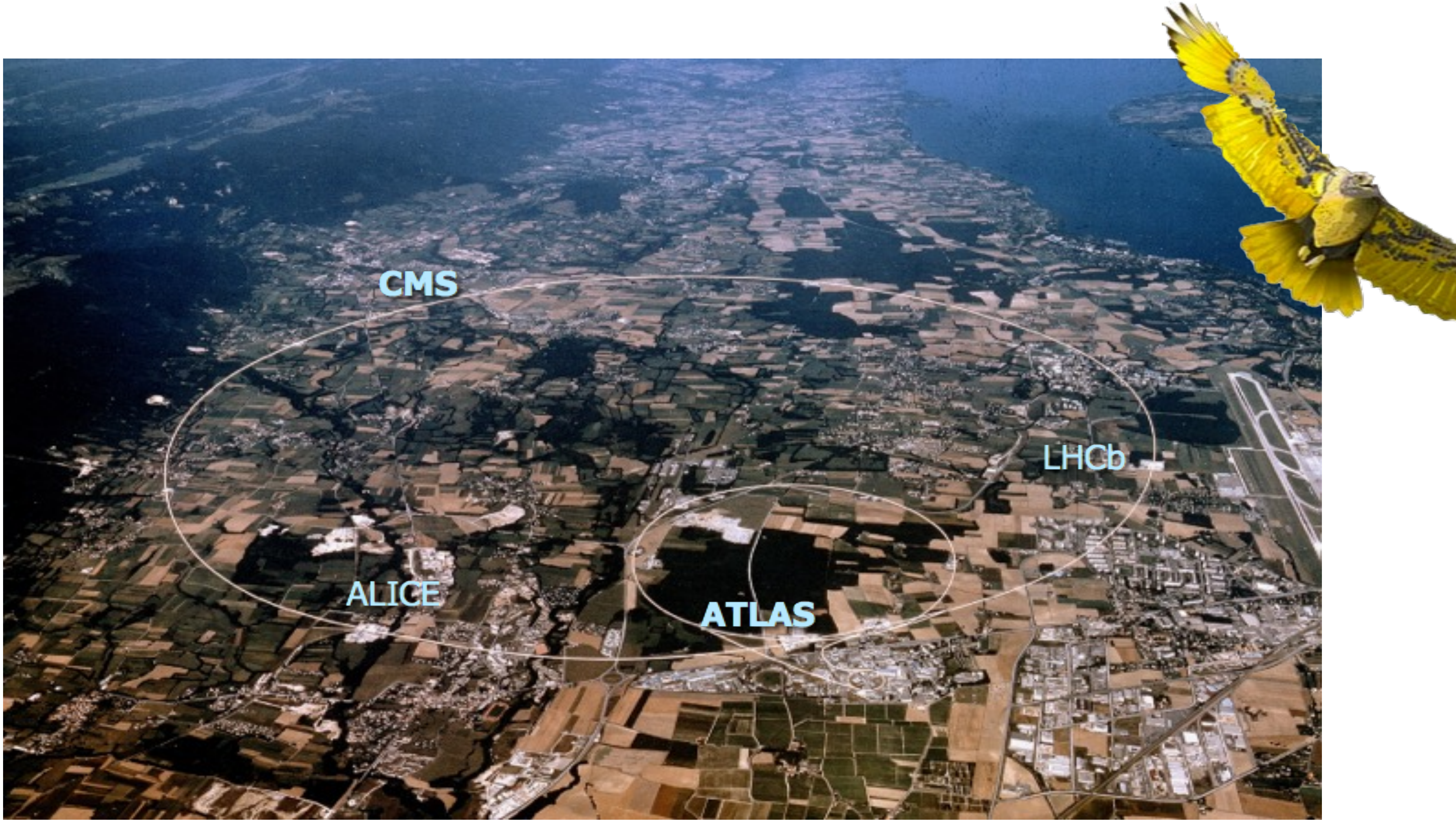
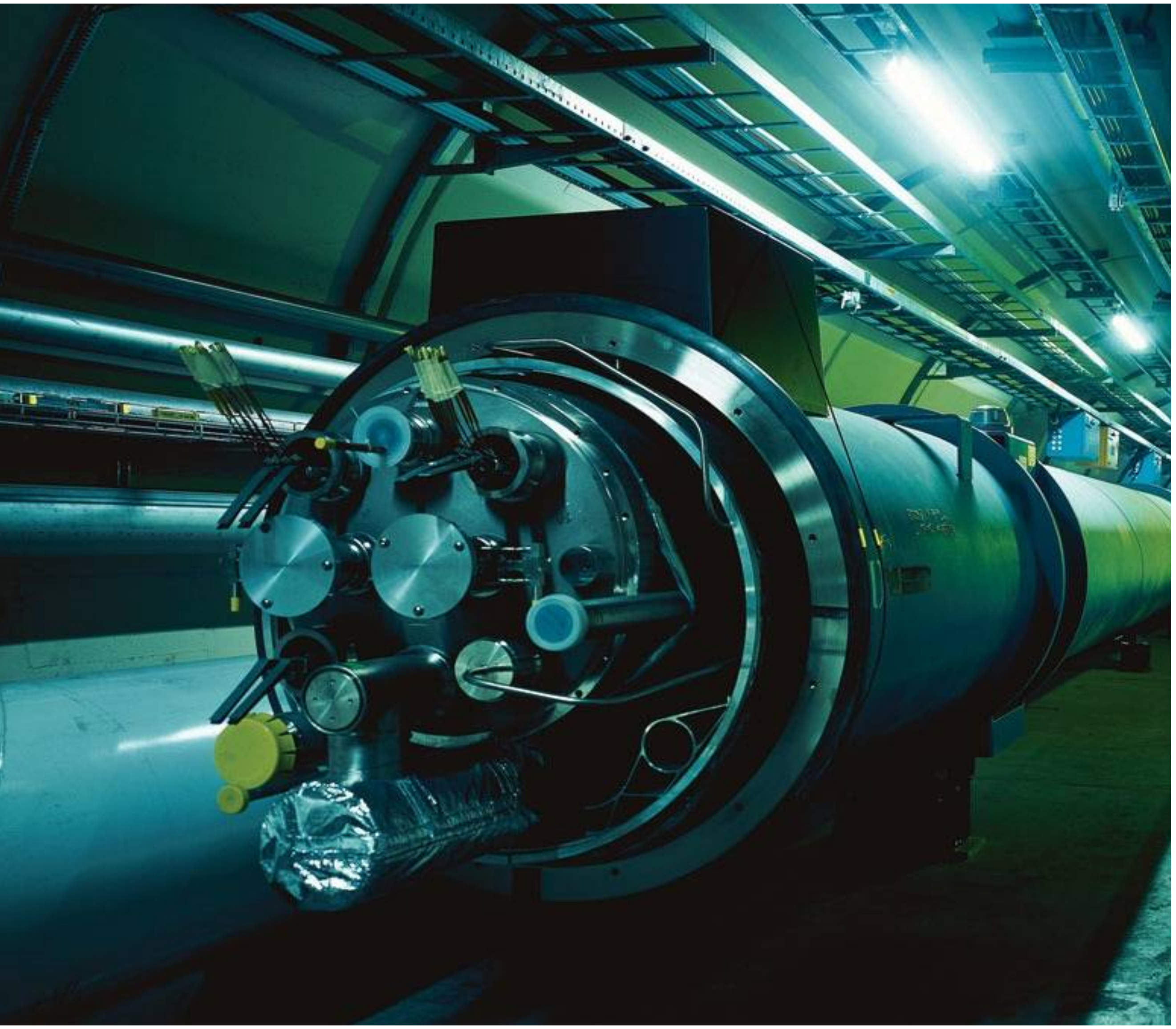
Physics at the Large Hadron Collider

Victor T. Kim

The Large Hadron Collider at CERN



The Large Hadron Collider: energies



туннель 27 км

p-p, p-pB, Pb-Pb

2009: 1.18 ТэВ x 1.18 ТэВ

2010-11: 3.5 ТэВ x 3.5 ТэВ

2012: 4 ТэВ x 4 ТэВ

2015-18: 6.5 ТэВ x 6.5 ТэВ

2022-23: 6.8 ТэВ x 6.8 ТэВ

Large Hadron Collider: in the Galaxy

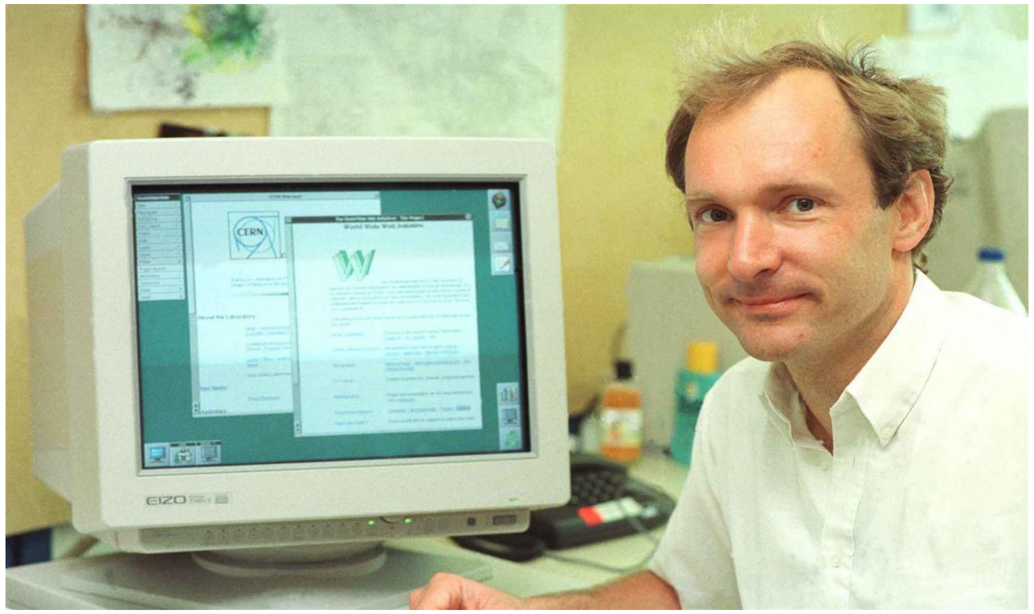
The hottest place in the Galaxy: $T \geq 5 \cdot 10^{12}$ K

$T_{Sun} = 1.6 \cdot 10^{7}$ K

The coolest place in the Galaxy: $T \leq 2$ K

CERN: WWW (Internet)

Tim Berners-Lee (1989)



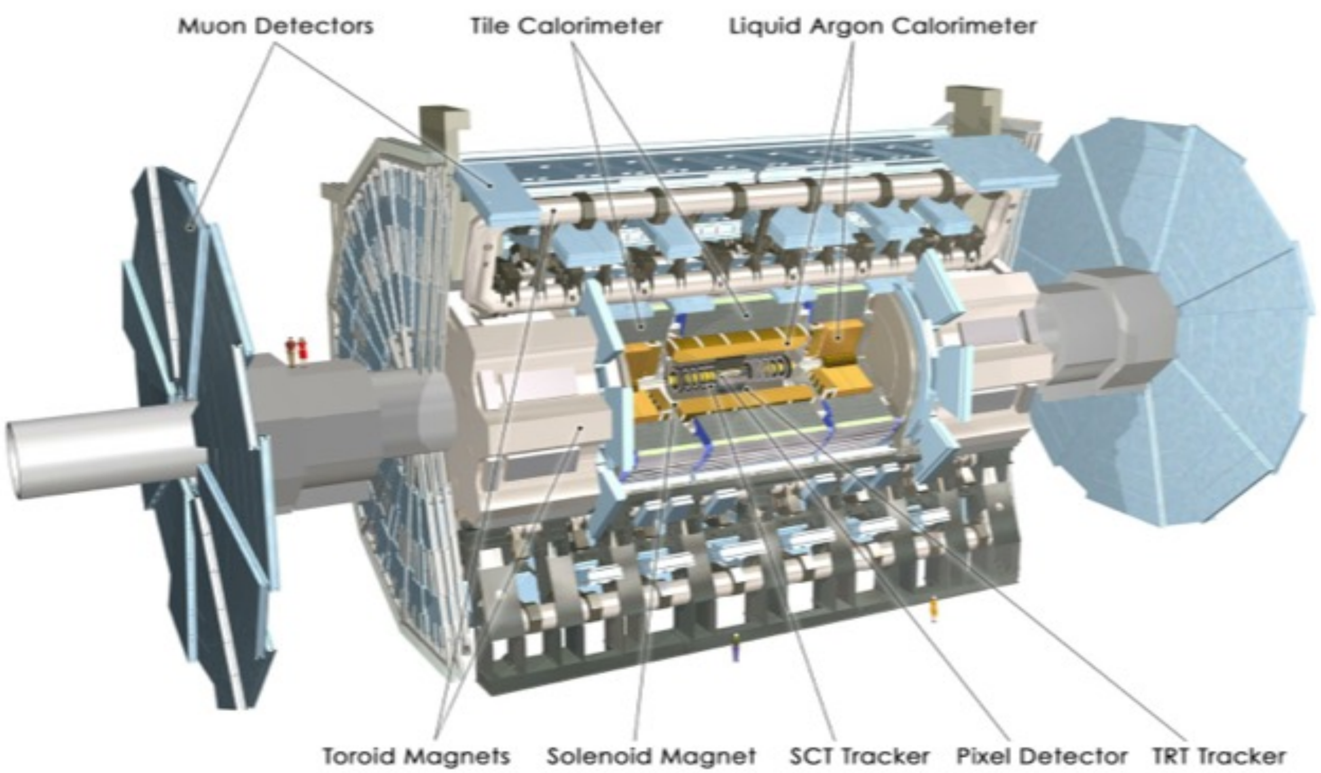
Internet without WWW only:
email, file transfer,
remote login.

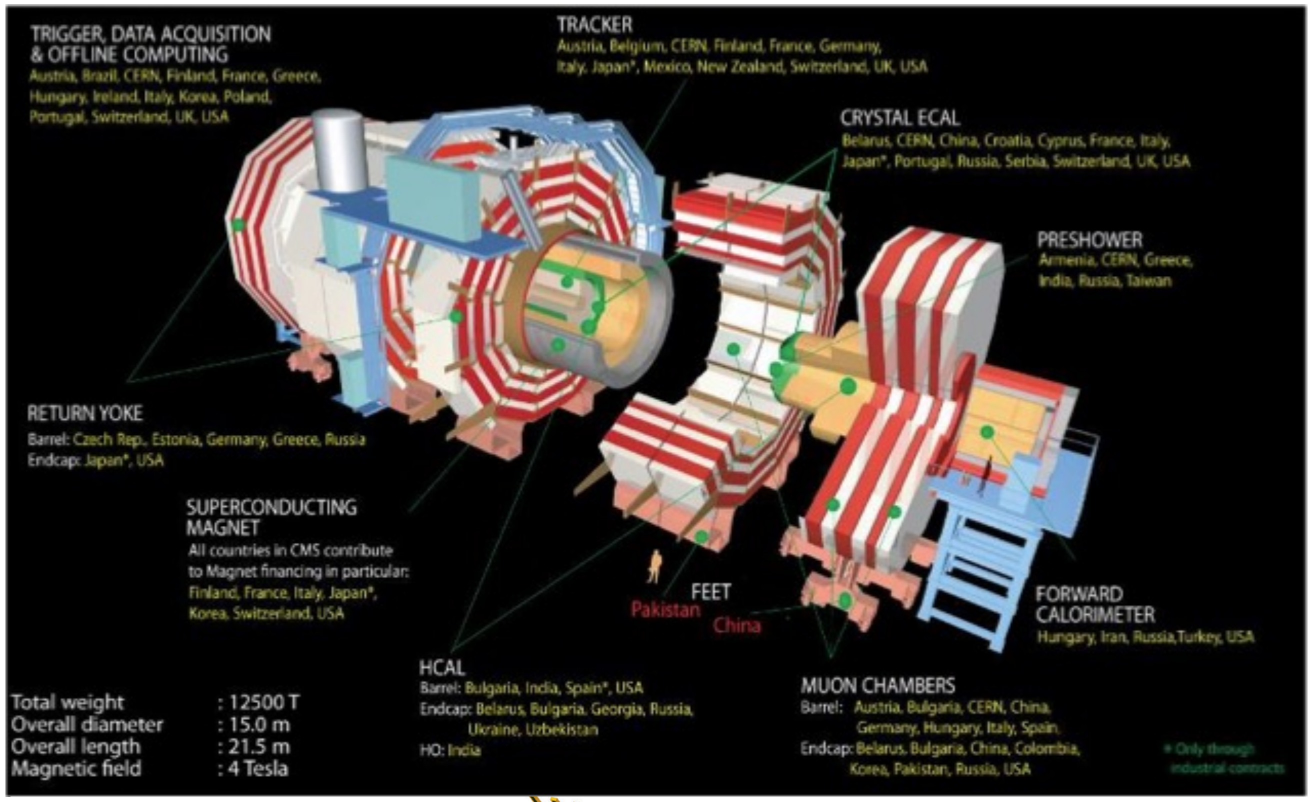
Data taking at the LHC: ~ 10 Gb/c
LHC GRID: distributed computing
and storage system at the LHC

