Precision measurements at the LHC in the Electroweak sector

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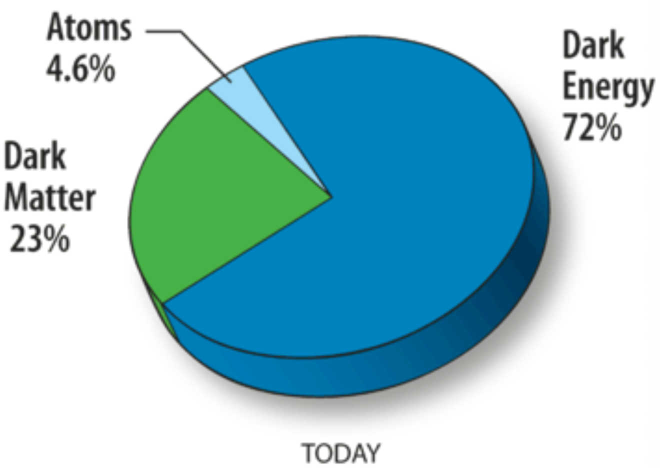
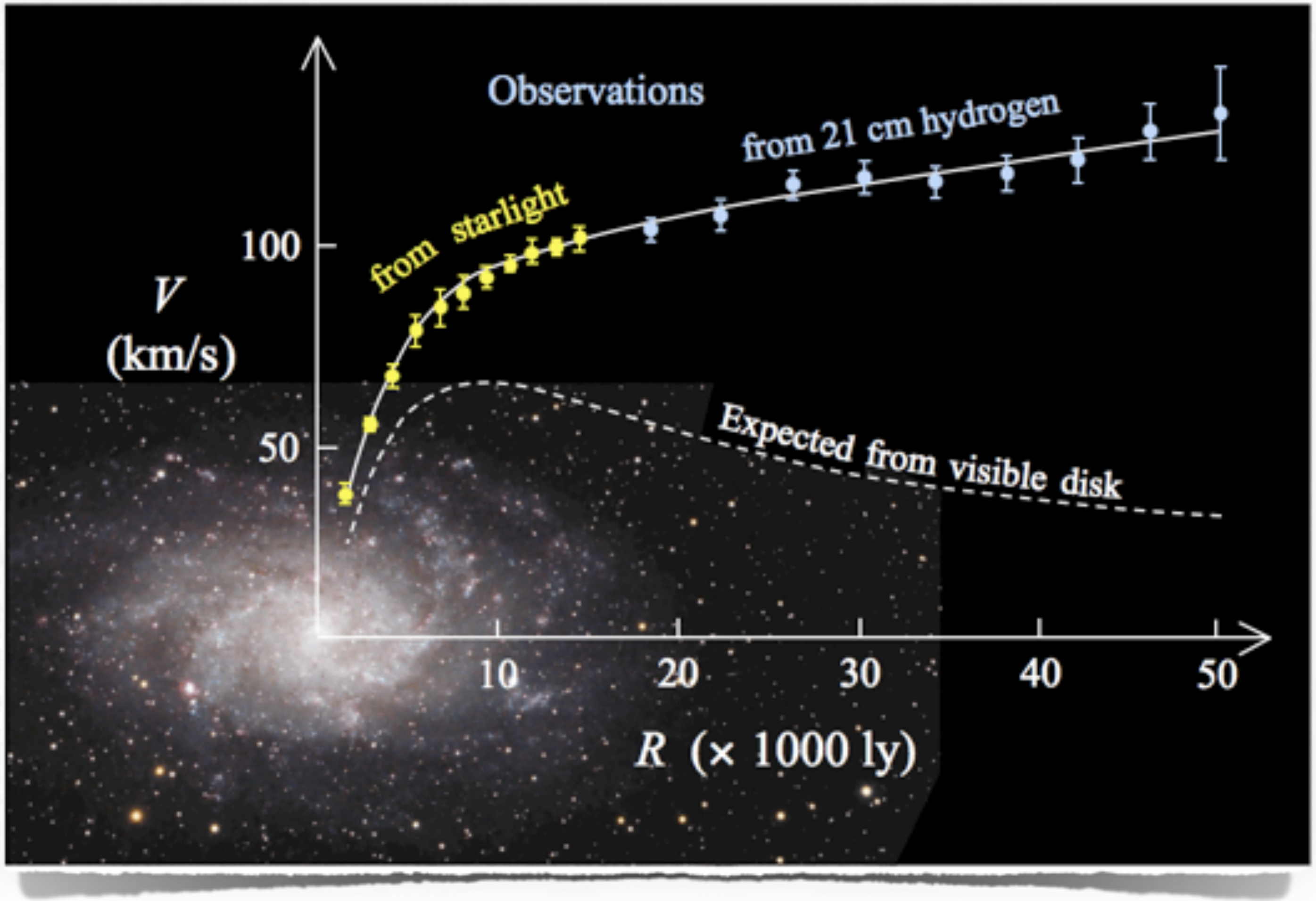
main reasons behind

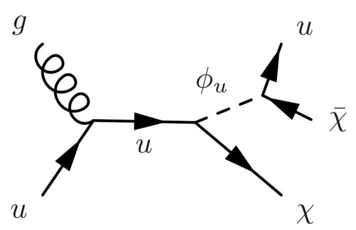
- compelling cosmological evidence of dark matter existence through its gravitational interaction

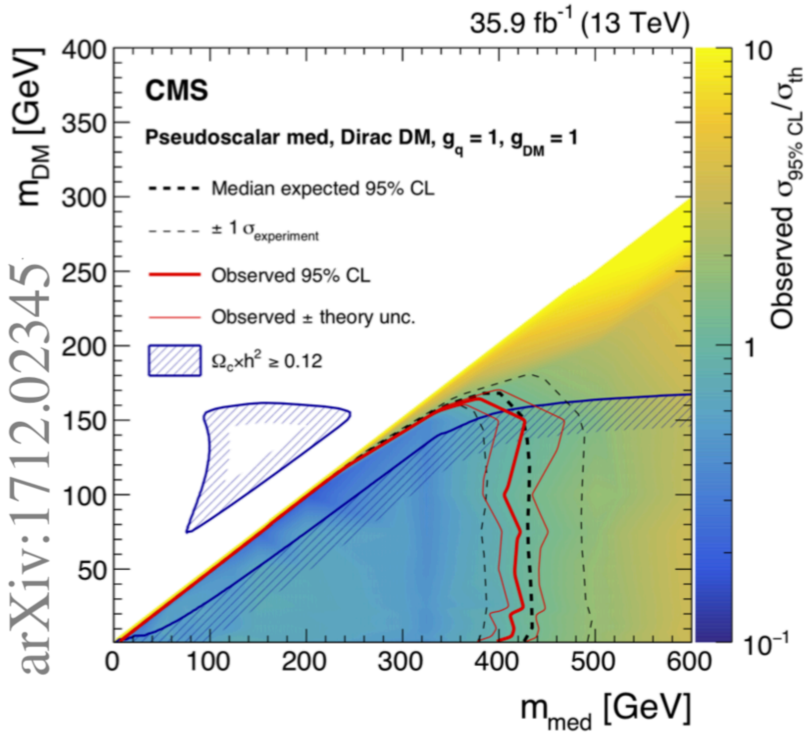


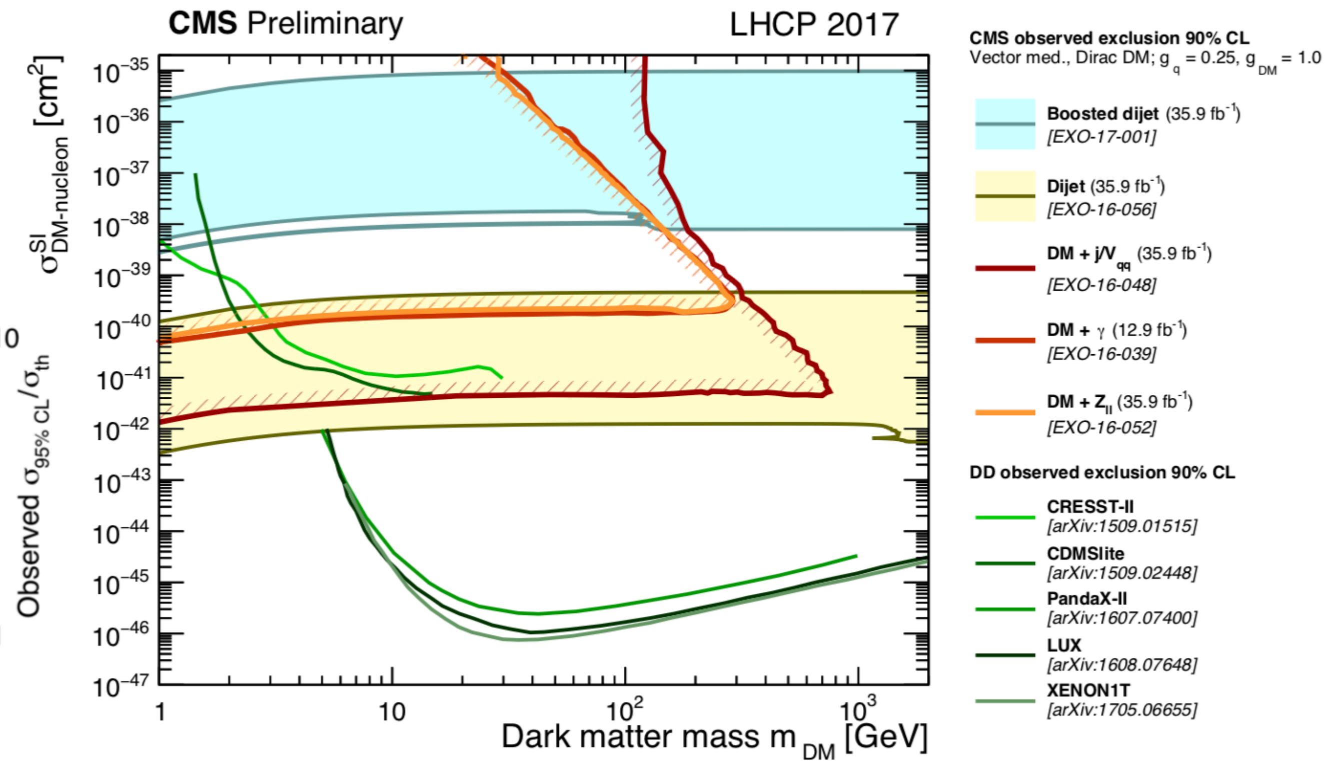


dark matter searches at LHC

- **nothing found so far**
- model-dependent studies
- large expectations from the the energy jump from 8 TeV to 13 TeV

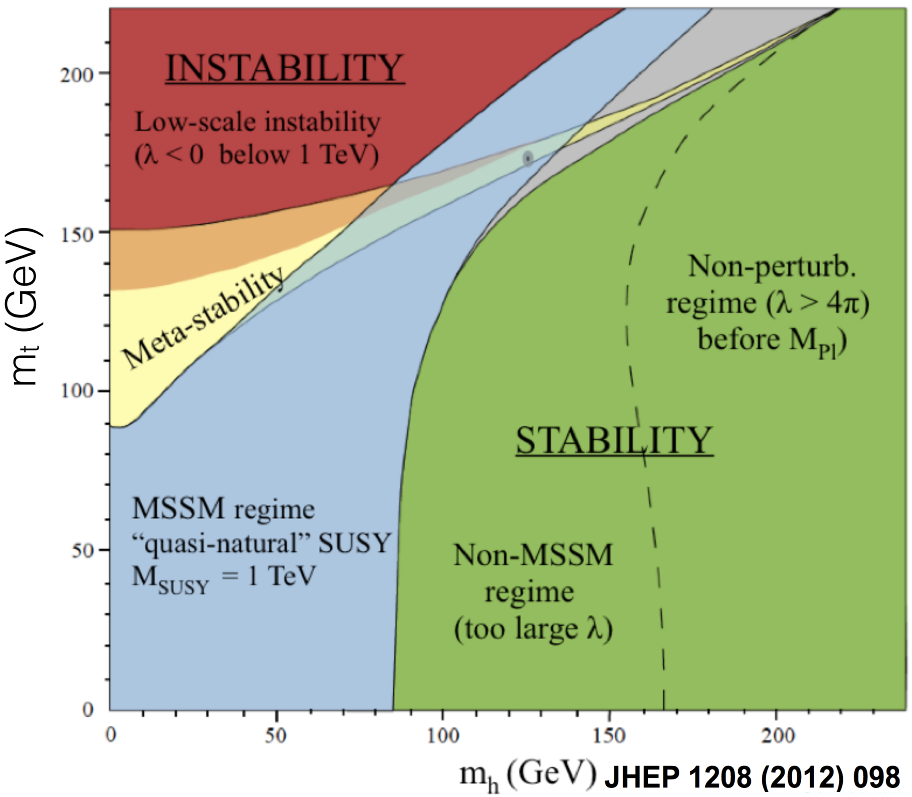




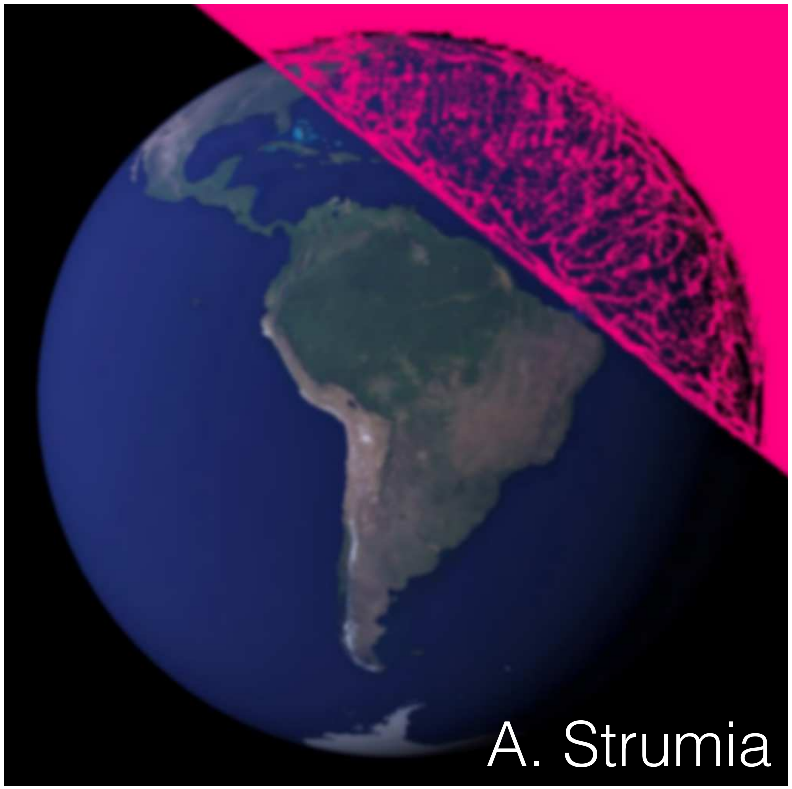


vacuum stability

- Higgs mass is unstable to large radiative corrections from much higher energy scales - fine-tuning needed to keep the Higgs light: **severe naturalness problem**
- the standard model alone exhibits a Higgs potential which is **meta-stable**, given the measured values of its parameters



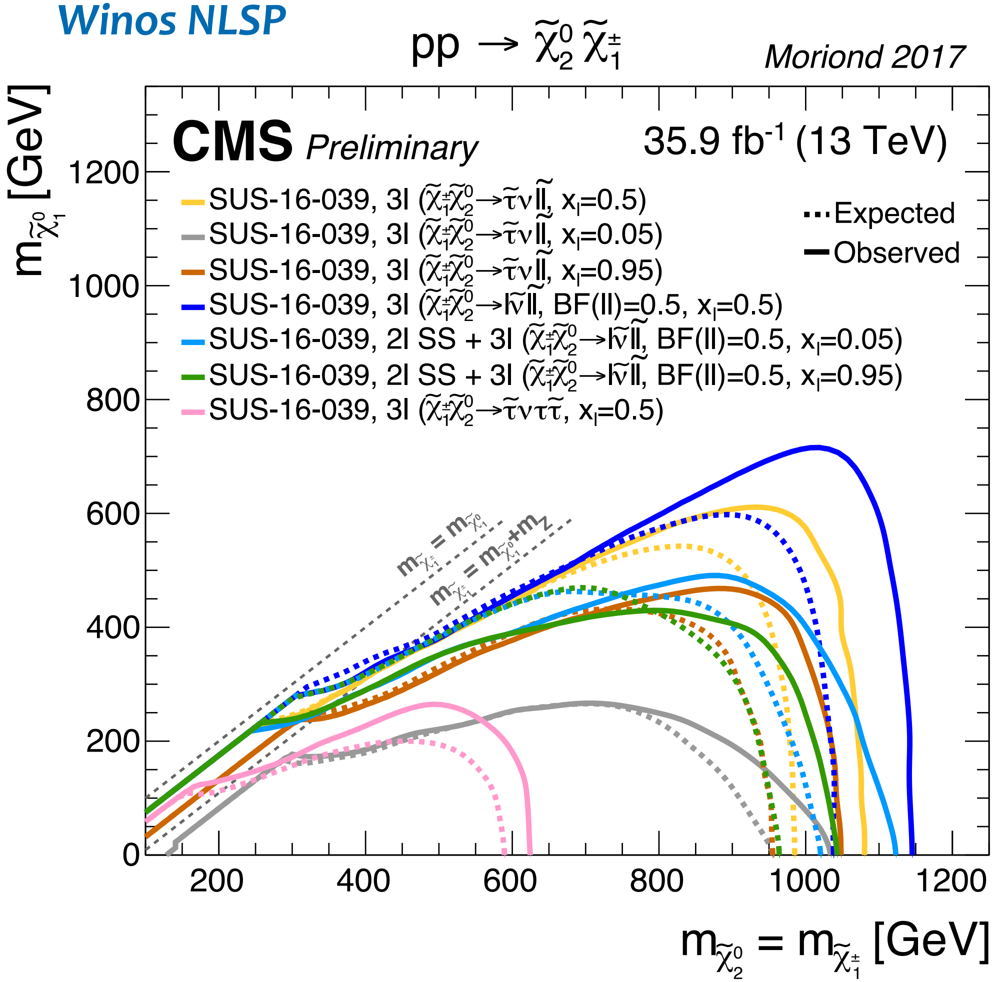
JHEP 1208 (2012) 098

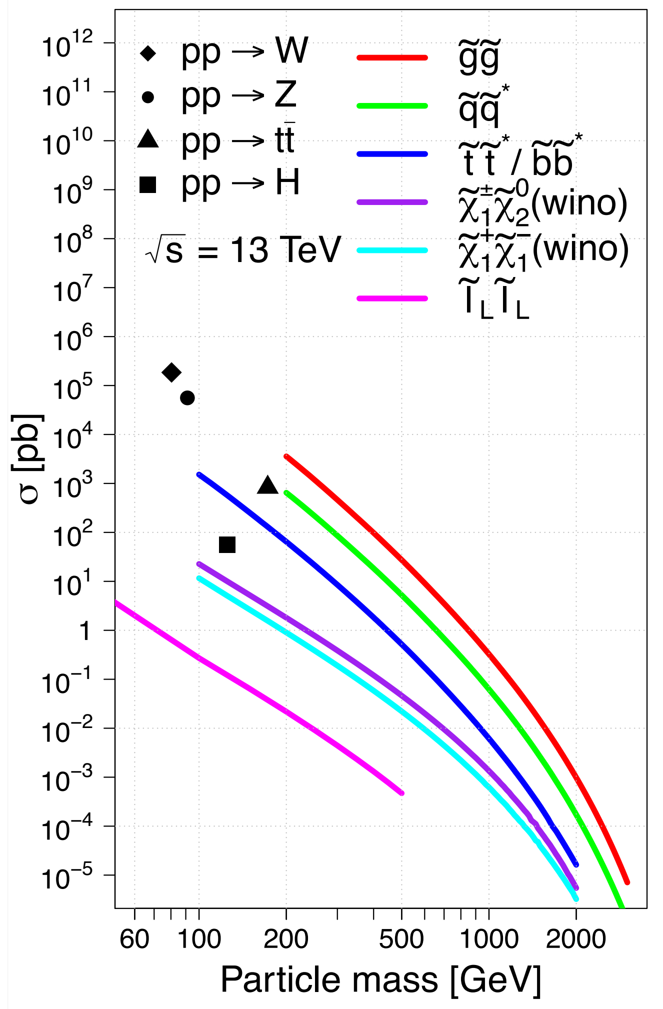


SUSY searches

- **nothing found so far**, mostly with simplified models, even in the 3rd generation and EWK production cases
- cross-sections fall at high mass

Winos NLSP





high-mass BSM resonances

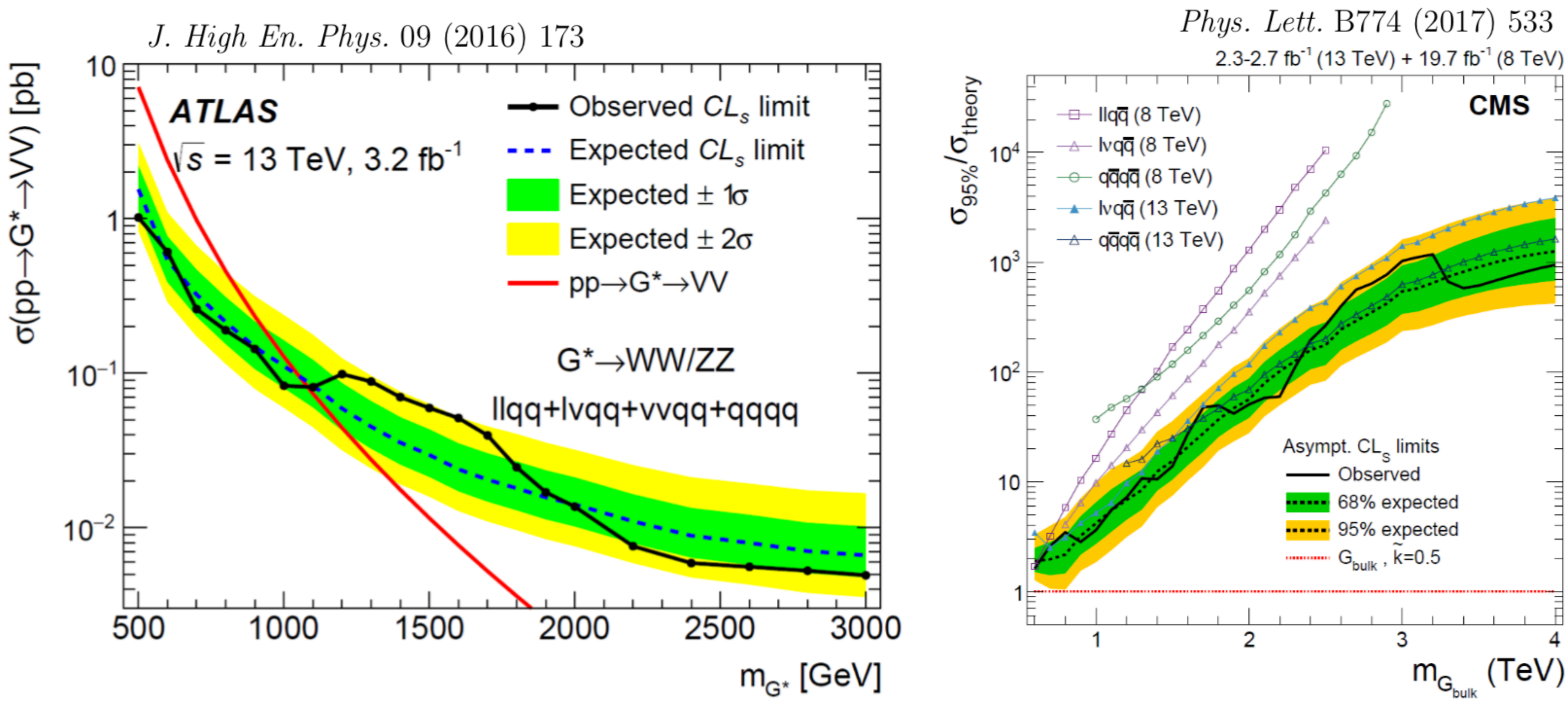
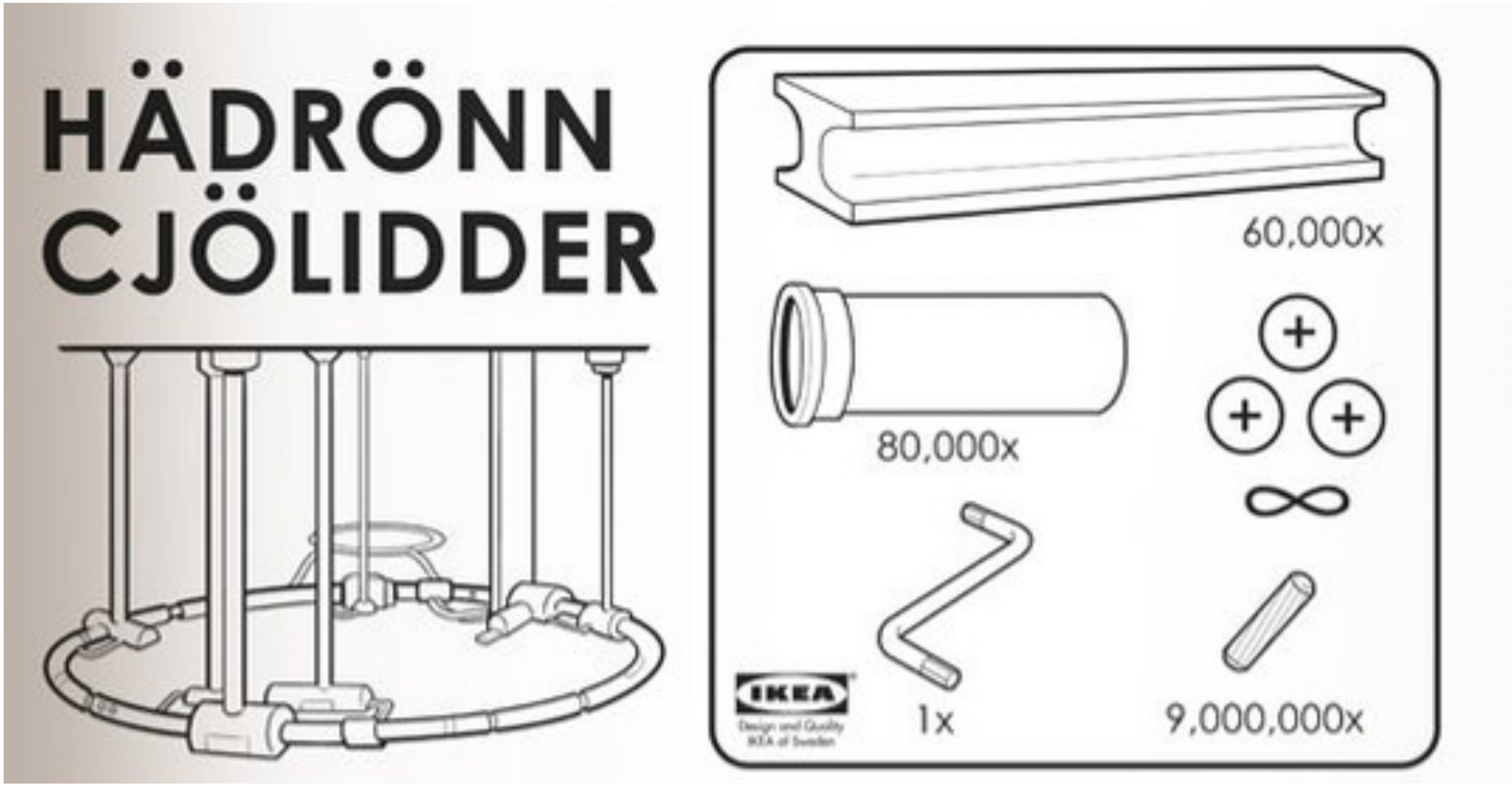


