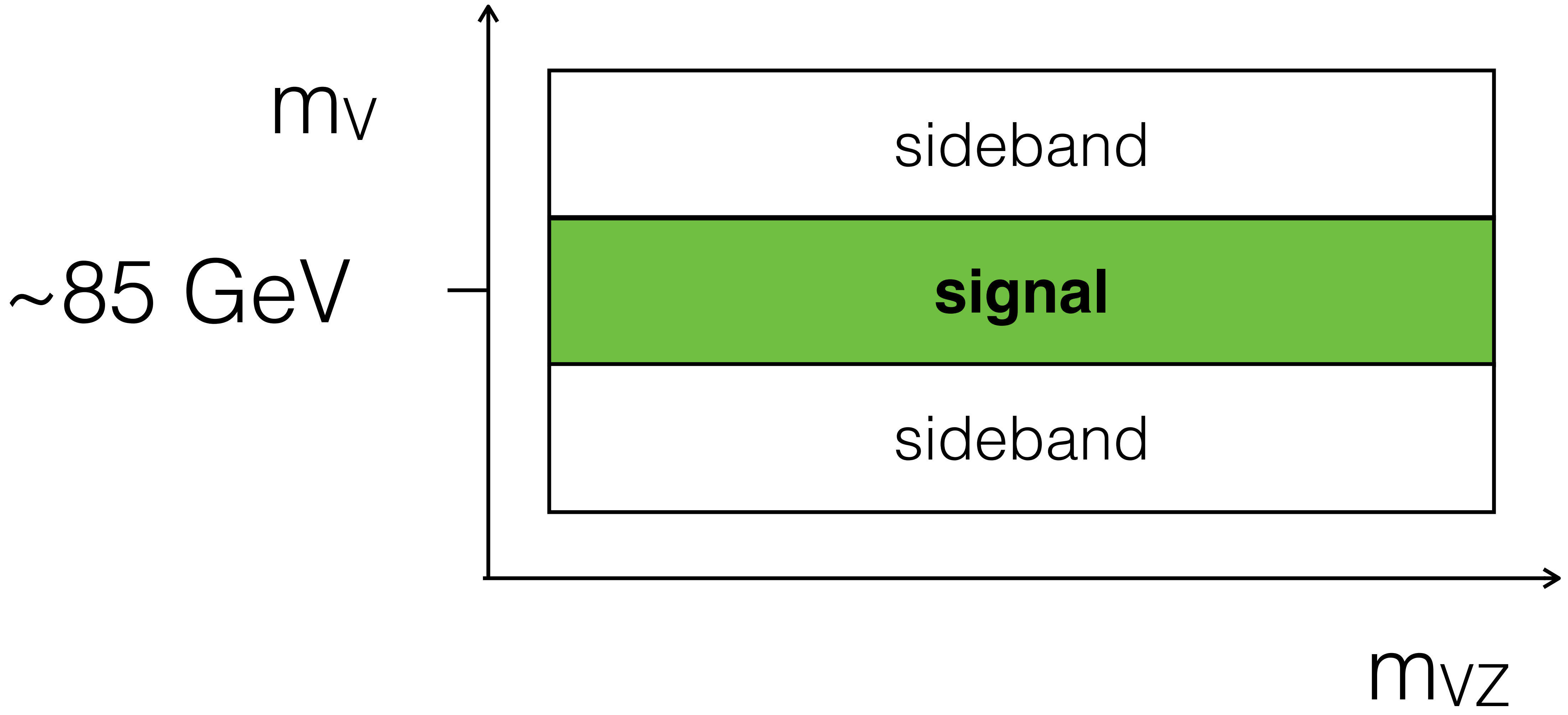


Variable	Resolved	Boosted	SHAP ranking Resolved	SHAP ranking Boosted
Lepton pseudorapidity	✓	✓	13	12
Lepton transverse momentum	✓	✓	16	10
Zeppenfeld variable for the lepton	✓	✓	2	2
Number of jets with $p_T > 30\,\text{GeV}$	✓	✓	7	3
Leading VBS tag jet p_T	-	✓	-	11
Trailing VBS tag jet p_T	✓	✓	7	6
Pseudorapidity interval $\Delta\eta_{jj}^{VBS}$ between tag jets	✓	✓	4	4
Quark/gluon discriminator of leading VBS tag jet	✓	✓	9	7
Azimuthal angle distance between VBS tag jets	✓	-	10	-
Invariant mass of the VBS tag jets pair	✓	✓	1	1
p_T of the leading V_{had} jet	✓	-	14	-
p_T of the trailing V_{had} jet	✓	-	12	-
Pseudorapidity difference between V_{had} jets	✓	-	8	-
Quark/gluon discriminator of the leading V_{had} jet	✓	-	3	-
Quark/gluon discriminator of the trailing V_{had} jet	✓	-	5	-
p_T of the AK8 V_{had} jet candidate	-	✓	-	8
Invariant mass of V_{had}	✓	✓	11	5
Zeppenfeld variable for V_{had}	-	✓	-	9
Centrality	-	✓	15	13



W+jets estimate

- measure the background cross-section **where no signal is expected**
- control region: sit **away from the hadronic W invariant mass**



m_V

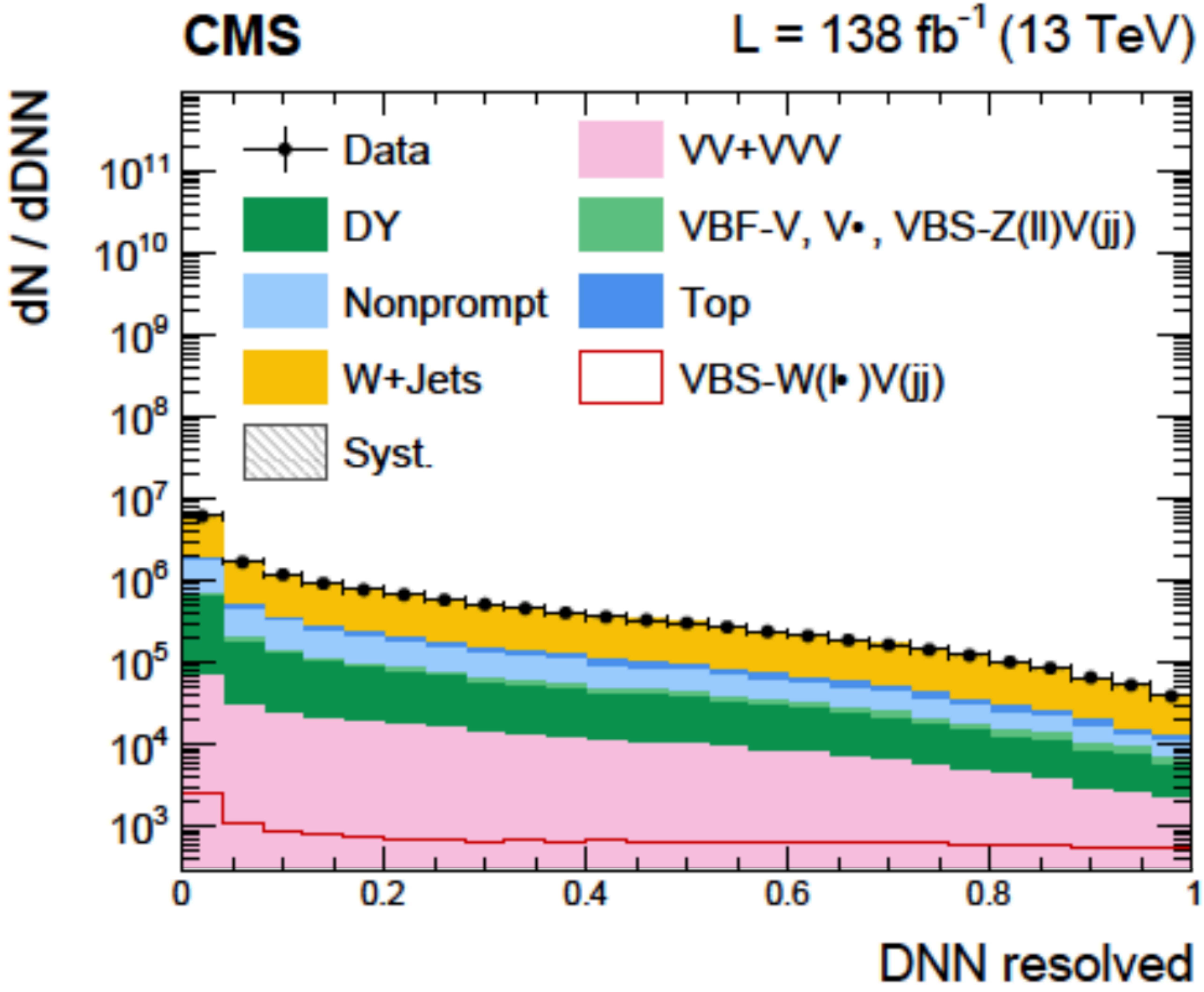
~85 GeV

sideband

signal

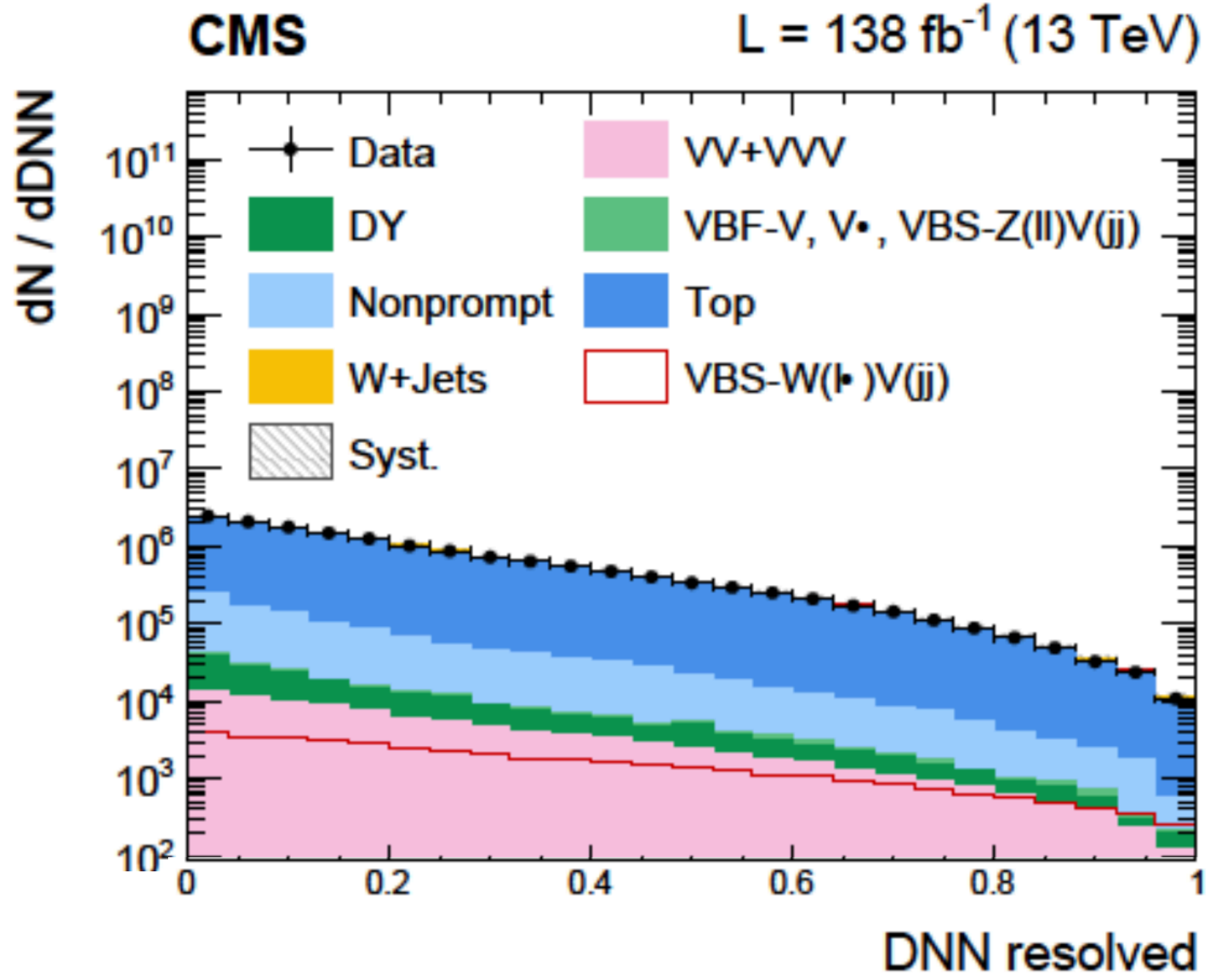
sideband

m_{VZ}



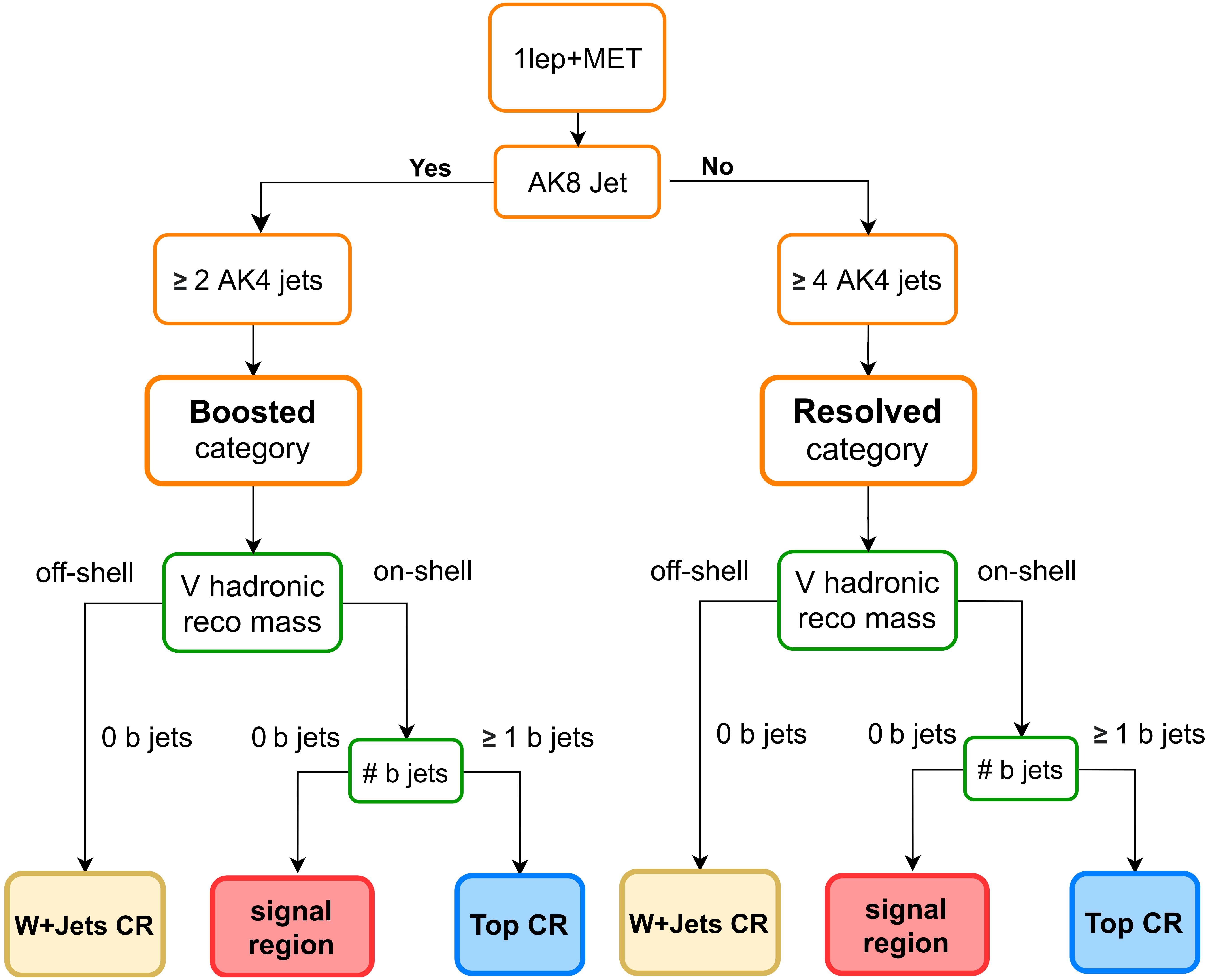
top background estimate

- select events with **at least one b-quark in the final state**



event classification

- **The VBS cross-section is measured with a joint fit** of all signal and control regions
- accounting for all correlations among the various regions



1lep+MET

AK8 Jet

Yes

No

≥ 2 AK4 jets

≥ 4 AK4 jets

Boosted category

Resolved category

off-shell

V hadronic reco mass

on-shell

0 b jets

b jets

≥ 1 b jets

W+Jets CR

signal region

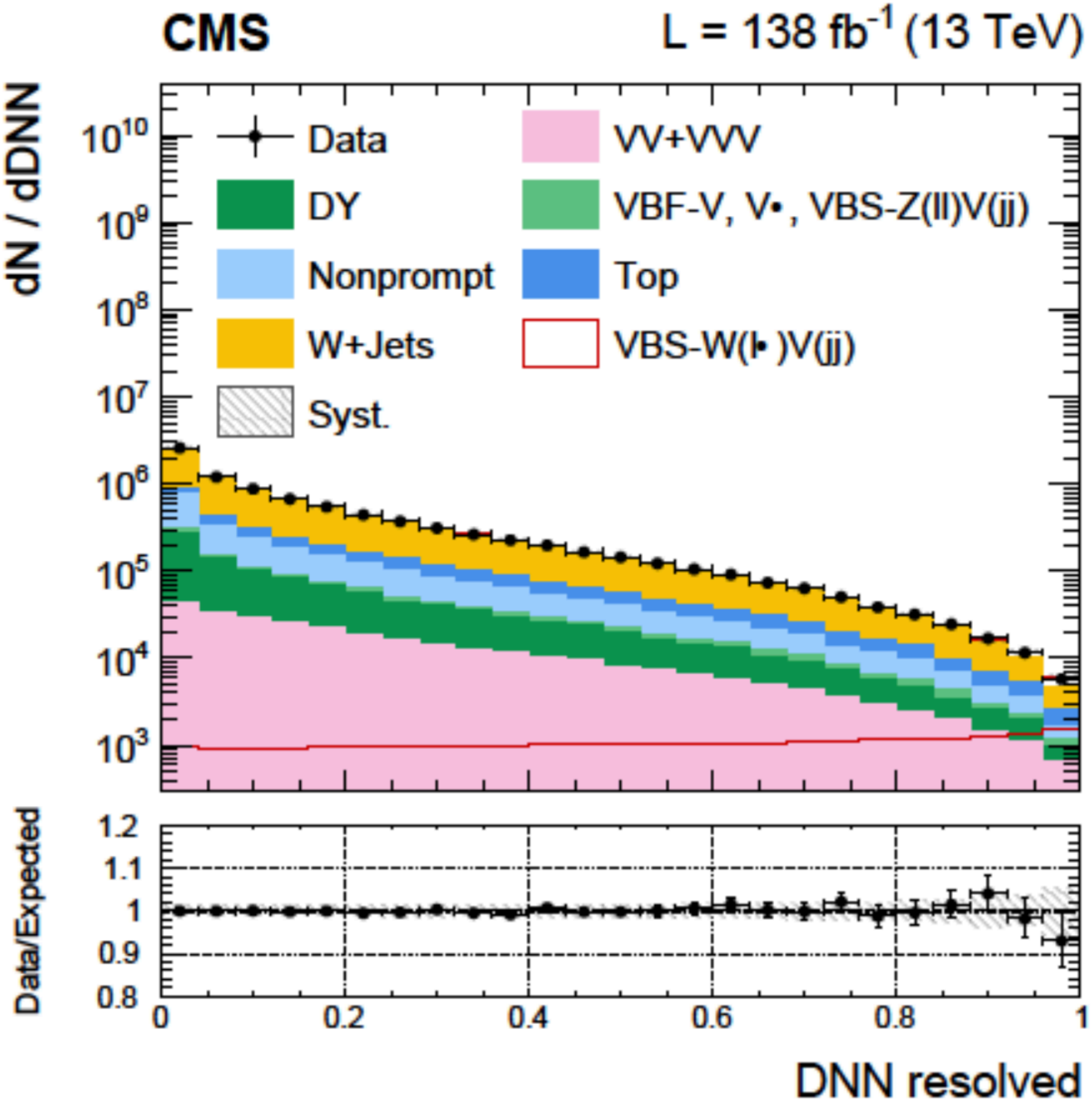
Top CR

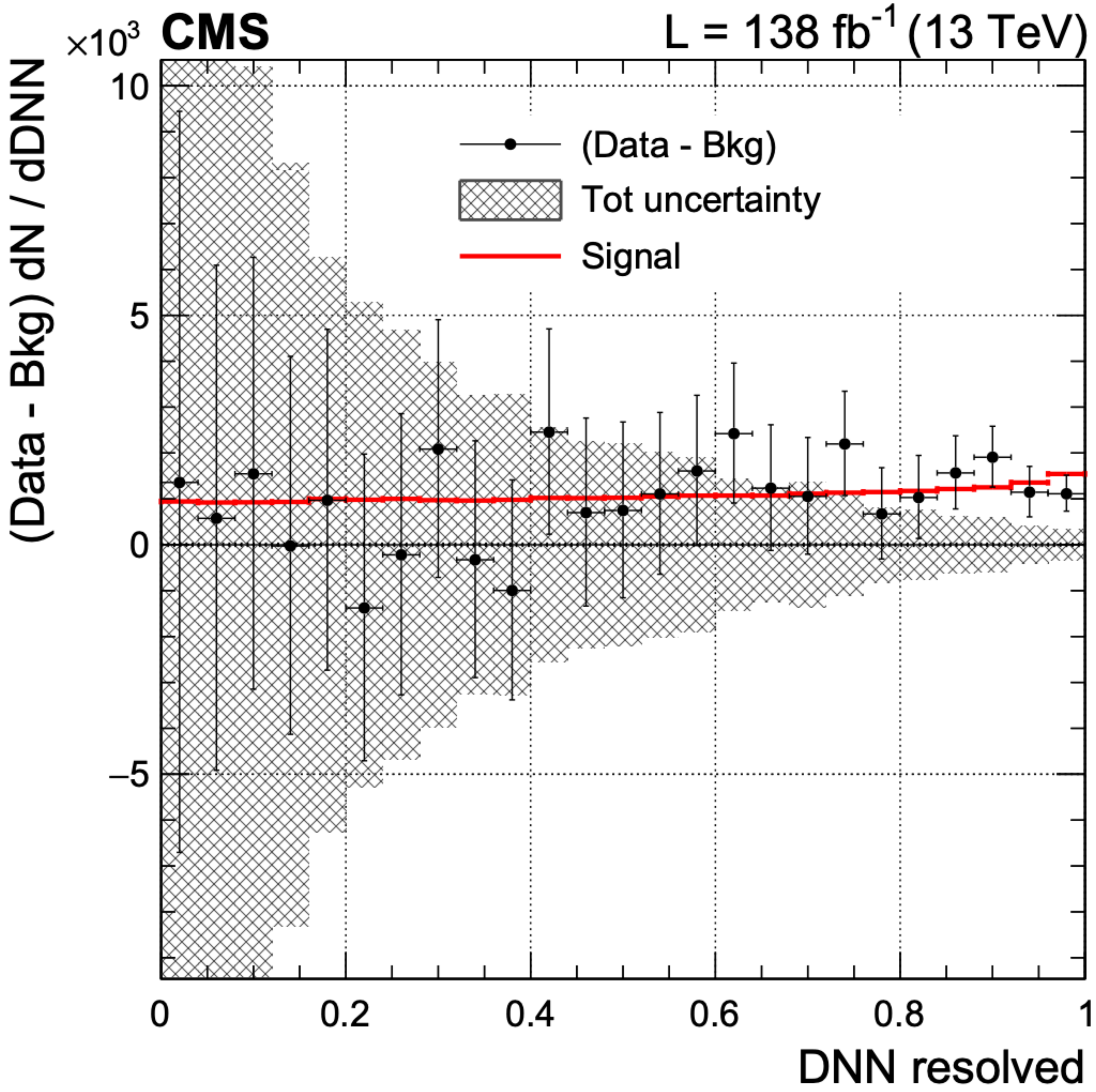
🟧 Object selection

🟩 Phase space selections

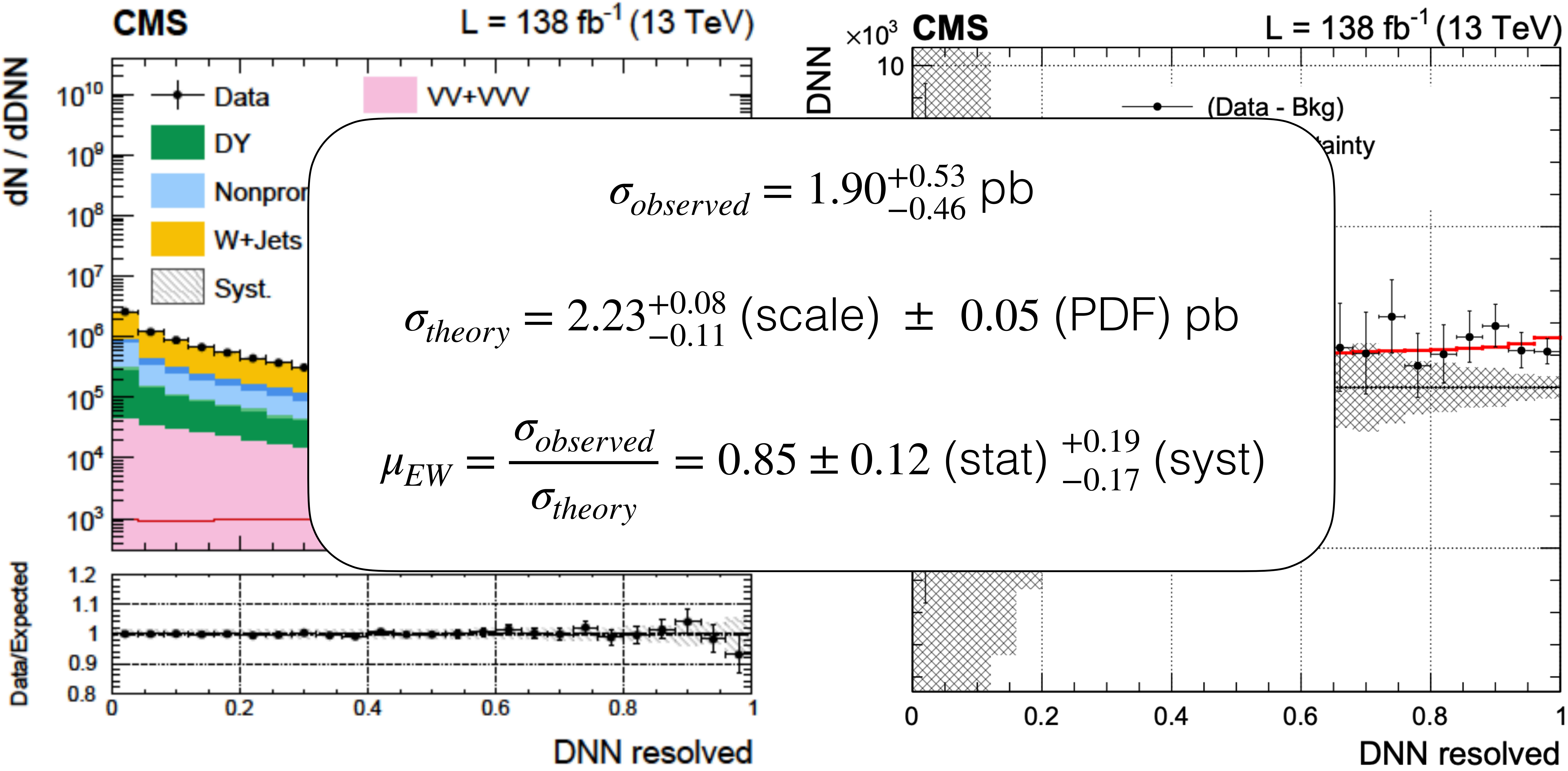
🟦 🟨 🟥 **simultaneous fit regions**

the fit result





the fit result

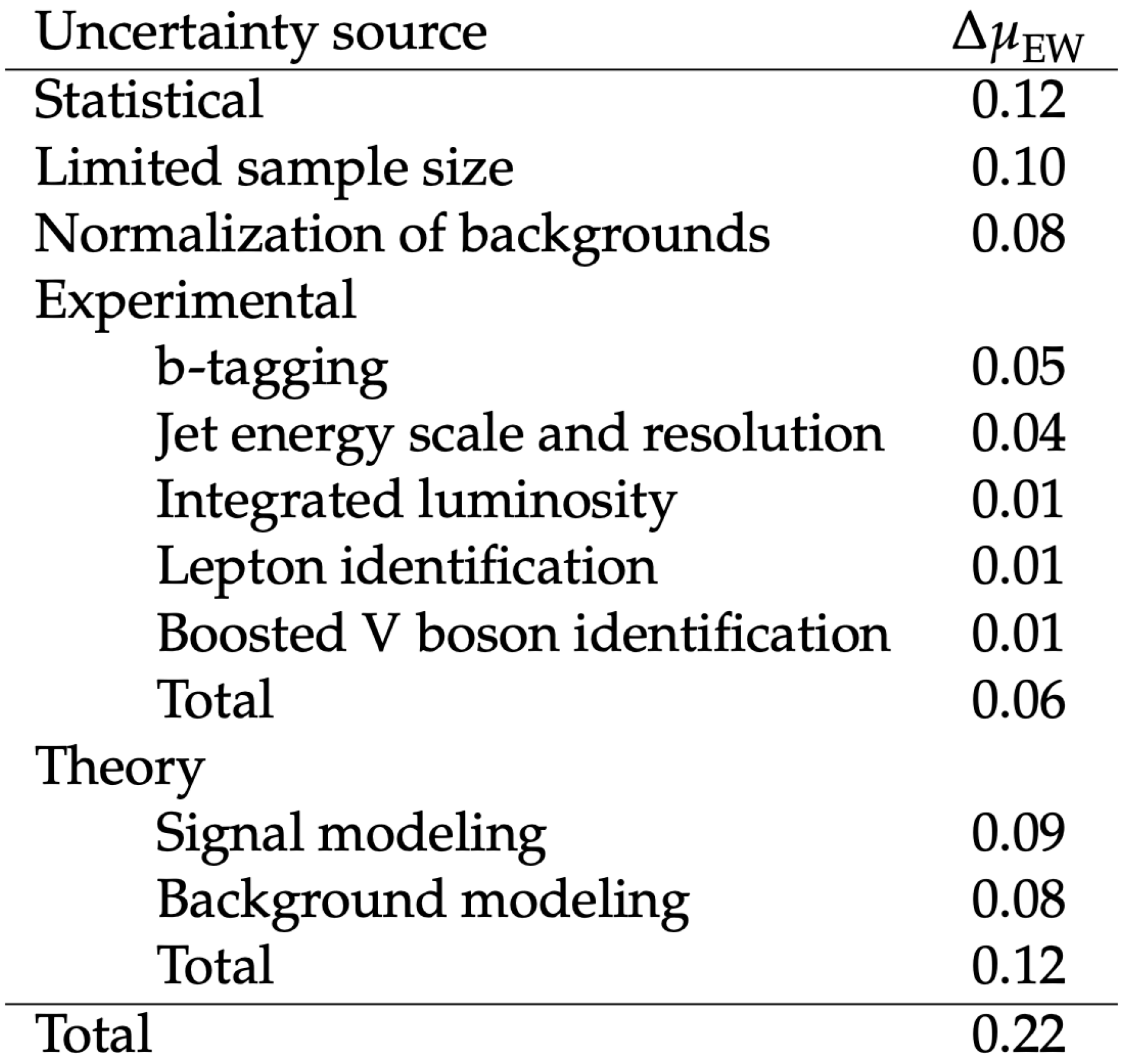


$$\sigma_{observed} = 1.90^{+0.53}_{-0.46}\ \text{pb}$$

$$\sigma_{theory} = 2.23^{+0.08}_{-0.11}\ \text{(scale)} \pm 0.05\ \text{(PDF) pb}$$