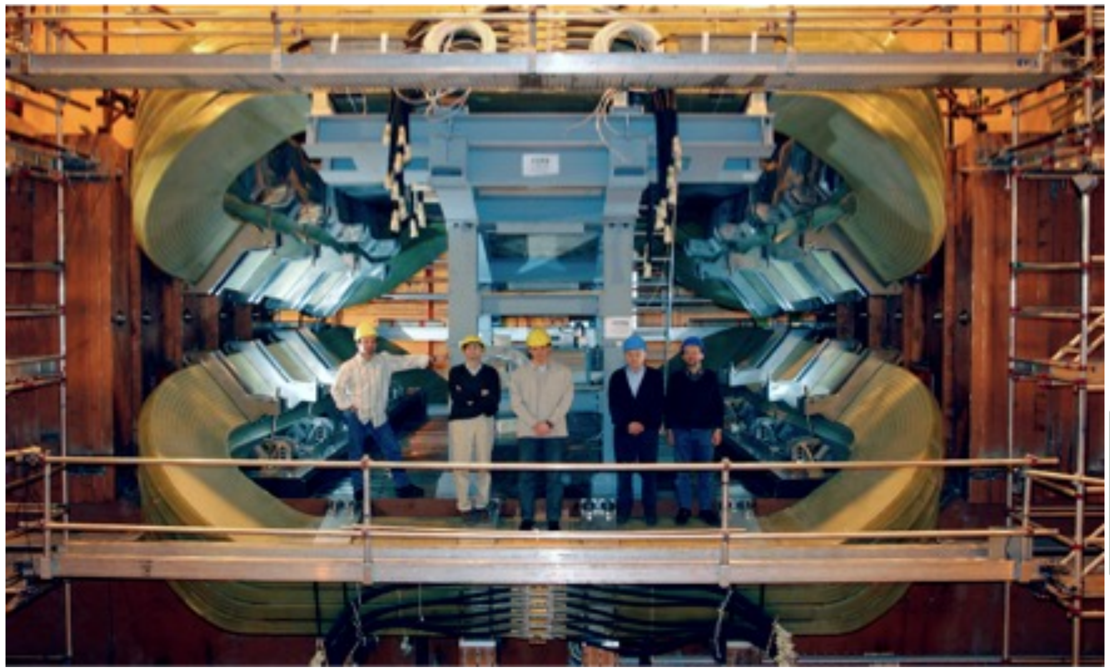
Russia & JINR, Dubna: ~5-7%

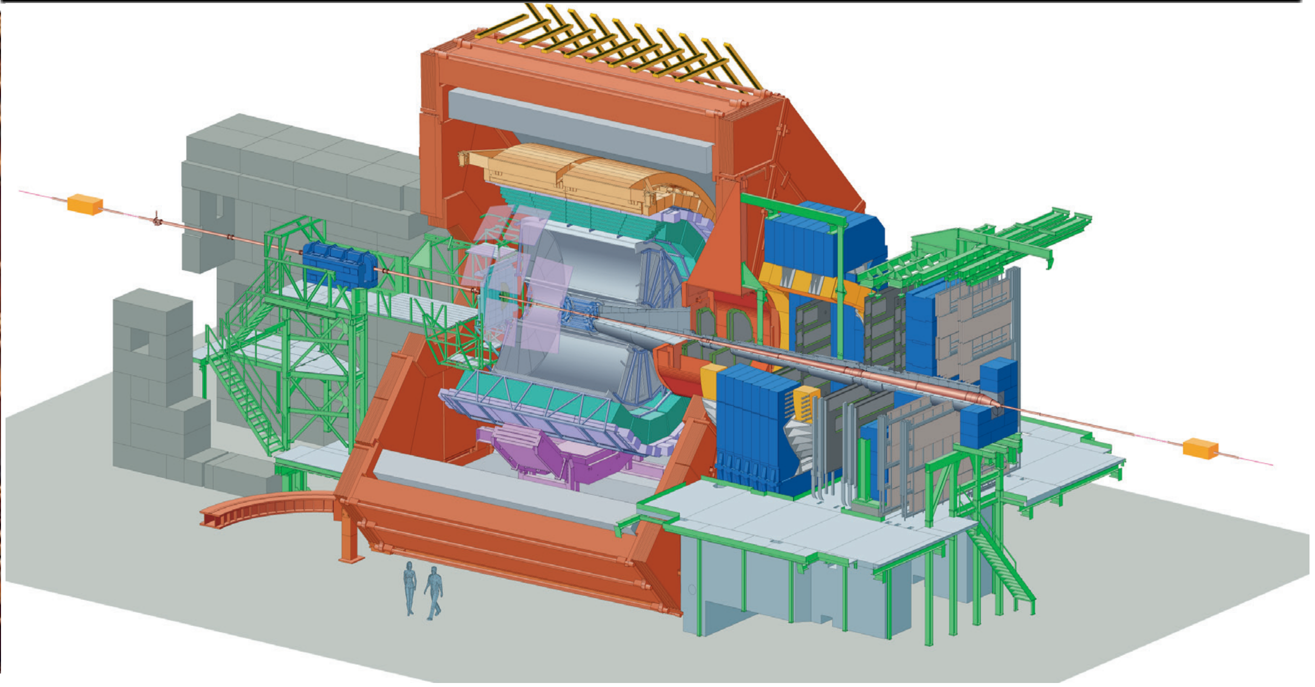
Experiments at the LHC

The Large Hadron Colliders: the experiments

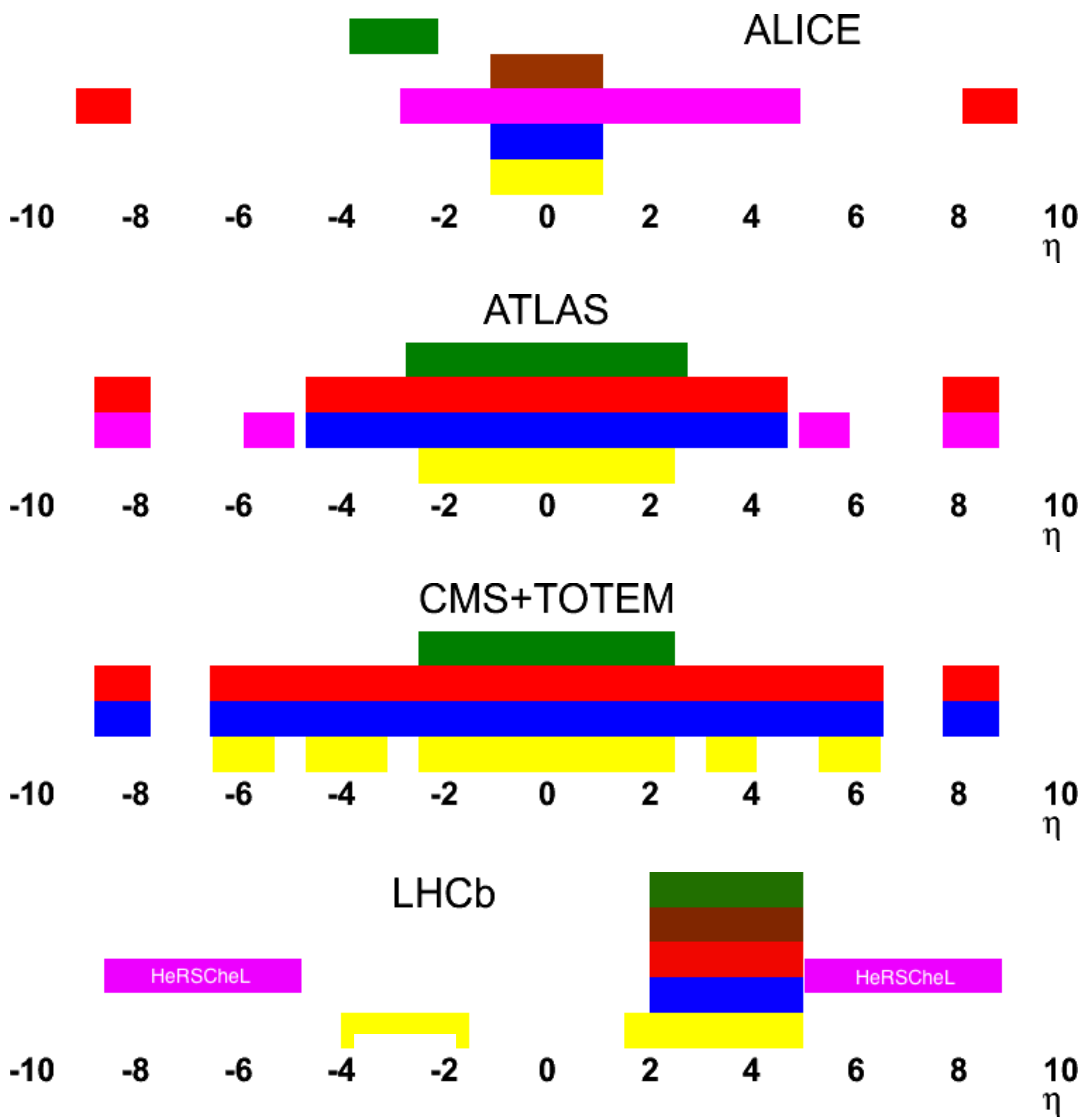




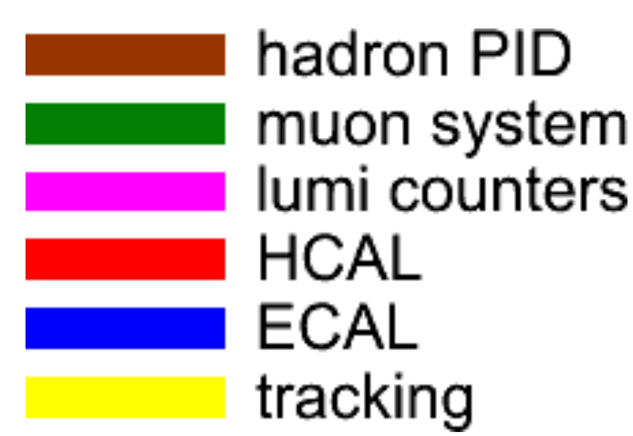




LHC detectors: ATLAS, CMS, LHCb & ALICE

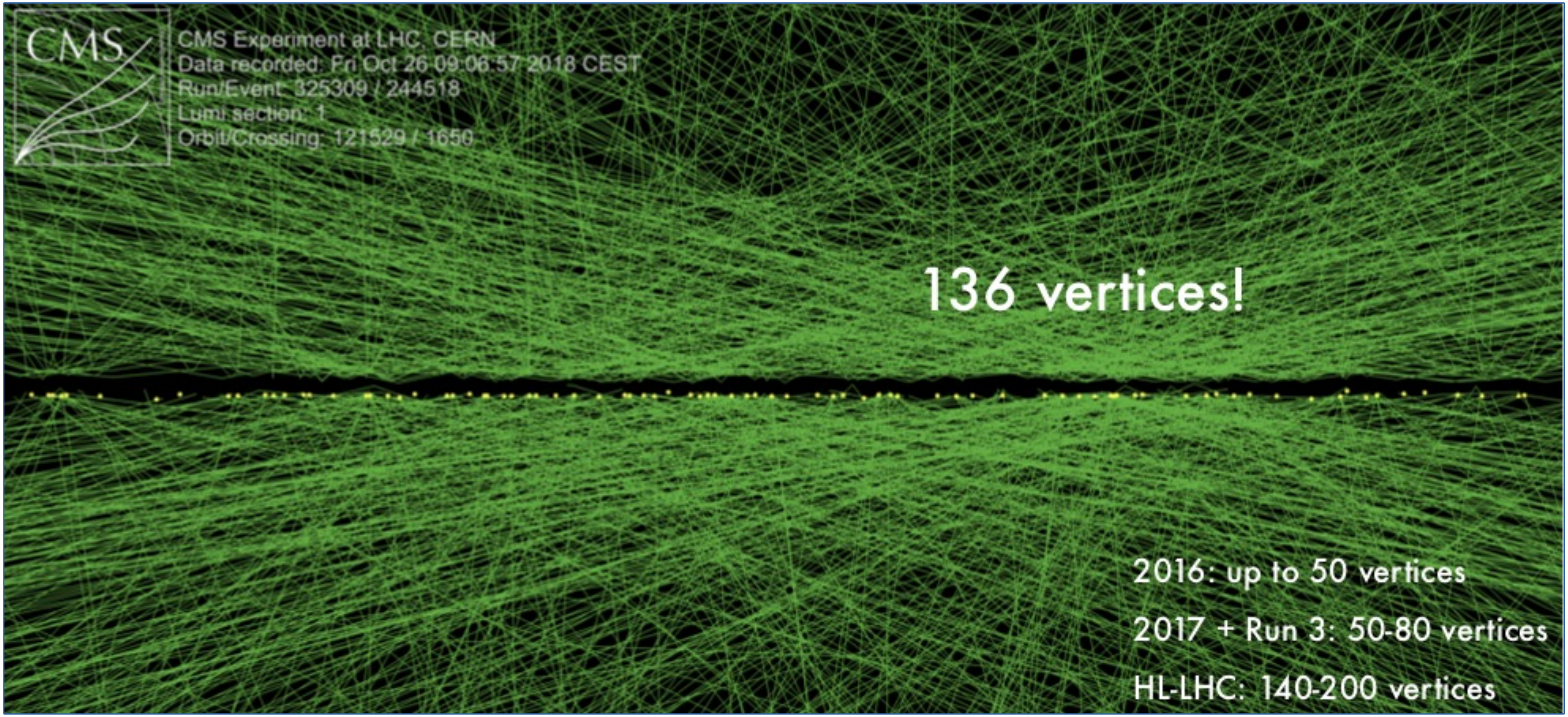


- ALICE
  - central detector
  - forward muon coverage
- ATLAS & CMS
  - central tracking detectors
  - forward calorimeter
- LHCb
  - forward detector
  - tracking, PID and calorimetry in the full acceptance



LHC: pile-up

ATLAS и CMS work at the large number of parallel pp-collisions (pileup)



LHC data taking: ATLAS and CMS

LHC data taking start at 7 TeV: 2010

Run 1

- 7 TeV (2011): ~**5 fb^{-1}**
- 8 TeV (2012): ~**20 fb^{-1}**

Run 2 (2015-2018): 13 TeV ~**140 fb^{-1}**

Run 3 (2022-2025): 13.6 TeV ~**300 fb^{-1}** **triple statistics** (from 140 to 440 fb^{-1})

HL-LHC (2029-2041): 14 TeV ~ **3000 fb^{-1}** **×20 statistics** (from 140 to 3000+ fb^{-1})

+ trigger/detector upgrades

reaction rate = luminosity x cross-section

event rate = time x reaction rate

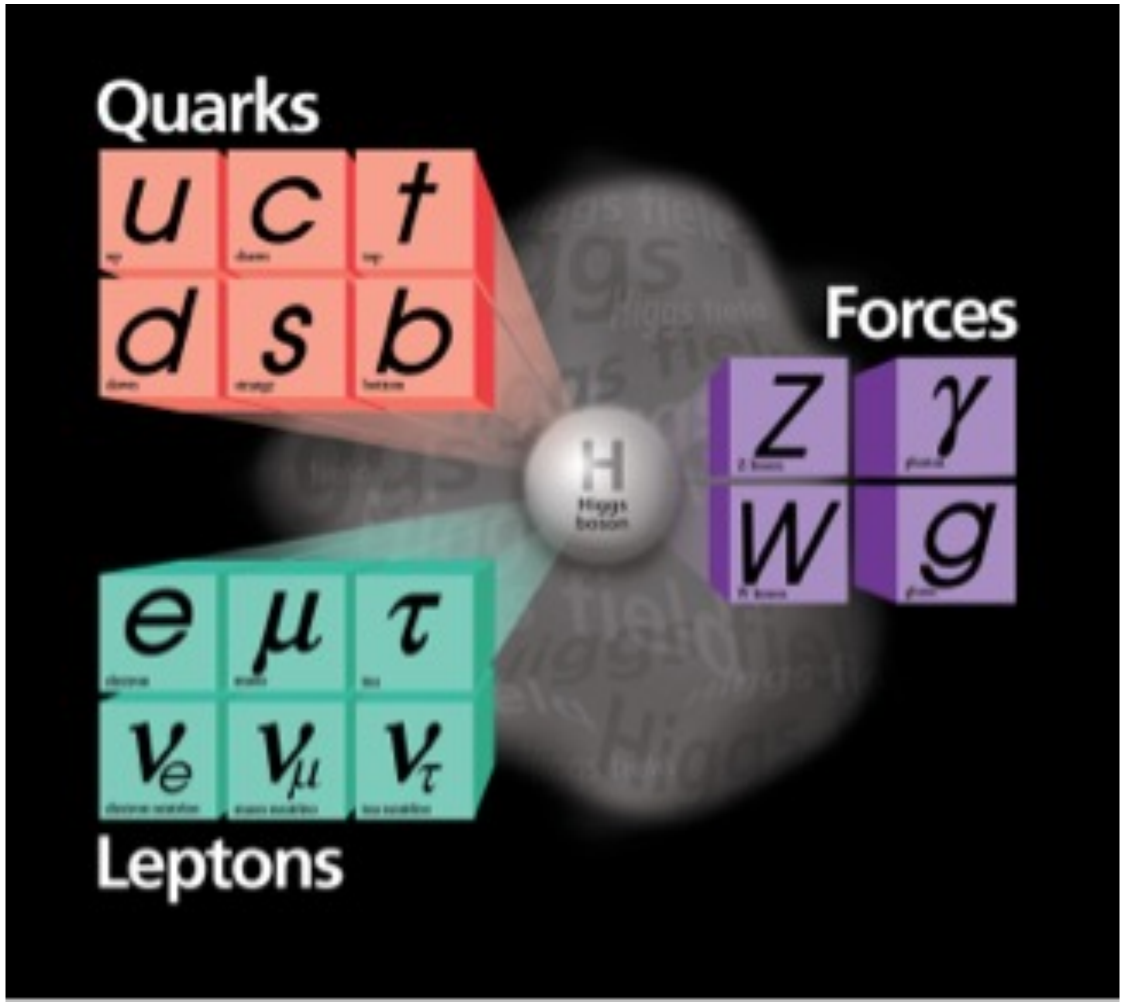
Large Hadron Collider (LHC): main goals

- Higgs boson of the Standard Model
- New particles and interactions beyond the Standard Model

and:

- Standard Model tests at new energies
- New dynamics of the Standard Model: new states of quark-gluon matter, asymptotic QCD (BFKL), ...

The Standard Model

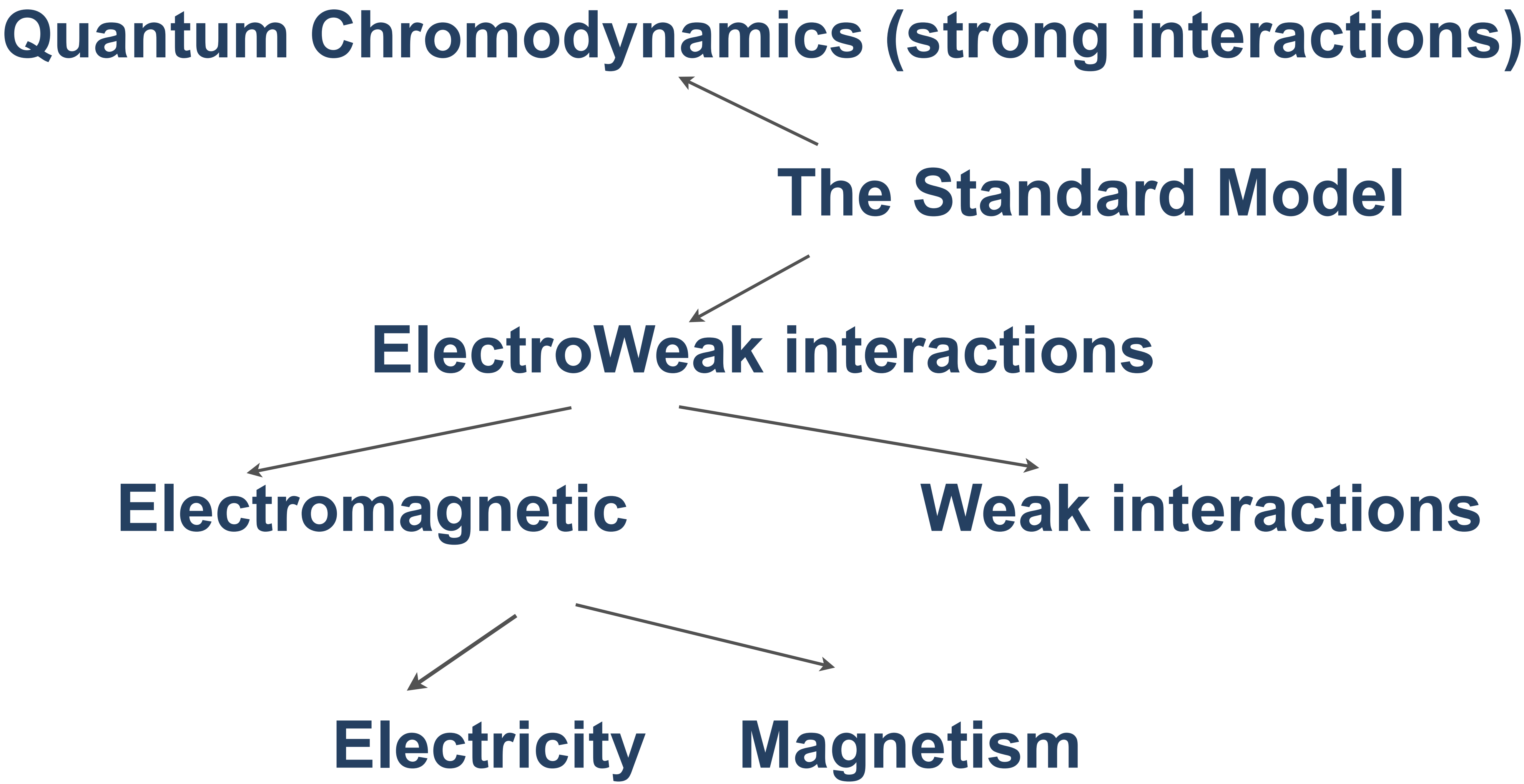


The Standard Model:
remarkable and experimentally
well tested theory

e.g. LEP and SM

Quantity	Value	Standard Model	Pull
m_t [GeV]	$172.7 \pm 2.9 \pm 0.6$	172.7 ± 2.8	0.0
M_W [GeV]	80.450 ± 0.058	80.376 ± 0.017	1.3
	80.392 ± 0.039		0.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0011	−0.7
Γ(had) [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—
Γ(inv) [MeV]	499.0 ± 1.5	501.65 ± 0.11	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.996 ± 0.021	—
σ_{had} [nb]	41.541 ± 0.037	41.467 ± 0.009	2.0
R_e	20.804 ± 0.050	20.756 ± 0.011	1.0
R_μ	20.785 ± 0.033	20.756 ± 0.011	0.9
R_τ	20.764 ± 0.045	20.801 ± 0.011	−0.8
R_b	0.21629 ± 0.00066	0.21578 ± 0.00010	0.8
R_c	0.1721 ± 0.0030	0.17230 ± 0.00004	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01622 ± 0.00025	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1031 ± 0.0008	−2.4
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0737 ± 0.0006	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1032 ± 0.0008	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23152 ± 0.00014	0.7
	0.2238 ± 0.0050		−1.5
A_e	0.15138 ± 0.00216	0.1471 ± 0.0011	2.0
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		−0.3
A_τ	0.136 ± 0.015		−0.7
	0.1439 ± 0.0043		−0.7
A_b	0.923 ± 0.020	0.9347 ± 0.0001	−0.6
A_c	0.670 ± 0.027	0.6678 ± 0.0005	0.1
A_s	0.895 ± 0.091	0.9356 ± 0.0001	−0.4
g_L^2	0.30005 ± 0.00137	0.30378 ± 0.00021	−2.7
g_R^2	0.03076 ± 0.00110	0.03006 ± 0.00003	0.6
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0396 ± 0.0003	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0
A_{PV}	-1.31 ± 0.17	-1.53 ± 0.02	1.3
Q_W(Cs)	-72.62 ± 0.46	-73.17 ± 0.03	1.2
Q_W(Tl)	-116.6 ± 3.7	-116.78 ± 0.05	0.1
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)}$	$3.35^{+0.50}_{-0.44} \times 10^{-3}$	$(3.22 \pm 0.09) \times 10^{-3}$	0.3
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	4511.07 ± 0.82	4509.82 ± 0.10	1.5
τ_τ [fs]	290.89 ± 0.58	291.87 ± 1.76	−0.4

The Standard Model of elementary particles



Elementary particle physics: symmetries and their violations

Principles:

minimal action

relativity

local gauge invariance

quantum uncertainty

…

Laws:

energy-momentum conservation

electric charge conservation

baryon charge conservation

…

Principles and Laws are related with symmetries!

And with their violations!

Principles and Laws in action:

Relativity principle -> special relativity theory

Local relativity principle
-> general relativity (gravity)

Energy conservation
-> neutrino prediction

Pauli principle -> color (strong charge) of quarks

Local gauge invariance principle
-> quantum field theory: the Standard Model

Standard Model: problems

Within the Standard Model:

- Where the Standard Model Higgs boson?
- Новые состояния кварк-глюонной материи?

Beyond the Standard Model:

- Too many parameters: > 20
- Origin of mass of and mass hierarchy?
- Origin of CP-violation?
- Baryon-antibaryon asymmetry of the Universe?
- How incorporate gravity?
- What are the Dark Matter and Dark Energy?

