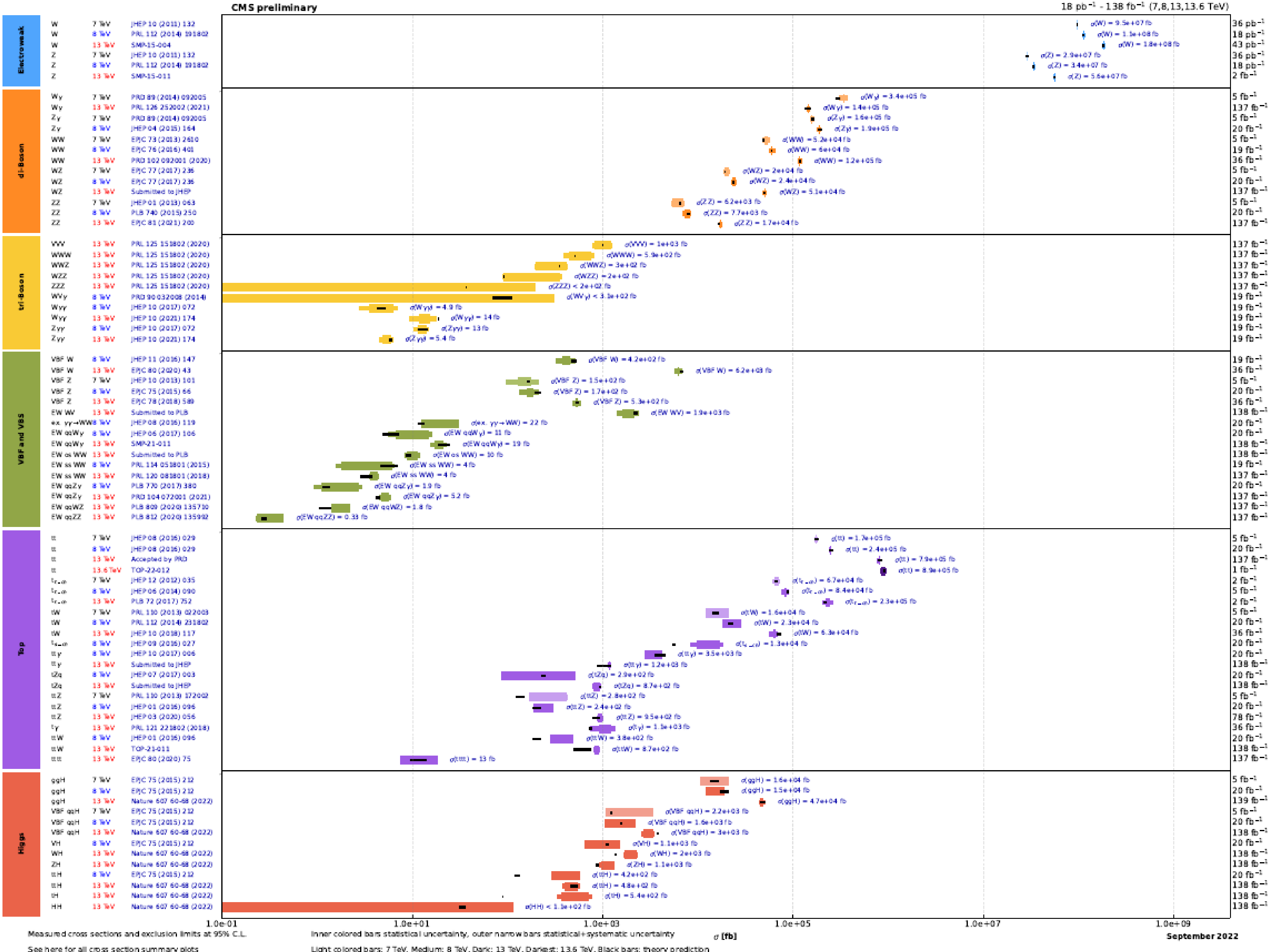
Latest CMS result on top mass

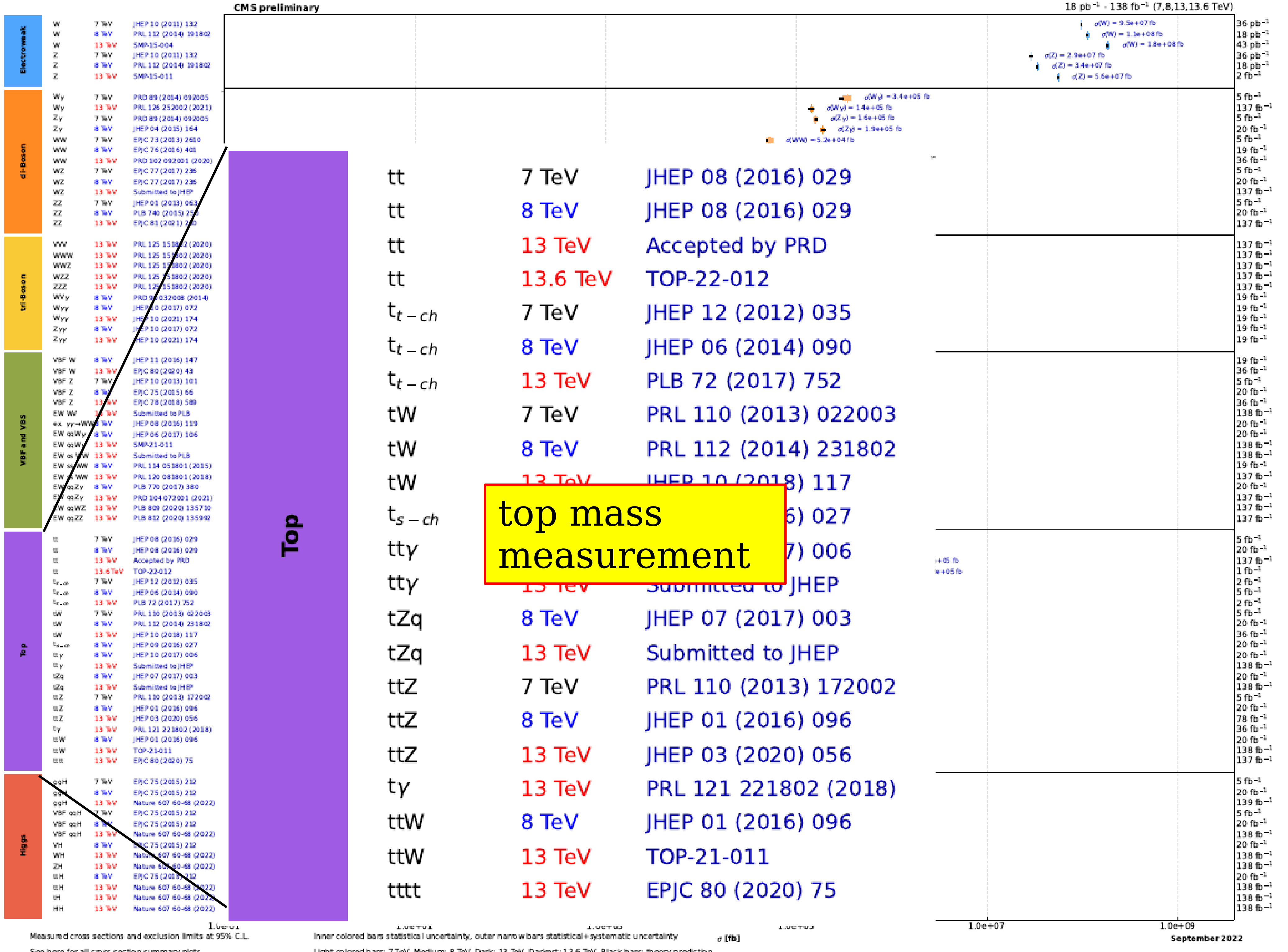
Artur Kalinowski

University of Warsaw

Overview of CMS cross section results

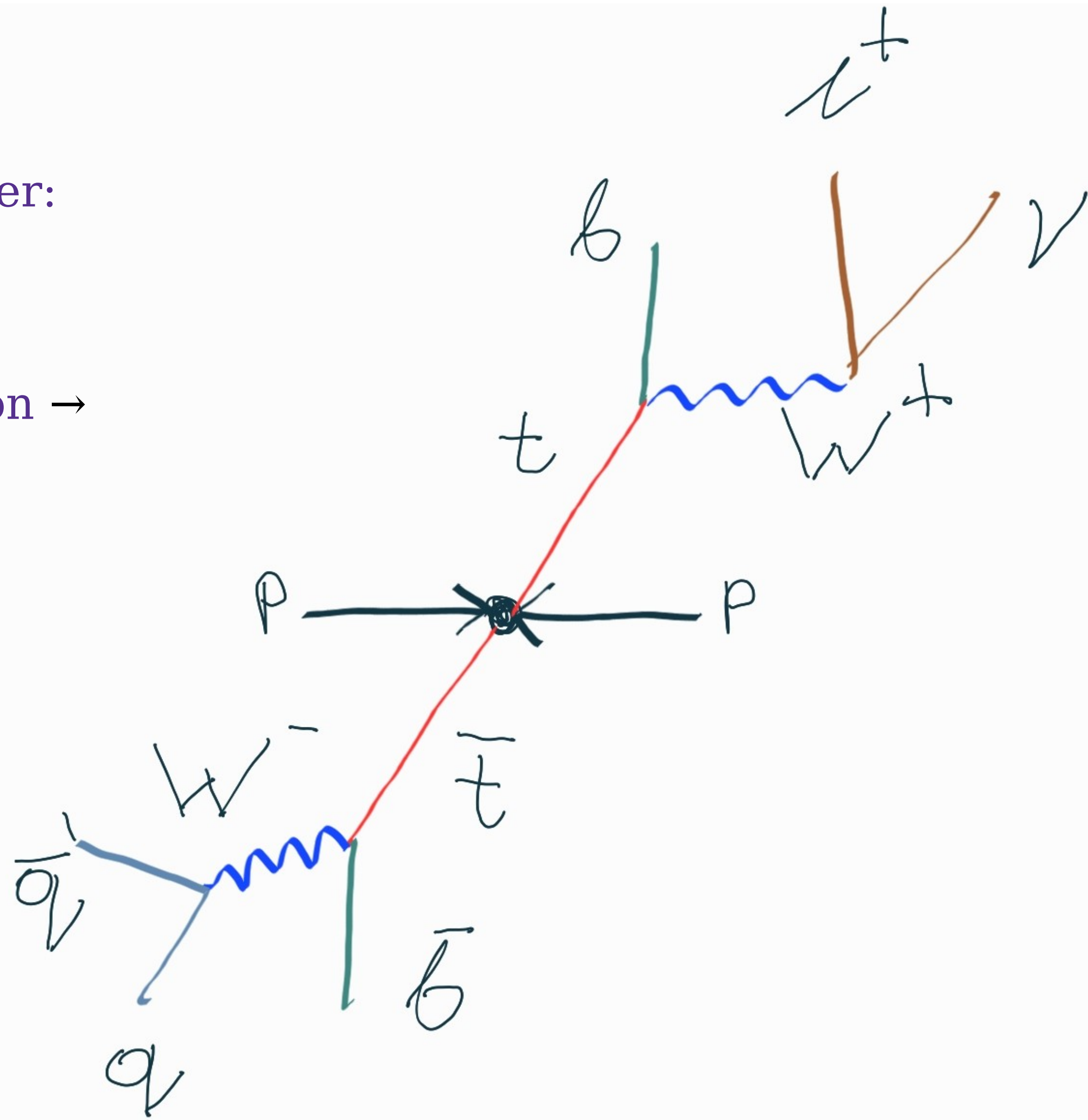


Overview of CMS cross section results



Event selection

- **decay mode:** leptons + jets
  - leptons provide handle for trigger:
    single muon/electron,
    p_T>24/27 GeV/c
  - jets provide good mass resolution →
    no missing E_T on the jet side



