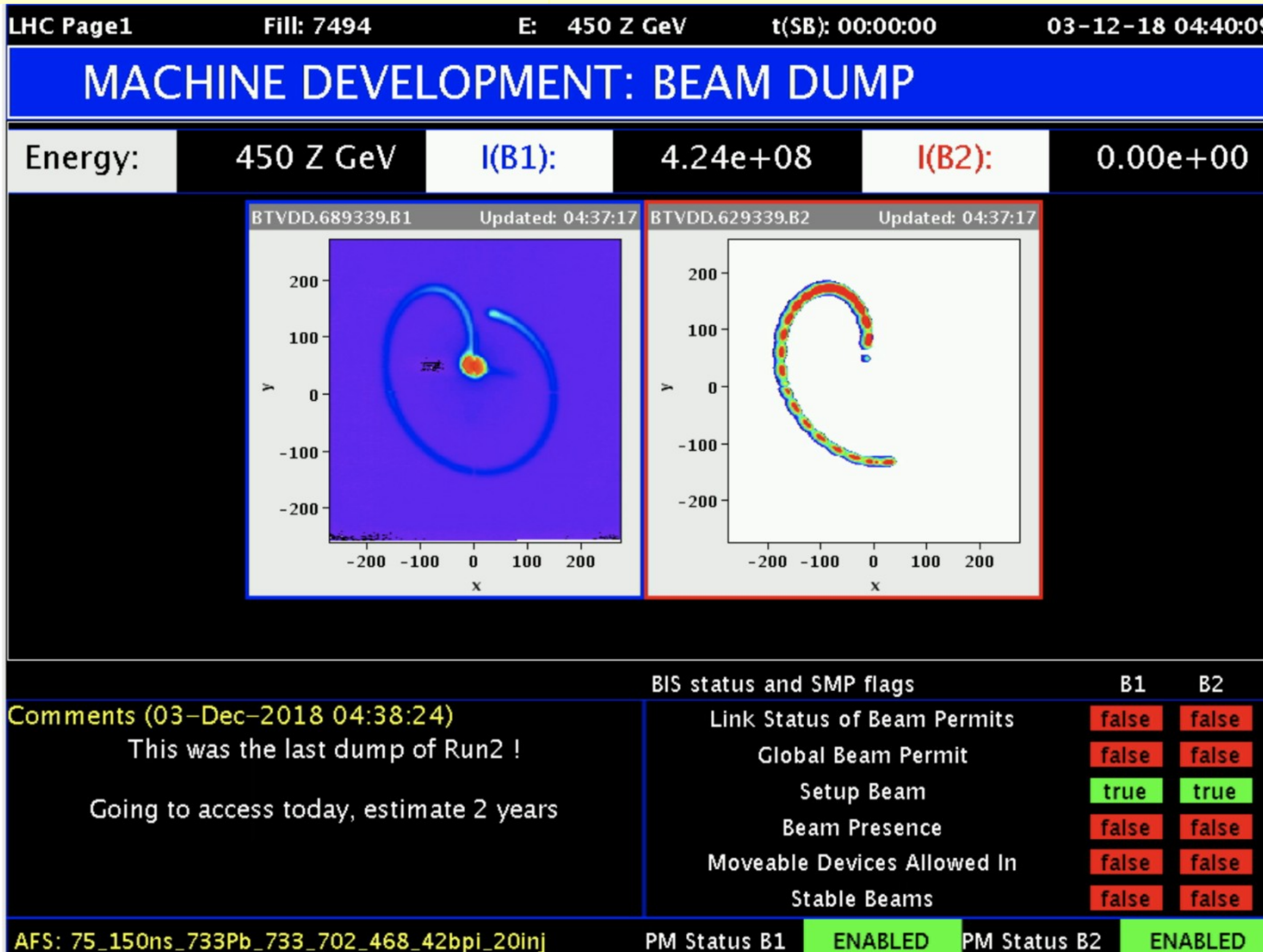
Highlights from the Run-2 LHC results

Artur Kalinowski



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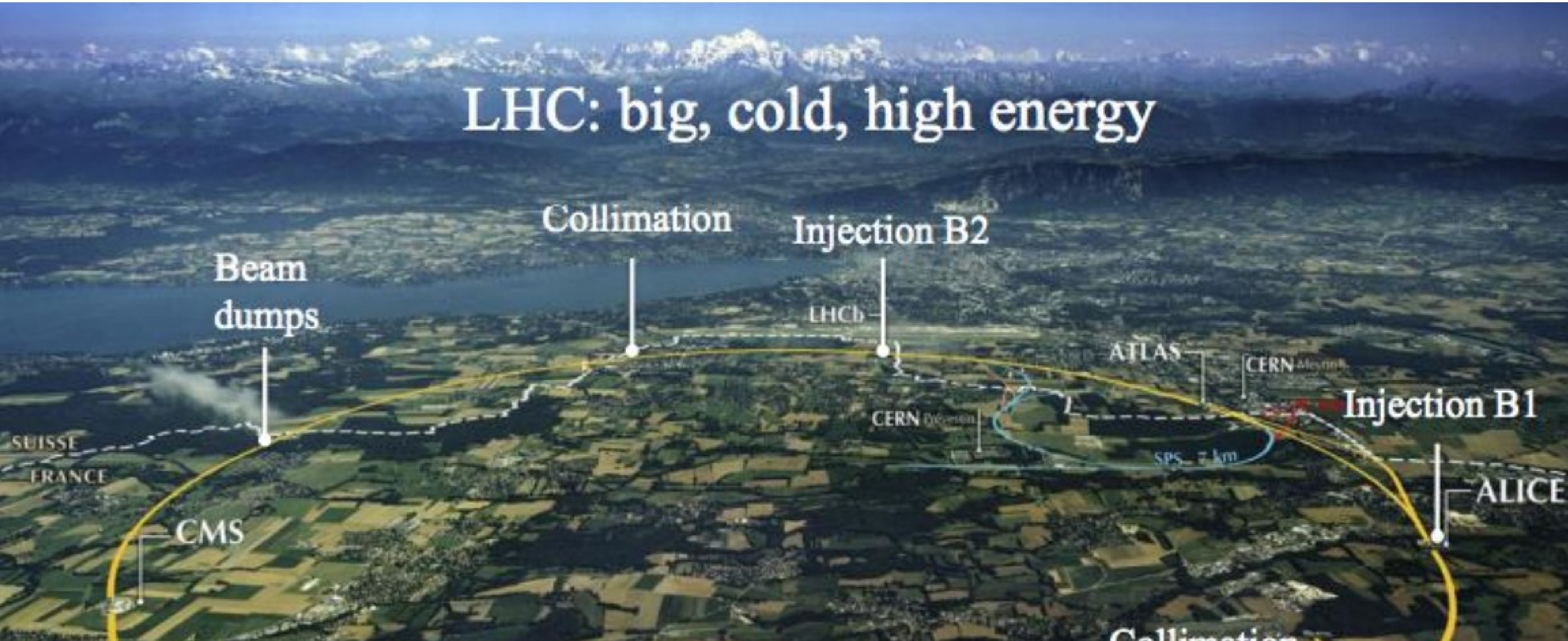
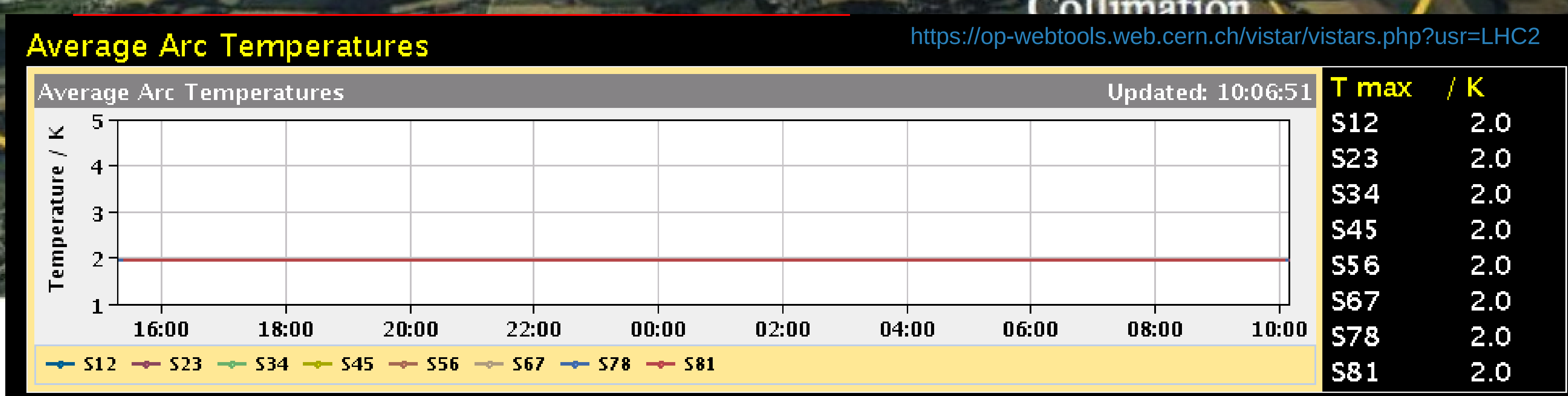
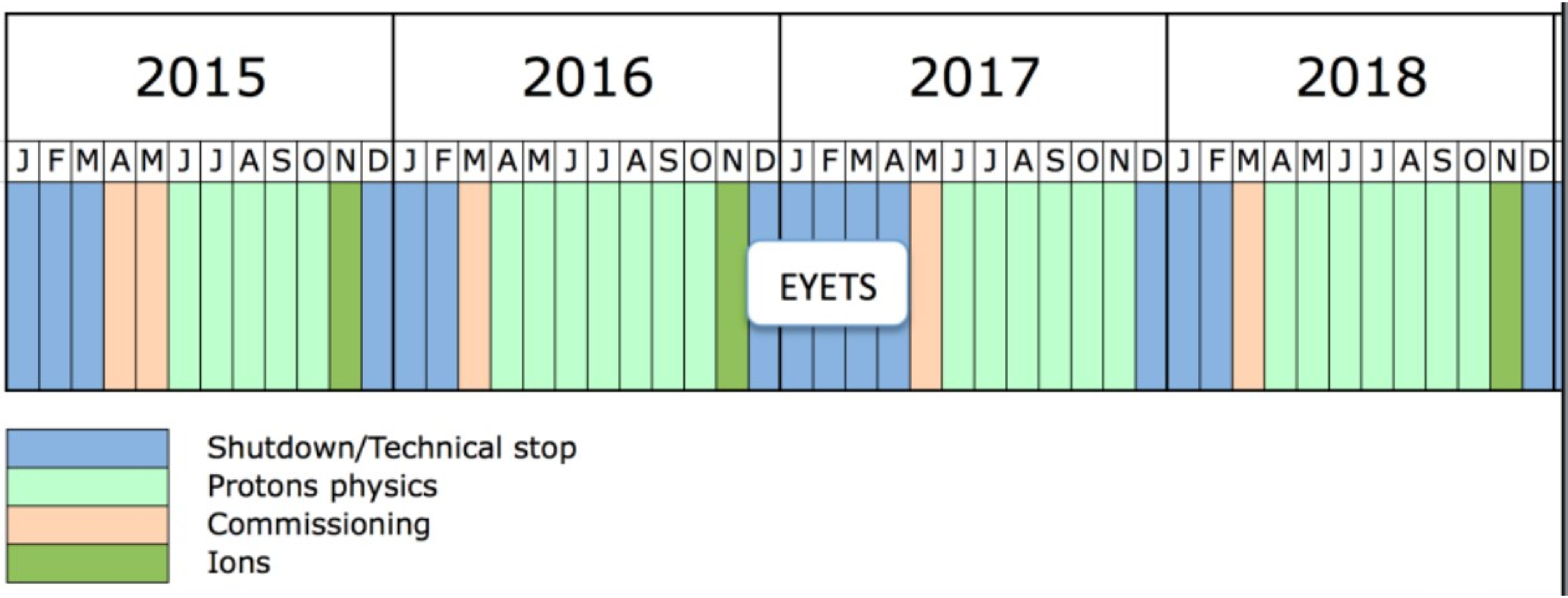
The LHC is still there

http://www.emfcsc.infn.it/issp2018/docs/talkBoyd.pdf





LHC Run 2



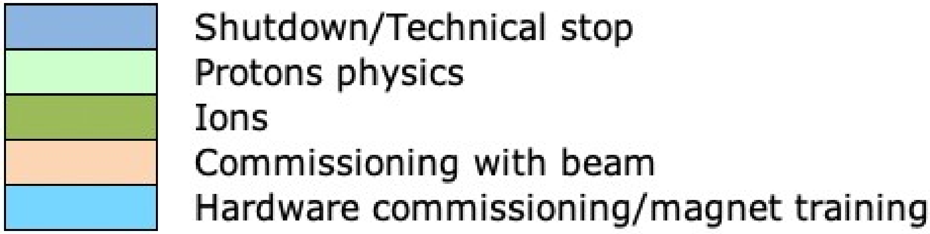
- started in 2015 after a 2 year Long Shutdown 1 (LS1)
  - increased collision energy from Run-1 **8 TeV to (nearly nominal) 13 TeV**
  - reduced bunch spacing from **50 ns to 25 ns → collisions rate increase → instantaneous luminosity increase**
- scheduled from 2015 to 2018

LHC Run 3

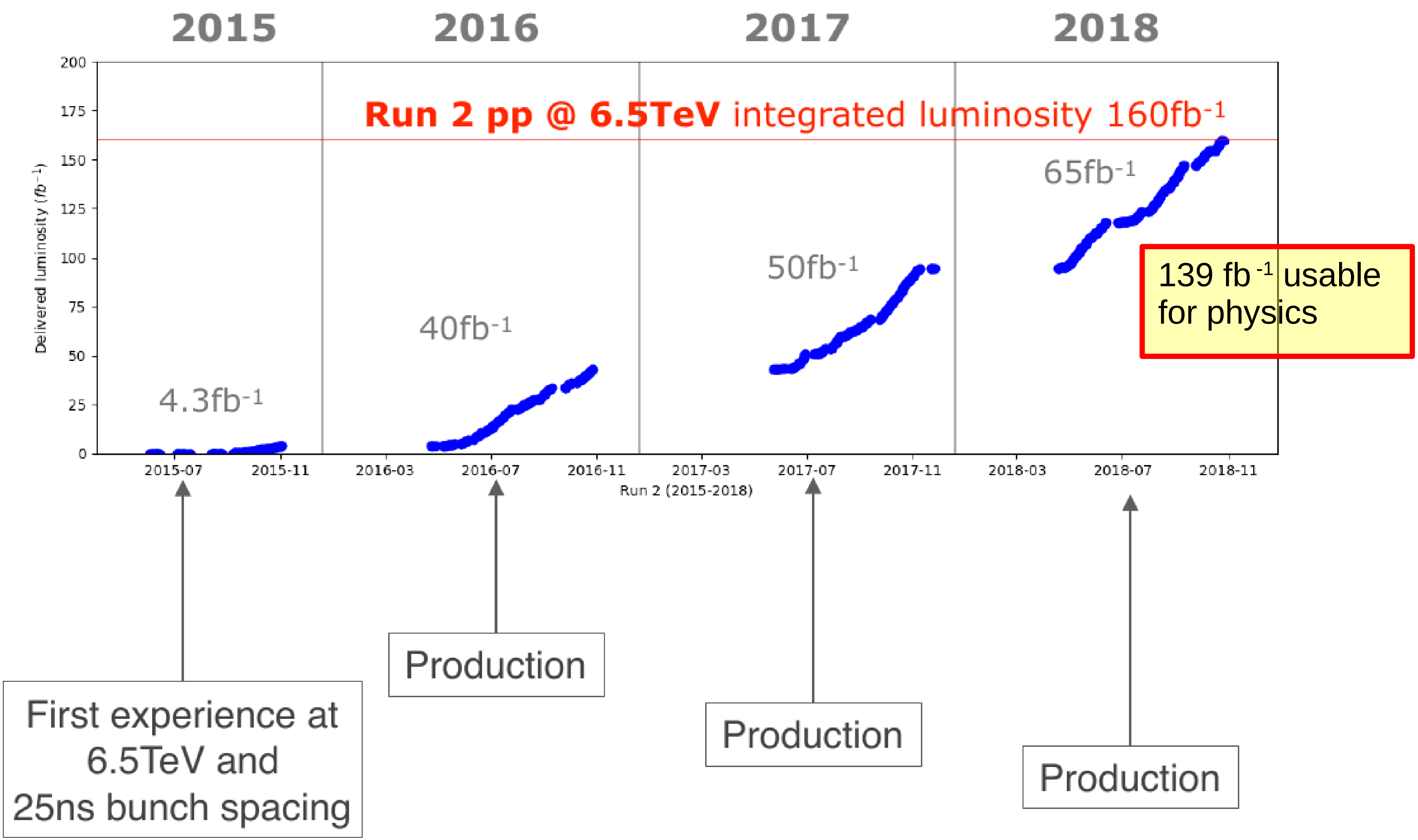
- Run-3 planned to start in 2022
  - increase collision energy from Run-2 **13 TeV to (almost nominal) 2x6.8 TeV ← still uncertain**
  - improve beam parameters → **2xRun-2 instantaneous luminosity increase**

- optimistic assumption:
  - **40 fb^{-1} to be collected in 2022**
  - **80 fb^{-1} to be collected in 2023**

- LS3 after Run-3 will be used for major LHC and detectors upgrade for the High Lumunosity (HL-LHC or Phase-2) phase:
  - **3000 fb^{-1} integrated luminosity in 10 years**



Run 2 luminosity history



https://indico.cern.ch/event/751857/timetable/

Why Run 2 only?