Higgs boson: portal into New Physics

-

The discovered Higgs boson:

- In SM, the Higgs boson's mass is the only free parameter in the Higgs sector – **must be measured**

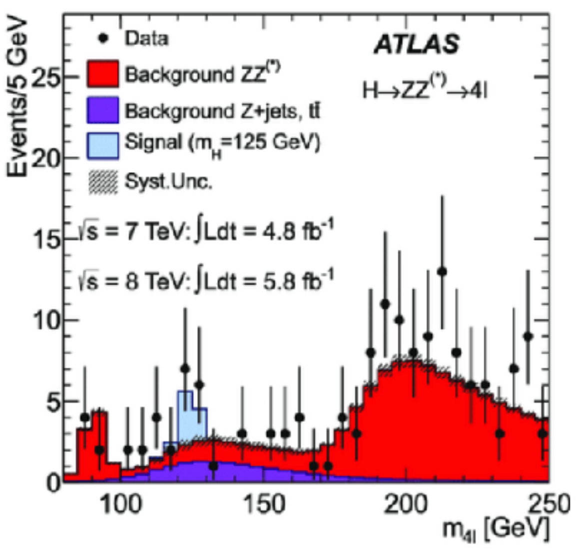
However:

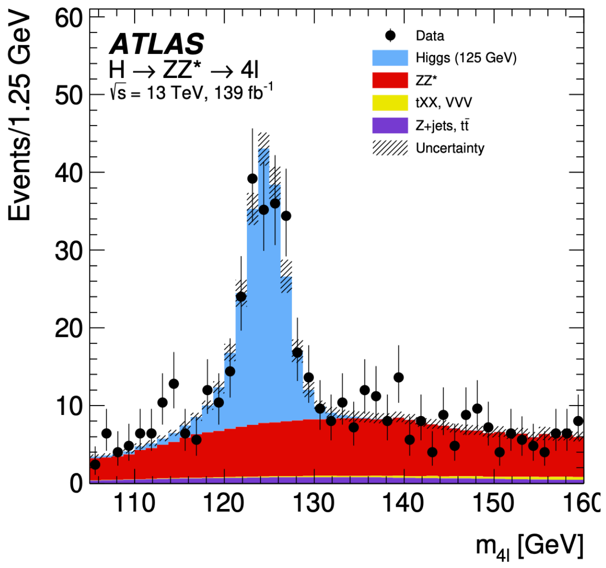
- being a theoretically-problematic oddity (scalar)
- and given its profound role in the SM,
- **Higgs boson just may turn out to be a unique portal to BSM unlike any other SM particle**

CMS has a broad program of searches for BSM associated with the discovered H_{125} :

- are there small deviations in H_{125} couplings to the SM particles?
- is it 100% pure CP-even scalar? is it truly point-like?
- are there BSM production modes? ($t \rightarrow q\mathrm{H}, X \rightarrow \mathrm{HH}$, abnormal non-resonant HH)
- are there BSM decay modes? (H width, H → invisible, H → $\ell\ell'$(CLFV), H → BSM particles)
- And, of course, are there more BSM spin-0 particles? (another scalar, pseudoscalar, $H^{\pm}$, $H^{\pm\pm}$)

Higgs boson: discovery in 2012





Since discovery stat increased x ~30

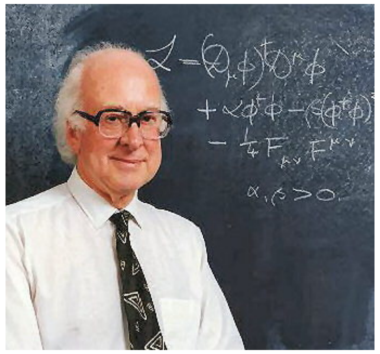
~10M Higgs produced per experiment

ATLAS ~180 papers, CMS ~150 papers published/submitted on Higgs physics after discovery

Entered in the Higgs precision physics era

Spontaneous symmetry breaking

Idea: L.D. Landau, V.L. Ginzburg
Conception: N.N. Bogolyubov – condensed matter
Y. Nambu (1960), J. Goldstone (1961) – particle physics



Brout-Enclert-Higgs mechanism:
- nonrelativistic version: Ph. Anderson (1962)
- relativistic version:

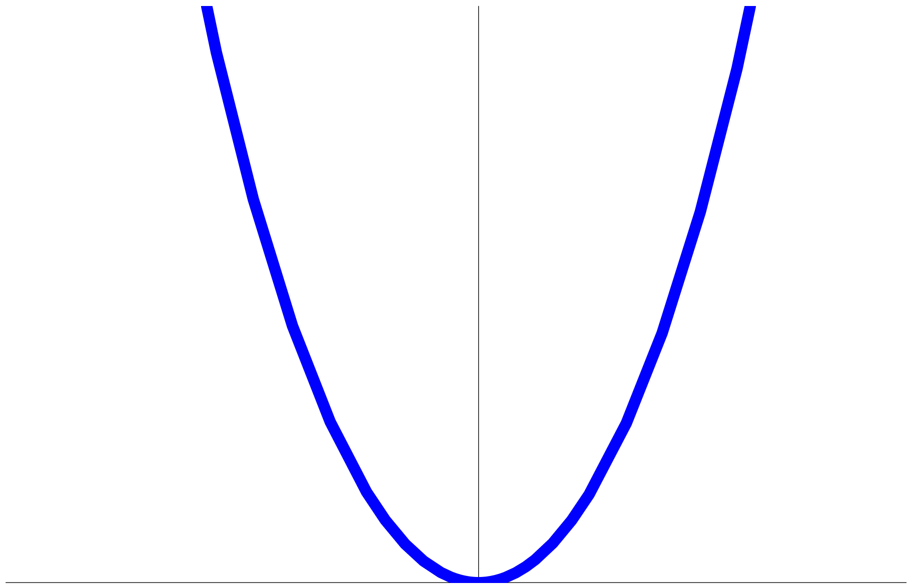
R. Brout, Ph. Engclert (1964)
P. Higgs (1964)
J.Guralnik, K.Hagen, T. Kibble (1964)

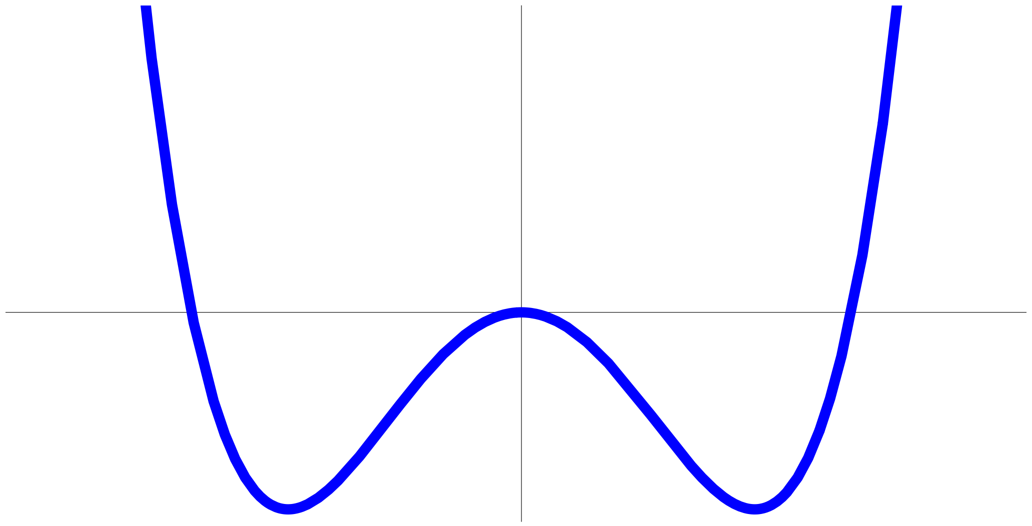
S. Weinberg (1967) и A. Salam (1968) applied Brout-Enclert-Higgs mechanism to electroweak theory of Sh. Glashow (1962)

->

Standard Model with massive W and Z vector bosons

Spontaneous symmetry breaking





$$< H >= 0$$

$$\langle H \rangle \sim \Lambda_{UV}$$

classical
->
symmetric
vacuum ground state

quantum fluctuation
->
nonsymmetric
vacuum ground state

July 2013: SM Higgs boson established!

July 2013, European Physics Society Conference

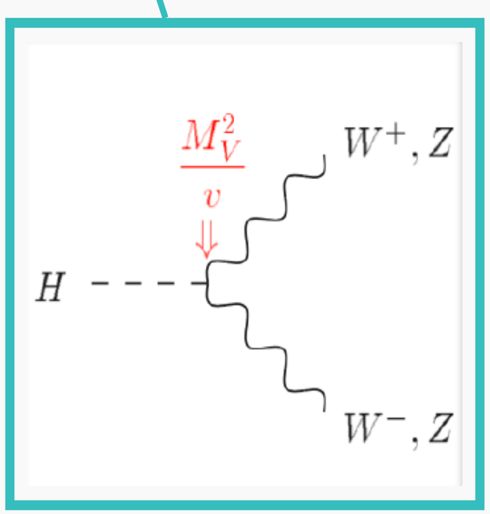
CMS and ATLAS: SM BEH boson 125 GeV

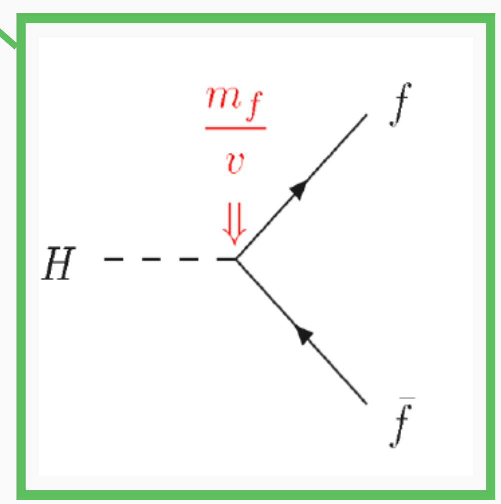
на уровне 7σ

François Englert and Peter Higgs
Photo: © CERN

2013 Nobel Prize in Physics

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$





In the SM, the Higgs mechanism provides masses to bosons and fermions

- Higgs boson discovery in 2012 opens a whole new sector of the Lagrangian
- Yukawa couplings not required by EWSB

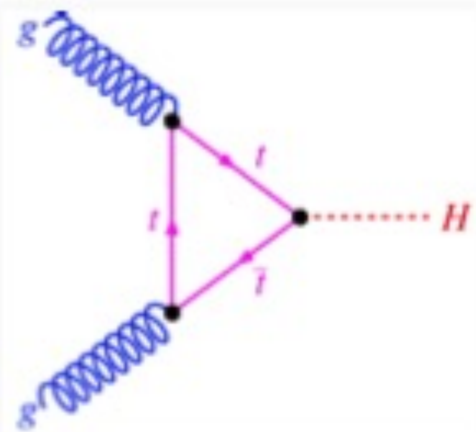
  ⇒ ad-hoc solution to generate fermion masses

Main questions to answer

- Is the SM structure of the Lagrangian correct ?
- Are the values of the couplings as predicted in the SM ?

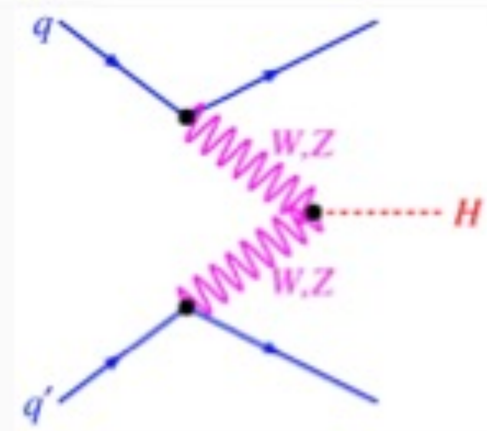
⇒ Broad programme at the LHC

LHC: Higgs boson –> main production modes



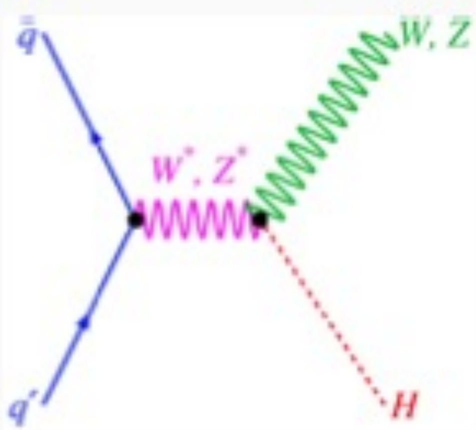
Gluon fusion (ggF)

- Dominant mode (88% of the total)



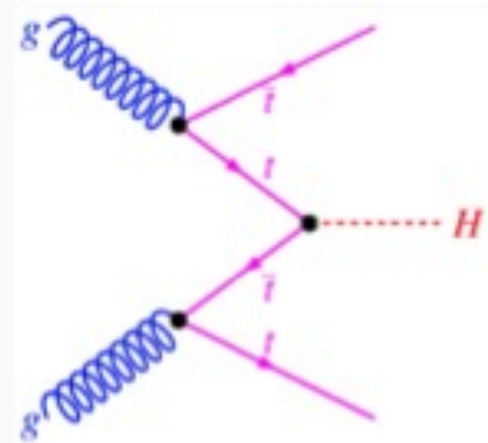
Vector boson fusion (VBF)

- 7% of the total



$VH = WH/ZH$

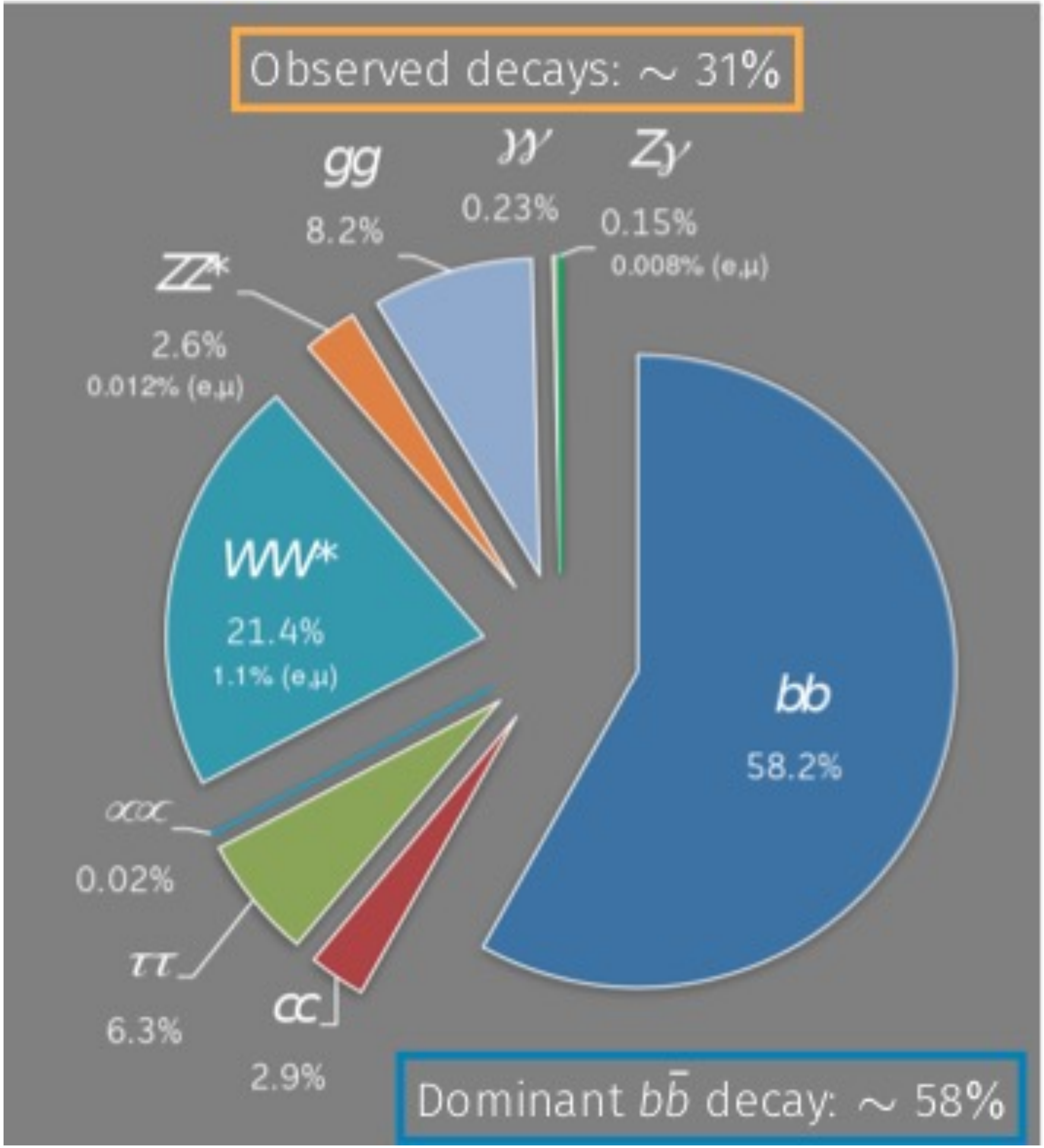
- 3% of the total



$t\bar{t}H$

- 1% of the total

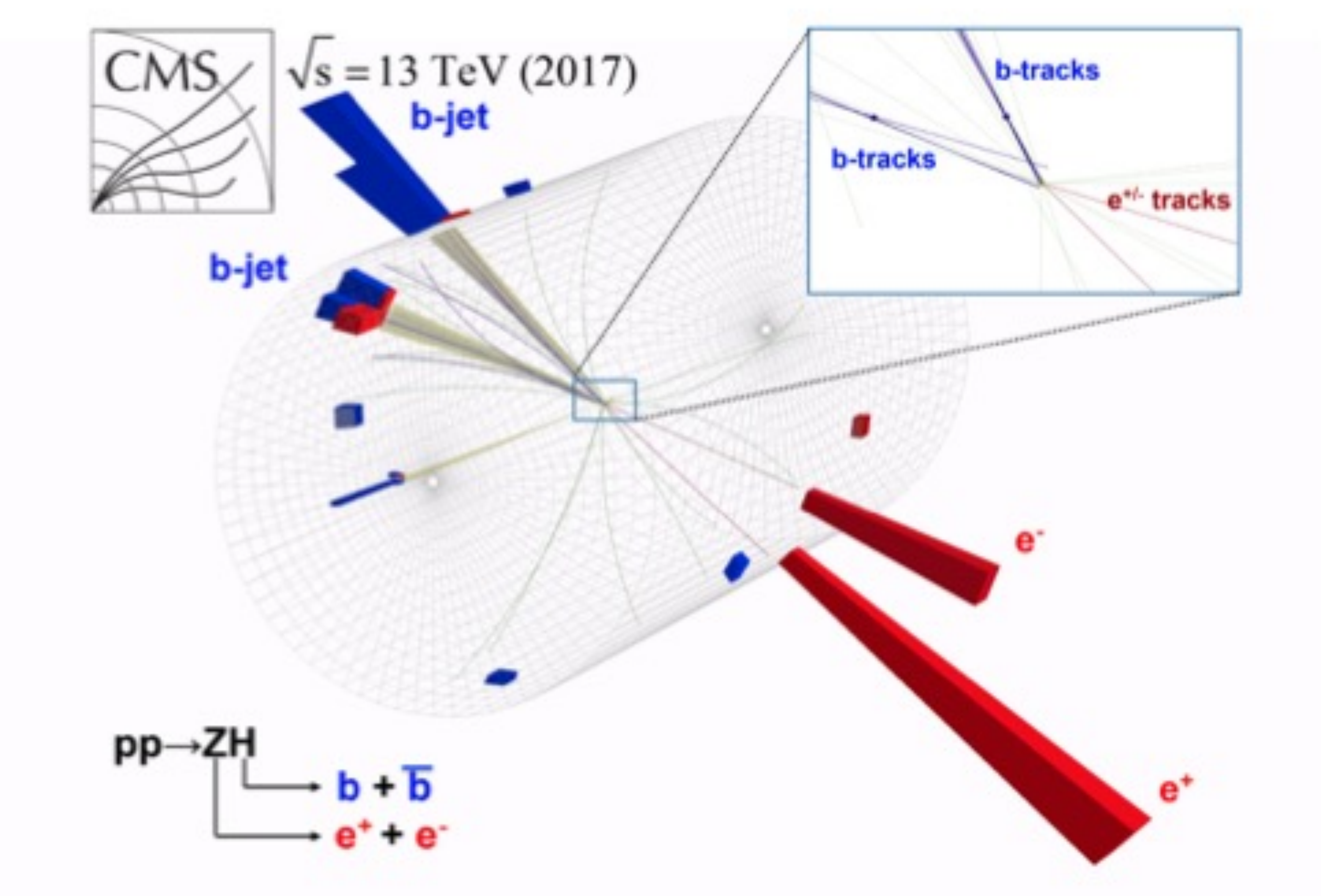
LHC: Higgs boson –> decay modes

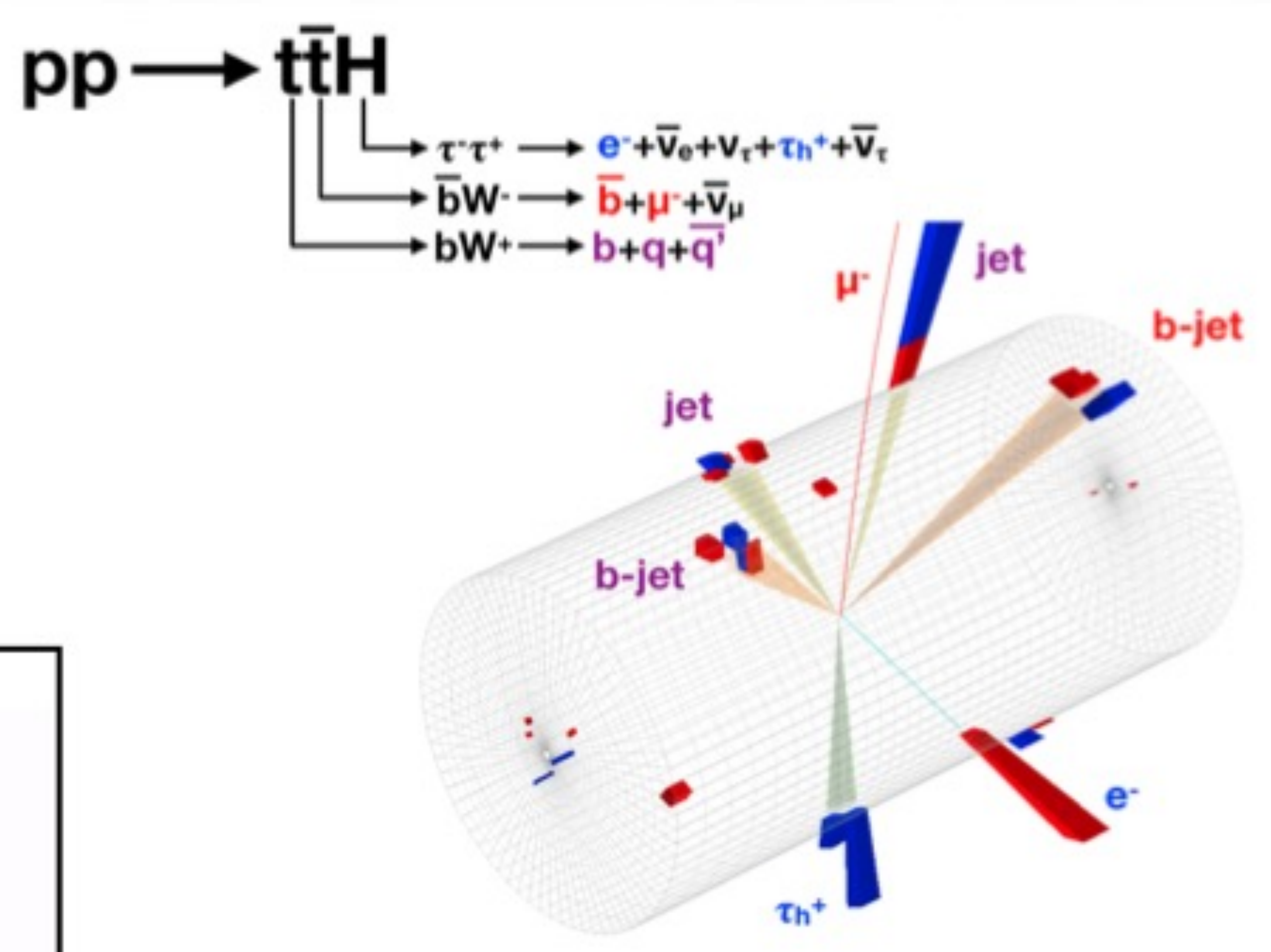


LHC: Higgs boson production with t quarks

Possible thanks to major advances in data analysis strategies that use novel neural network algorithms!