- **event selection:**
  - exactly one lepton
  - at least four jets with
    E_T>30 GeV, $|\eta|$<2.4
  - exactly two b-jets tagged with a Machine Learning algorithm: DeepJet

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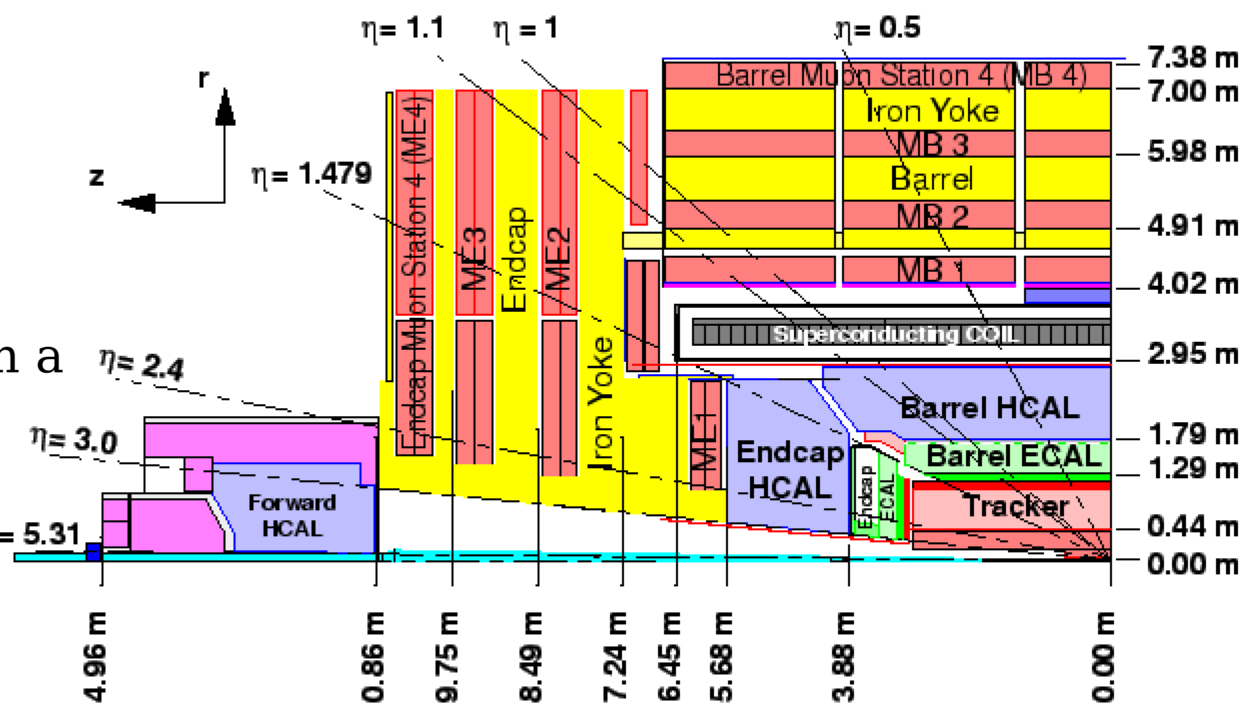
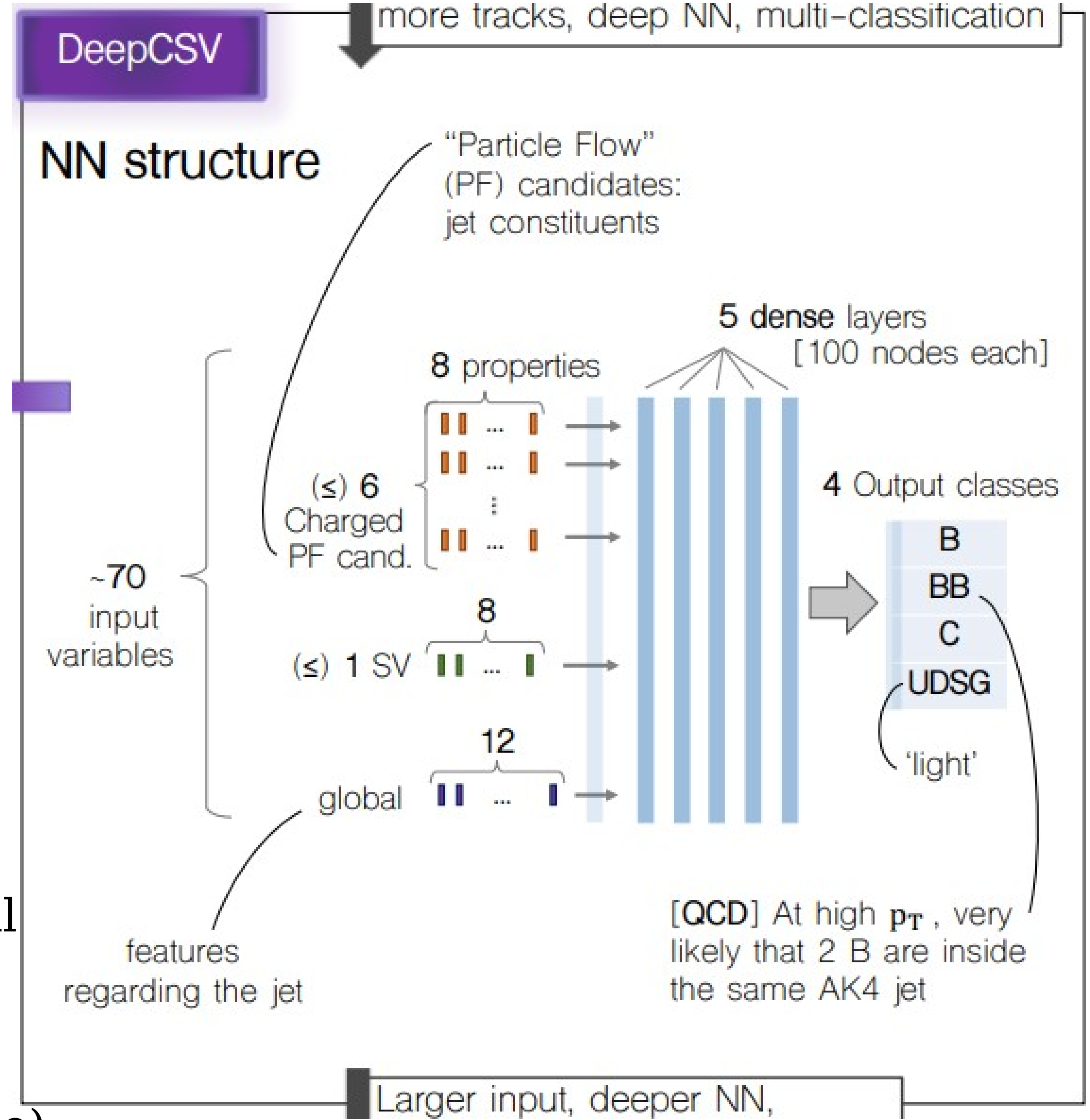


DeepCSV architecture

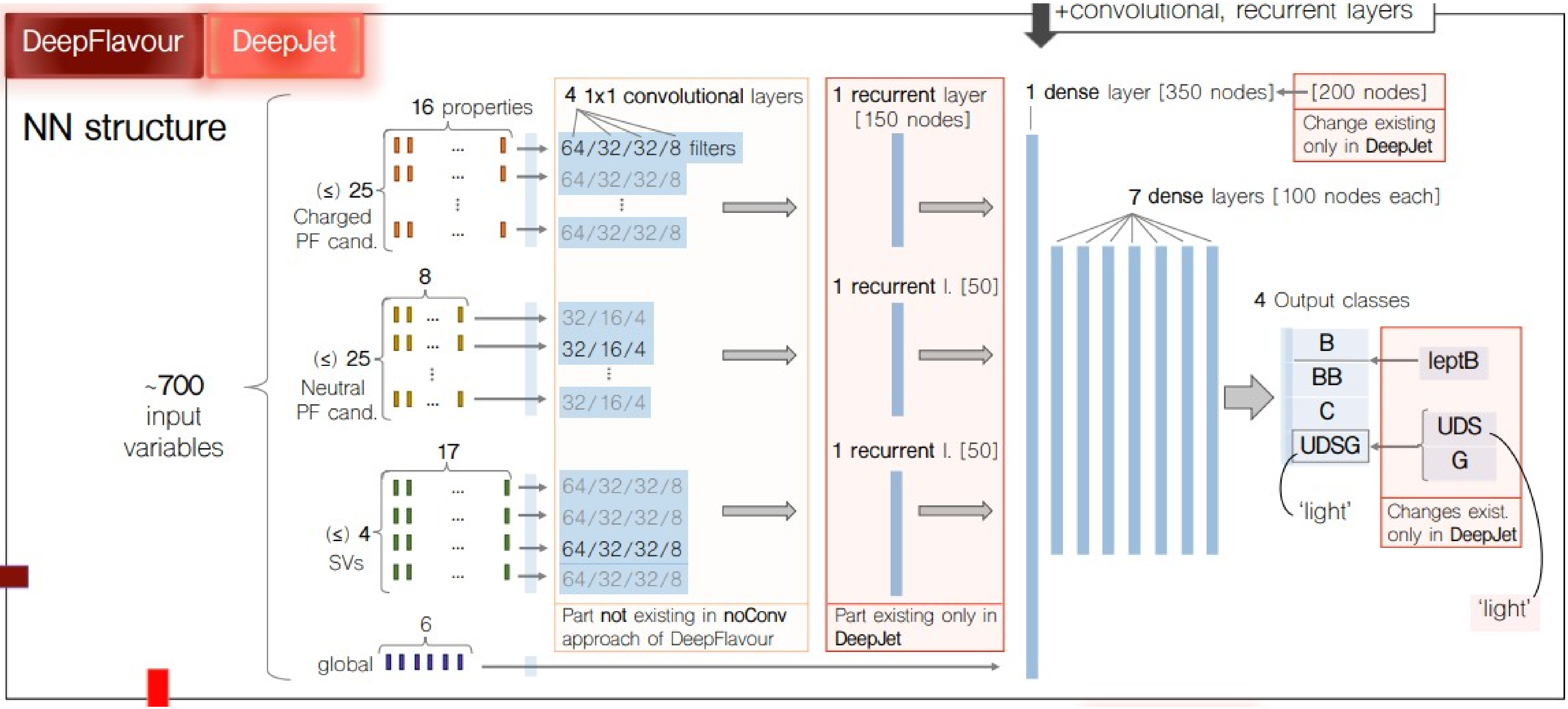
- **DeepCSV (created round 2016)**:
  - input: ~70 variables: global jet parameters, secondary vertex, up to 6 tracks
  - architecture: “ordinary” neural network