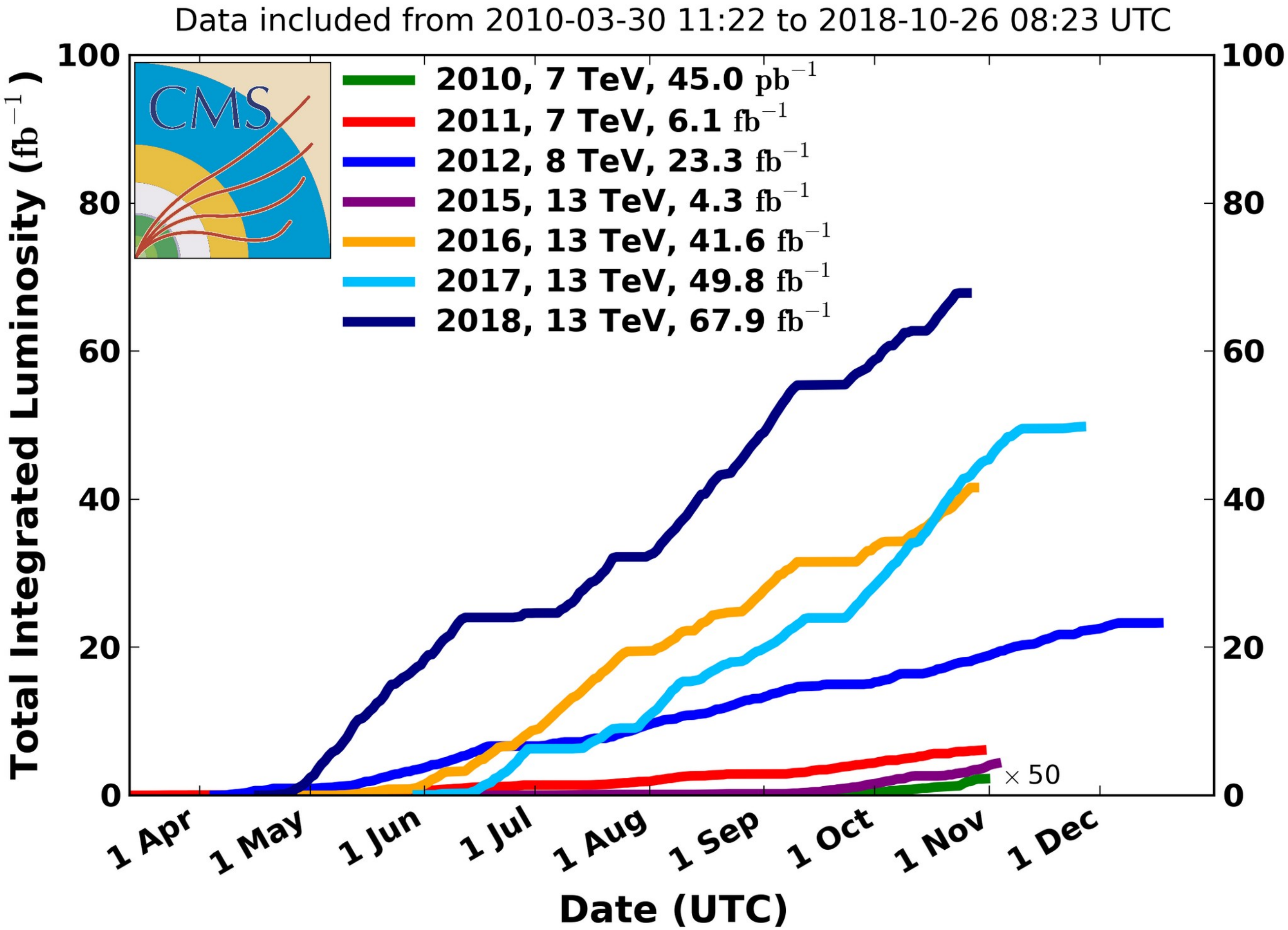
- Run-1 was taken with lower, and changing, collision energy → **complicates analysis flow (different Monte Carlo, different cross sections)**

- Run-1 provided "only" 30 fb^{-1} → **gain not worth the pain from combination effort with newer data**

Run 1+2 Poisson uncertainty reduction of order 4%:

$$\frac{\sigma_{13\,TeV}}{\sigma_{8\,TeV}} \simeq 2$$

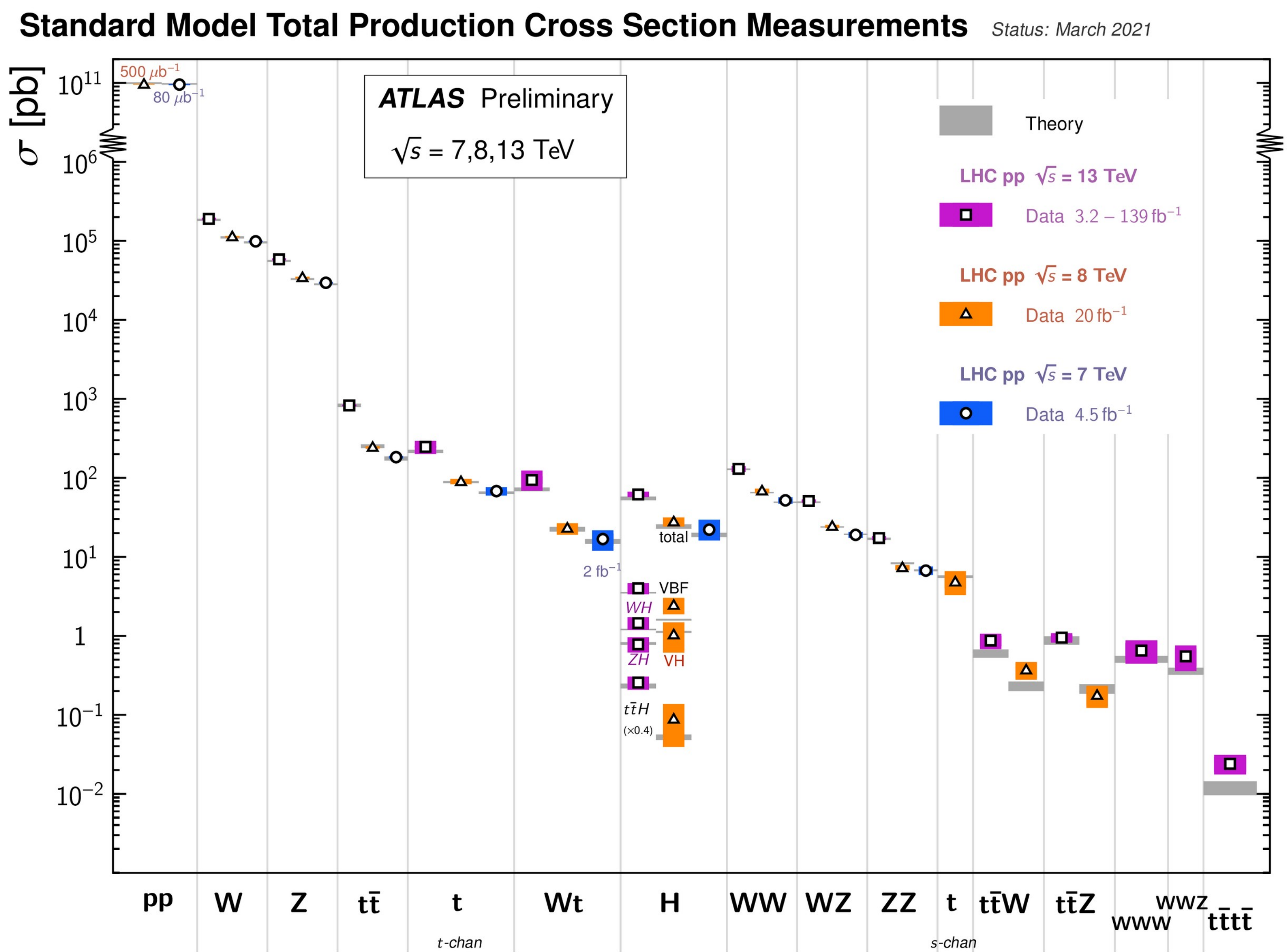
$$\frac{\Delta_{Run\,1+2}}{\Delta_{Run\,2}} \simeq \sqrt{\frac{160}{160+30\cdot 0.5}} = 0.96$$



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

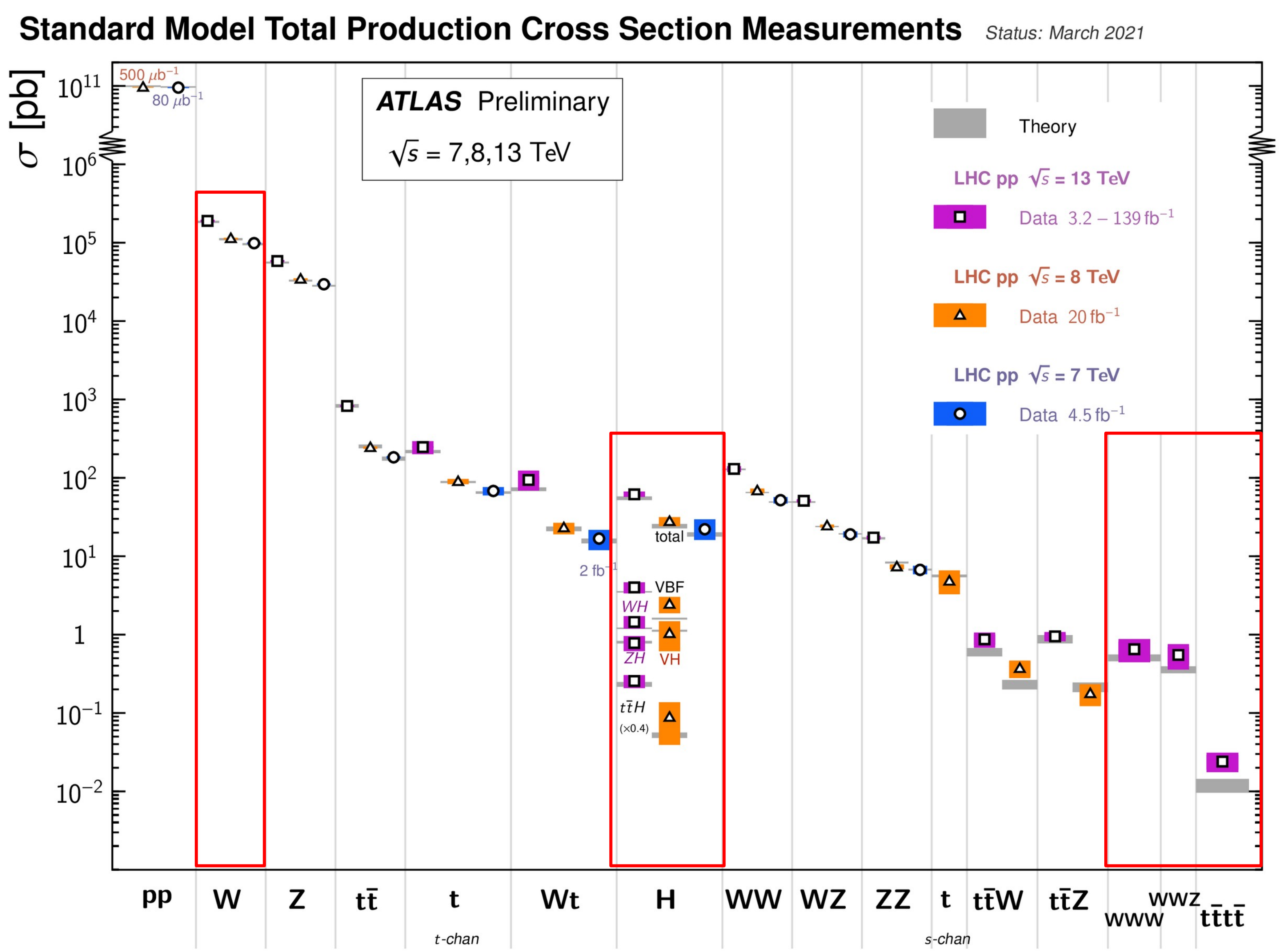
Standard Model measurements

ATL-PHYS-PUB-2021-005



Standard Model measurements

ATL-PHYS-PUB-2021-005

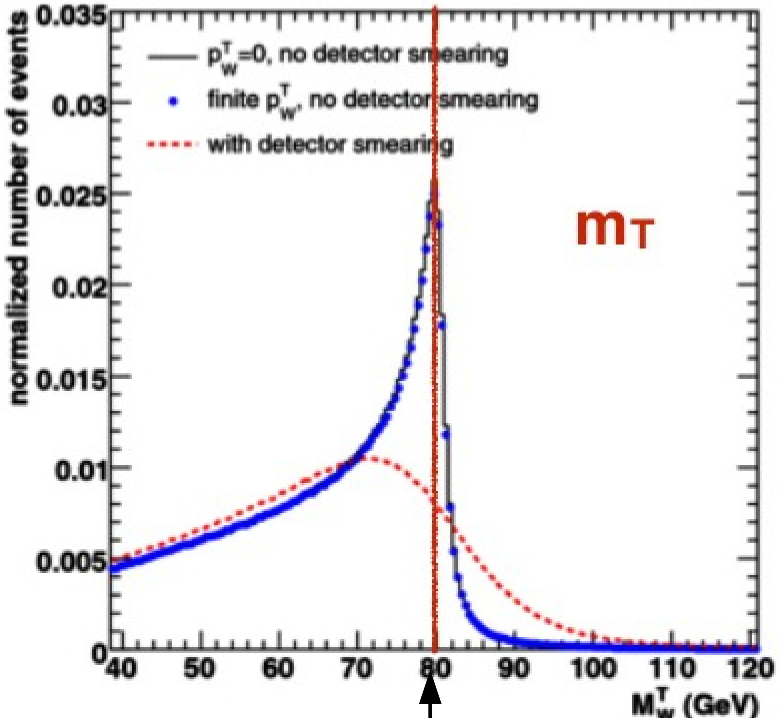


ATLAS W boson mass measurement

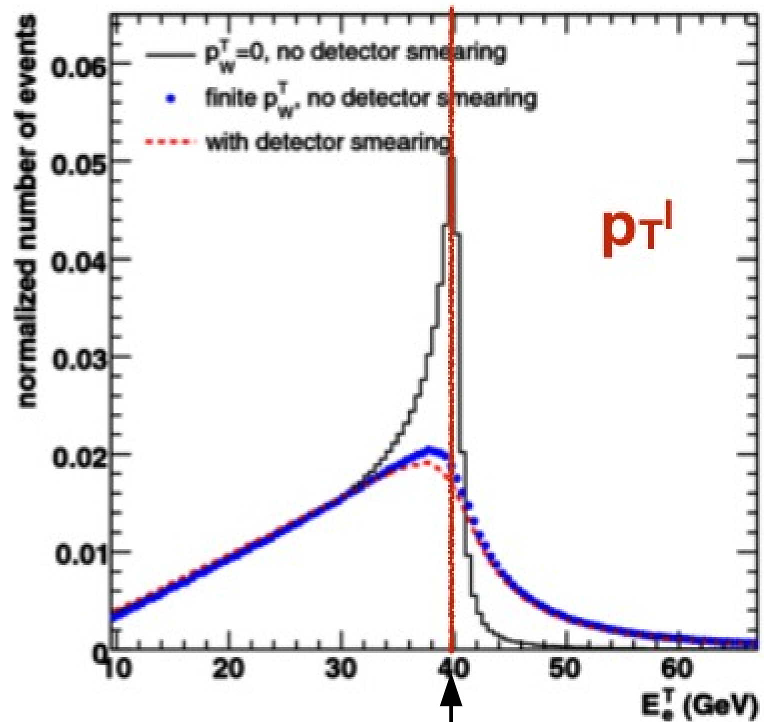
Observables sensitive to m_W:

- transverse mass of (l, E_T^{mis}) system: $m_T = \sqrt{2p_T^{\ell}p_T^{miss}(1 - cos\Delta\phi)}$
- transverse momentum of the lepton from the W decay

ATL-PHYS-SLIDE-2017-521

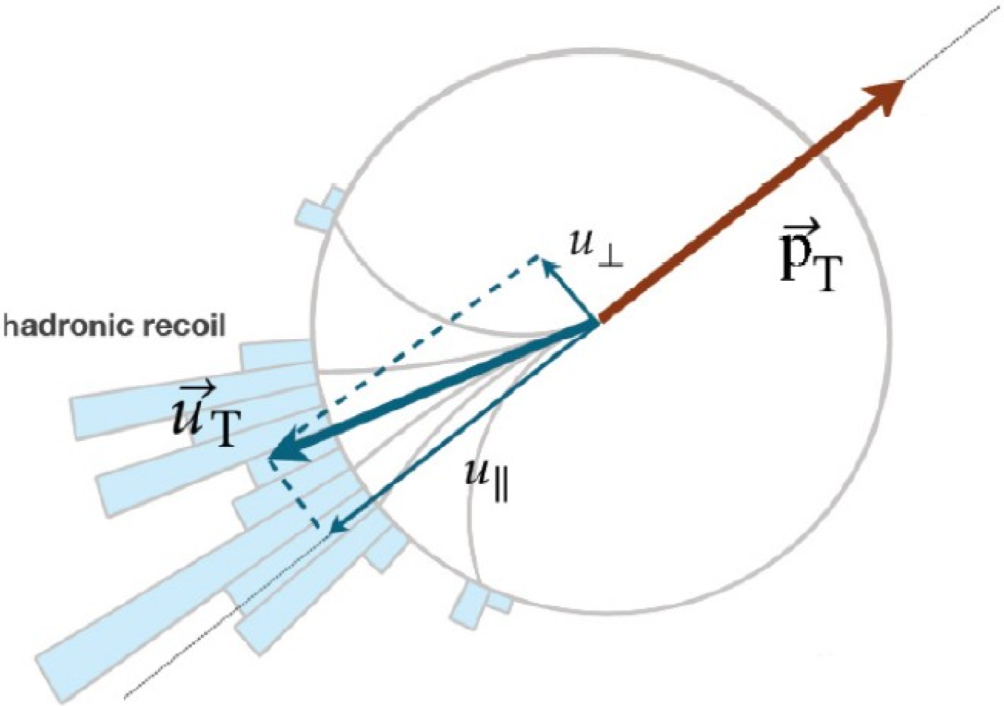


Jacobian peak at the m_W



Jacobian peak at the $m_W/2$

ATLAS W boson mass measurement



Event selection:

- $p_T^l > 30$ GeV
- $u_T < 30$ GeV → reject high W p_T events (difficult to model)
- $p_T^{miss} > 60$ GeV
- $m_T > 60$ GeV

$$\vec{u}_T = \sum_i \vec{E}_{T,i}$$

sum over calorimeter clusters. u_T estimates the W boson p_T

$$\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right)$$

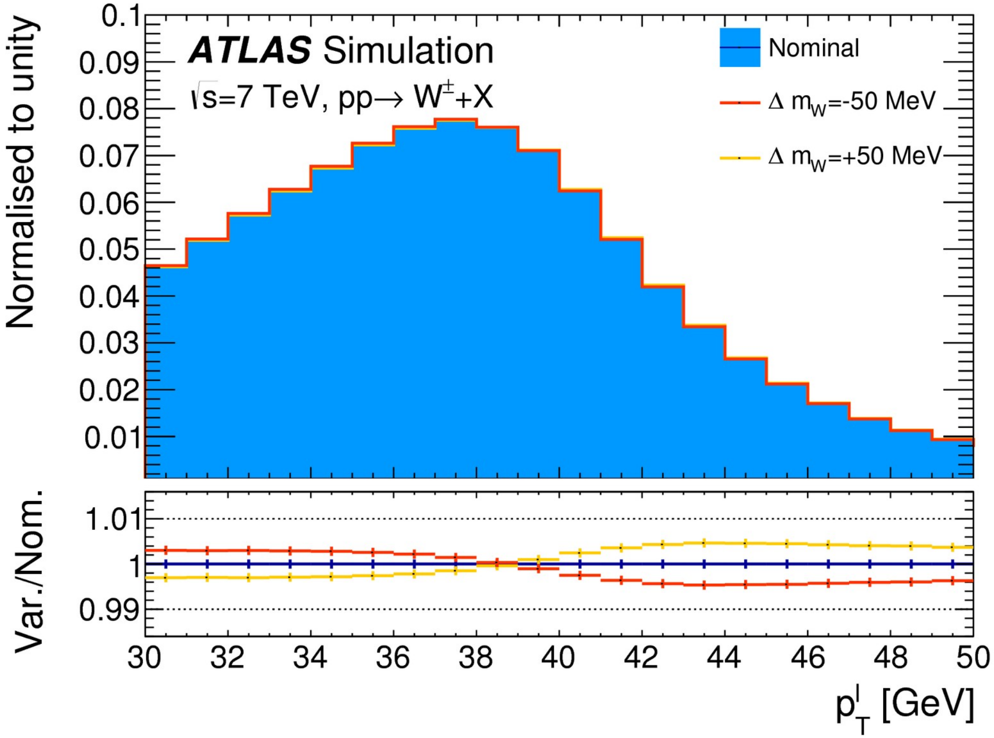
u_T calibration:

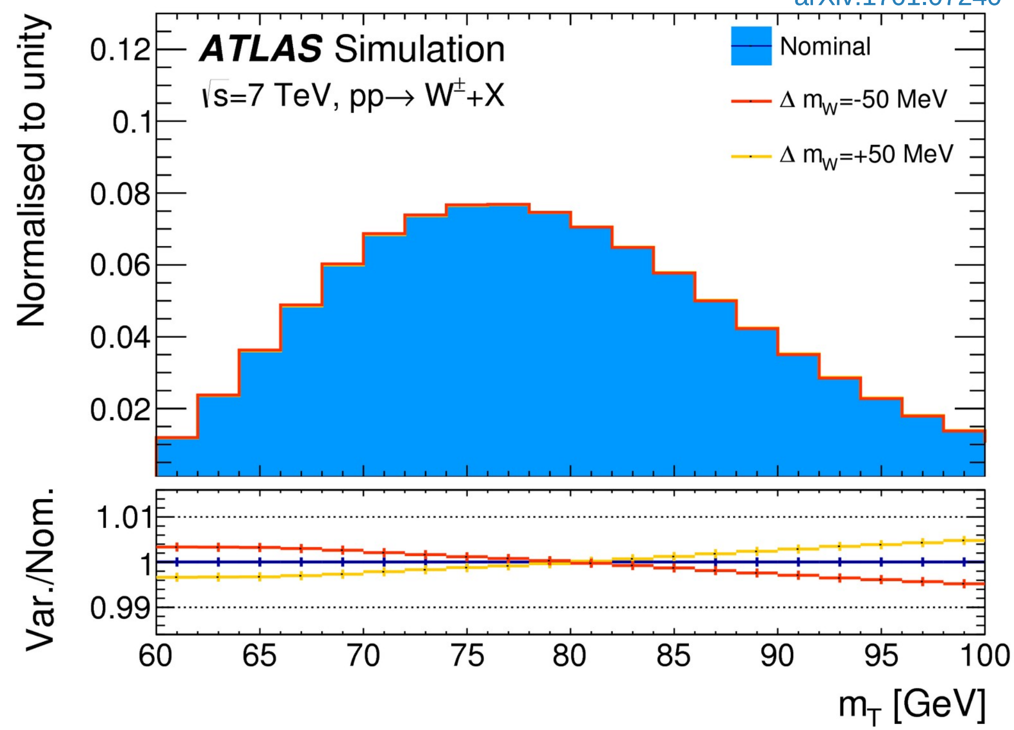
- MC ΣE_T response for W and Z events
- residual u_T DATA-MC difference calibrated with Z events (and used for W)

ATLAS W boson mass measurement

- W mass estimated by choosing a best fit template generated for different m_W
- the measurement is particularly sensitive to the W p_T modeling and the PDFs

arXiv:1701.07240





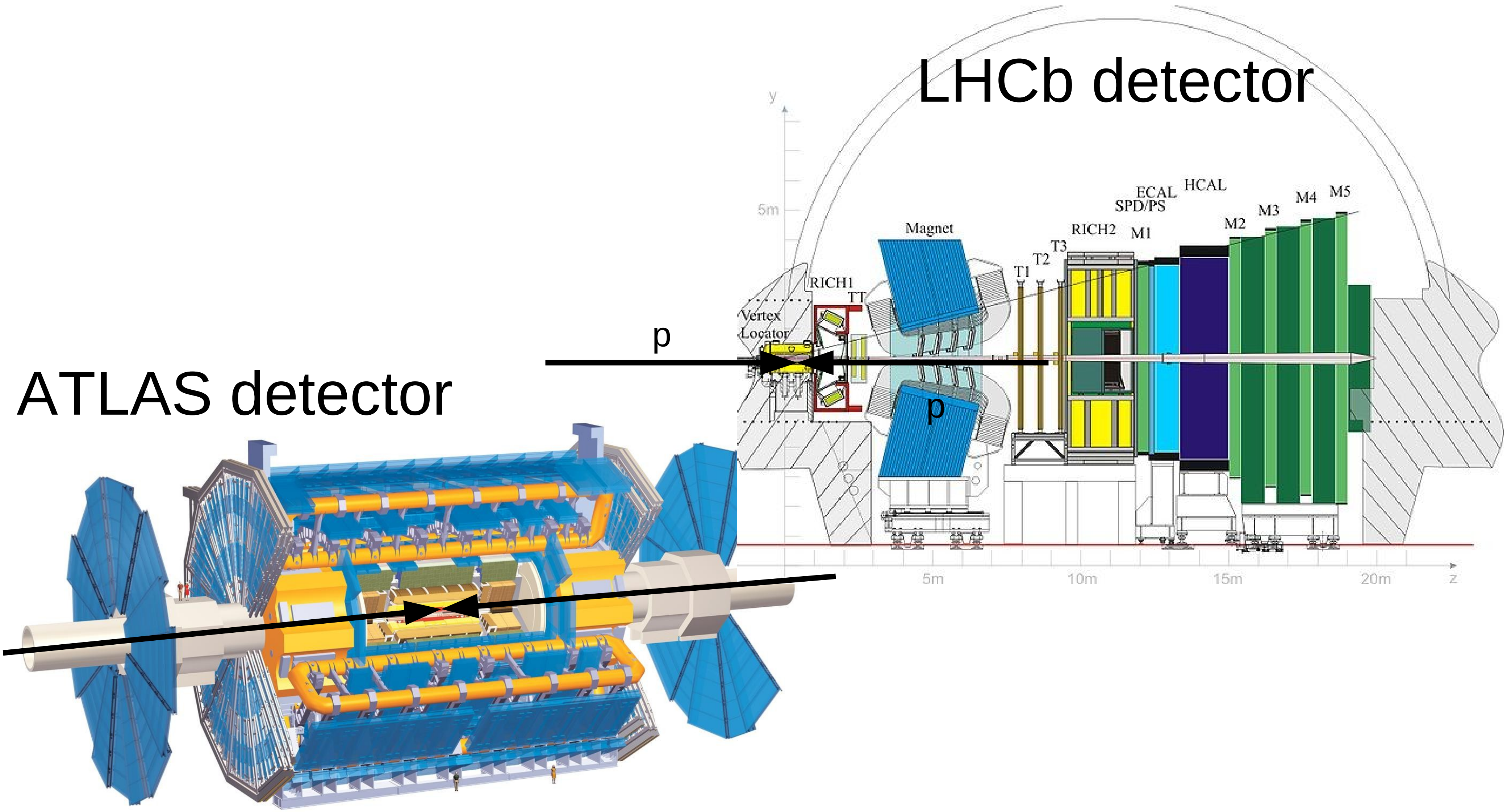
$$m_W = 80369.5 \pm 6.8\,\text{MeV}(\text{stat.}) \pm 10.6\,\text{MeV}(\text{exp. syst.}) \pm 13.6\,\text{MeV}(\text{mod. syst.})$$
$$= 80369.5 \pm 18.5\,\text{MeV},$$

similar contributions from e/μ/MET calibrations

dominated by parton PDF uncertainty

ATLAS and LHCb settings

http://cdsweb.cern.ch/record/1087860



https://cds.cern.ch/record/1095924

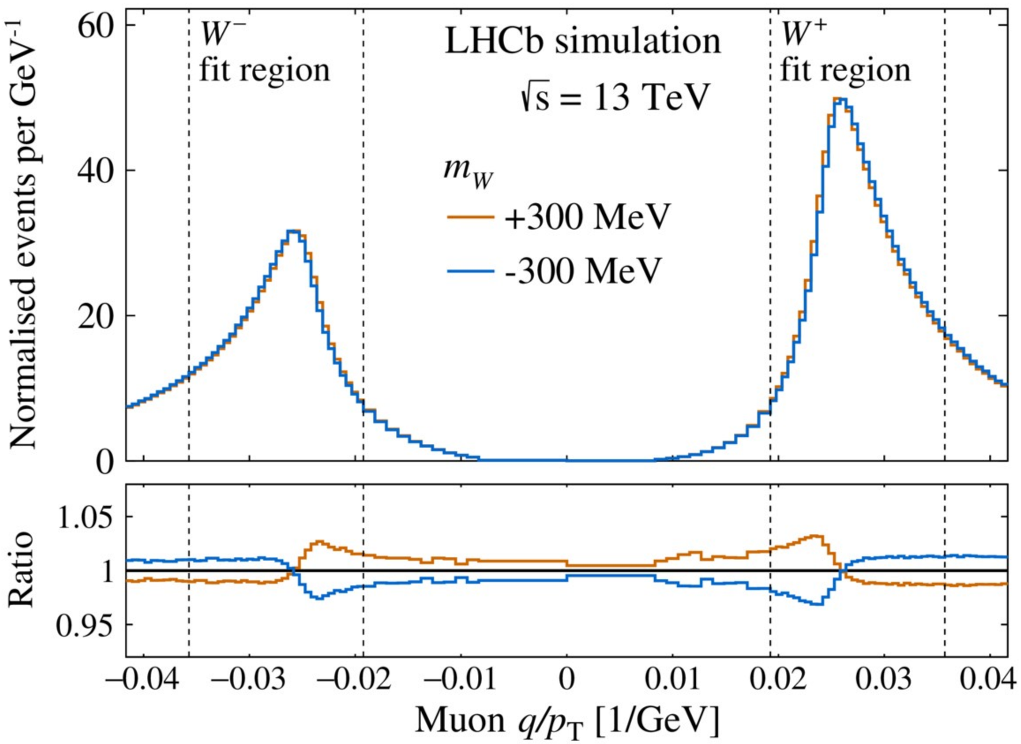
LHCb W boson mass measurement

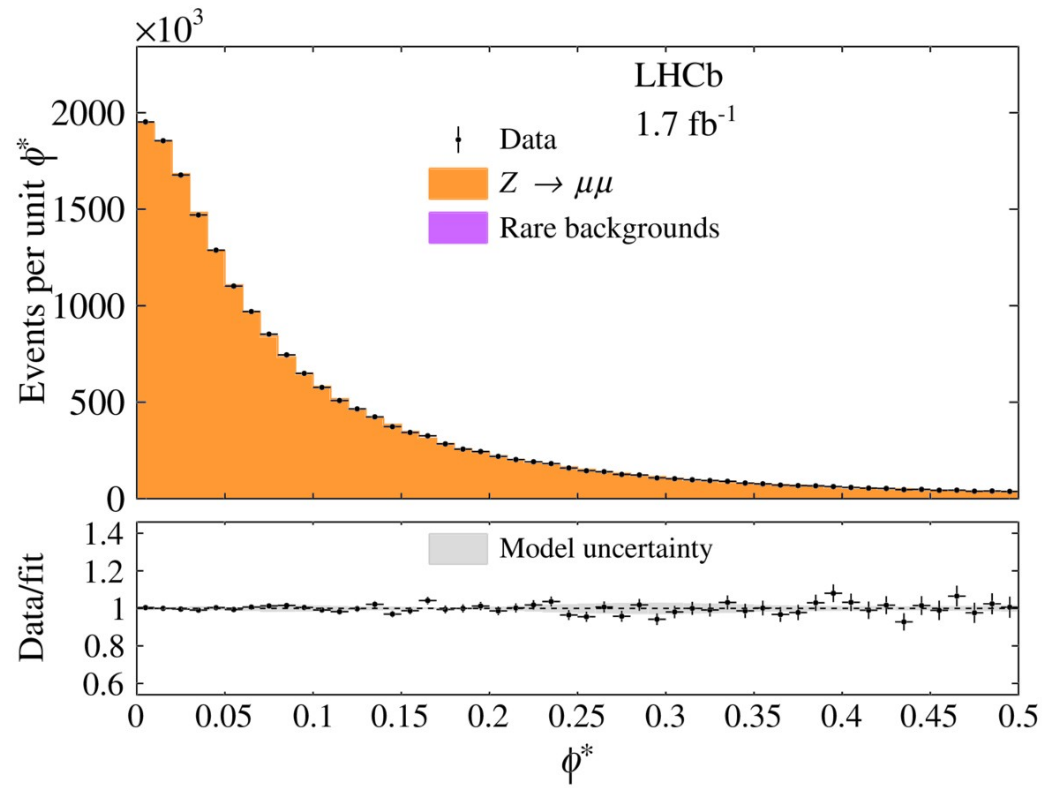
The method: simultaneous fit to q/p_T^l templates for different W mass, and Z boson variable ϕ^*:

only Run-2 2016 data used – 1.6 fb^{-1} (full LHCb Run-2 data is 6 fb^{-1})

$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{M}$$

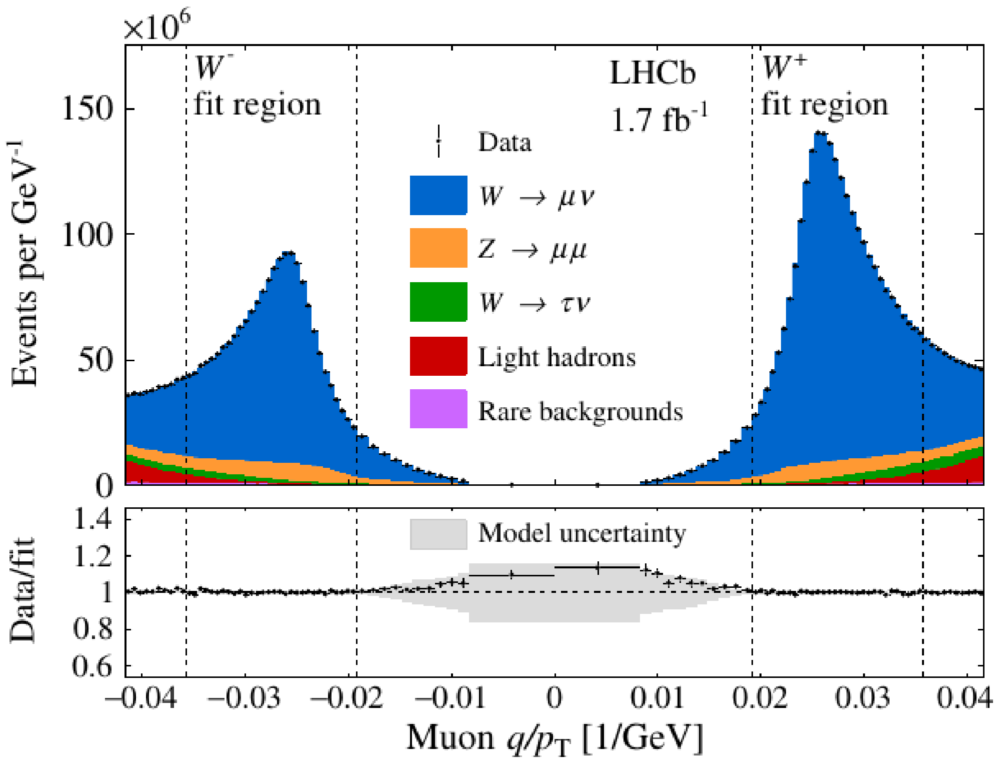
https://arxiv.org/abs/2109.01113

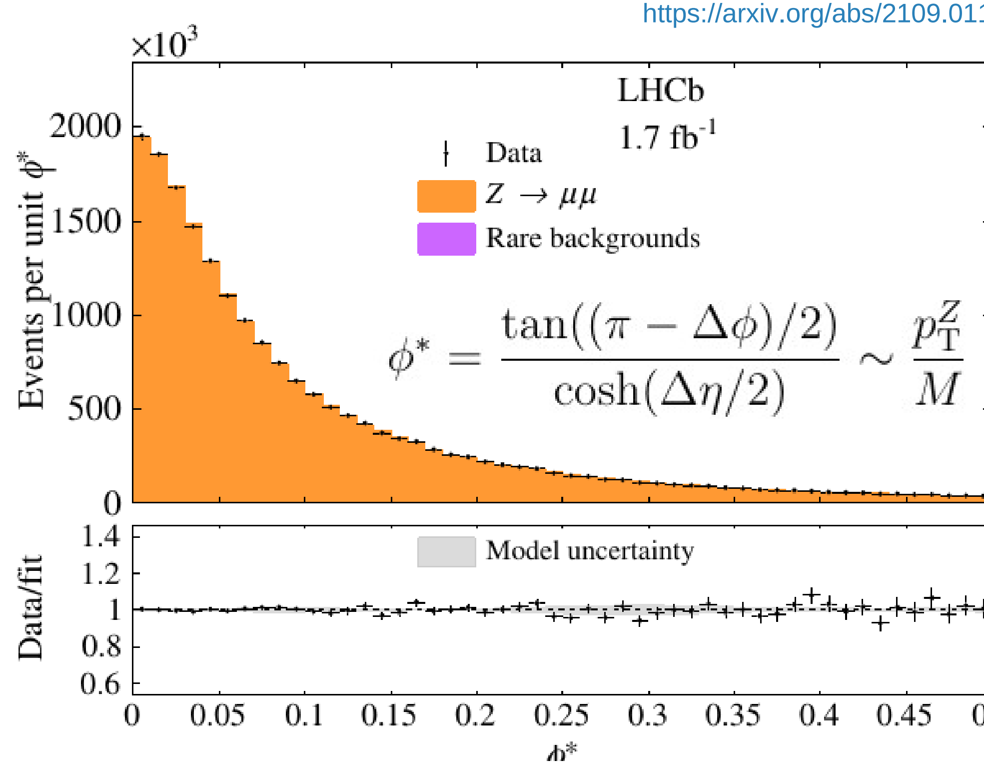




LHCb W boson mass measurement

https://arxiv.org/abs/2109.01113





- Z → $\mu\mu$ is fixed by the fit to ϕ^*

Parameter	Value
Fraction of $W^+ \to \mu^+\nu$	0.5288 ± 0.0006
Fraction of $W^- \to \mu^-\nu$	0.3508 ± 0.0005
Fraction of hadron background	0.0146 ± 0.0007
α_s^Z	0.1243 ± 0.0004
α_s^W	0.1263 ± 0.0003
k_T^{intr}	1.57 ± 0.14 GeV
A_3 scaling	0.975 ± 0.026
m_W	80362 ± 23 MeV