$$\mu_{EW} = \frac{\sigma_{observed}}{\sigma_{theory}} = 0.85 \pm 0.12\ \text{(stat)}\ ^{+0.19}_{-0.17}\ \text{(syst)}$$

uncertainties on the signal strength

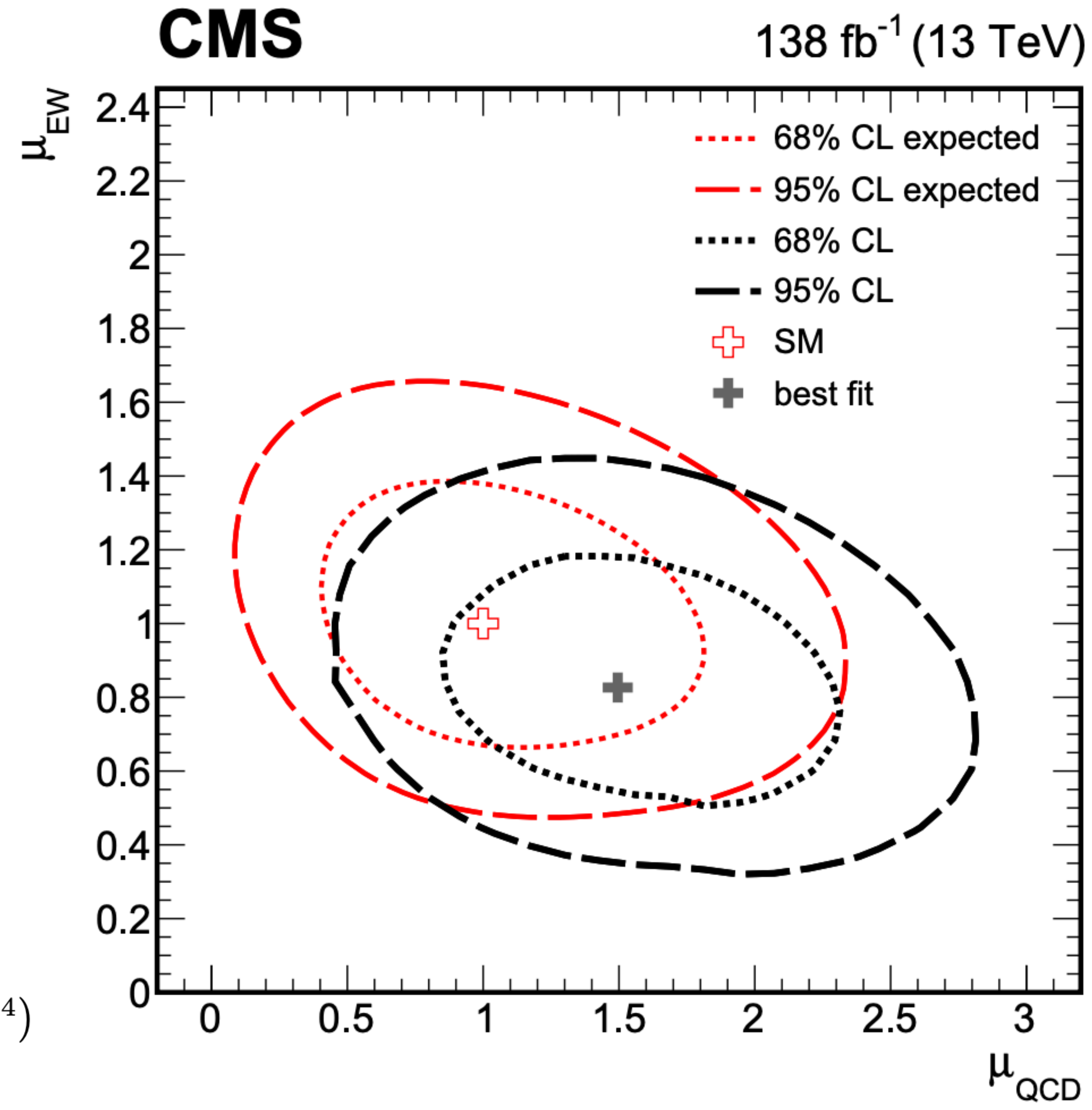


Uncertainty source	$\Delta\mu_{\mathrm{EW}}$
Statistical	0.12
Limited sample size	0.10
Normalization of backgrounds	0.08
Experimental	
b-tagging	0.05
Jet energy scale and resolution	0.04
Integrated luminosity	0.01
Lepton identification	0.01
Boosted V boson identification	0.01
Total	0.06
Theory	
Signal modeling	0.09
Background modeling	0.08
Total	0.12
Total	0.22

consistency of the Standard Model

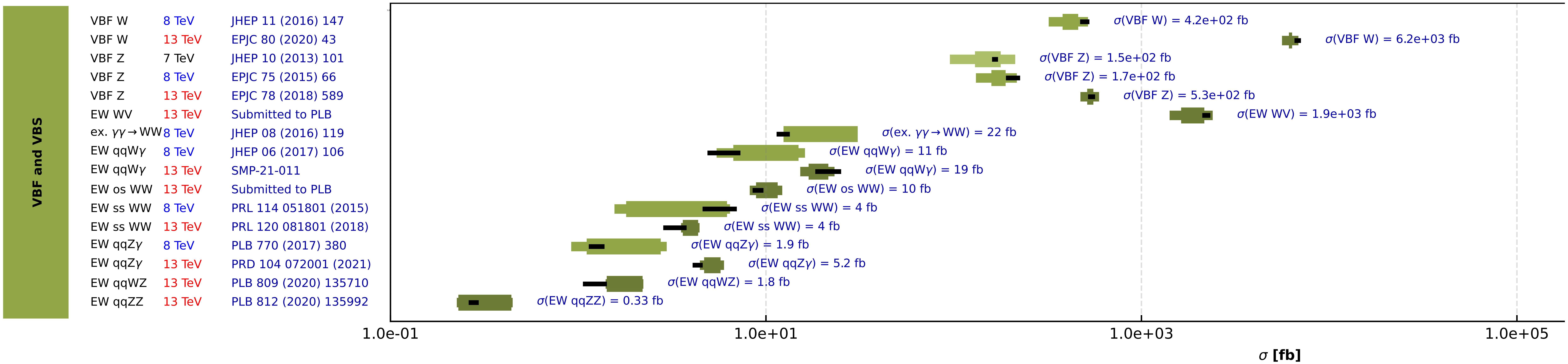
- test whether the data and backgrounds behave as expected by the theory
- **two-dimensional fit**: QCD- and EW-induced VBS (at LO in perturbation theory) cross-sections fitted together
- it’s a **simplistic extension of the standard model**

$$\begin{tikzcd}
\mathbf{LO} & & \mathcal{O}(\alpha^6) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & & \mathcal{O}(\alpha_s\alpha^5) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & & \mathcal{O}(\alpha_s^2\alpha^4) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & \\
\mathbf{NLO} & \mathcal{O}(\alpha^7) & & \mathcal{O}(\alpha_s\alpha^6) & & \mathcal{O}(\alpha_s^2\alpha^5) & & \mathcal{O}(\alpha_s^3\alpha^4)
\end{tikzcd}$$



more VBS results

https://arxiv.org/abs/2102.10991



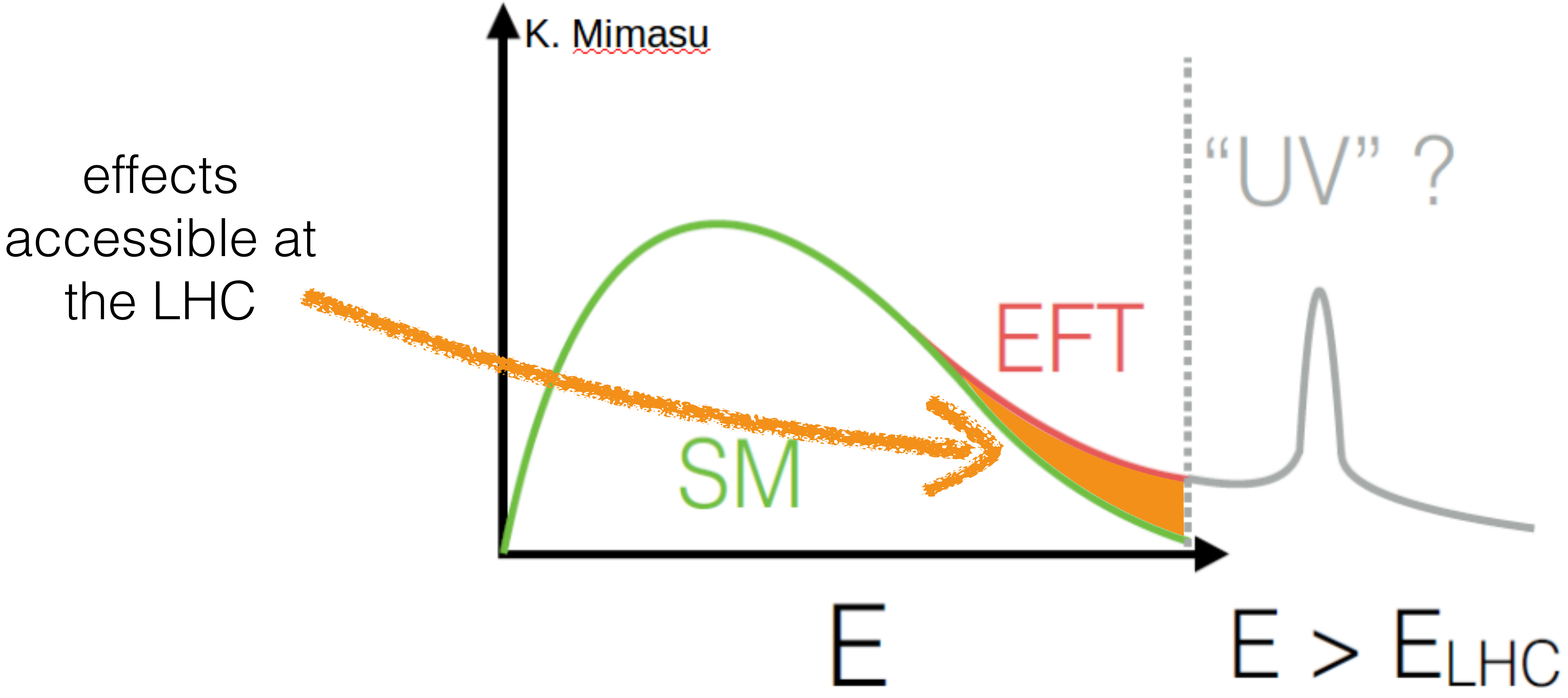
Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots

Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light colored bars: 7 TeV, Medium bars: 8 TeV, Dark bars: 13 TeV, Black bars: theory prediction

+ ATLAS corresponding set of results

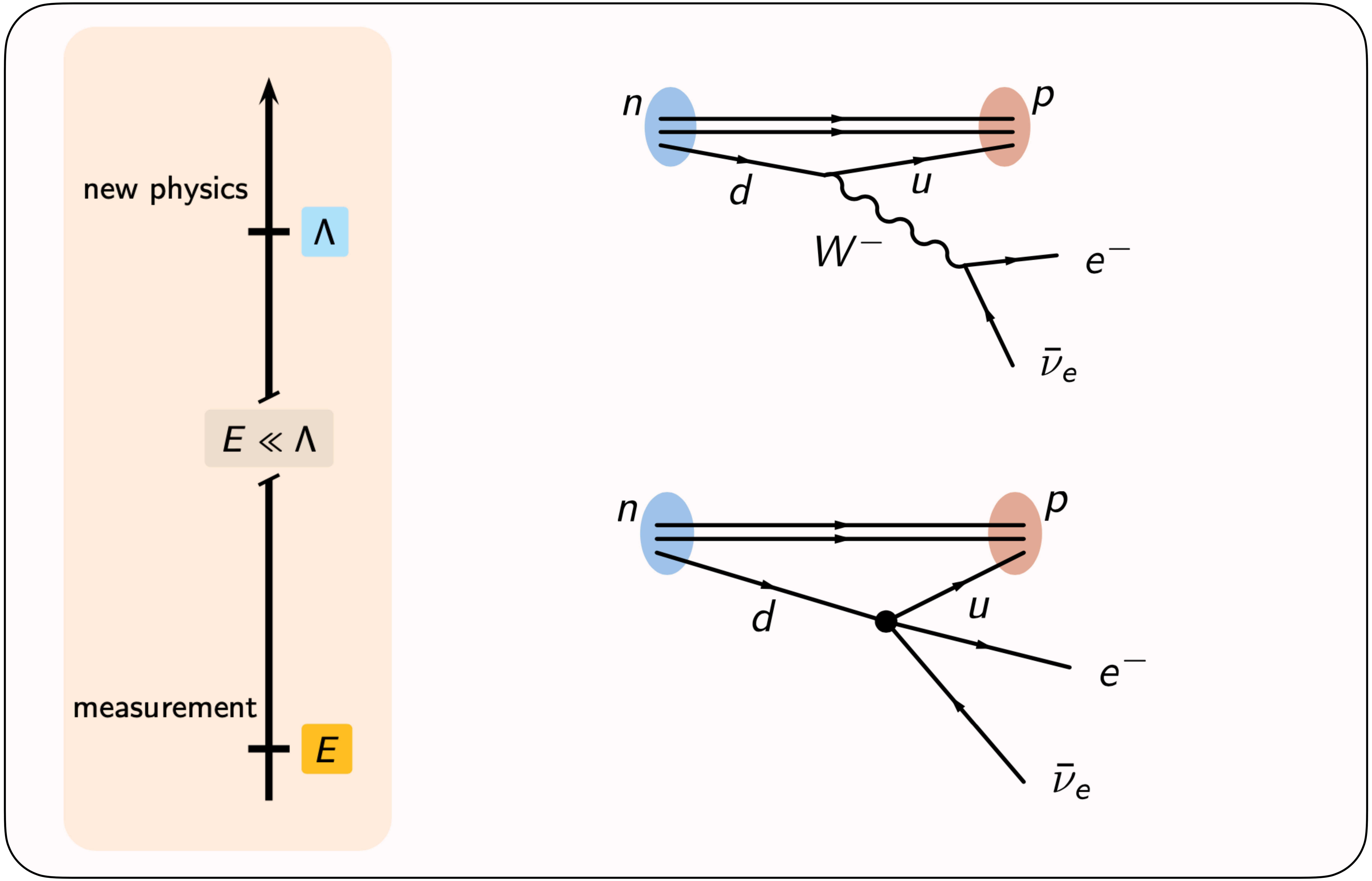
indirect measurements

- (precise) measurement of **low-energy effects of a high energy unknown theory**



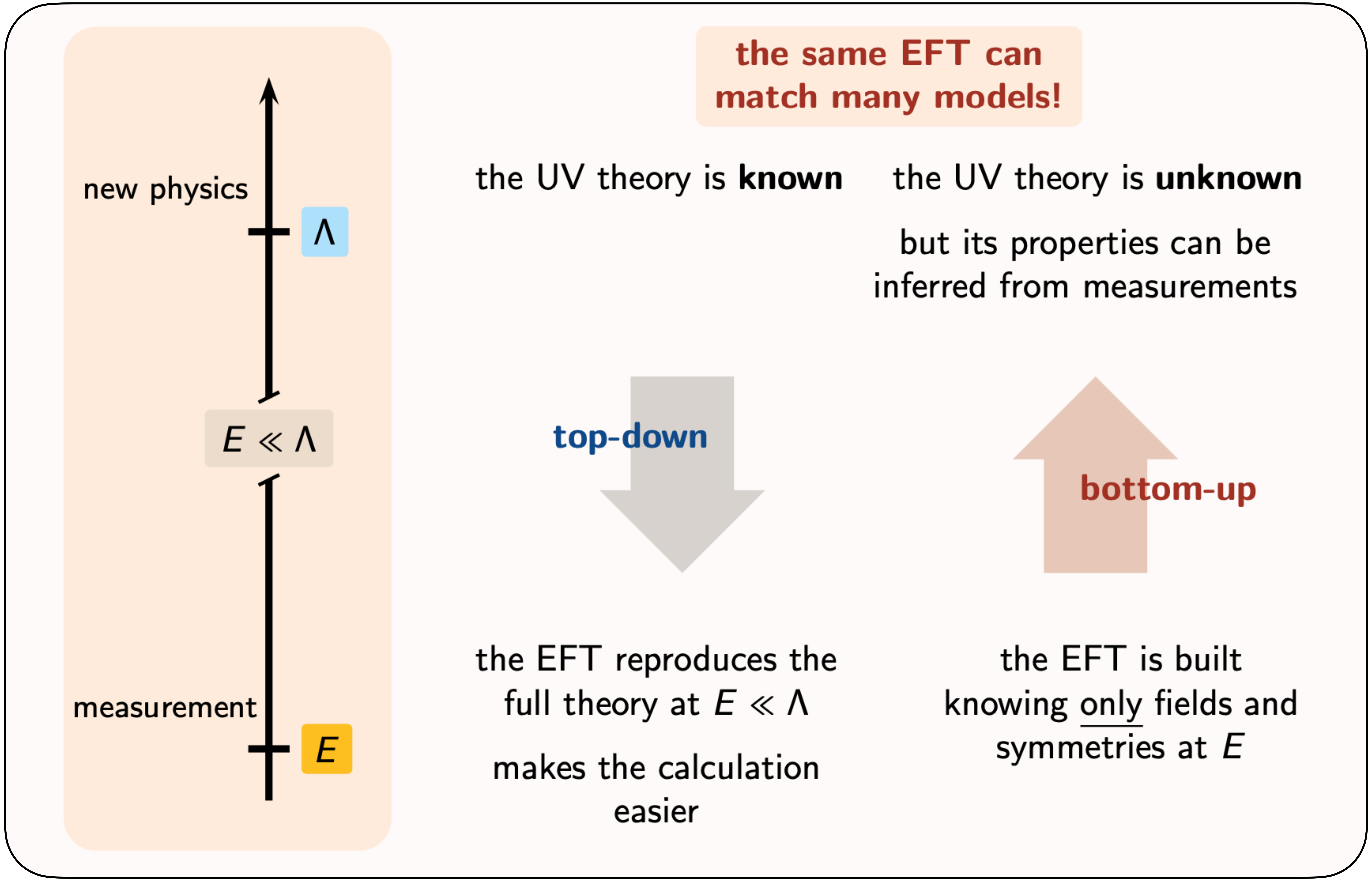
historical example: fermi interactions

courtesy of
I. Brivio



the effective field theory approach

courtesy of
I. Brivio



new physics

Λ

$E \ll \Lambda$

measurement

E

the same EFT can match many models!

the UV theory is **known**

top-down

the EFT reproduces the full theory at $E \ll \Lambda$

makes the calculation easier

the UV theory is **unknown**

but its properties can be inferred from measurements

bottom-up

the EFT is built knowing only fields and symmetries at E

the Effective Field Theory (EFT) model

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} + \frac{c_i}{\Lambda^4} O_i^{(8)} + \ldots$$

🟦 c_i Wilson coefficients

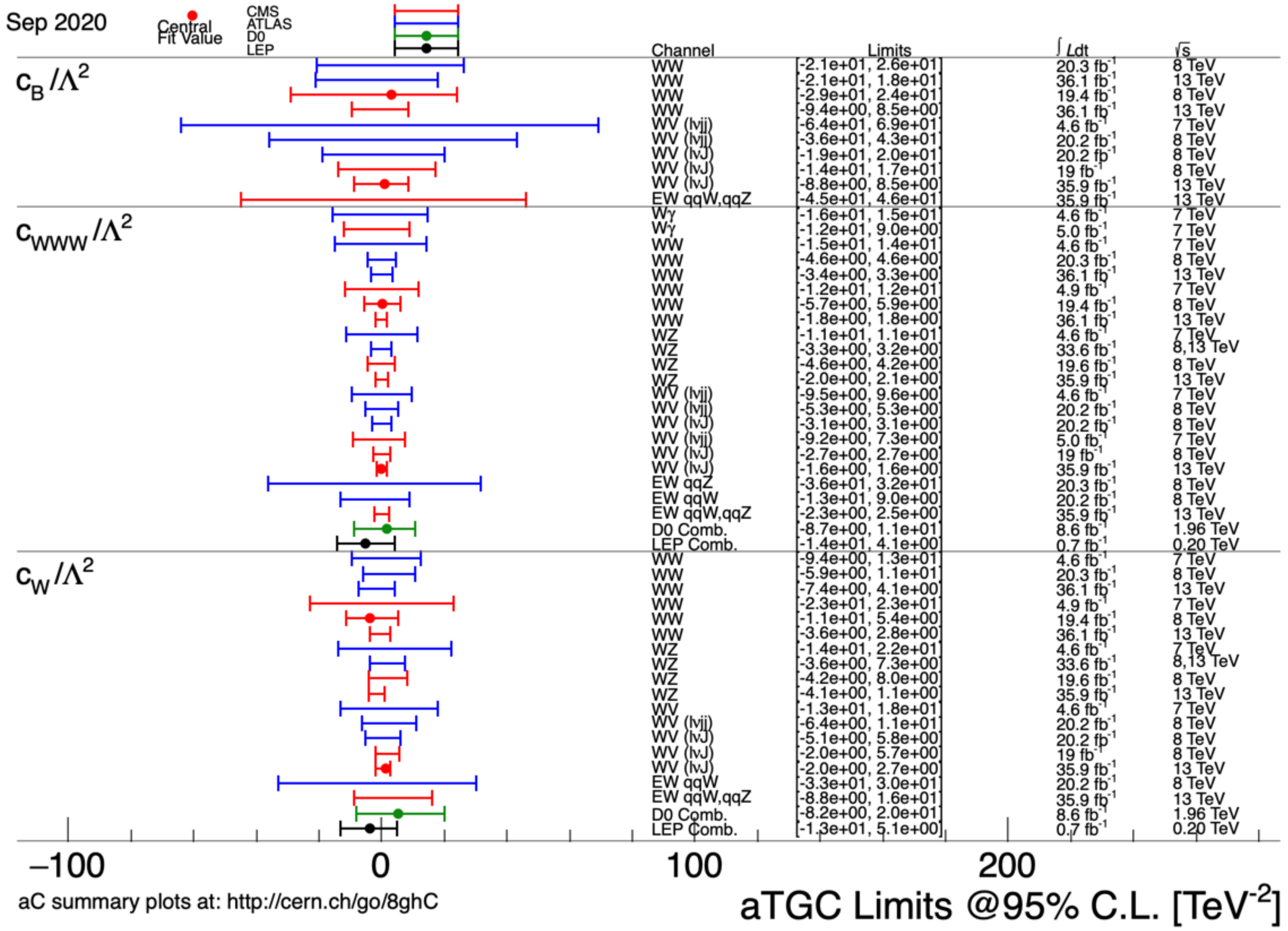
🟥 Λ unknown NP energy scale

- **2499 additional parameters** at dimension-6
- may be reduced significantly with **reasonable requirements** (e.g. lepton universality)
- **odd terms** would break symmetries, like the lepton and barion number conservation

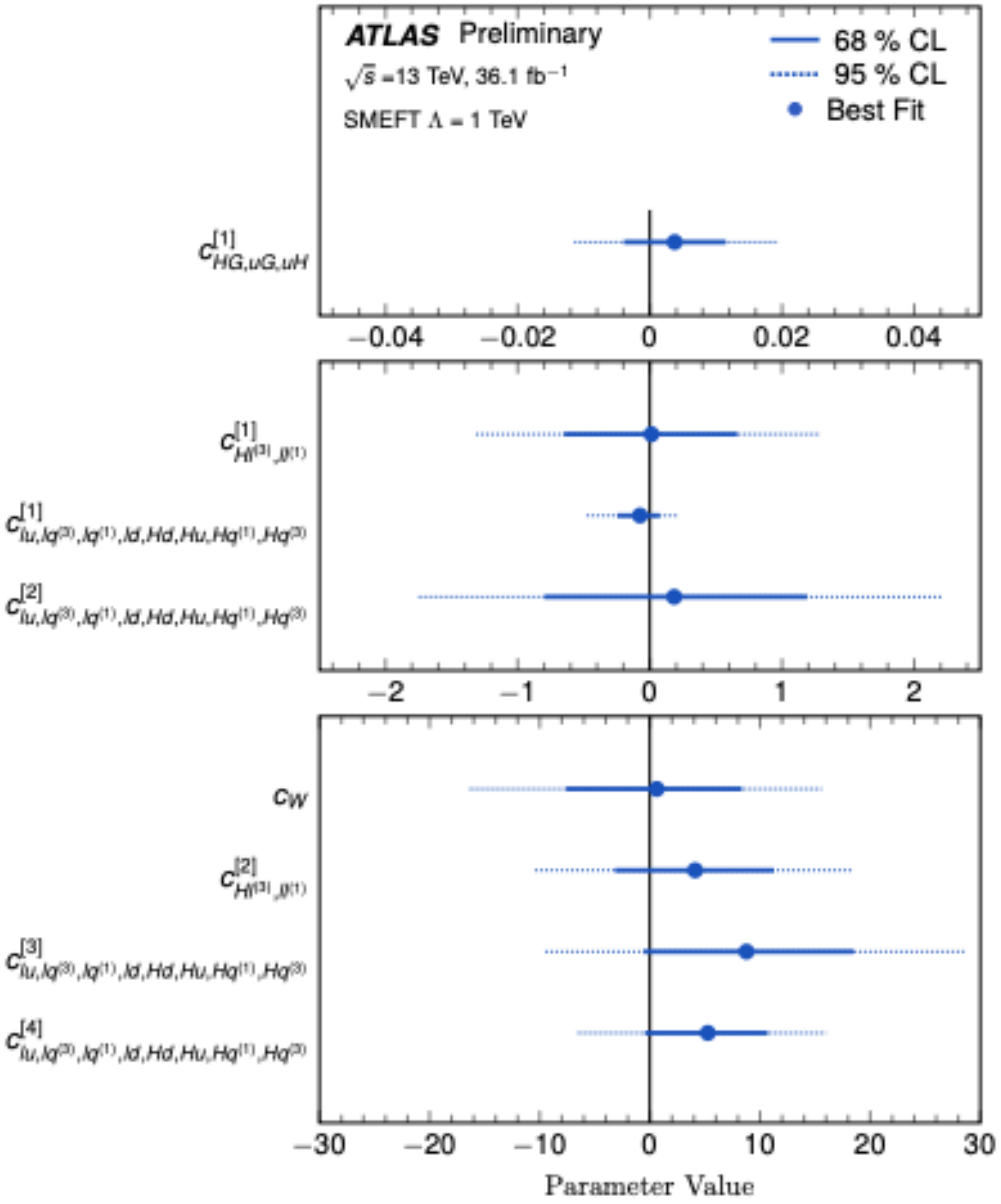
existing studies

http://go.web.cern.ch/go/7LSN
ATL-PHYS-PUB-2021-010

- calculated in **simplified configurations** (“anomalous couplings”)
- on a **small sub-set of operators**
- often derived from **single analysis channels**