Analysis workflows made more efficient thanks to a more compressed data format.

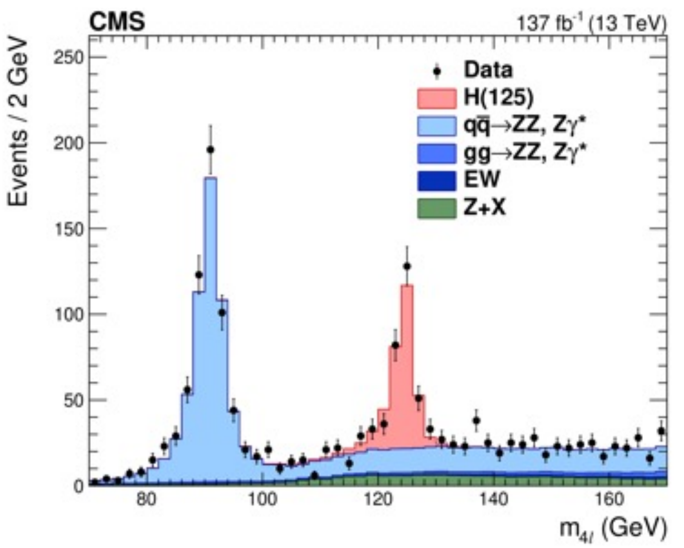




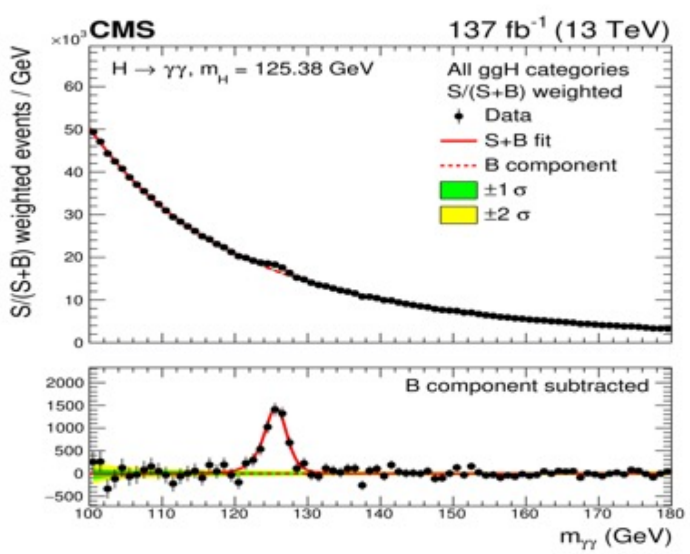
- Higgs boson and top quarks: Phys. Rev. Lett. 120 (2018) 231801
- Higgs boson to bottom quarks: Phys. Rev. Lett. 121 (2018) 121801
- Higgs boson to tau leptons: Phys. Lett. B 779 (2018) 283

Higgs boson: mass

$H \to ZZ \to 4\ell$ [Run 2]



$H \to \gamma\gamma$ [Run 2]



$H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$ are workhorse channels

Run 1 + 2016 results: 125.38 ± 0.14 GeV PLB 805 (2020) 135425

still the most precise

$H \to ZZ \to 4\ell$:	125.26 ± 0.20(stat) ± 0.08(syst) GeV	JHEP11(2017)047
$H \to \gamma\gamma$:	125.78 ± 0.18(stat) ± 0.18(syst) GeV	PLB 805 (2020) 135425

Statistical powers of the two channels are similar

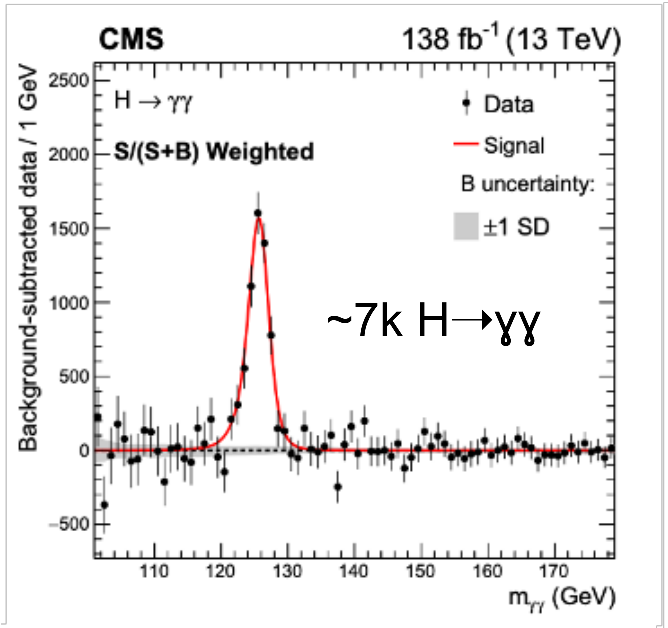
Emerging challenge in $H \to \gamma\gamma$: syst. uncertainties become a limiting factor

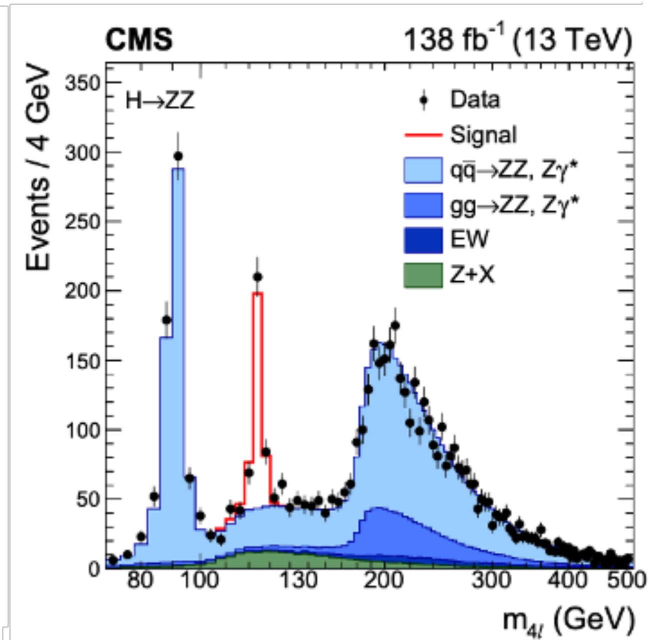
Run 2: Results in 2023, *expect precision <100 MeV*

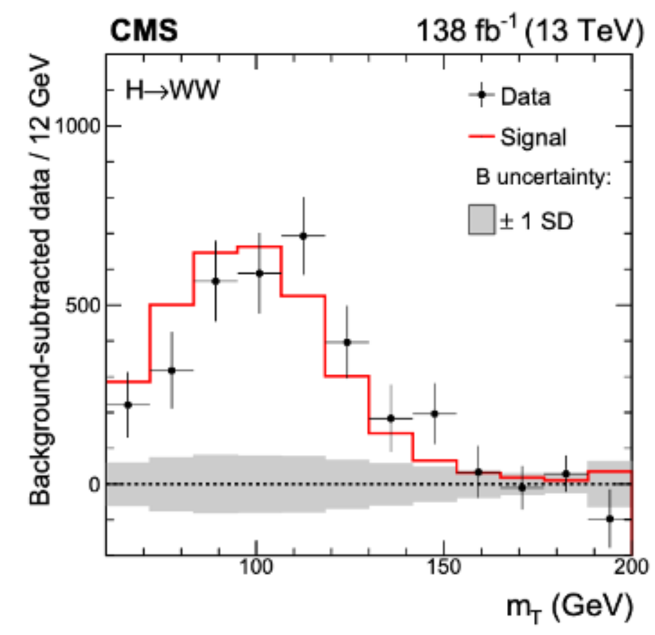
HL-LHC: Expected precision ~20 MeV CMS PAS FTR-21/007 and 21/008

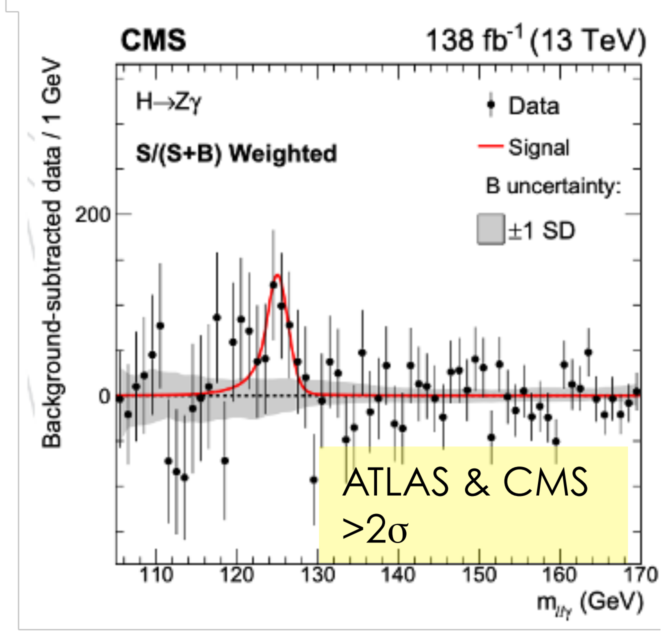
Higgs boson: coupling with bosons and fermions

H→bosons

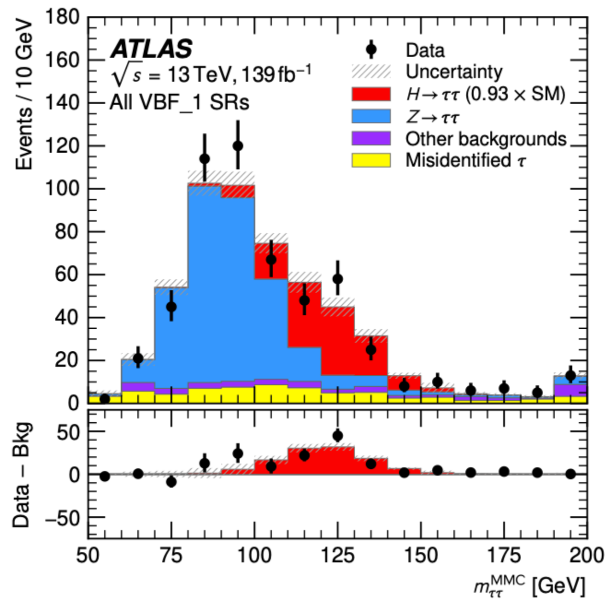


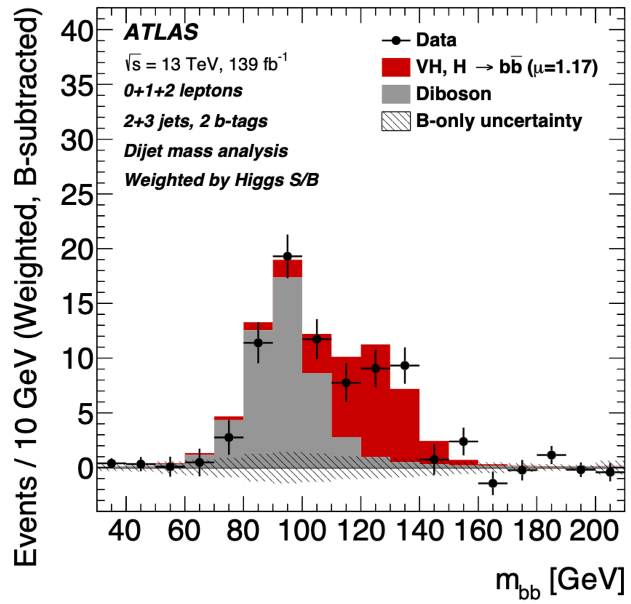


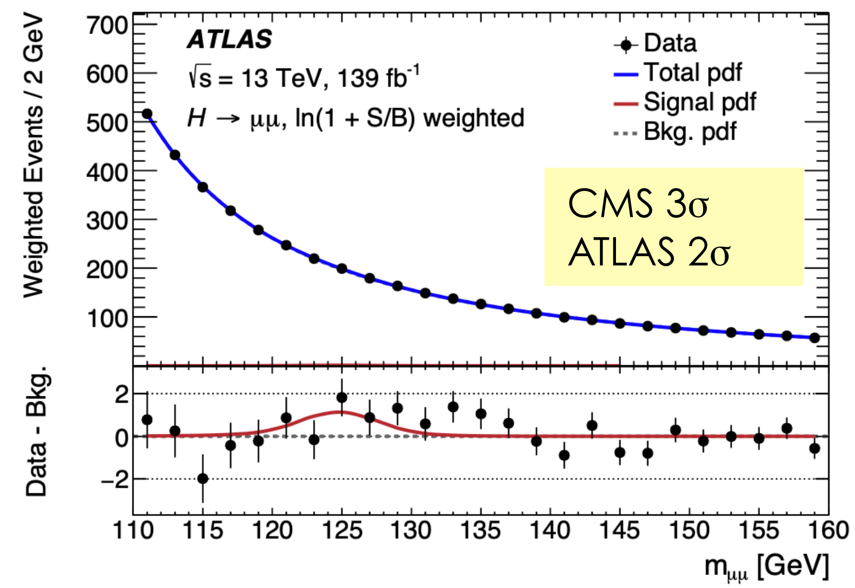




H→fermions





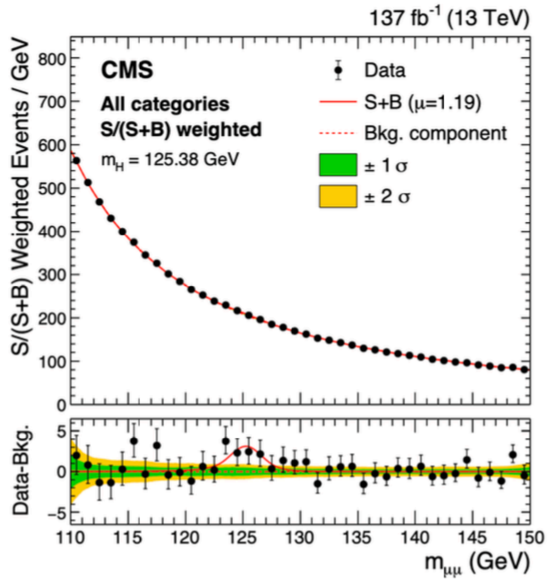


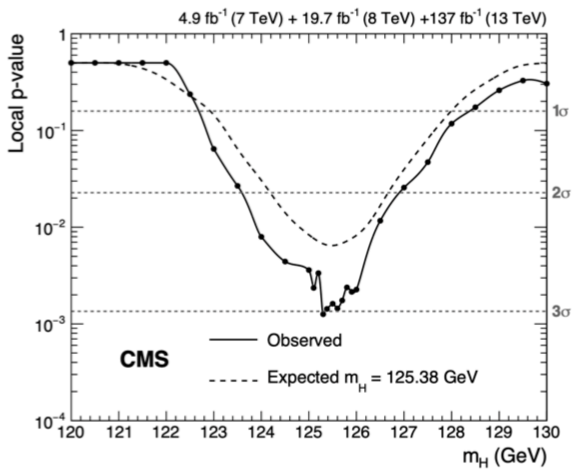
Agreement with the SM within available uncertainties

Recent results: coupling with 2nd generation

H→μμ

ATLAS: PLB 812 (2021) 135980
CMS: JHEP 01 (2021) 148





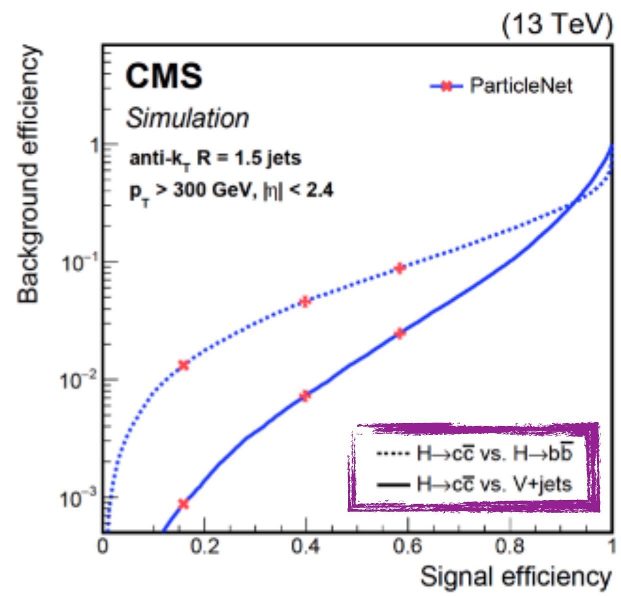
First evidence for coupling with 2nd generation fermions

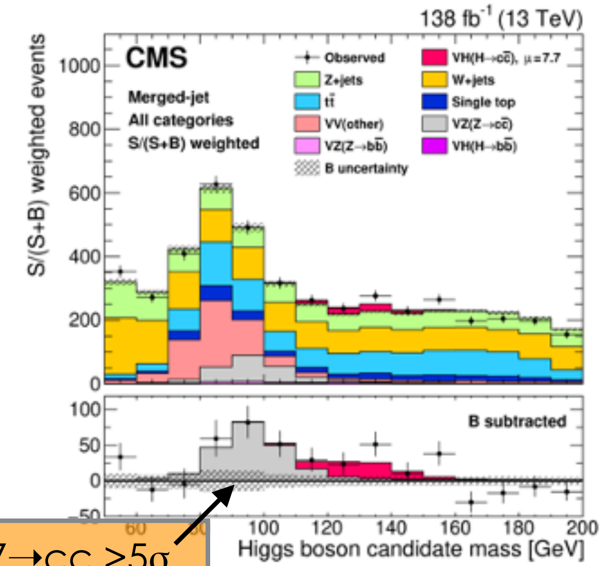
ATLAS: **2.0σ** (1.7 exp) μ=1.2 ± 0.6

CMS: **3.0σ** (2.4 exp) μ=1.19 ± 0.43

H→cc

ATLAS: Eur. Phys. J. C 82 (2022) 717
CMS: arXiv:2205.05550





Z→cc >5σ

One of the most striking progress in Run2:
Reached sensitivity to ~ x8 SM (BR H→cc 0.029)

Huge improvement thanks to novel H→cc taggers

Agreement with the SM within available uncertainties

Higgs boson: decay width

Higgs width from off-shell production: a breakthrough after Higgs discovery

– ~10% of H→ZZ off-shell (m_{ZZ}>200 GeV), negative interference with SM continuum

Ratio off-shell to on-shell sensitive to Γ_H

$$\sigma^{\mathrm{on-shell}}_{\mathrm{gg\to H\to VV}} \sim \frac{g^2_{\mathrm{Hgg}} g^2_{\mathrm{HVV}}}{m_{\mathrm{H}} \Gamma_{\mathrm{H}}}$$

Γ^{SM}_{H} = 4.07 MeV

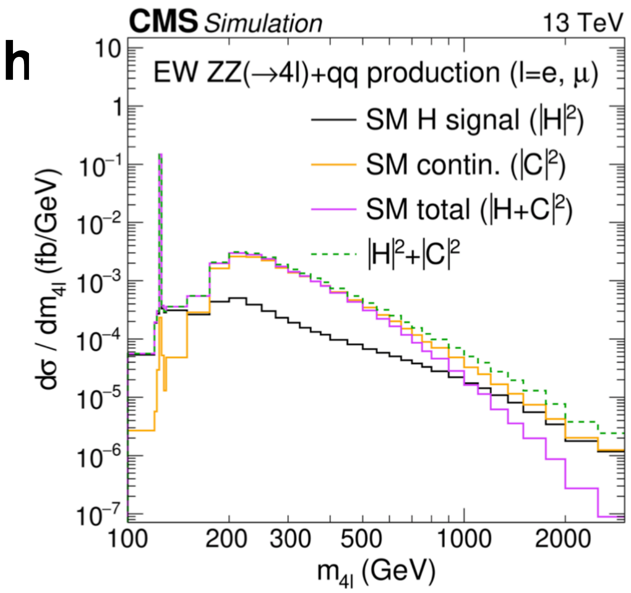
$$\sigma^{\mathrm{off-shell}}_{\mathrm{gg\to H\to VV}} \sim \frac{g^2_{\mathrm{Hgg}} g^2_{\mathrm{HVV}}}{m^2_{\mathrm{VV}}}$$