Figure 1: *95% CL upper limits on the cross section of production of bulk gravitons obtained by the most stringent searches: the ATLAS result reported in [323] (left), and the CMS result reported in [329].*

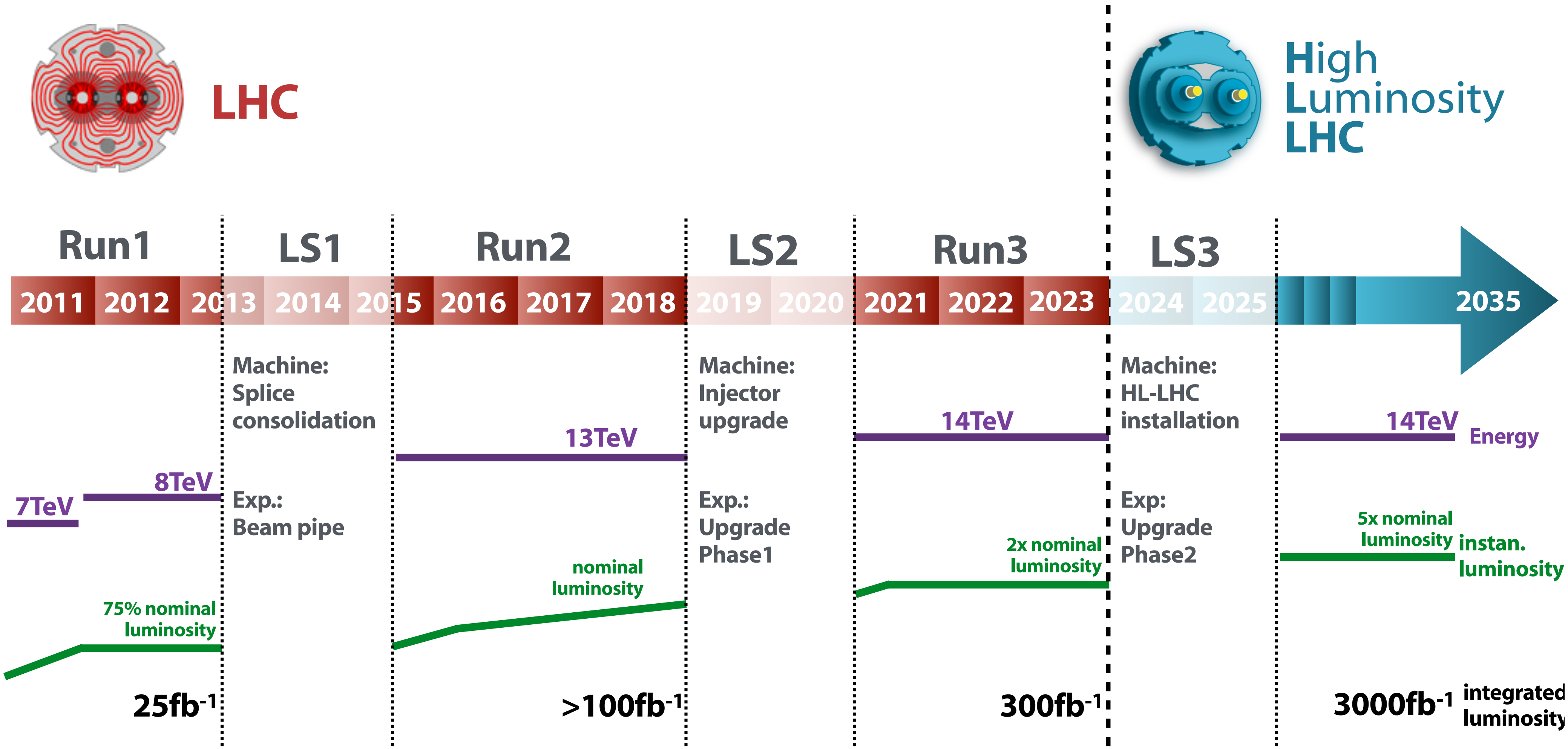
arXiv:1802.00354

the Large Hadron Collider

- proton-proton collider at CERN
- current centre-of-mass energy of the *pp* system: 13 TeV
- planned to take data until year 2035



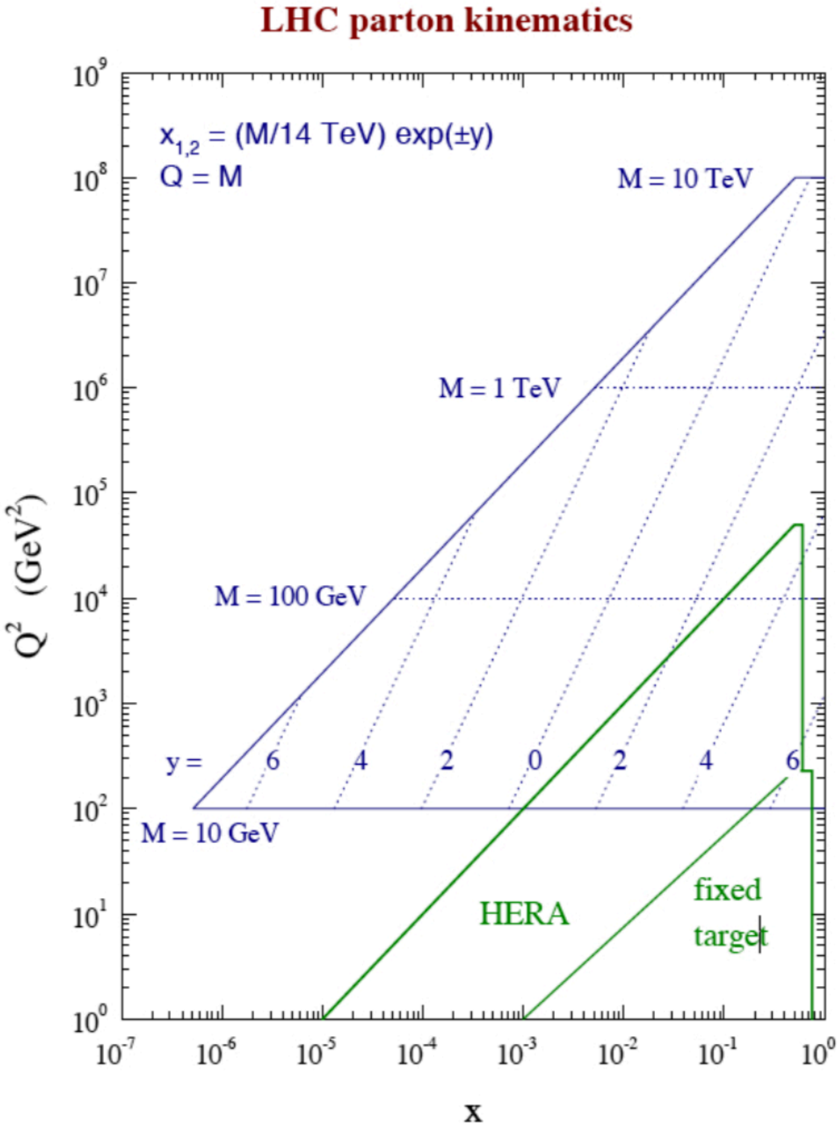
the LHC operations plan

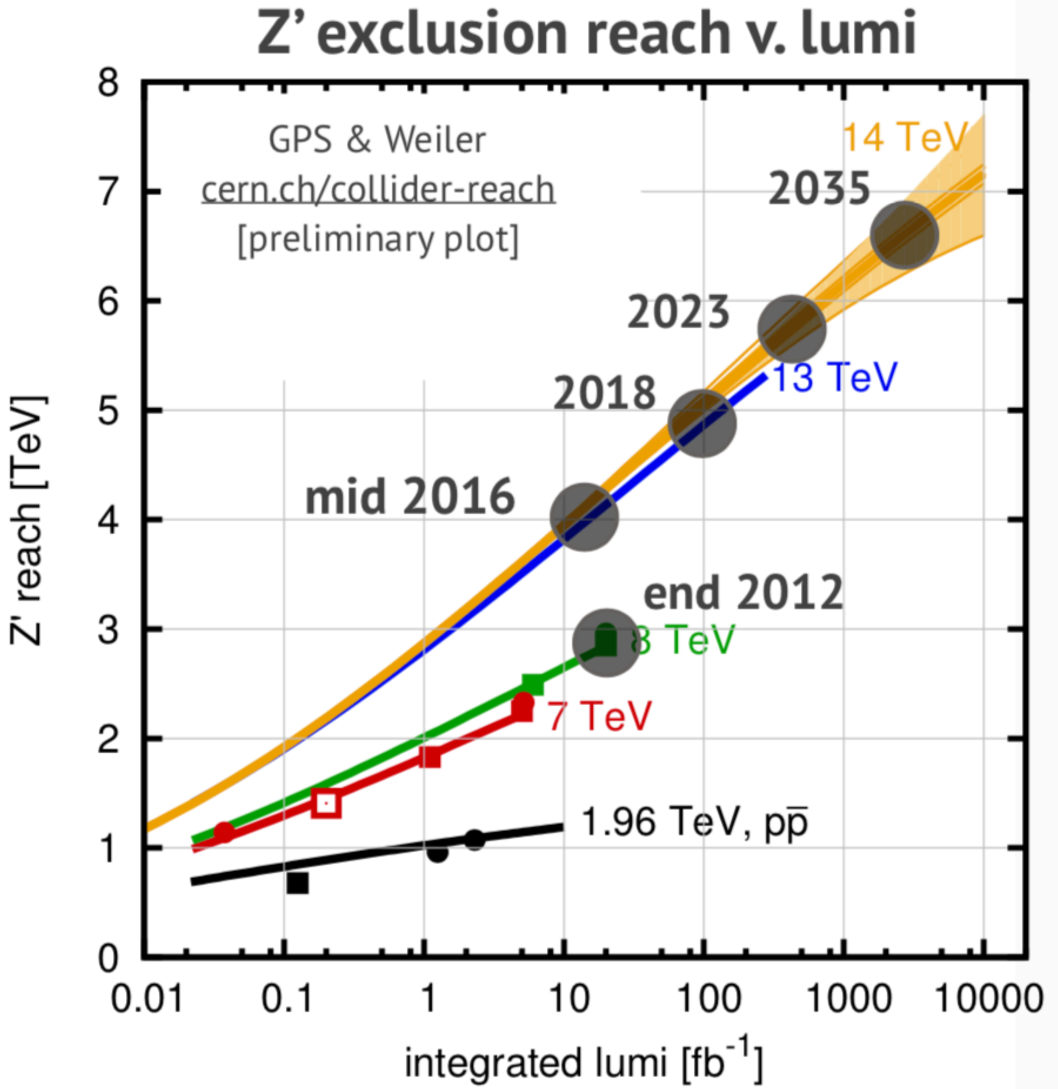


the LHC energy reach

Gavin Salam, CERN

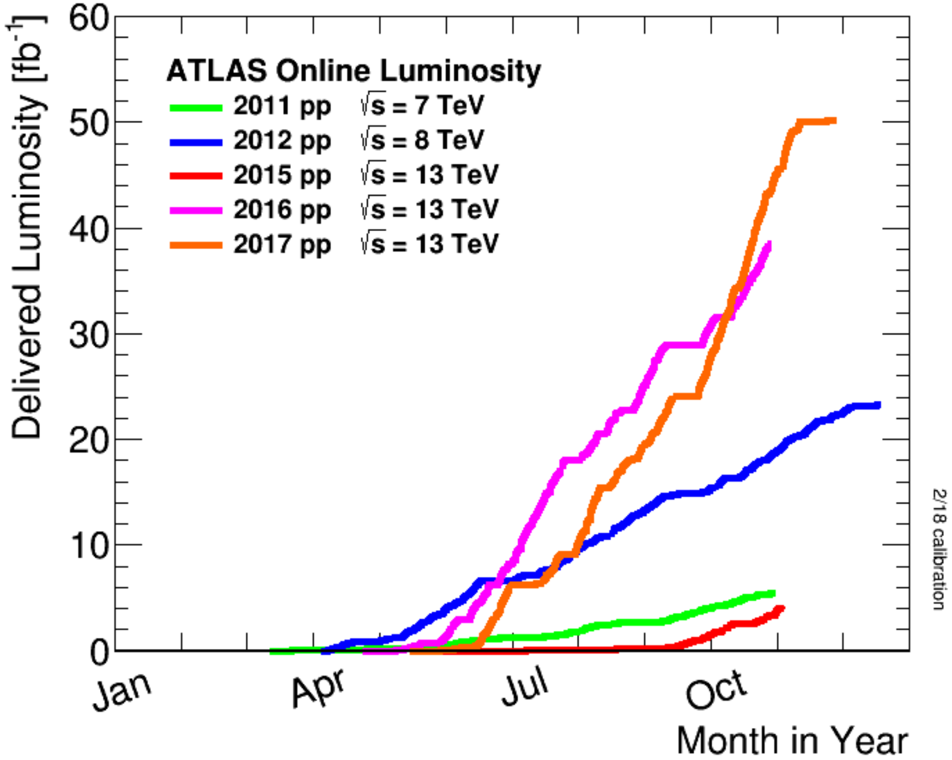
PSI Summer School Exothiggs, Zuoz, August 2016

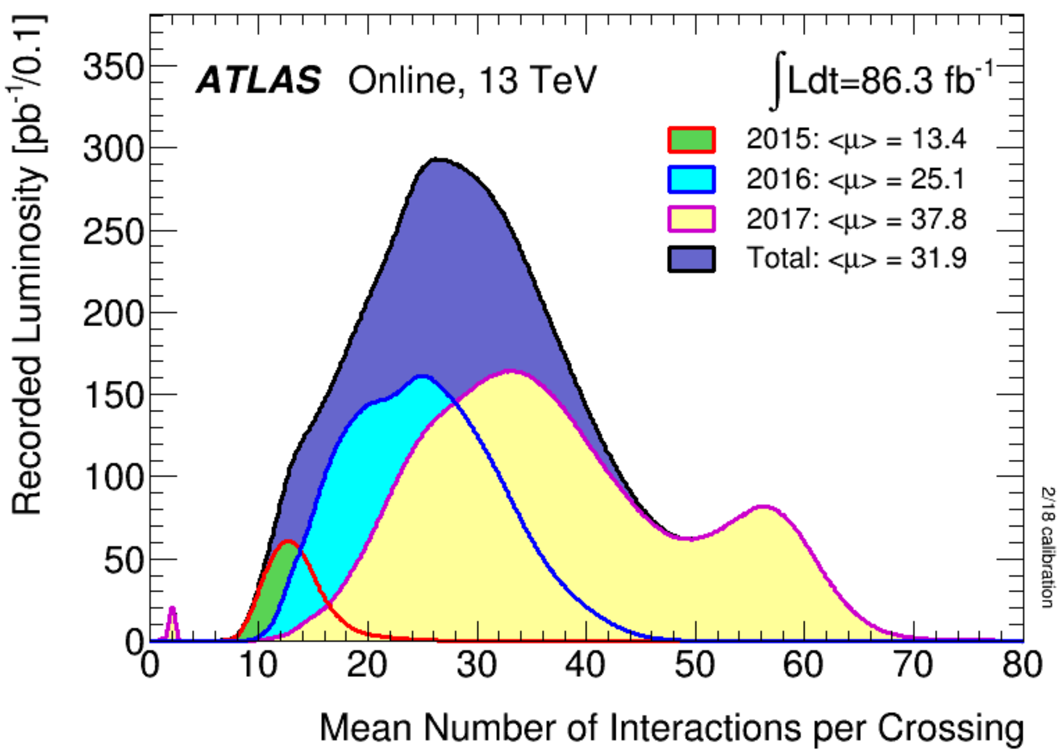




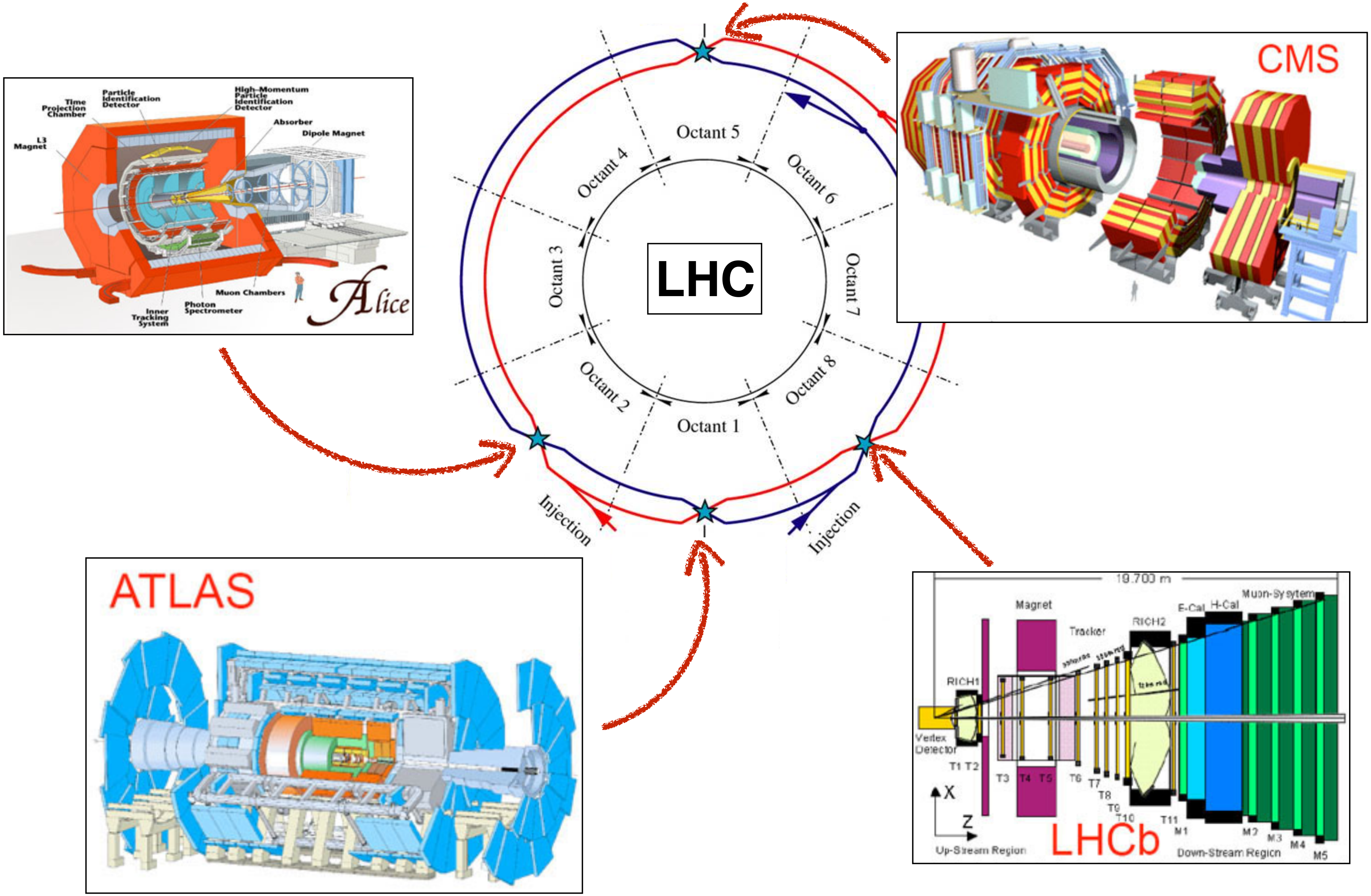
the proton collisions

- LHC delivered about 50/fb of data in 2017 at 13 TeV of centre-of-mass energy, on top of about 40/fb in 2016
- the number of **pile-up** increases with the instantaneous luminosity
- **on-line selection** of events needed, and more difficult with high instantaneous luminosity and pileup