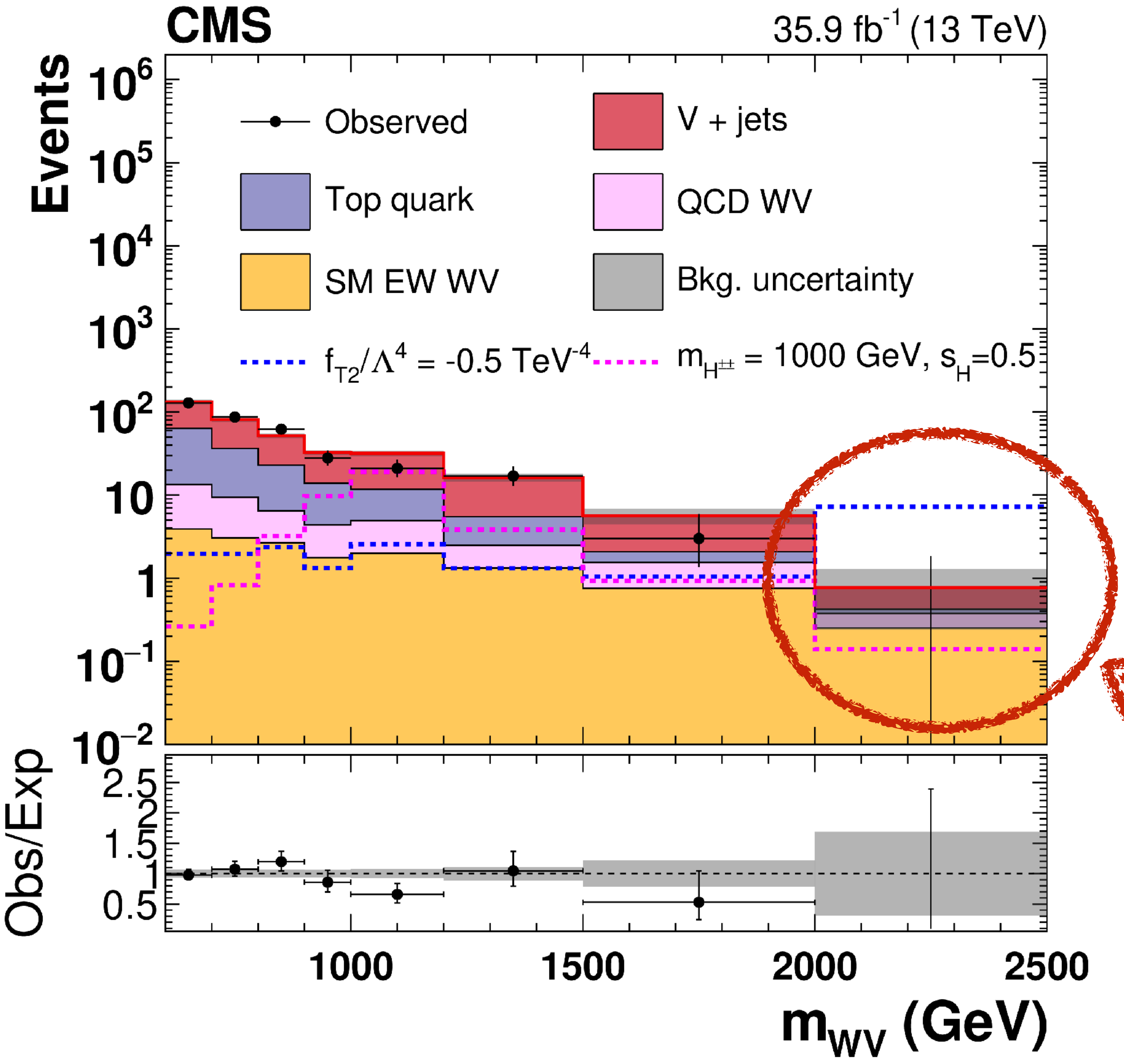


Channel	Limits	$\int L dt$	$\sqrt{s}$
WW	[-2.1e+01, 2.6e+01]	20.3 fb^{-1}	8 TeV
WW	[-2.1e+01, 1.8e+01]	36.1 fb^{-1}	13 TeV
WW	[-2.9e+01, 2.4e+01]	19.4 fb^{-1}	8 TeV
WW	[-9.4e+00, 8.5e+00]	36.1 fb^{-1}	13 TeV
WV (lνjj)	[-6.4e+01, 6.9e+01]	4.6 fb^{-1}	7 TeV
WV (lνjj)	[-3.6e+01, 4.3e+01]	20.2 fb^{-1}	8 TeV
WV (lνJ)	[-1.9e+01, 2.0e+01]	20.2 fb^{-1}	8 TeV
WV (lνJ)	[-1.4e+01, 1.7e+01]	19 fb^{-1}	8 TeV
WV (lνJ)	[-8.8e+00, 8.5e+00]	35.9 fb^{-1}	13 TeV
EW qqW,qqZ	[-4.5e+01, 4.6e+01]	35.9 fb^{-1}	13 TeV
Wγ	[-1.6e+01, 1.5e+01]	4.6 fb^{-1}	7 TeV
Wγ	[-1.2e+01, 9.0e+00]	5.0 fb^{-1}	7 TeV
WW	[-1.5e+01, 1.4e+01]	4.6 fb^{-1}	7 TeV
WW	[-4.6e+00, 4.6e+00]	20.3 fb^{-1}	8 TeV
WW	[-3.4e+00, 3.3e+00]	36.1 fb^{-1}	13 TeV
WW	[-1.2e+01, 1.2e+01]	4.9 fb^{-1}	7 TeV
WW	[-5.7e+00, 5.9e+00]	19.4 fb^{-1}	8 TeV
WW	[-1.8e+00, 1.8e+00]	36.1 fb^{-1}	13 TeV
WZ	[-1.1e+01, 1.1e+01]	4.6 fb^{-1}	7 TeV
WZ	[-3.3e+00, 3.2e+00]	33.6 fb^{-1}	8,13 TeV
WZ	[-4.6e+00, 4.2e+00]	19.6 fb^{-1}	8 TeV
WZ	[-2.0e+00, 2.1e+00]	35.9 fb^{-1}	13 TeV
WV (lνjj)	[-9.5e+00, 9.6e+00]	4.6 fb^{-1}	7 TeV
WV (lνjj)	[-5.3e+00, 5.3e+00]	20.2 fb^{-1}	8 TeV
WV (lνJ)	[-3.1e+00, 3.1e+00]	20.2 fb^{-1}	8 TeV
WV (lνjj)	[-9.2e+00, 7.3e+00]	5.0 fb^{-1}	7 TeV
WV (lνJ)	[-2.7e+00, 2.7e+00]	19 fb^{-1}	8 TeV
WV (lνJ)	[-1.6e+00, 1.6e+00]	35.9 fb^{-1}	13 TeV
EW qqZ	[-3.6e+01, 3.2e+01]	20.3 fb^{-1}	8 TeV
EW qqW	[-1.3e+01, 9.0e+00]	20.2 fb^{-1}	8 TeV
EW qqW,qqZ	[-2.3e+00, 2.5e+00]	35.9 fb^{-1}	13 TeV
D0 Comb.	[-8.7e+00, 1.1e+01]	8.6 fb^{-1}	1.96 TeV
LEP Comb.	[-1.4e+01, 4.1e+00]	0.7 fb^{-1}	0.20 TeV
WW	[-9.4e+00, 1.3e+01]	4.6 fb^{-1}	7 TeV
WW	[-5.9e+00, 1.1e+01]	20.3 fb^{-1}	8 TeV
WW	[-7.4e+00, 4.1e+00]	36.1 fb^{-1}	13 TeV
WW	[-2.3e+01, 2.3e+01]	4.9 fb^{-1}	7 TeV
WW	[-1.1e+01, 5.4e+00]	19.4 fb^{-1}	8 TeV
WW	[-3.6e+00, 2.8e+00]	36.1 fb^{-1}	13 TeV
WZ	[-1.4e+01, 2.2e+01]	4.6 fb^{-1}	7 TeV
WZ	[-3.6e+00, 7.3e+00]	33.6 fb^{-1}	8,13 TeV
WZ	[-4.2e+00, 8.0e+00]	19.6 fb^{-1}	8 TeV
WZ	[-4.1e+00, 1.1e+00]	35.9 fb^{-1}	13 TeV
WV	[-1.3e+01, 1.8e+01]	4.6 fb^{-1}	7 TeV
WV (lνjj)	[-6.4e+00, 1.1e+01]	20.2 fb^{-1}	8 TeV
WV (lνJ)	[-5.1e+00, 5.8e+00]	20.2 fb^{-1}	8 TeV
WV (lνJ)	[-2.0e+00, 5.7e+00]	19 fb^{-1}	8 TeV
WV (lνJ)	[-2.0e+00, 2.7e+00]	35.9 fb^{-1}	13 TeV
EW qqW	[-3.3e+01, 3.0e+01]	20.2 fb^{-1}	8 TeV
EW qqW,qqZ	[-8.8e+00, 1.6e+01]	35.9 fb^{-1}	13 TeV
D0 Comb.	[-8.2e+00, 2.0e+01]	8.6 fb^{-1}	1.96 TeV
LEP Comb.	[-1.3e+01, 5.1e+00]	0.7 fb^{-1}	0.20 TeV



in the VBS case

https://arxiv.org/abs/1905.07445

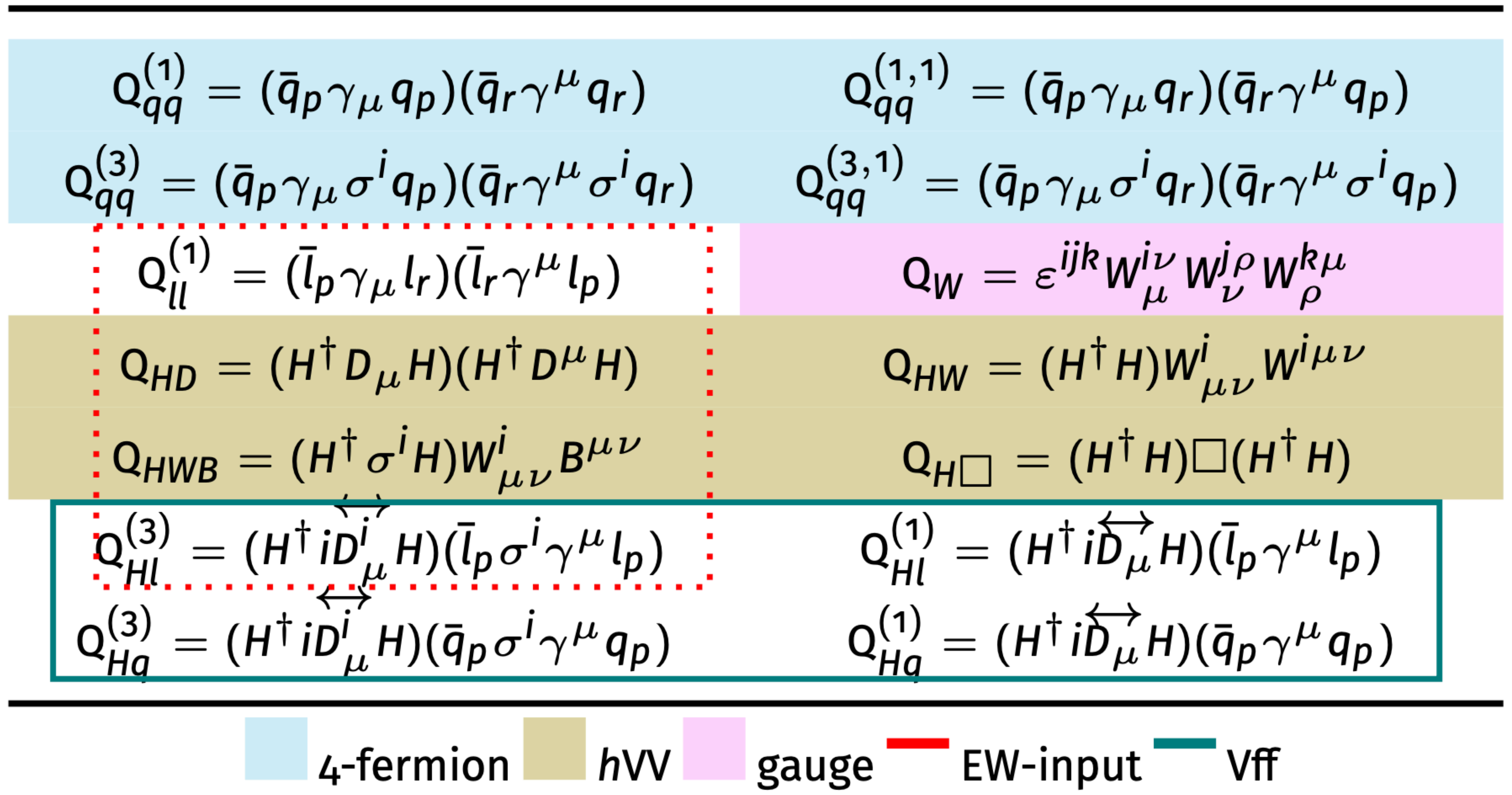


typical high-energy effect on the di-boson invariant mass

a study of VBS sensitivity

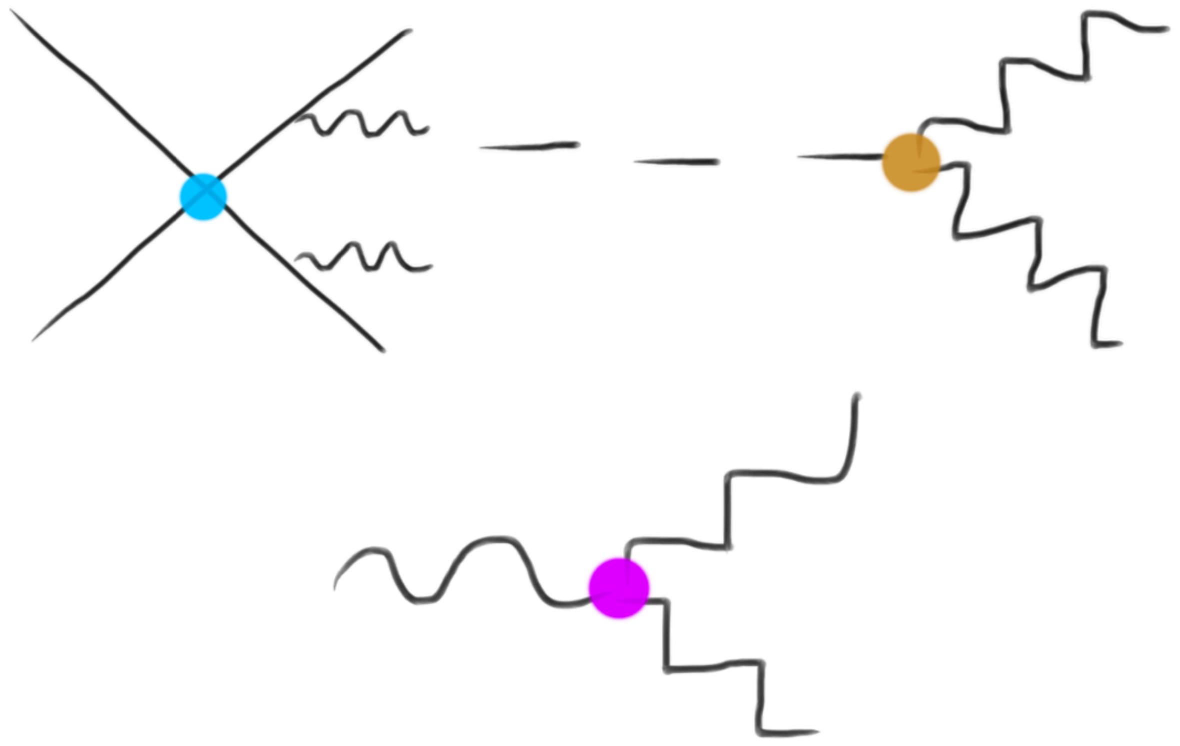
JHEP05(2022)039

- parton-level simulated study of the VBS impact in constraining **dimension-6 EFT operators in the SMEFT framework**
- access to **several operators**, thanks to the complexity of the VBS diagrams



$Q_{qq}^{(1)} = (\bar{q}_p\gamma_\mu q_p)(\bar{q}_r\gamma^\mu q_r)$	$Q_{qq}^{(1,1)} = (\bar{q}_p\gamma_\mu q_r)(\bar{q}_r\gamma^\mu q_p)$
$Q_{qq}^{(3)} = (\bar{q}_p\gamma_\mu\sigma^i q_p)(\bar{q}_r\gamma^\mu\sigma^i q_r)$	$Q_{qq}^{(3,1)} = (\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_r\gamma^\mu\sigma^i q_p)$
$Q_{ll}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{l}_r\gamma^\mu l_p)$	$Q_W = \varepsilon^{ijk}W_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$
$Q_{HD} = (H^\dagger D_\mu H)(H^\dagger D^\mu H)$	$Q_{HW} = (H^\dagger H)W_{\mu\nu}^i W^{i\mu\nu}$
$Q_{HWB} = (H^\dagger\sigma^i H)W_{\mu\nu}^i B^{\mu\nu}$	$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$
$Q_{Hl}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{l}_p\sigma^i\gamma^\mu l_p)$	$Q_{Hl}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_p)$
$Q_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{q}_p\sigma^i\gamma^\mu q_p)$	$Q_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_p)$

4-fermion hVV gauge EW-input Vff



$$N \propto \overbrace{|\mathcal{A}_{SM}|^2}^{\text{SM}} + \sum_\alpha \frac{c_\alpha}{\Lambda^2} \cdot \underbrace{2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}_{Q_\alpha}^\dagger)}_{\text{Lin}} + \frac{c_\alpha^2}{\Lambda^4} \cdot \overbrace{|\mathcal{A}_{Q_\alpha}|^2}^{\text{Quad}} + \sum_{\alpha,\beta} \frac{c_\alpha c_\beta}{\Lambda^4} \cdot \underbrace{\mathrm{Re}(\mathcal{A}_{Q_\alpha}\mathcal{A}_{Q_\beta}^\dagger)}_{\text{Mix}}$$

courtesy of G. Boldrini

processes considered

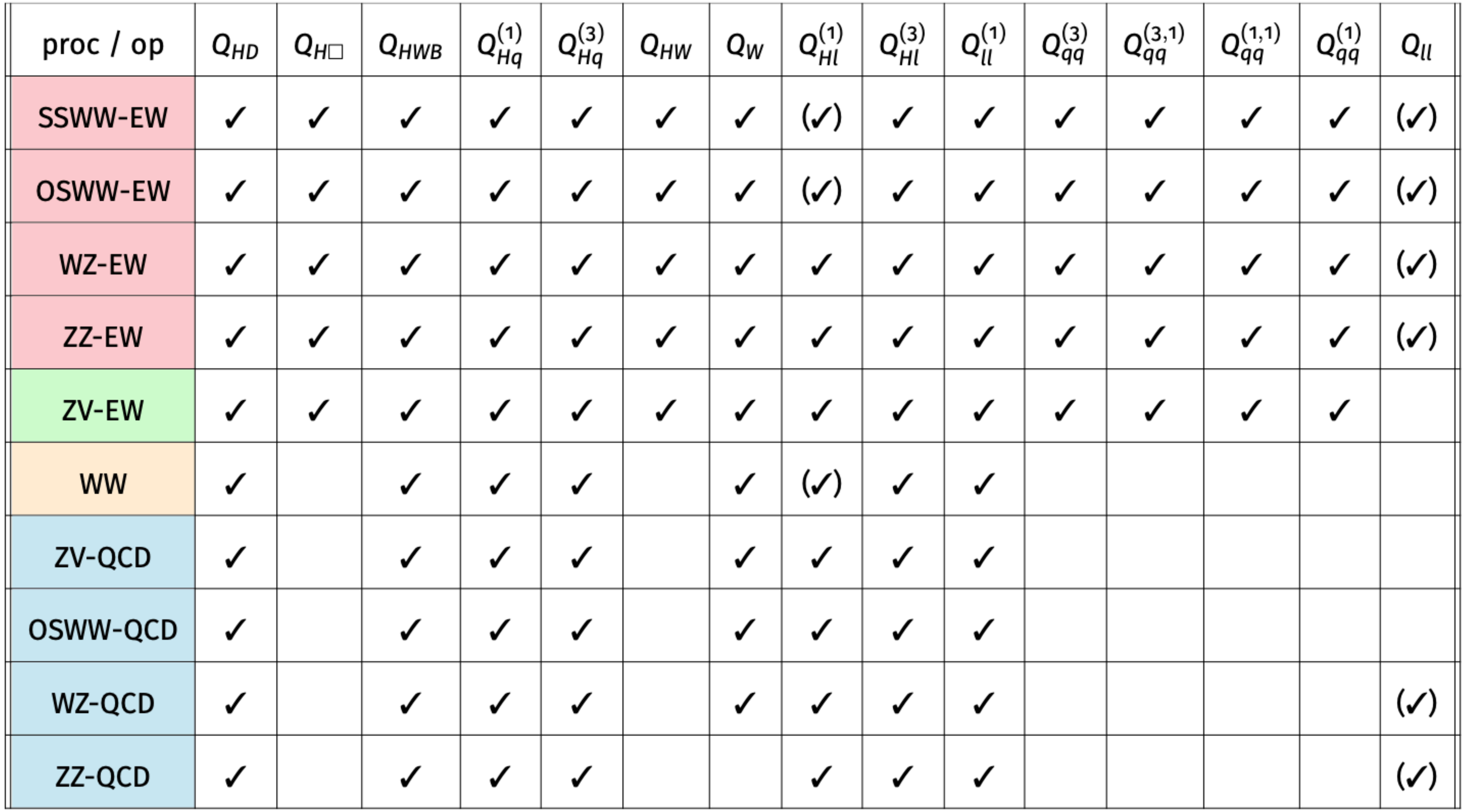
- **major irreducible backgrounds** included
- **LHC-like selections** applied

- **Same-sign WW:** $\mathrm{p\,p} > \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \nu_\mu\, \mathrm{j\,j}$
- **Opposite-sign WW (QCD):** $\mathrm{p\,p} > \mathrm{e}^+ \nu_\mathrm{e}\, \mu^- \bar{\nu_\mu}\, \mathrm{j\,j}$
- **WZ+2j(QCD):** $\mathrm{p\,p} > \mathrm{e}^+ \mathrm{e}^- \mu^+ \nu_\mu\, \mathrm{j\,j}$
- **ZZ+2j(QCD):** $\mathrm{p\,p} > \mathrm{e}^+ \mathrm{e}^- \mu^+ \mu^-$
- **ZV+2j(QCD):** $\mathrm{p\,p} > \mathrm{z\,w}^+(\mathrm{w}^-, \mathrm{z}) > \mathrm{l}^+ \mathrm{l}^- \mathrm{j\,j\,j\,j}$
- **WW:** $\mathrm{p\,p} > \mathrm{e}^+ \nu_\mathrm{e}\, \mu^- \bar{\nu_\mu}$

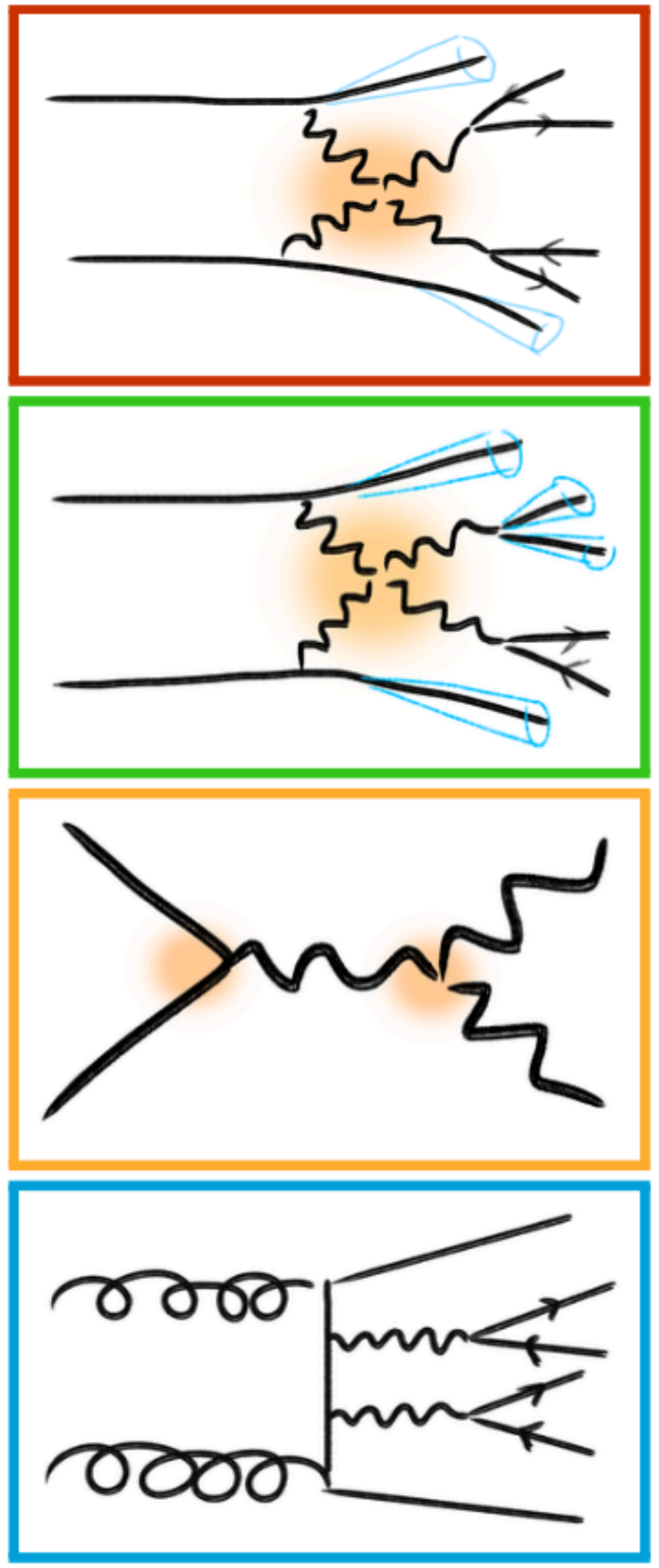
not VBS: used as a comparison term

processed involved - EFT sensitivity

- **Full 2 → 6 VBS processes generated** including non-resonant diagrams.