Main assumption: same on/off-shell couplings

CMS $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

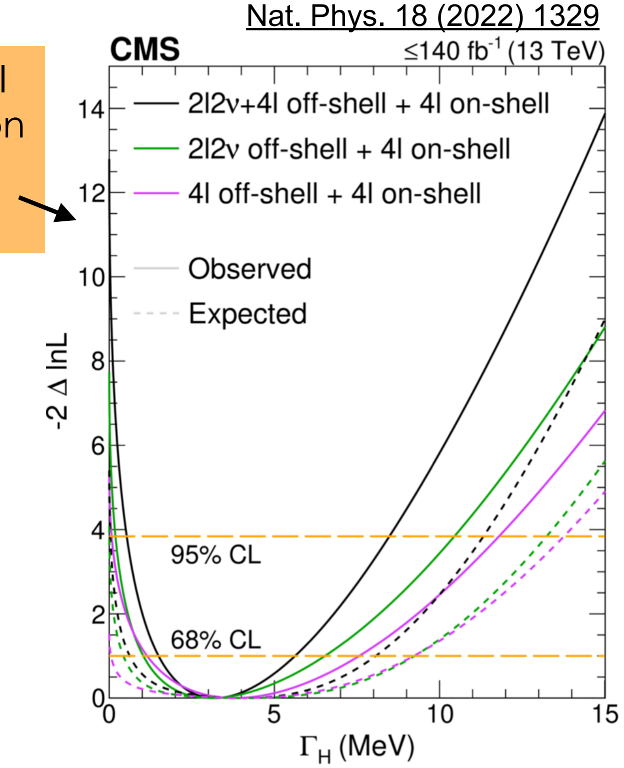
ATLAS $\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV

ATLAS-CONF-2022-068



Nat. Phys. 18 (2022) 1329

No off-shell contribution excluded at 3.6σ

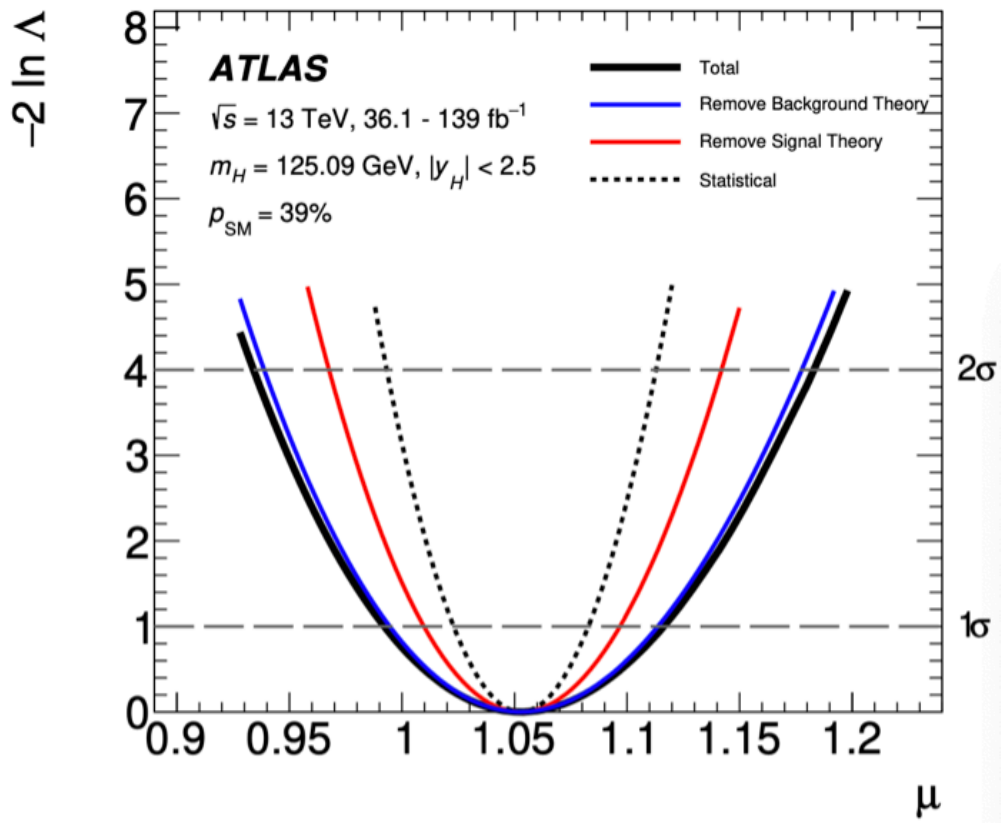


Interference with off-shell Higgs boson

Higgs boson: signal strength

Fit data from all production modes and decays with a common signal strength wrt SM

$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$



ATLAS Run2 $\mu = 1.05 \pm 0.04(th) \pm 0.03(exp) \pm 0.03(stat)$

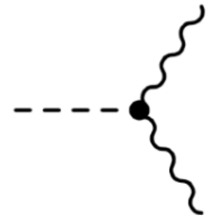
CMS Run2 $\mu = 1.002 \pm 0.036(th) \pm 0.033(exp) \pm 0.029(stat)$

ATLAS+CMS Run1 (20+20 fb^{-1} @ 8 TeV) $\mu = 1.09 \pm 0.07(sig.\ th) \pm 0.03(bkg.\ th) \pm 0.04(exp) \pm 0.07(stat)$

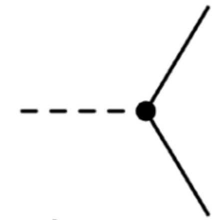
JHEP 2016, 45 (2016)

Agreement with the SM within available uncertainties

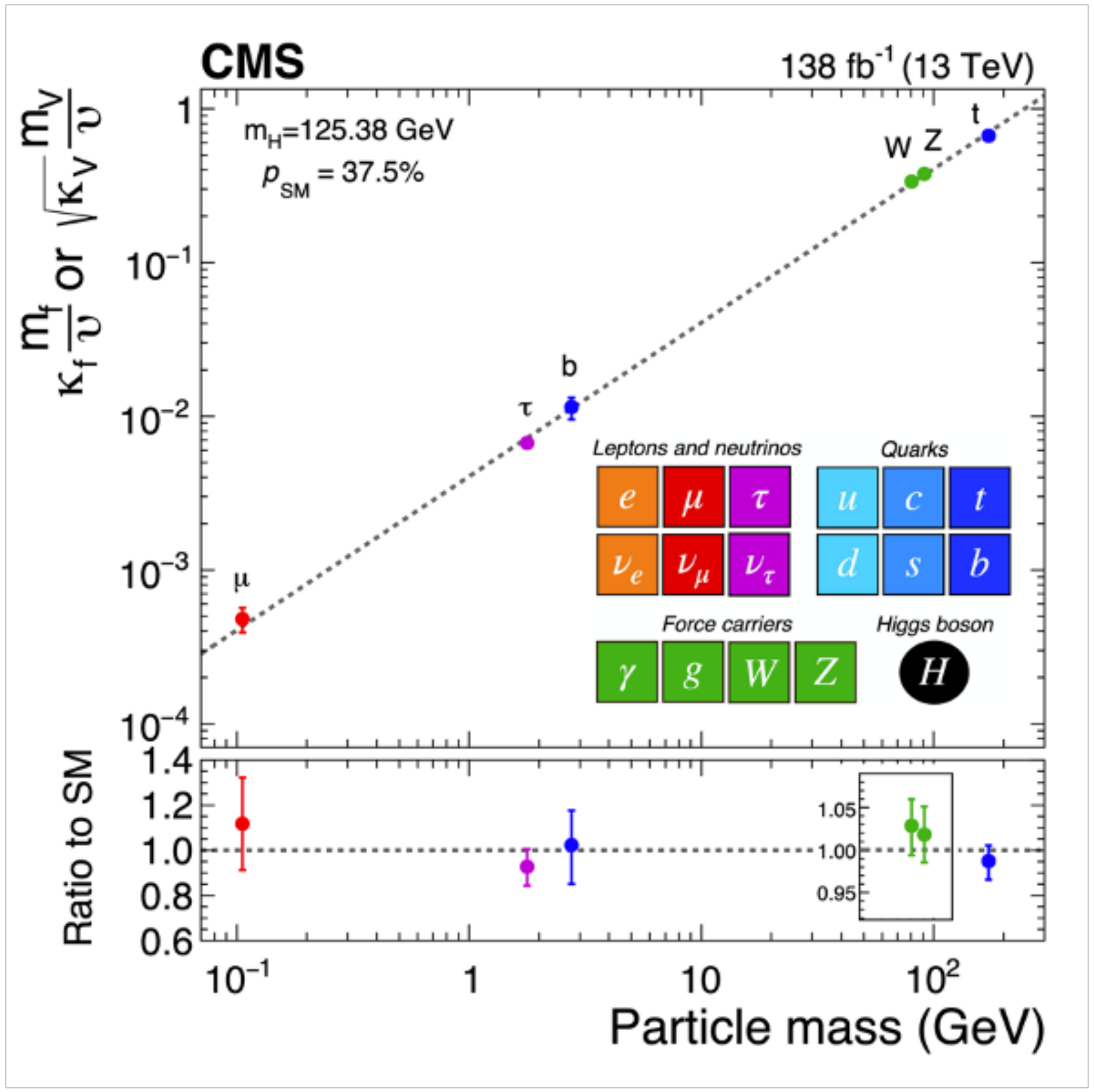
Higgs boson: coupling with the SM particles

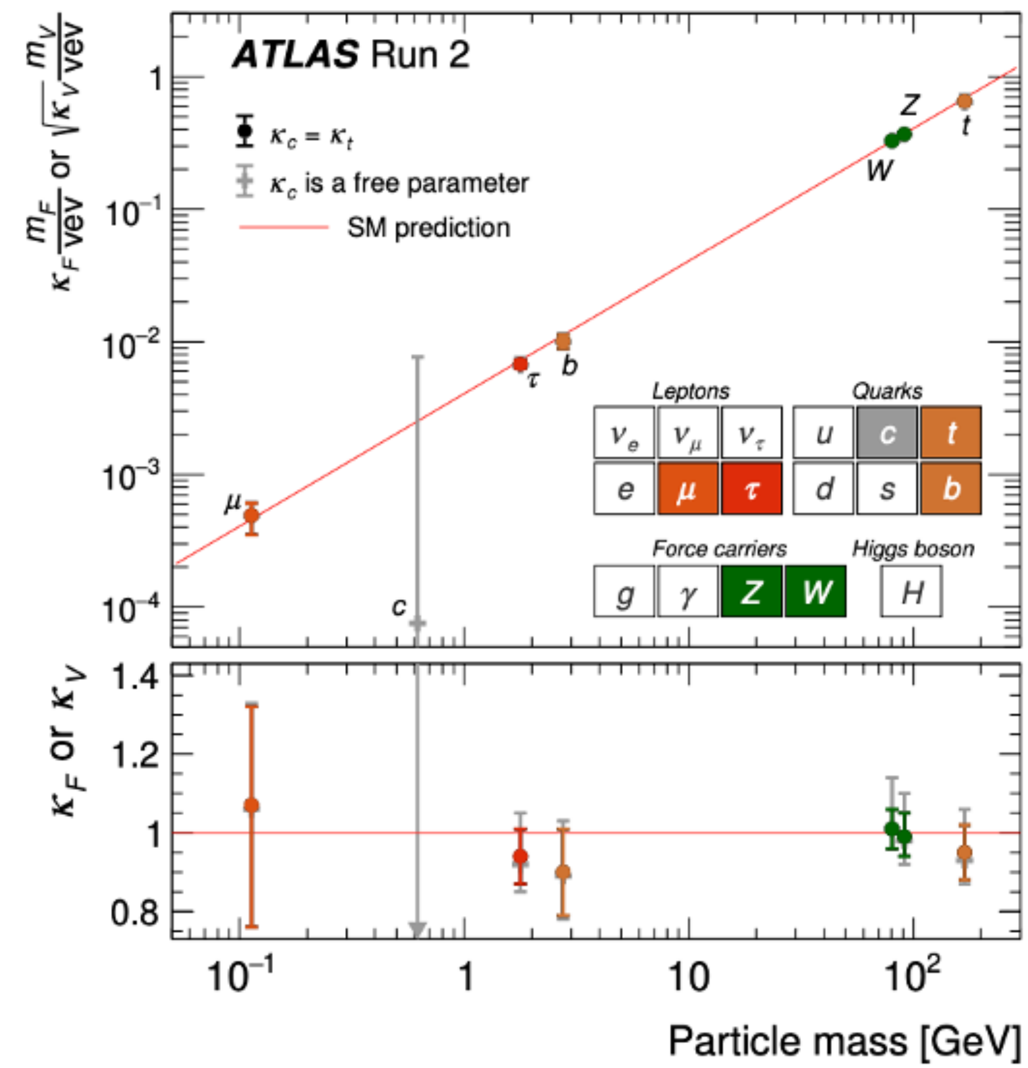


$$g_V = 2\frac{m_V^2}{v}$$



$$g_F = \sqrt{2}\frac{m_f}{v}$$





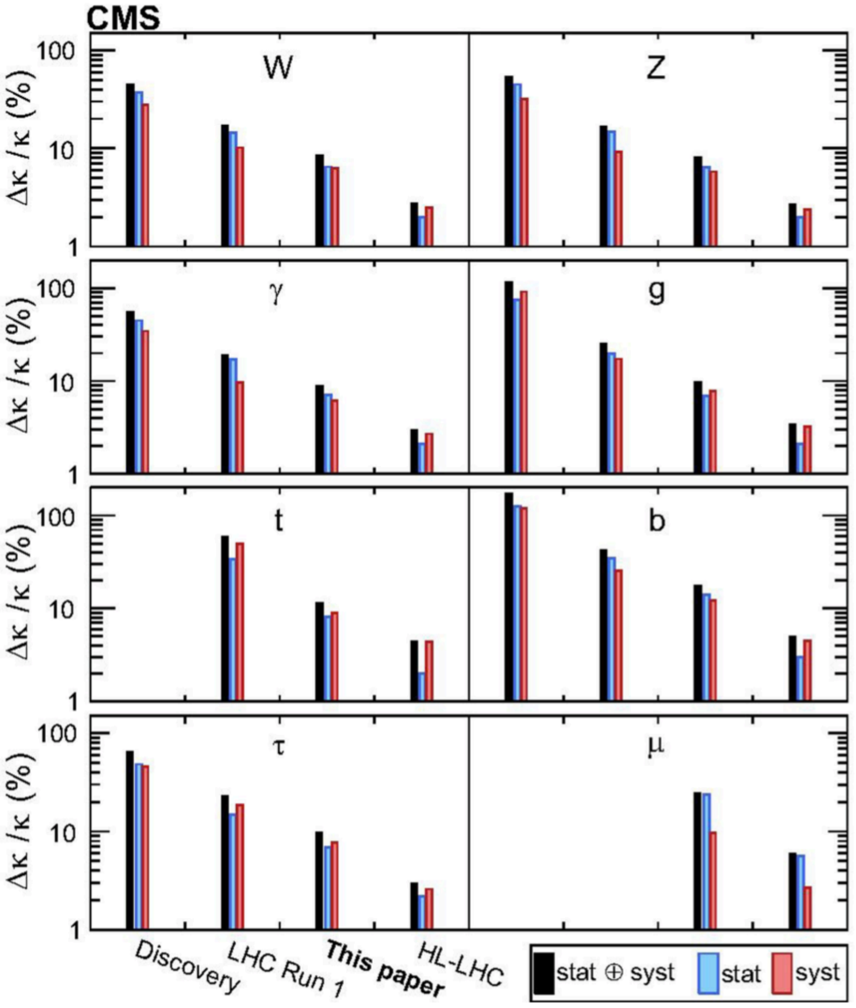
Agreement with the SM
within available uncertainties

Higgs boson: precision physics

The ATLAS/CMS Higgs Run2 legacy: entered the Higgs precision physics era

- Mass at 0.1%
- Boson couplings known at ~5%, ~10% for heaviest fermions
- Huge progress to look for 2nd generation couplings, self-coupling, anomalous BSM couplings

These performance are much better than what expected just 10 years ago: theory & experiment interactions a game changer



Run3: double Run2 stat, ~300 fb^{-1}@13.6 TeV

From 2029 HL-LHC: up to 4000 fb^{-1}, ATLAS/CMS detector upgrades

- ~180M Higgs/experiment by end of HL-LHC
- Prospects are very high
- Projections keep improving (thanks to better delivered analysis sensitivities)

A possible deviation from the SM: New Physics indication

Running masses in the standard model

Running couplings: α_{QCD}, α_{EW}

Running masses

Different mass parameterizations
(different approaches to include higher orders):
- pole (on-shell) mass
- running mass

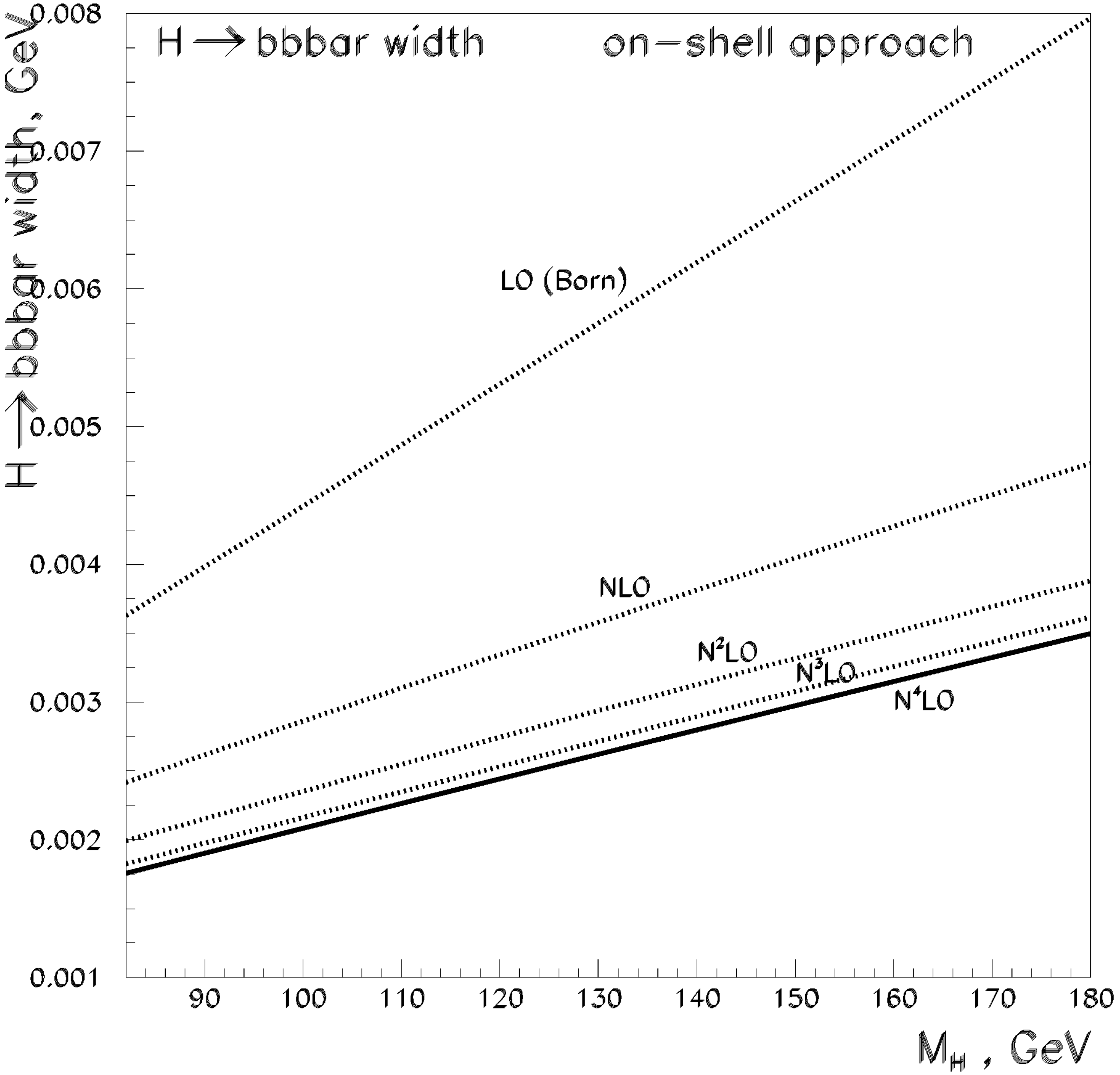
SM running masses
- fermions and vector bosons: logarithmic
- scalar Higgs boson: logarithmic or/and quadratic ?
quadratic -> “non-naturalness”