- **DeepJet (created around 2017)**:
  - input: ~700 variables: 16 features for 25 charged particles, 8 features for 25 neutral particles, etc.
  - architecture: complicated neutral network (convolution, recurence)

https://indico.cern.ch/event/559774/contributions/2661212/attachments/1513835/2361654/deepJetTaggerPoster_ICNFP17_AnnaStakia.pdf

DeepJet architecture



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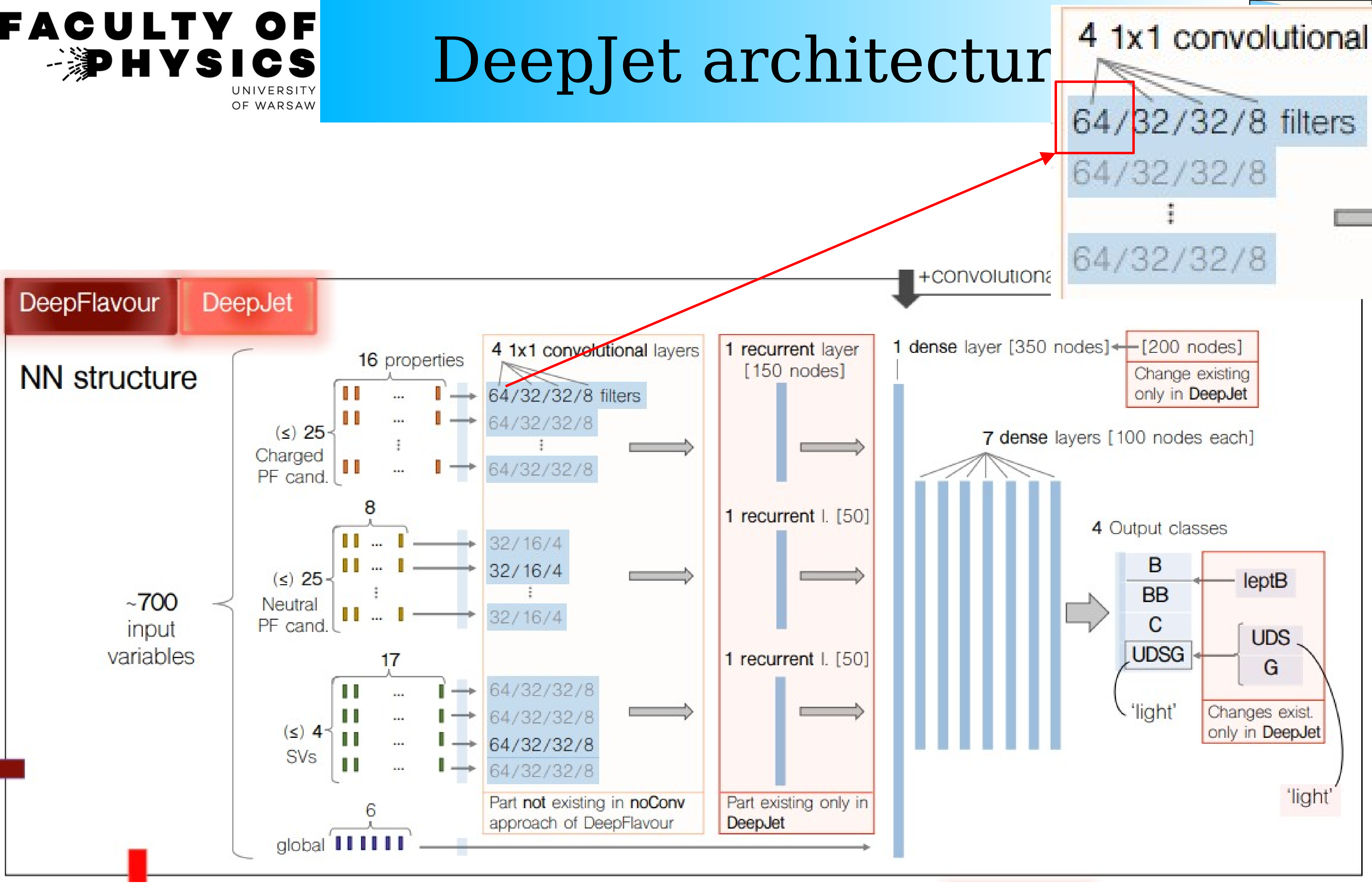


https://indico.cern.ch/event/559774/contributions/2661212/attachments/1513835/2361654/deepJetTaggerPoster_ICNFP17_AnnaStakia.pdf

1x1 convolution

human invented “features”

$x_0 = \eta$ relative to the jet axis	$\cdot w_0^0$	…	$\cdot w_0^{63}$
$x_1 = p_T$ relative to the jet axis	$\cdot w_1^0$	…	$\cdot w_1^{63}$
$x_2 = \Delta R$ between the jet axis and the track	$\cdot w_2^0$	…	$\cdot w_2^{63}$
$x_3 =$ track 2D impact parameter value	$\cdot w_3^0$	…	$\cdot w_3^{63}$
$x_{15} = \ldots$	$\cdot w_i^0$	…	$\cdot w_i^{63}$

AI invented “features”: $\sum_i x_i \cdot w_i^0, \ldots, \sum_i x_i \cdot w_i^{63}$

1x1 convolution

64 AI invented "features"

$$y_0 = \sum_{i=0}^{15} x_i \cdot w_i^0 \quad \cdot w_0^0 \quad \ldots \quad \cdot w_0^{31}$$

$$y_1 = \sum_{i=0}^{15} x_i \cdot w_i^1 \quad \cdot w_1^0 \quad \ldots \quad \cdot w_1^{31}$$

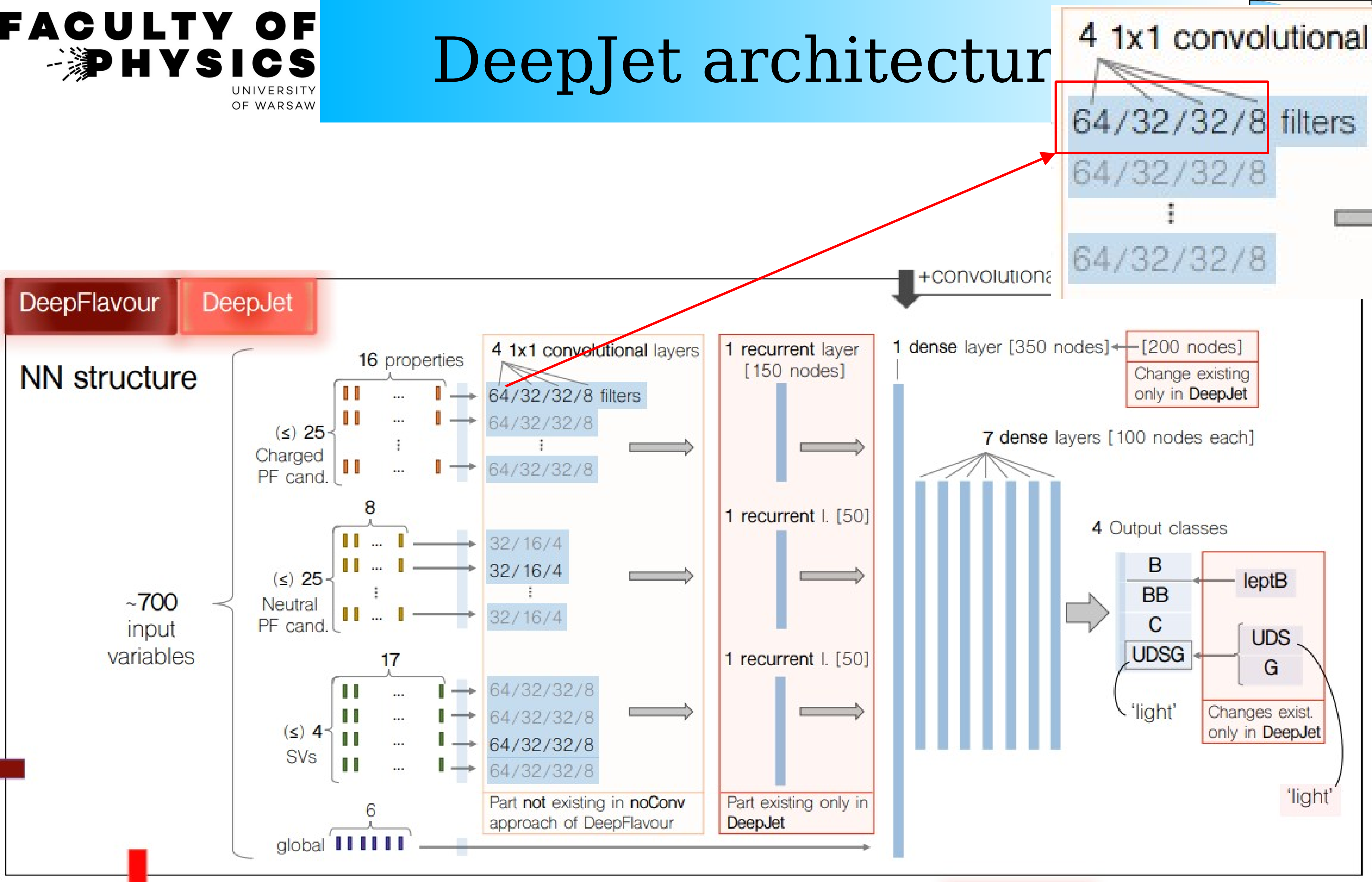
$$y_2 = \sum_{i=0}^{15} x_i \cdot w_i^2 \quad \cdot w_2^0 \quad \ldots \quad \cdot w_2^{31}$$

$$\ldots \quad \cdot w_3^0 \quad \ldots \quad \cdot w_3^{31}$$

$$y_{63} = \sum_{i=0}^{15} x_i \cdot w_i^{63} \quad \cdot w_i^0 \quad \ldots \quad \cdot w_i^{31}$$