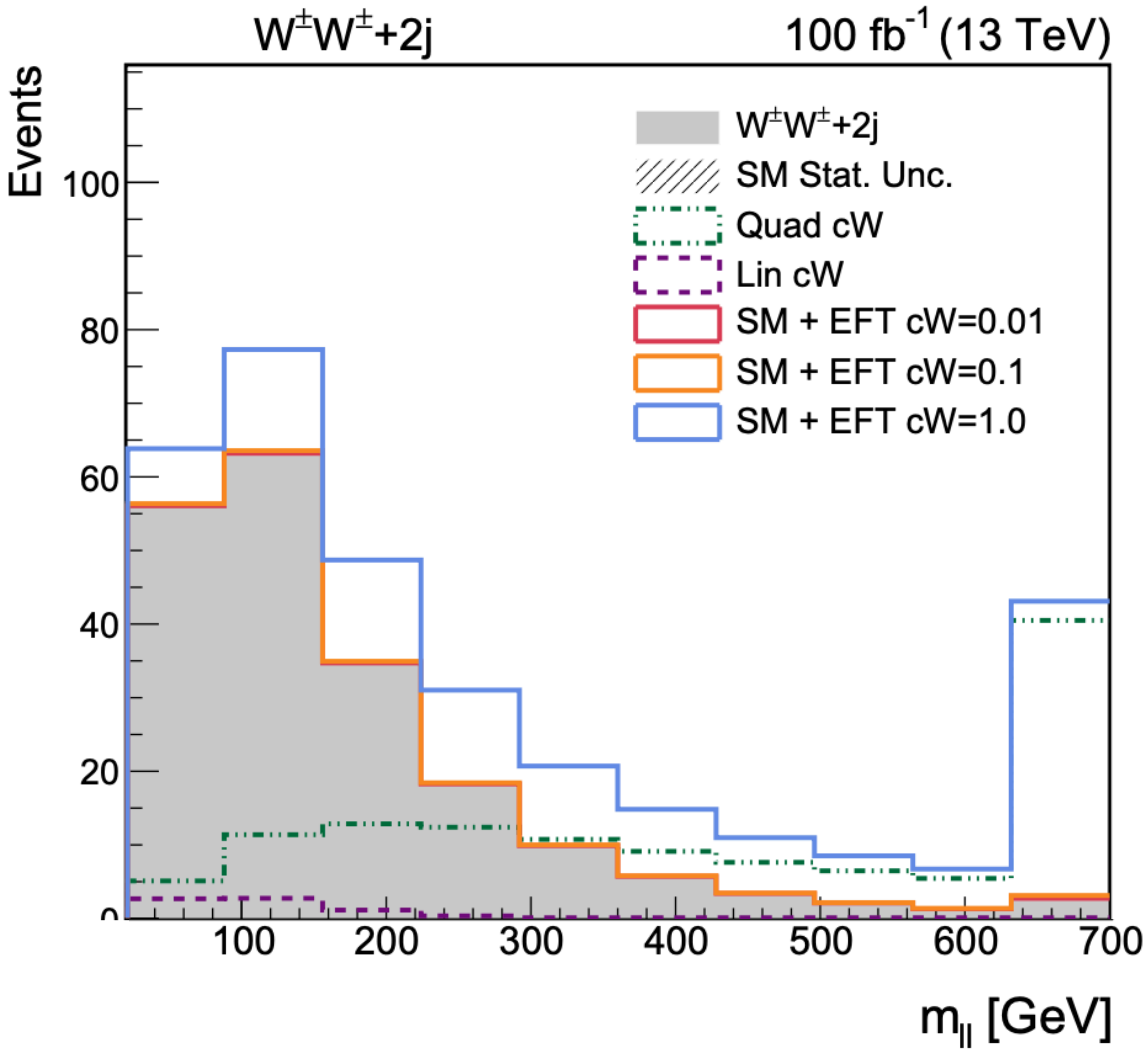


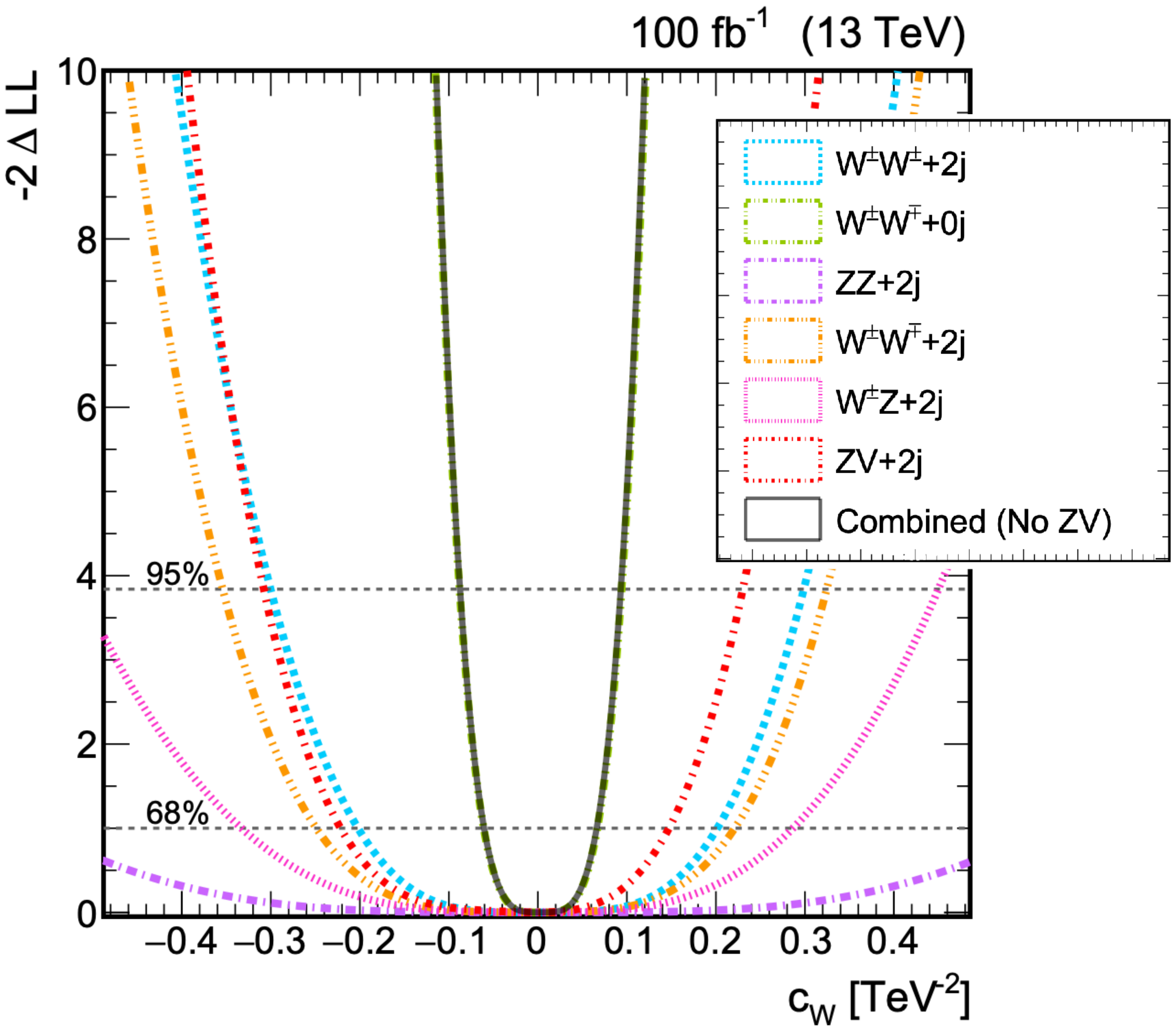
proc / op	Q_{HD}	$Q_{H\Box}$	Q_{HWB}	$Q_{Hq}^{(1)}$	$Q_{Hq}^{(3)}$	Q_{HW}	Q_{W}	$Q_{Hl}^{(1)}$	$Q_{Hl}^{(3)}$	$Q_{ll}^{(1)}$	$Q_{qq}^{(3)}$	$Q_{qq}^{(3,1)}$	$Q_{qq}^{(1,1)}$	$Q_{qq}^{(1)}$	Q_{ll}
SSWW-EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
OSWW-EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
WZ-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZZ-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZV-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
WW	✓		✓	✓	✓		✓	(✓)	✓	✓					
ZV-QCD	✓		✓	✓	✓		✓	✓	✓	✓					
OSWW-QCD	✓		✓	✓	✓		✓	✓	✓	✓					
WZ-QCD	✓		✓	✓	✓		✓	✓	✓	✓					(✓)
ZZ-QCD	✓		✓	✓	✓			✓	✓	✓					(✓)



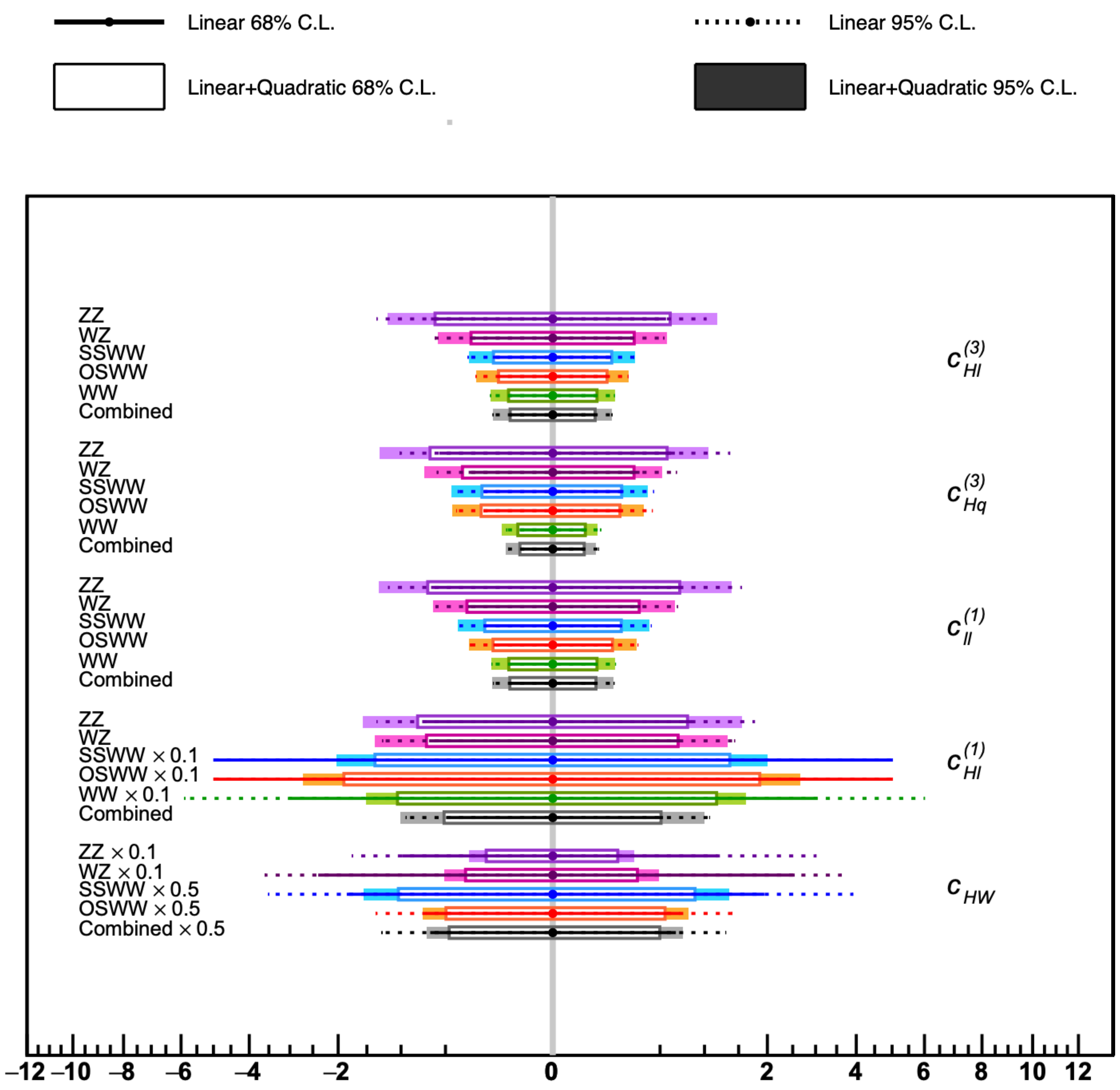
sensitivity determination

- fit the most sensitive variable with **Wilson coefficients as free parameters**





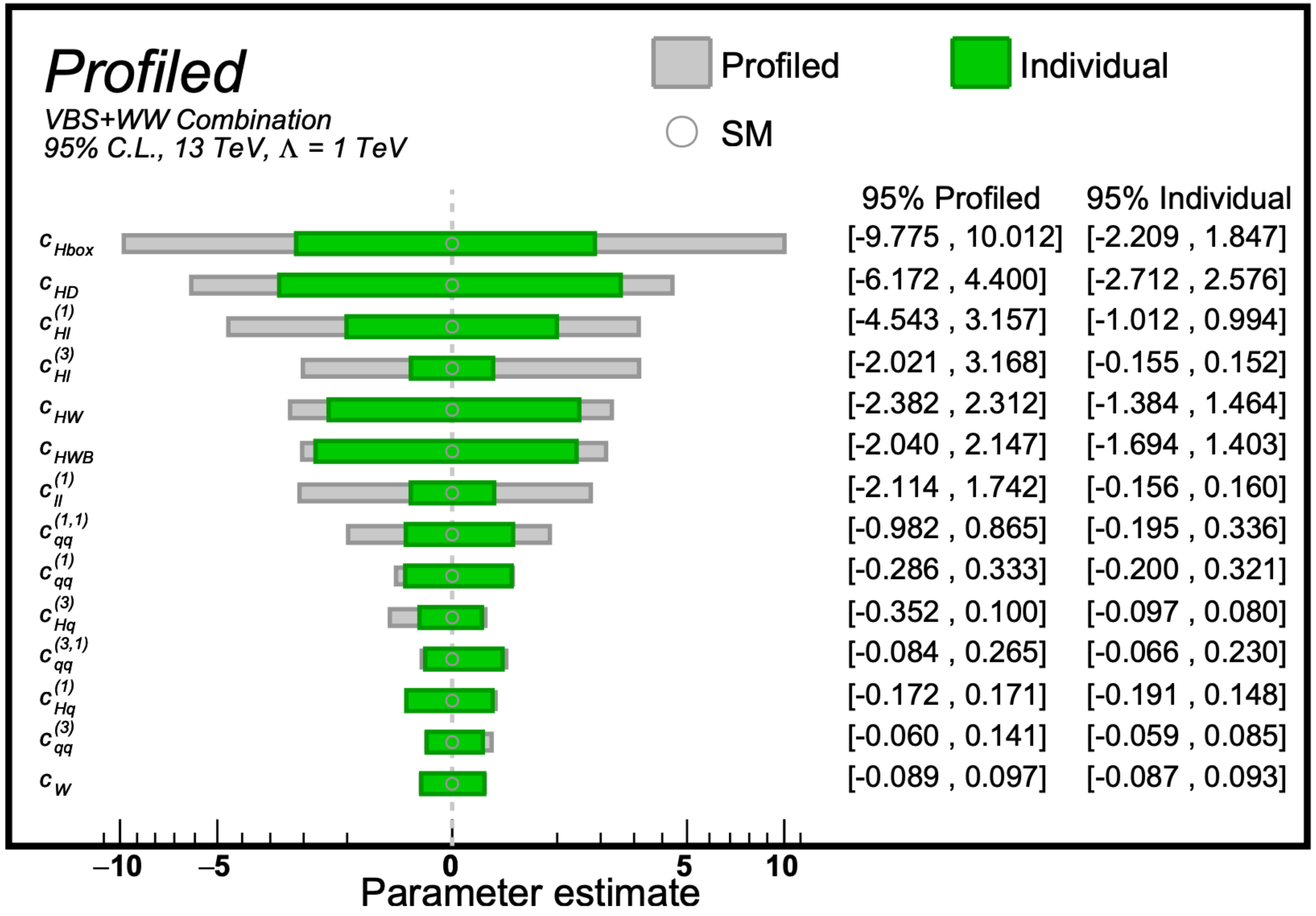
constraints on individual coefficients



- **one Wilson coefficient free two float** at a time (the others set to zero)
- most stringent limits on **four-fermion operators**
- **competitive with di-boson** studies for some operators
- $Q^{(1)}_{Hl}$, Q_{HW}, $Q_{H\Box}$, Q_{HD} only constrained by VBS
- $Q^{(1)}_{Hl}$ mostly constrained by VBS WZ/ZZ

profiled constraints

- **All parameters free to float** in likelihood maximisation
- Individual limits on operators obtained by **profiling the other Wilson coefficients**

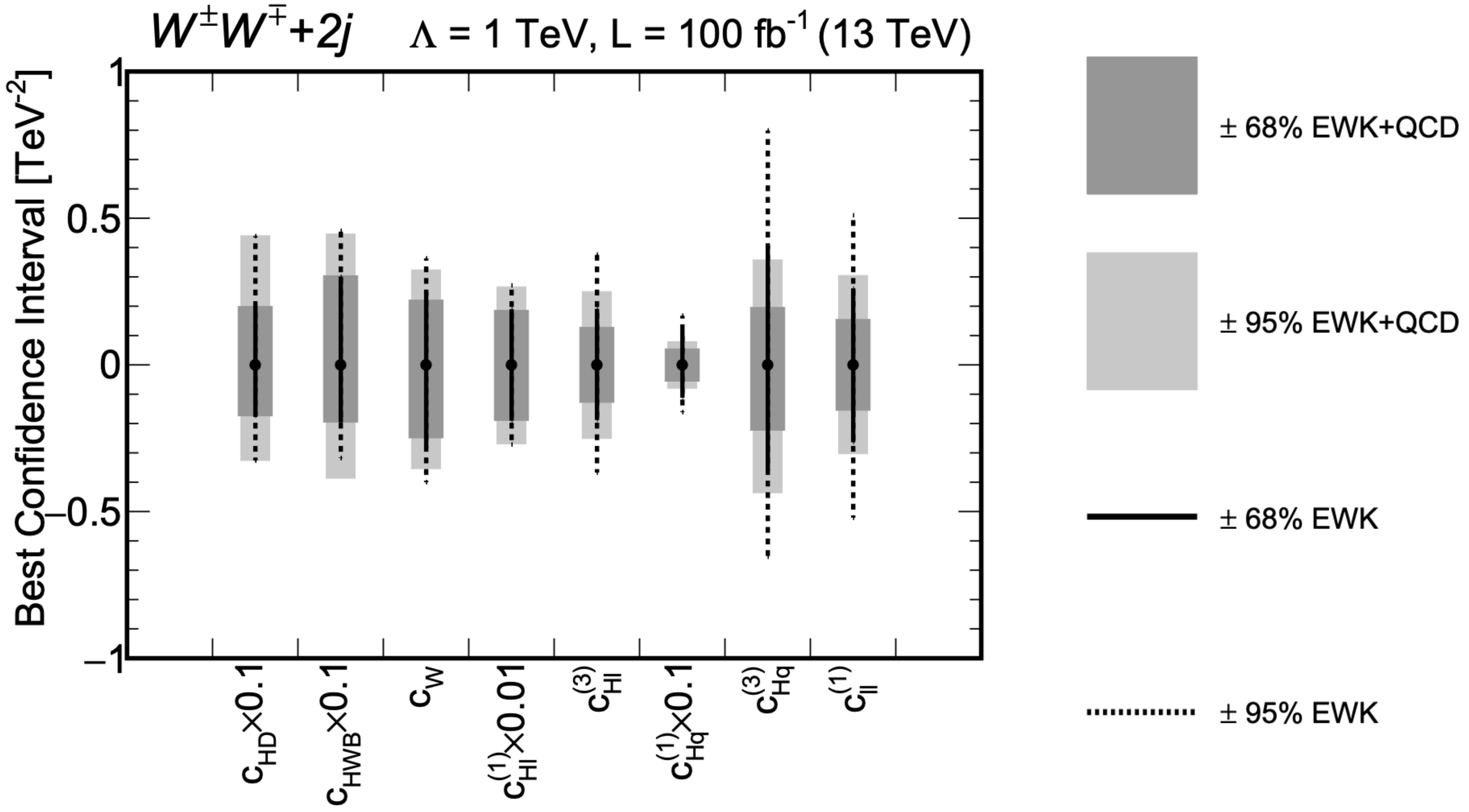


	95% Profiled	95% Individual
c_{Hbox}	[-9.775 , 10.012]	[-2.209 , 1.847]
c_{HD}	[-6.172 , 4.400]	[-2.712 , 2.576]
$c_{Hl}^{(1)}$	[-4.543 , 3.157]	[-1.012 , 0.994]
$c_{Hl}^{(3)}$	[-2.021 , 3.168]	[-0.155 , 0.152]
c_{HW}	[-2.382 , 2.312]	[-1.384 , 1.464]
c_{HWB}	[-2.040 , 2.147]	[-1.694 , 1.403]
$c_{ll}^{(1)}$	[-2.114 , 1.742]	[-0.156 , 0.160]
$c_{qq}^{(1,1)}$	[-0.982 , 0.865]	[-0.195 , 0.336]
$c_{qq}^{(1)}$	[-0.286 , 0.333]	[-0.200 , 0.321]
$c_{Hq}^{(3)}$	[-0.352 , 0.100]	[-0.097 , 0.080]
$c_{qq}^{(3,1)}$	[-0.084 , 0.265]	[-0.066 , 0.230]
$c_{Hq}^{(1)}$	[-0.172 , 0.171]	[-0.191 , 0.148]
$c_{qq}^{(3)}$	[-0.060 , 0.141]	[-0.059 , 0.085]
c_{W}	[-0.089 , 0.097]	[-0.087 , 0.093]

including the background in the fit

$$N(\mathrm{EWK{+}QCD}) \propto SM^{EWK} + SM^{QCD} + \frac{c_\alpha}{\Lambda^2}\left(Lin^{EWK} + Lin^{QCD}\right) + \frac{c_\alpha^2}{\Lambda^4}\left(Quad^{EWK} + Quad^{QCD}\right)$$

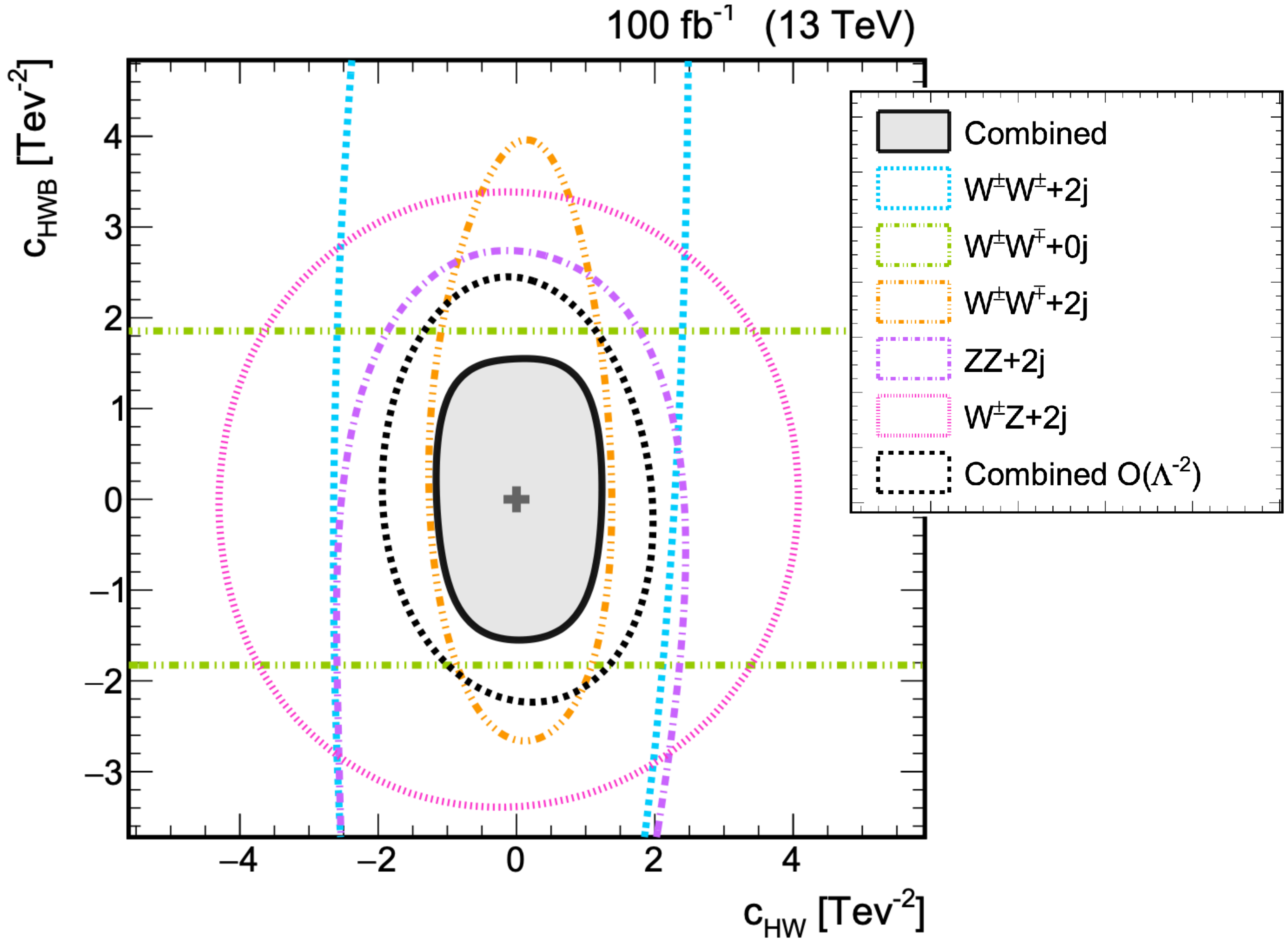
$$N(\mathrm{EWK}) \propto SM^{EWK} + SM^{QCD} + \frac{c_\alpha}{\Lambda^2} Lin^{EWK} + \frac{c_\alpha^2}{\Lambda^4} Quad^{EWK}$$



- the analysis sensitivity is **never reduced** by including the dependence of the irreducible backgrounds on EFT operators

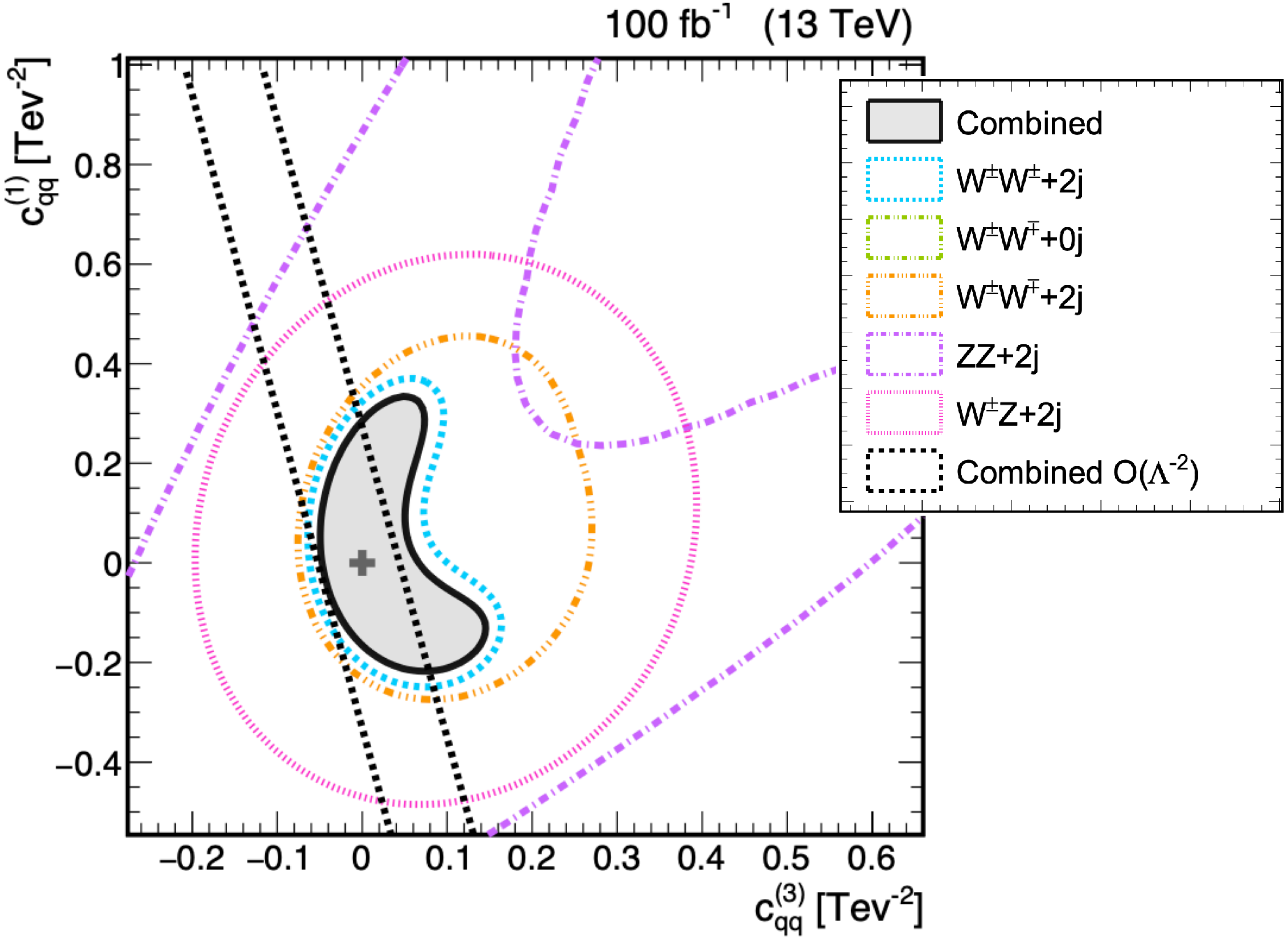
multi-dimensional limits

- **two Wilson coefficients free to float simultaneously** (the others are set to zero)
- the **combination and complementarity of different analysis channels** allows for a narrower limit area definition



multi-dimensional limits

- **Flat directions resolved** thanks to combination of different channels or by the impact of $O(\Lambda^{-4})$ terms
- **Linear-only limits sometimes are better** (differently from 1D): the mixed interference between dim-6 amplitudes can mitigate deviations