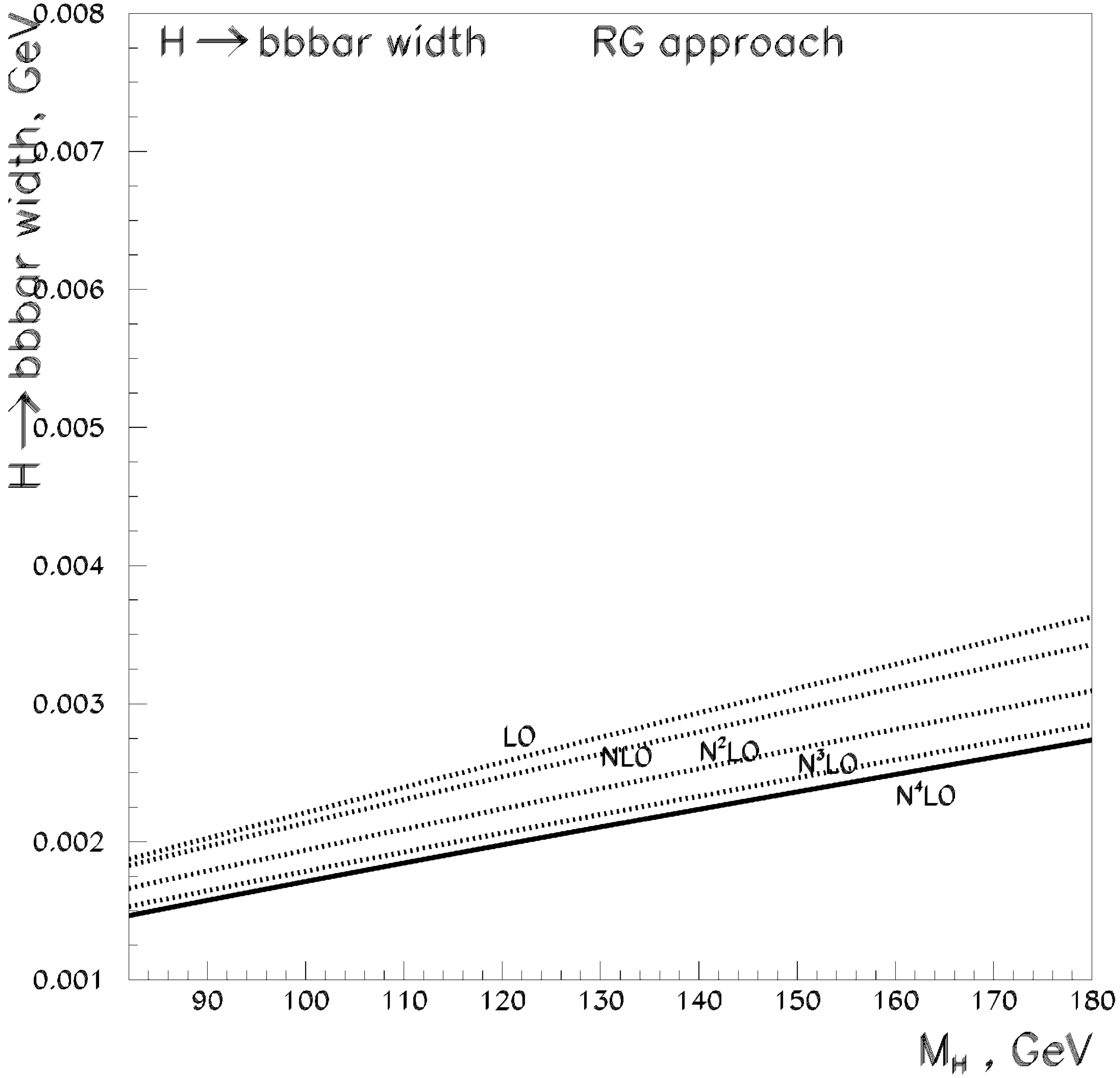
Higgs boson decay width

Width of Higgs boson decay into b-quarks (up to N^4LO)

P. Baikov, K. Chetyrkin, J. Kuhn (2006)

A. Kataev, V. K. (2008)





b-quark mass - 4.5 GeV Upsilon

- 2.8 GeV Higgs boson

Standard Model with 125 GeV Higgs boson

Higgs boson: if logarithmic mass evolution

Higgs boson defines electroweak vacuum density
(meta)stable vacuum up to Planck scales

F. Bezrukov, M. Kalmykov, B. Kiehl & M. Shaposhnikov, JHEP 10 (2012) 140

One may conclude:
(Almost) no need for a New Physics up to Planck scales
Only needs:
- (~ 1 GeV) BSM neutral leptons to explain Dark Matter
- strong CP-problem
- neutrino masses
- baryon-antibaryon asymmetry

...

- and still explain why there is naturalness (New Physics?!)

Standard Model with 125 GeV Higgs boson

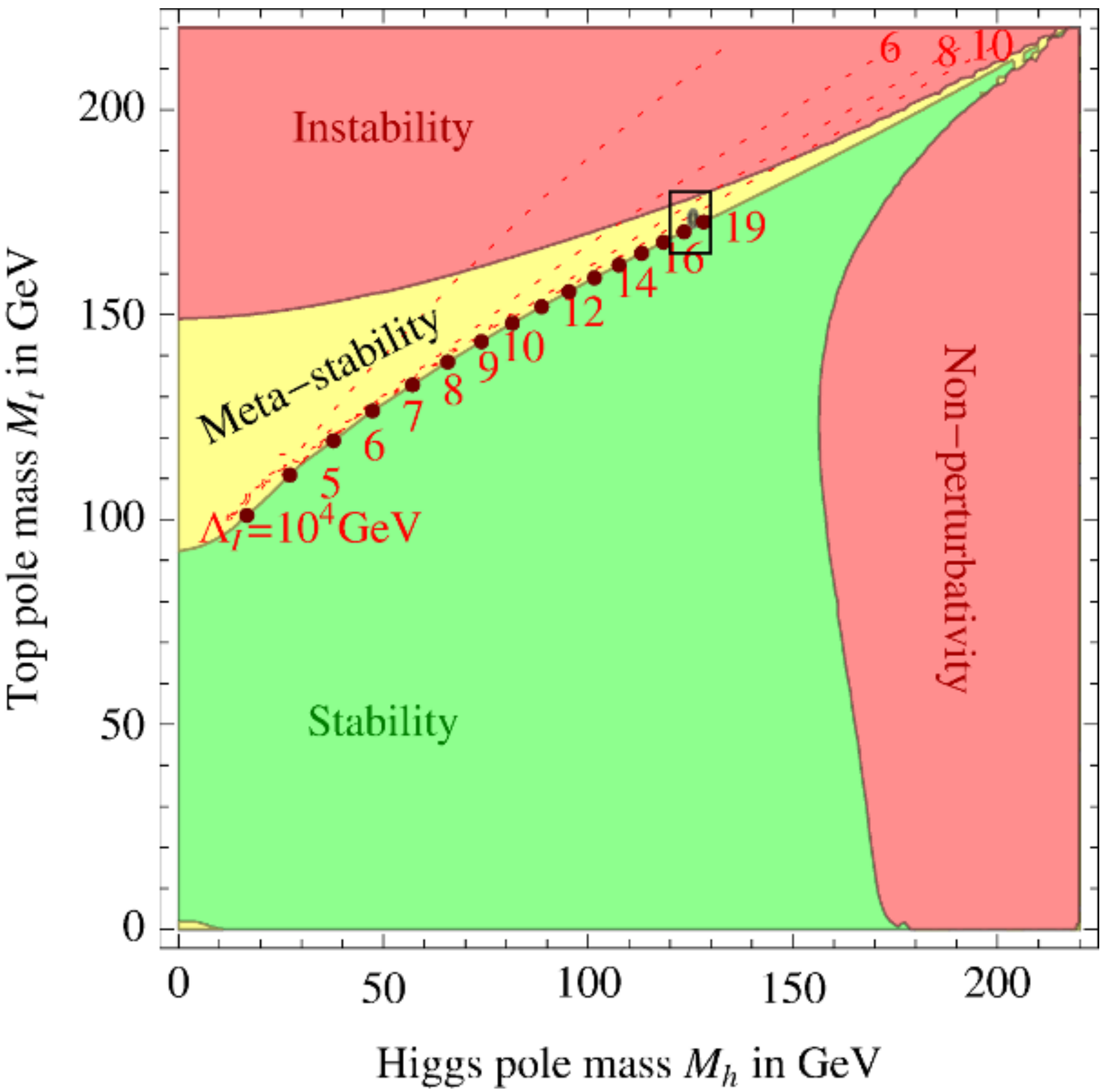
Higgs boson mass defines electroweak vacuum density

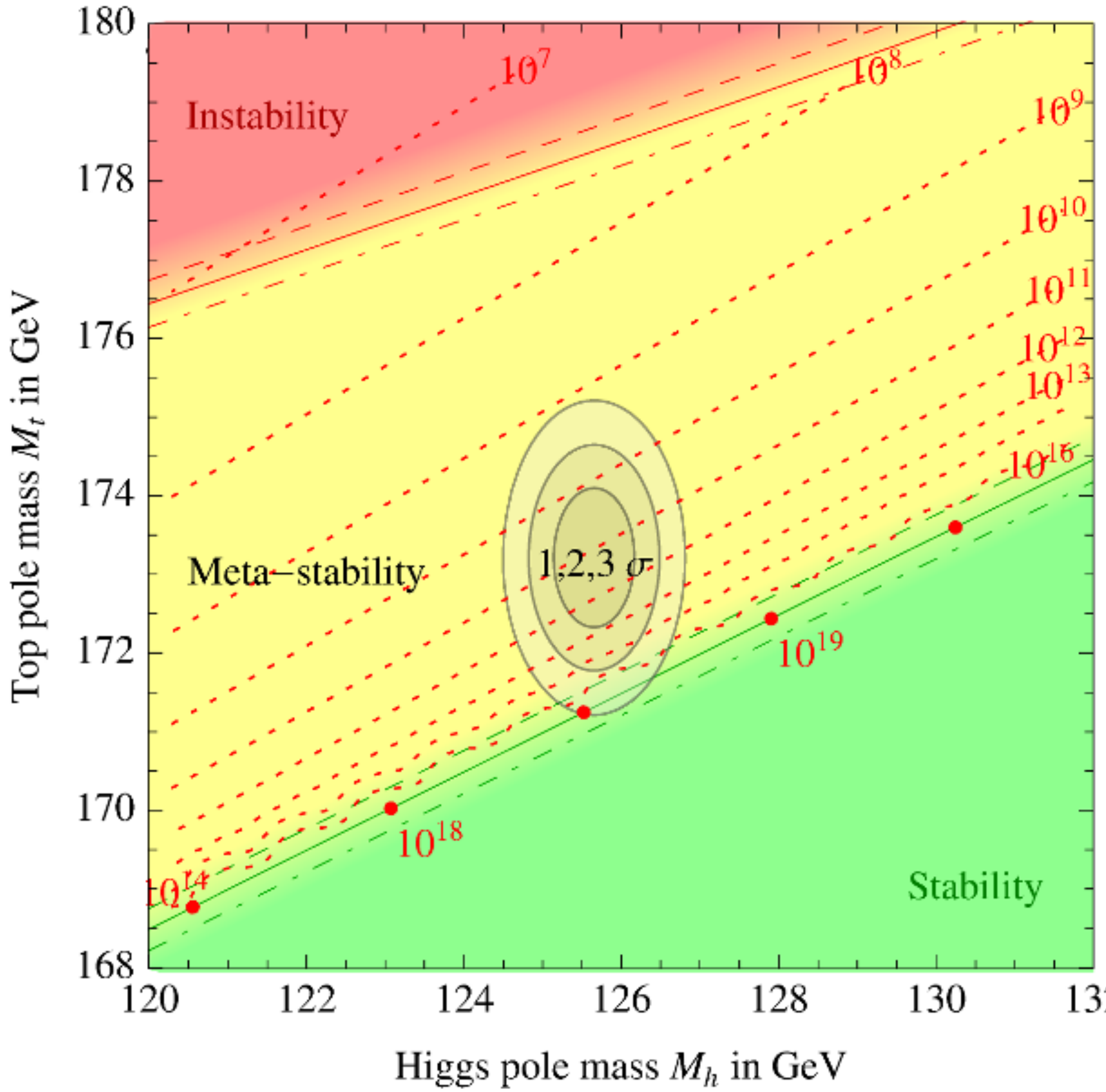
Meta-stable vacuum

G. Degrassi et al., JHEP 08 (2012) 098

D. Butazzo et al., JHEP 12 (2013) 089

A. Bednyakov et al., Phys. Rev. Lett. 115 (2015) 201802





(Non-)Naturalness of the standard model

Logarithmic evolution of theory parameters: weak dependence between low and very large scales -> concept of "Naturalness"

- **Scalar field is simple, but "non-natural": scalar mass evolution is quadratic, not logarithmic**

  K. Wilson, Phys. Rev. D3 (1971) 1818
  L. Susskind, Phys. Rev. D20 (1979) 2619

- **Scalar field is not protected by a symmetry, while fermions are protected by chiral symmetry**

  G. 't Hooft, Proc. Cargese Summer Inst. (1980)

for reviews see G. Giudice, (2008)

Naturalness of the Standard Model in 1-loop

M. Veltman, Acta Phys. Pol. B12 (1981) 437

renormalization scheme dependence for scalar particles:

$$m_H^2 = m_0{}_H^2 + C_L(\lambda_i, m_i) \cdot \log\left(\frac{\Lambda_{UV}^2}{m^2}\right) + C_X(\lambda_i, m_i) \cdot \Lambda_{UV}^2$$

"physical" schemes $\rightarrow C_X \neq 0$

schemes with dim. regularization ($\overline{\text{MS}}$, ...) $\rightarrow C_X = 0$

MSbar reproduces quadratic divergence at D = 2, L=1

$$m_H^2 = m_{H0}^2 + \delta m_H^2 \qquad v = 246\,\text{GeV}$$

$$\delta m_H^2 \approx \frac{\Lambda^2}{16\pi^2}\left(24 y_t^2 - 6(2y_W^2 + y_Z^2 + y_H^2)\right) \sim 8.2\frac{\Lambda^2}{16\pi^2} \qquad y_i \equiv \frac{m_i}{v}$$

Non-naturalness of Higgs boson at Λ > 550 GeV (Veltman criterion):

$$\delta m_H^2 \approx m_H^2 \qquad (\Lambda = 550\,\text{GeV},\ m_H = 125\,\text{GeV})$$

Naturalness of Standard Model

Barbieri-Giudice (BG) condition:
sensitivity physical parameters for small variation of bare ones
R. Barbieri, G.F. Giudice, Nucl. Phys. B306 (1988) 63

Using BG condition with both quadratic and logarithmic contributions leads to extention of Naturalness domain of SM: up ~ O(10 TeV) instead of ~ O (1 TeV)
VK, G. Pivovarov, Phys. Rev. D78 (2008) 016001

Regular way for scalar boson mass evolution with quadratic mass divergences
G. Pivovarov, Phys. Rev. D81 (2010) 076077

Landau pole like in λH^4:

$$\lambda(Q) \simeq \frac{\lambda(v)}{1 - \frac{3}{4\pi^2}\lambda(v)\ln\left(Q^2/v^2\right)}$$

SM with "non-natural" Higgs boson

Proper physical consideration with quadratic evolution for Higgs boson mass:

Higgs boson observables (mass, self-coupling, EW vacuum density) gets critical values at larger scales than in popular "standard" treatments with scale ~ O(1 TeV)

-> only at the scales ~ O(10 TeV) one should expect new physics manifestations:
- **new strong EW dynamics**
- **or/and New Physics beyond Standard Model**

G.B. Pivovarov, V.K. (2008)
V.K. (2023)

New Physics: direct and indirect searches

New physics within the Standard Model:

- new quark-gluon matter states
- new hadron states: pentaquarks, tetraquarks, ...
- new asymptotic regime: BFKL
- new hadron spin properties
- ...

New physics beyond the Standard Model:

- new particles and interactions:
  - -direct
  - -indirect (via virtual contributions): EDM, rare decays, g-2,..

INP KZ (NA62, HIKE)

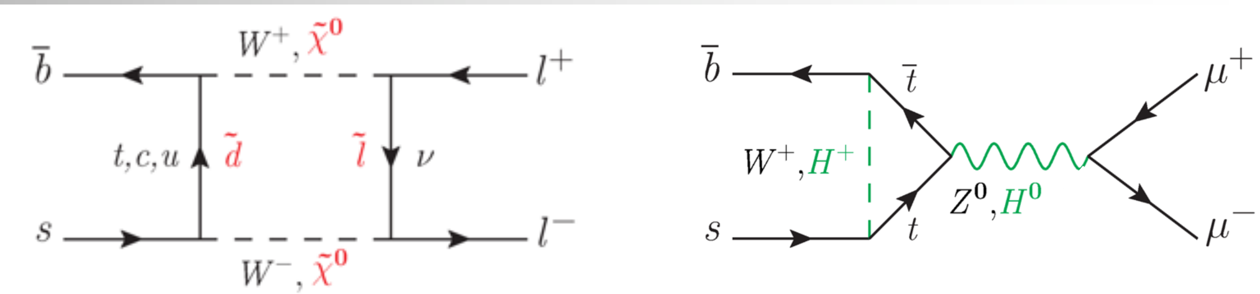
Indirect searches for New Physics: rare B-meson decays

SM and BSM: $B \to \mu\mu$

CMS PAS BPH-21-006
(Dec 20, 2022)
[Run 2]

Motivations:

- $B \to \mu\mu$ is highly suppressed in SM, which can make BSM-induced decays more visible



Examples of Feynman diagrams: black – SM particles
red/green - BSM

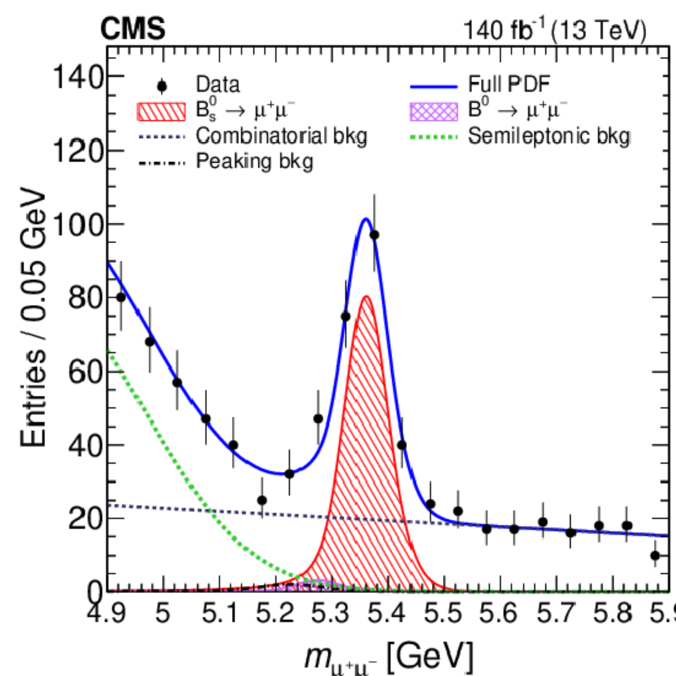
Analysis:

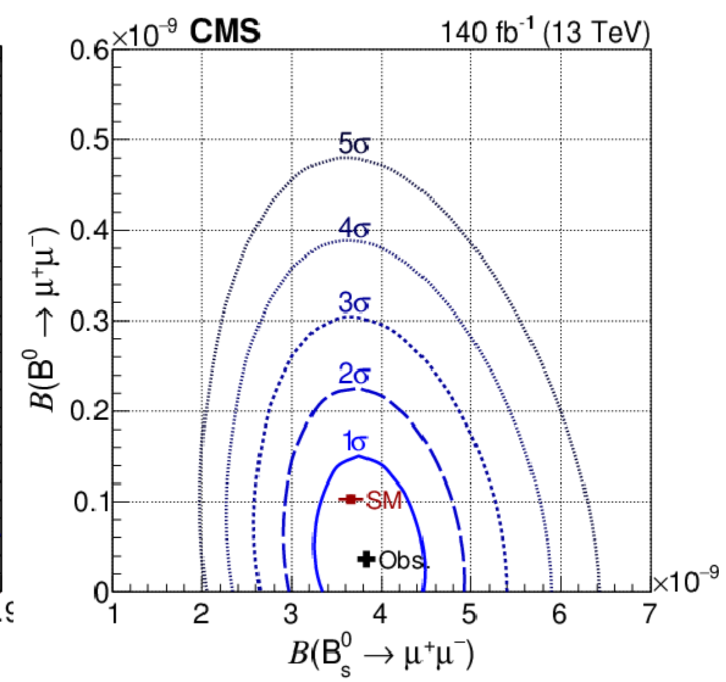
- Two muons, forming a common displaced vertex
- MVA to suppress backgrounds. Main bkgs:
  - muons from different heavy-flavor mesons
  - muons from B-meson cascade decays
  - $B \to K\pi, B_s \to KK$ (mis-id)

Results:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left[4.02^{+0.40}_{-0.38}\,(\text{stat})\,^{+0.28}_{-0.23}\,(\text{syst})\,^{+0.18}_{-0.15}\,(\mathcal{B})\right] \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.5 \times 10^{-10} \text{ at 90\% CL}$$