AI features on AI features: $\sum_i x_i \cdot w_i^0, \ldots, \sum_i x_i \cdot w_i^{31}$

DeepJet architectur



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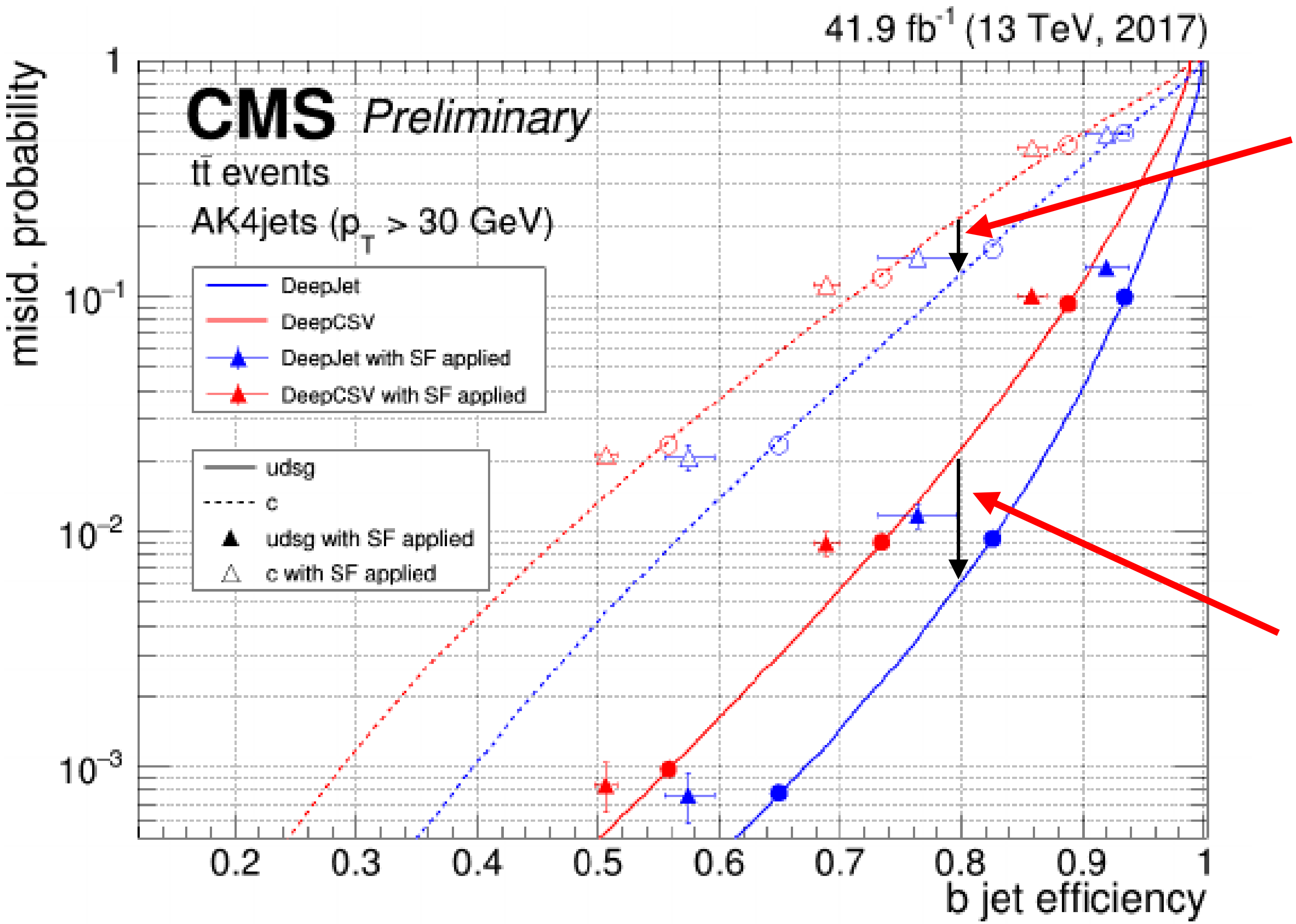
DeepCSV/Jet performance

CMS-DP-2018_058



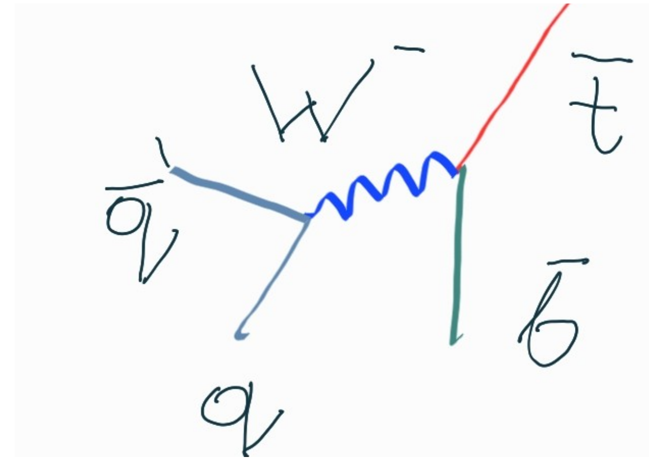
factor ~2 less c jest mistagged as b jets

factor ~3 less udsg jets mistagged as b jets

Mass observables

TOP-20-008

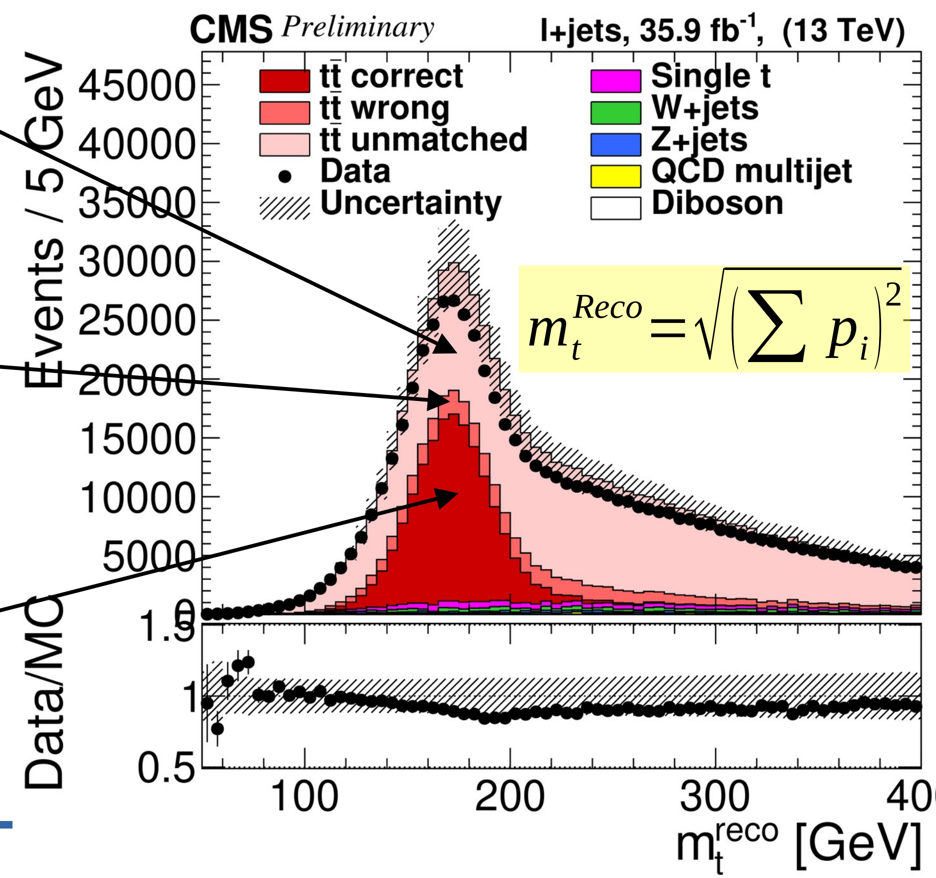
$\mathbf{m_t^{Reco}}$ - invariant mass of hadronically decaying top



some jets from top/antitop decay are not selected in top four jets

wrong assignment of jets to top/antitop side

correct assignment of jets to top/antitop side



$$m_t^{Reco} = \sqrt{\left(\sum p_i\right)^2}$$

Mass observables

m_t^{fit} – invariant mass after kinematic fit of constituents properties x:

- minimize χ^2 between "true" and measured kinematical properties of constituents:

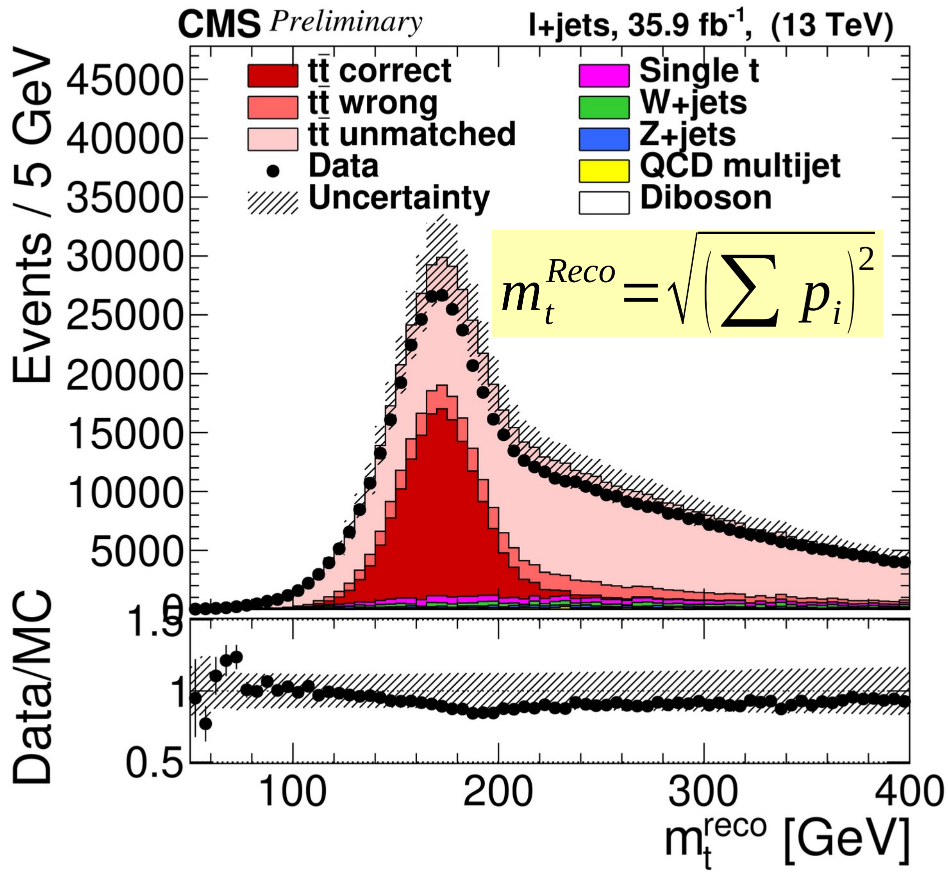
$$\chi^2 = \left(x^{Fit} - x^{Reco}\right)^T V^{-1} \left(x^{Fit} - x^{Reco}\right)$$

- impose kinematical constraints:
  - decay of two heavy particles: t, of the same mass are observed
  - heavy particles decay as t → Wb, with m_W = 80.4 GeV/c^2
  - jet → side assignment ambiguity resolved by choosing with lowest configuration $P_{gof} = e^{-1/2\chi^2}$