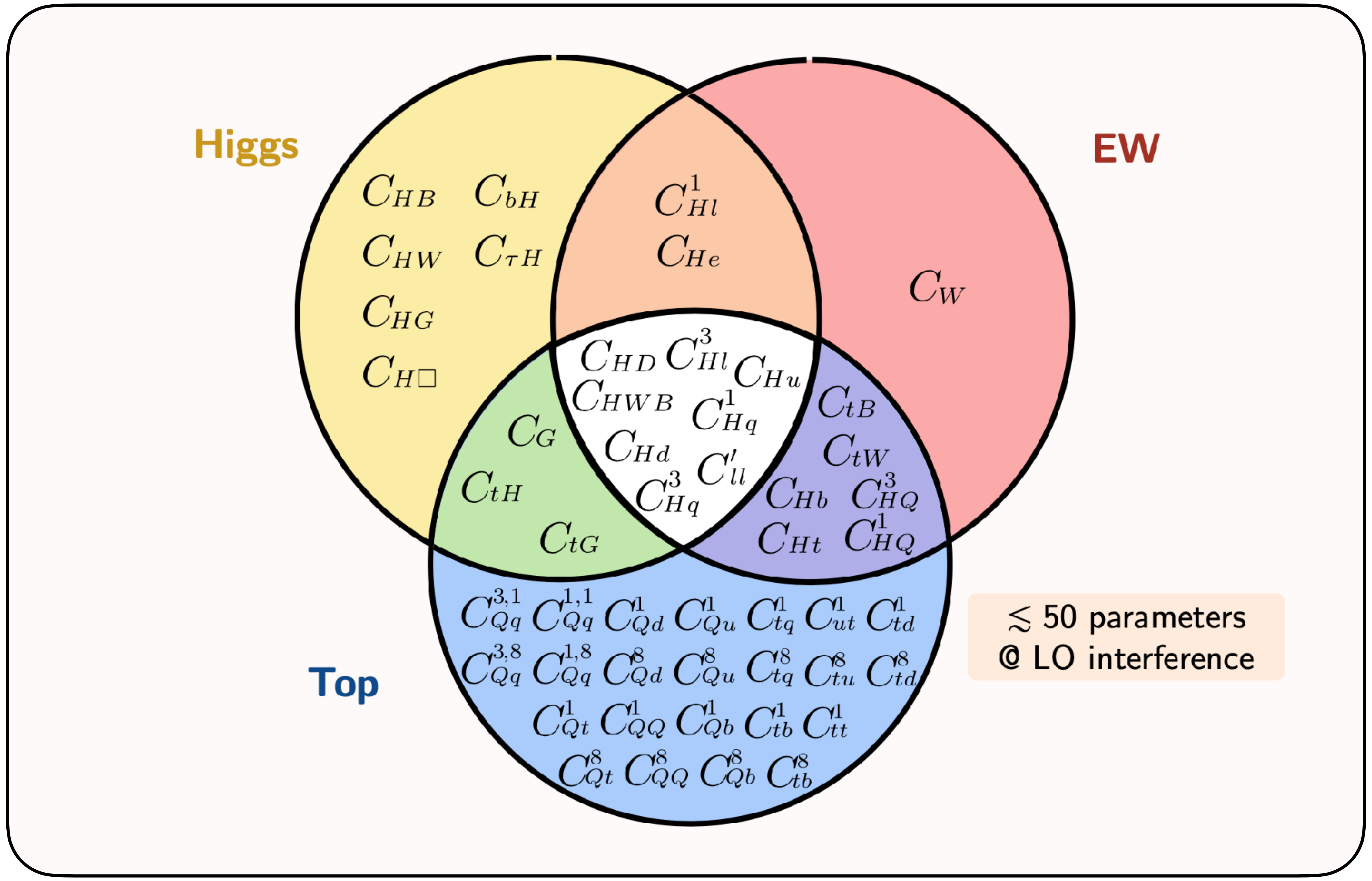


in the long run

as of today, LHC collected about **5% of the total dataset** it's expected to deliver

testing the standard model

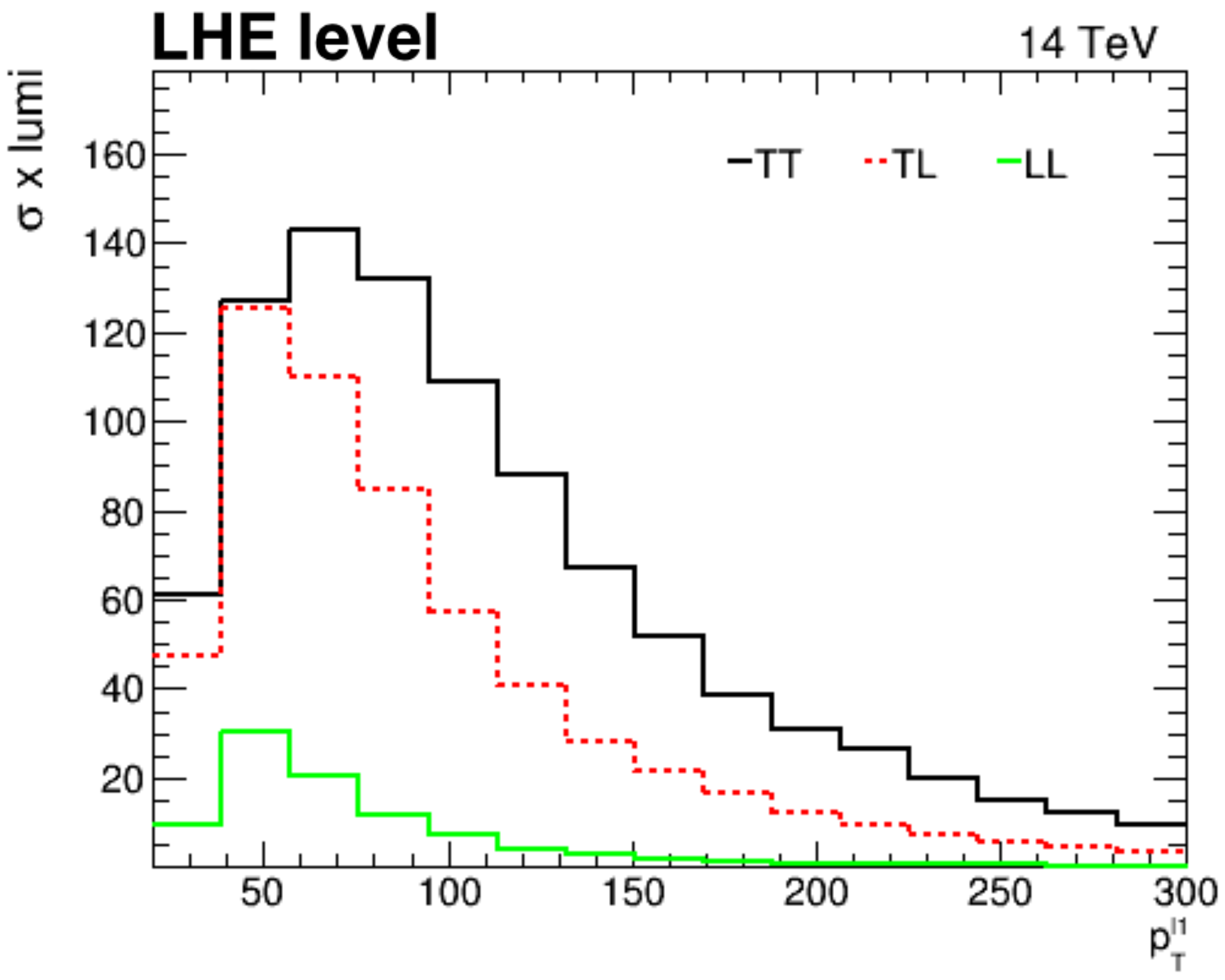
- the **combination of information** from several different analyses is necessary
- to constrain the **largest number of EFT operators** is possible
- **to avoid biases** in the results interpretation (some operators may have very similar effects in some final states, and different ones in others)

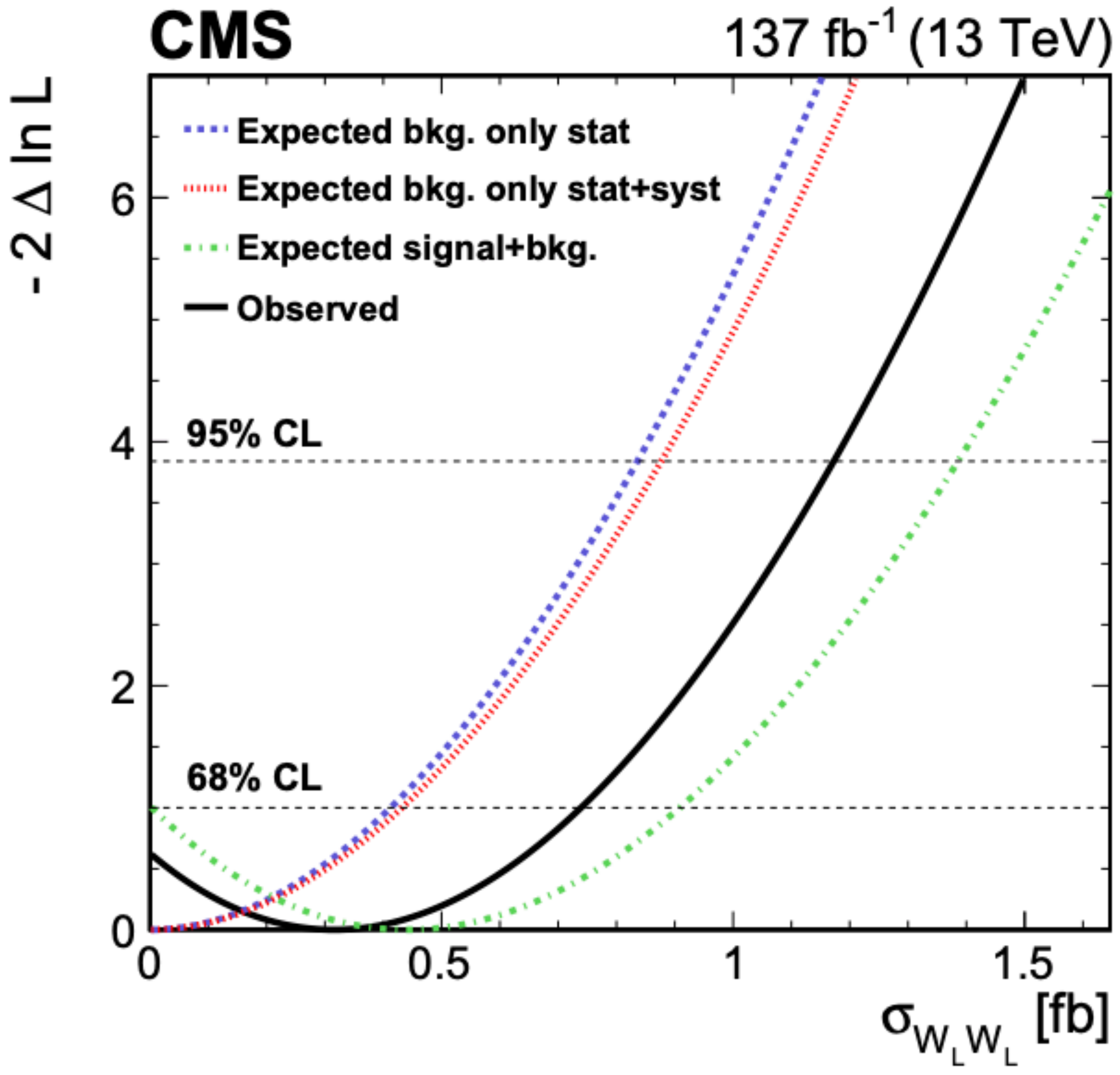


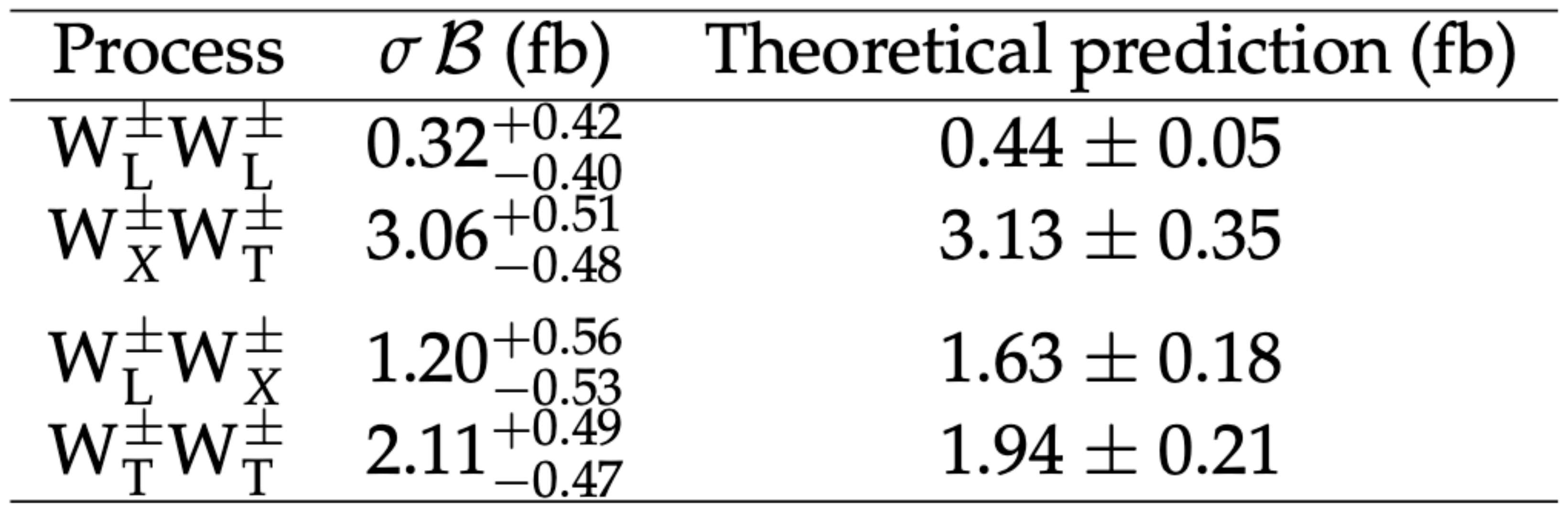
longitudinally-polarised VBS

https://arxiv.org/abs/2009.09429

- vector boson masses arise from the interaction with the Higgs boson, that **provides them with a longitudinal polarisation** as well
- the longitudinal component of the scattering is expected to be **the most sensitive to any new physics in the electroweak symmetry breaking**





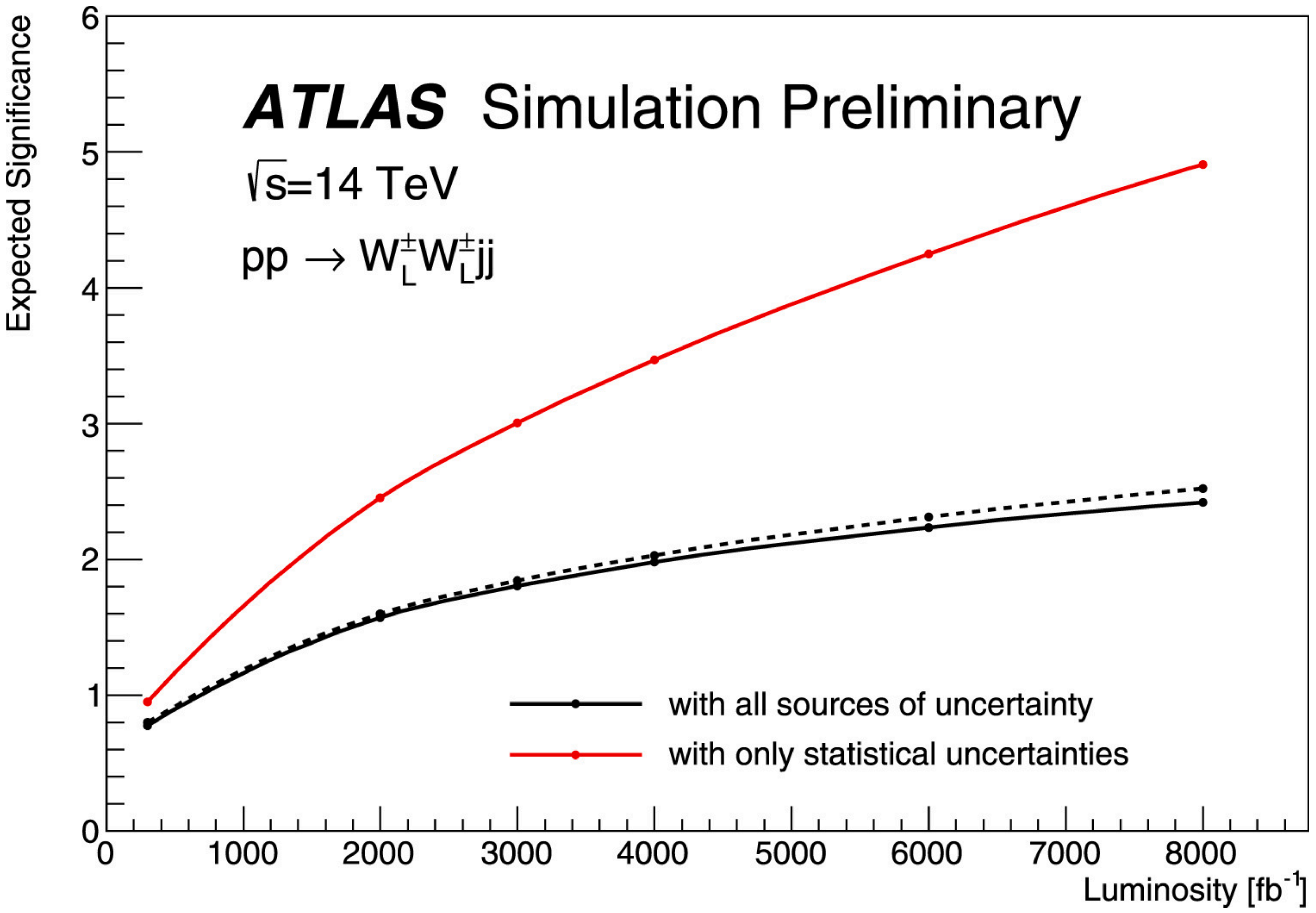


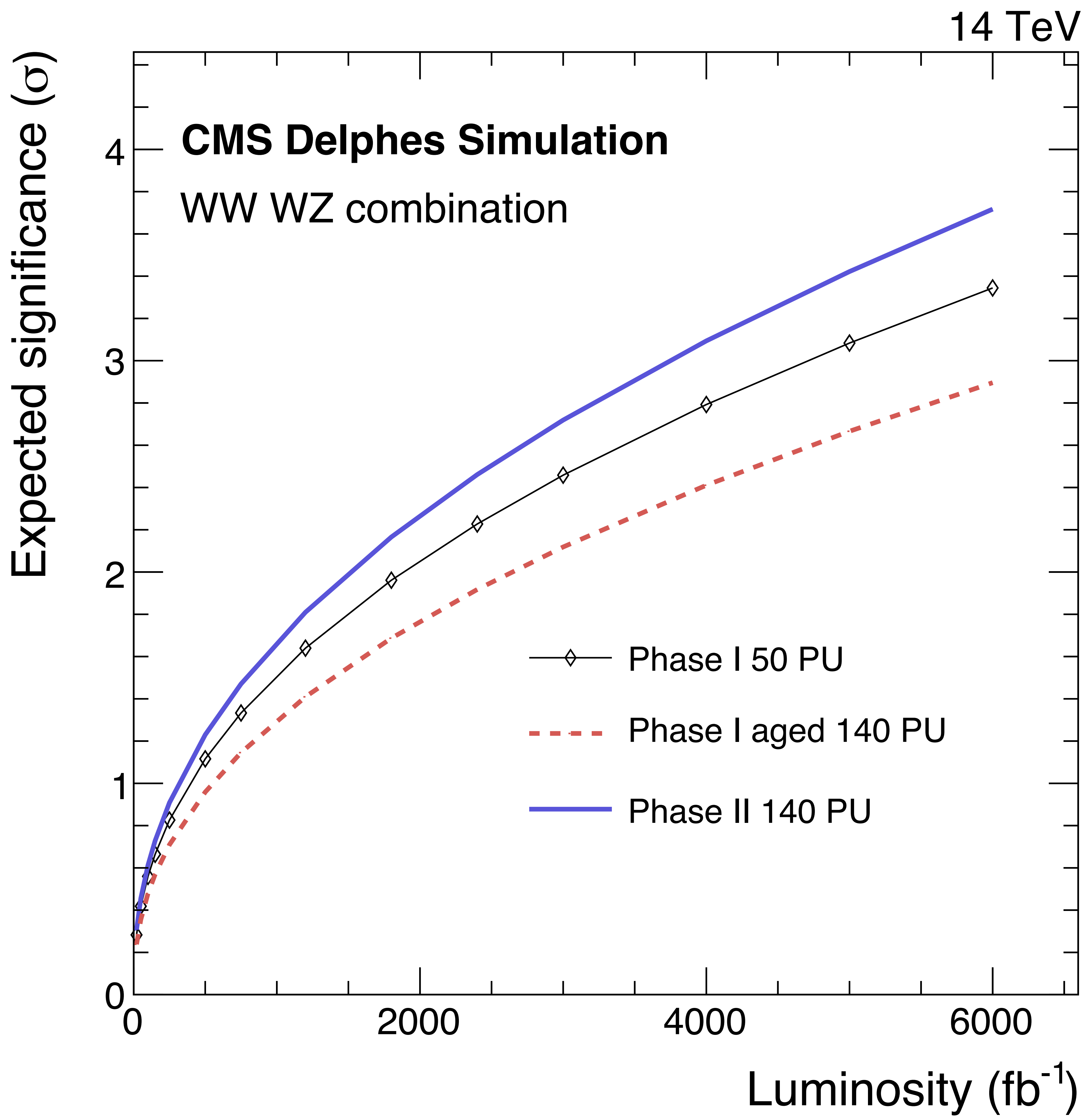
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^{\pm}_{X}W^{\pm}_{T}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^{\pm}_{L}W^{\pm}_{X}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^{\pm}_{T}W^{\pm}_{T}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

some projections

CMS-PAS-SMP-14-008

https://doi.org/10.1016/j.revip.2022.100071





conclusions

- vector boson scattering **stems from the electroweak symmetry breaking** and is tightly connected with the physics of the Higgs sector
- its low cross-section and complex final state make it a **challenge at the LHC**, from the point of view of the event reconstruction, signal definition and isolation
- we will be able to **fully exploit its potential** with the whole LHC dataset
- fully embedding it in the **search for new physics through precision measurements**, within the EFT paradigm
- an interesting and useful **playground for training of young physicists**!

conclusions

- vector boson scattering **stems from the electroweak symmetry breaking** and is tightly connected with the physics of the Higgs sector
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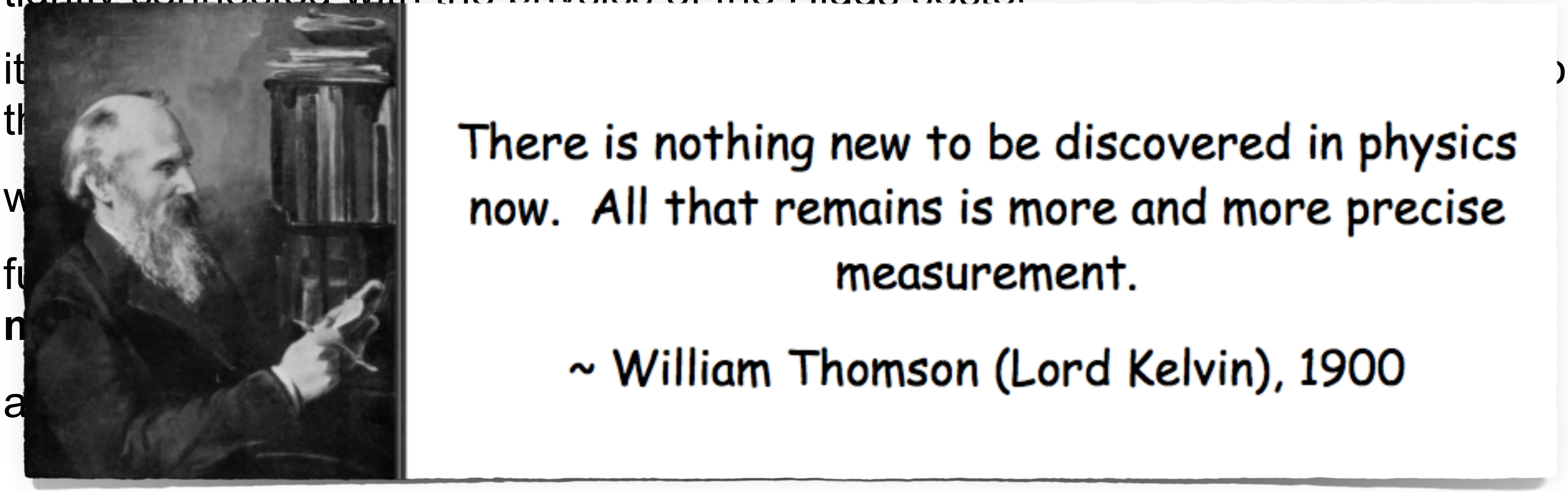
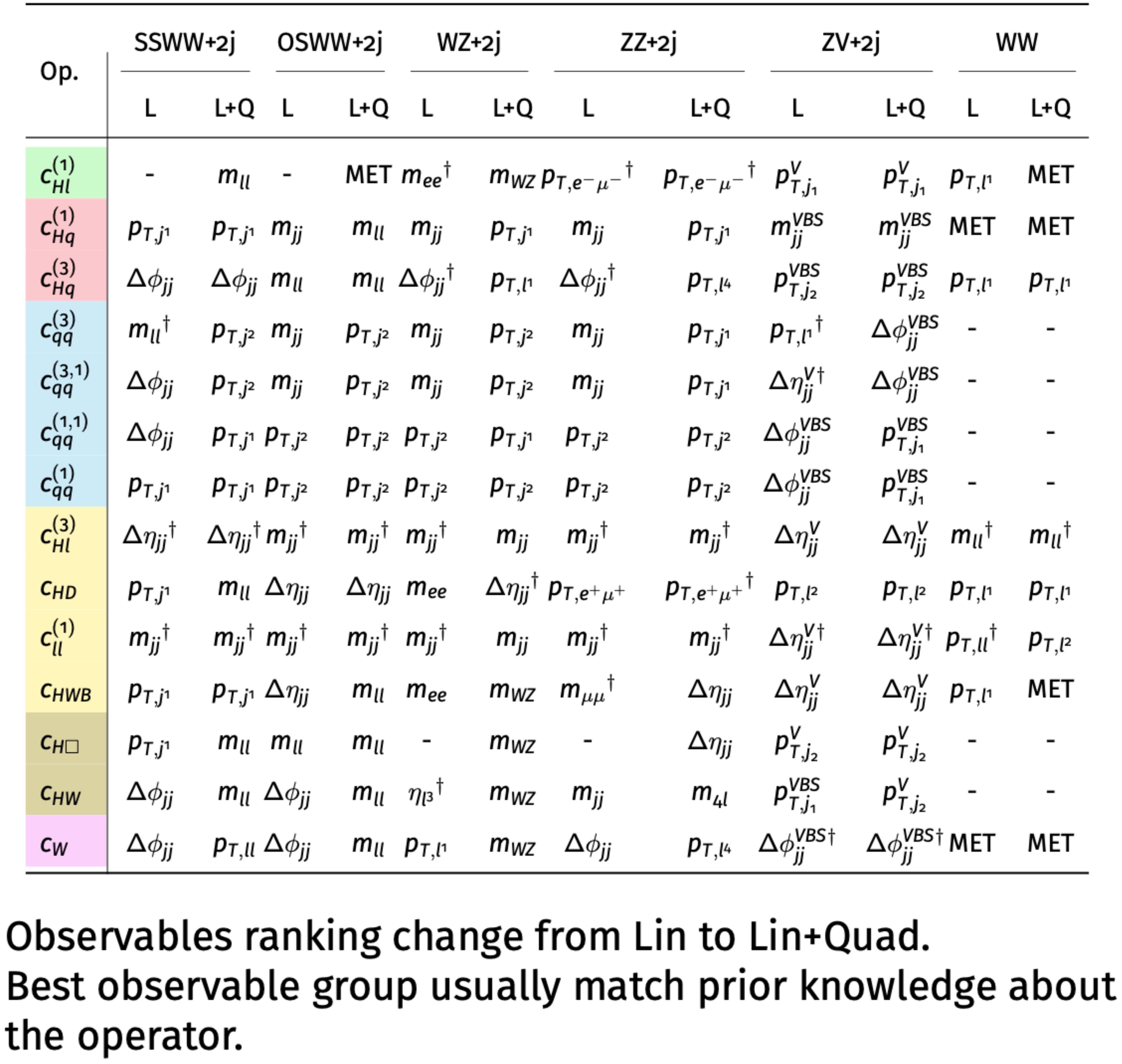