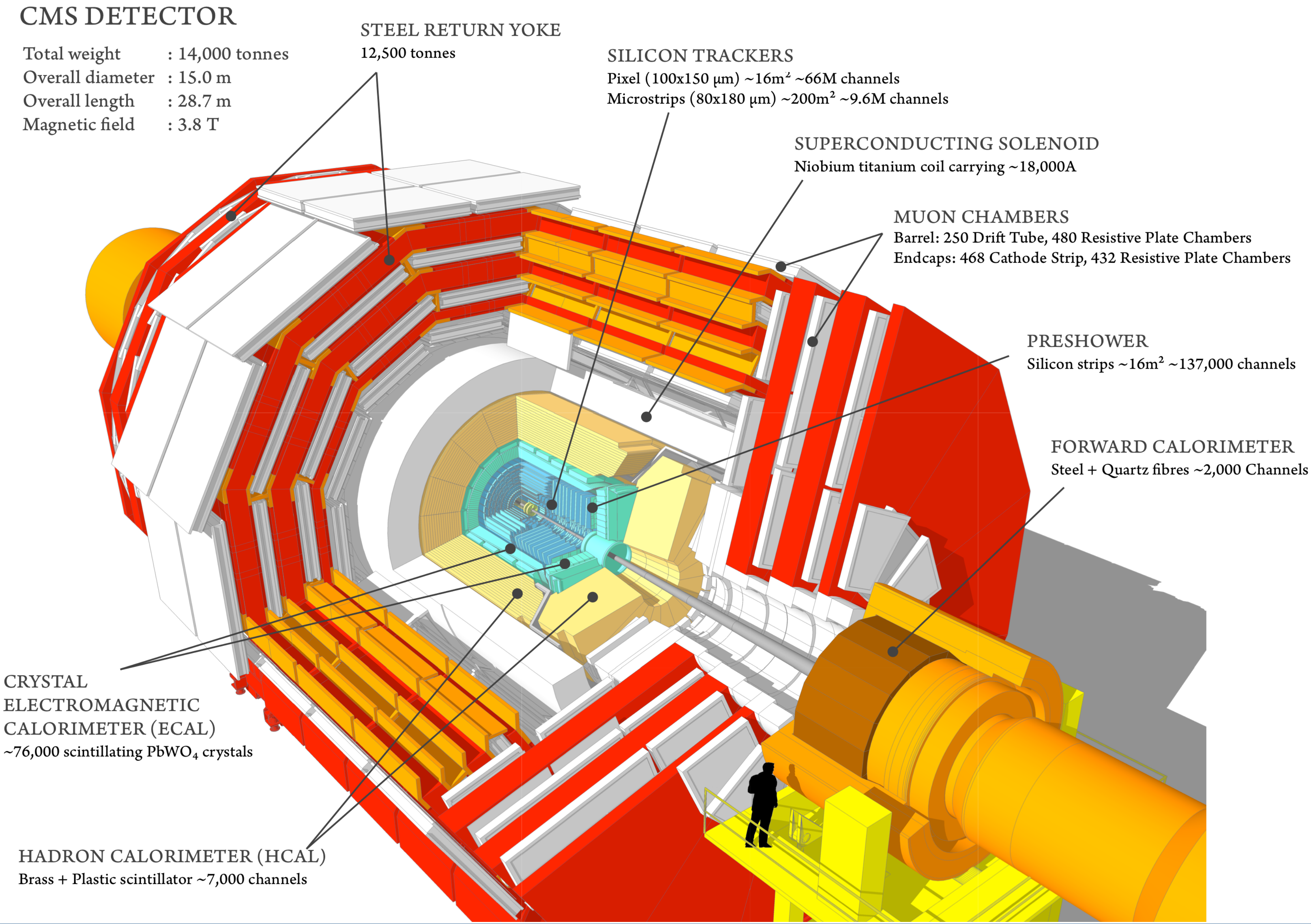




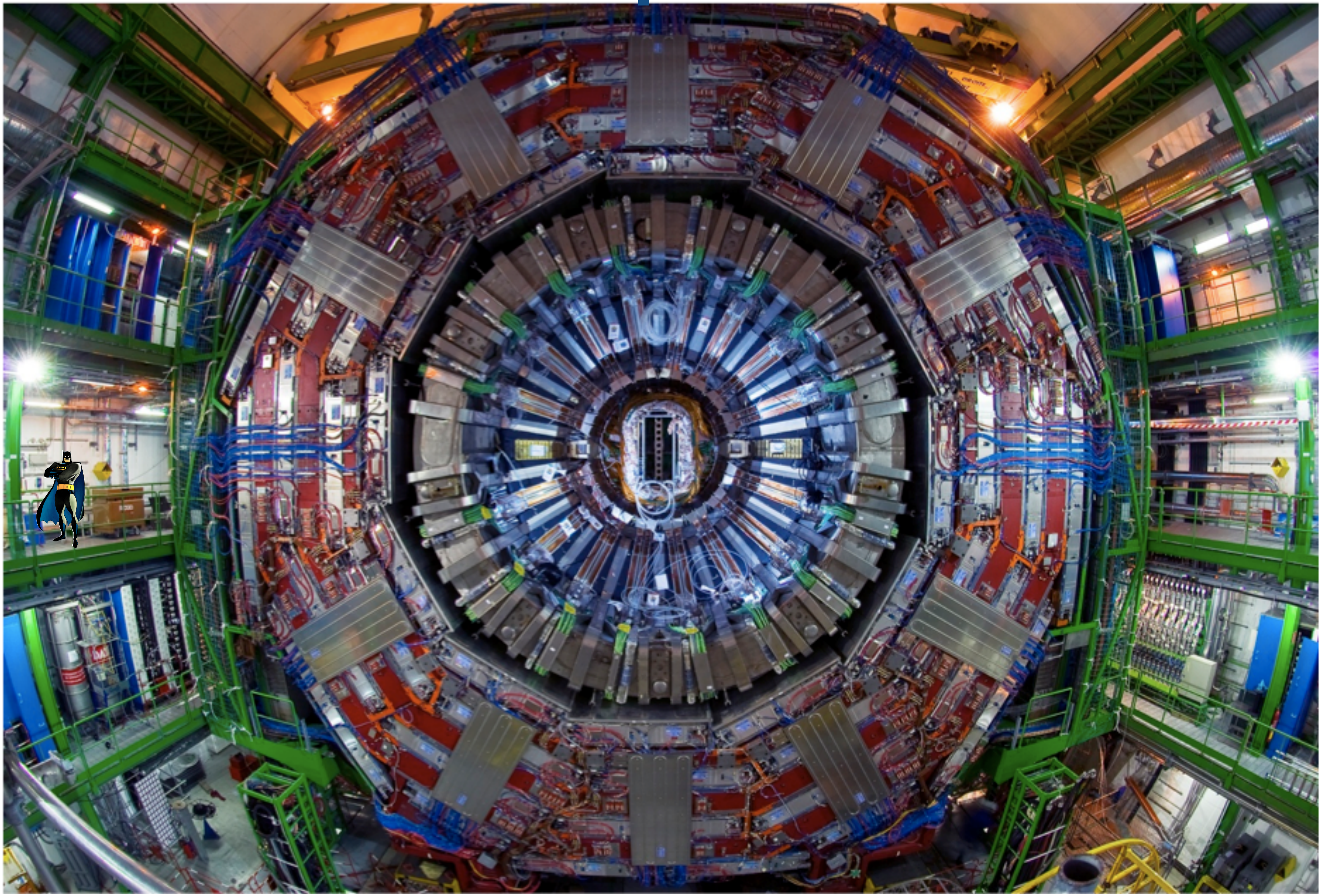
the LHC detectors



compact muon solenoid, CMS



the detector components



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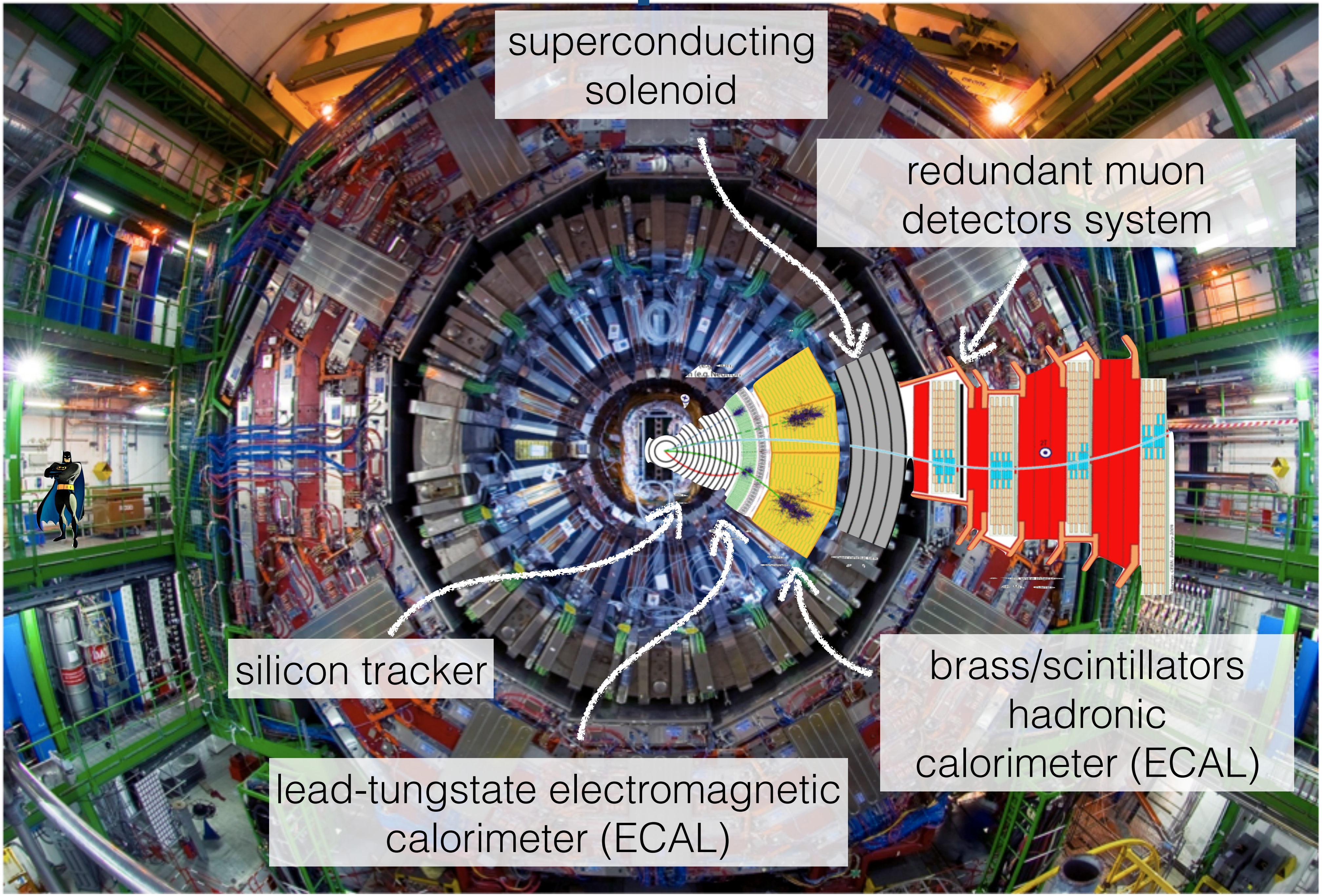
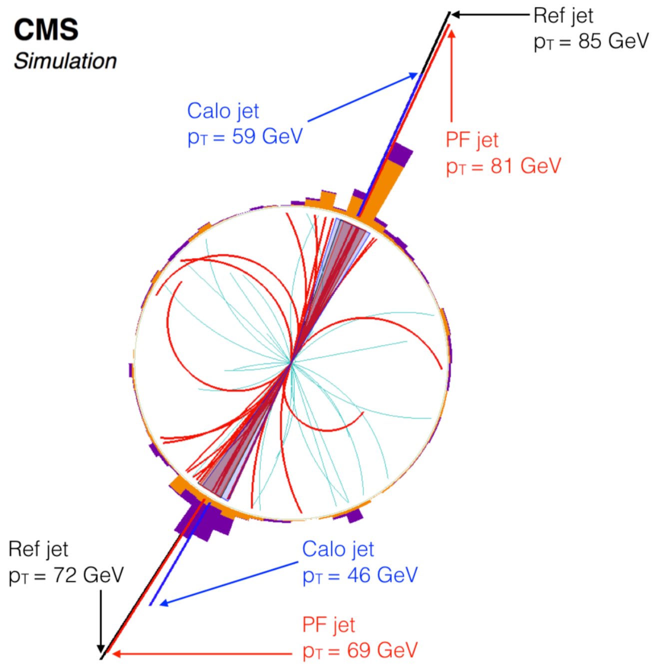
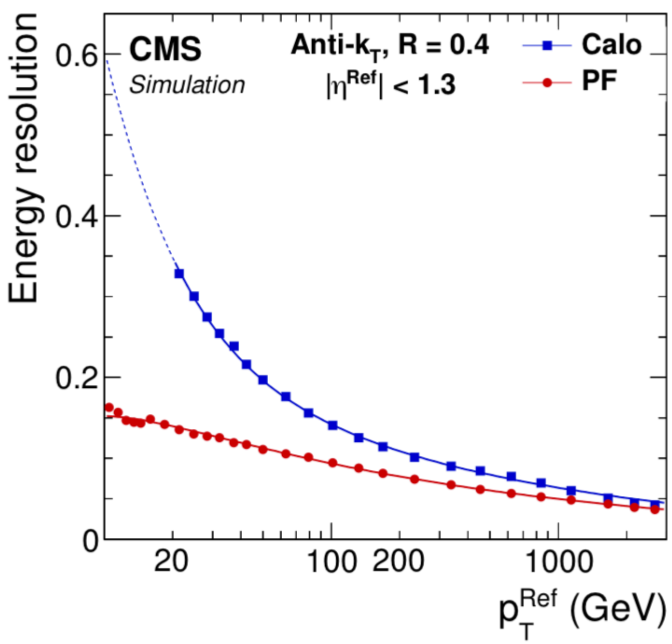
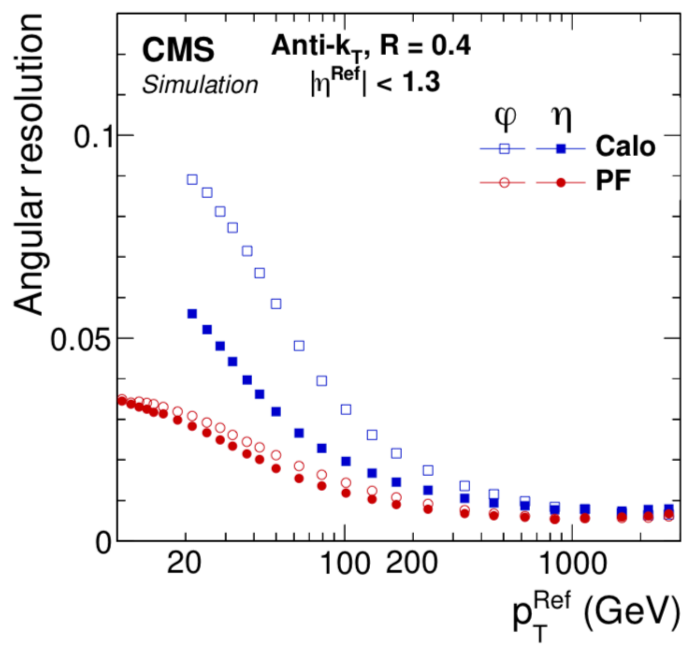


the event reconstruction

- identify and reconstruct **each individual particle in the detector**: charged hadrons, neutral hadrons, photons, muons, electrons
- identify and **remove charged particles from pile-up** from vertex information
- **jets** clustered with anti-kT algorithm of radius 0.4
- **MET** is the negative sum of transverse momenta of all particles
- very close to the Monte Carlo event simulation



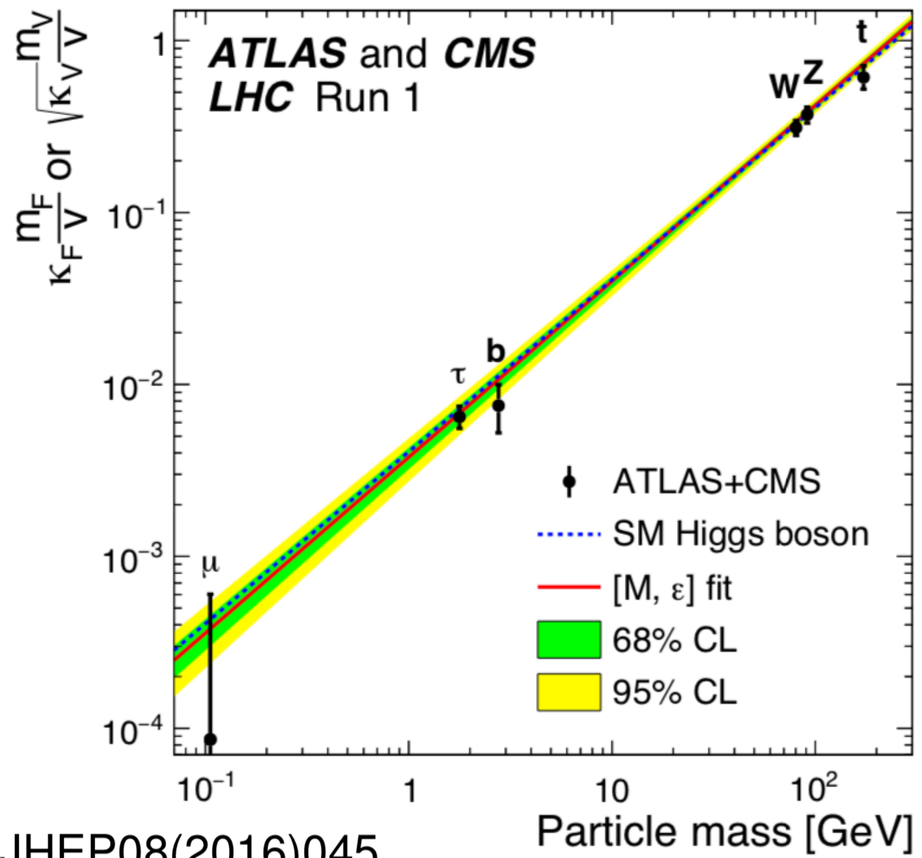




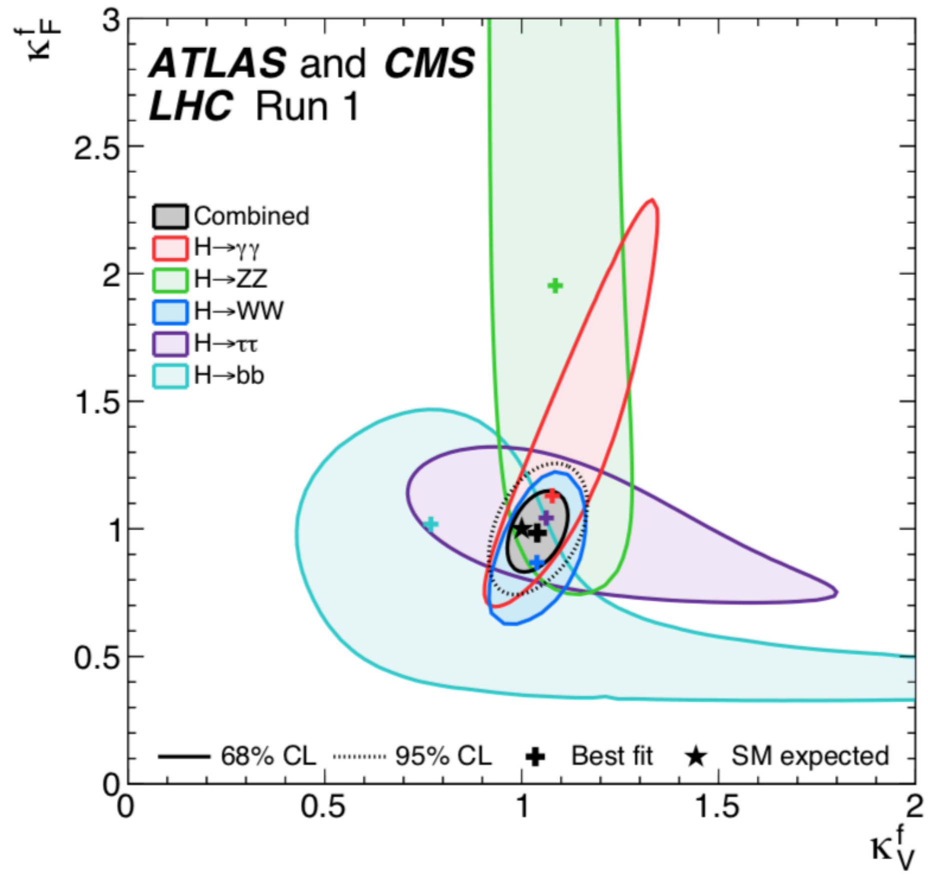
the Higgs boson discovery

- discovered with LHC Run1, and did not disappear in Run2
- **SM-like behaviour** within (not small) uncertainties

$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV}$$



JHEP08(2016)045



the uncertainty on the XS

- there is still **plenty of room for** physics beyond the standard model (**BSM**)

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig}),$$

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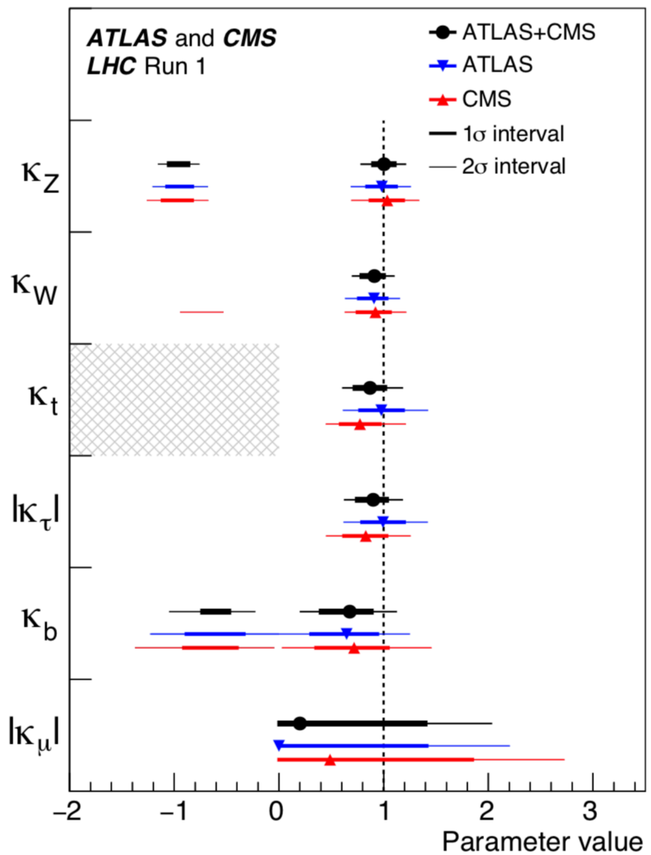
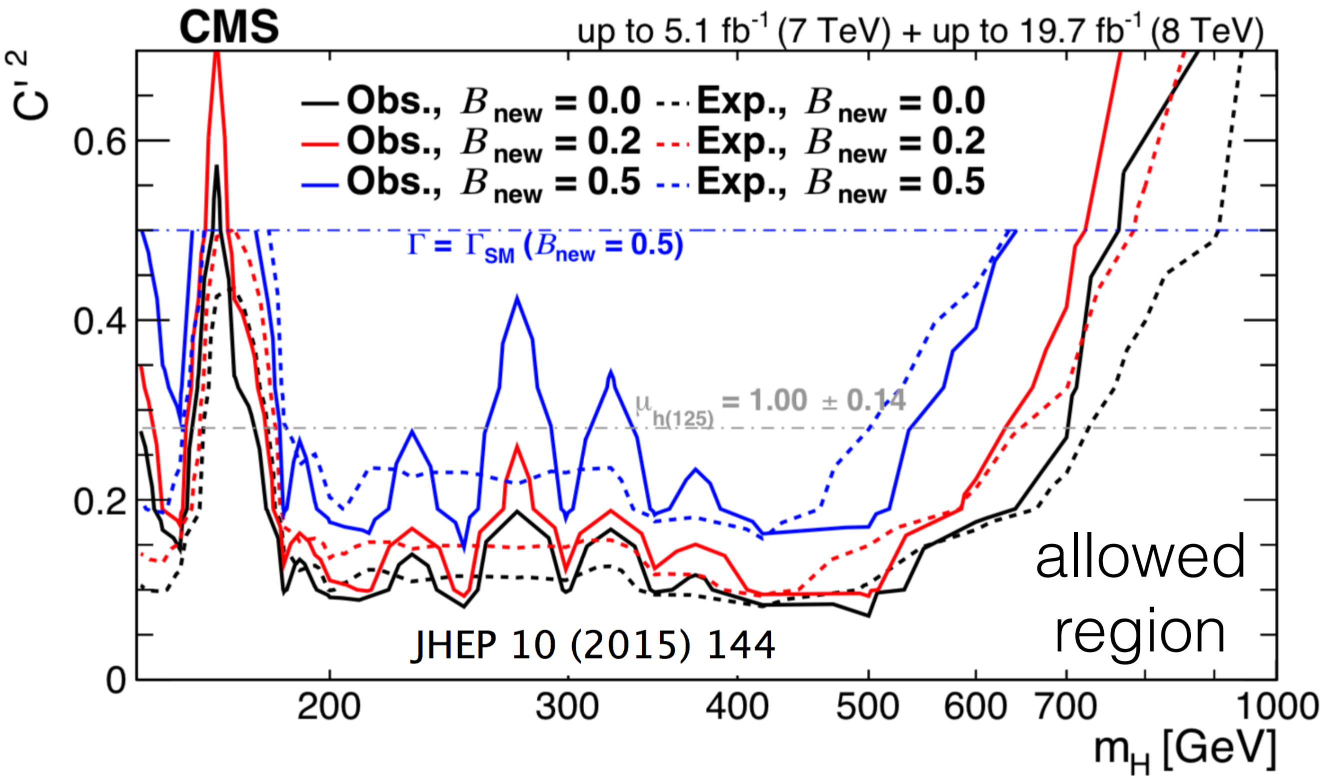




electro-weak singlet extension of the SM

impact of several BSM models

- generic size of coupling modifications when the scale of new physics is consistently taken to be M ~ 1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

arXiv:1310.8631

latest news from Moriond EWK

H→WW*: results **New!**

Ioannis Nomidis
on behalf of the ATLAS collaboration

- Signal strength:

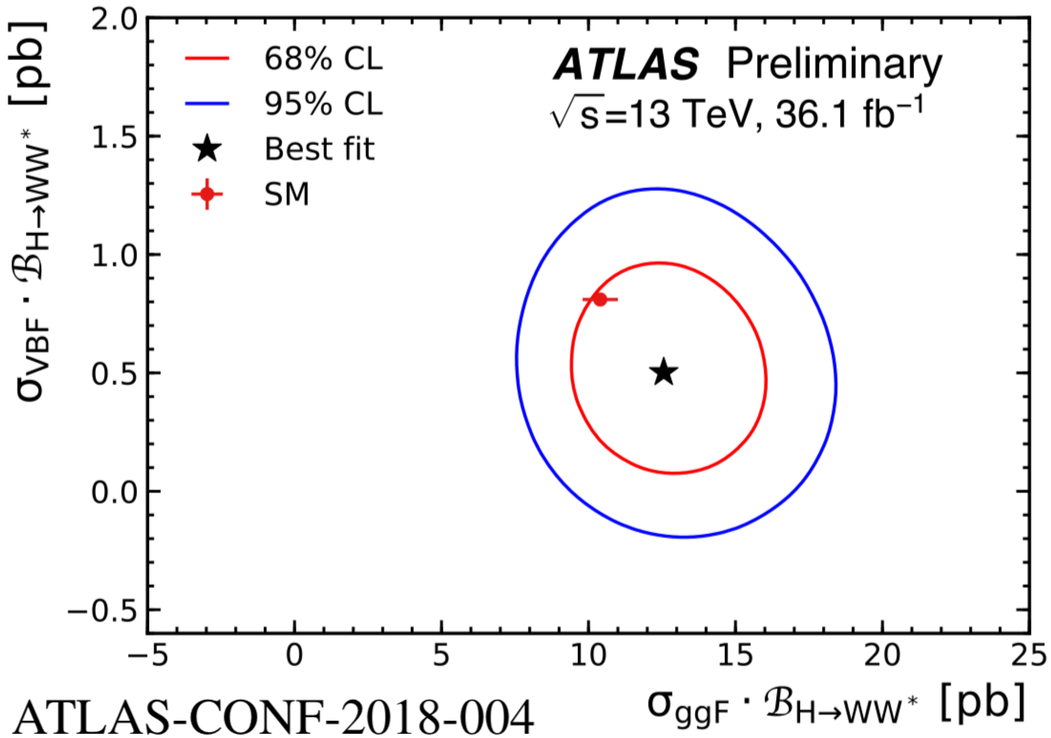
$$\mu_{ggF} = 1.21^{+0.12}_{-0.11}(\text{stat.})^{+0.18}_{-0.17}(\text{sys.}) = 1.21^{+0.22}_{-0.21}$$

$$\mu_{VBF} = 0.62^{+0.30}_{-0.28}(\text{stat.}) \pm 0.22(\text{sys.}) = 0.62^{+0.37}_{-0.36}$$

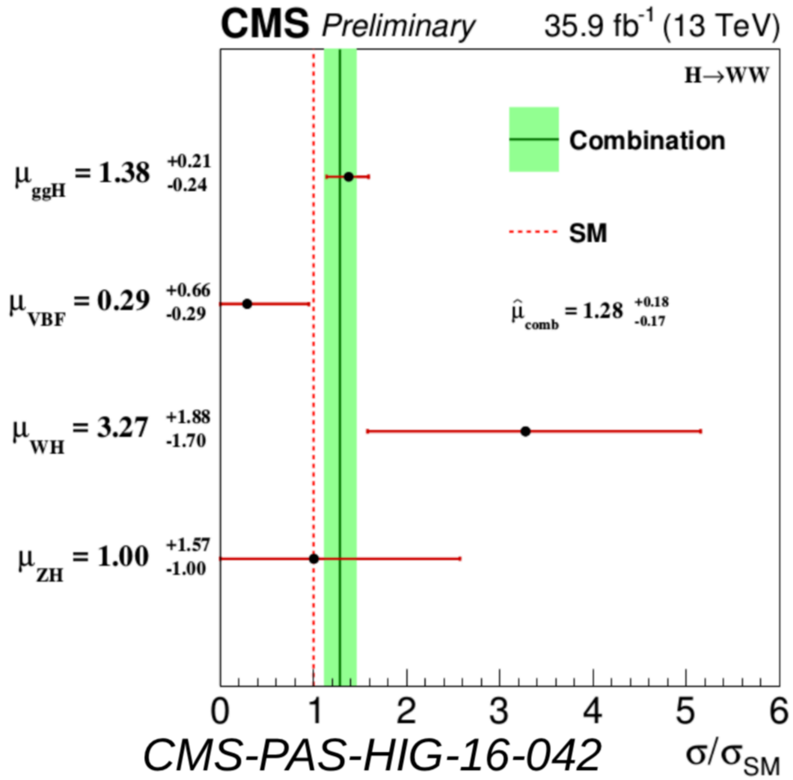
David Sperka (University of Florida)

On behalf of the ATLAS and CMS collaborations

$$\hat{\mu} = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10(\text{stat})^{+0.11}_{-0.11}(\text{syst})^{+0.10}_{-0.07}(\text{theo.})$$



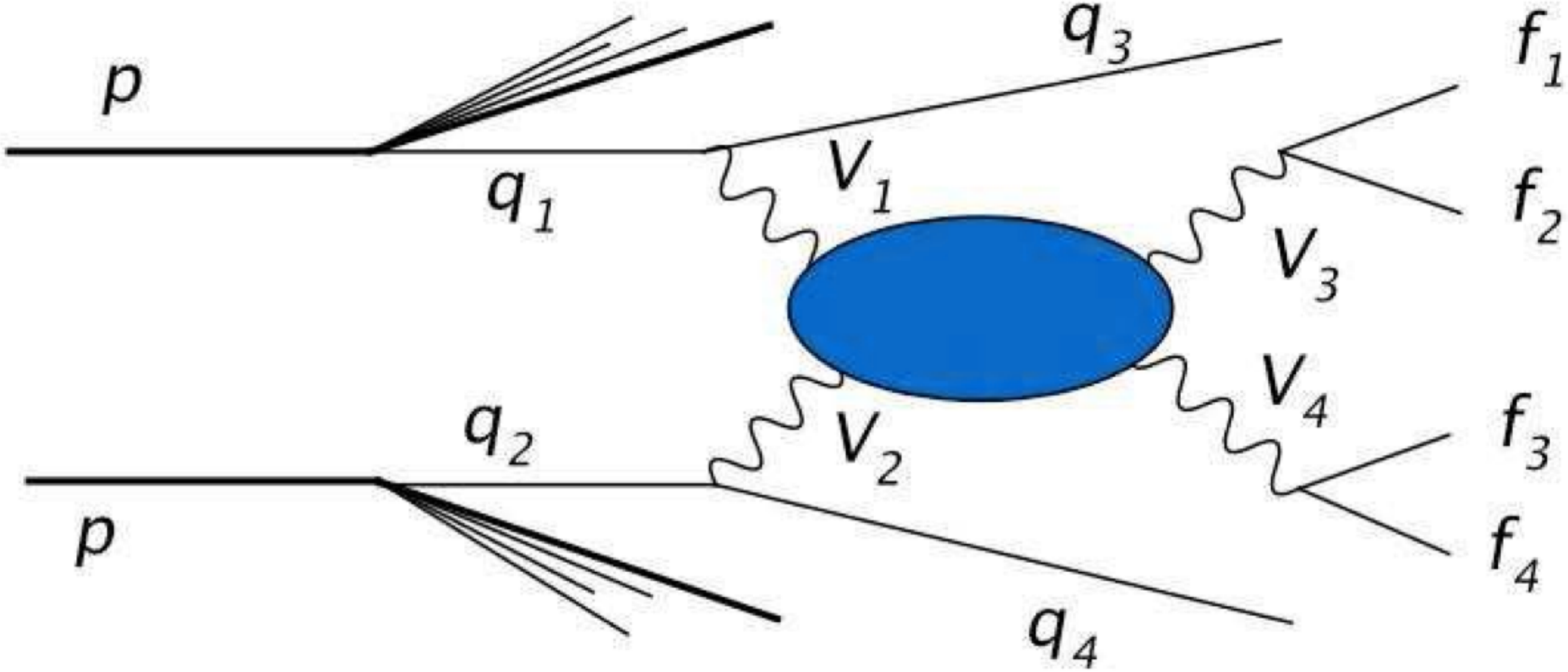
ATLAS-CONF-2018-004



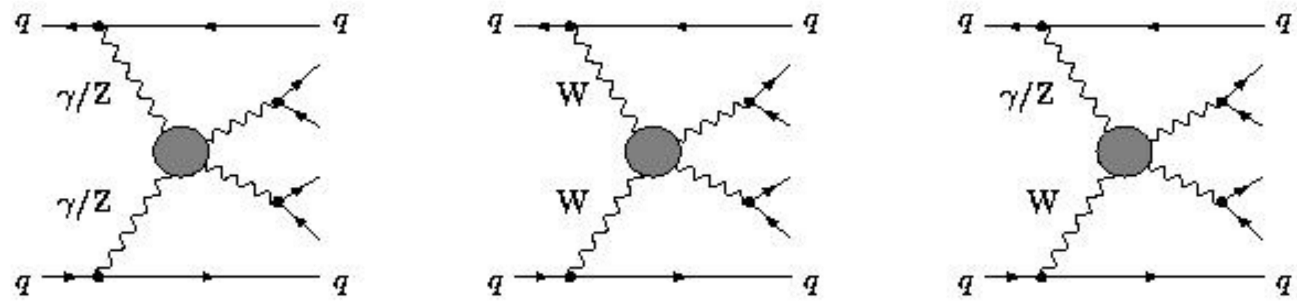
CMS-PAS-HIG-16-042

the vector boson scattering

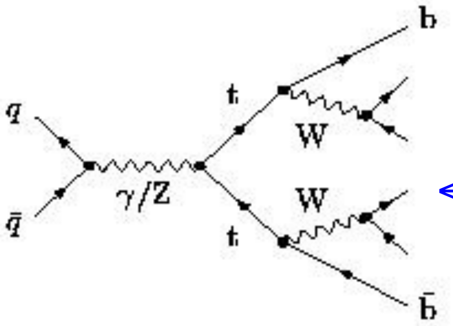
- **six fermions** final state
- input partons radiate the interacting vector bosons, that scatter
- the **outgoing jets** enter the detector volume
- **EWK process**: at leading order it's proportional to $\boldsymbol{\alpha}^6$



the actual VBS contributions

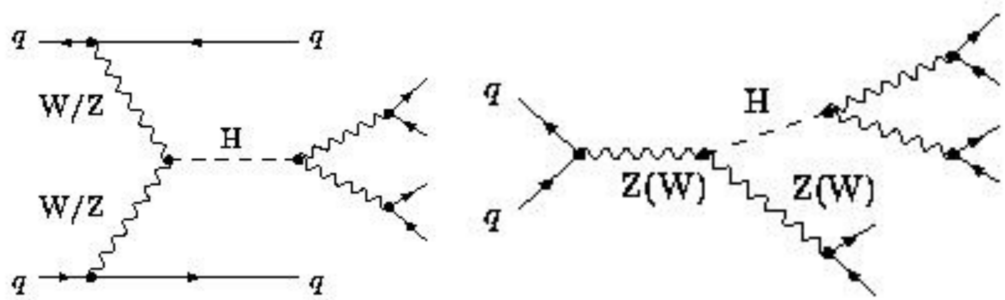


← VV-fusion

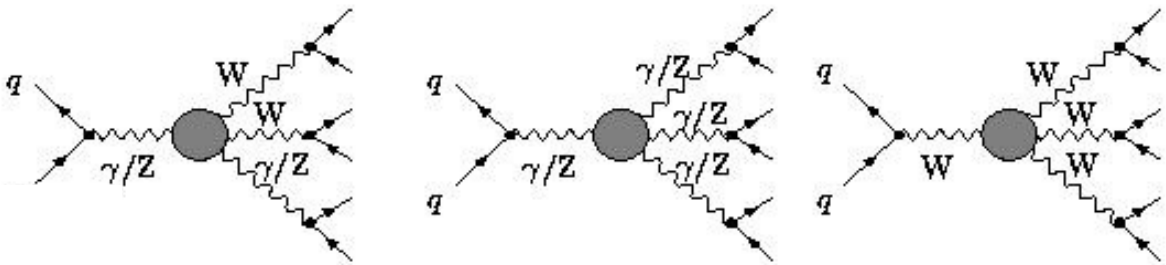


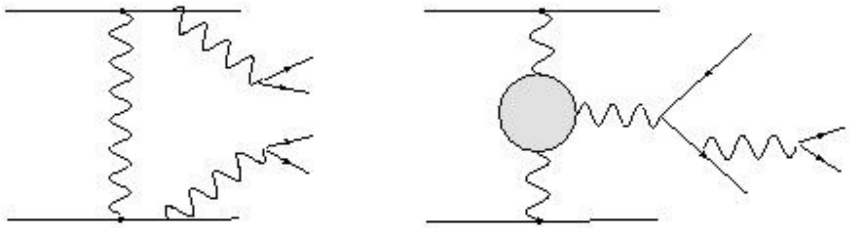
← top-top (EW)

Higgs →



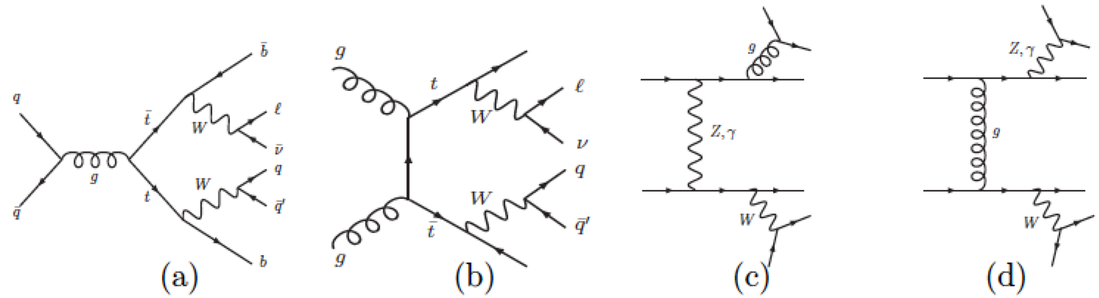
TGC & QGC →



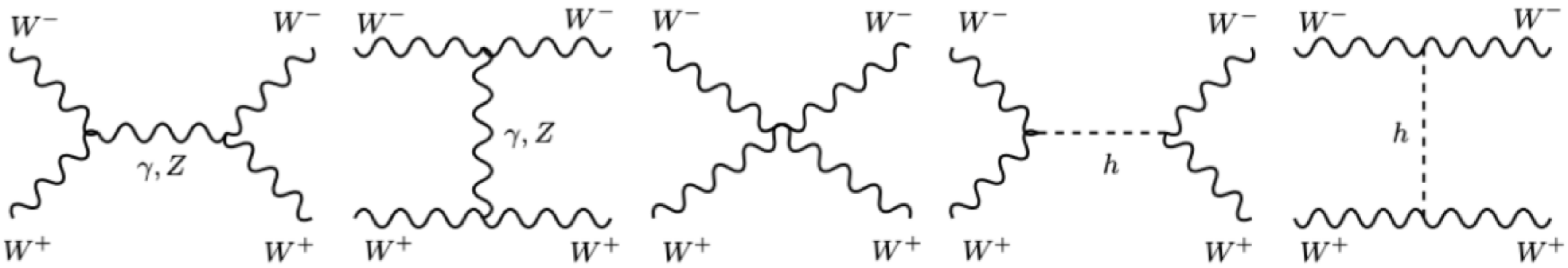


← VV and non resonant

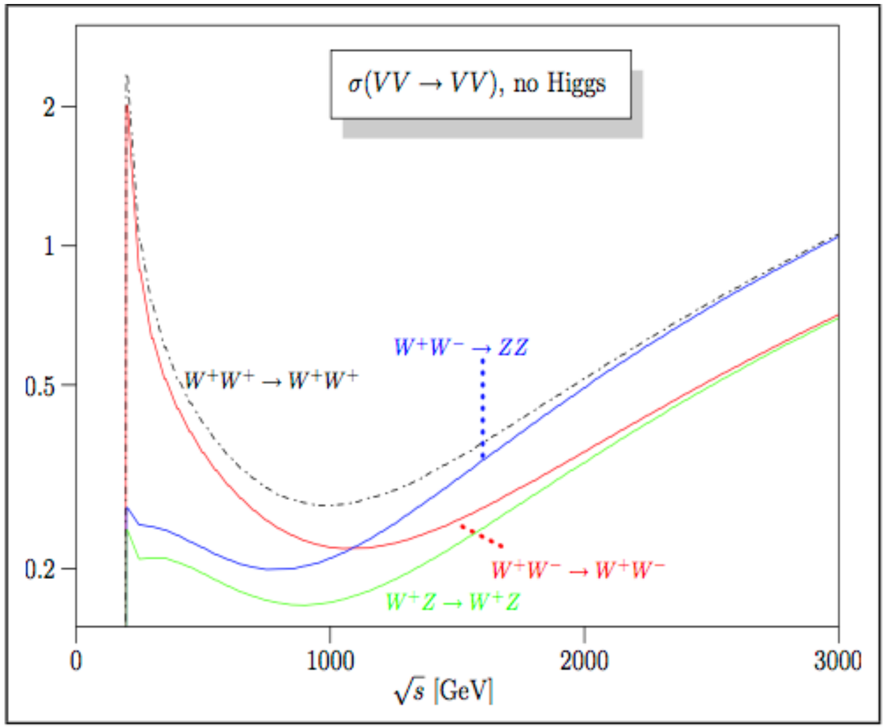
And $\alpha^2_s\alpha^4_{EW}$ →

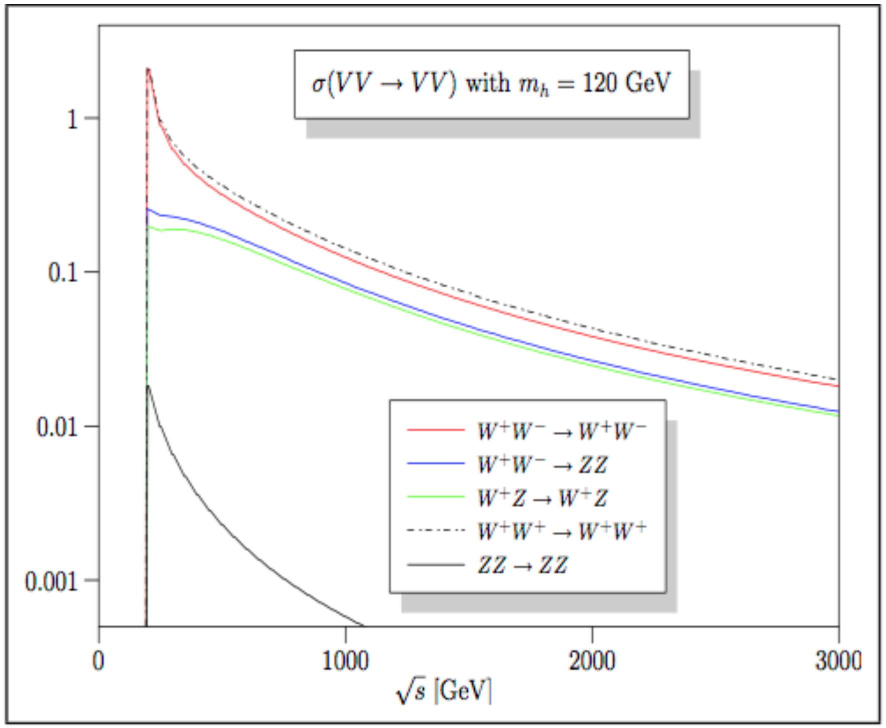


the VBS unitarity in the SM



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





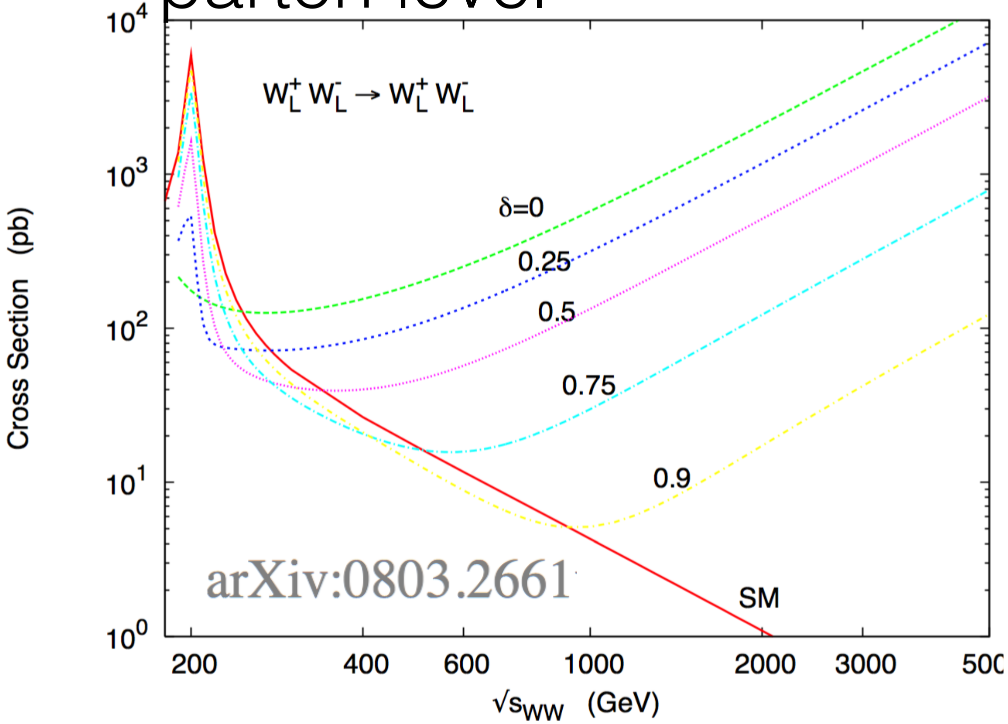
in case of anomalies

- if the delicate equilibrium is perturbed:

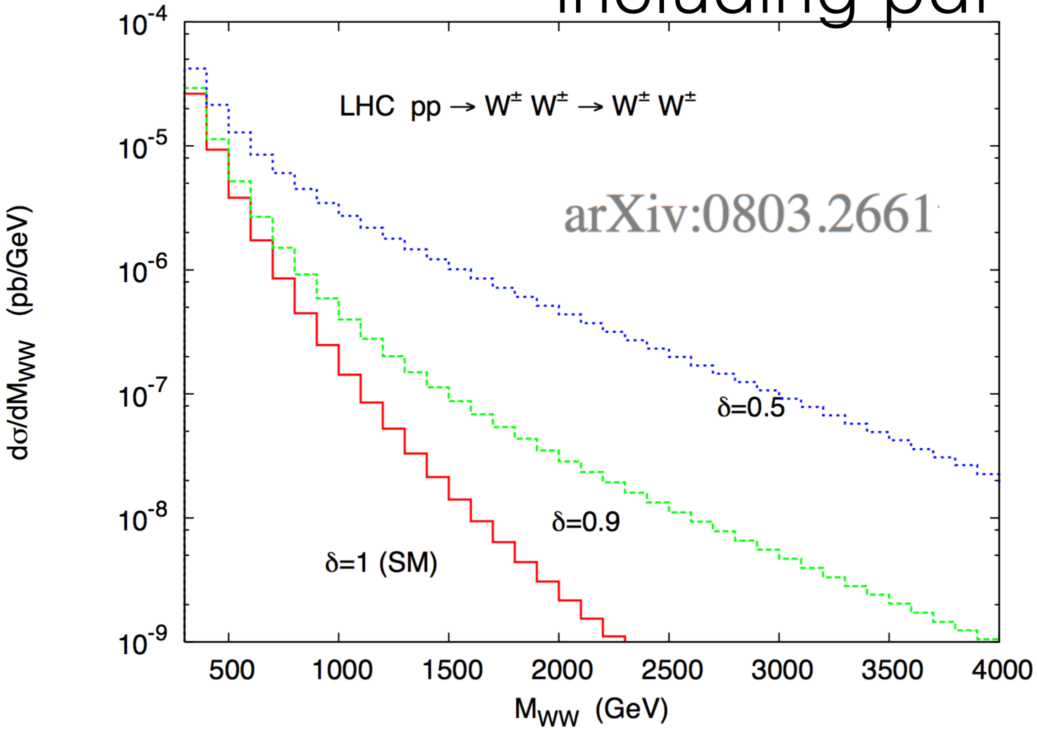
$$\mathcal{M}_{gauge} \simeq i\frac{g^2}{4M_W^2}[s+t]\,,\quad \mathcal{M}_{Higgs} \simeq -i\frac{g^2}{4M_W^2}[s+t]\,(\delta)$$

- any deviations signal **new physics in a model-independent way** and hints on the scale of NP

parton level



including pdf



effective field theory

- add to the SM Lagrangian additional BSM terms
- generic **low-energy parameterisation of an unknown model** that would become apparent at (too) high energies

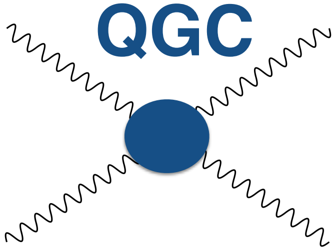
Dim 6 | **Dim 8**

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\dots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\dots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$