Mass observables

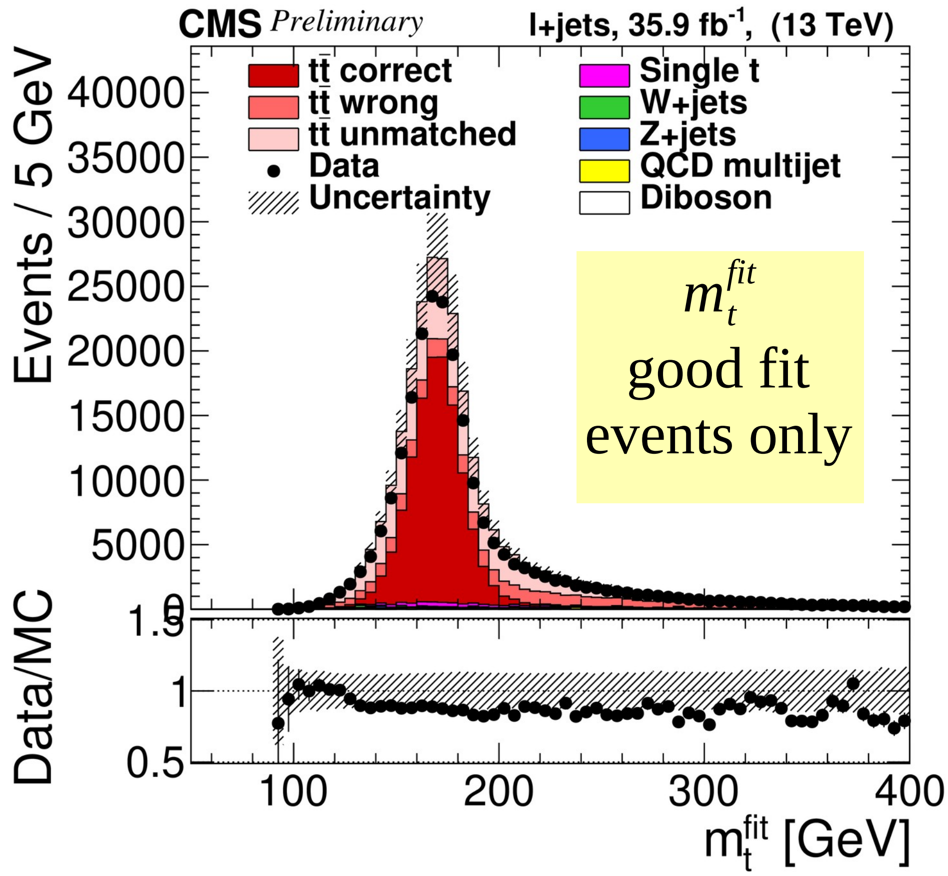
TOP-20-008

Invariant mass from measured four-momenta



$$m_t^{Reco} = \sqrt{\left(\sum p_i\right)^2}$$

Invariant mass from four-momenta after kinematical fit



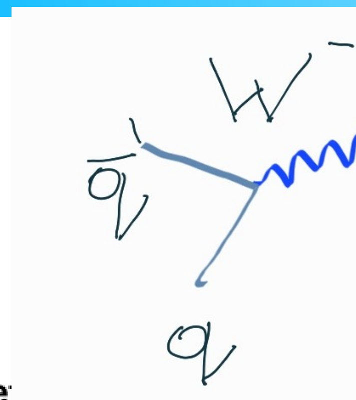
m_t^{fit}

good fit events only

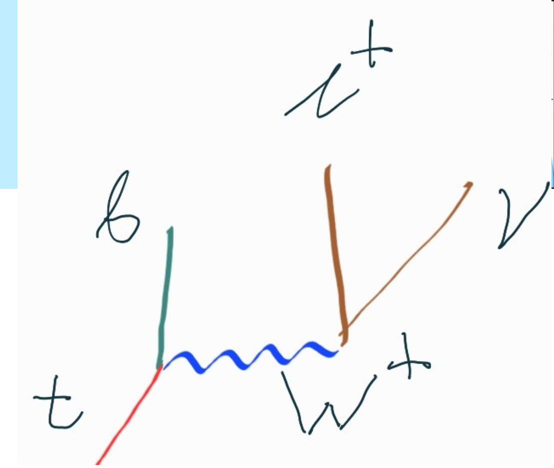
Other observables

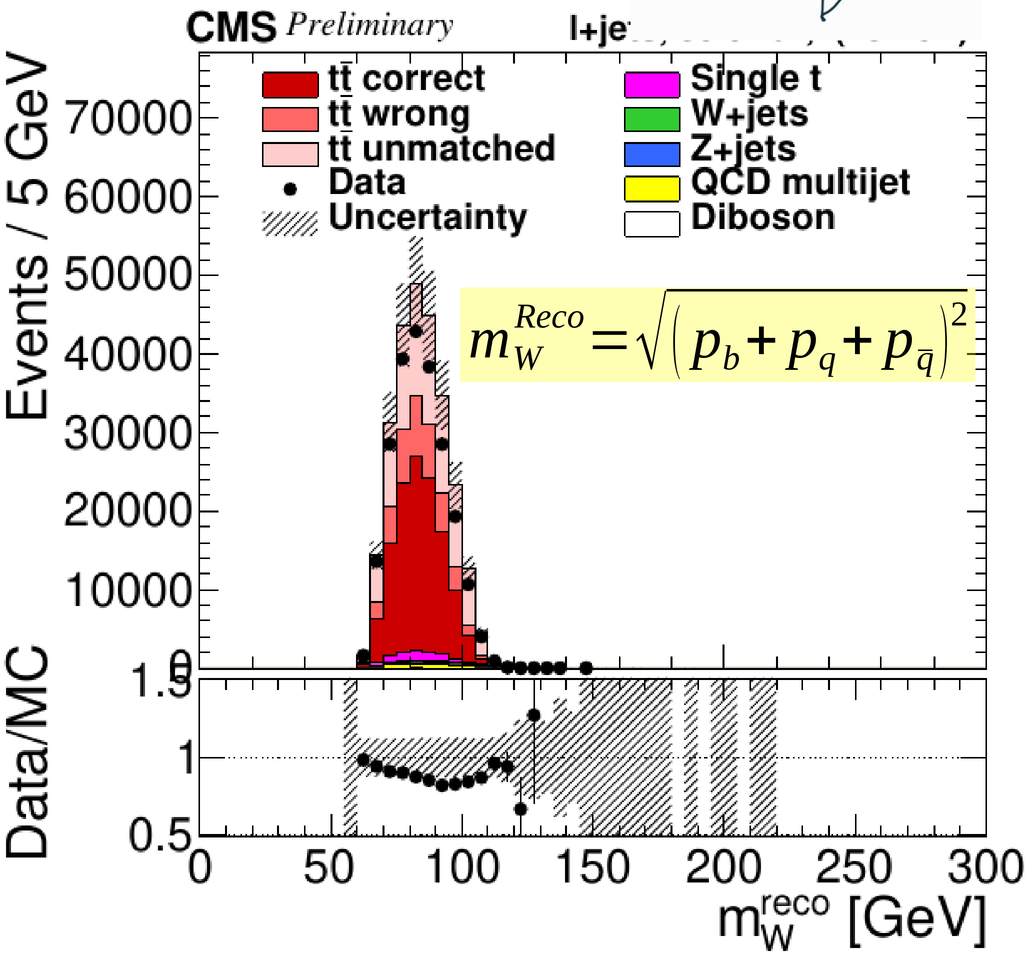
TOP-20-008

Invariant mass of hadronically decaying W

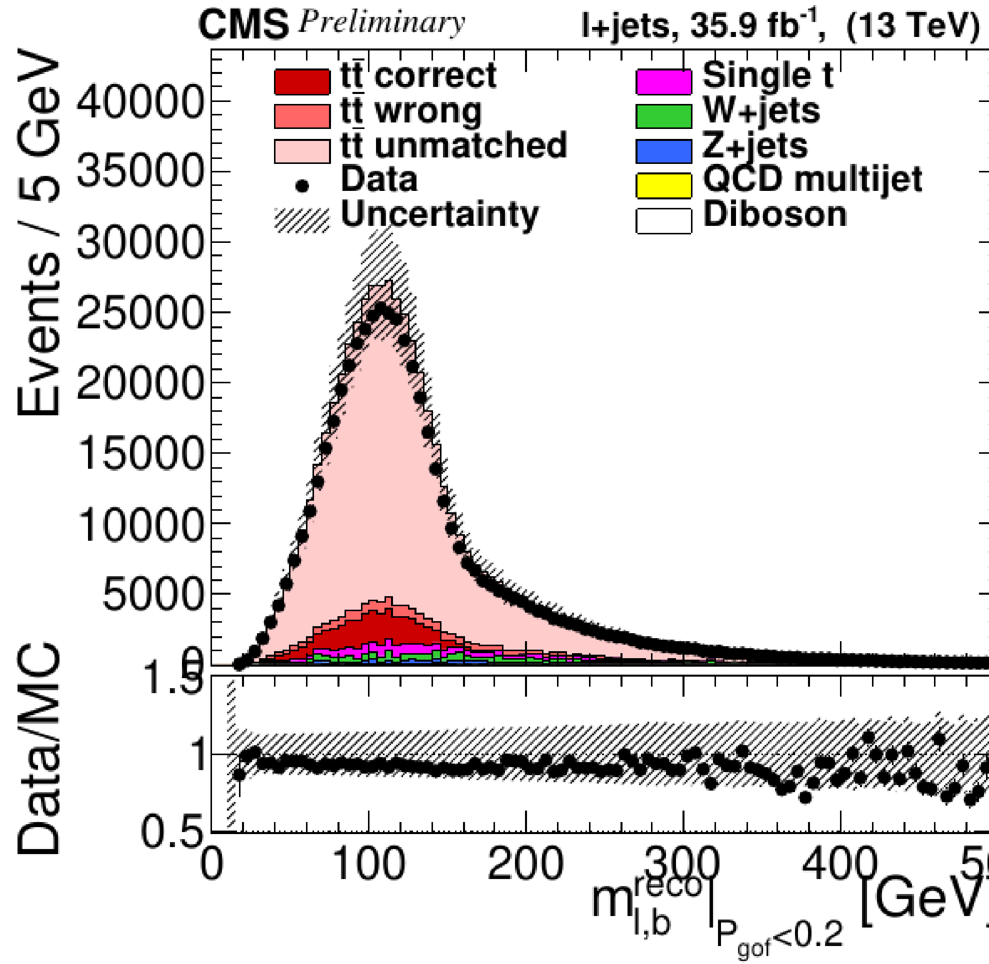


Lepton – b jet invariant mass





$$m_W^{Reco} = \sqrt{\left(p_b + p_q + p_{\bar{q}}\right)^2}$$



Other observables

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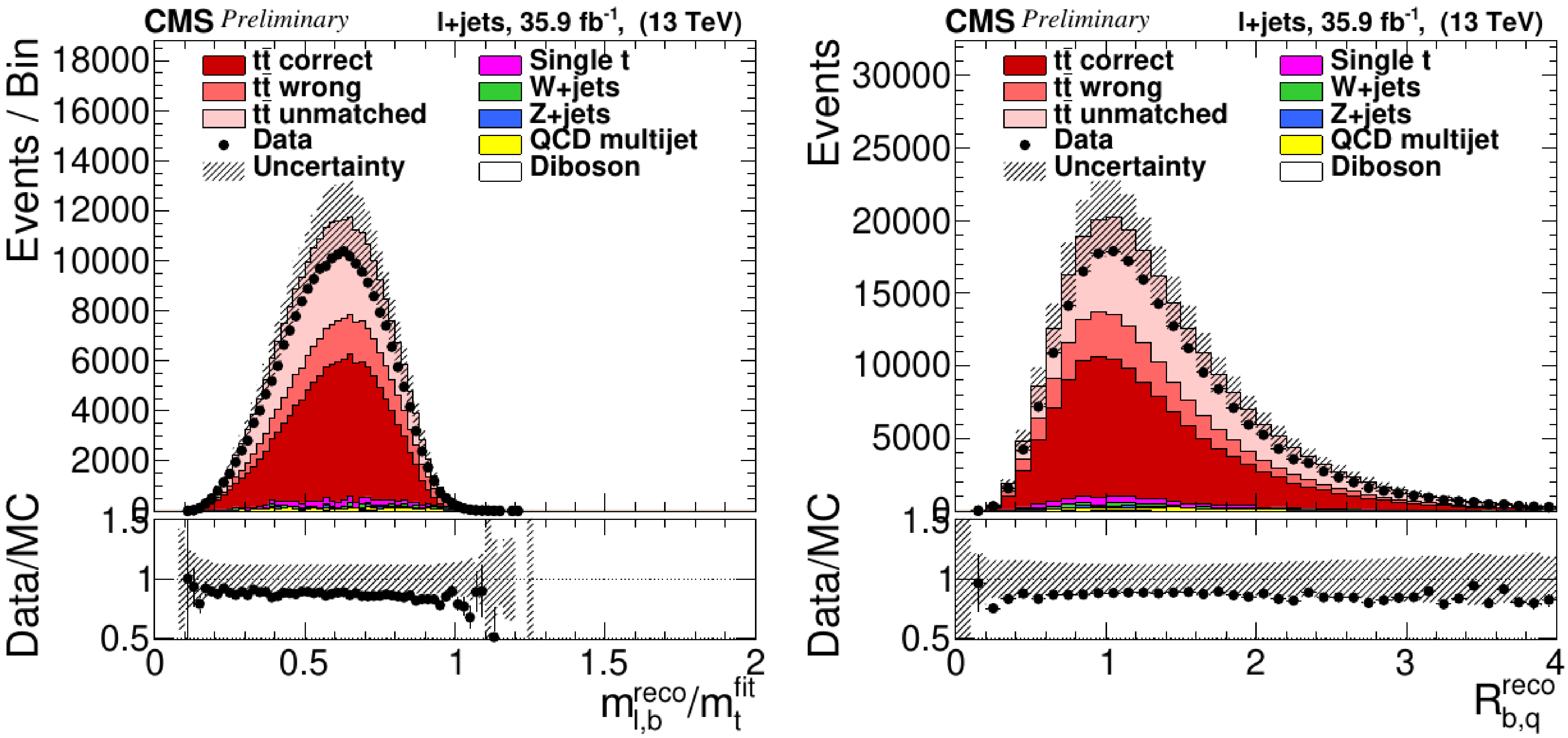
$$R_{\mathrm{bq}}^{\mathrm{reco}} = (p_{\mathrm{T}}^{\mathrm{b1}} + p_{\mathrm{T}}^{\mathrm{b2}})/(p_{\mathrm{T}}^{\mathrm{q}\,1} + p_{\mathrm{T}}^{\mathrm{q}\,2})$$



Likelihood definition

TOP-20-008

- **top mas estimate:** maximum likelihood fit

$$\lambda(m_t, \vec{\theta} | data) = \lambda(data | m_t, \theta) P(theta)$$

nuissance parameters:
- systematic effects
- statistical bin counts uncertainty in Monte Carlo

- **data:** histograms for five observables:
  - m_t^{fit}, m_W^{Reco},
  - m_{lb}^{Reco}, m_{lb}^{Reco}/m_t^{fit},
  - R_{bq}^{Reco}

- **data likelihood:**

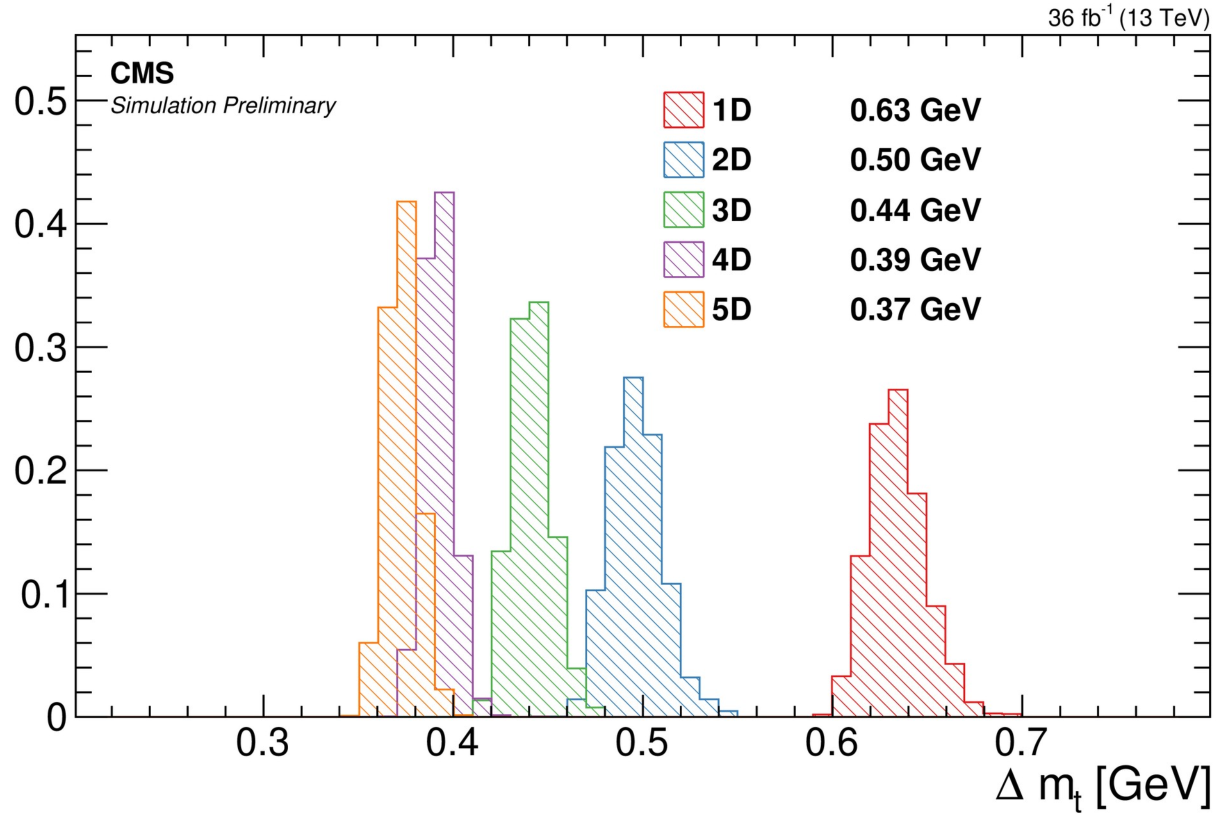
$$\lambda(data | m_t, \theta) = \prod_{\text{over histogram bins}} \frac{Poisson(n_{obs} | m_t, \theta)}{Poisson(n_{obs} | n_{obs})}$$