There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

~ William Thomson (Lord Kelvin), 1900

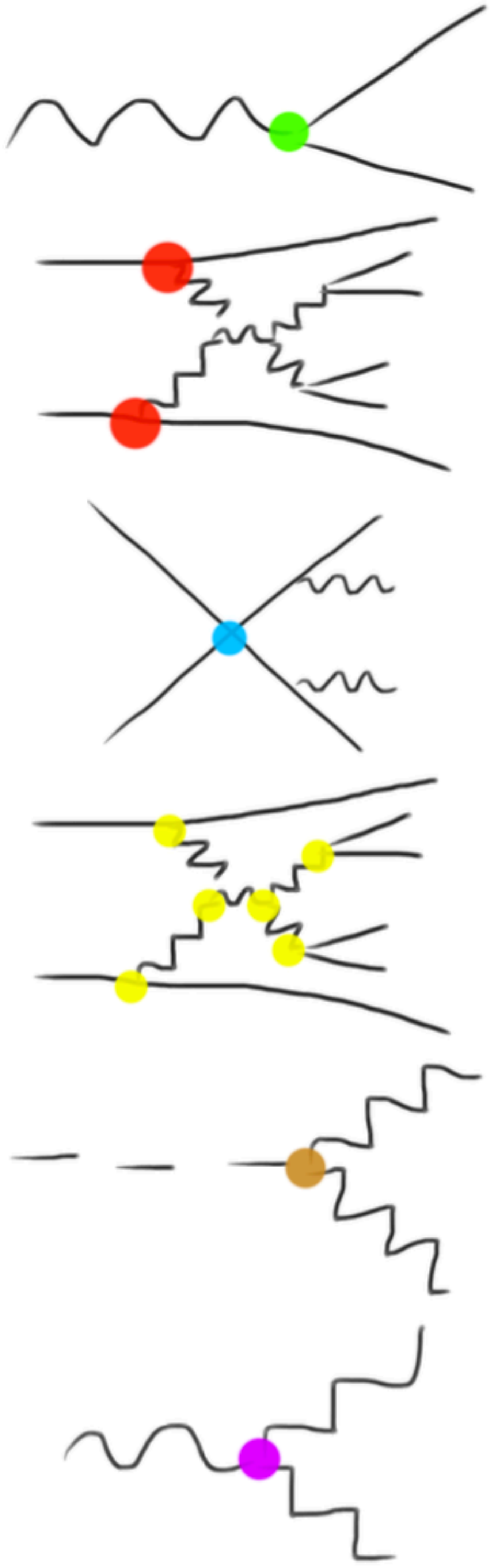
additional material

the variable choice in the EFT fits

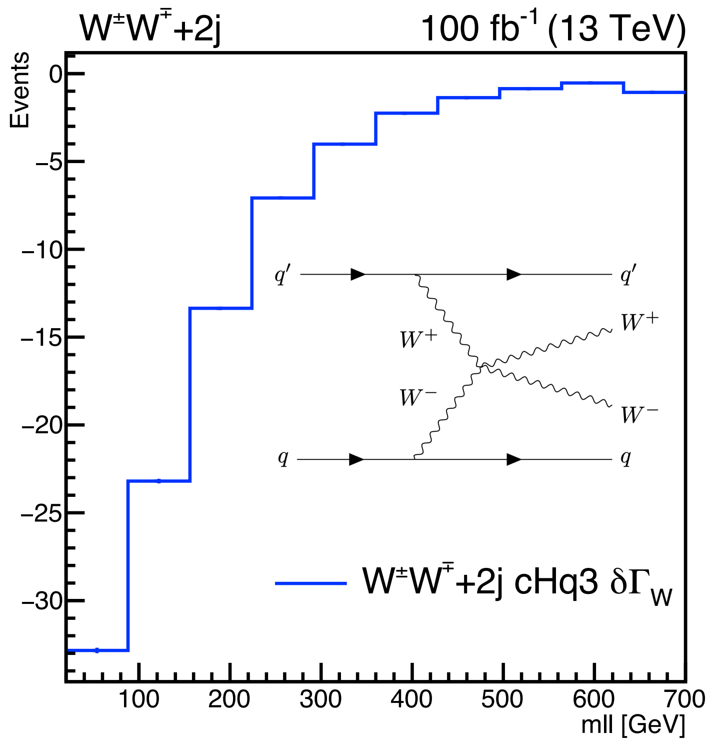


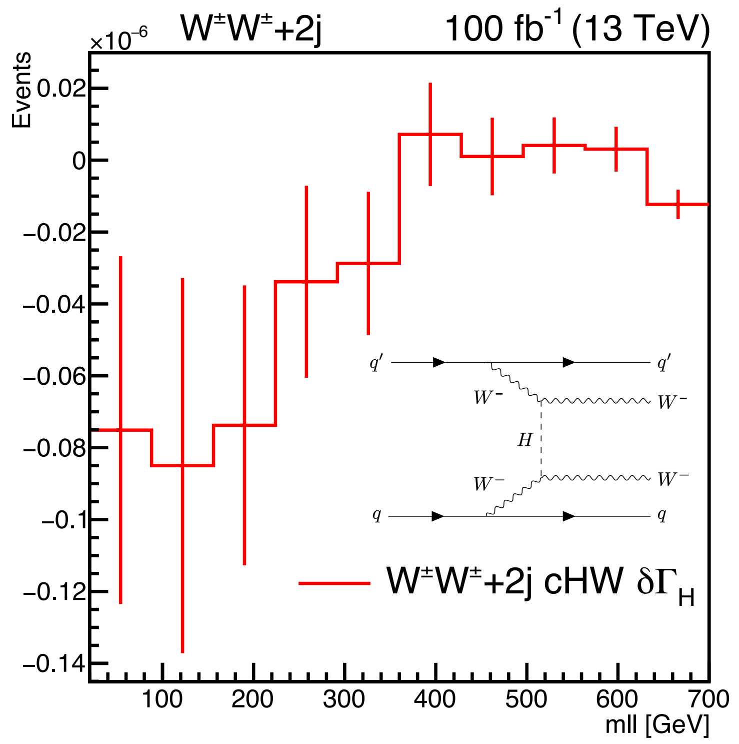
Op.	SSWW+2j		OSWW+2j		WZ+2j		ZZ+2j		ZV+2j		WW	
	L	L+Q	L	L+Q	L	L+Q	L	L+Q	L	L+Q	L	L+Q
$c_{Hl}^{(1)}$	-	m_{ll}	-	MET	$m_{ee}{}^{\dagger}$	m_{WZ}	$p_{T,e^-\mu^-}{}^{\dagger}$	$p_{T,e^-\mu^-}{}^{\dagger}$	p^{V}_{T,j_1}	p^{V}_{T,j_1}	p_{T,l^1}	MET
$c_{Hq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	m_{jj}	m_{ll}	m_{jj}	p_{T,j^1}	m_{jj}	p_{T,j^1}	m_{jj}^{VBS}	m_{jj}^{VBS}	MET	MET
$c_{Hq}^{(3)}$	$\Delta\phi_{jj}$	$\Delta\phi_{jj}$	m_{ll}	m_{ll}	$\Delta\phi_{jj}{}^{\dagger}$	p_{T,l^1}	$\Delta\phi_{jj}{}^{\dagger}$	p_{T,l^4}	p^{VBS}_{T,j_2}	p^{VBS}_{T,j_2}	p_{T,l^1}	p_{T,l^1}
$c_{qq}^{(3)}$	$m_{ll}{}^{\dagger}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$p_{T,l^1}{}^{\dagger}$	$\Delta\phi_{jj}^{VBS}$	-	-
$c_{qq}^{(3,1)}$	$\Delta\phi_{jj}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$\Delta\eta_{jj}^{V\dagger}$	$\Delta\phi_{jj}^{VBS}$	-	-
$c_{qq}^{(1,1)}$	$\Delta\phi_{jj}$	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi_{jj}^{VBS}$	p^{VBS}_{T,j_1}	-	-
$c_{qq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi_{jj}^{VBS}$	p^{VBS}_{T,j_1}	-	-
$c_{Hl}^{(3)}$	$\Delta\eta_{jj}{}^{\dagger}$	$\Delta\eta_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	m_{jj}	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$\Delta\eta_{jj}^{V}$	$\Delta\eta_{jj}^{V}$	$m_{ll}{}^{\dagger}$	$m_{ll}{}^{\dagger}$
c_{HD}	p_{T,j^1}	m_{ll}	$\Delta\eta_{jj}$	$\Delta\eta_{jj}$	m_{ee}	$\Delta\eta_{jj}{}^{\dagger}$	$p_{T,e^+\mu^+}$	$p_{T,e^+\mu^+}{}^{\dagger}$	p_{T,l^2}	p_{T,l^2}	p_{T,l^1}	p_{T,l^1}
$c_{ll}^{(1)}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	m_{jj}	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$\Delta\eta_{jj}^{V\dagger}$	$\Delta\eta_{jj}^{V\dagger}$	$p_{T,ll}{}^{\dagger}$	p_{T,l^2}
c_{HWB}	p_{T,j^1}	p_{T,j^1}	$\Delta\eta_{jj}$	m_{ll}	m_{ee}	m_{WZ}	$m_{\mu\mu}{}^{\dagger}$	$\Delta\eta_{jj}$	$\Delta\eta_{jj}^{V}$	$\Delta\eta_{jj}^{V}$	p_{T,l^1}	MET
$c_{H\square}$	p_{T,j^1}	m_{ll}	m_{ll}	m_{ll}	-	m_{WZ}	-	$\Delta\eta_{jj}$	p^{V}_{T,j_2}	p^{V}_{T,j_2}	-	-
c_{HW}	$\Delta\phi_{jj}$	m_{ll}	$\Delta\phi_{jj}$	m_{ll}	$\eta_{l^3}{}^{\dagger}$	m_{WZ}	m_{jj}	m_{4l}	p^{VBS}_{T,j_1}	p^{V}_{T,j_2}	-	-
c_{W}	$\Delta\phi_{jj}$	$p_{T,ll}$	$\Delta\phi_{jj}$	m_{ll}	p_{T,l^1}	m_{WZ}	$\Delta\phi_{jj}$	p_{T,l^4}	$\Delta\phi_{jj}^{VBS\dagger}$	$\Delta\phi_{jj}^{VBS\dagger}$	MET	MET

Observables ranking change from Lin to Lin+Quad.
Best observable group usually match prior knowledge about the operator.



SMEFT corrections to propagators





$$N^{int}_{\alpha} = N^{int}_{\alpha,\mathrm{vert.}} + N^{int}_{\alpha,\delta\Gamma_W} + N^{int}_{\alpha,\delta\Gamma_Z} + N^{int}_{,\delta\Gamma_H}$$

versus $N^{int}_{\alpha} = N^{int}_{\alpha,\mathrm{vert.}}$

Limits change up to a factor ~ 5

$$\delta\Gamma_W/\Gamma^{SM}_W = \frac{4}{3}c^{(3)}_{Hq} - \frac{4}{3}c^{(3)}_{Hl} - c^{(1)}_{ll}\,,$$

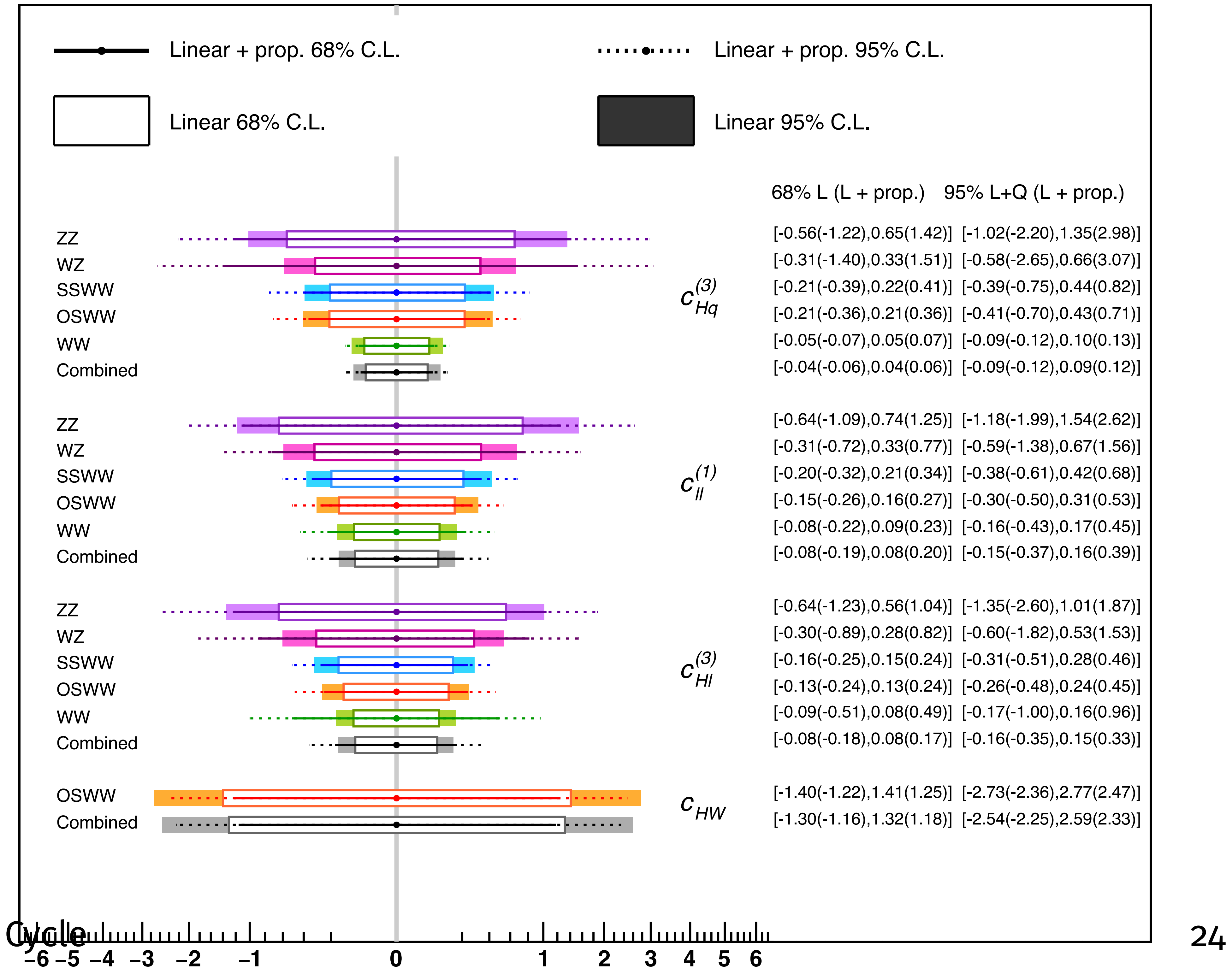
$$\delta\Gamma_Z/\Gamma^{SM}_Z = 1.61c^{(3)}_{Hq} - 1.37c^{(3)}_{Hl} + c^{(1)}_{ll} + 0.47c^{(1)}_{Hq} - 0.18c^{(1)}_{Hl} - 0.07c_{HD} + 0.46c_{HWB}\,,$$

$$\delta\Gamma_H/\Gamma^{SM}_H = 0.36c^{(3)}_{Hq} - 2.62c^{(3)}_{Hl} + 1.40c^{(1)}_{ll} + 1.83c_{H\Box} - 0.46c_{HD} - 1.26c_{HW} + 1.23c_{HWB}$$

Mass terms and decay widths of the SM particles generally **receive corrections** from $\mathcal{L}_6$ operators.

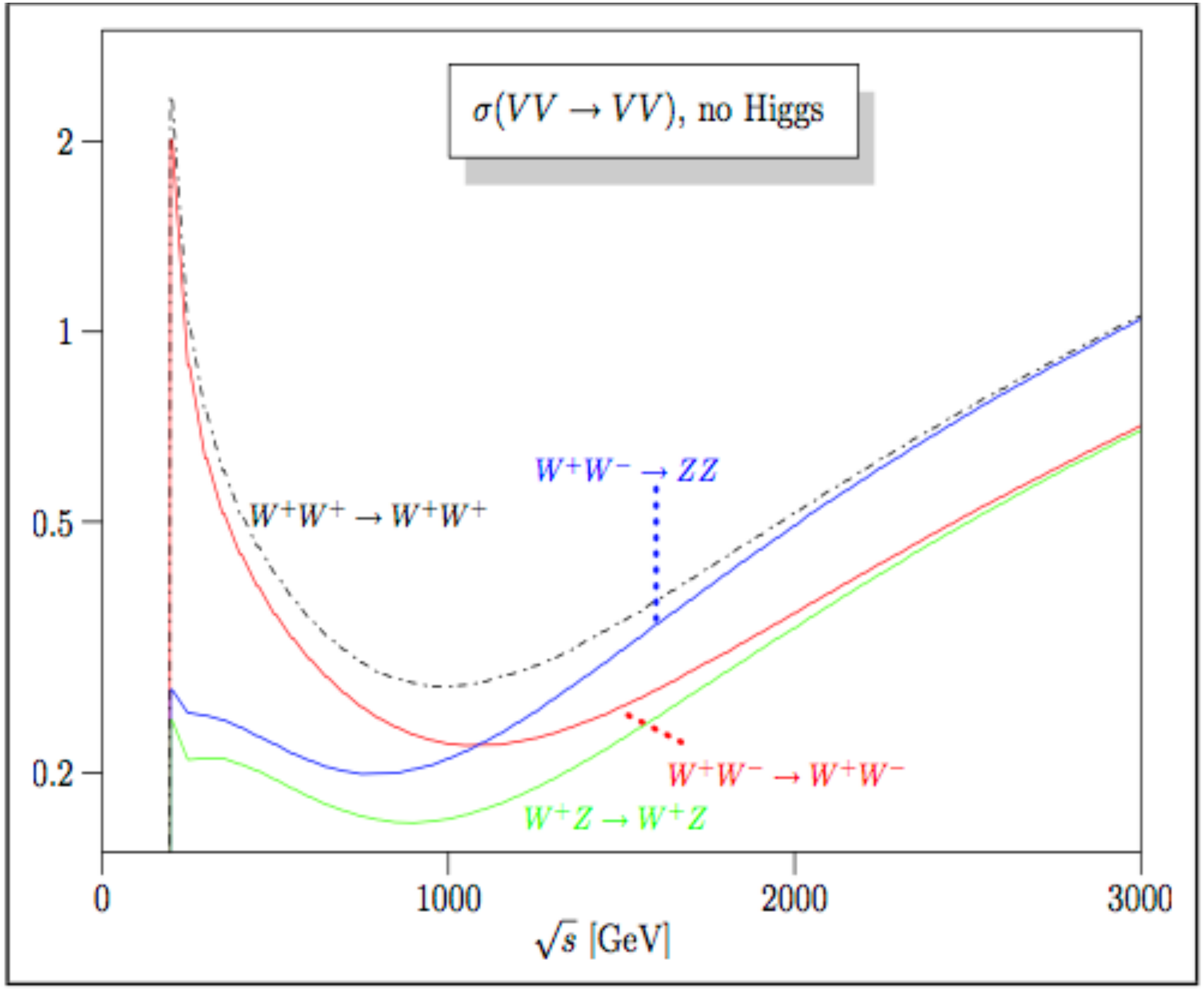
$\{m_W, m_Z, G_F\} \to \delta m_W = 0, \delta m_Z = 0, \Gamma \neq 0$.

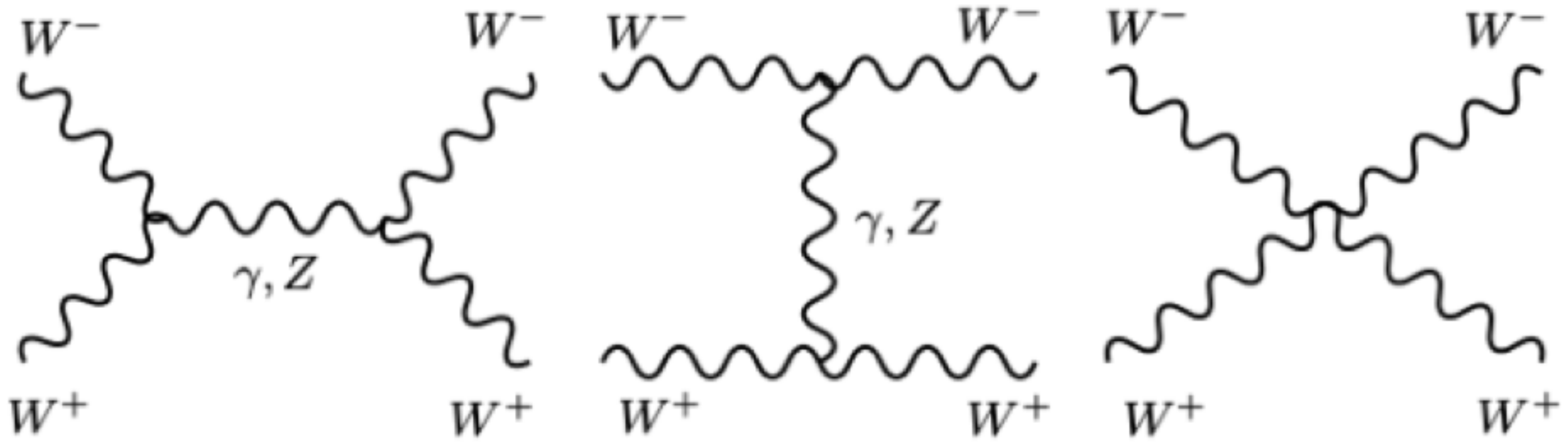
Propagator corrections **relevant only if close to the mass shell**. Corrections for different ops share the same shape except for normalization.



vector boson scattering unitarity

arXiv:0806.4145

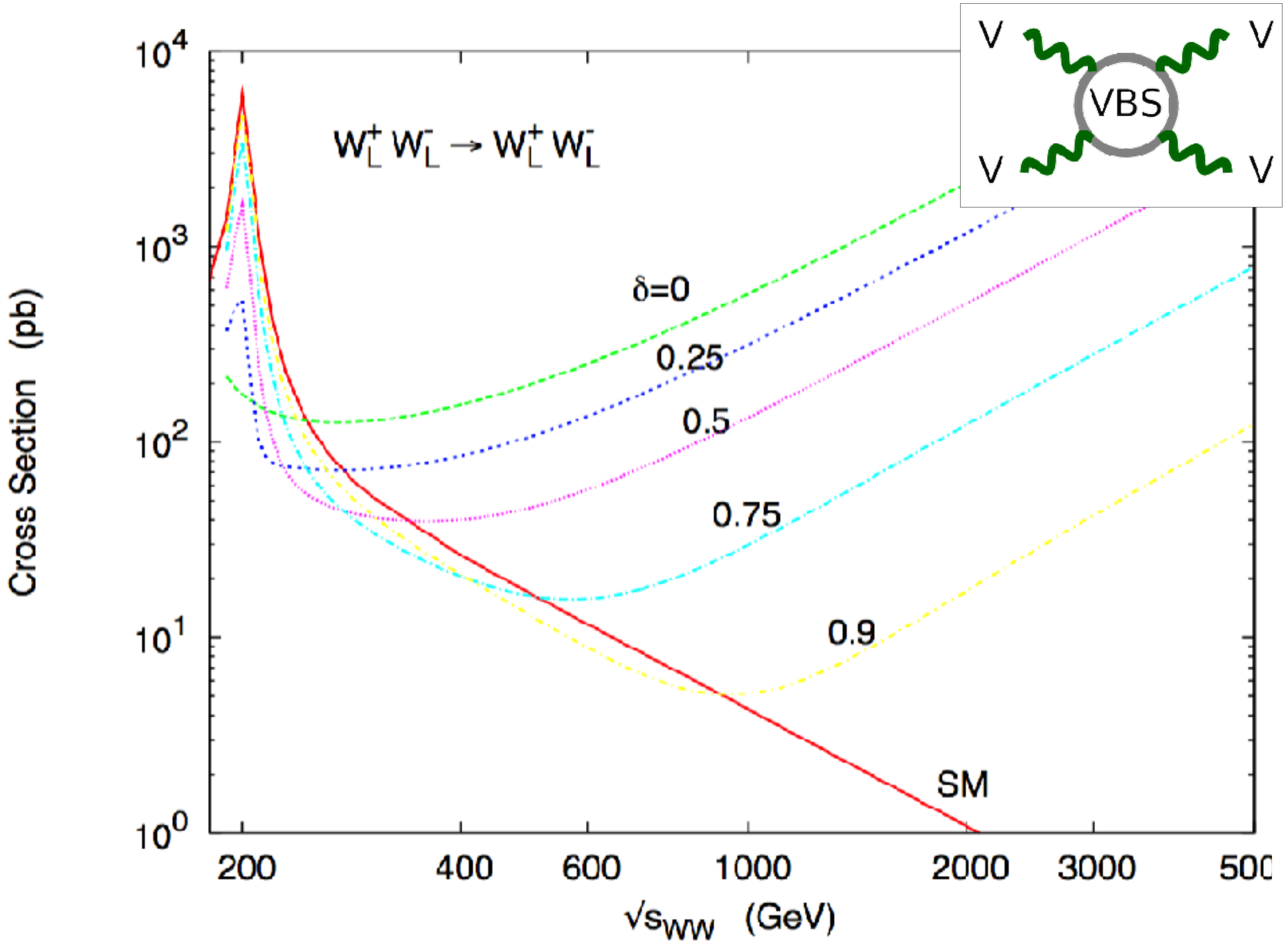


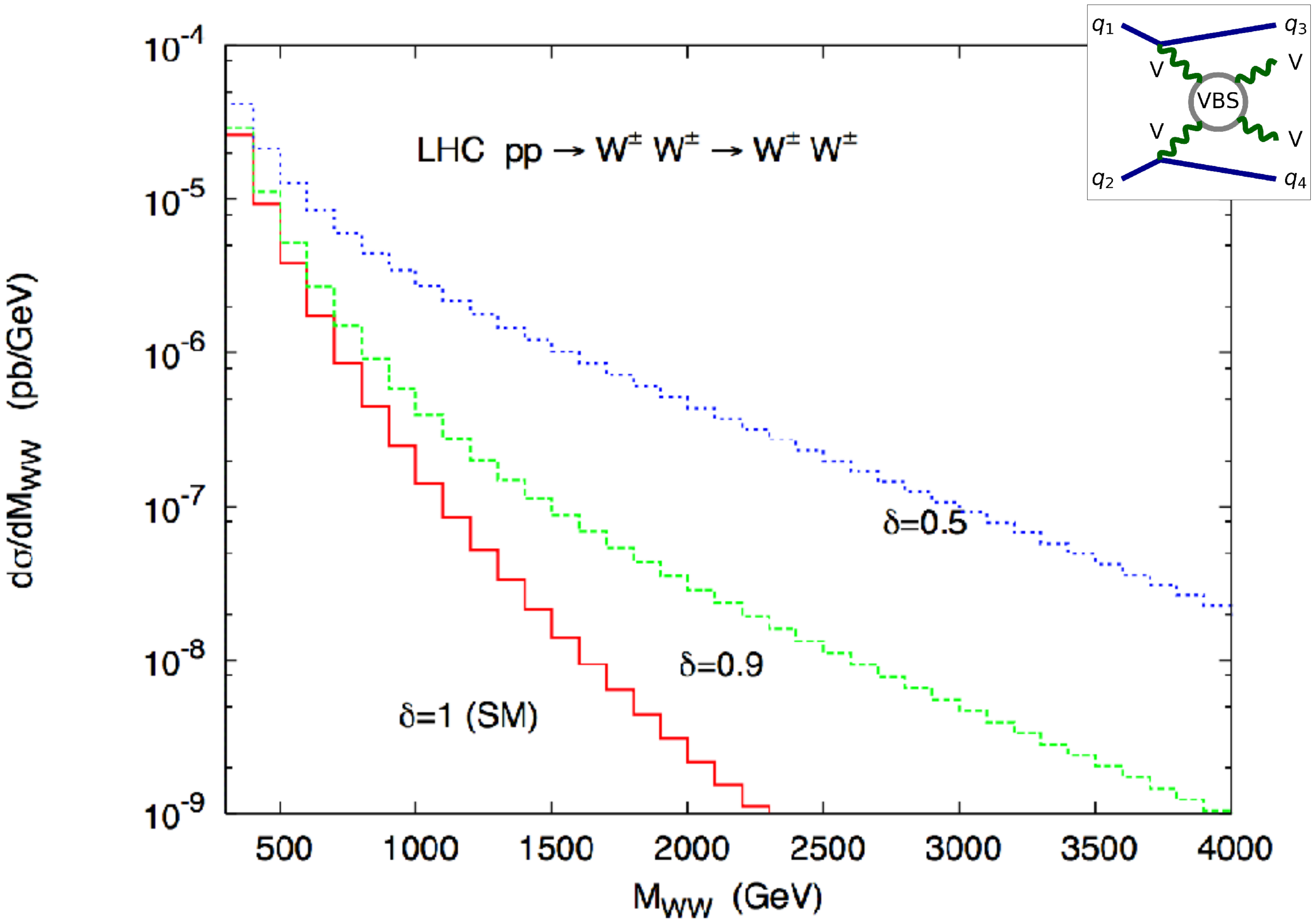


simple approach: search for anomalies

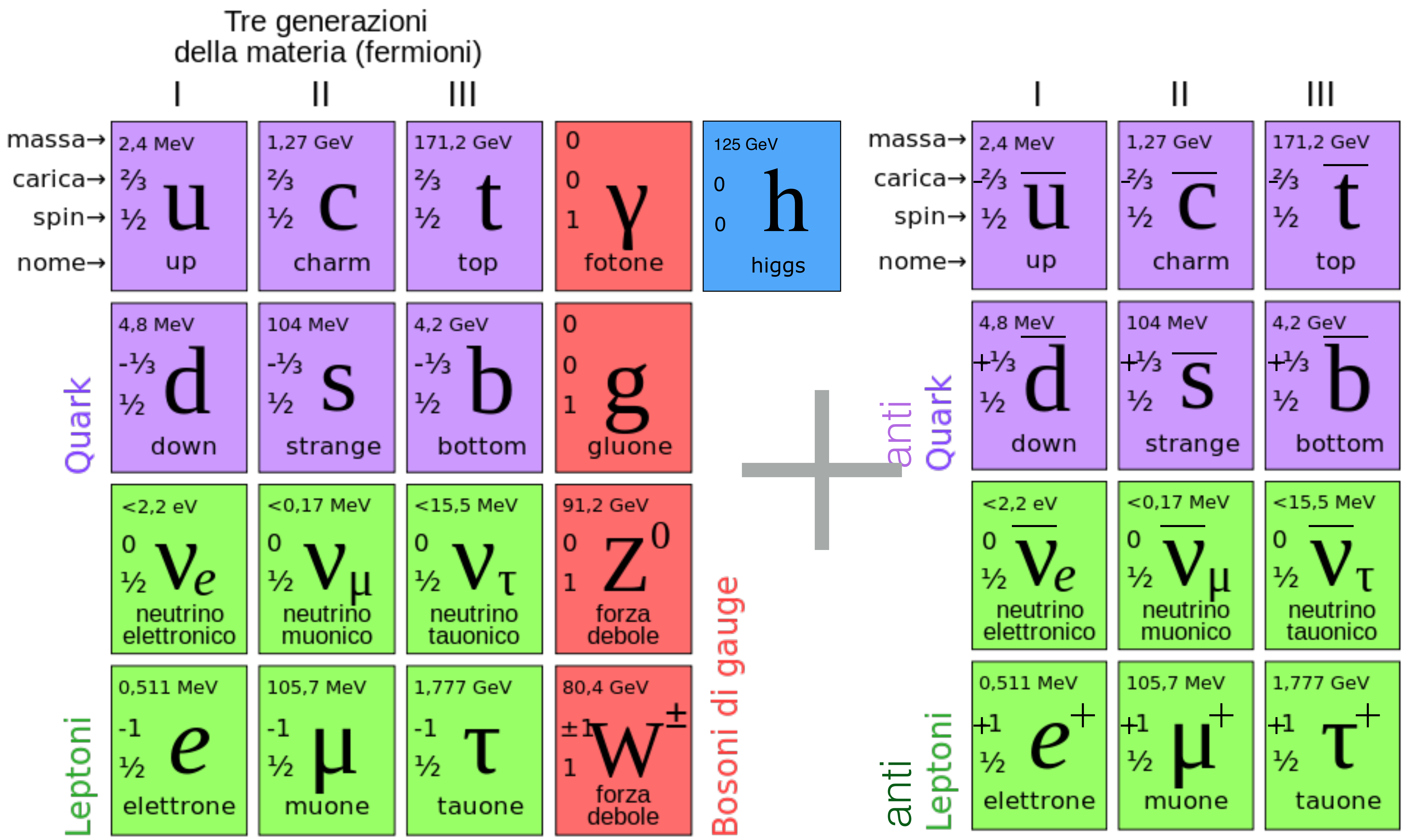
arXv:0803:2661

$$\mathcal{M}_{gauge} \simeq i\frac{g^2}{4M_W^2}[s+t]\,, \quad \mathcal{M}_{Higgs} \simeq -i\frac{g^2}{4M_W^2}[s+t]\ (\delta)$$