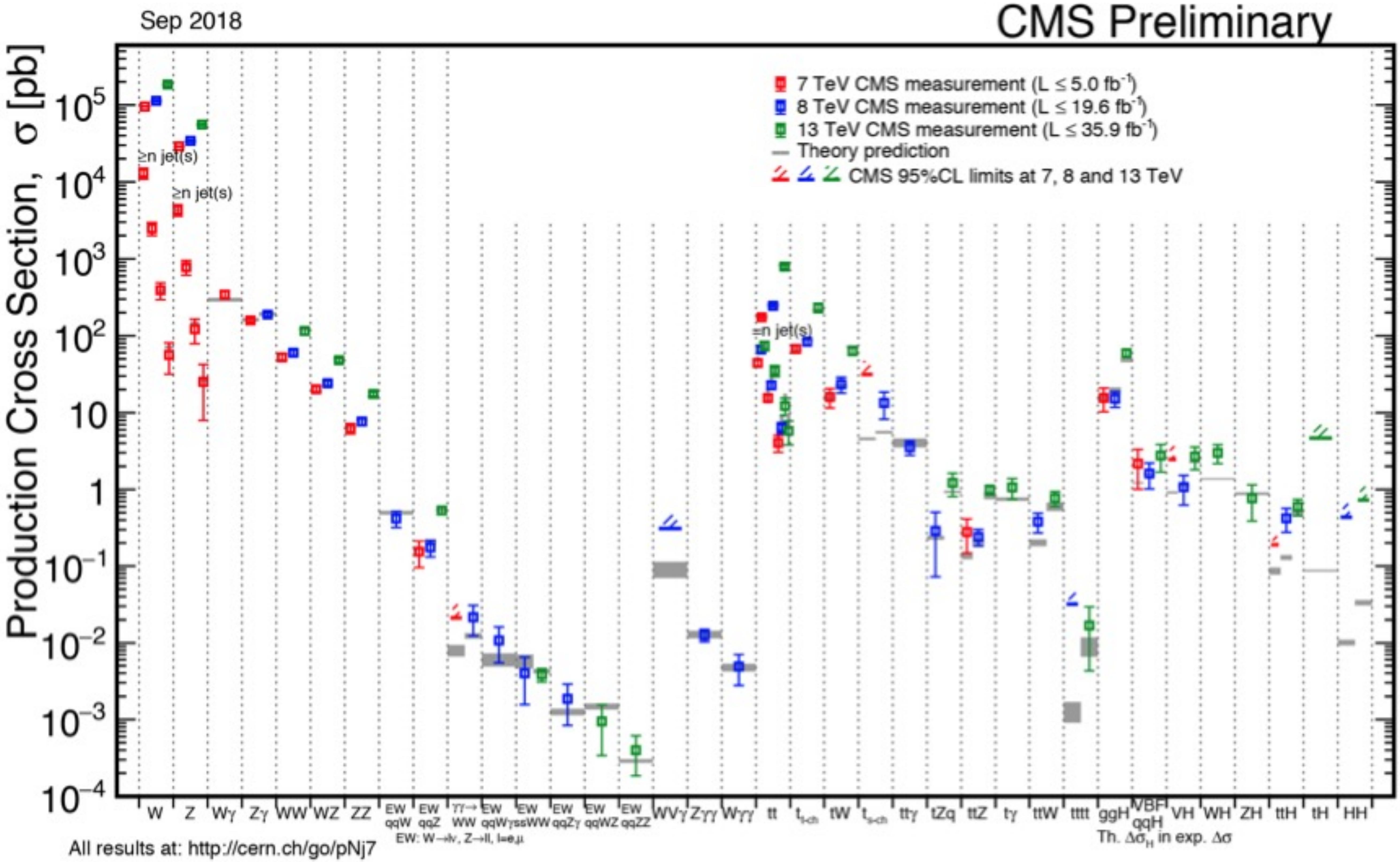




Both agree with the SM and are the most precise to date

Agreement with the SM within available uncertainties

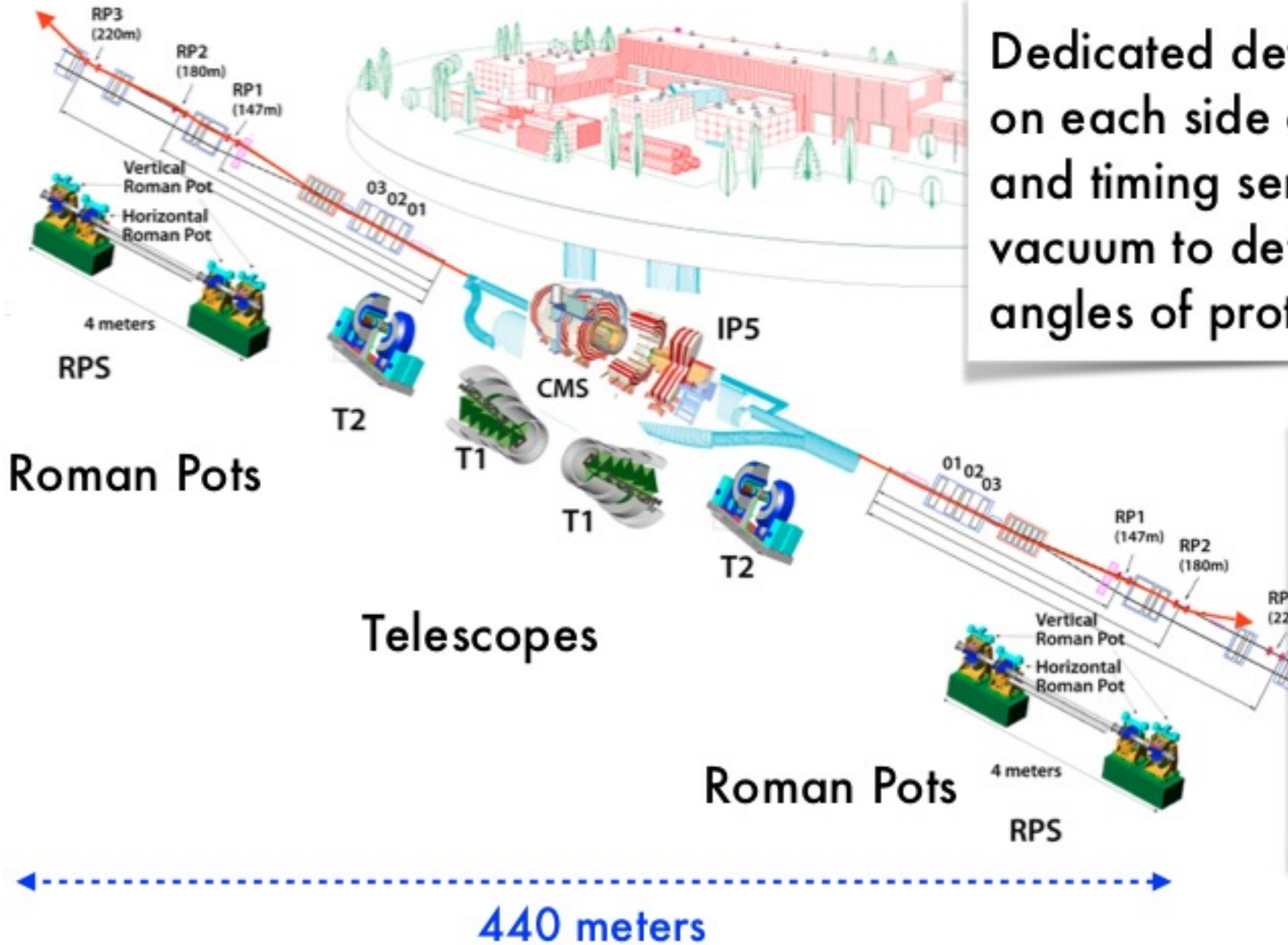
LHC: SM precision measurements



LHC: TOTEM experiment (unified CMS)

Total & Elastic Cross-Section Measurements Experiment

Designed to measure protons that emerge intact from the LHC collisions at small angles due to elastic or diffractive physics processes



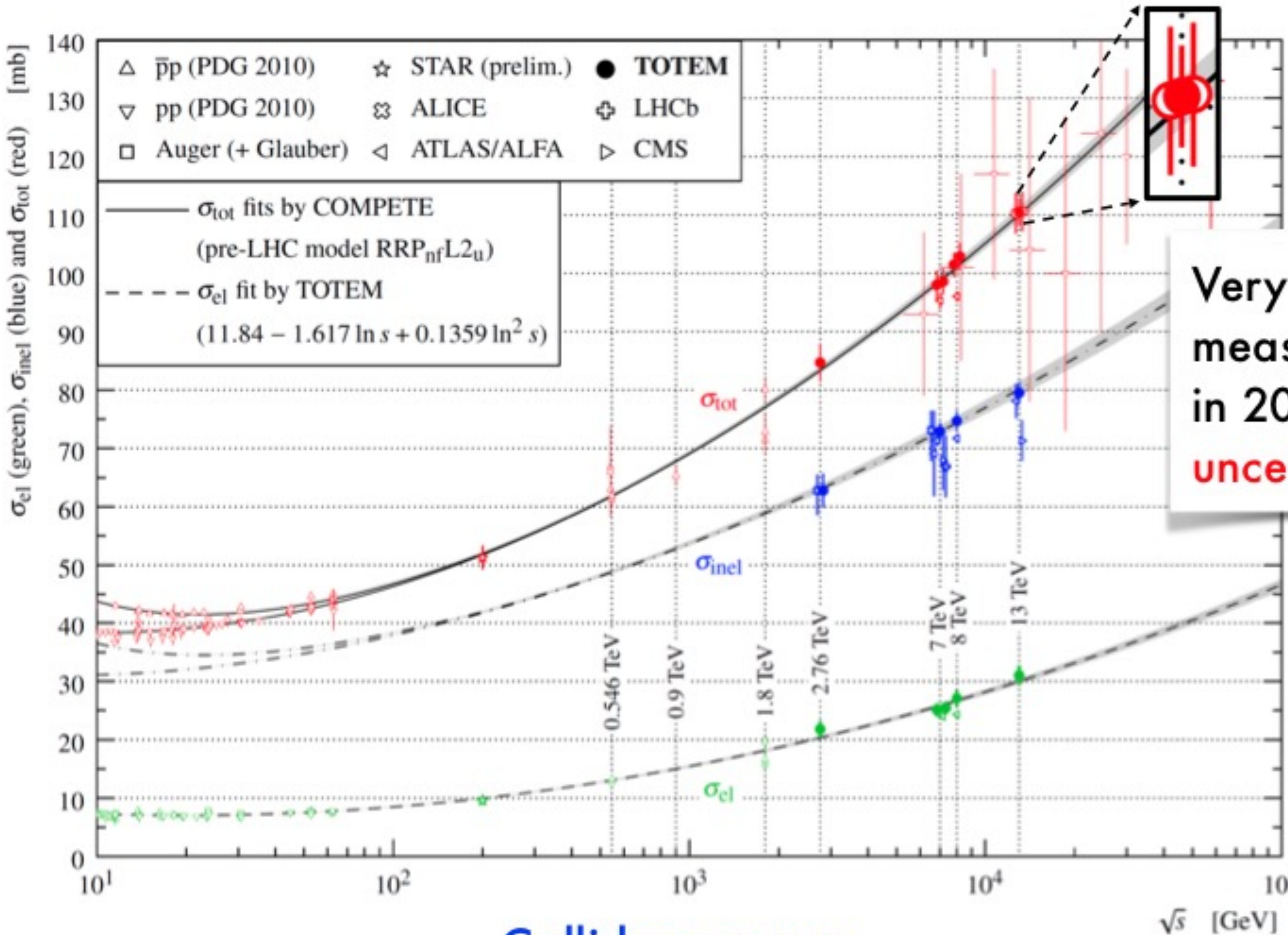
Dedicated detectors located up to 220m on each side of CMS: consist in tracking and timing sensors inserted in the LHC vacuum to detect the smallest scattering angles of protons

As of 2015, the CMS and TOTEM collaborations coordinate efforts to perform combined measurements of unprecedented accuracy!

TOTEM: total and elastic cross sections

Total & Elastic Cross-section Measurements Experiment

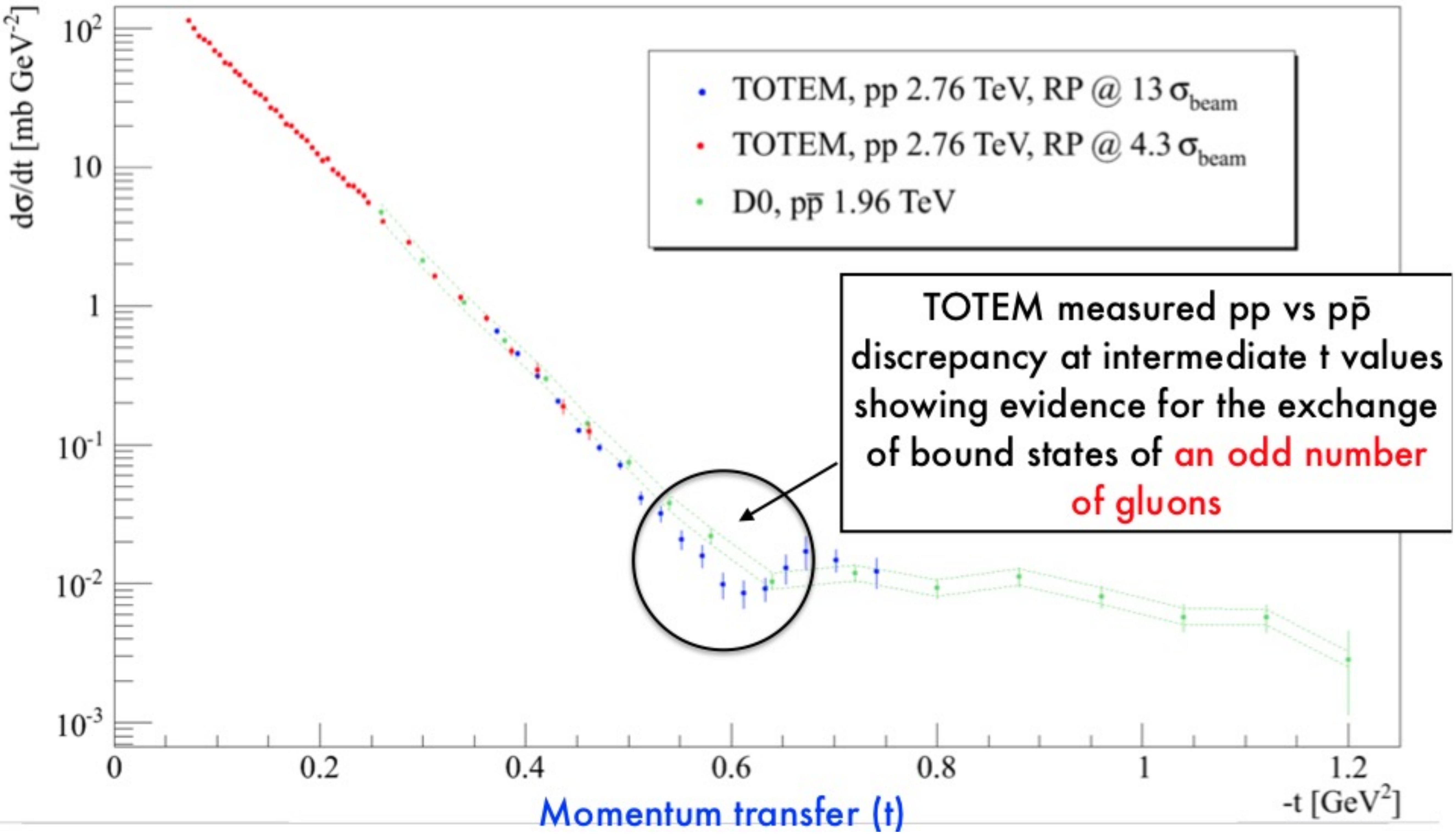
Total probability of protons to interact



Collider energy

Very accurate TOTEM measurement at 13 TeV in 2018 (2.2% uncertainty)

TOTEM experiment: elastic cros section → Odderon?

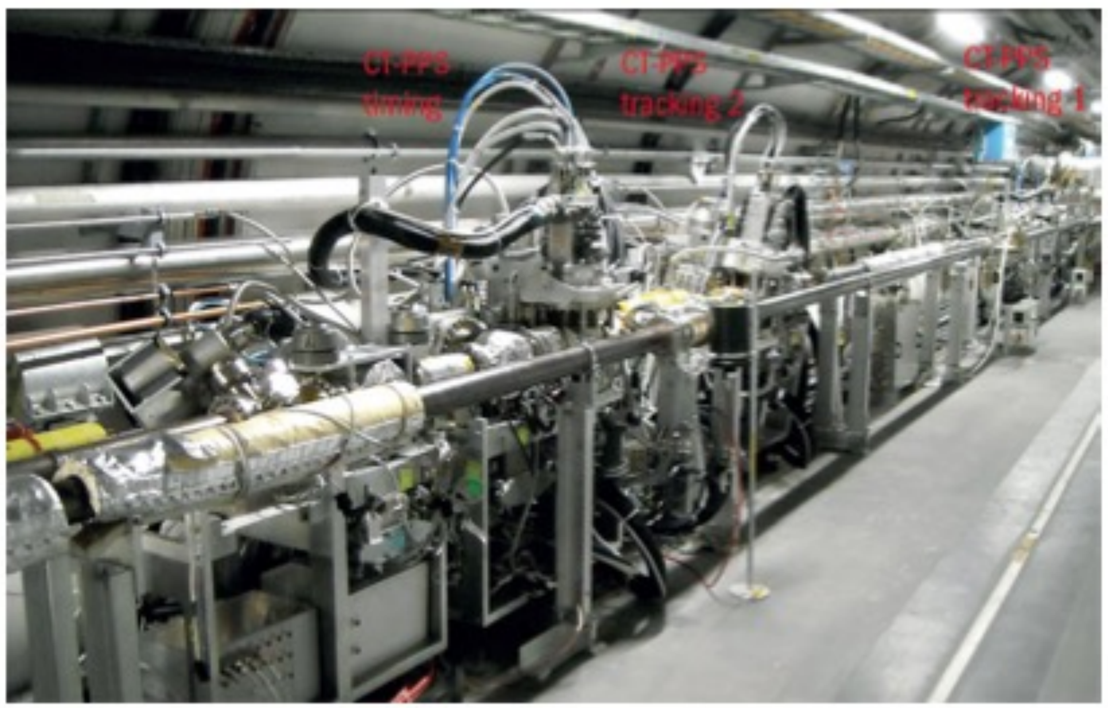


LHC as photon-photon collider

Precision Proton Spectrometer

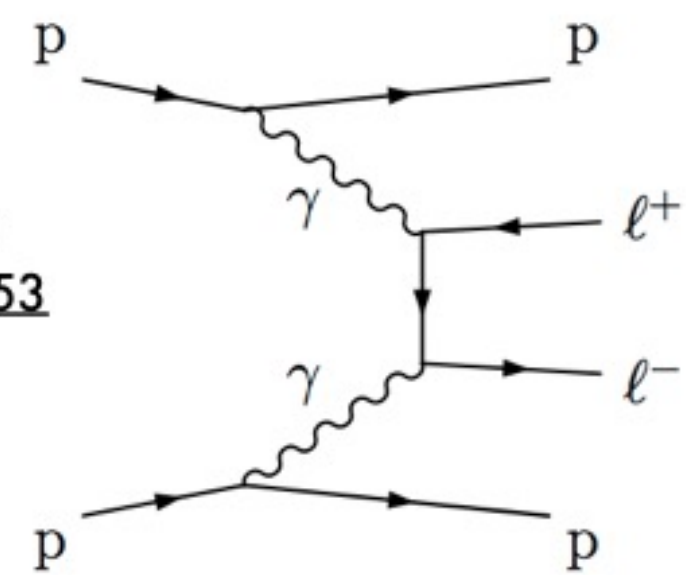
PPS is a magnetic spectrometer that uses the LHC magnets and detector stations, to bend protons to measure their trajectories.
Fully integrated into the CMS data-taking system and data reconstruction software.