affect hadronisation simulation

A_3 – parameter in differential cross section. Depends on W polarisation

LHCb W boson mass measurement

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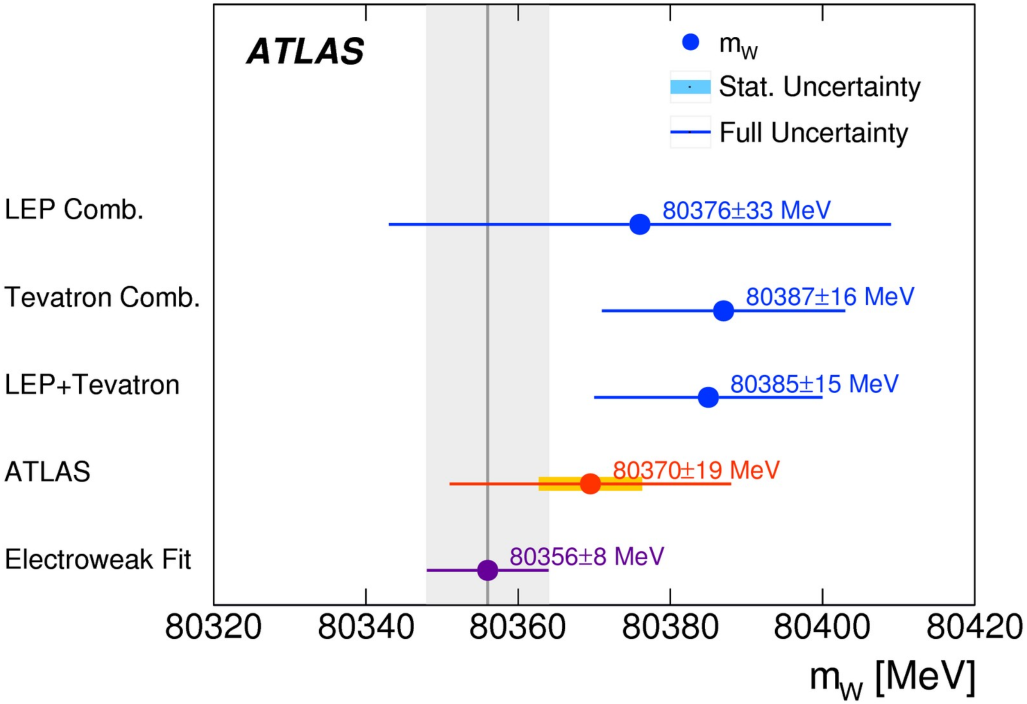
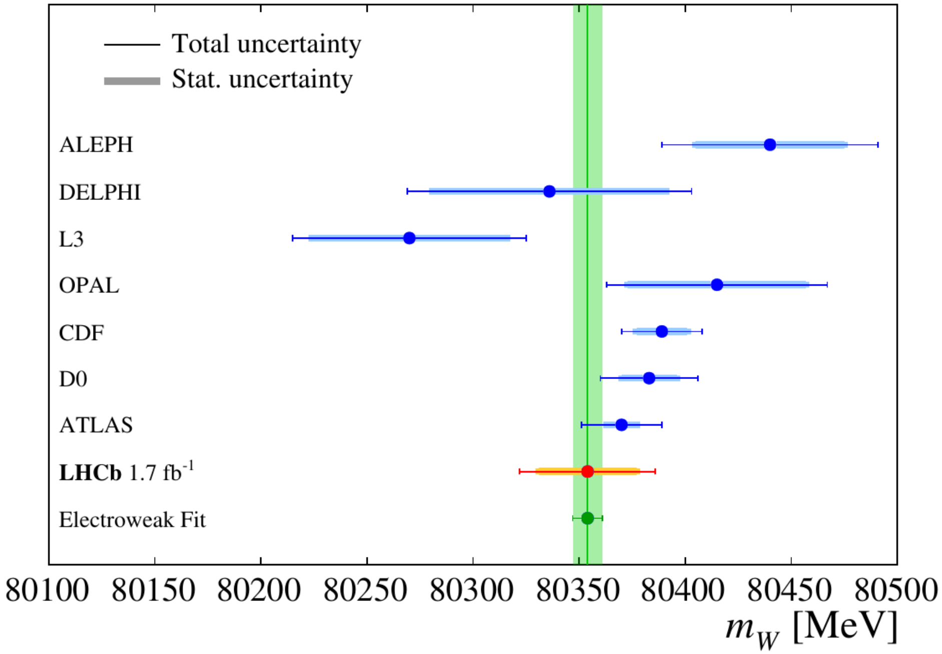
arXiv:1701.07240



https://arxiv.org/abs/2109.01113



NNPDF3.1 $m_W = 80362 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ MeV,

CT18 $m_W = 80350 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 12_{\text{PDF}}$ MeV,

MSHT20 $m_W = 80351 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 7_{\text{PDF}}$ MeV,

average over different PDF sets

$$m_W = 80354 \underbrace{\pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}}_{32\text{ MeV}}\ \text{MeV}.$$

3x more data waiting → <20 MeV precision accessible

Higgs mass

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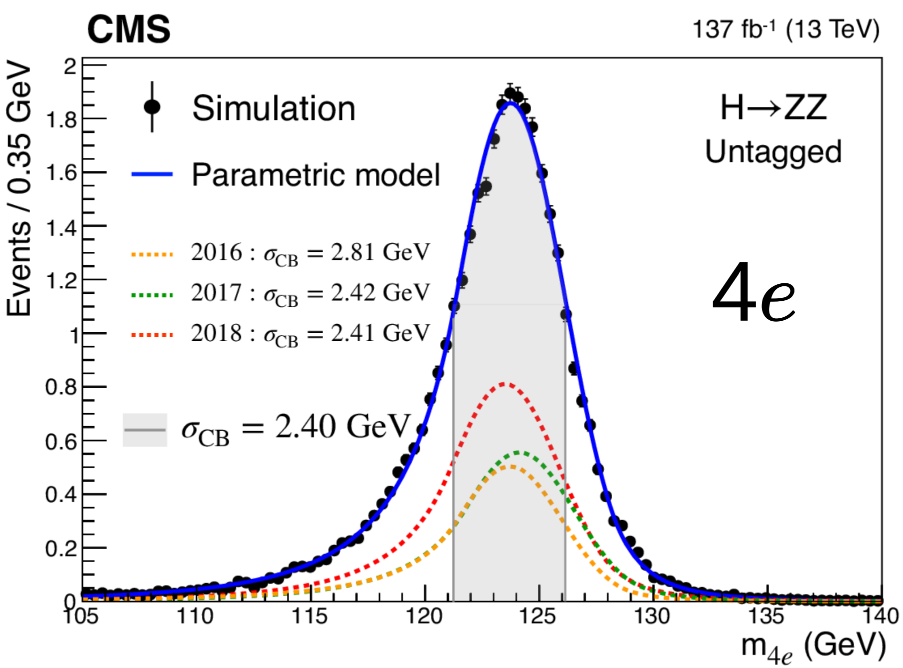
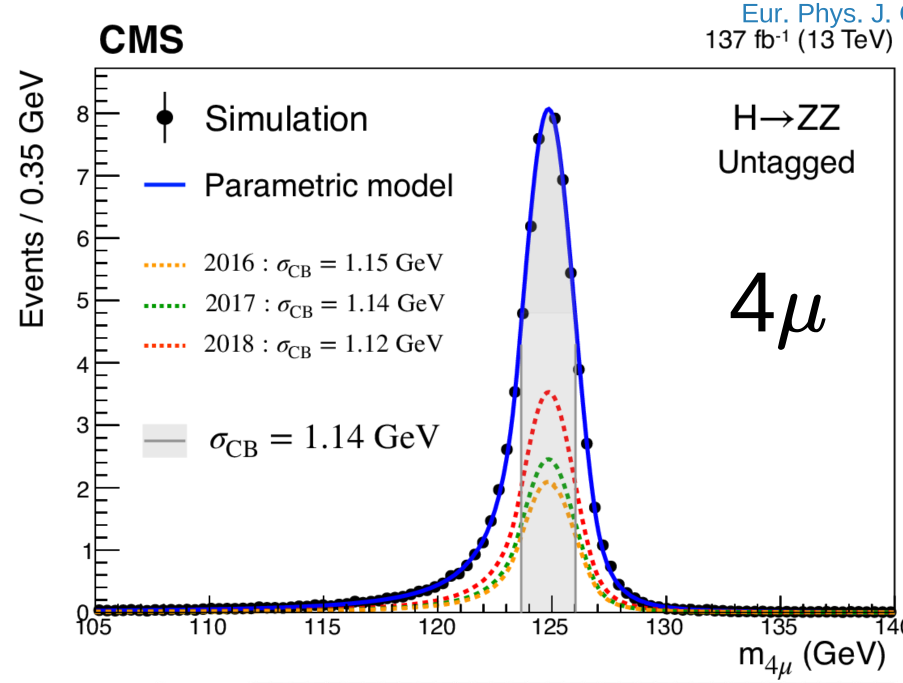
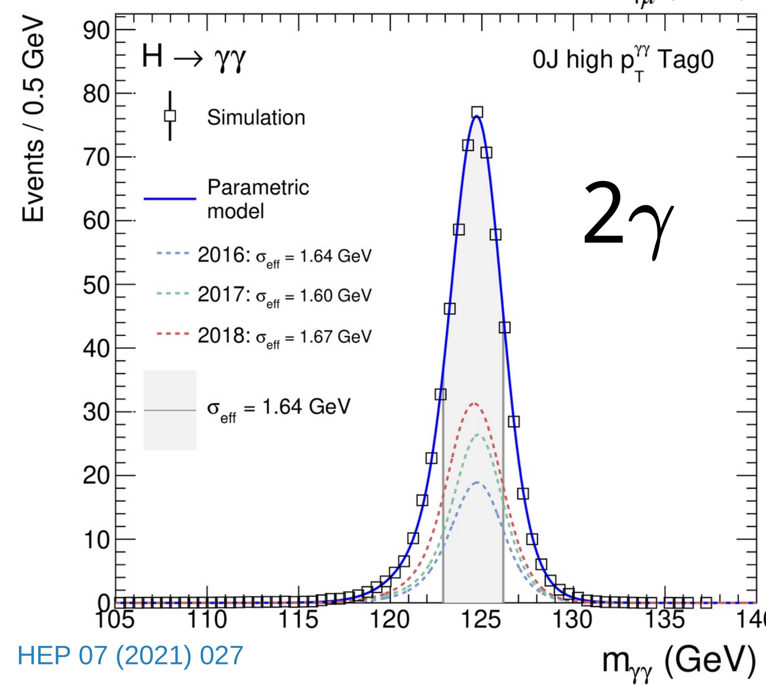




- the Higgs mass is best measured in $H\rightarrow ZZ\rightarrow 4l$ and $H\rightarrow \gamma\gamma$

- the measurement is still dominated by statistics

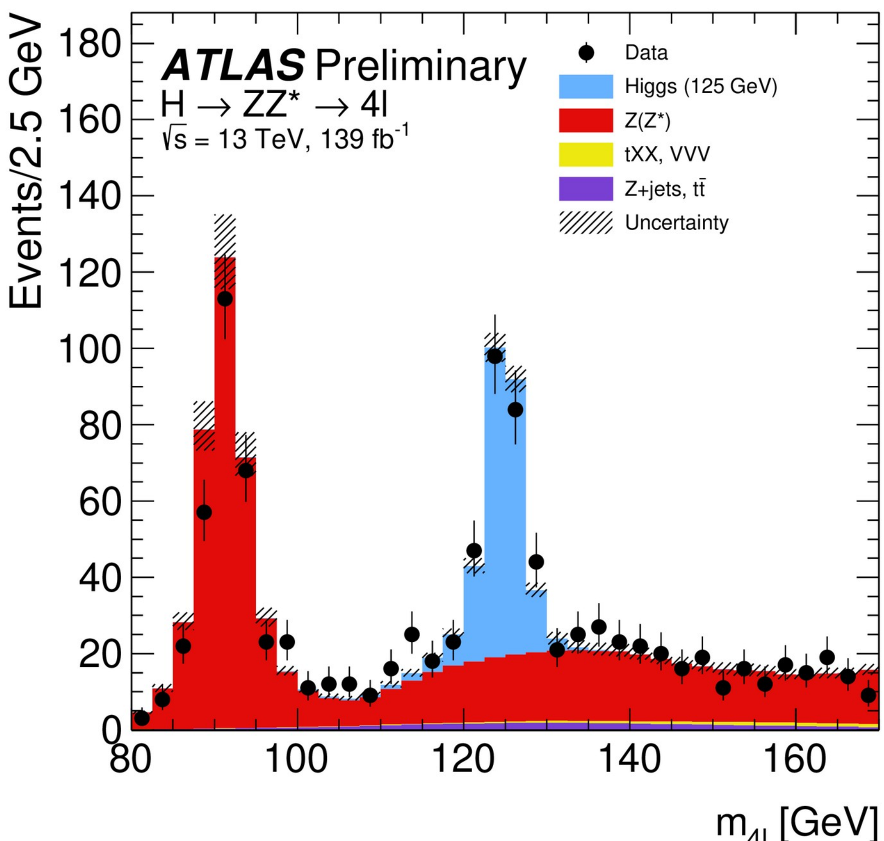


HEP 07 (2021) 027

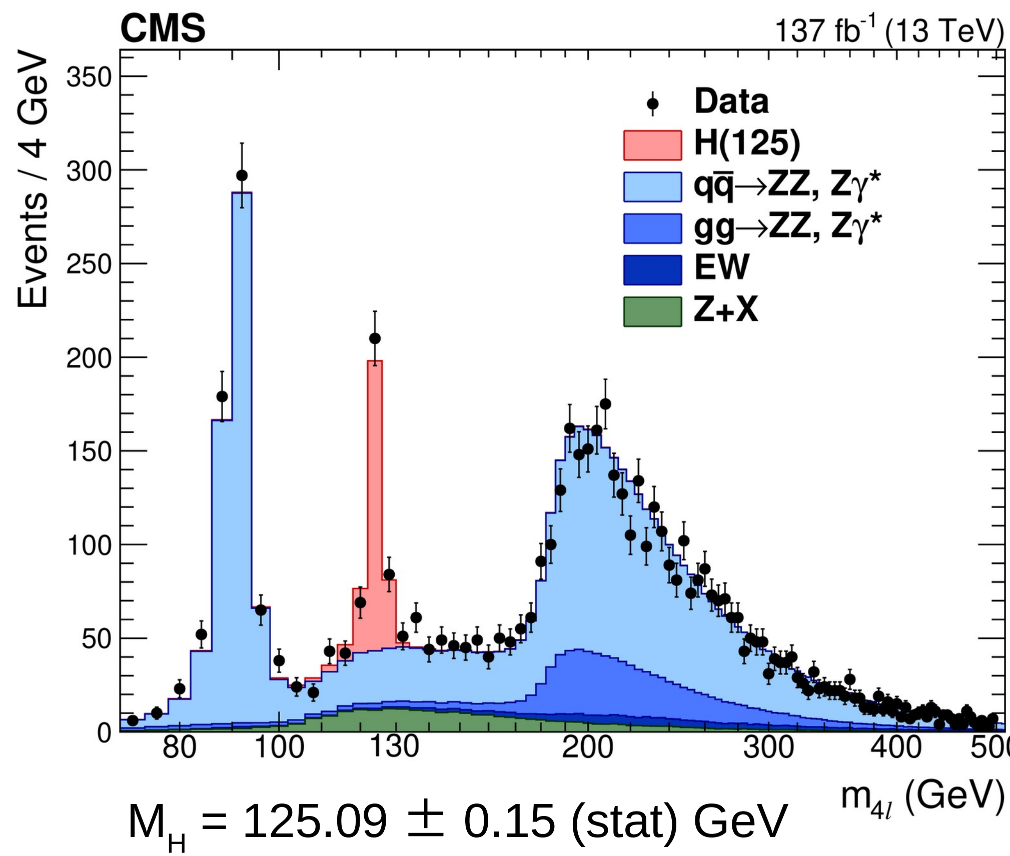
Higgs mass

$$\text{ATLAS}\ H\rightarrow ZZ:\quad m_H = 124.92 \pm 0.19\,(stat.)^{+0.09}_{-0.06}\,(syst.)\,GeV$$

$$\text{CMS}\ H\rightarrow\rightarrow ZZ,\gamma\gamma,\text{Run-1+2016}:\quad m_H = 125.38 \pm 0.14\,GeV$$