the standard model particles



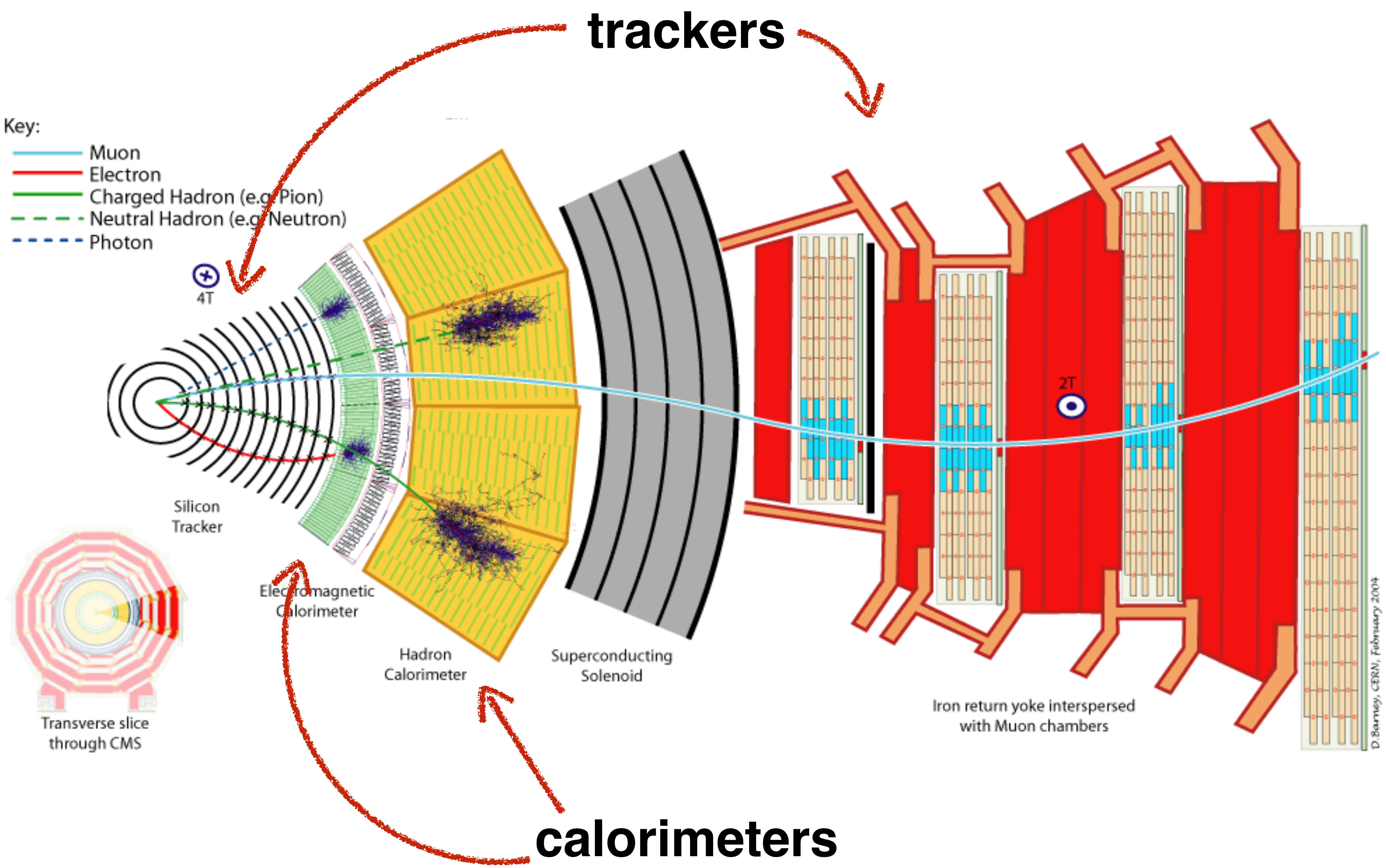
Tre generazioni della materia (fermioni)

	I	II	III		
massa→ carica→ spin→ nome→	2,4 MeV ⅔ ½ u up	1,27 GeV ⅔ ½ c charm	171,2 GeV ⅔ ½ t top	0 0 1 γ fotone	125 GeV 0 0 h higgs
Quark	4,8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4,2 GeV -⅓ ½ b bottom	0 0 1 g gluone	
	<2,2 eV 0 ½ ν_e neutrino elettronico	<0,17 MeV 0 ½ ν_μ neutrino muonico	<15,5 MeV 0 ½ ν_τ neutrino tauonico	91,2 GeV 0 1 Z^0 forza debole	Bosoni di gauge
Leptoni	0,511 MeV -1 ½ e elettrone	105,7 MeV -1 ½ μ muone	1,777 GeV -1 ½ τ tauone	80,4 GeV ±1 1 $W^\pm$ forza debole	

+

	I	II	III
massa→ carica→ spin→ nome→	2,4 MeV -⅔ ½ $\bar{u}$ up	1,27 GeV -⅔ ½ $\bar{c}$ charm	171,2 GeV -⅔ ½ $\bar{t}$ top
anti Quark	4,8 MeV +⅓ ½ $\bar{d}$ down	104 MeV +⅓ ½ $\bar{s}$ strange	4,2 GeV +⅓ ½ $\bar{b}$ bottom
	<2,2 eV 0 ½ $\bar{\nu}_e$ neutrino elettronico	<0,17 MeV 0 ½ $\bar{\nu}_\mu$ neutrino muonico	<15,5 MeV 0 ½ $\bar{\nu}_\tau$ neutrino tauonico
anti Leptoni	0,511 MeV +1 ½ e^+ elettrone	105,7 MeV +1 ½ μ^+ muone	1,777 GeV +1 ½ τ^+ tauone

particle detection in CMS

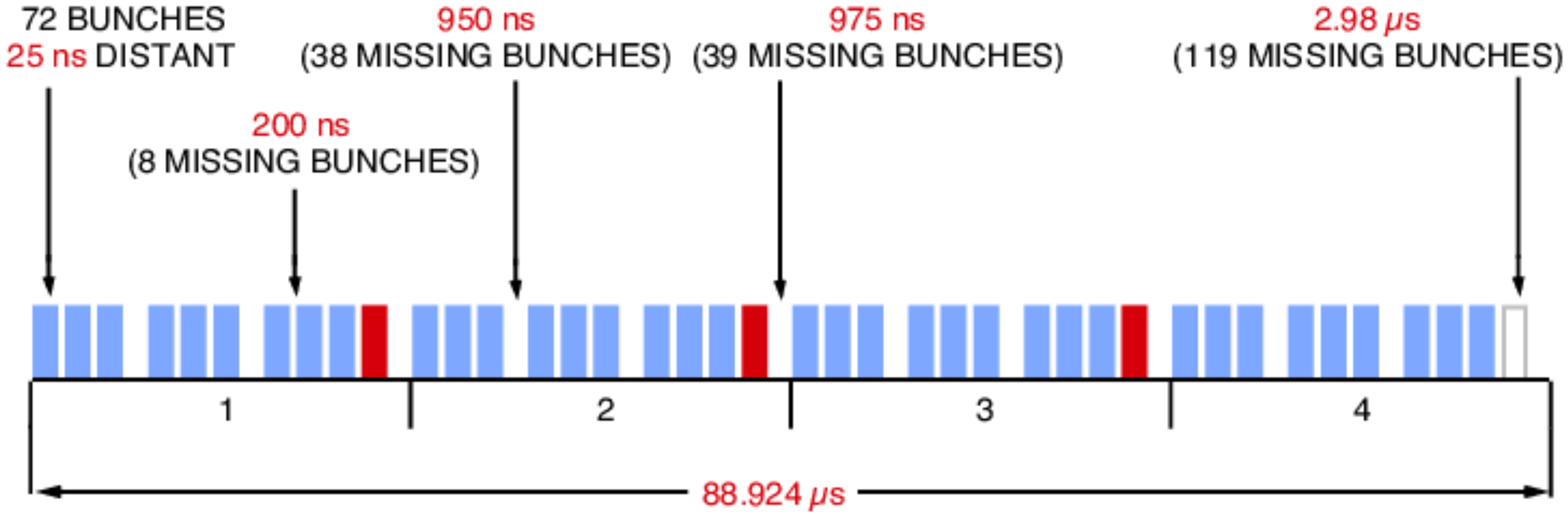


trackers

calorimeters

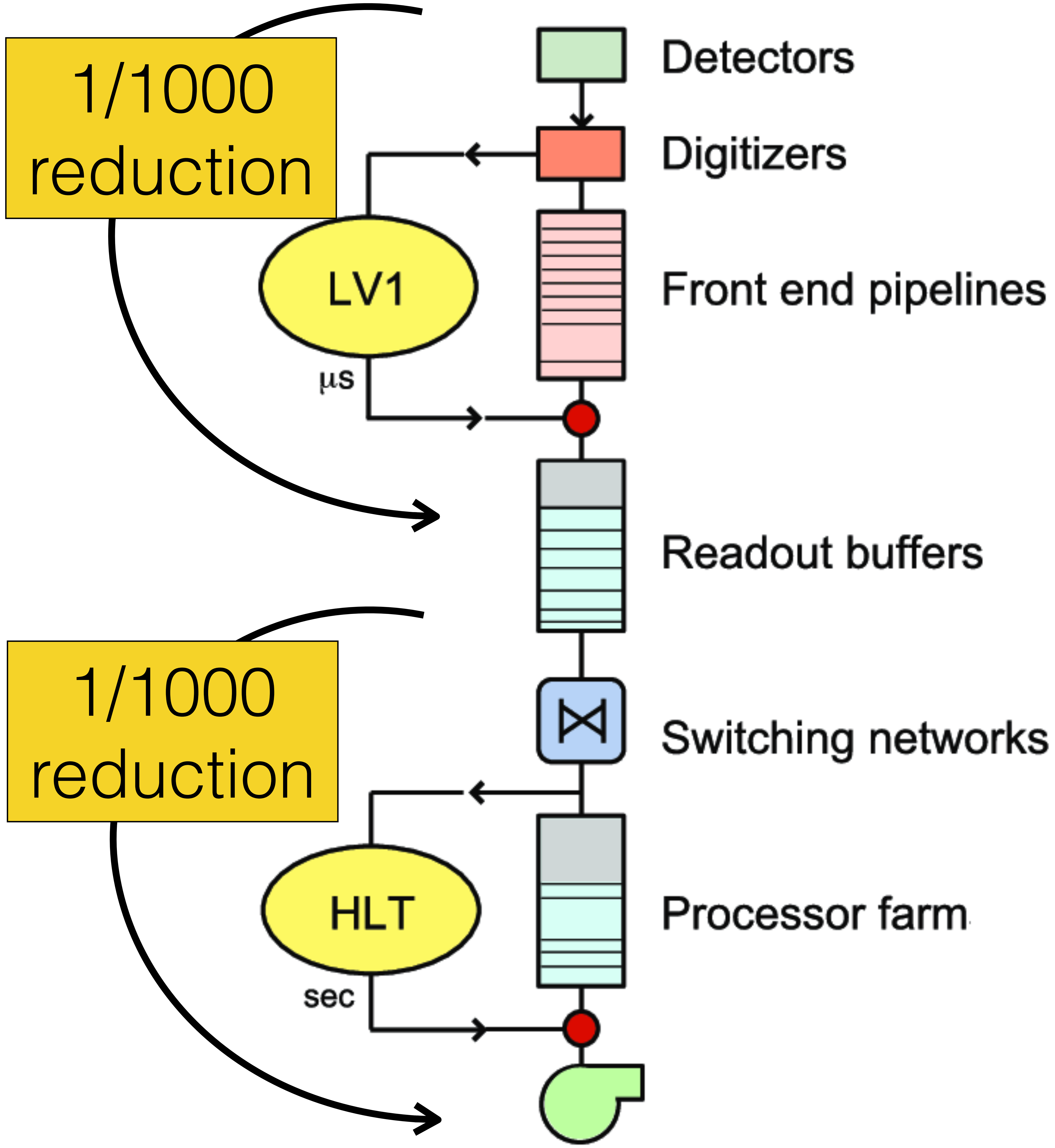
LHC bunches scheme

- beam composed of single packets (bunches) of particles, organised in “trains”



number of bunches	n_b	2556 at most
revolution frequency	f_{rev}	11 kHz
particles per bunch	$N_1, \ N_2$	$1.15 \cdot 10^{11}$
bunch crossing frequency		40 MHz

online vs offline reconstruction



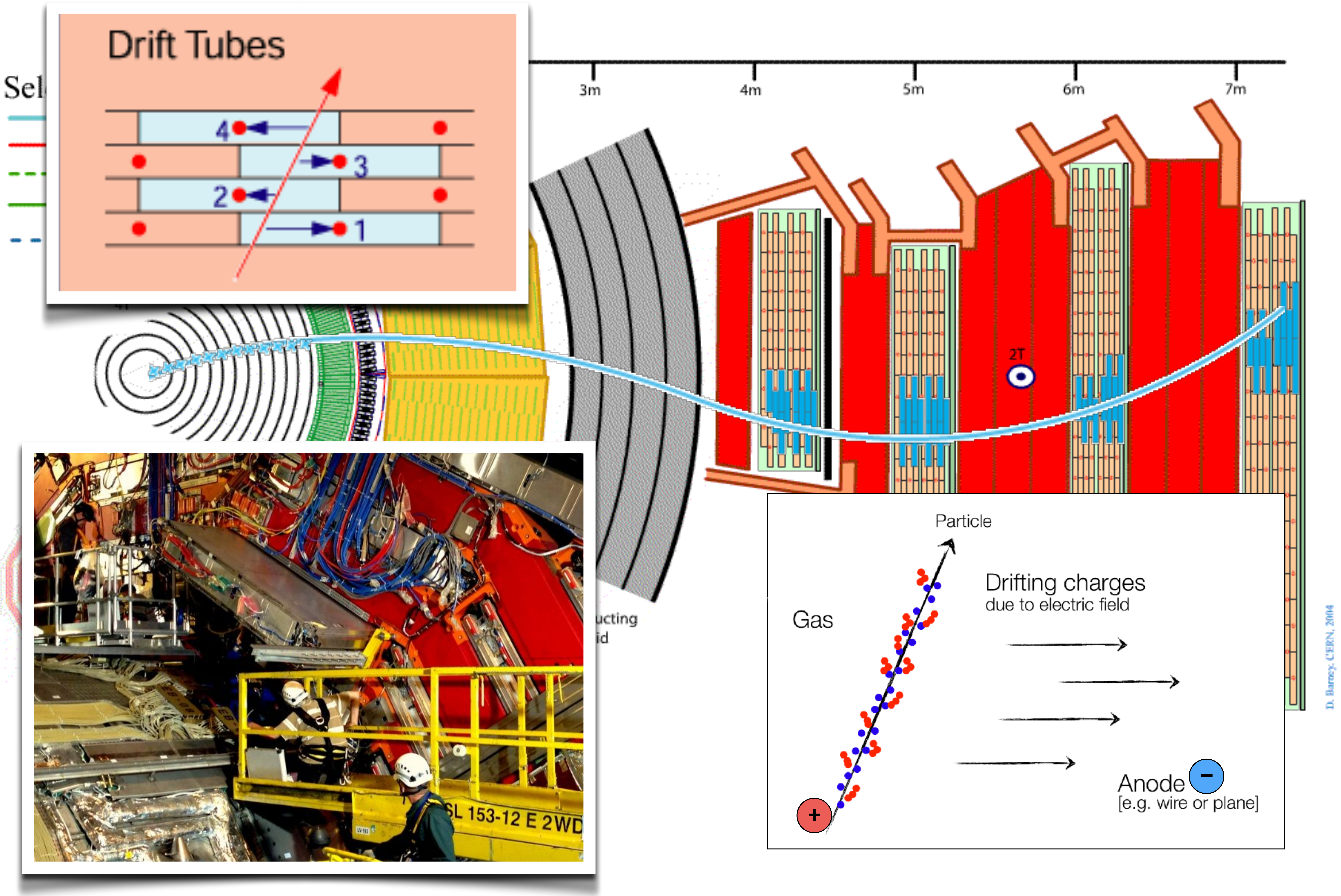
HLT

- **fast and solid**, to identify events interesting for physics during data acquisition