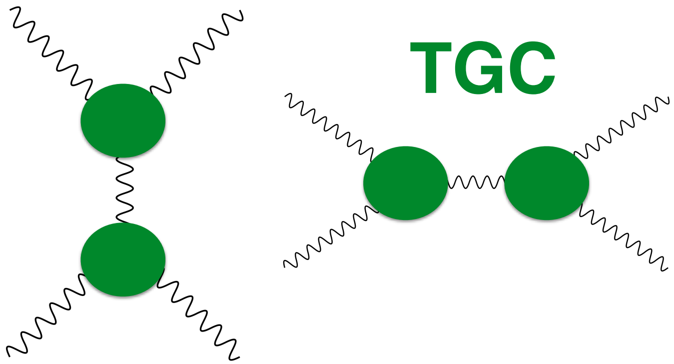
Pure Higgs field | **Pure Field-strength tensor** | **Mixed Higgs-field-strength**

- simplistic realisation: choose a basis and associate operators to vertices in form of anomalous couplings:

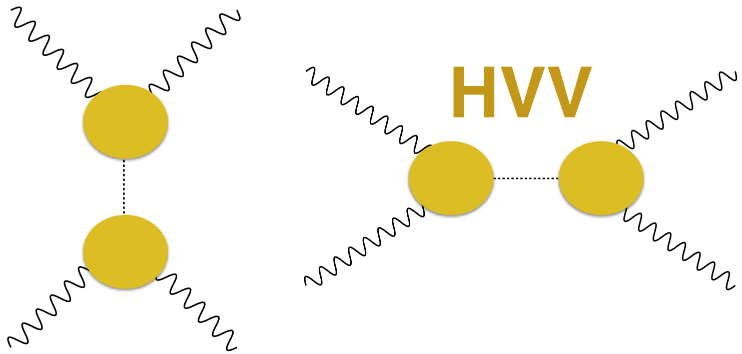
QGC



TGC



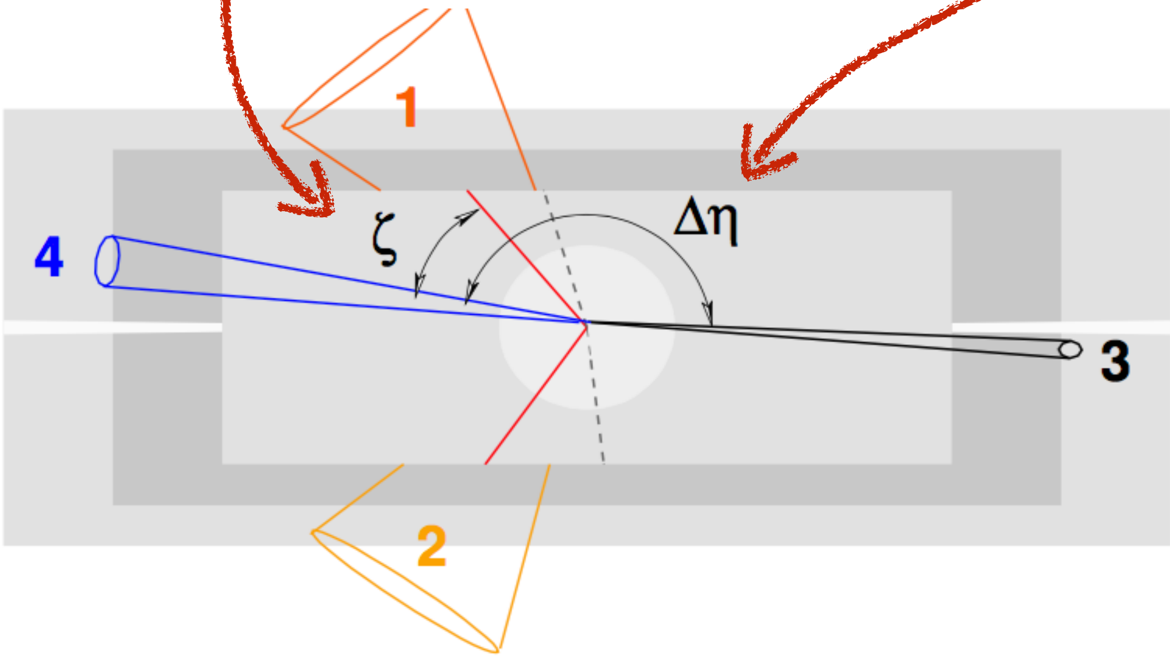
HVV

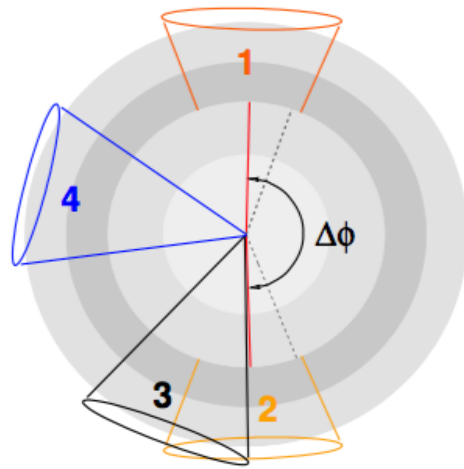


the VBS signature

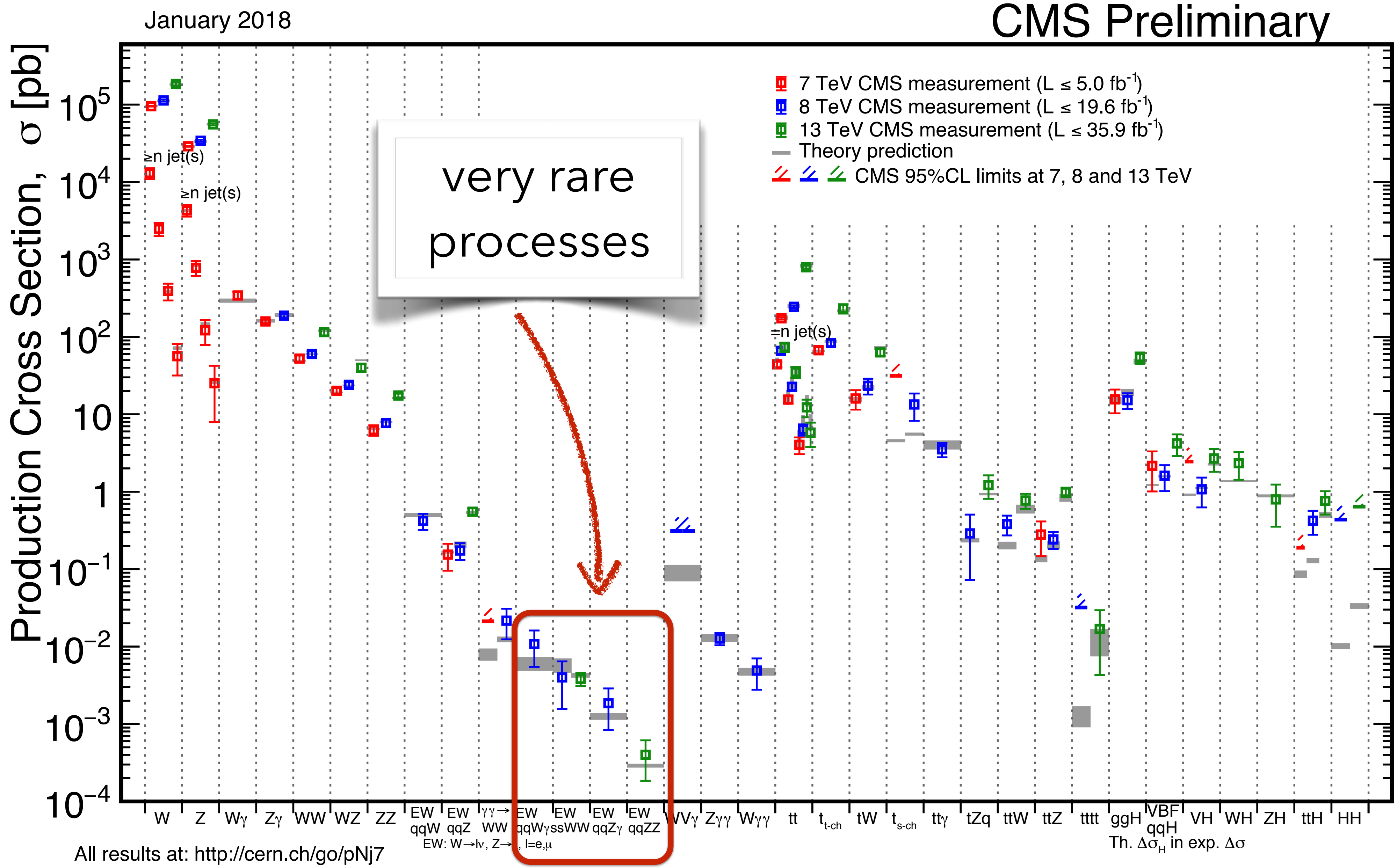
- Two highly energetic jets (**tag jets**)
  - Large invariant mass of di-jet system
  - Large pseudo rapidity gap between jets
- No hadronic activity in the **rapidity gap** of the two tagging jets
- Decay products of the vector bosons lying between the tagging jets
- **high-pT isolated leptons** (or MET) in the event from the V decays

colorless V exchange





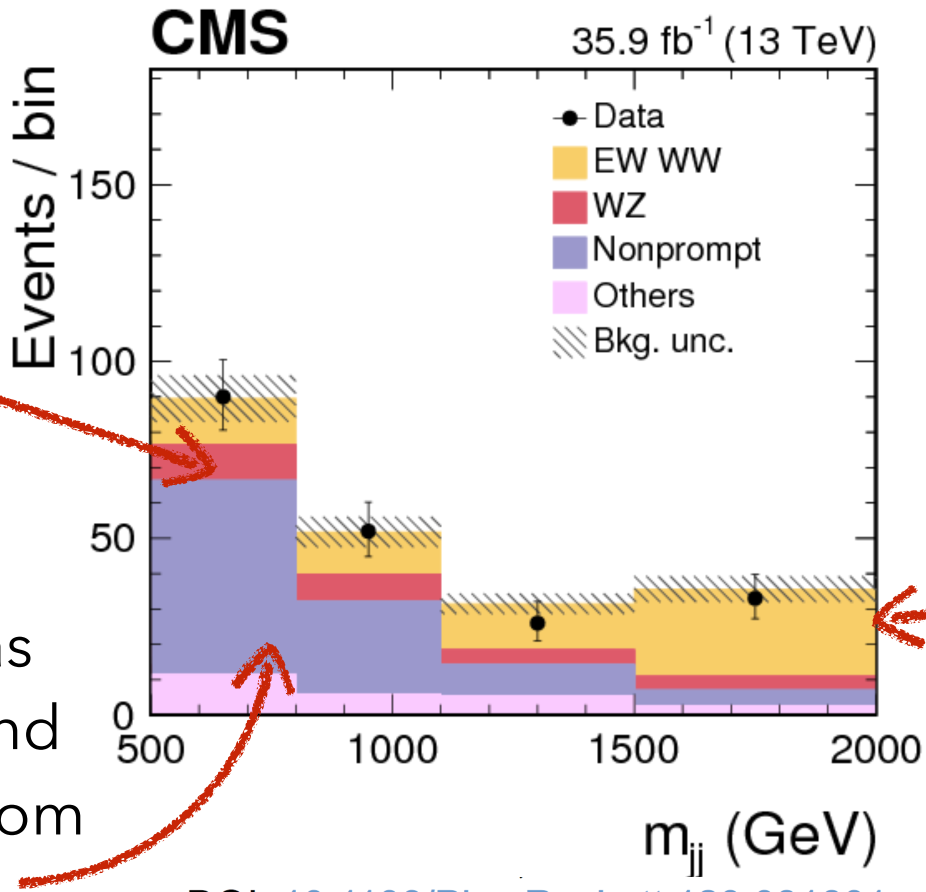
the statistics challenge

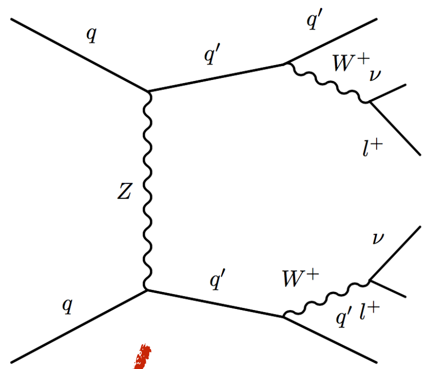


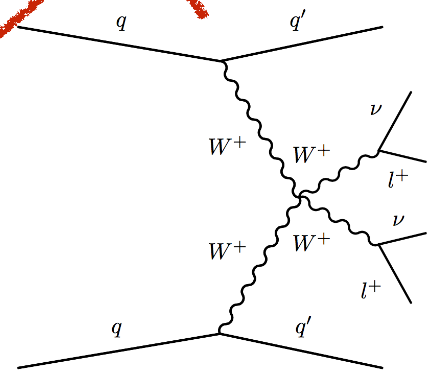
same-sign W±W± scattering

- Low cross-section and very low backgrounds
- **First observation** at 5.5σ (5.7 exp.) by the CMS experiment
- **Fiducial XS**: $\sigma_{fid}(W^{\pm}W^{\pm}jj)$ = 3.83±0.66(stat) ±0.35(syst) fb
  in agreement with the SM expectation 4.25±0.21 fb (MG5 LO)

WZ +2 jets with a missed charged lepton





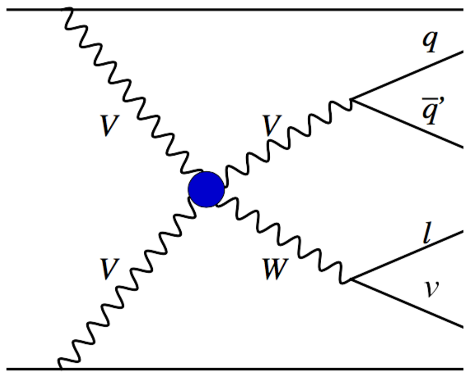


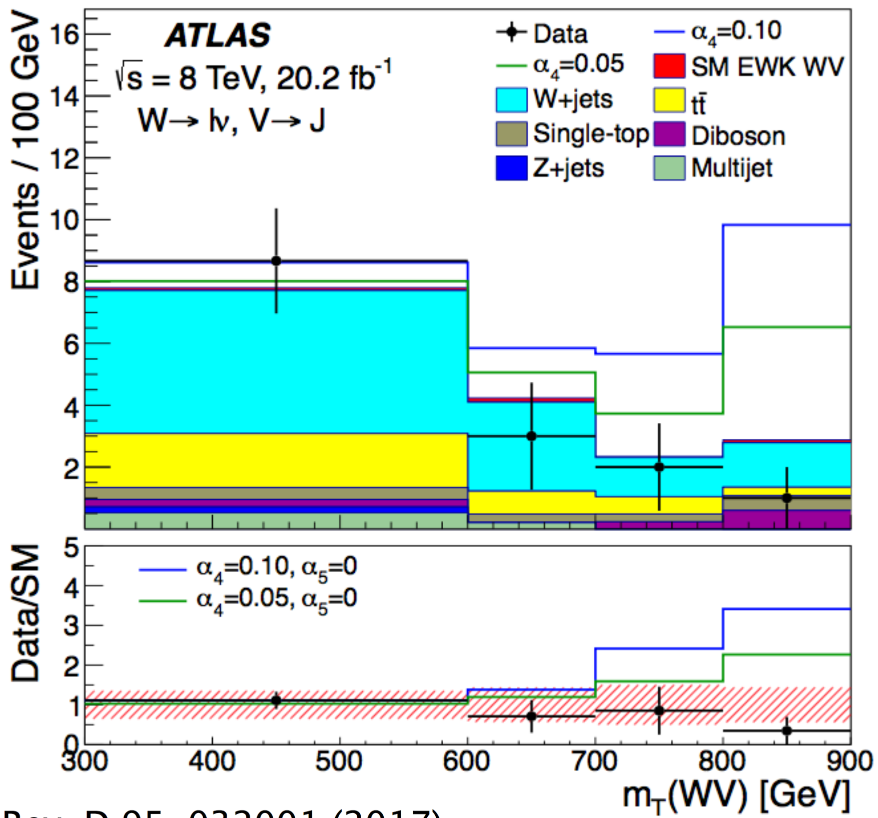
jets misidentified as charged leptons and charged leptons from hadron decays

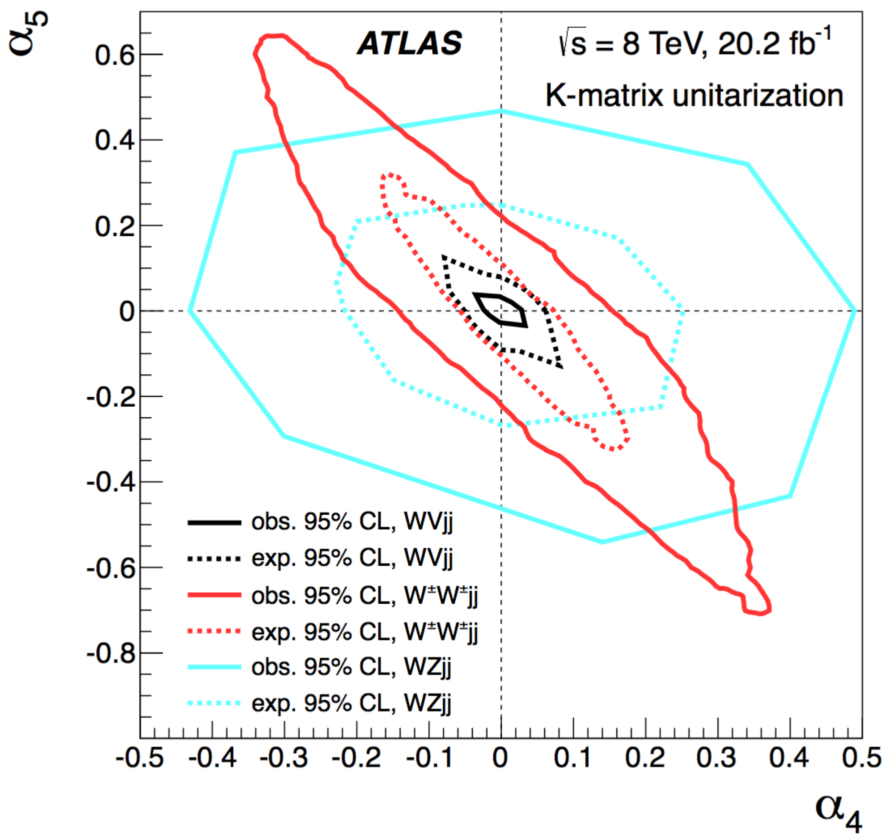
DOI: 10.1103/PhysRevLett.120.081801

semi-leptonic WW scattering

- larger expected statistics, much more background
- large **sensitivity to BSM deviations**
- jet assignment ambiguity to be solved as well
- access to **(almost) the full kinematics** of the event







Phys. Rev. D 95, 032001 (2017)

ZZ scattering

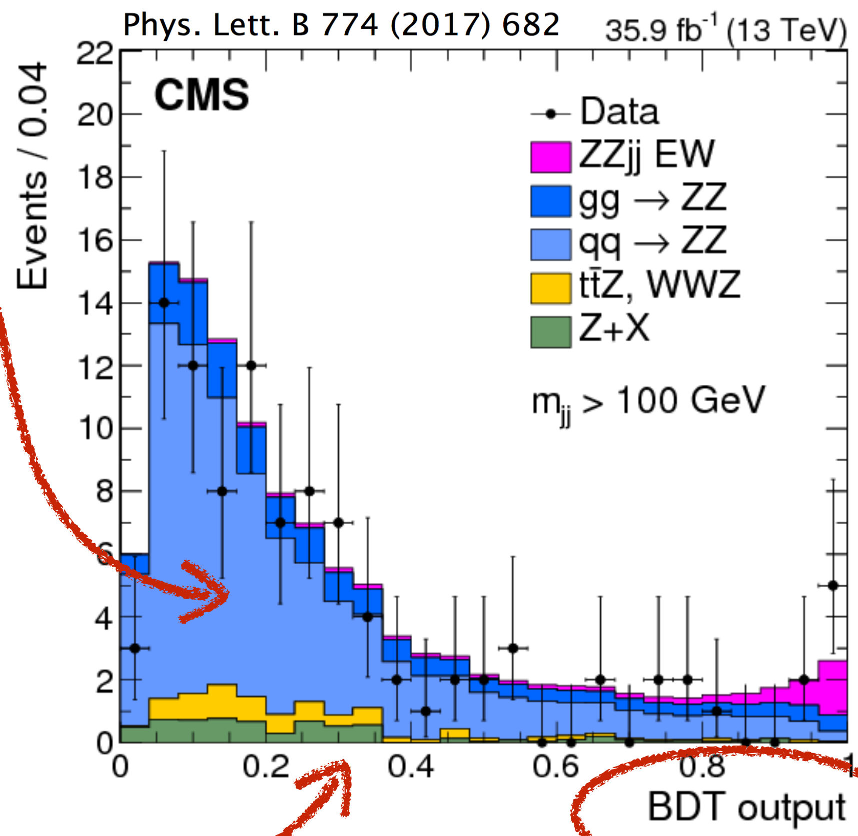
- **four charged leptons** final state
- very clean, **very low statistics**

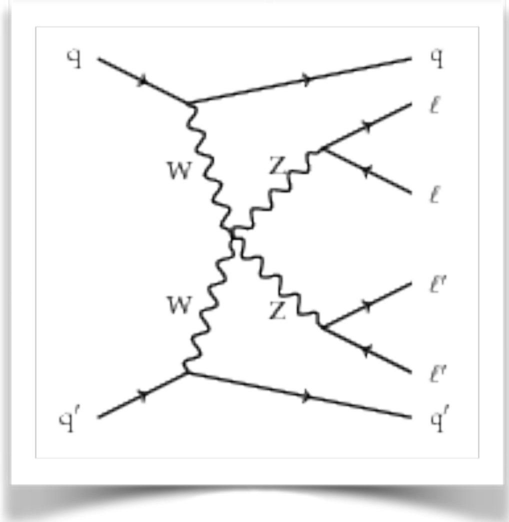
$$\sigma_{\text{fid}} = 0.40^{+0.21}_{-0.16}(\text{stat})^{+0.13}_{-0.09}(\text{syst})\ \text{fb}$$

0.29±0.03 fb expected

Background-only hypothesis excluded with 1.6 σ expect., **2.7 σ observed**

QCD irreducible bkg: from simulation, validated in control regions





reducible bkg measured in data

multivariate classifier fit to extract the signal

existing measurements

- several channels already studied at the LHC, in both CMS and ATLAS
- very few reach interesting sensitivity already

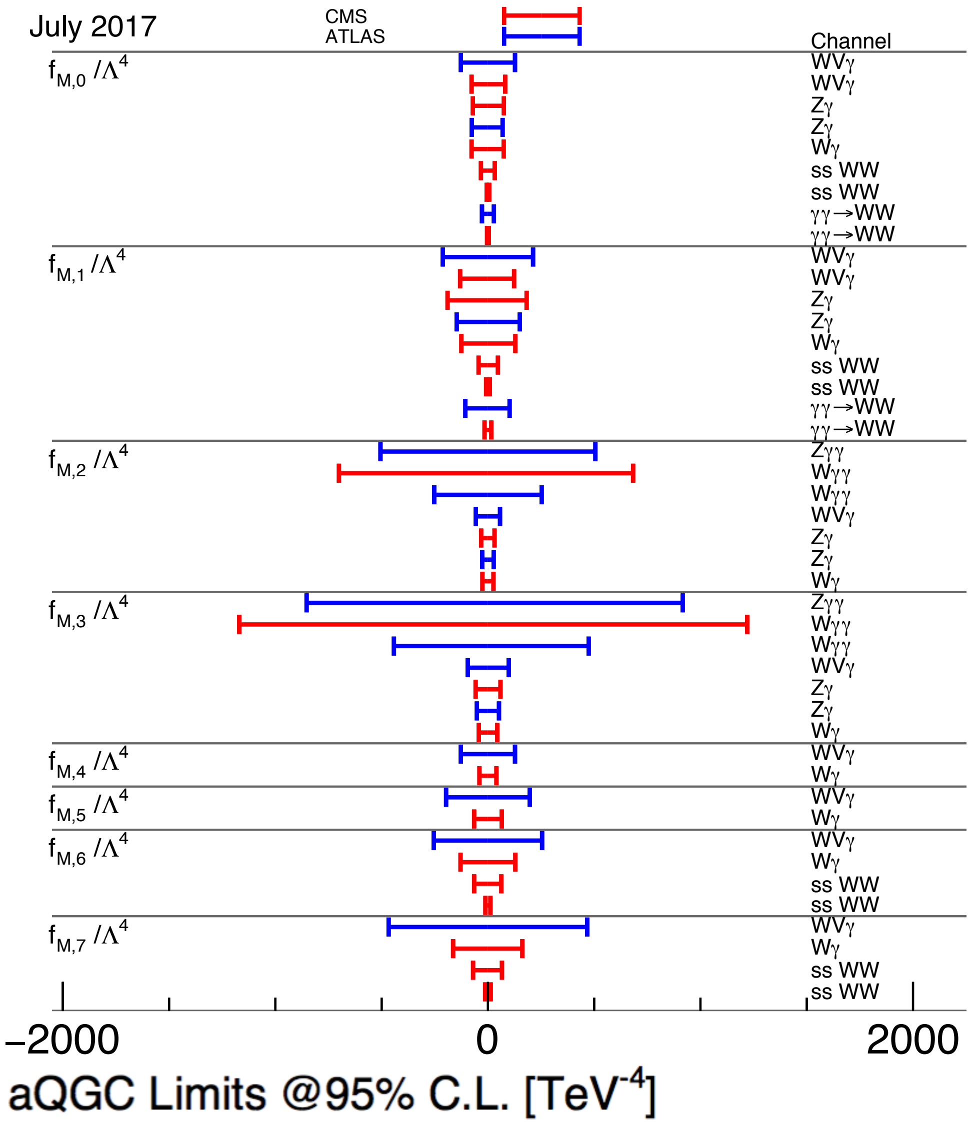
Channel	$\sqrt{s}$		Luminosity [fb^{-1}]		Observed (expected) significance	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$Z(\ell\ell)\gamma$	8 TeV	8 TeV	20.2	19.7	2.0σ (1.8σ) [81]	3.0σ (2.1σ) [82]
$Z(\nu\nu)\gamma$	8 TeV	–	20.2	–	Only aQGC lim. [81]	–
$W^{\pm}W^{\pm}$	8 TeV	8 TeV	20.3	19.4	3.6σ (2.3σ) [5], [4]	2.0σ (3.1σ) [6]
$W^{\pm}W^{\pm}$	–	13 TeV	–	35.9	–	5.5σ (5.7σ) [7]
$W(\ell\nu)\gamma$	–	8 TeV	–	19.7	–	2.7σ (1.5σ) [83]
$Z(\ell\ell)Z(\ell\ell)$	–	13 TeV	–	35.9	–	2.7σ (1.6σ) [84]
$W(\ell\nu)Z(\ell\ell)$	8 TeV	8 TeV	20.2	19.4	Only aQGC lim. [85]	N/A [6]
$W(\ell\nu)V(qq)$	8 TeV	–	20.2	–	Only aQGC lim. [86]	–
$\gamma\gamma \to WW$	–	7 TeV	–	5.05	–	$\sim 1\sigma$ [87]
$\gamma\gamma \to WW$	8 TeV	7+8 TeV	20.2	24.8	3.0σ [88]	3.4σ (2.8σ) [89]