ATLAS-CONF-2020-005



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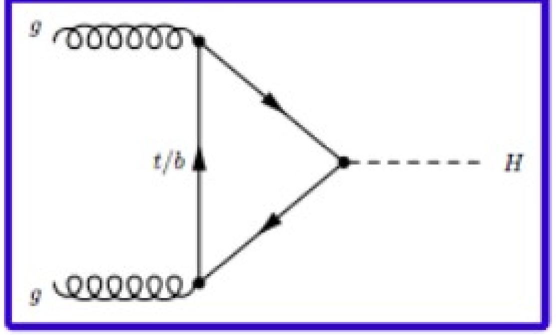
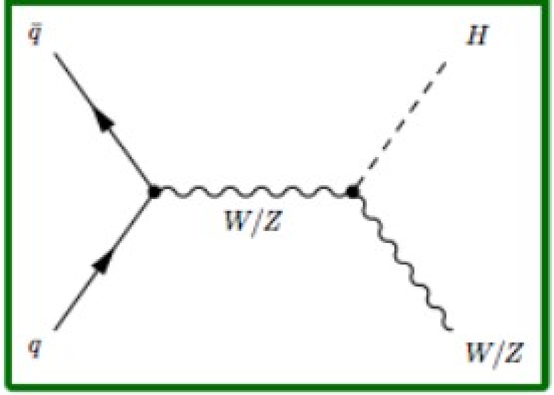
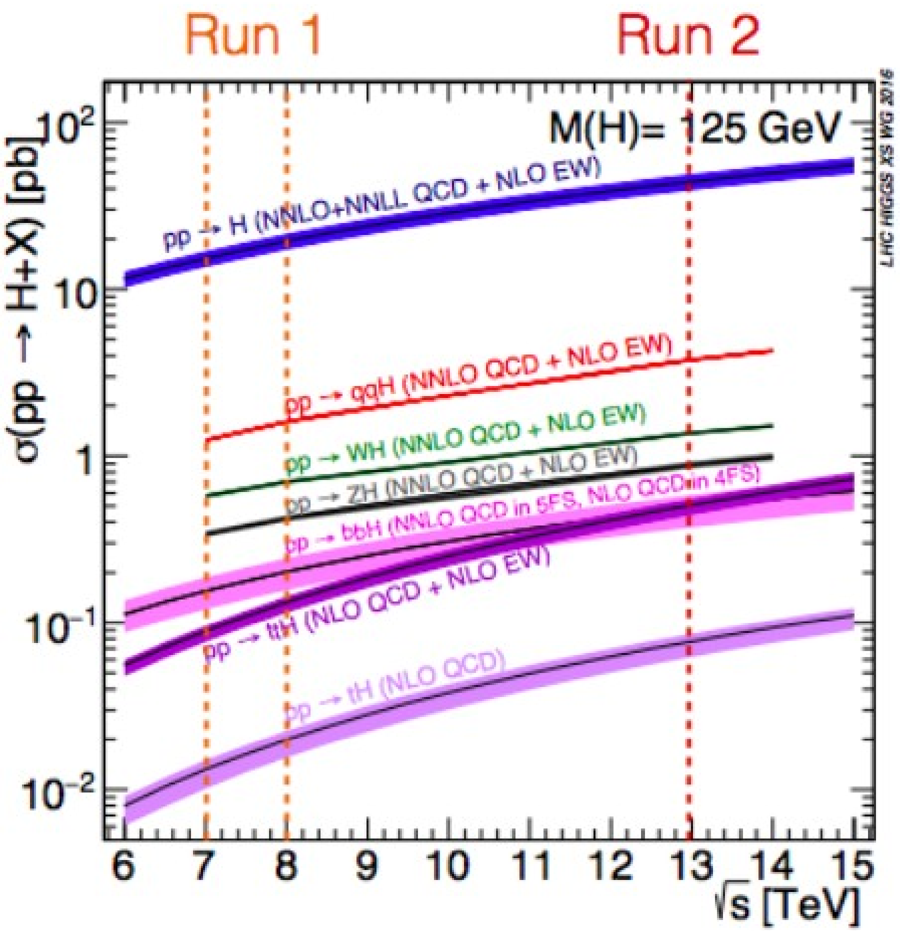
Higgs production

gluon-gluon-fusion

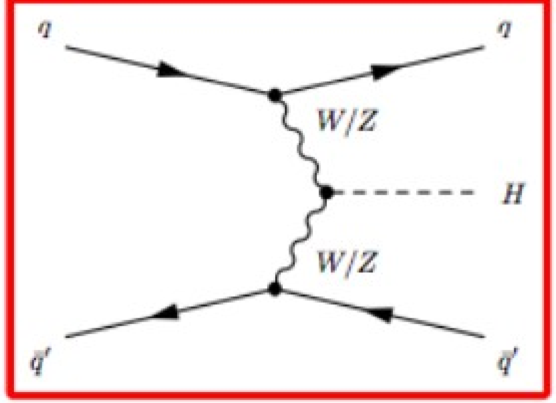


W/Z + H

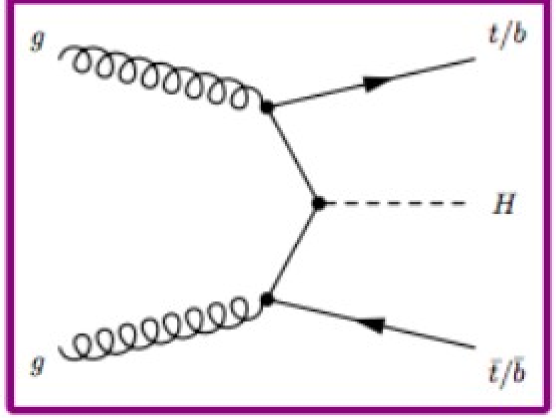




VBF



bbH / ttH



http://www.emfcsc.infn.it/issp2018/docs/talkBoyd.pdf

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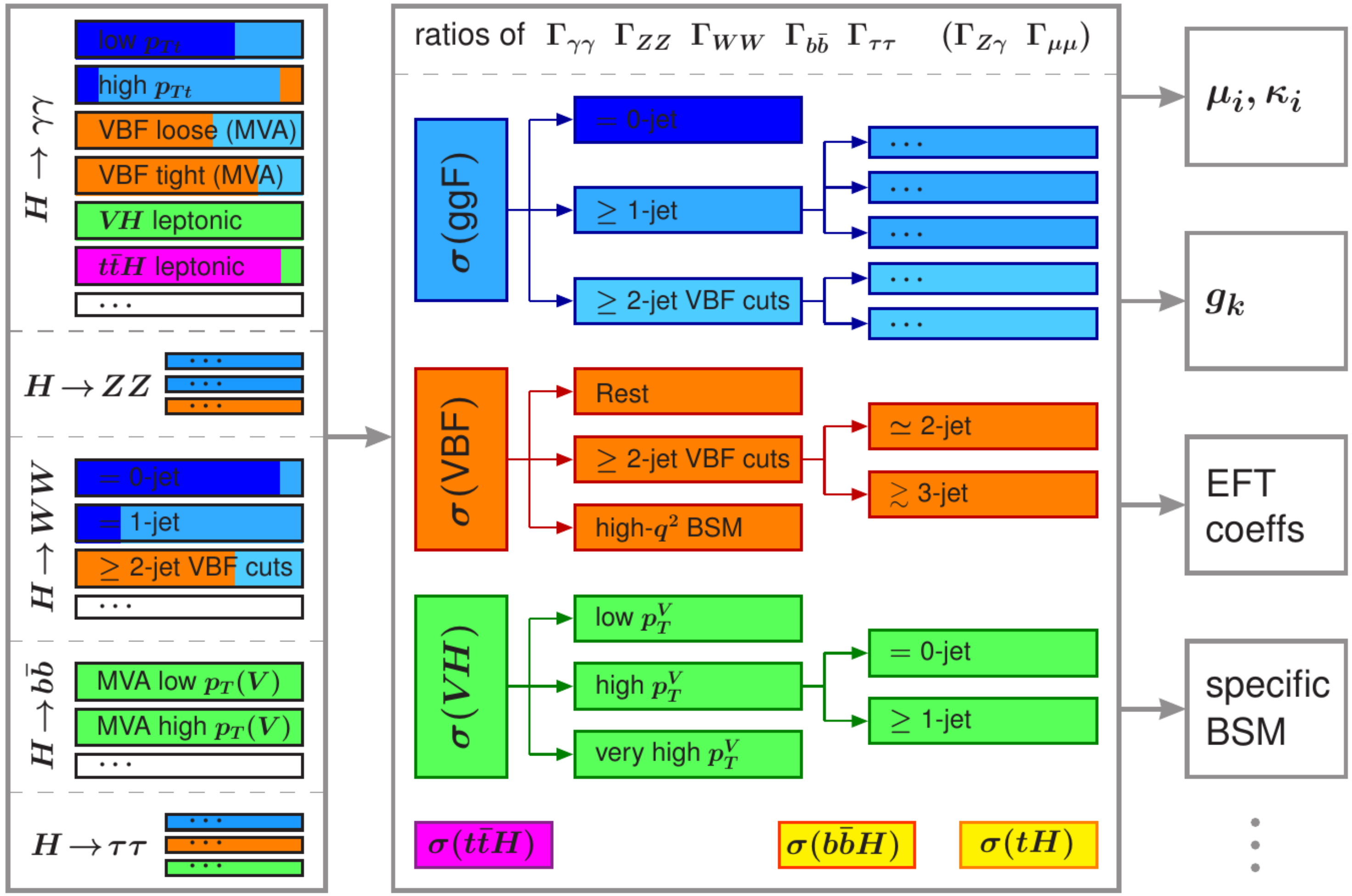
Simplified Template X-Sections (STXS)



- STXS – exclusive kinematic regions in the H production phase space common for all H analyses, both ATLAS and CMS

- aims at reducing the measurements theory dependency

Higgs production

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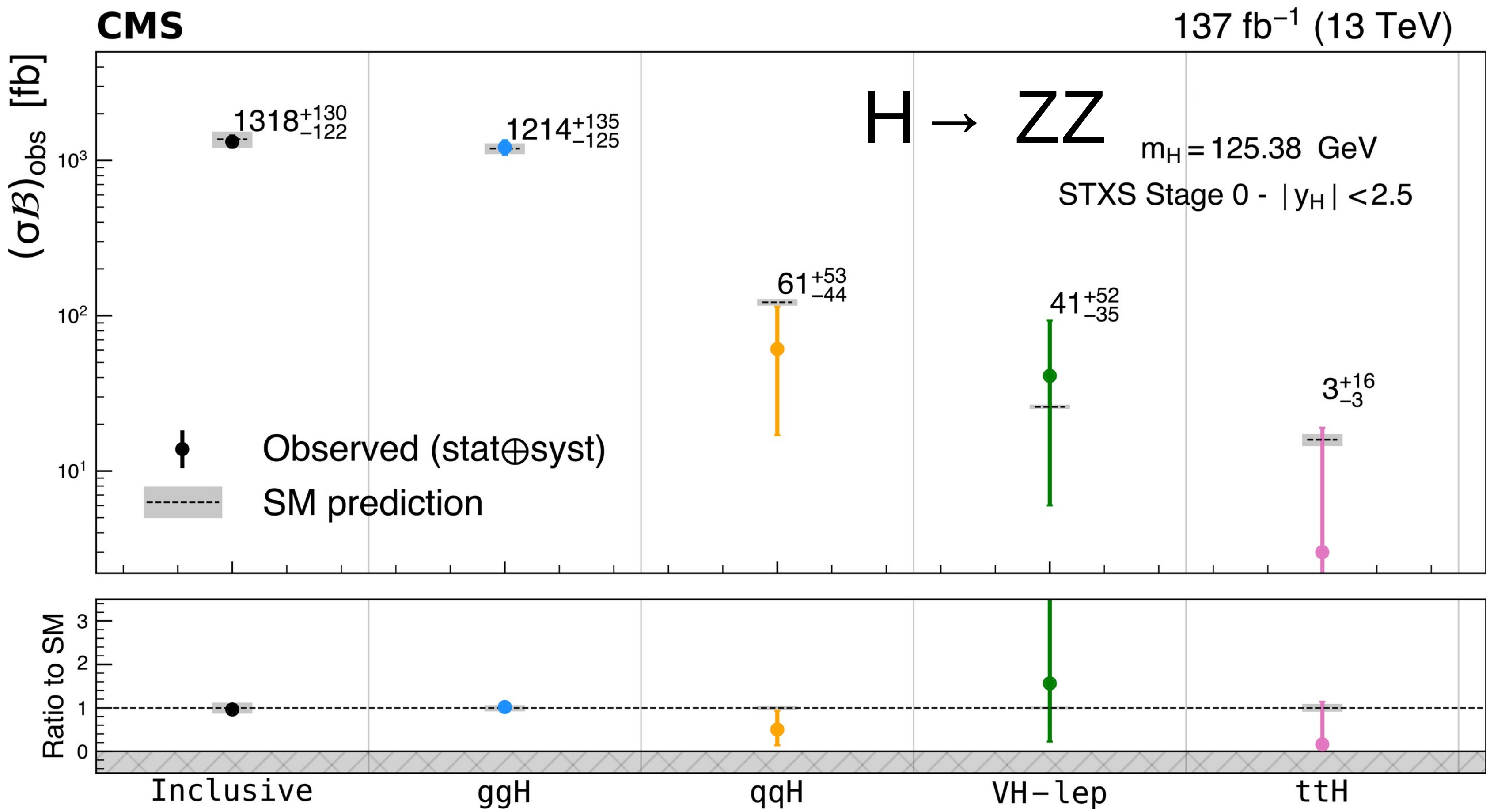

- STXS Stage-0 – an inclusive cross section in each production mode

→ **no surprises here**

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Higgs production

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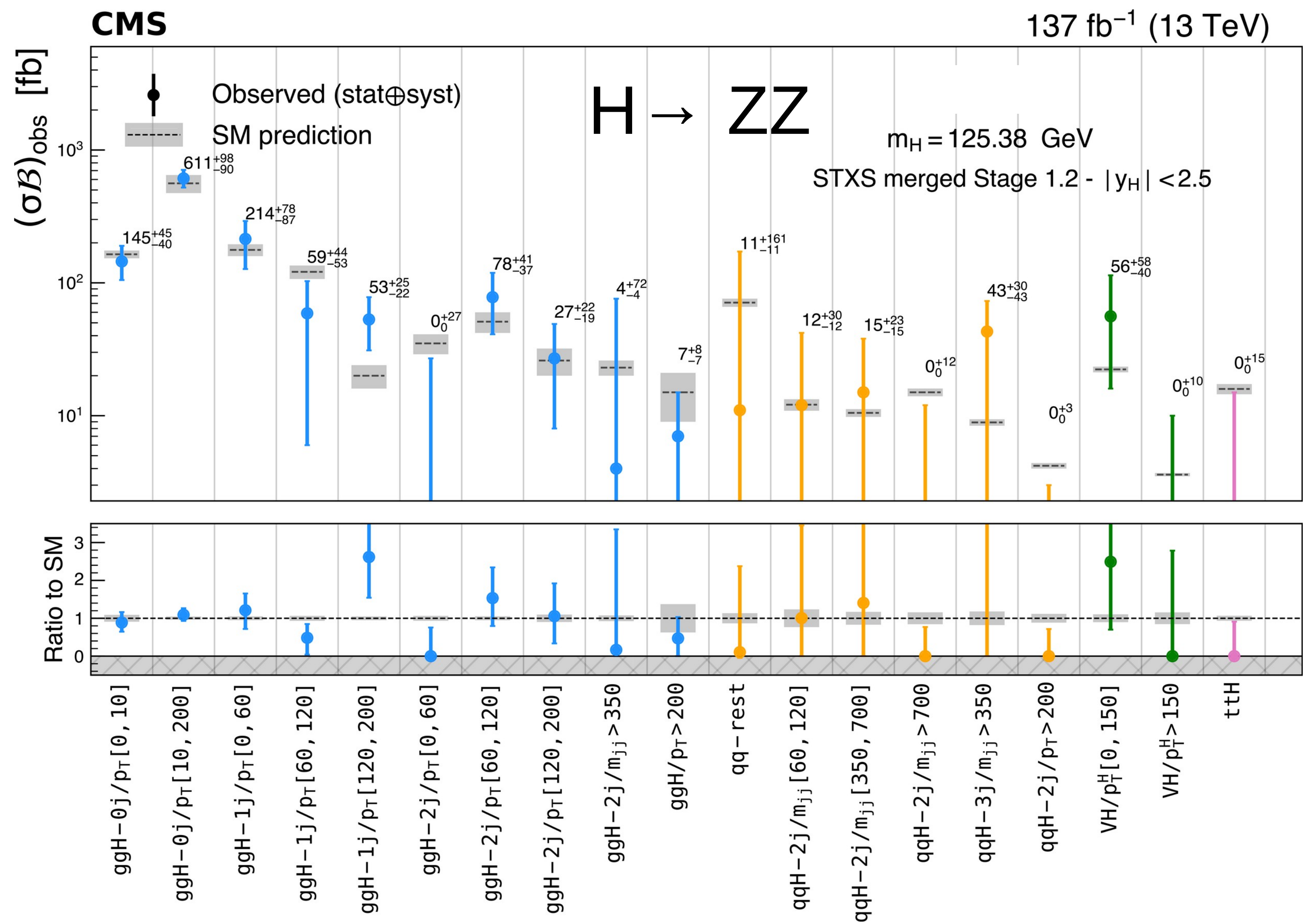

- STXS Stage-1.2 – results in most refined bins
  → **still suffer from statistical uncertainty**