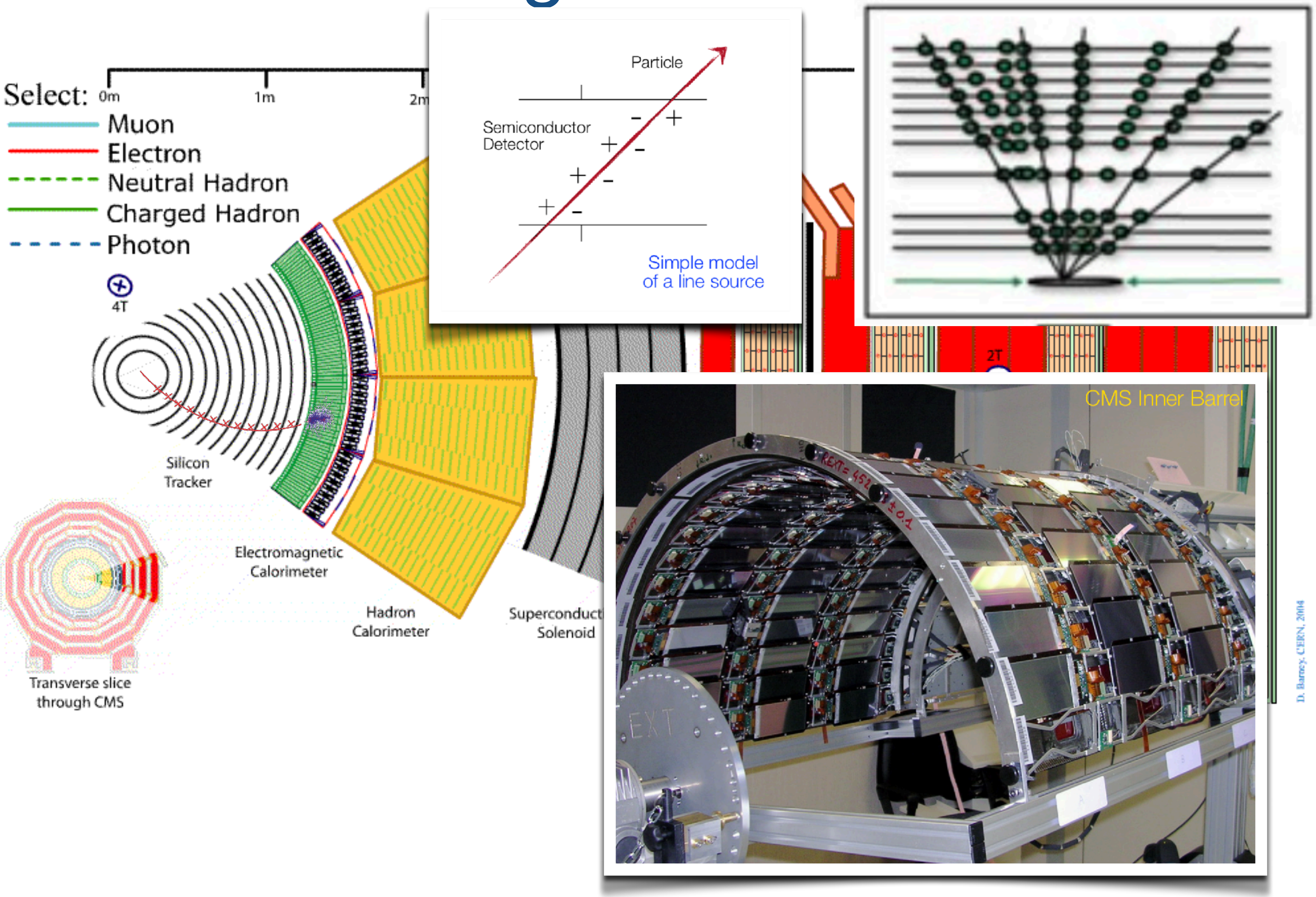
offline reconstruction

- **slow and careful**, to perform the data analysis

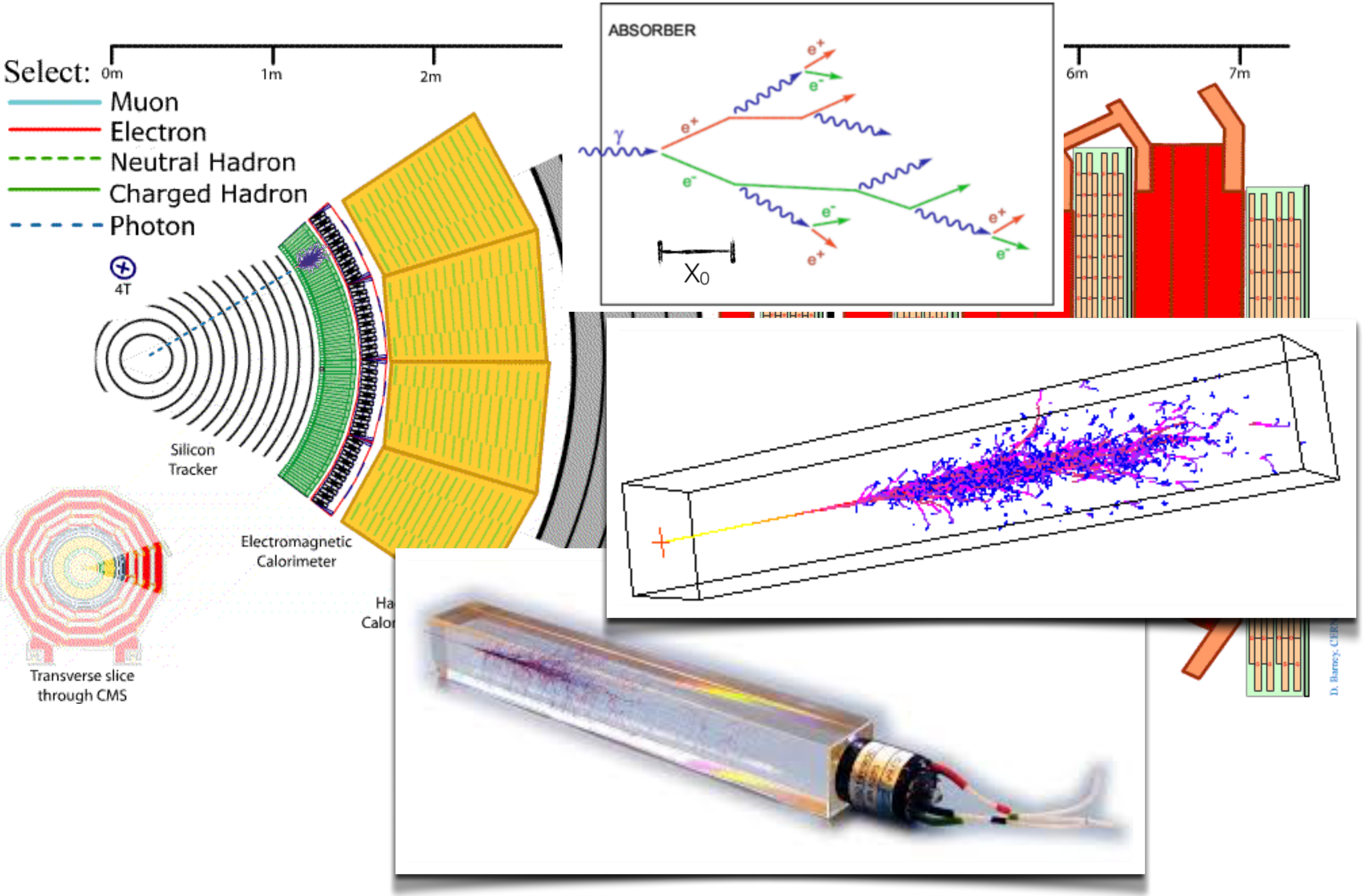
muons: the clean ones



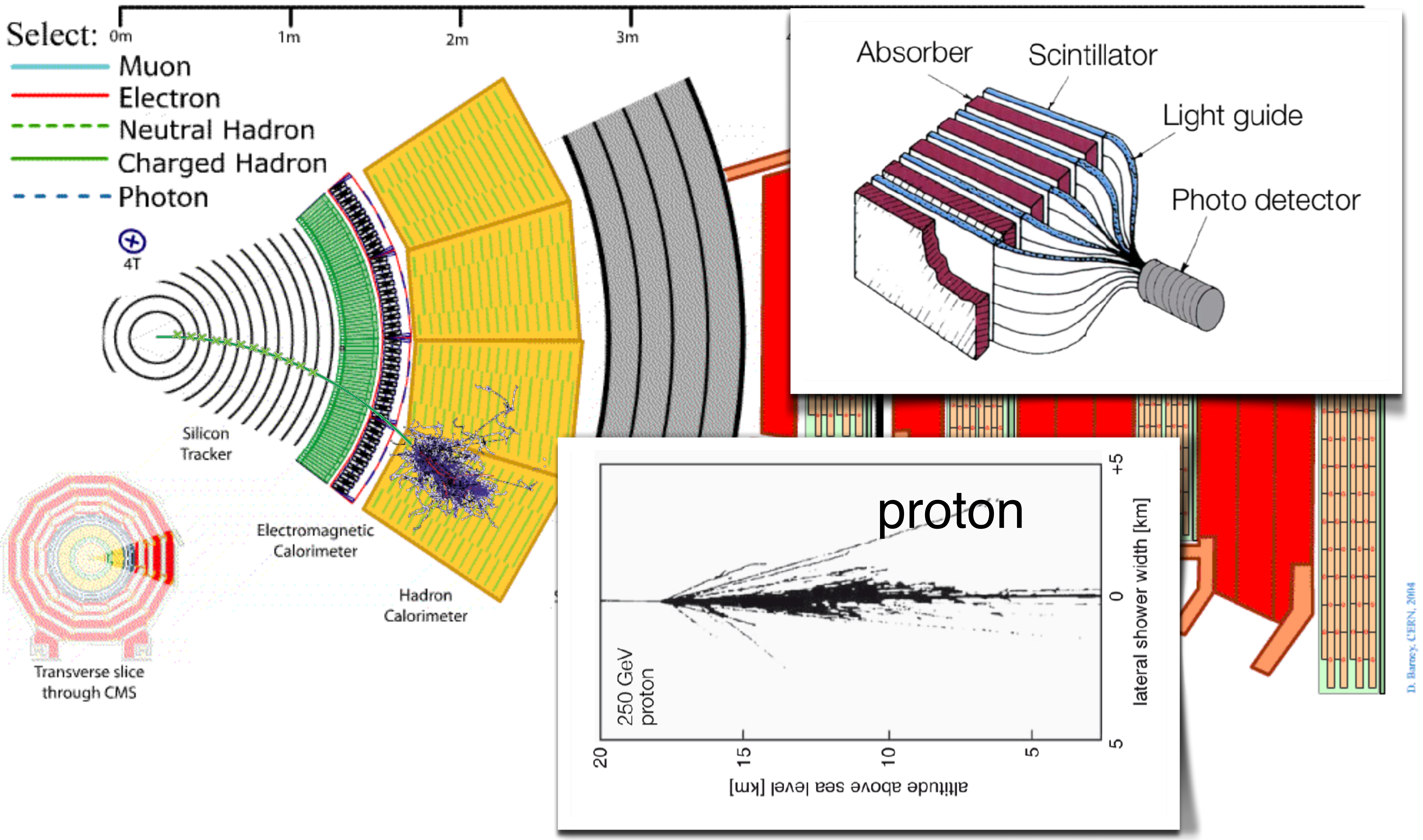
electrons: the radiating ones



photons: the isolated ones

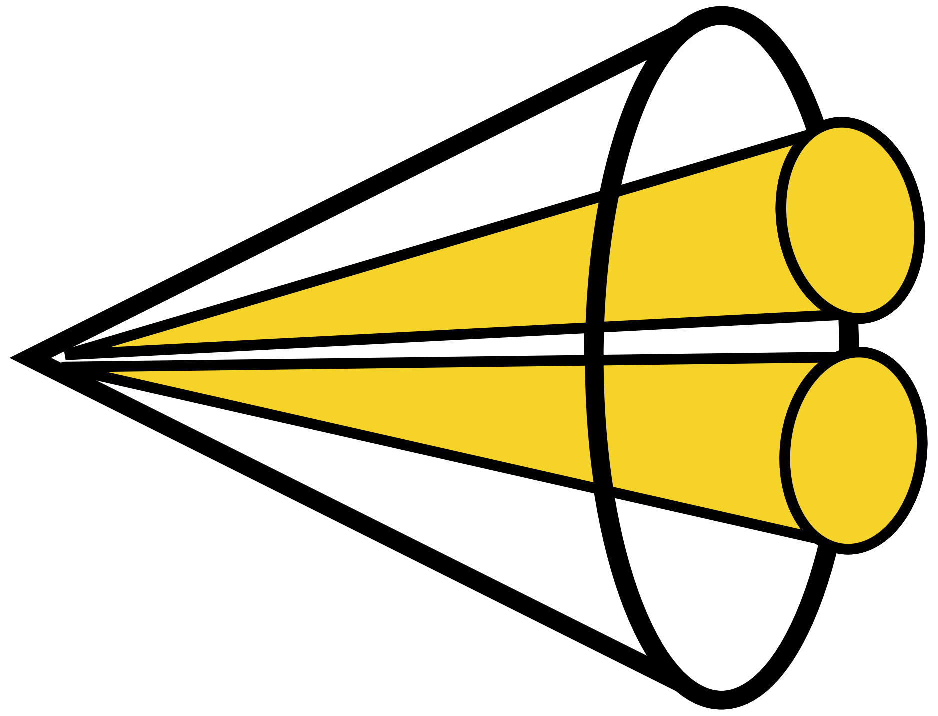


jets: the tough ones

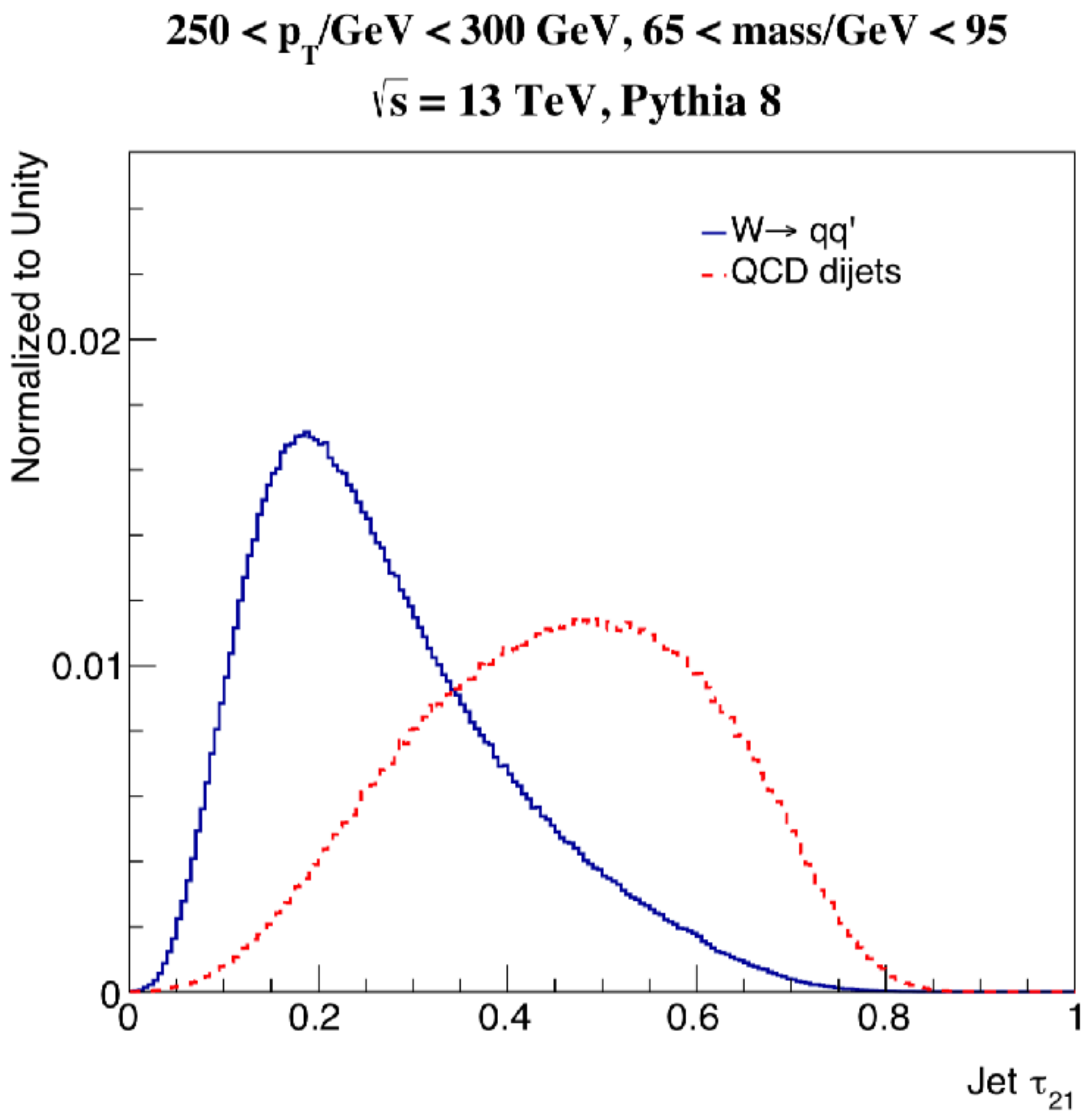


boosted jets

- hadronic 2-prong or 3-prong decay of boosted particle originate collimated objects
- reconstructed as single jets
  - **grooming**: clean the jets up by removing
  - **tagging**: identify the features of hard decays and cut on them

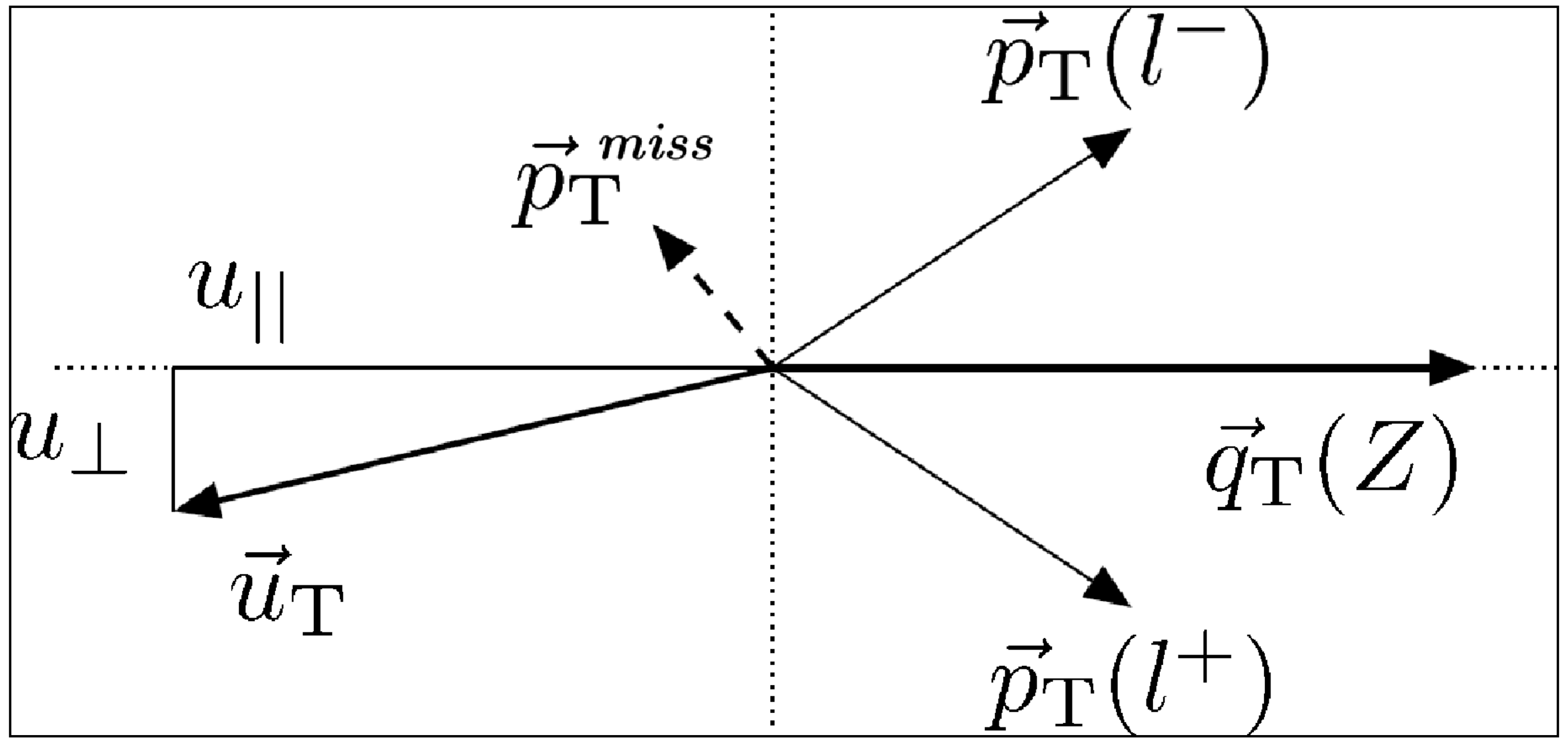


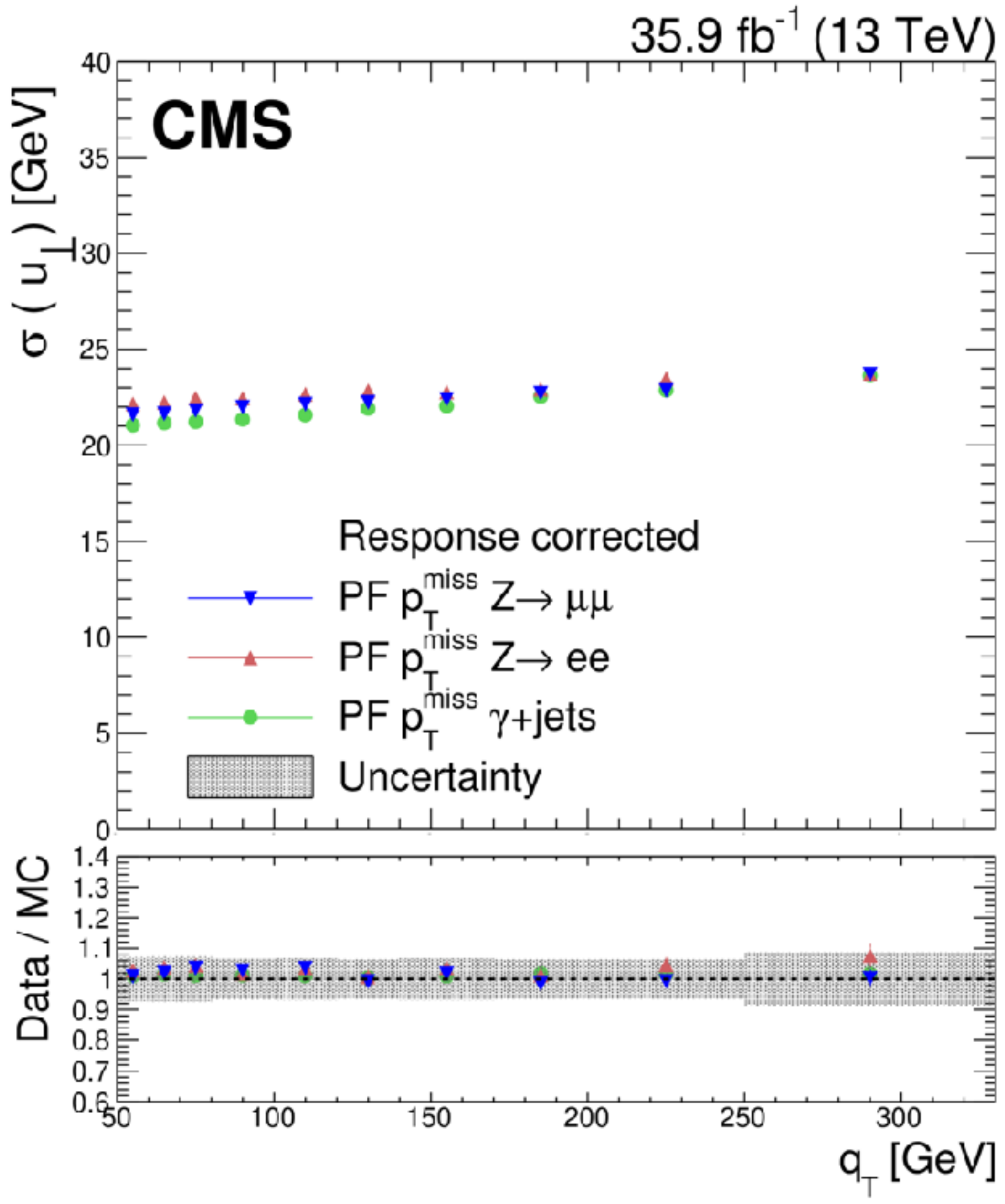
dedicated variables to identify jets originated by the shower of more than one particle (arXiv:1901.10342)



neutrinos: missing transverse energy

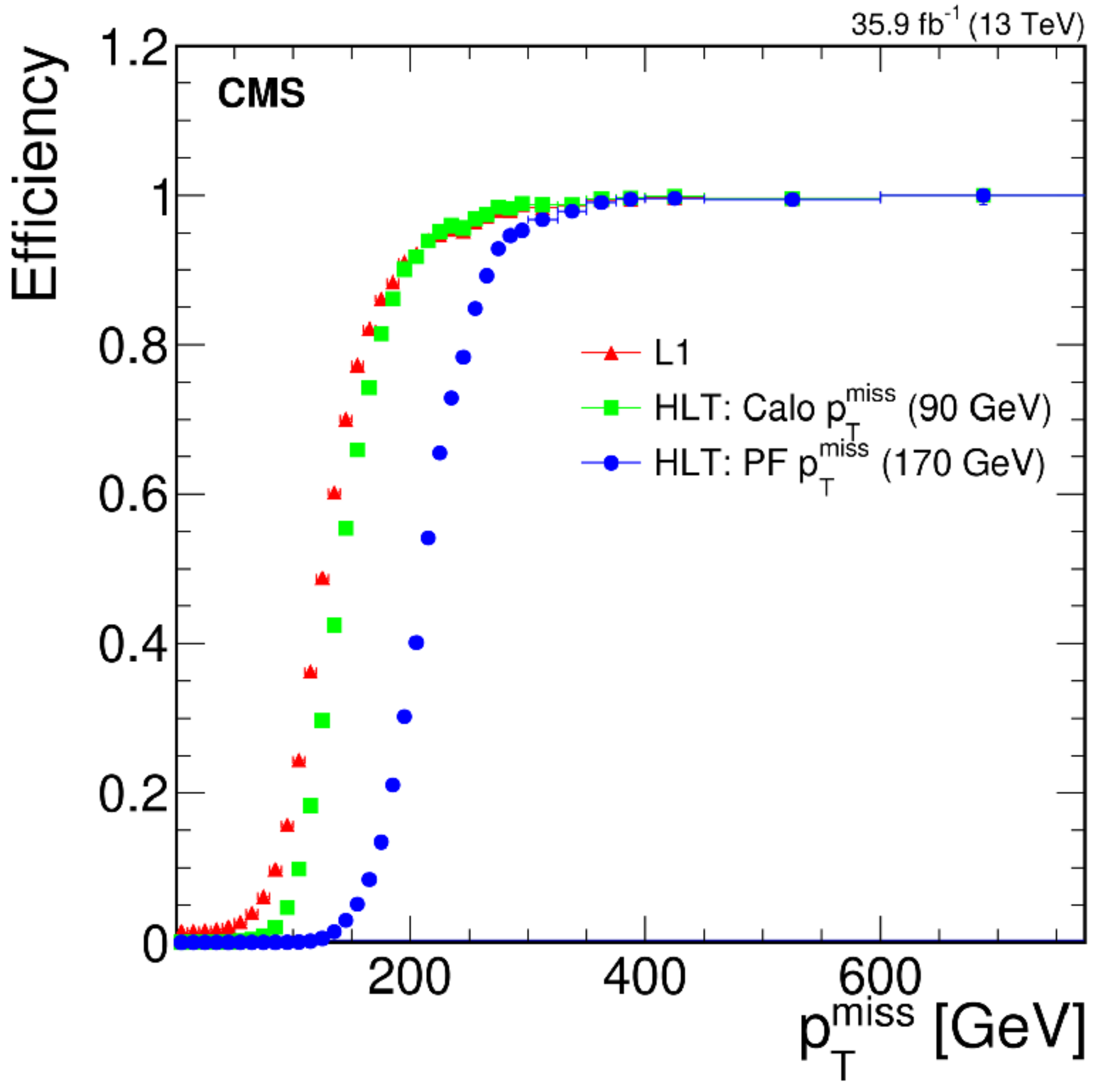
$$\vec{p}_{\mathrm{T}}^{\,miss} = -\sum_{\text{other}} \vec{p}_{\mathrm{T},i}$$



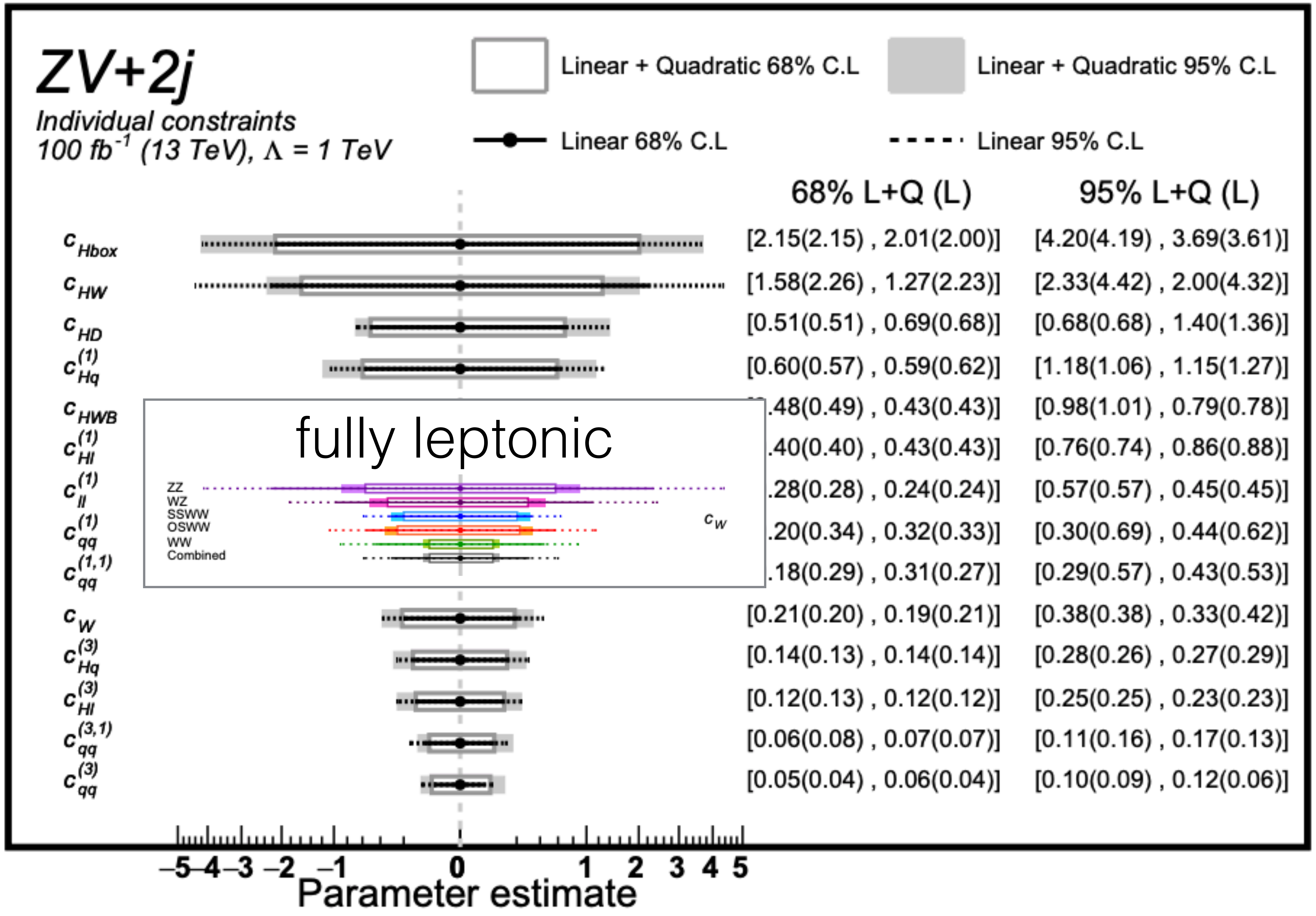


resolution affected by all other particles

very large turn-on curve



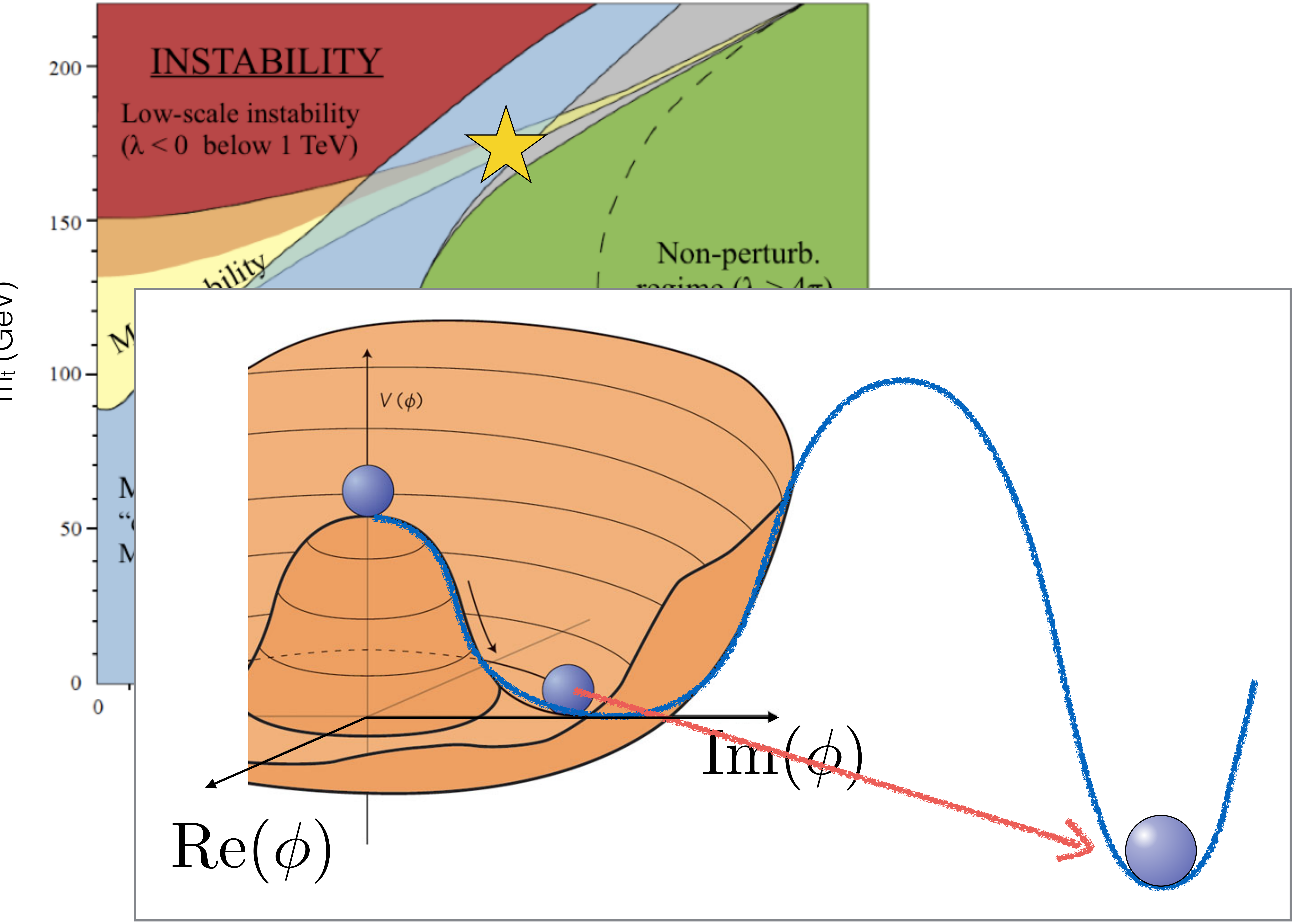
semi-leptonic final states

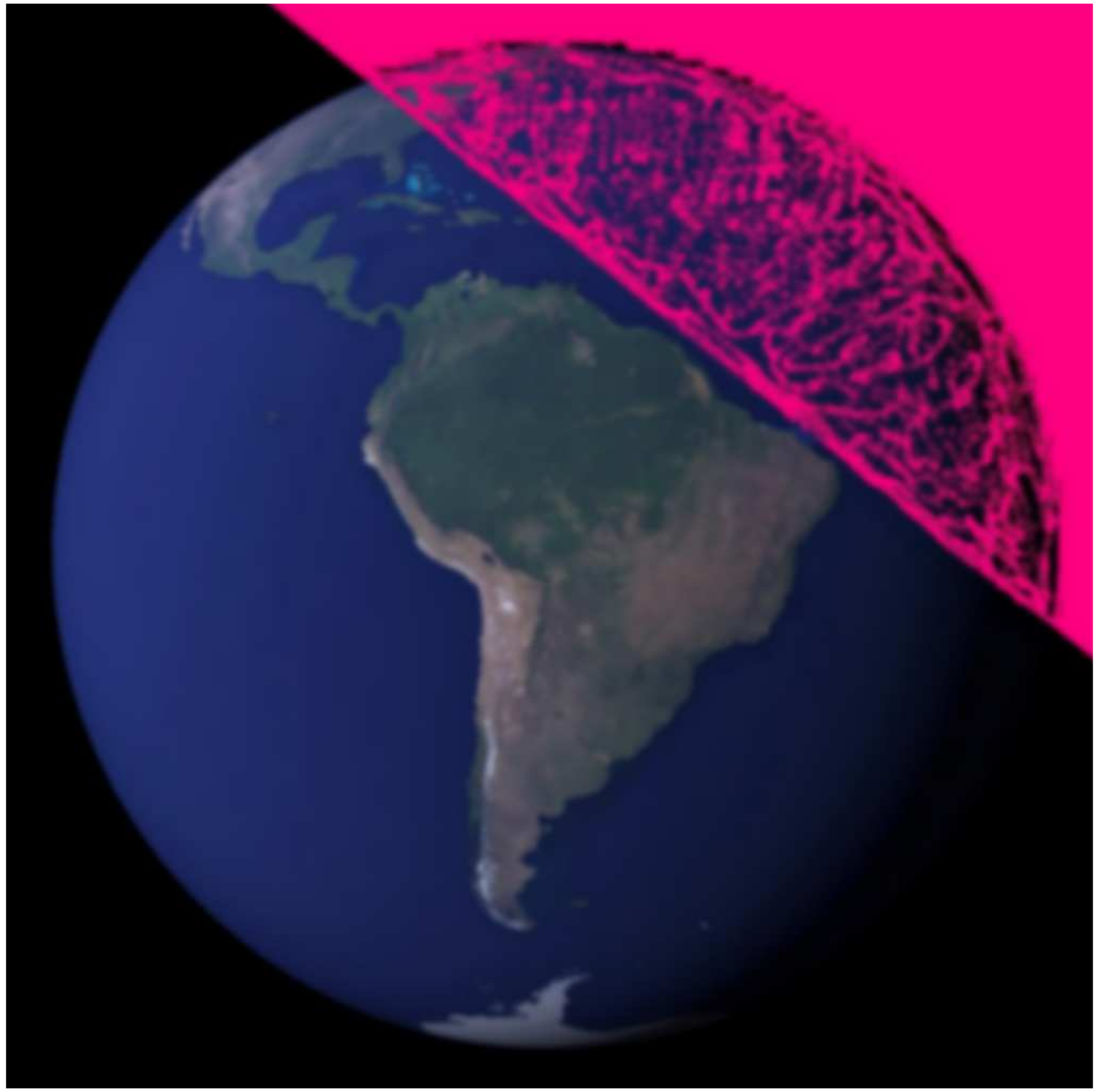


- gain in **statistical precision**
- at high energies the reducible backgrounds **significantly loose importance**

Higgs vacuum stability

drawing from
A. Strumia





H±± exclusion

Phys. Rev. Lett. 120, 081801

- **VBF production of $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$**