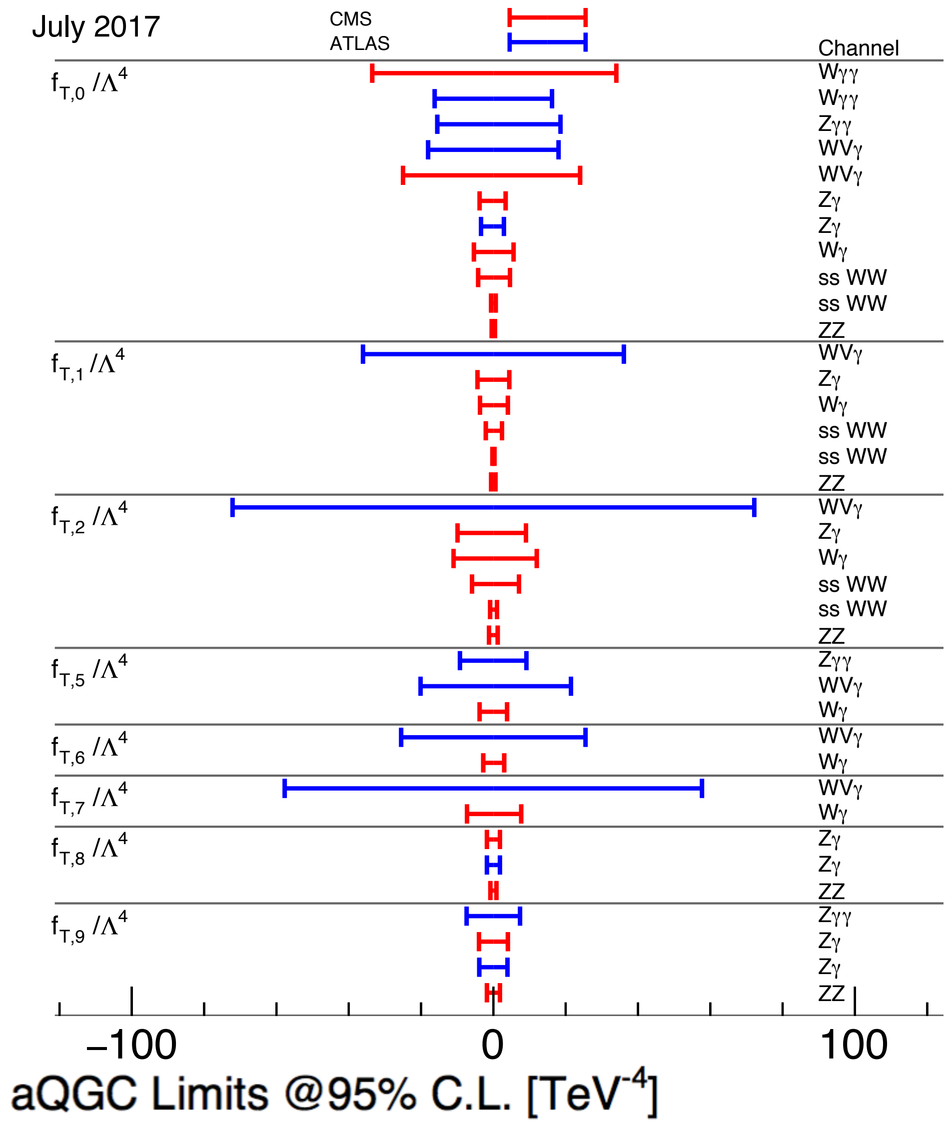
Table 6: Summary of all published experimental results on VBS processes by final state with the details on luminosity and energy at the center of mass $\sqrt{s}$ used for the measurements. When available both expected and observed significances are provided. Channels for which "Only aQGC limits" were studied are indicated in the significance column.

arXiv:1801.04203

anomalous couplings

- VBS studies start to impact in anomalous coupling measurements

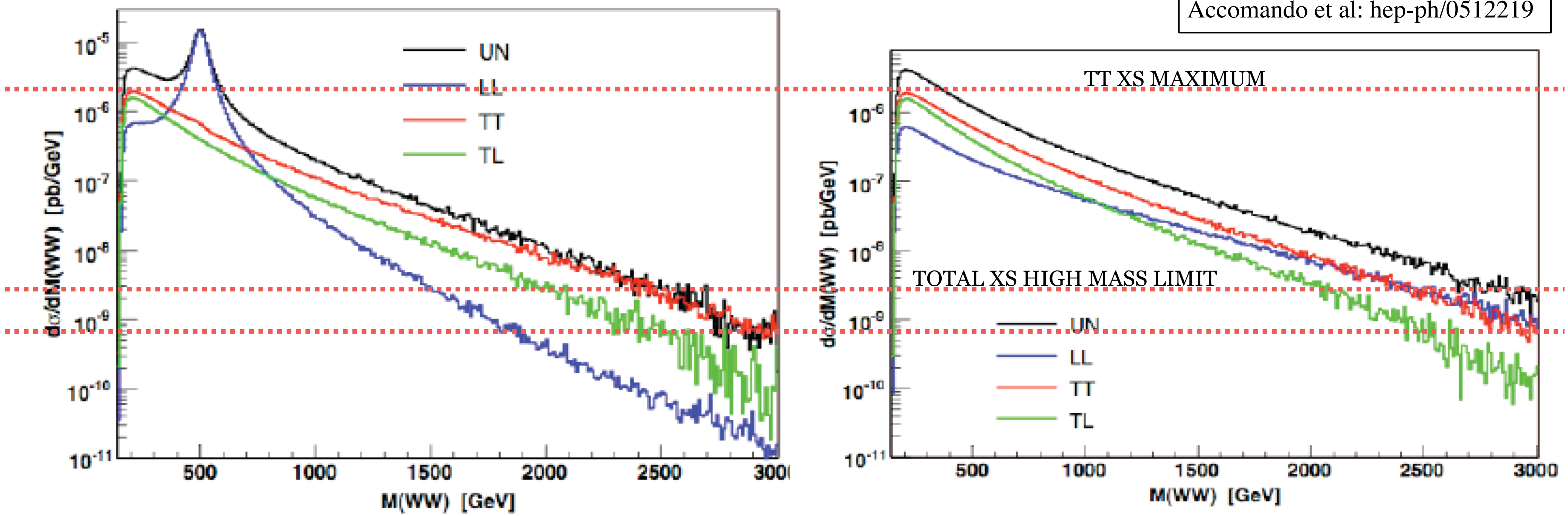




the longitudinal component

- $V_L V_L$ is where the EWSB plays its role
- At large M(VV) the $V_L V_L$ cross-section is of the same order as the $V_T V_T$ one (in the no-Higgs case)
- If there is a new resonance at a scale Λ, **the $V_L V_L$ cross-section will be anomalous until Λ**

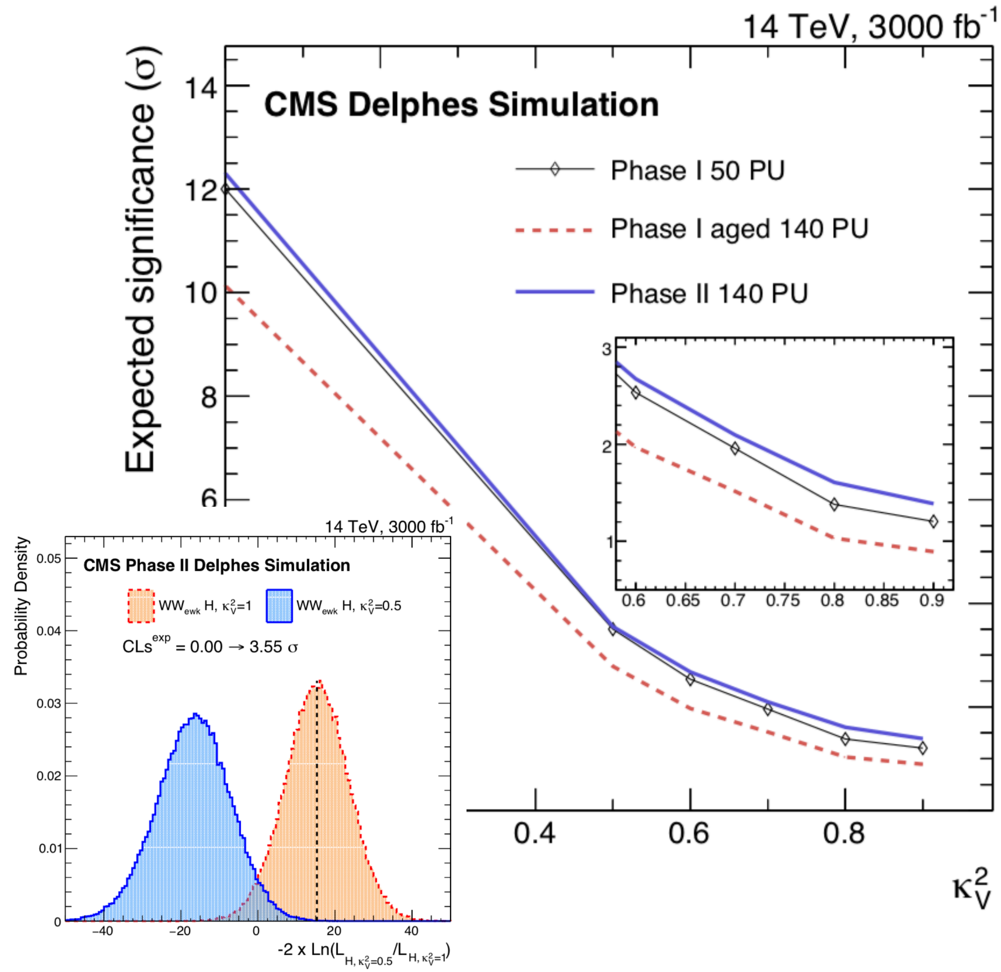
Accomando et al: hep-ph/0512219



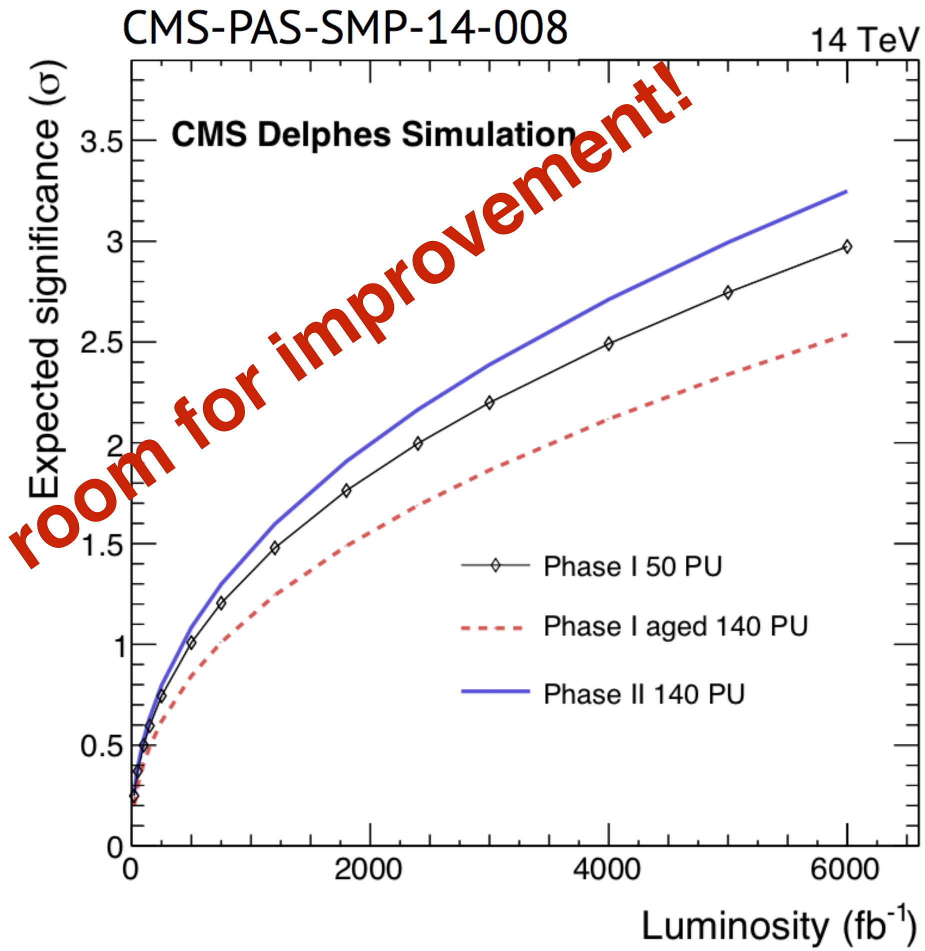
Higgs   no Higgs

projections for HL-LHC

- simplified detector performance, including the pile-up
- reducible backgrounds considered as well



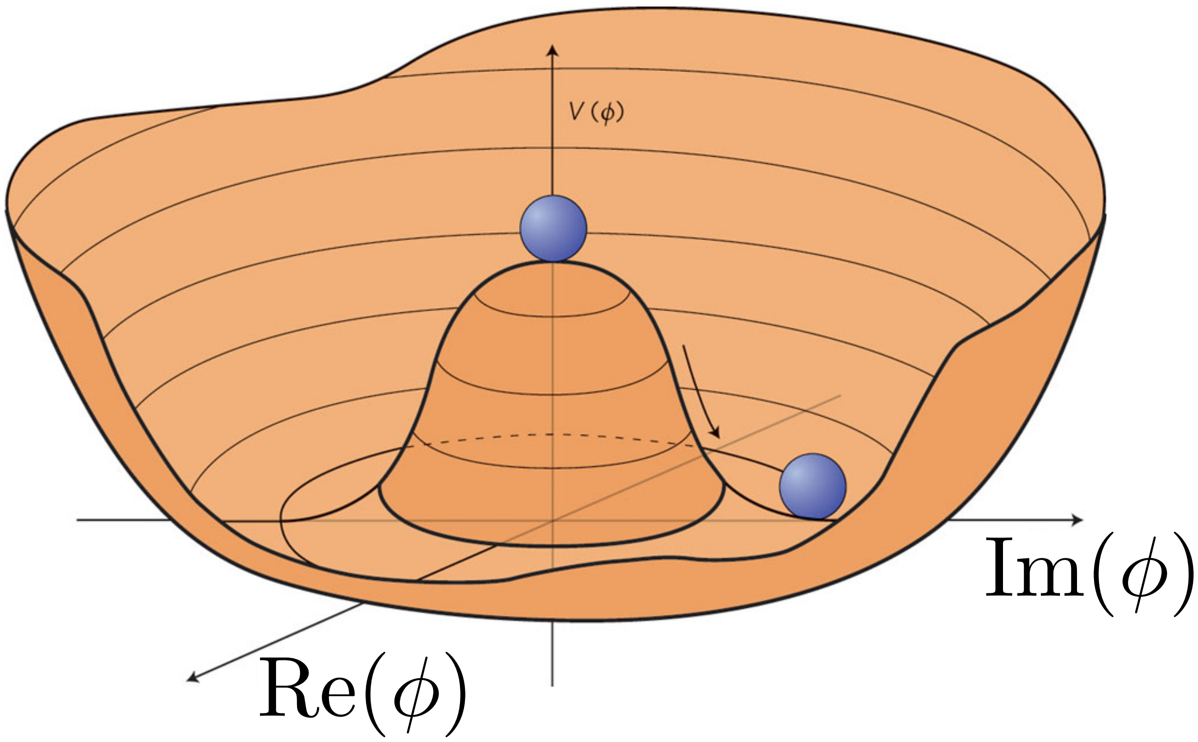
partial unitarisation



$V_L V_L$ component

the di-Higgs measurement

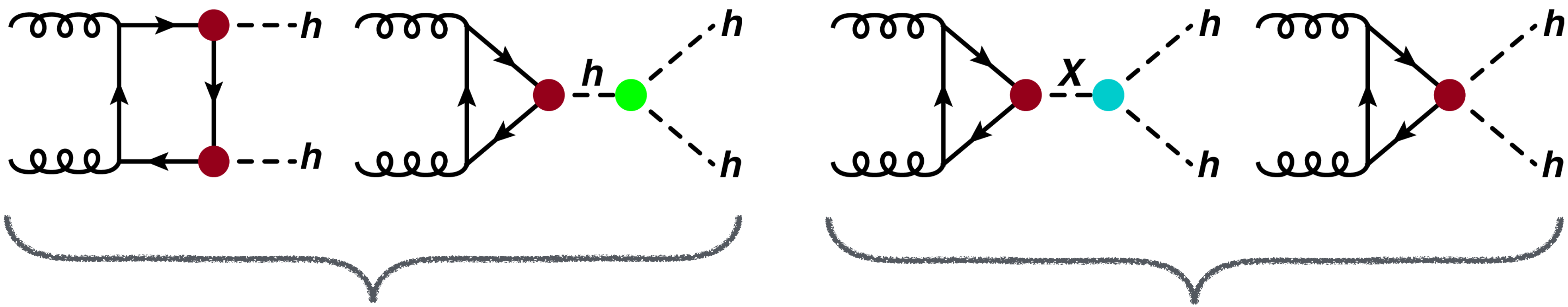
- other crucial aspect of the SM: the **potential** of the field
- $V(\phi) \sim -\mu^2(\phi\phi^\dagger) + \lambda(\phi\phi^\dagger)^2$
- The non-resonant HH production is the principal way to extract the **Higgs boson trilinear coupling (λ_{HHH})** to probe EWSB and measure shape of the Higgs potential



the Higgs trilinear coupling

- Precision measurements of Higgs boson physics give us insights into the **nature of electroweak symmetry breaking**.
- **new Physics might affect the trilinear Higgs coupling**:
  - new resonances, new particles in loops, modified couplings
- trilinear coupling could be **measured at LHC from Higgs pair production**

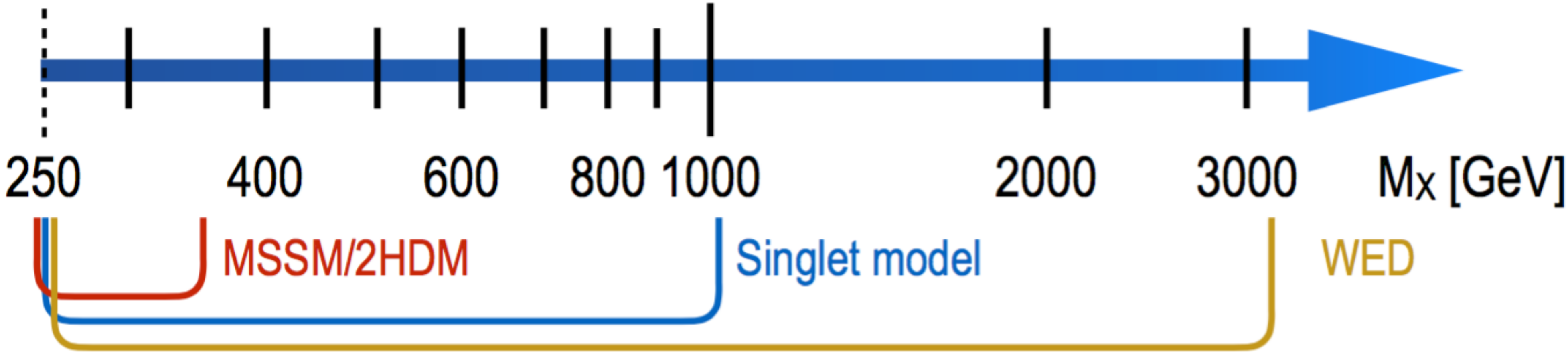
$\sigma^{SM}_{hh}(13\text{TeV}) = 33.49\ ^{+4.3}_{-6.0}\ (\text{scale}) \pm 2.1(\text{PDF}) \pm 2.3\ (\alpha_S)$ fb
HXSWG YR4 arXiV:1610.07922



SM production: very low cross-section because of large interference

BSM production: new couplings (hhtt, ggh, gghh) or resonances

models for new resonances



- **MSSM/2HDM**: additional Higgs doublet gives CP-even scalar H
  - probe the low m_H - low tanβ region of the MSSM plane where BR (H→hh) is sizeable
- **Singlet model**: additional Higgs singlet gives an extra scalar H
  - sizeable BR beyond 2 x m_t, non negligible width at high m_H
- **Warped Extra Dimensions**: spin-2 (KK-graviton) and spin-0 (radion) resonances
  - different phenomenology if SM particles are allowed (bulk RS) or not (RS1 model) to propagate in the extra-dimensional bulk

L. Cadamuro

BSM in non resonant production

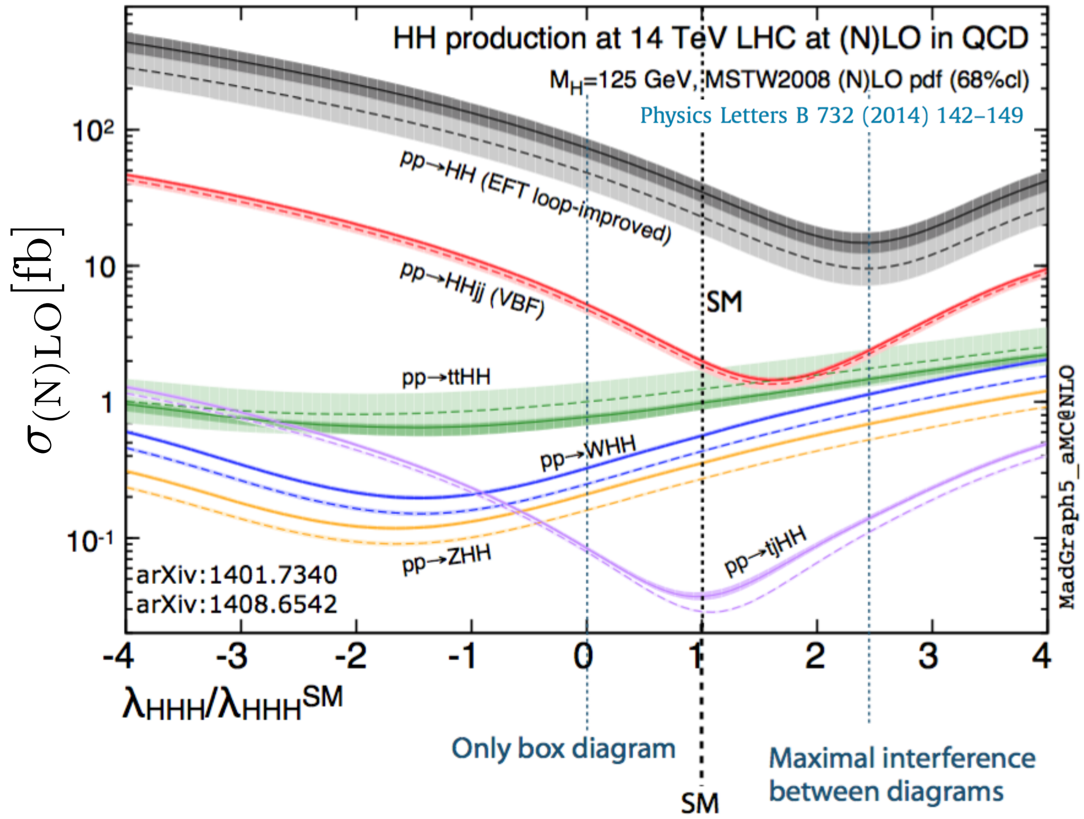
- SM cross-section at 13 TeV is at the order of **33.4 fb**
  - (gluon fusion Higgs production is ~44 pb)
- **BSM effects** modify existing vertices and add new diagrams
- **large enhancements** in the cross-section can happen