Expected uncertainty

TOP-20-008

histogram observable	category	1D	2D	3D	4D	5D
m_t^{fit}	$P_{gof} \geq 0.2$	x	x	x	x	x
m_W^{reco}	$P_{gof} \geq 0.2$		x	x	x	x
$m_{\ell b}^{reco}$	$P_{gof} < 0.2$			x	x	x
$m_{\ell b}^{reco} / m_t^{fit}$	$P_{gof} \geq 0.2$				x	x
R_{bq}^{reco}	$P_{gof} \geq 0.2$					x

$$R_{bq}^{reco} = (p_T^{b1} + p_T^{b2}) / (p_T^{q\,1} + p_T^{q\,2})$$



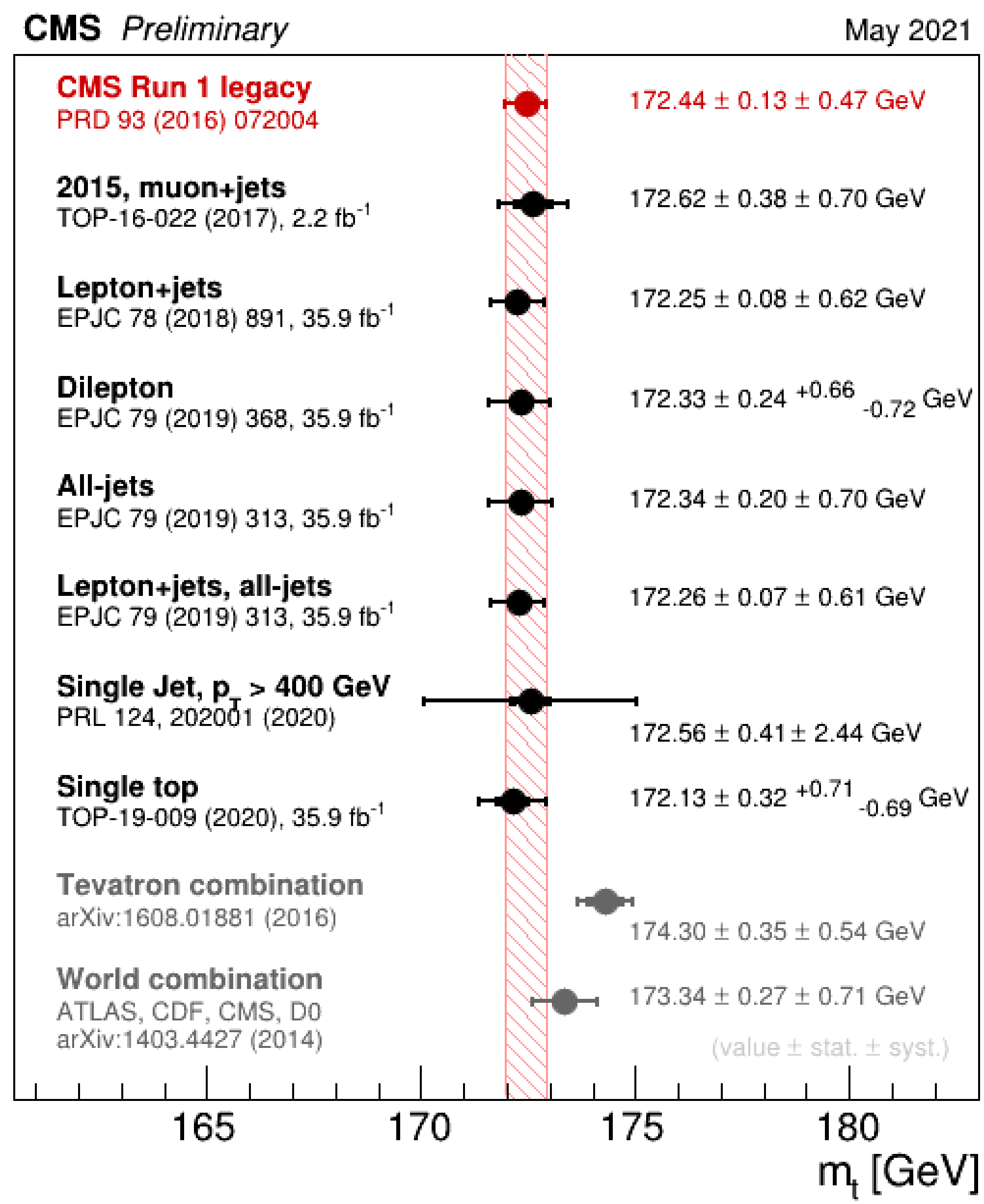
top mass

TOP-20-008

$$m_t = 171.77 \pm 0.38\,\mathrm{GeV}/c^2$$

$$stat\ uncertainty: 0.04\,\mathrm{GeV}/c^2$$

The most (to date) precise single ("Monte Carlo") top mas measurement



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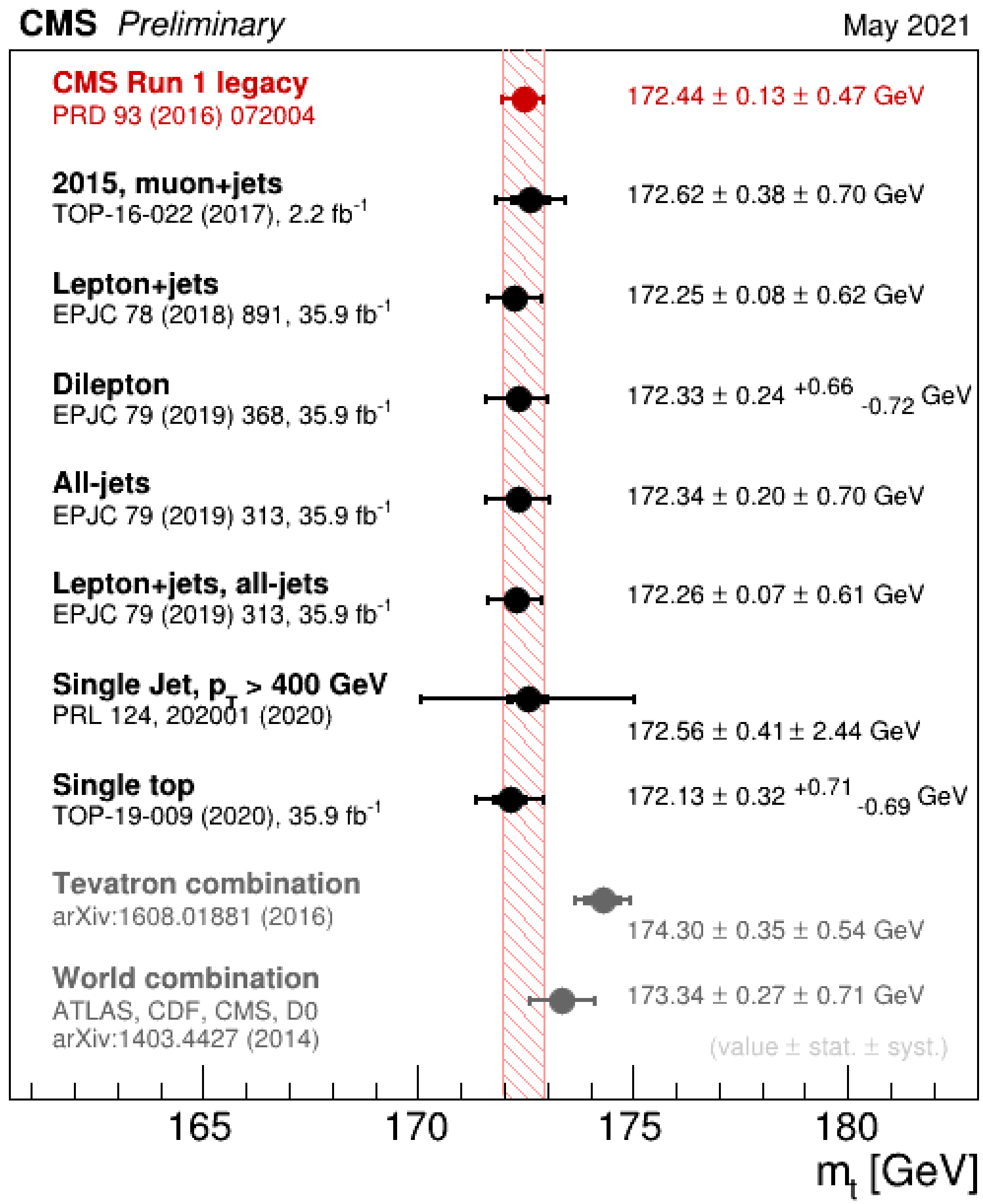
The most (to date) precise single ("Monte Carlo") top mas measurement

$$m_{t\,pole} = m_{T\,MC} + \Delta_{QCD\,corr}$$
$$\Delta_{QCD\,corr} \sim 0.5\, GeV/c^2$$

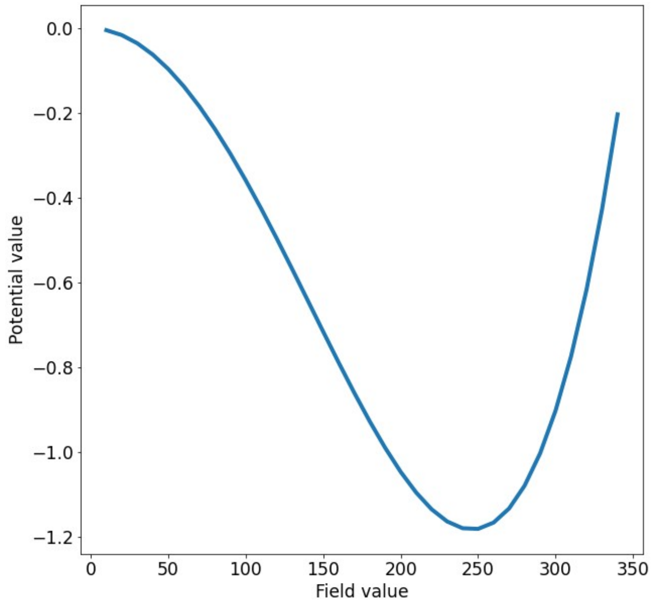


Top mass – why it matters?