Higgs production

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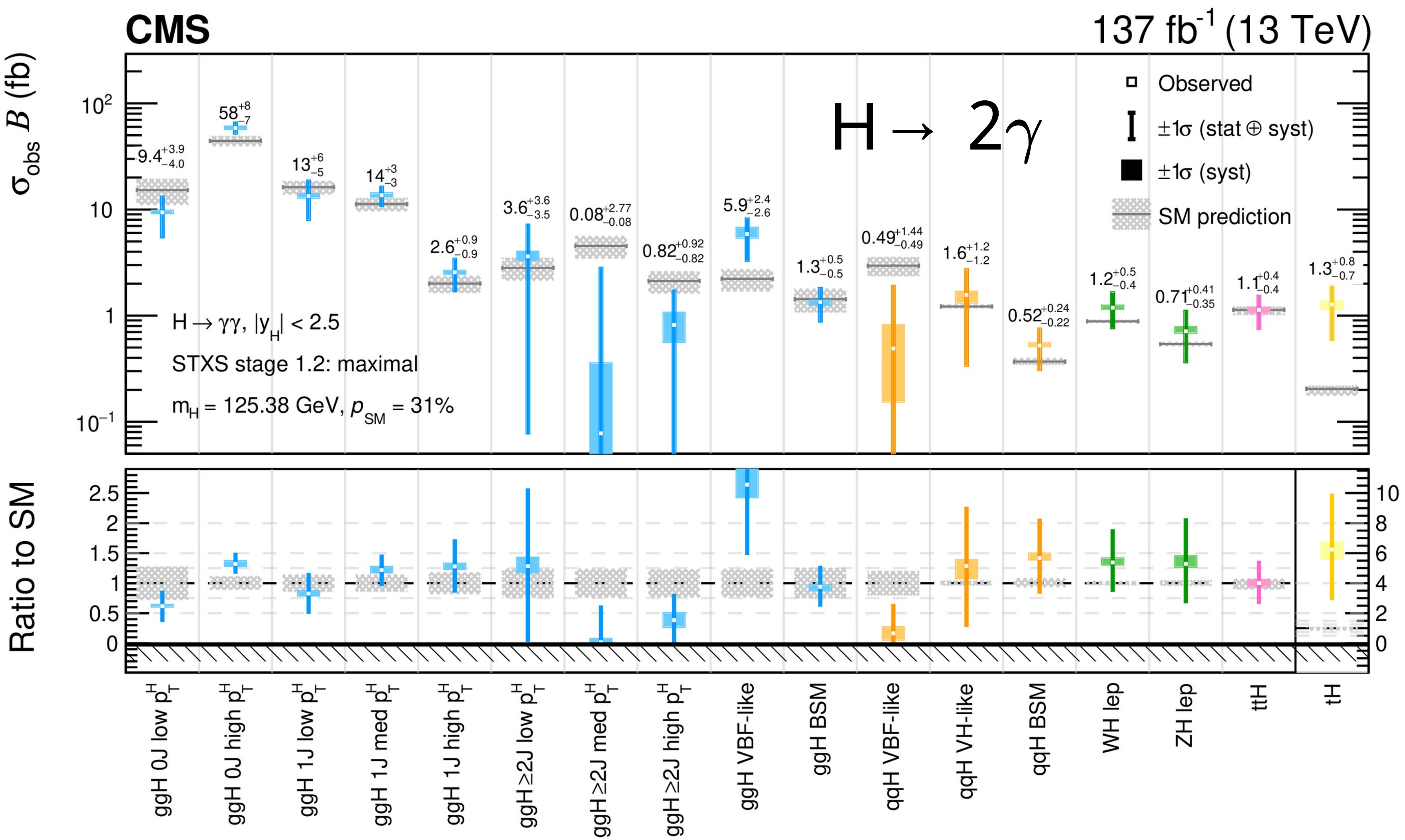
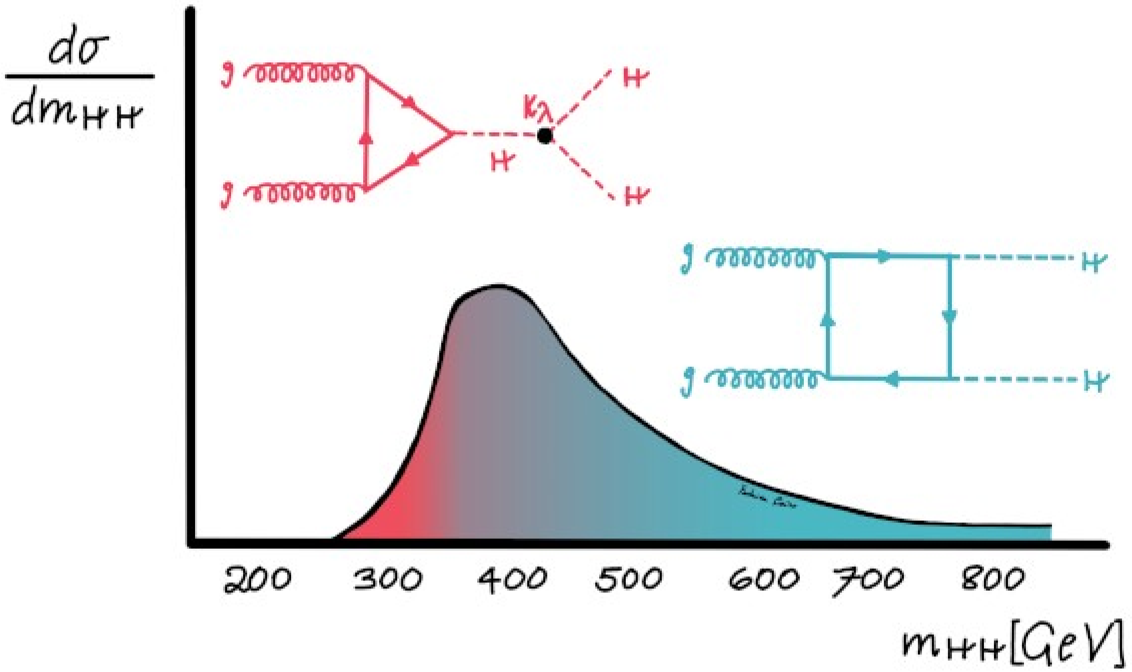
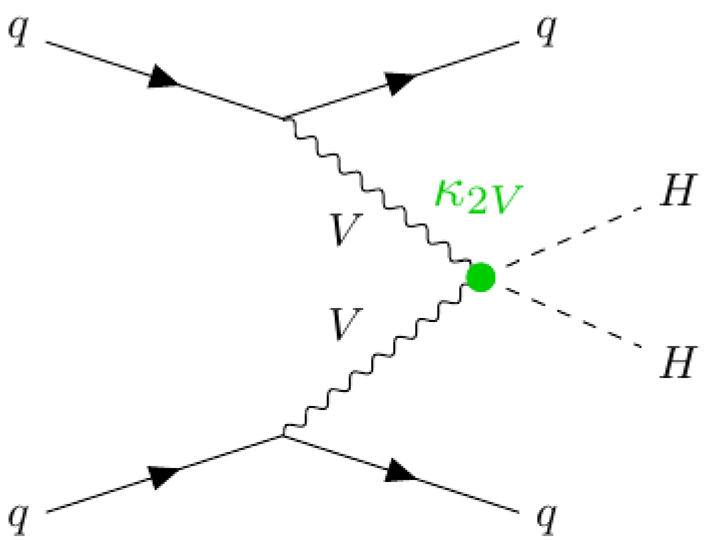


- STXS Stage-1.2 – results in most refined bins
  - → **still suffer from statistical uncertainty**

Double Higgs production

https://atlas.cern/updates/briefing/twice-higgs-twice-challenge





- two main diagrams contribute to gluon fussion
- destructive interference between diagrams → **small gg→HH cross section**
- the VBF mode has clean signature, but even smaller cross section:

$$\sigma_{g\,g\rightarrow HH}=31\,fb^{-1}\rightarrow 5000 \text{ events in Run 2 data}$$

$$\sigma_{qq\rightarrow HH}=1.73\,fb^{-1}\rightarrow 280 \text{ events in Run 2 data}$$

Double Higgs production

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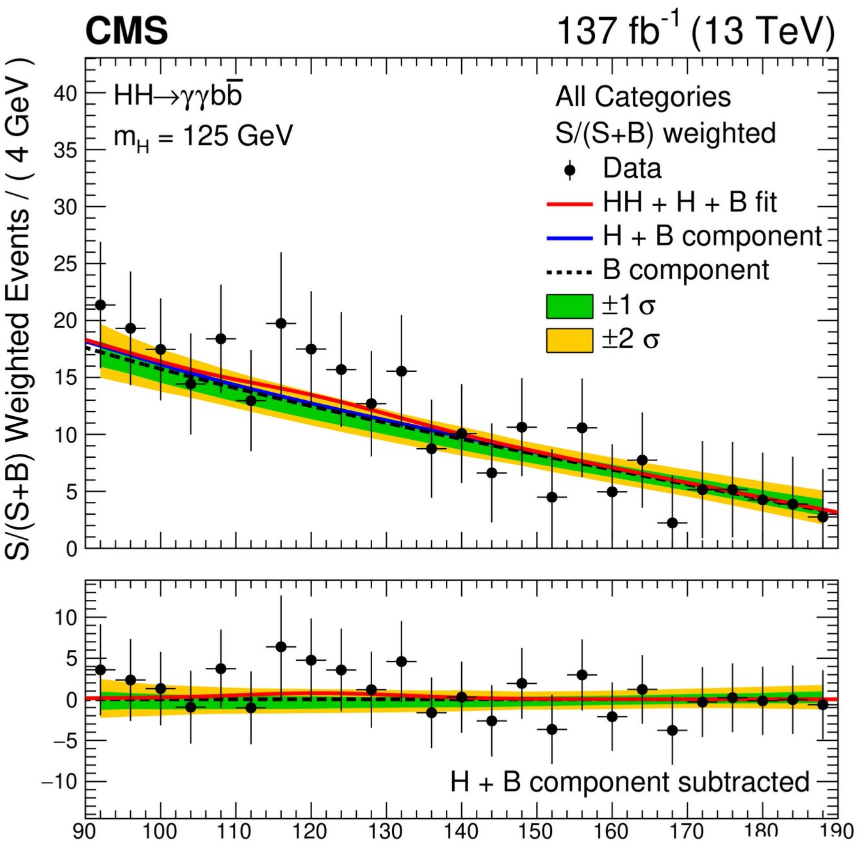
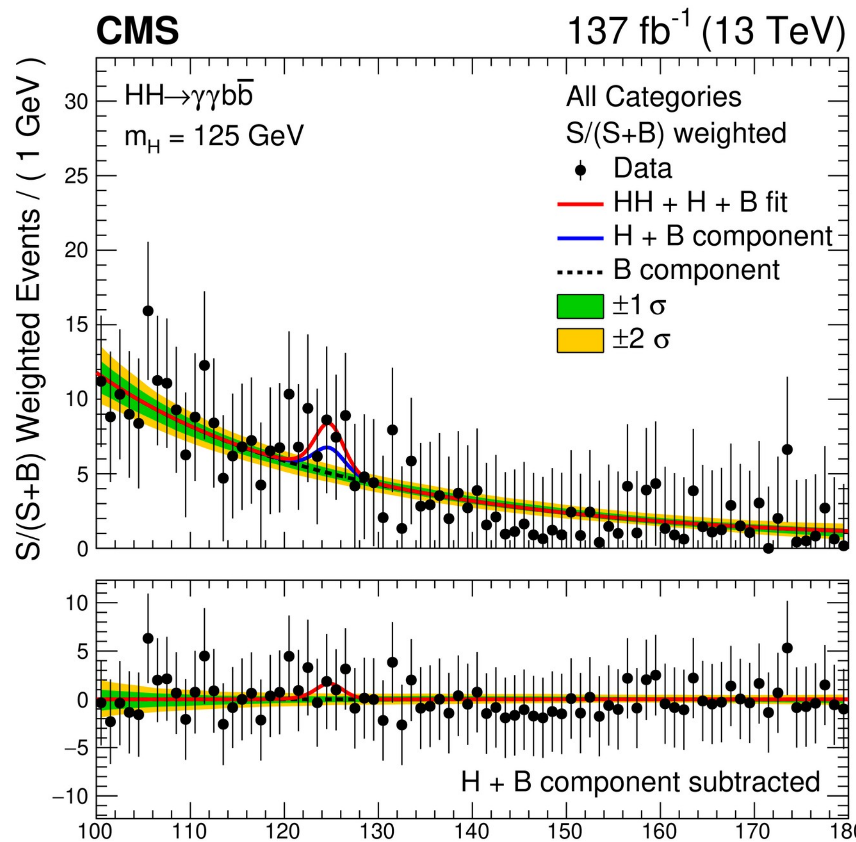


$m_{b\bar{b}}$



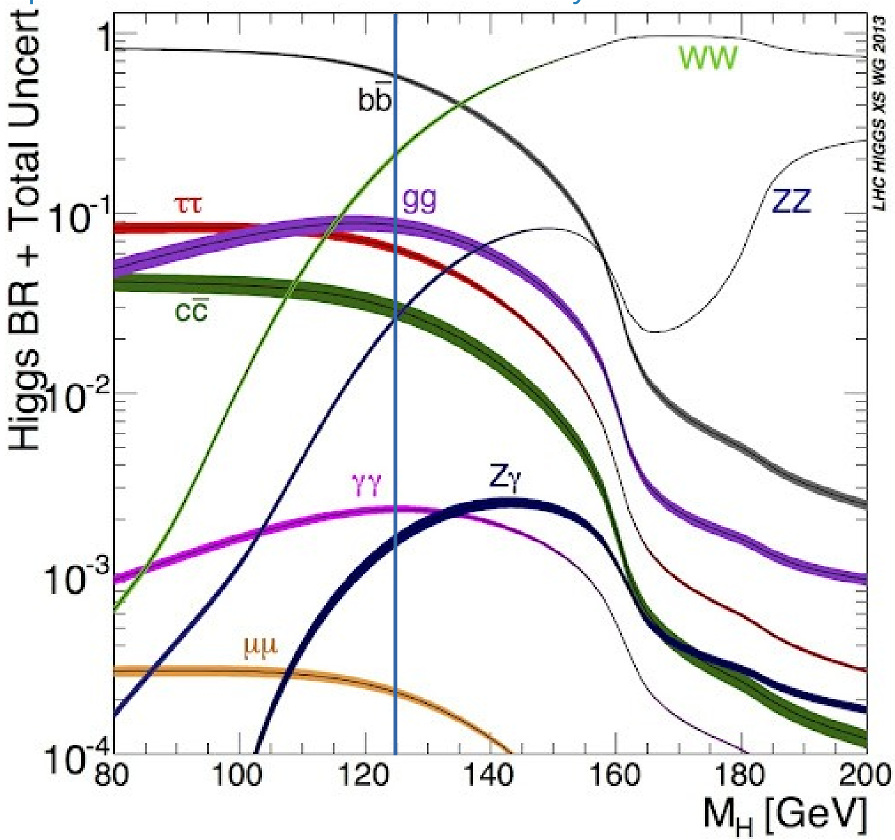
$m_{\gamma\gamma}$

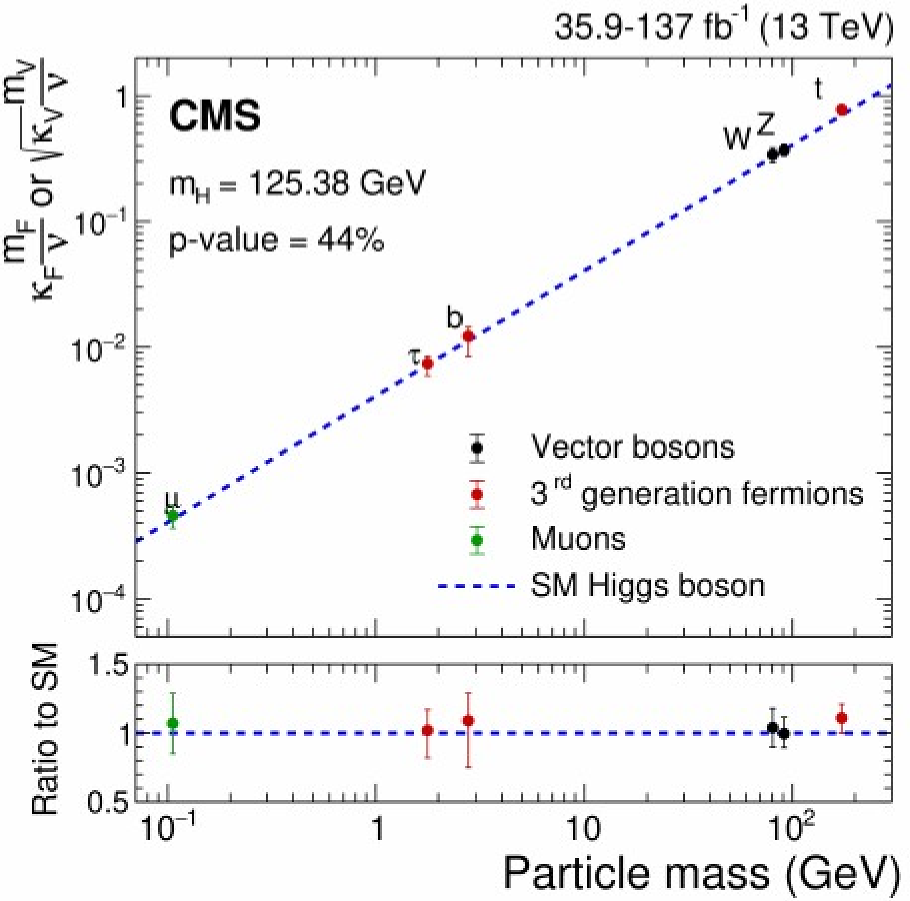
- H required to decay to high BR channel: H→ bb
- the other H required to decay to: $\gamma\gamma$, bb, WW, $\tau\tau$

$\sigma_{gg\to HH, qq\to HH} < 4.1\,(7.7) \times SM\ \sigma_{gg\to HH, qq\to HH}$ for ATLAS (CMS)

Higgs decay

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





• increasing amount of data allows to dwell into more and more difficult decay modes: μμ, cc, μμγ

•H→cc is still very difficult: only upper limits of order of 26xSM cross section expectation reached

H→μμ

Phys. Lett. B 812 (2021) 135980

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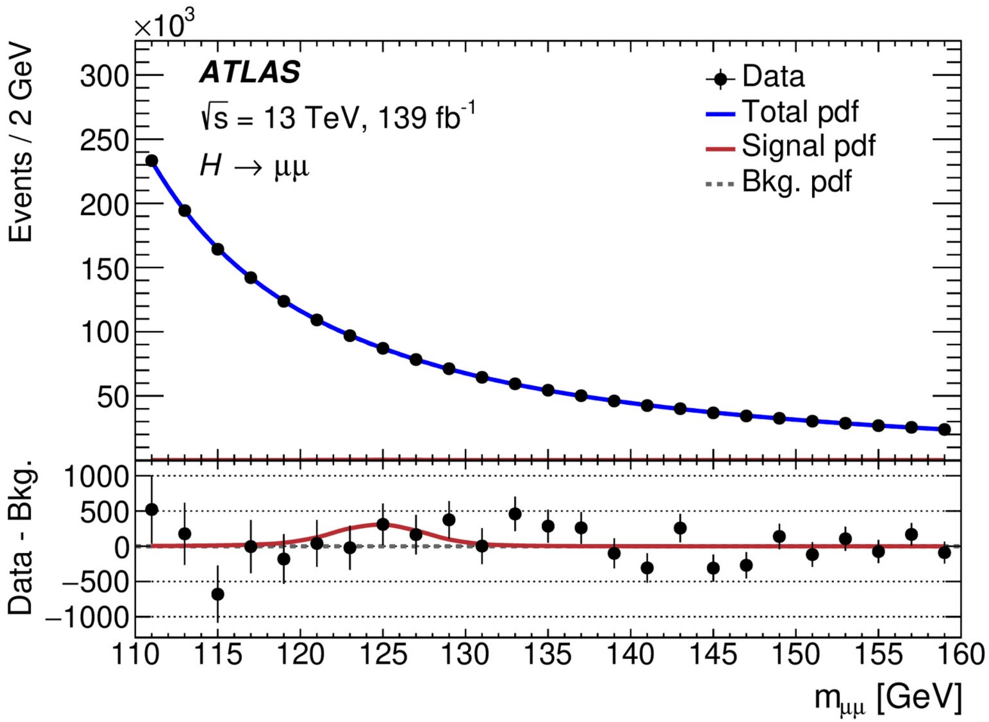
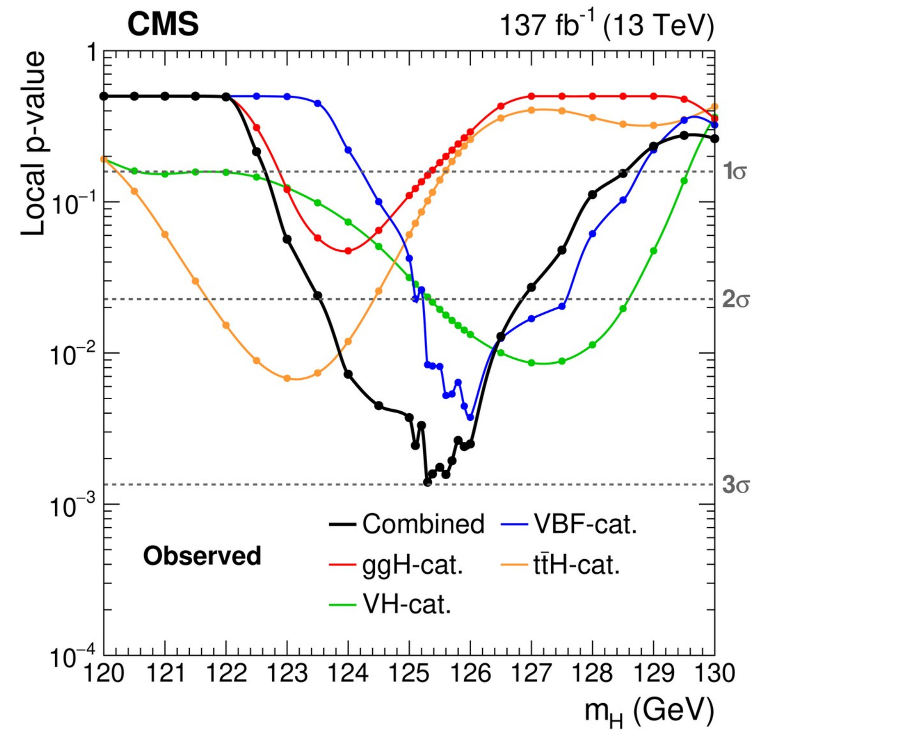