- **effective parameterisation** (EFT) of BSM effects:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i O_i}{\Lambda^2}$$

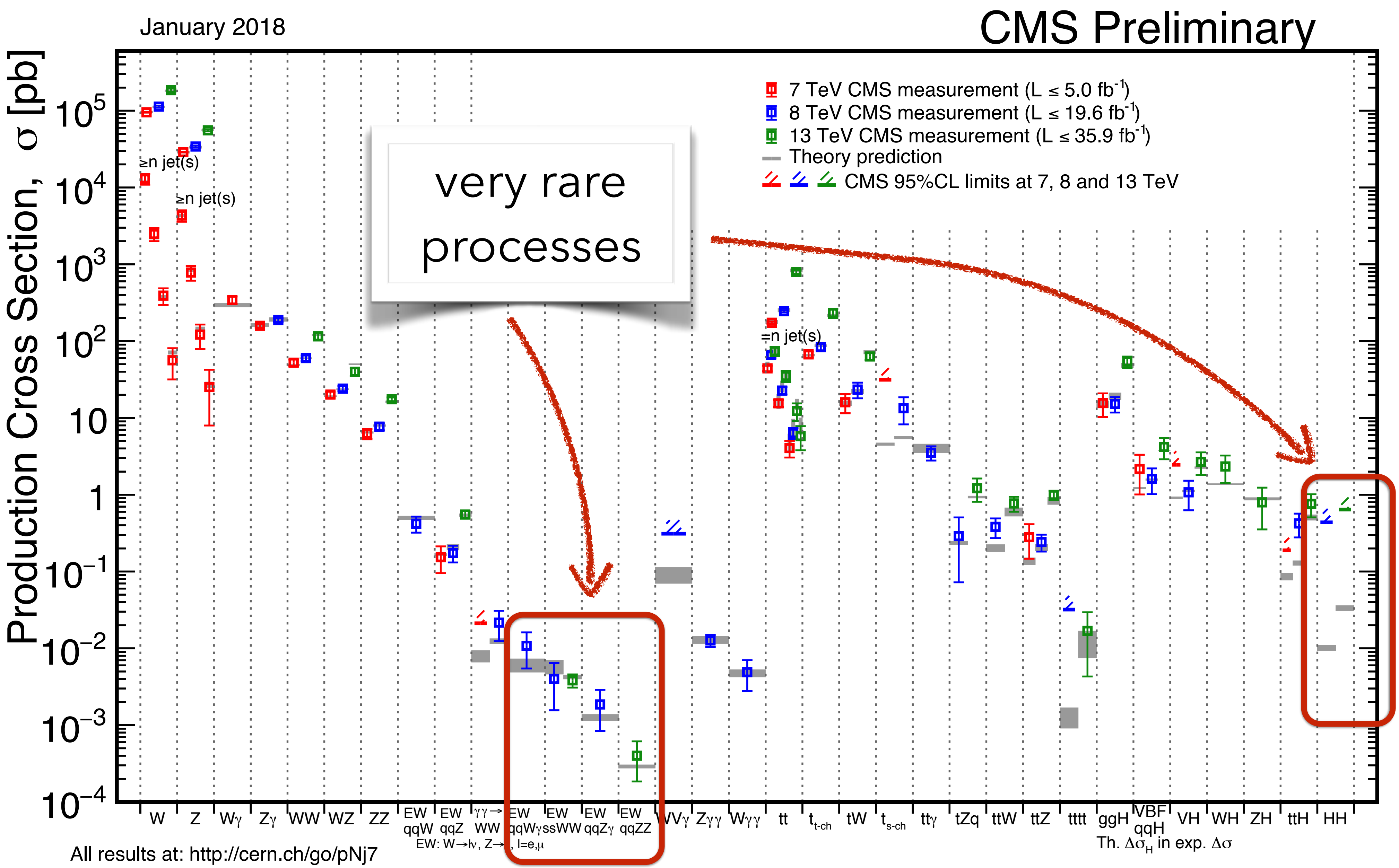
- five independent **parameters**:

$$\lambda_{hhh} \quad c_2 \quad c_{2g} \quad c_g \quad y_t$$



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGHH

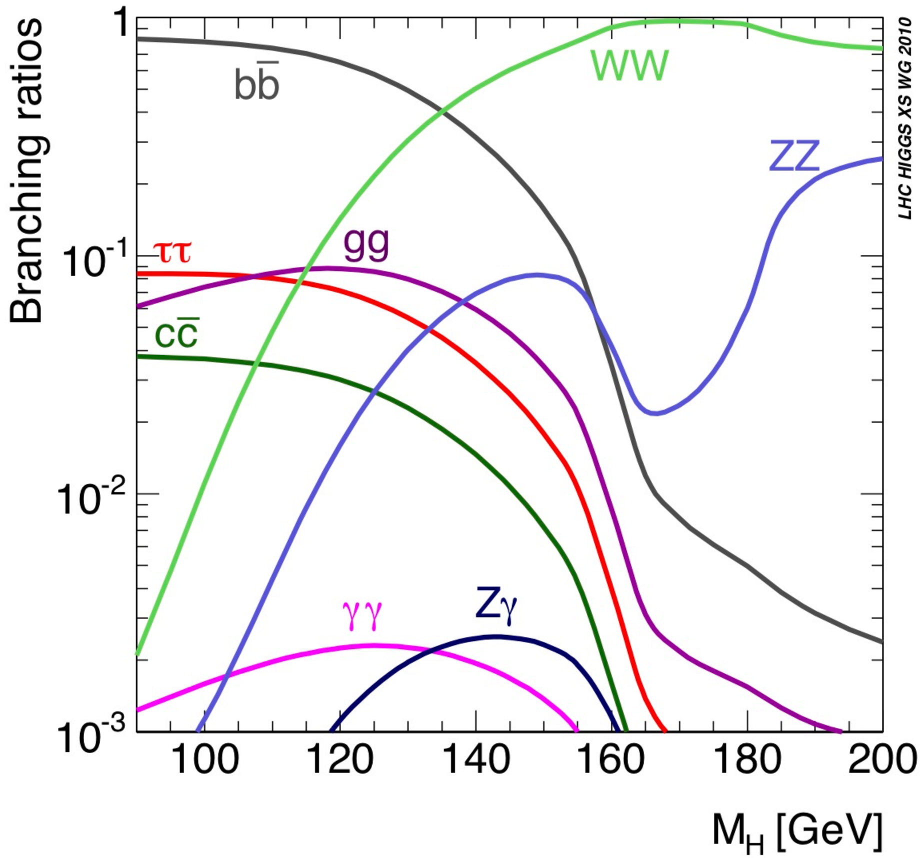
the statistics challenge



the analysis final states at LHC

- given the low expected cross-sections, search for at least **one Higgs boson decaying into bb pairs**
- the second one is searched for in **several final states**

bb bb	large branching ratio, large QCD and tt bkg
bb WW	large branching ratio, large tt contamination
bb $\tau\tau$	tradeoff between purity and branching ratio
bb $\gamma\gamma$	high purity, low branching ratio

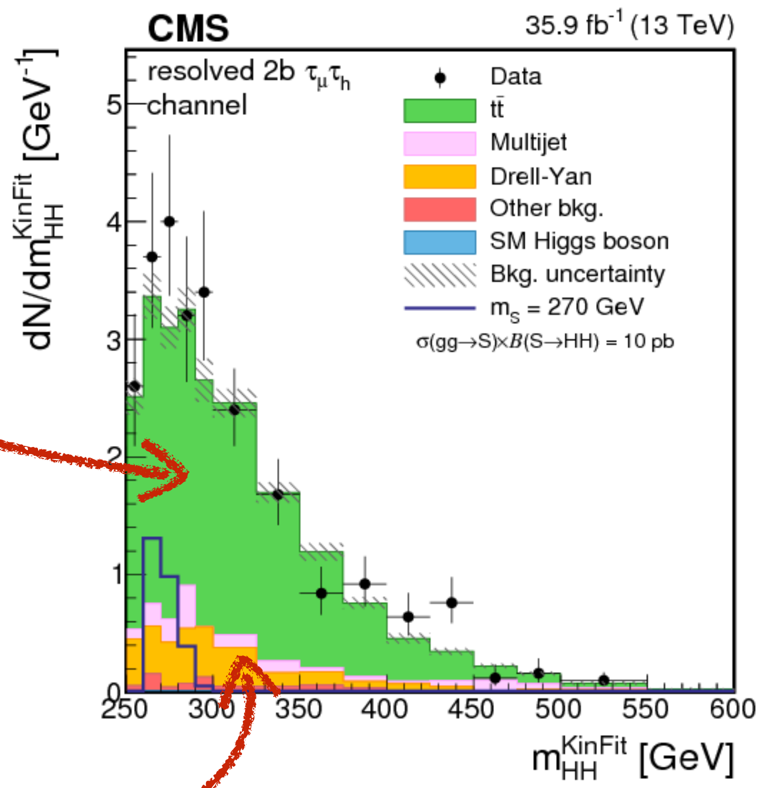


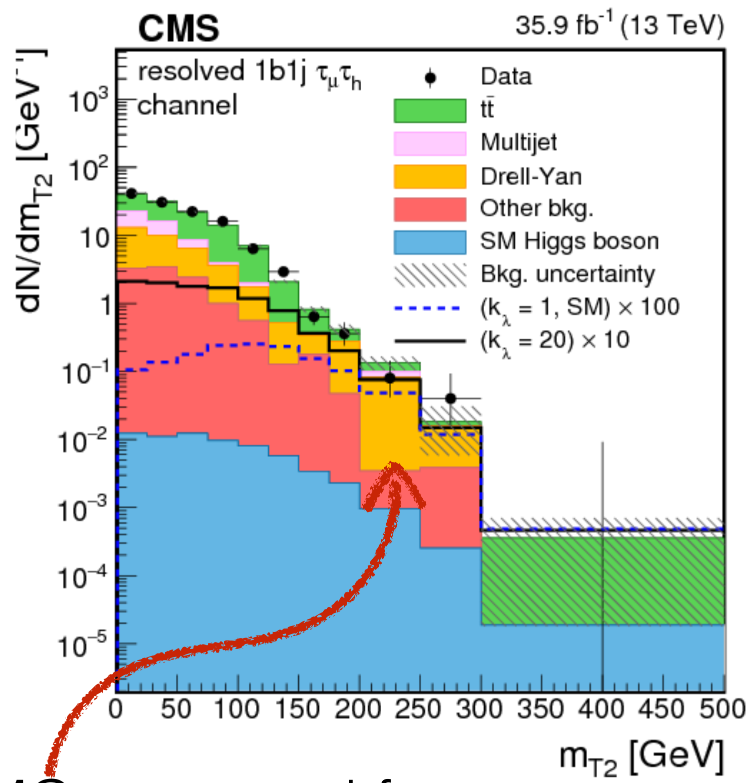
(the SM branching ratios are assumed)

HH → bb ττ

- three **final states** studied: bb eτ_h, bb μτ_h, bb $\tau_h\tau_h$
- **trigger** selections based on electrons, muons and hadronic taus
- leptons should have a minimal pT (~20 GeV) and be isolated
- **BDT** trained against ttbar for the non-resonant analysis

MC with kinematic pT reweighing to data





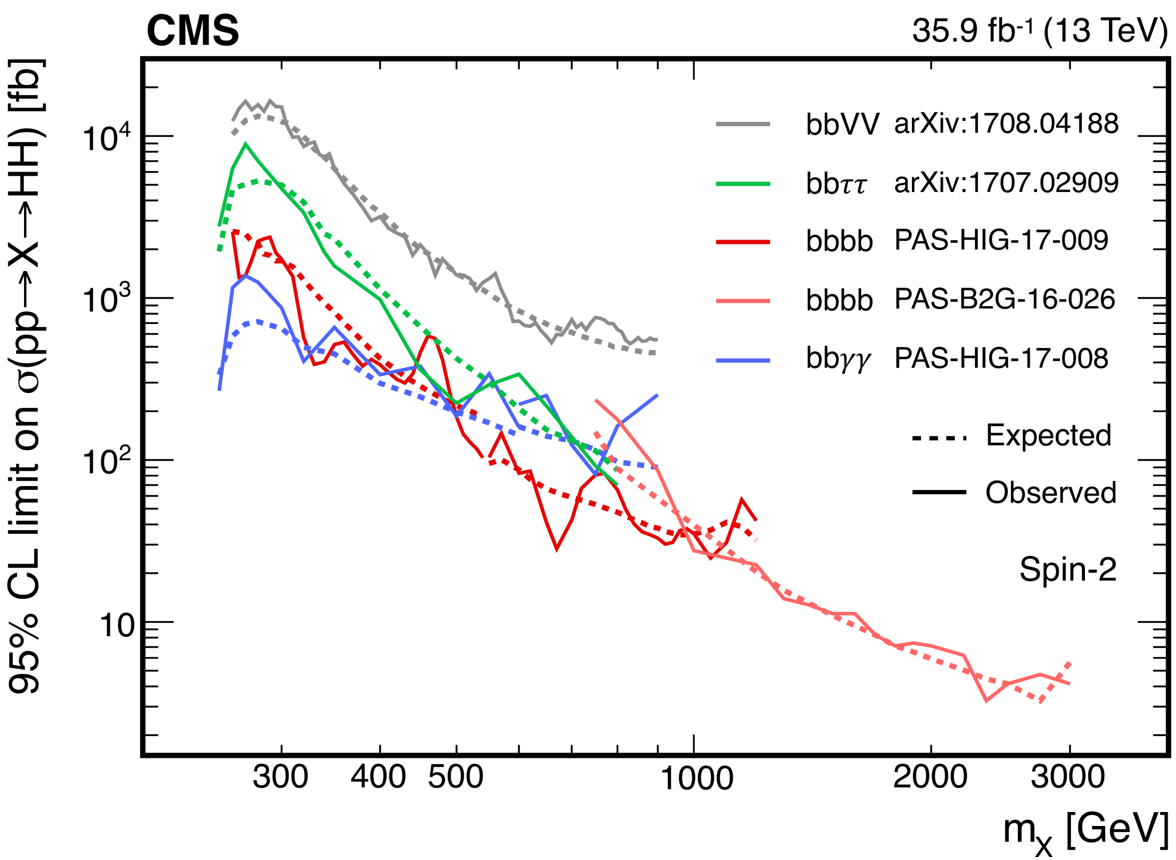
QCD from same-sign anti-isolated τ_h region

MC corrected for b-tagging eff.

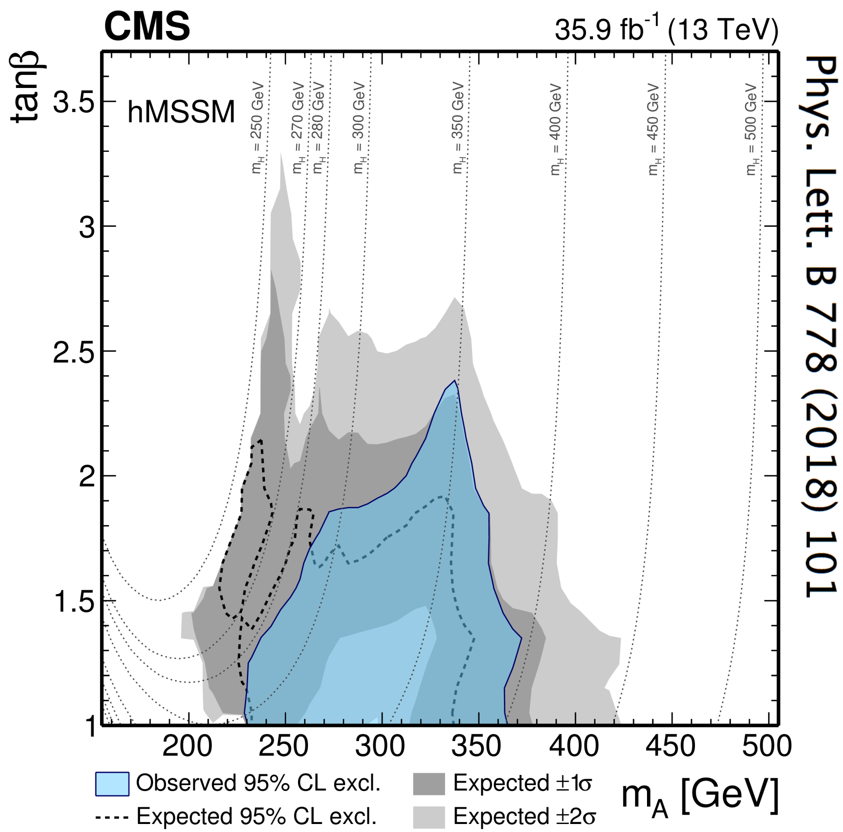
Phys. Lett. B 778 (2018) 101

resonant searches results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

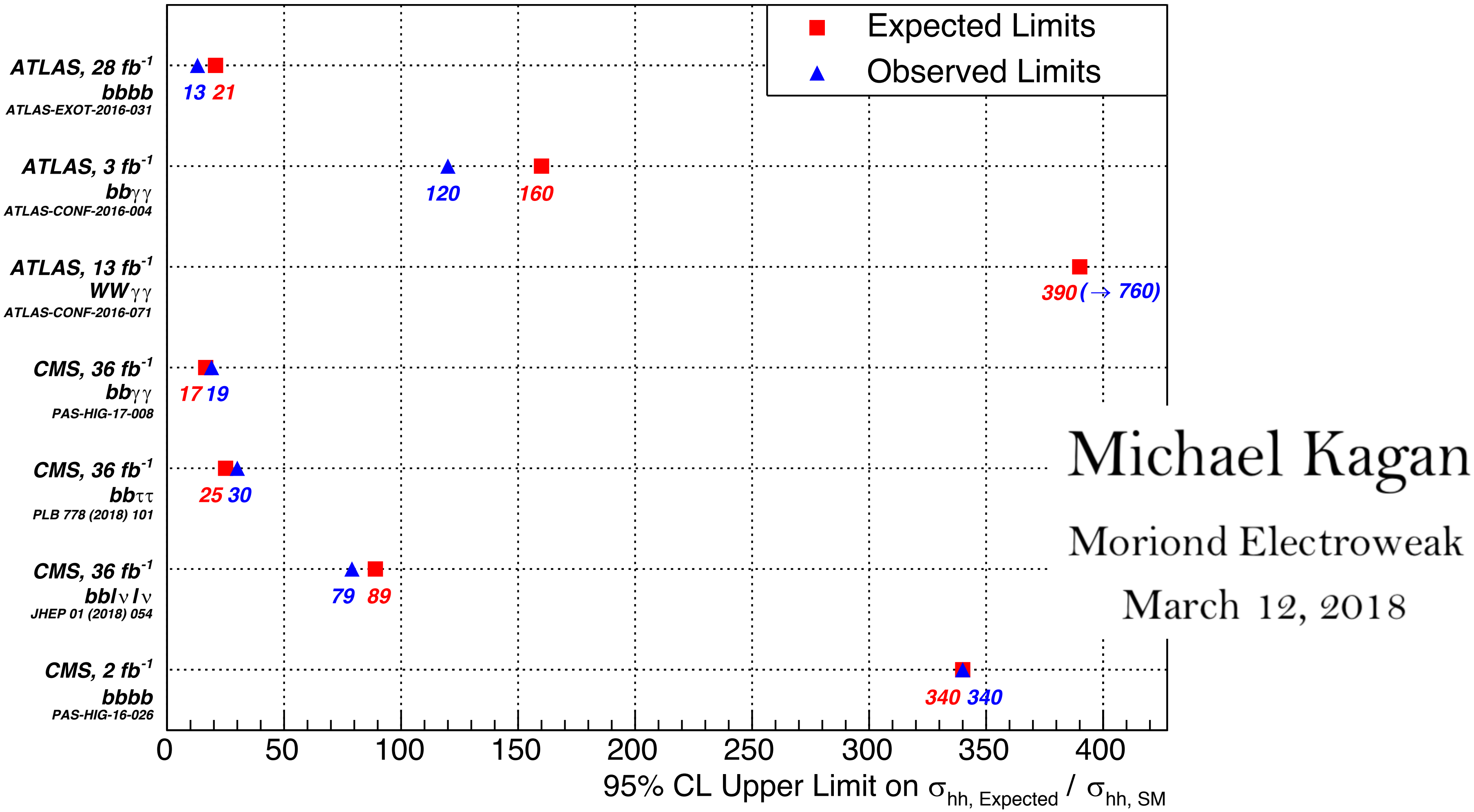


Observed and expected 95% confidence level upper limits on the production for a spin-2 resonance



exclusion limit in the hMSSM model (the CP-even lighter scalar is assumed to be the 125 GeV Higgs)

the non-resonant case



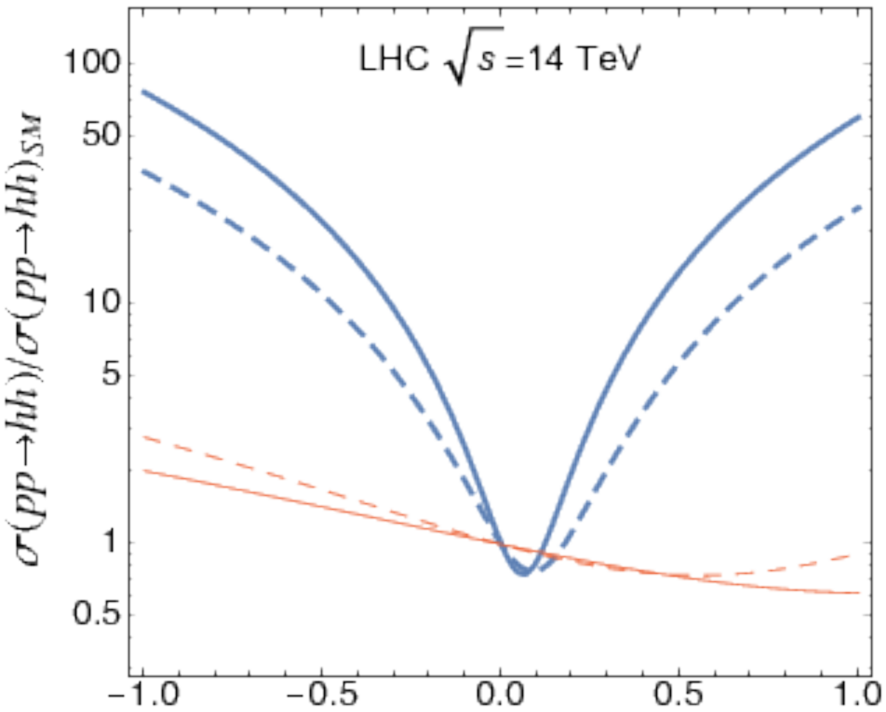
best channel limits on anomalous trilinear coupling:

$\lambda/\lambda_{SM} \in [-8, 15]$

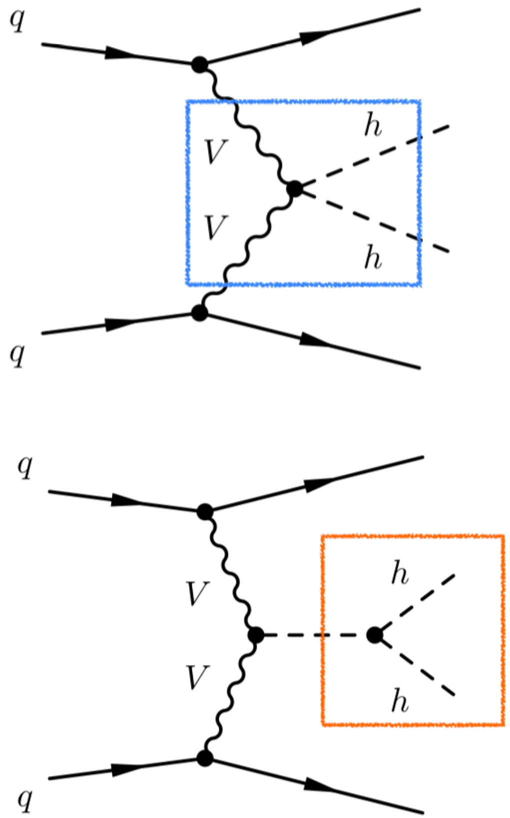
VBF production mode

- cross-section is even lower
- the presence of the VBS-like tag-jets helps suppressing some bkg
- sensitive to **different terms in the EFT expansion**