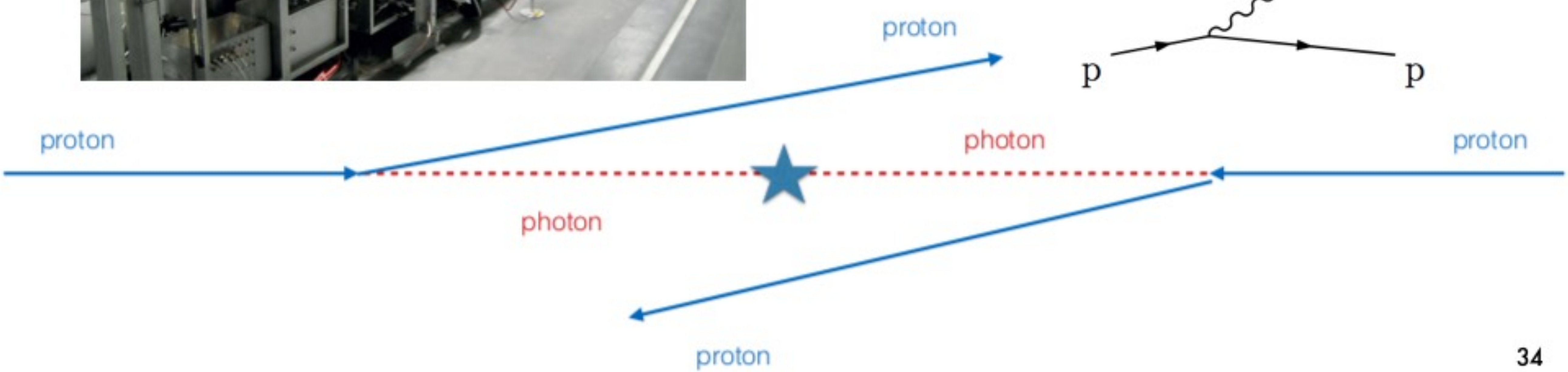
Total of > 100 fb^{-1} recorded at 13 TeV with Roman Pots inserted since 2016



Allows study of rare collisions:

first publication:
JHEP 07 (2018) 153





High energy asymptotics of pQCD

- Large-angle scattering (hard processes):

QCD in Bjorken limit

- GLAPD: V. Gribov & L. Lipatov (71-72); L. Lipatov (74);
  G. Altarelli & G. Parisi (77); Yu. Dokshitzer (77)

- Small-angle scattering ("semi-hard" processes):

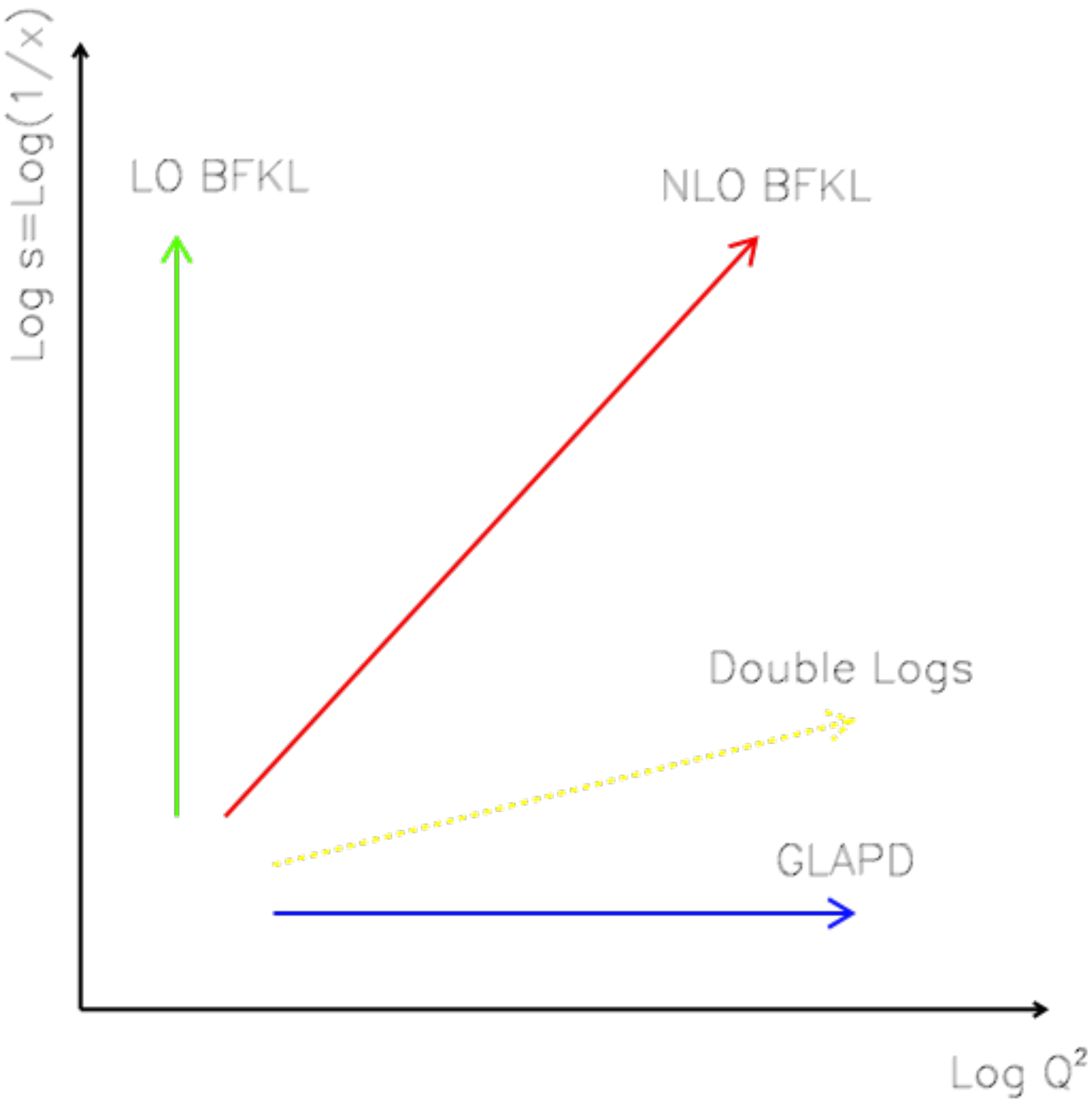
QED in Gribov-Regge limit

- V. Gribov, V. Gorshkov, L. Lipatov & G. Frolov (67-70)
  H. Cheng & T. Wu (66-70)

QCD in Gribov-Regge limit

- BFKL: V. Fadin, E. Kuraev & L. Lipatov (75-78)
  I. Balitsky & L. Lipatov (78)

pQCD x-section asymptotics

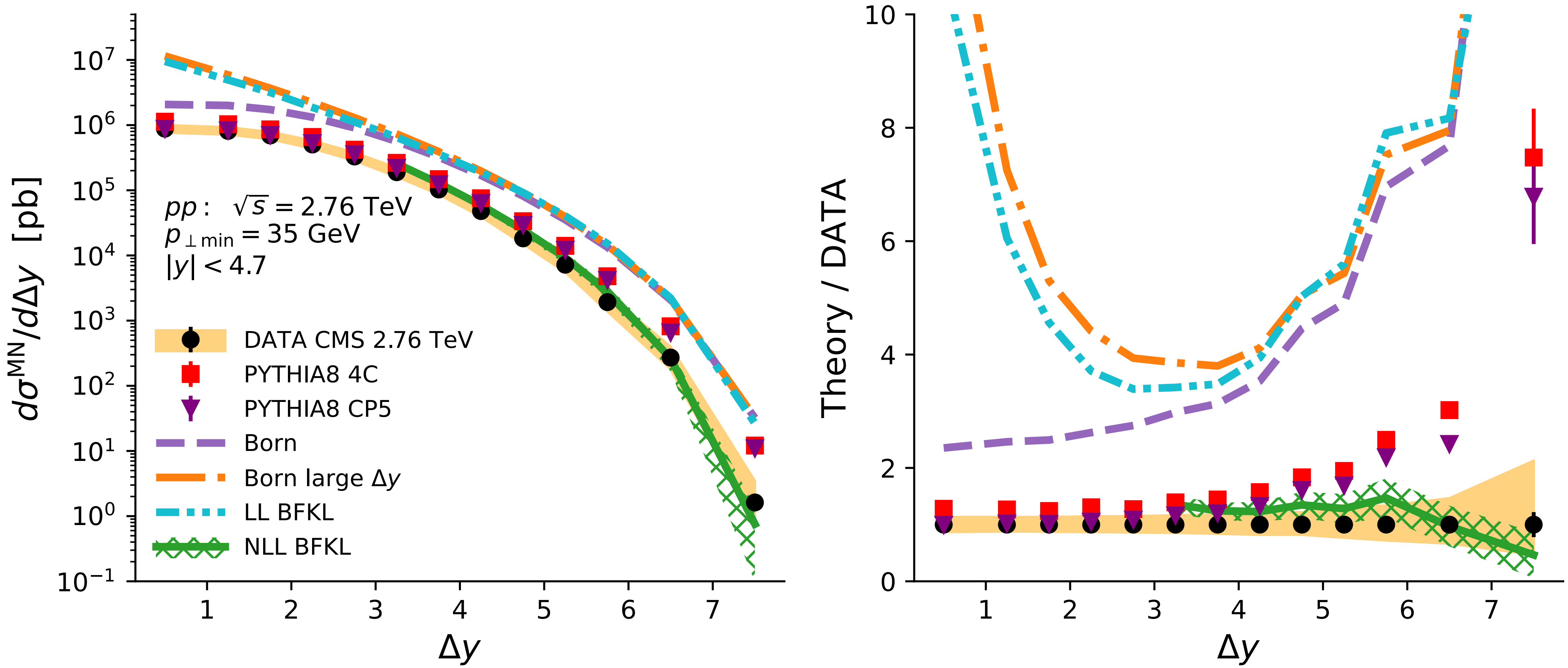


Bjorken limit (GLAPD):
$s \sim Q^2 >> m^2$
$Q^2/s = x \sim 1$
Large-angle (large-x) scattering

Gribov-Regge limit (BFKL):
$s >> Q^2 >> m^2$
$Q^2/s = x \to 0$
Small-angle (small-x) scattering

MN dijets within NLL BFKL+BFKLP: 2.76 TeV

A. Egorov & V.K. Phys. Rev. D (2023)



CMS (2022)
2.76 TeV, pT_min = 35 GeV

Search for New Physics beyond the Standard Model:

We are ready to admit being approximated:

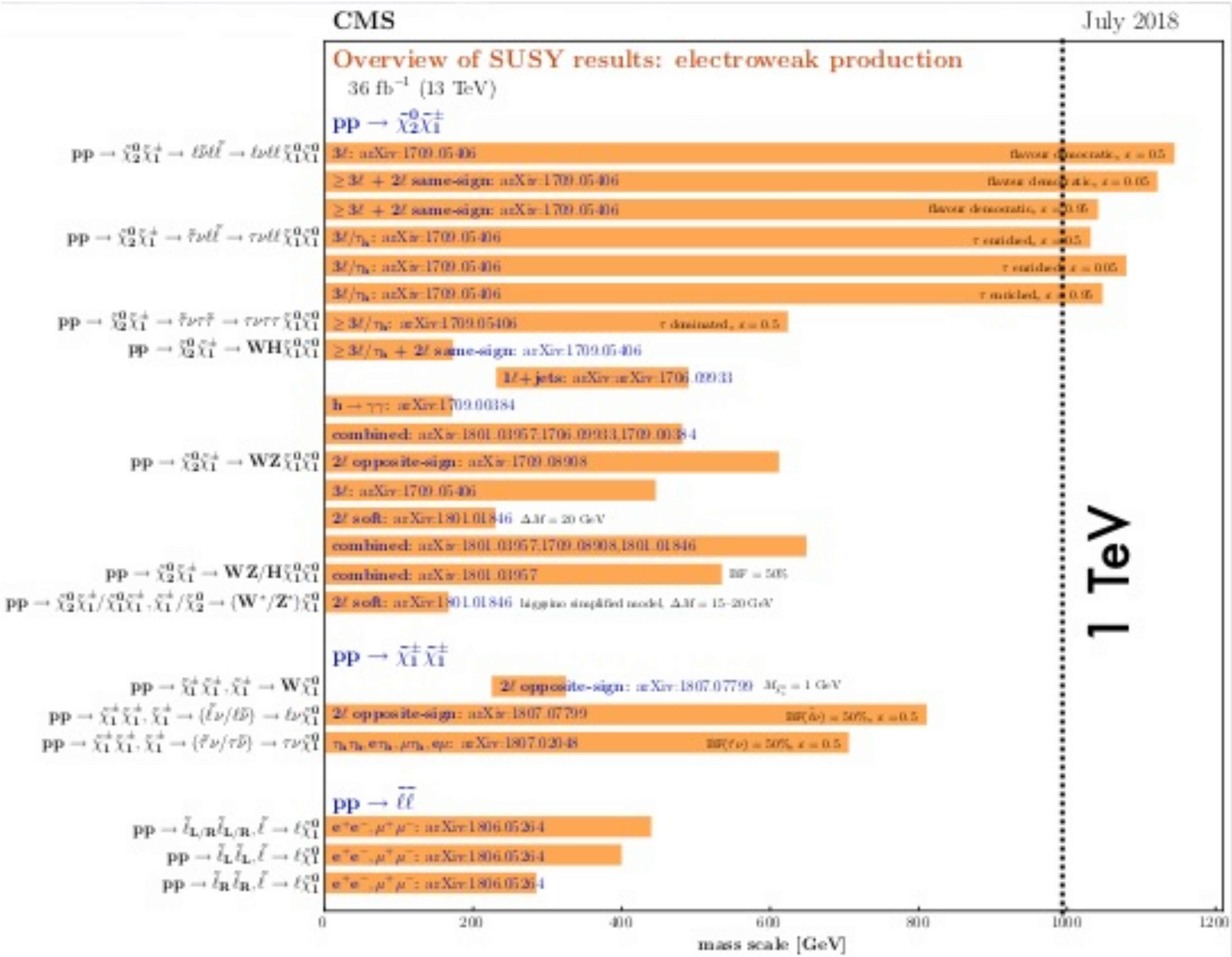
- laws: conservation of energy, momentum, charge, ...

- and even principles:
relativity, gauge invariance, ...

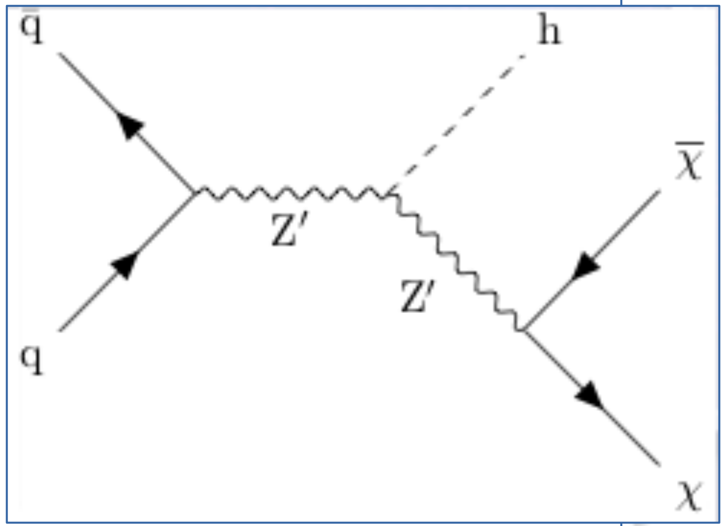
- and fundamental parameters: space dimension, gravity dimension ...

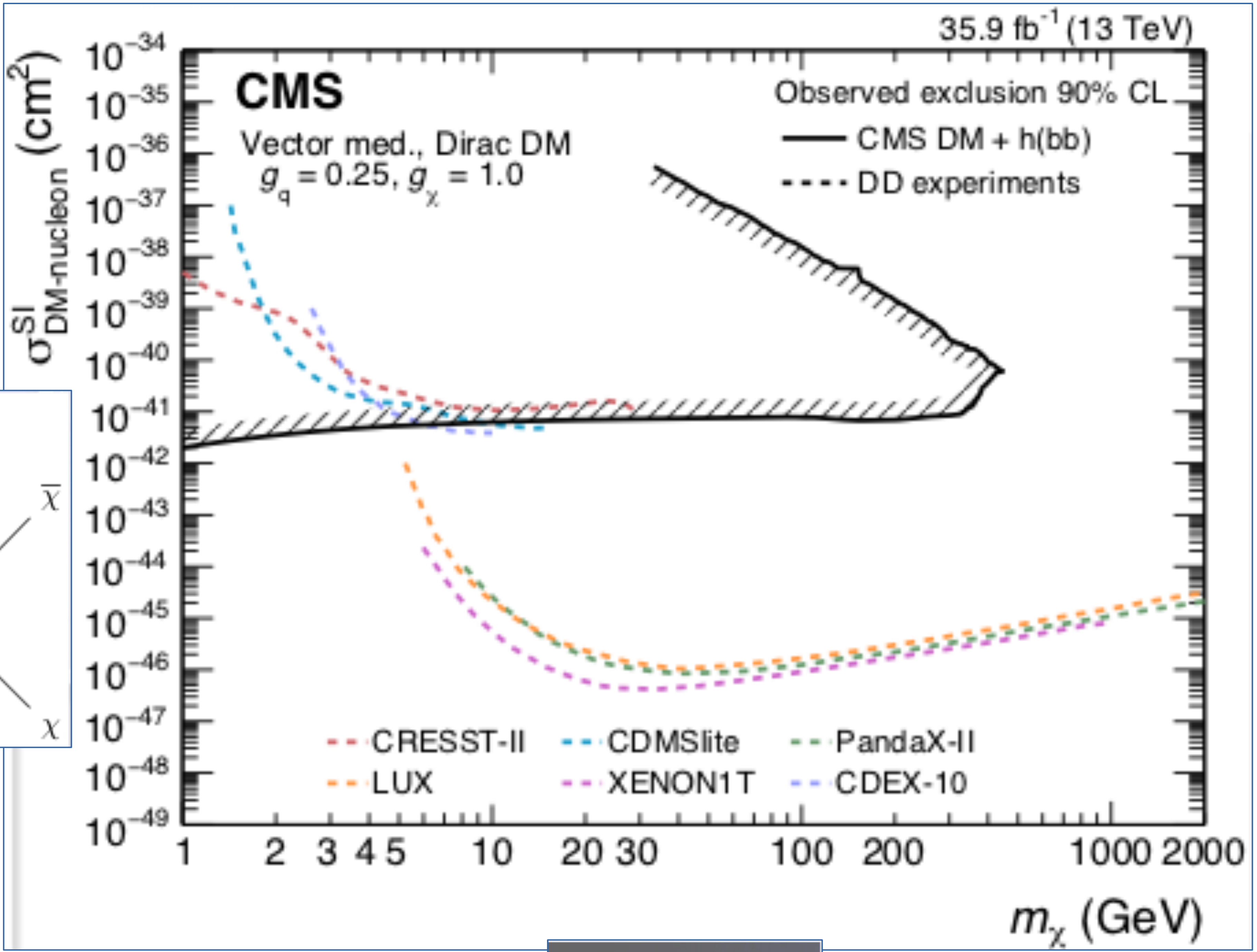
! However:
Preserving all description power of the Standard Model in the established domain of its validity

LHC: SUSY searches



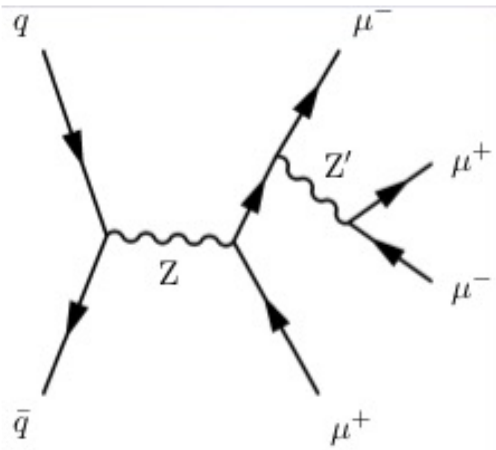
LHC: Dark matter search

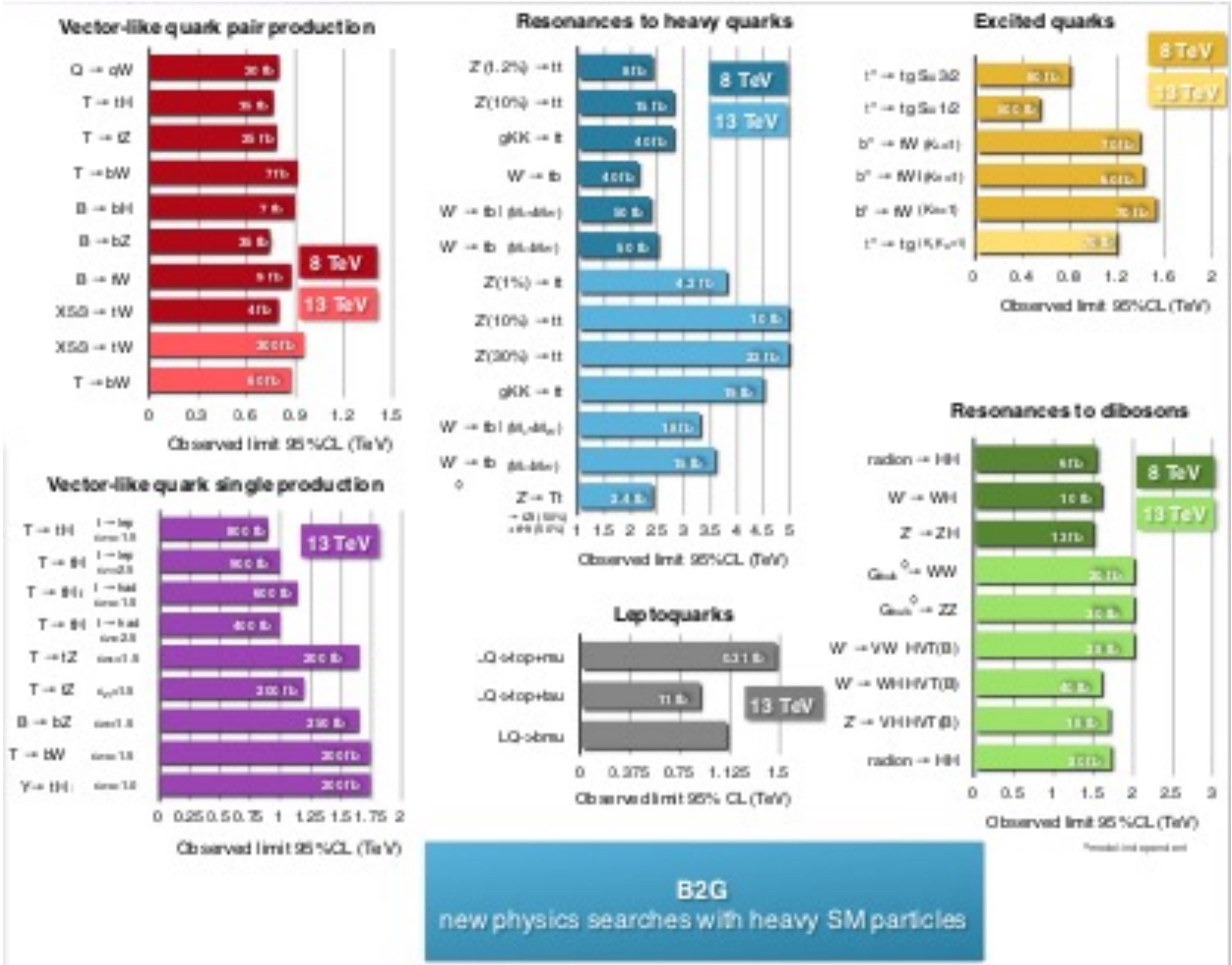




EXO-16-050
Submitted to EPJC

LHC searches: new resonances, leptoquarks, ...





Information about particle physics and the LHC

http://public.web.cern.ch
http://atlas.ch
http://cmsinfo.cern.ch/outreach

In Russian:

Научно-популярный сайт:
http://elementy.ru

- "Страсти по частицам" ("Particle Fever") YouTube

- Виртуальная академия ФВЭ (ОИЯИ, Дубна)

LHC Physics: summary

- Many parameters of the Standard Model measured at the unprecendent accuracy

- The Standard Model domain of validity is enormously extended

- There few finding anomalies

- Data taking presently is ~5 % of the planning data at the High-Luminosity LHC

-> Most probably major news are waiting ahead!