- BR(H→μμ) = 0.02% to be compared with BR(H→ZZ→4μ) = 0.004%

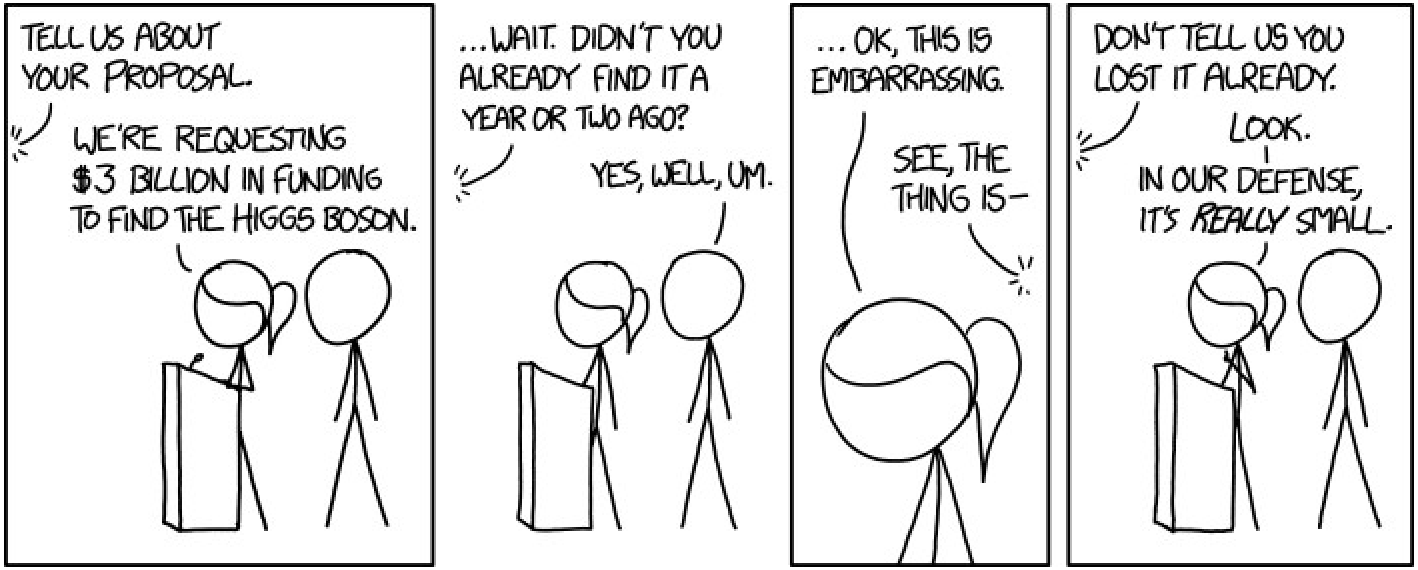
CMS: $\mu = 1.19^{+0.40}_{-0.39}(\text{stat.})^{+0.15}_{-0.14}(\text{syst.})$ significane: $3.0\,\sigma$

ATLAS: $\mu = 1.2 \pm 0.6$ significane: $2.0\,\sigma$

Conclusions

- no new spectacular results from the LHC since the Higgs discovery 2012
- still we need not to leave a stone unturned in looking for deviations from SM

…until we get a new shiny 10x more powerful collider



https://xkcd.com/1437/

References

- Large Hadron Collider Physics Conference, LHCP2021
  https://indico.cern.ch/event/905399

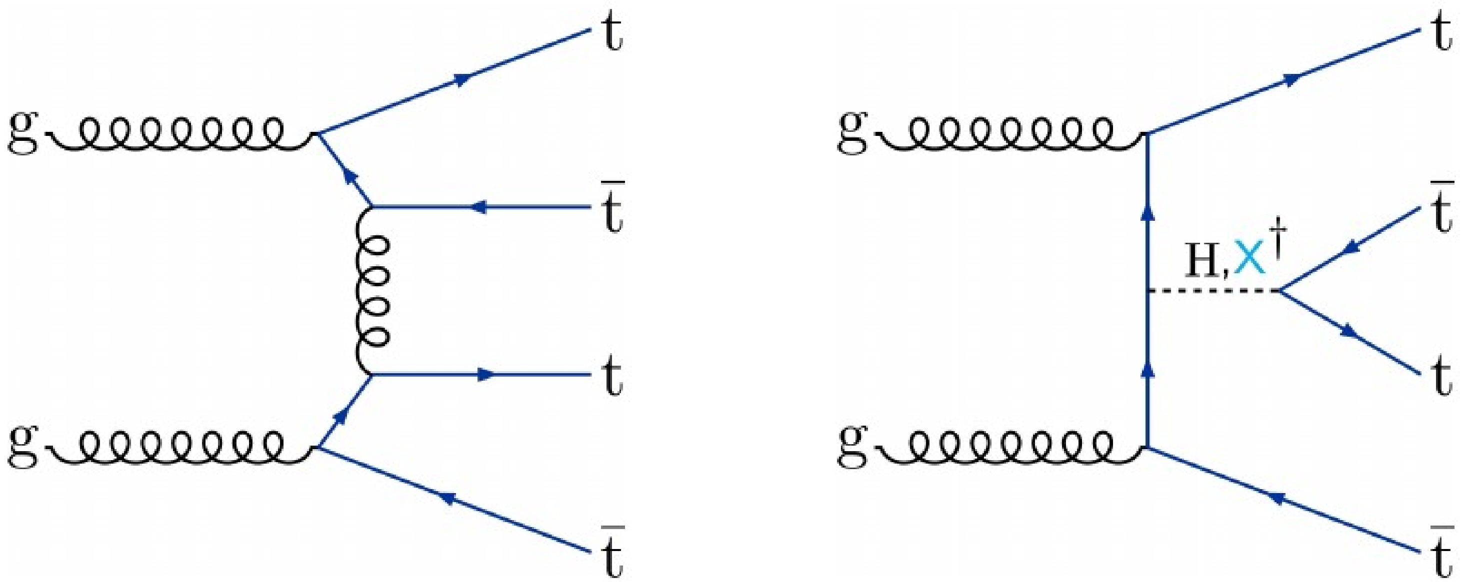
- European Physical Society conference on high energy physics EPS-HEP 2021
  https://indico.desy.de/event/28202/timetable/#20210726

- ATLAS public results
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#PhysicsGroups

- CMS public results
  http://cms-results.web.cern.ch/cms-results/public-results/publications/

- LHCb results
  https://lhcb-public.web.cern.ch/Welcome.html#news

Four top production



- the top quark has large coupling to Higgs boson

- top could be also have large coupling to hypothetical particles, e.g. additional Higgs bosons

Four top production

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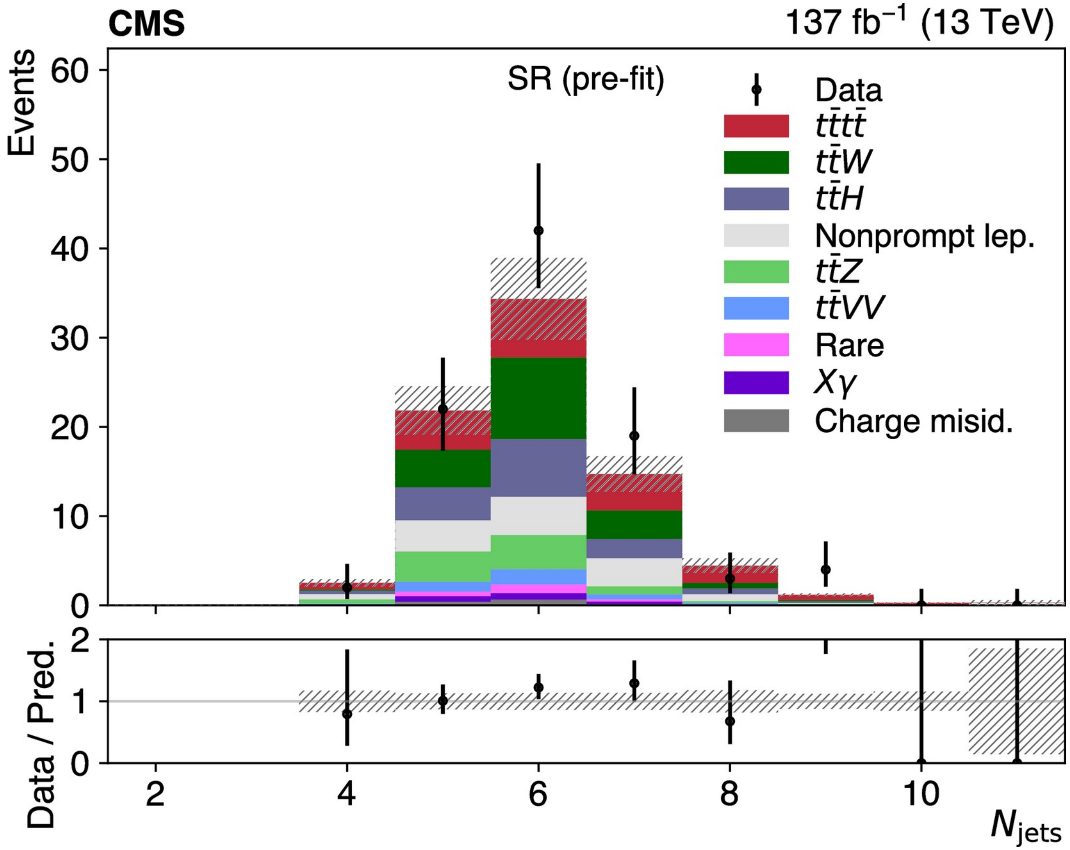
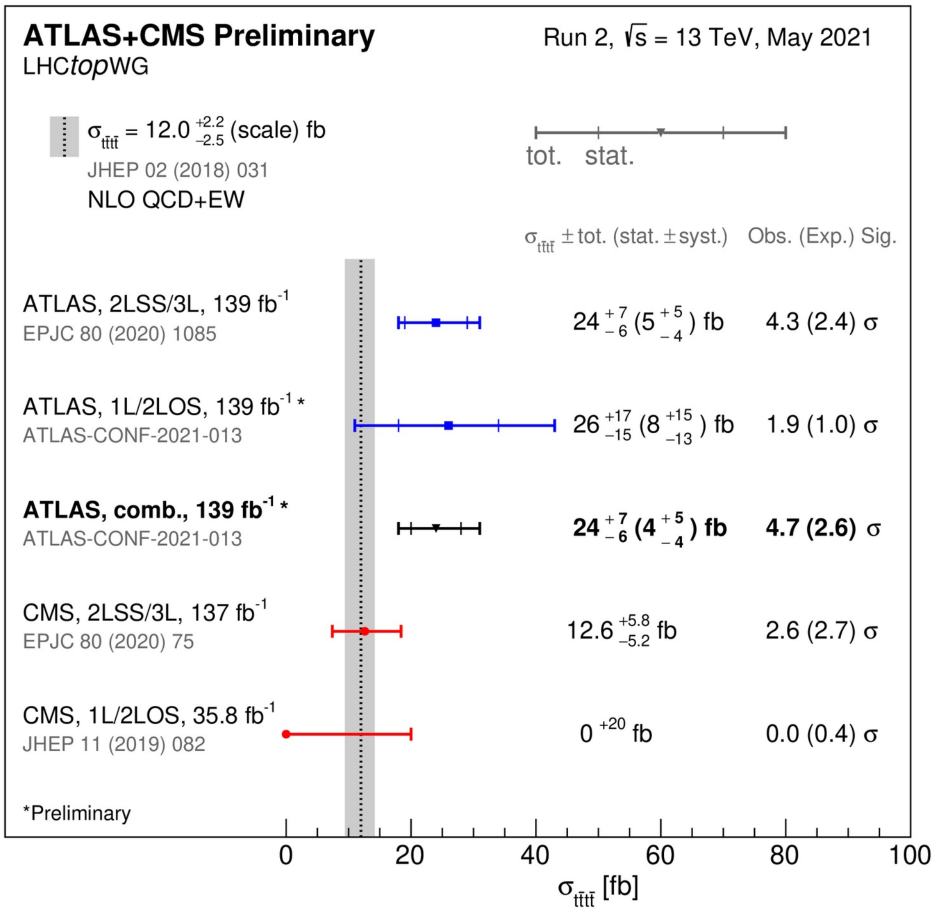
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots



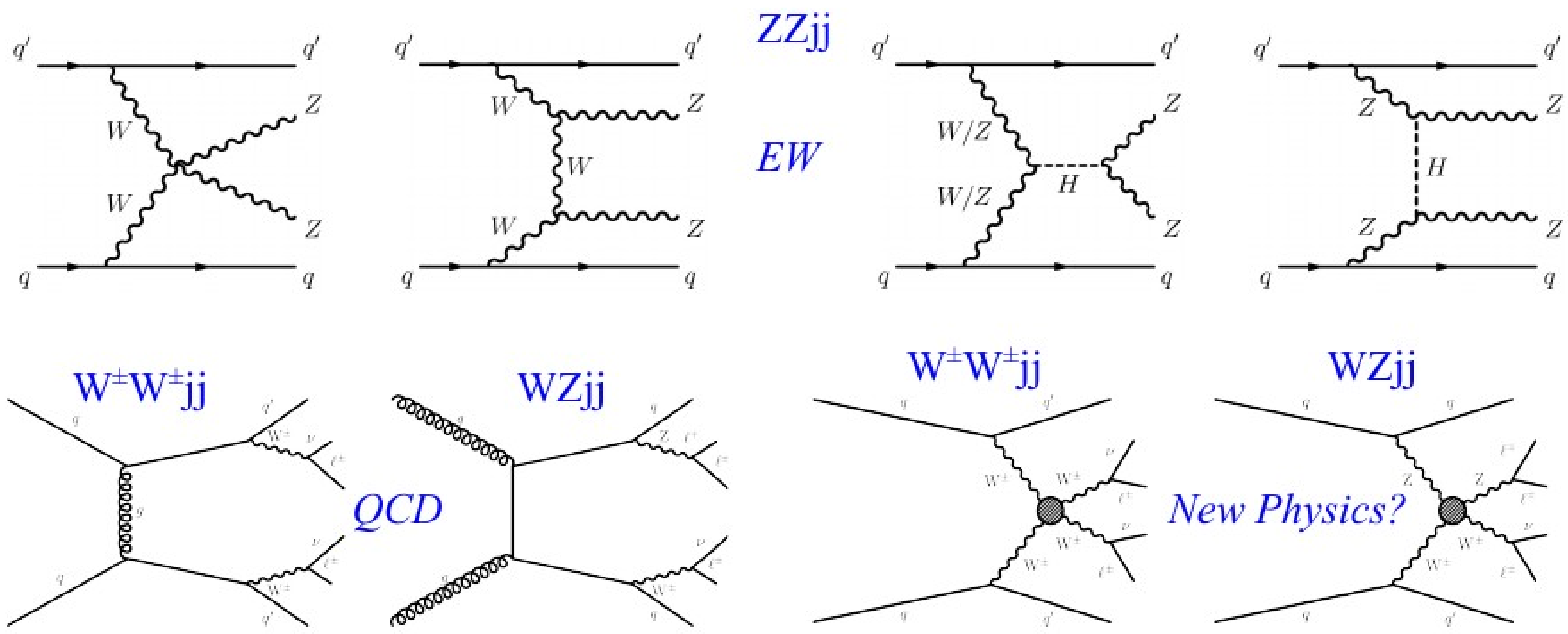


- two main analysis streams:
  - single lepton or 2 opposite sign leptons – 1L/2LOS
  - two same sign leptons or three leptons – 2LSS/3L

ATLAS: $\sigma_{4t} = 24^{+7}_{-6}$ fb significance: $4.7\,\sigma$

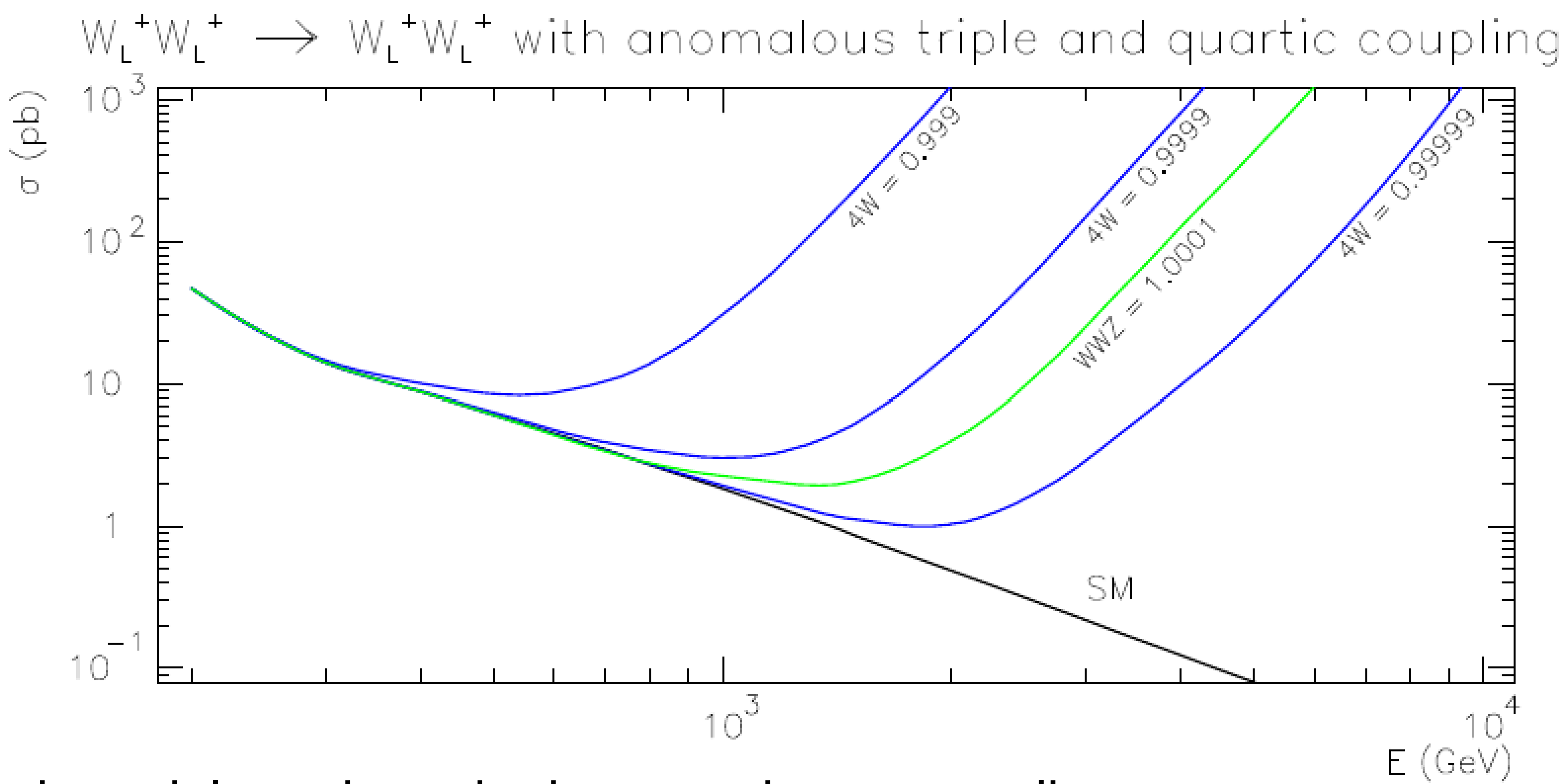
CMS: $\sigma_{4t} = 13^{+6}_{-5}$ fb significance: $2.6\,\sigma$