Eur.Phys.J. C77 (2017) no.7, 481

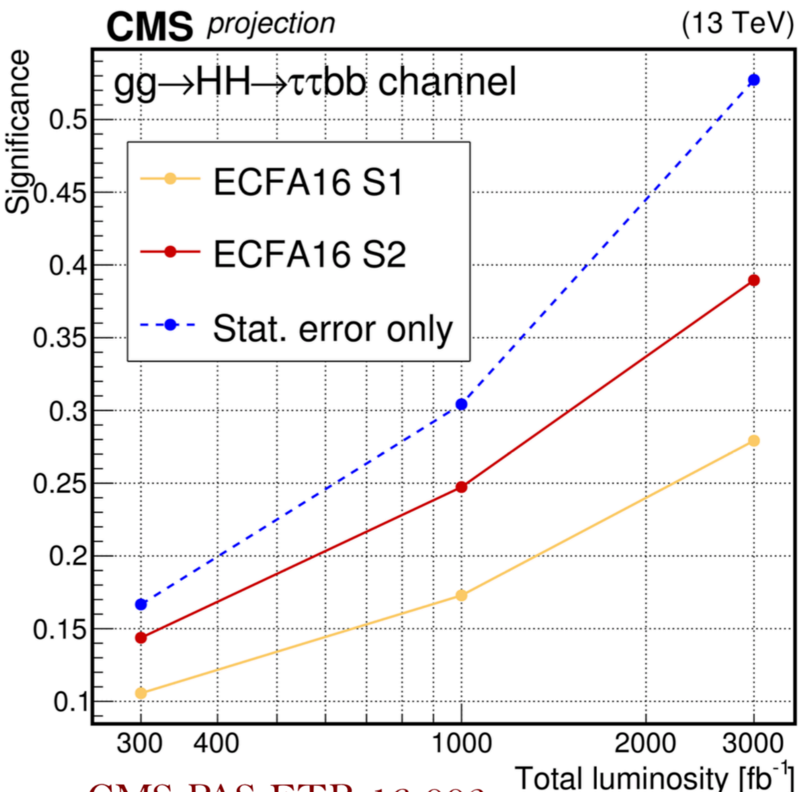


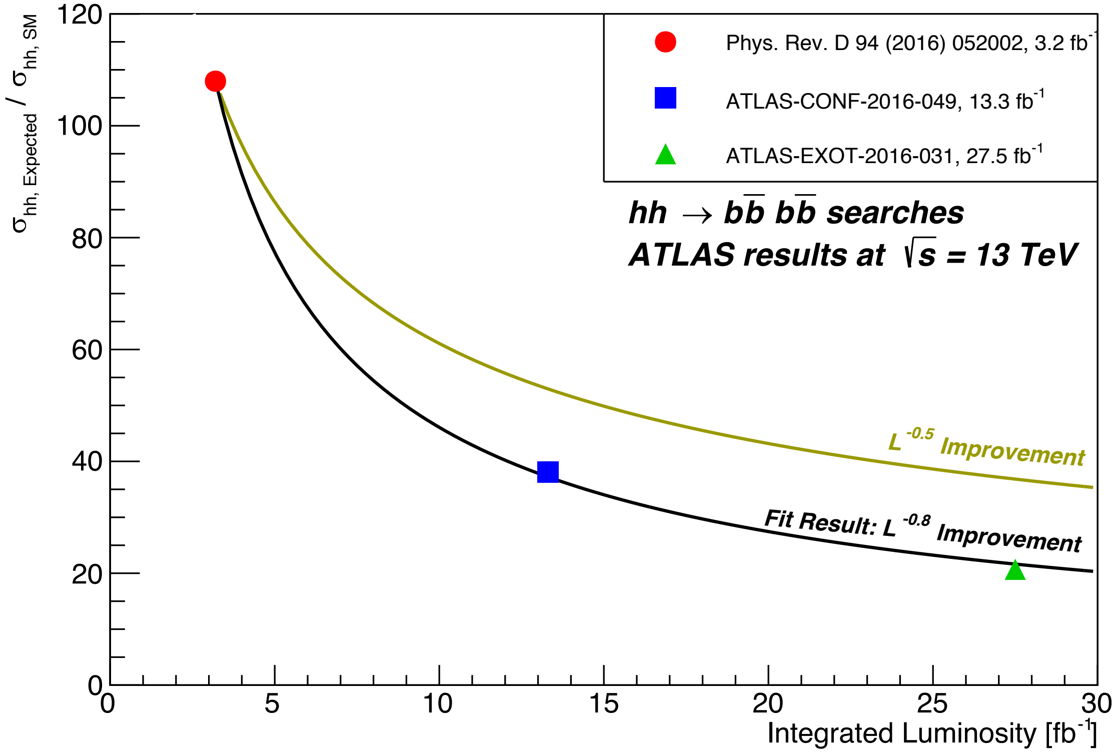
$$\delta = \lambda/\lambda_{SM} - 1$$



future expectations

- HL-LHC projections show a **challenging future**: limits on the SM cross section
- improvements in the analysis techniques bring in a **better evolution curve than the one expected by statistics only** already with existing data



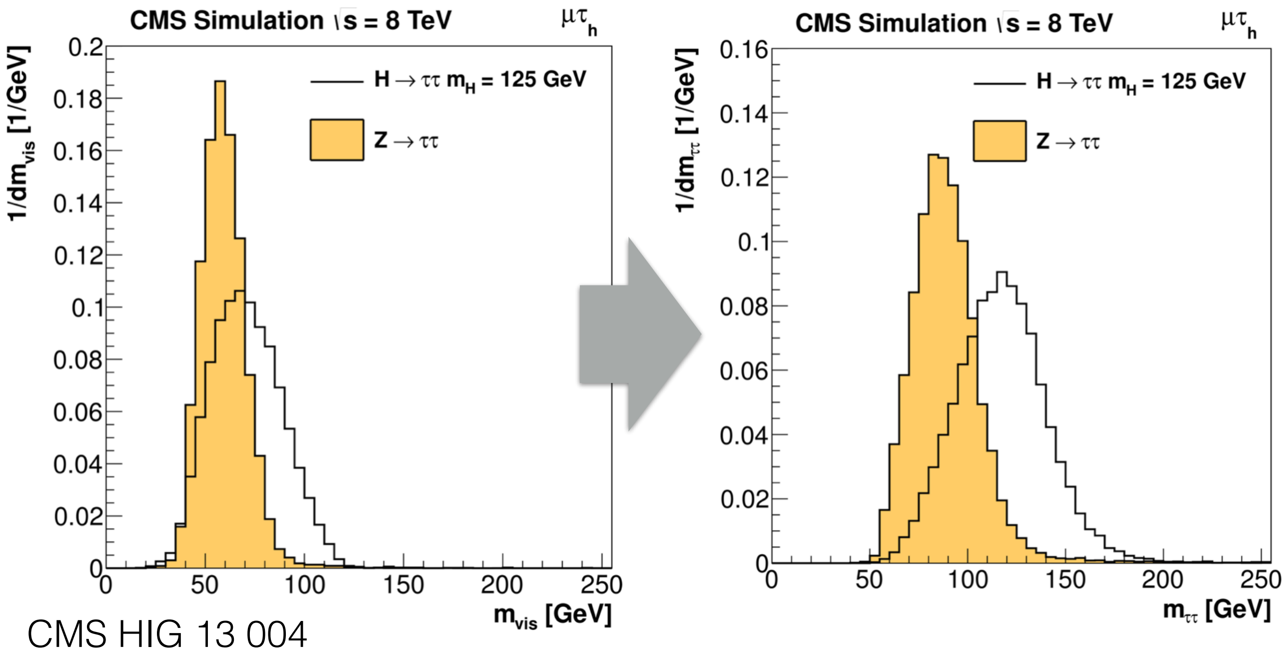


next steps

- VBS and HH studies face the problem of **very low cross-sections**
- they share the use of **tools which deserve deep understanding**, like boosted object decay reconstruction, EFT fits, high-energy lepton reconstruction, exploiting machine learning capabilities
- in particular in the future, they will be dealing with **harsh PU conditions** and not necessarily a clear peak to look for
- to get the largest statistics is possible, they will have to **trigger as many final states as possible**
- high-multiplicity final states, or loop-induced processes, are **difficult to calculate and simulate** with good precision

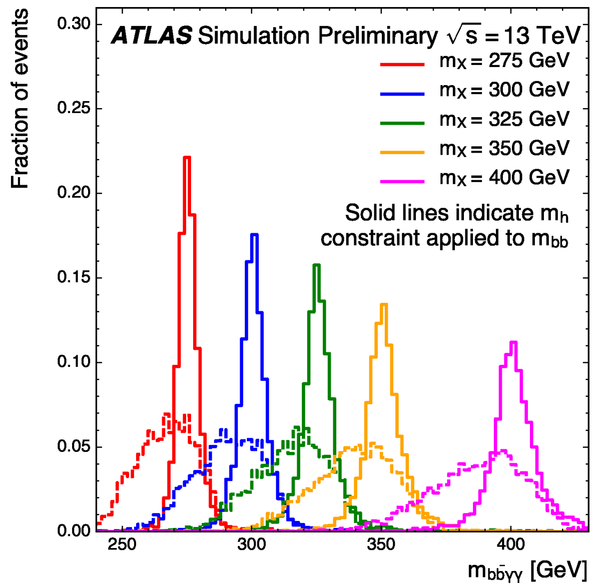
challenges: invariant masses

- tau leptons and b quarks in HH are **not reconstructed with good resolution**
- use kinematic constraints to improve the invariant mass resolution of the **single Higgs resonances**



CMS HIG 13 004

effect on the CMS likelihood fit in the **di-tau invariant mass** reconstruction

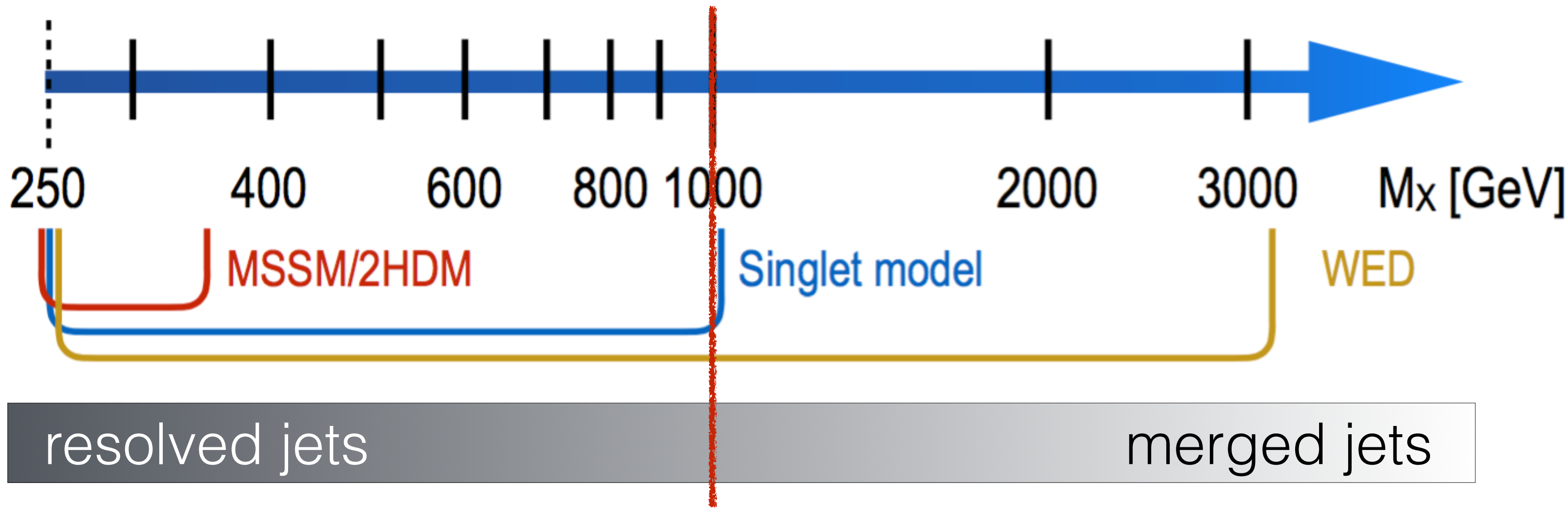


effect of **m_h/m_{bb} rescaling** on the high-mass resonance resolution in ATLAS

challenges: the boosted regime

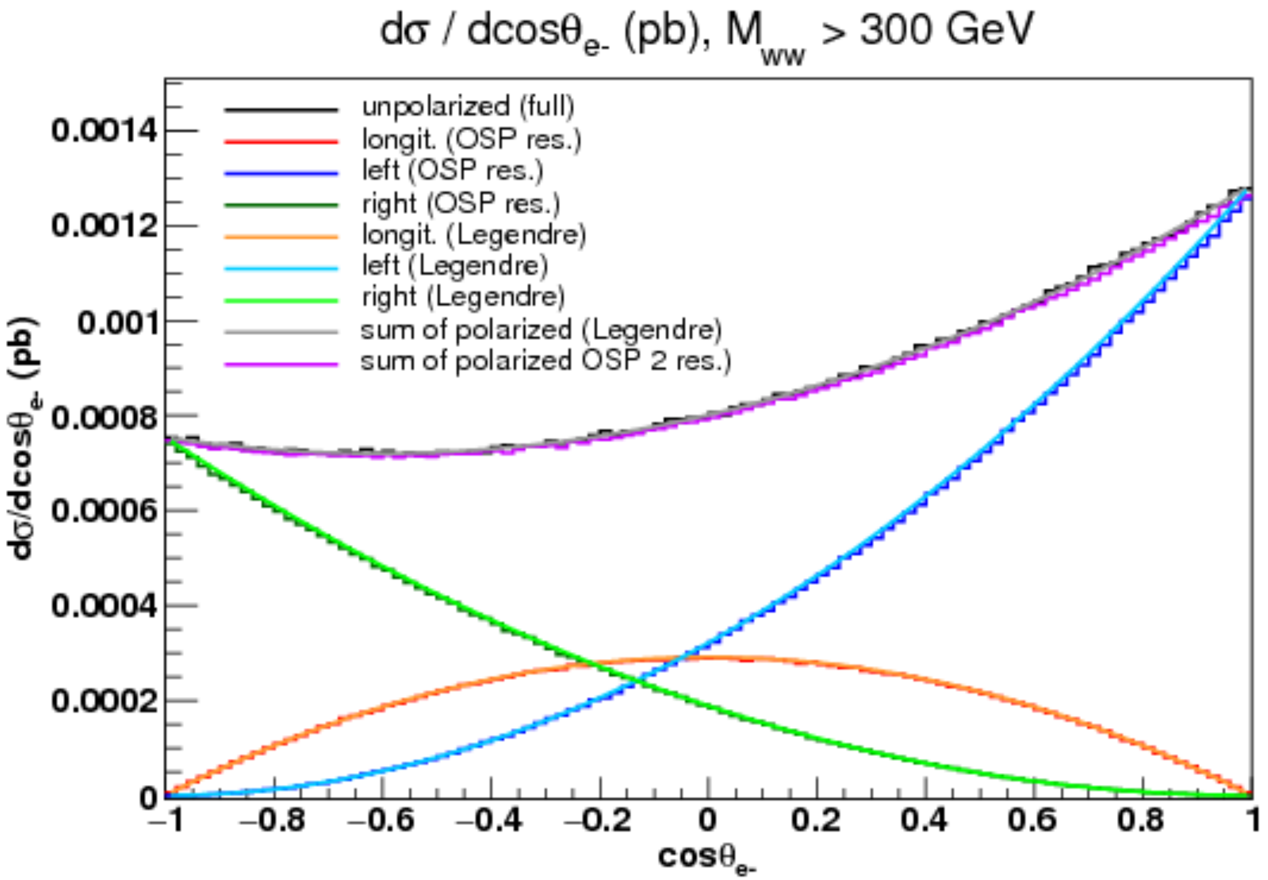
- highly boosted bosons produce **collimated pairs of objects**
- for new resonances of very large invariant mass they are reconstructed as **single large jets**
  - for b pairs or tau pairs **from H boson** decays
  - for **W or Z boson** hadronic decays
  - b-tagging and tau-identification need to be performed within the large jet

$$R < \frac{2 \cdot m_h}{p_T^{(h)}}$$



challenges: the V polarisation

- polarisation of vector bosons affects decay products angular distribution
- not yet fully exploited in LHC analyses

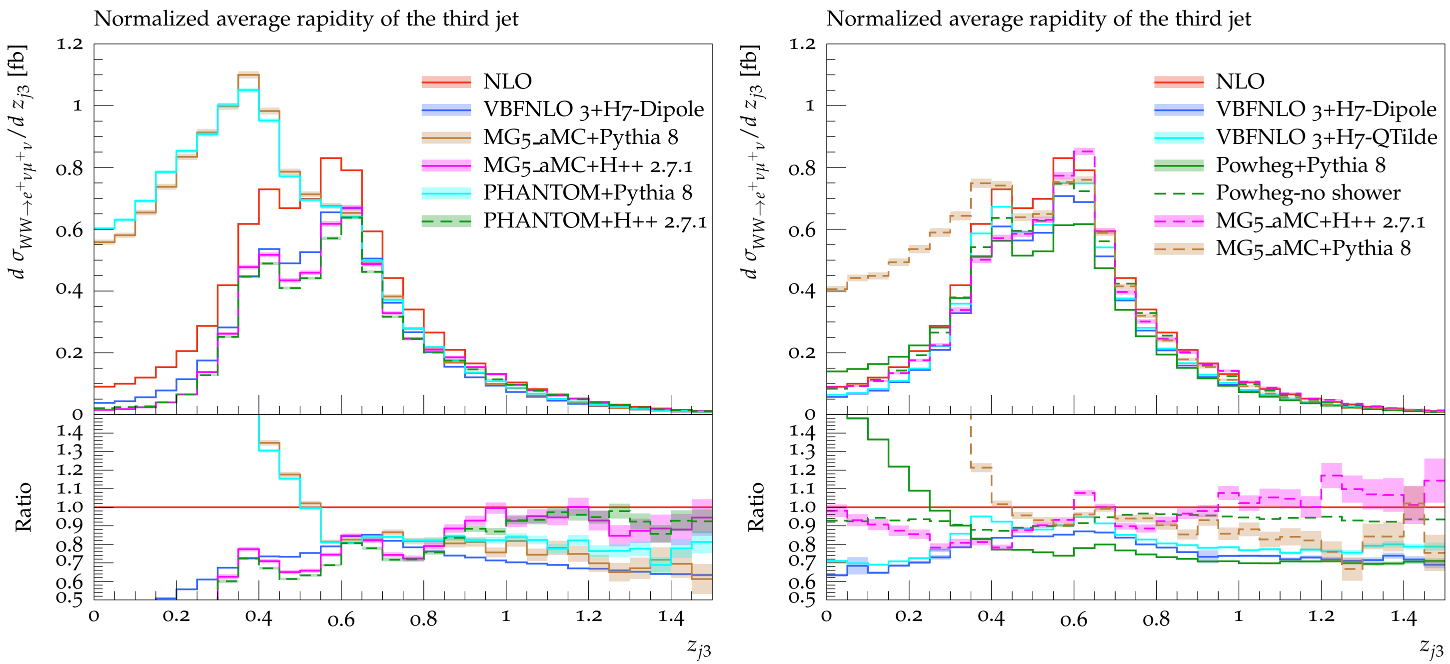


decay angle wrt V direction,
in the V reference frame

arXiv:1710.09339

challenges: higher precision

- **jets beyond the tree level** collision need to be understood better
- to be published soon

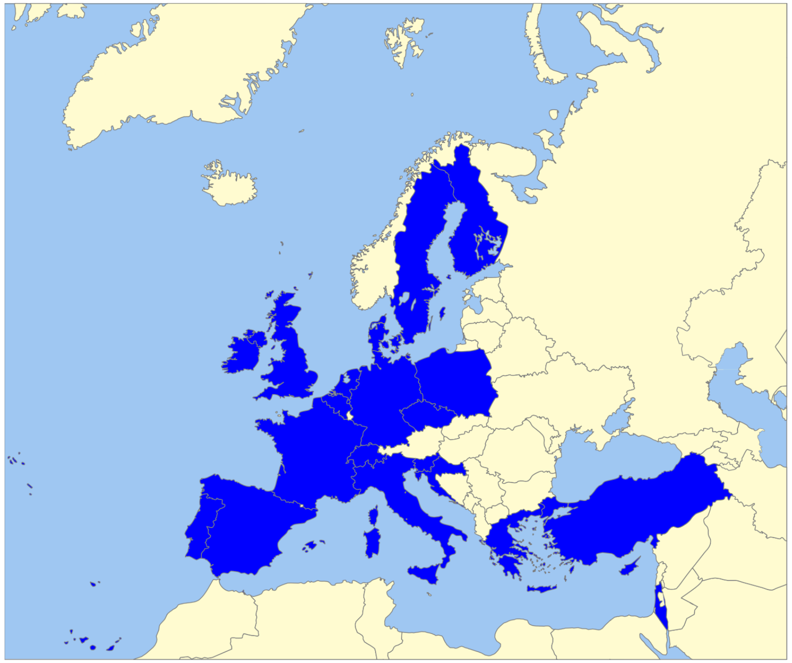


- Much larger discrepancies appear for the third jet. In particular Pythia8 tends to enhance the rate in the central region (still to be understood)

$$z_{j_3} = \frac{|y_{j_3} - (y_{j_1} + y_{j_2})/2|}{|\Delta y_{jj}|}$$

VBSCan

- COST Action targeting VBS studies
- involves more than 20 EU countries and a few extra-EU partners



Investigate the Vector Boson Scattering (VBS) process and its implications for the Standard Model, by coordinating existing theoretical and experimental efforts in the area and by best exploiting hadron colliders data, thereby laying the groundwork for long-term studies of the subject and creating a solidly interconnected community of VBS experts

http://govoni.web.cern.ch/govoni/VBSCan/

the VBSCan participants

- **Theory**: experts of Effective Field Theory, members from the communities of the major multi-purpose generators, authors of generators dedicated to VBS, VBF, vector bosons (Phantom, VBFNLO)
- **CMS Experiment**: authors of VBS analyses, authors of VBF analyses
- **ATLAS Experiment**: authors of VBS analyses, authors of VBF analyses
- **data mining**: experts from Politecnico di Milano

- ***Main guideline**: collect all the relevant knowhow to perform the best VBS analysis. Some will be actual VBS analysts and will profit of all the pieces of info available, some will be experts of some parts of it, and will profit of the discussions on a subject of interest for them*

the VBSCan participants

- **Theory**: experts of Effective Field Theory, member ... ma ... ors ... ed ... is (... aut ... hors o
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- ... vhow t ... ill be actual VBS analysts an ... e, some will be experts of so... parts of it, and will profit of the discussions ... them

N(N)LO QCD and EWK predictions

high-energy leptons reconstruction

machine learning

background estimates

EFT fits

quark-gluon discrimination

EFT unitarisation

signal isolation

PU mitigation

results combination

polarised-V tagging

boosted jets reconstruction

signal definition

BSM models

the VBSCan structure

management committee		
P. Govoni, M. Mozer		
WG1: theoretical understanding	*M. Pellen, M. Zaro*	EWK QCD
WG2: analysis techniques	*J. Manjarres, M. Mozer*	ATLAS CMS
WG3: experimental measurements	*L. S. Bruni, S. Duric*	ATLAS CMS
WG4: knowledge exchange and cross-activities	*K. Lohwasser, I. Puljak*	
WG5: Inclusiveness Policies	*M. Slawinska, C. Petridou*	

ongoing work on EFT

- define a **sound minimal basis** for the measurements
- define **publication guidelines** to allow for the best exploitation from the theory community
- starting with codes comparison

- several implementations available
  - SMEFTsim [Brivio, Jiang, Trott]
  - VBFNLO [MR, Zeppenfeld *et al.*]
  - Whizard [Reuter, Song; Sekulla *et al.*]
- pick one VBS process as example

  suggestion: $pp \to e^+ \nu_e \mu^+ \nu_\mu$ jj (same-sign $W^+ W^+$ production via VBS)
  - existing SM setup ($\to$ MC comparison)
  - fewer Feynman diagrams $\to$ less CPU time needed
  - largest experimental sensitivity
- restrict to a small subset of operators
  - $\mathcal{O}(3-4)$
  - representative of different features: longitudinal, transverse, CP-odd
- compare the codes numerically and understand any differences showing up

the Thessaloniki meeting

- the next general meeting will happen on June, 21st and 22nd in Thessaloniki
- **you are very welcome to join us** there, if interested in our activities!
- https://indico.cern.ch/event/706178/

when the play gets tough

- HH and VBS searches still at their infancy
- first measurements started appearing since about two years ago
- basically **statistically-limited**, will profit a lot of the future LHC dataset
- open complementary paths to **test the solidity of EWSB**
- challenging processes both theoretically and experimentally
- significant interest in both the experimental the theory community
- new territories and lots to be done
- **exciting time ahead of us**