Vector Boson Scattering (VBS)



- a difficult analysis – significant, gauge dependent interference with other diagrams
- in most cases the cross section is dominated by the QCD diagrams
- the topic extensively presented in May 2021 by M. Szleper

Vector Boson Scattering (VBS)



arXiv:1412.8367 by M. Szleper, NCBJ

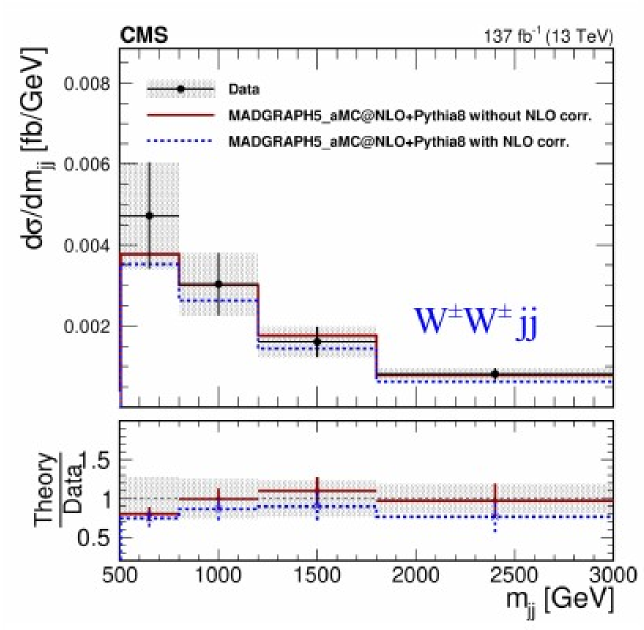
• VBS probes triple and quadratic gauge boson couplings

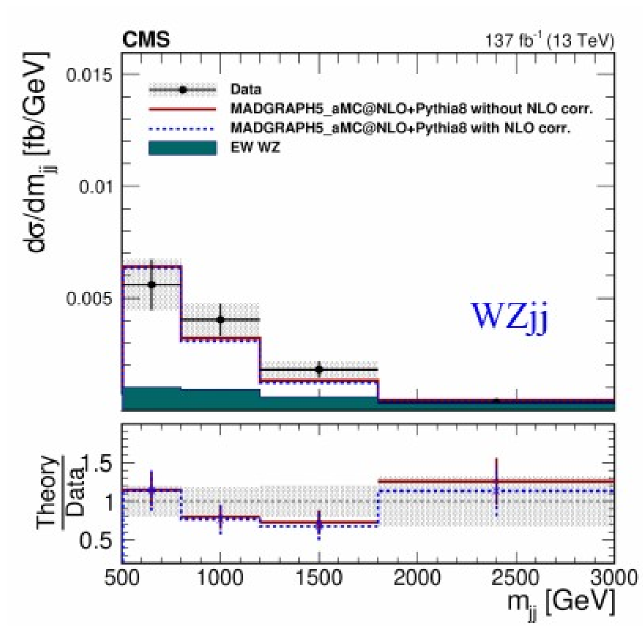
• anomalous VVV or VVVV couplings are hints of new physics or deviations from standard EWK breaking mechanism

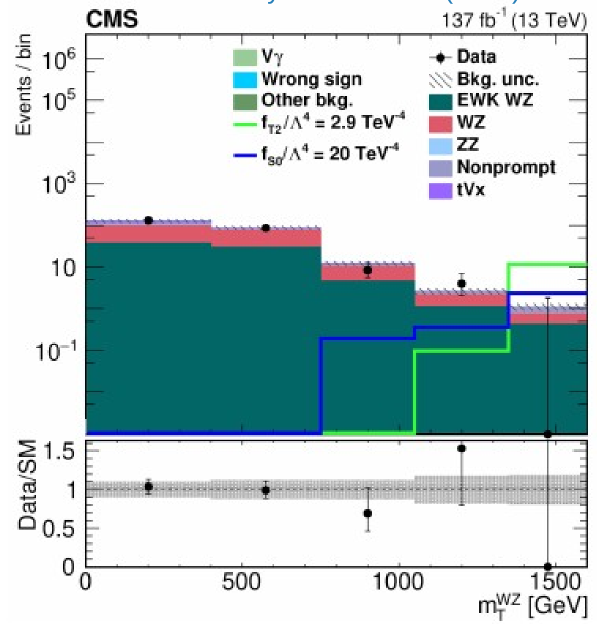
• caveat: **the effect is strongest for the longitudinally polarised V**

Vector Boson Scattering (VBS)

Phys. Lett. B 809 (2020) 135710







• same sign WW and WZ leptonic final states chosen to increase the signal purity

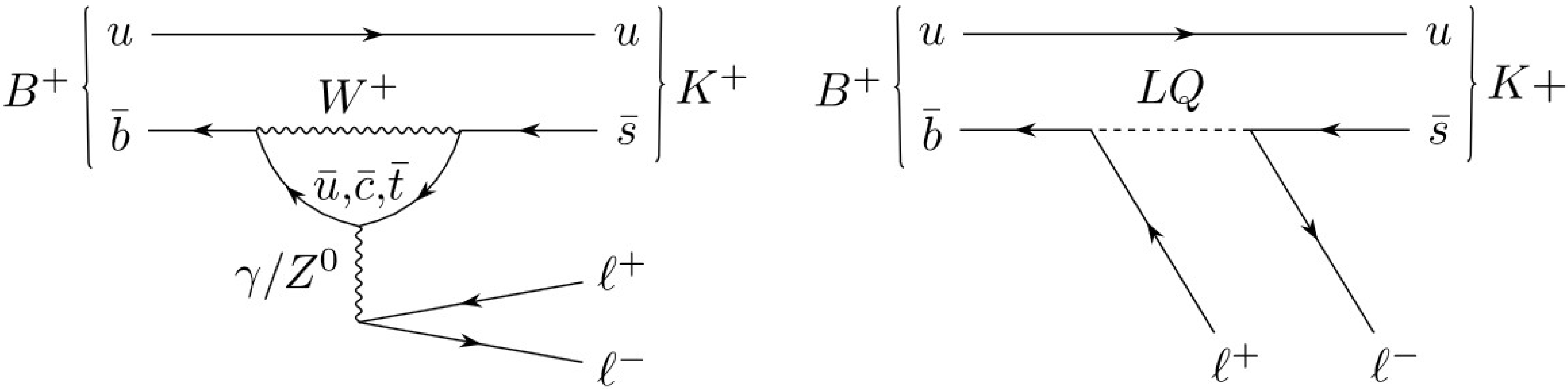
• anomalous VVVV enhances the production cross section at large masses of the WW and WZ

• no signal of excess wrt. SM expectation observed

Lepton universality

https://lhcb-public.web.cern.ch/Welcome.html#RK2021

Lepton non-universality in b → s l^+l^- decay would be a sign of physics beyond SM



Number of interest:

$$R_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathrm{d}q^2} \mathrm{d}q^2} \overset{\mathrm{SM}}{=} 1 \pm \mathcal{O}(10^{-2})\ \text{EM correction}$$

Q^2 – di-lepton invariant mass squared

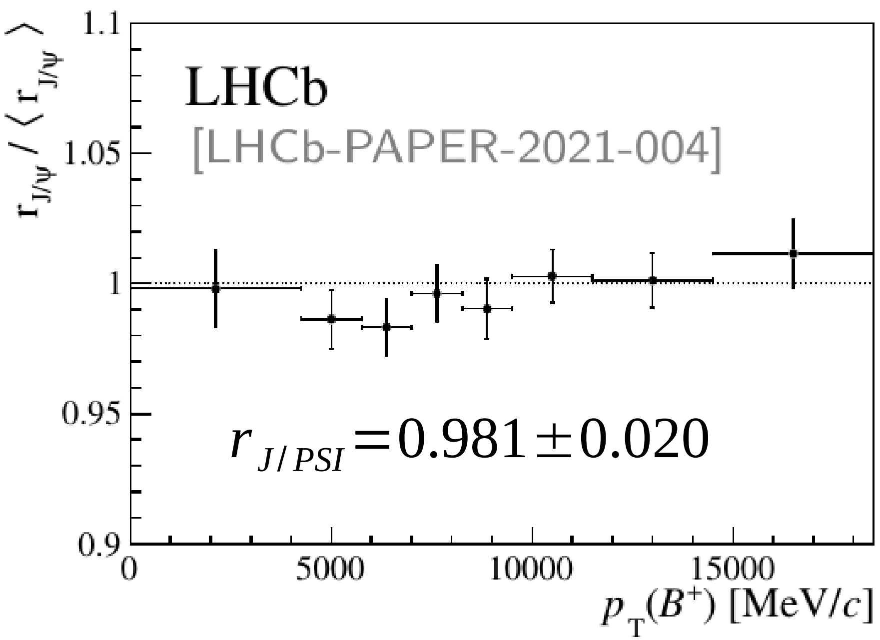
R_K definition in a real life

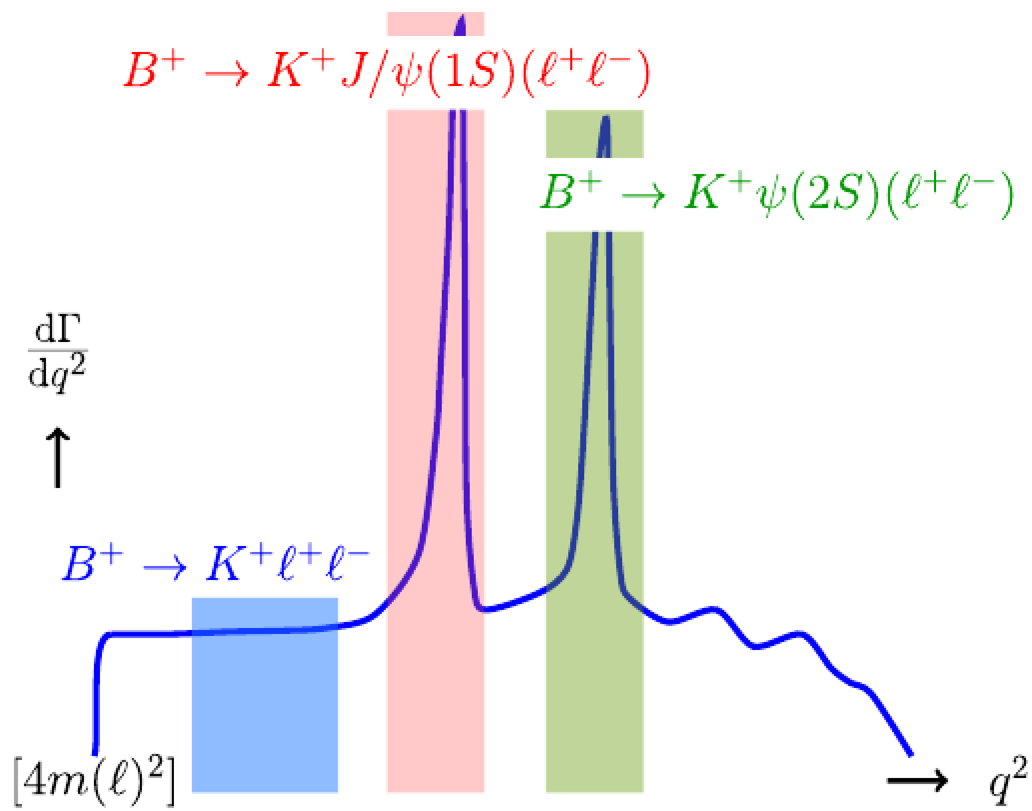
- difficult analysis – e/μ are the same in couplings, but not in detector

- e/μ efficiency differences controlled by measurement of double ratio

$$R_K = \left(\frac{N^{\mu\mu}_{\text{rare}}}{\varepsilon^{\mu\mu}_{\text{rare}}} \Big/ \frac{N^{ee}_{\text{rare}}}{\varepsilon^{ee}_{\text{rare}}} \right) \Bigg/ \underbrace{\left(\frac{N^{\mu\mu}_{\text{control}}}{\varepsilon^{\mu\mu}_{\text{control}}} \Big/ \frac{N^{ee}_{\text{control}}}{\varepsilon^{ee}_{\text{control}}} \right)}_{r_{J/\psi}} =$$

$$\left(\frac{N^{\mu\mu}_{\text{rare}}}{N^{\mu\mu}_{\text{control}}} \Big/ \frac{\varepsilon^{\mu\mu}_{\text{rare}}}{\varepsilon^{\mu\mu}_{\text{control}}} \right) \Bigg/ \left(\frac{N^{ee}_{\text{rare}}}{N^{ee}_{\text{control}}} \Big/ \frac{\varepsilon^{ee}_{\text{rare}}}{\varepsilon^{ee}_{\text{control}}} \right)$$





$K^+l^+l^-$ invariant mass

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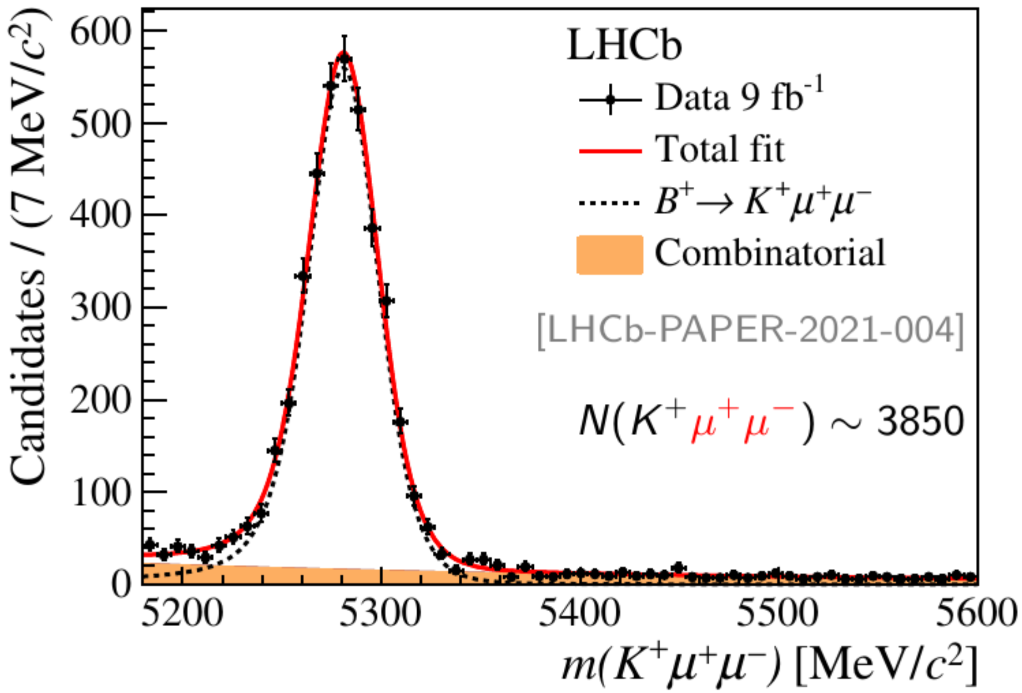

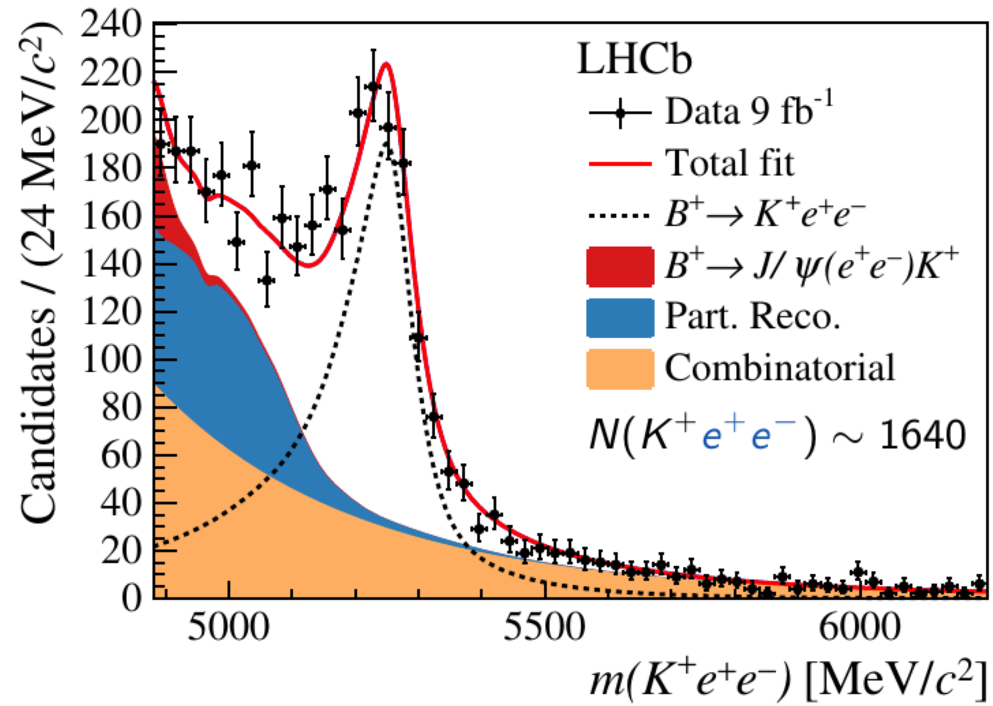

- R_K calculated in simultaneous fit to $m(K^+ l^+l^-)$ invariant mass distributions
- extracted event count ratio corrected for e/μ efficiency ratio know with 1% accuracy
- mass shape parameters fixed by the monte carlo simulations

R_K measurement

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$$R_K = 0.846^{+0.042}_{-0.039}\,(\text{stat.})^{+0.013}_{-0.012}\,(\text{syst.})$$

- uncertainty still dominated by statistics
- 3.1σ significance of deviation from SM value
- the topic extensively presented in April 2021 by M. Krzemień