- **Higgs boson potential:**

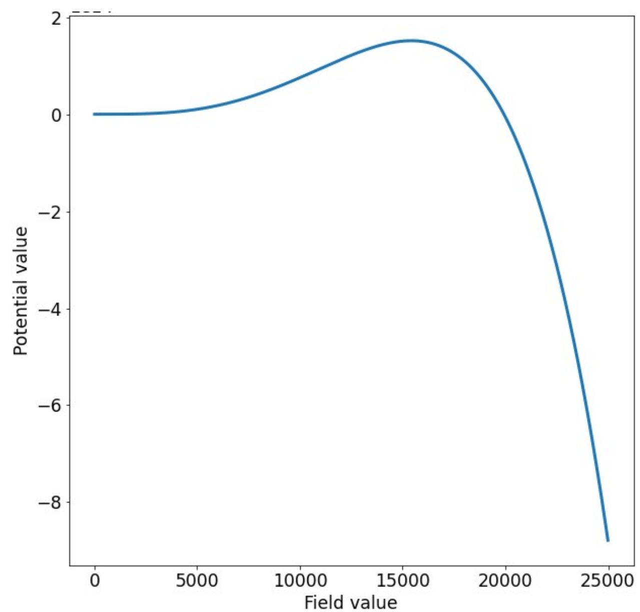
$$V(\phi) = -\frac{1}{2} m_H^2 \phi^2 + \frac{1}{4} \lambda \phi^4$$

$\lambda = const.$ →

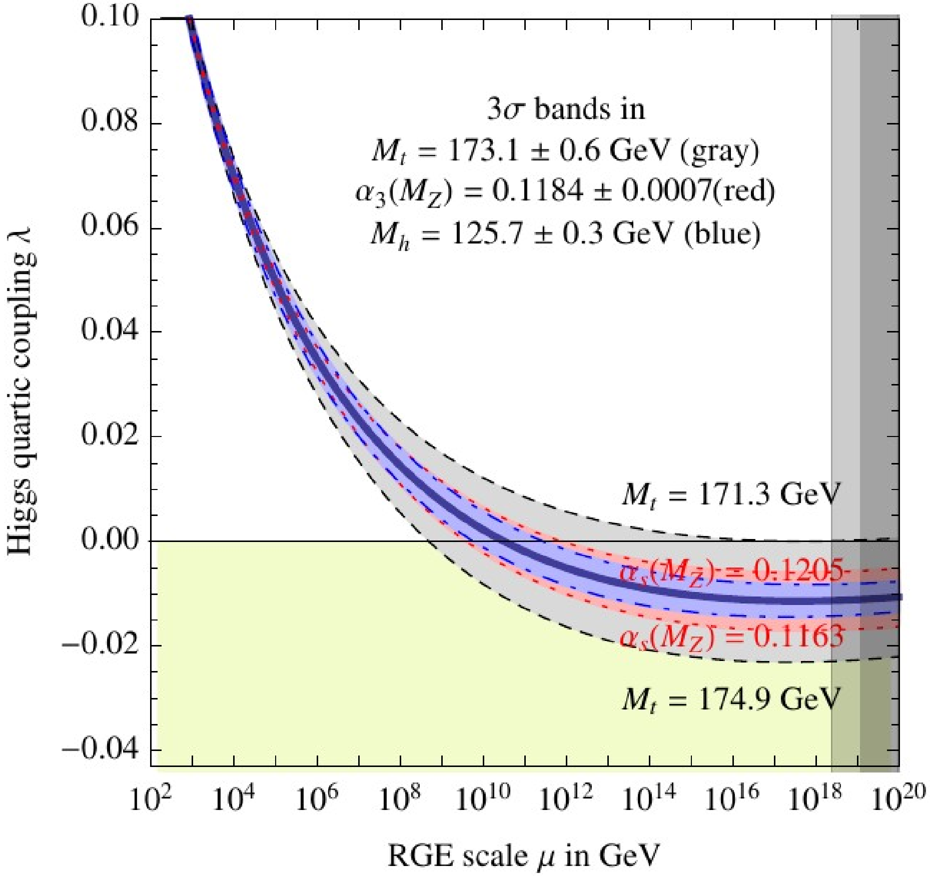


$\lambda = \lambda(\mu)$

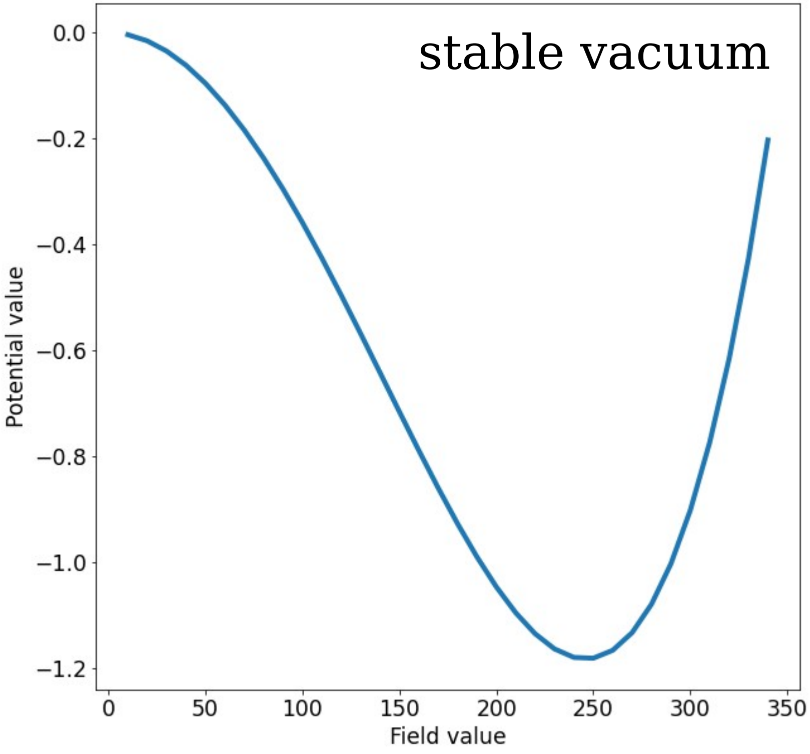
$\lambda(\mu_0) < 0$ →

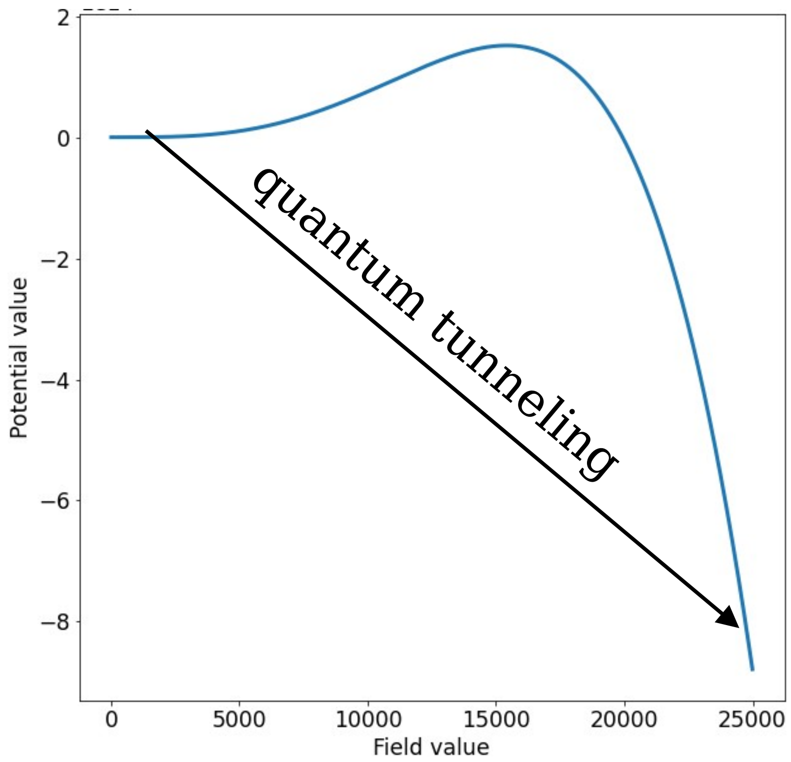


https://arxiv.org/abs/1205.6497



Vacuum stability





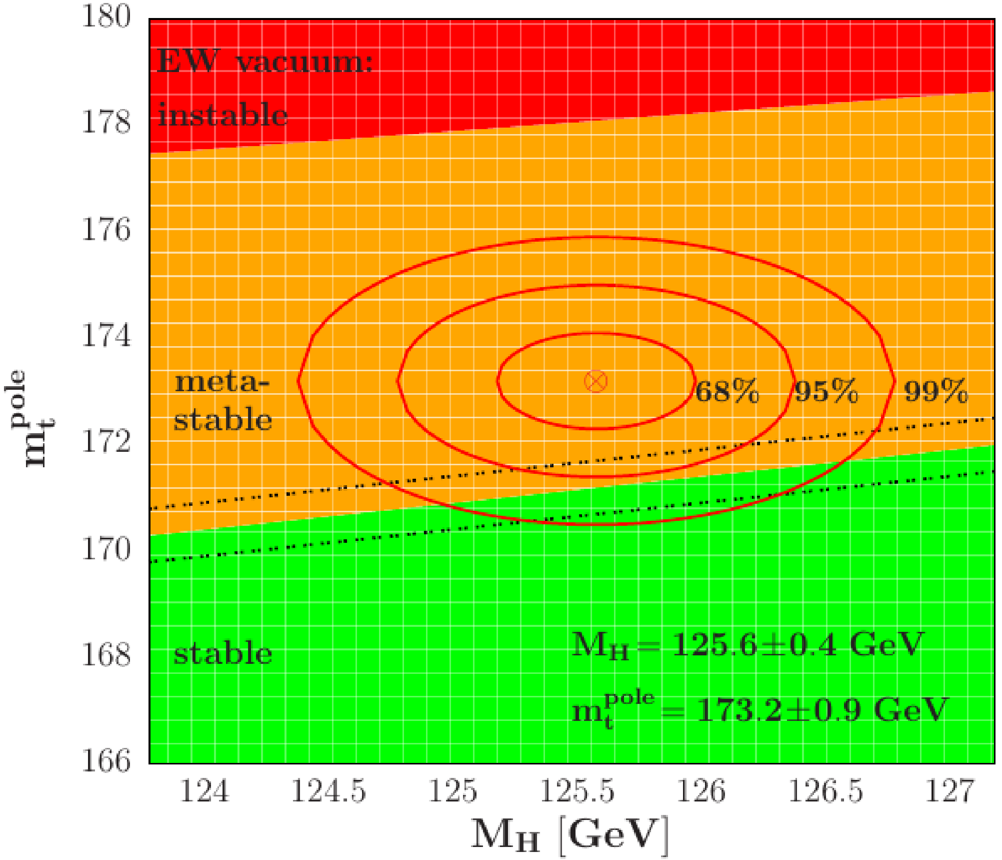
SM vacuum life time > age of the Universe
→ meta-stable vacuum

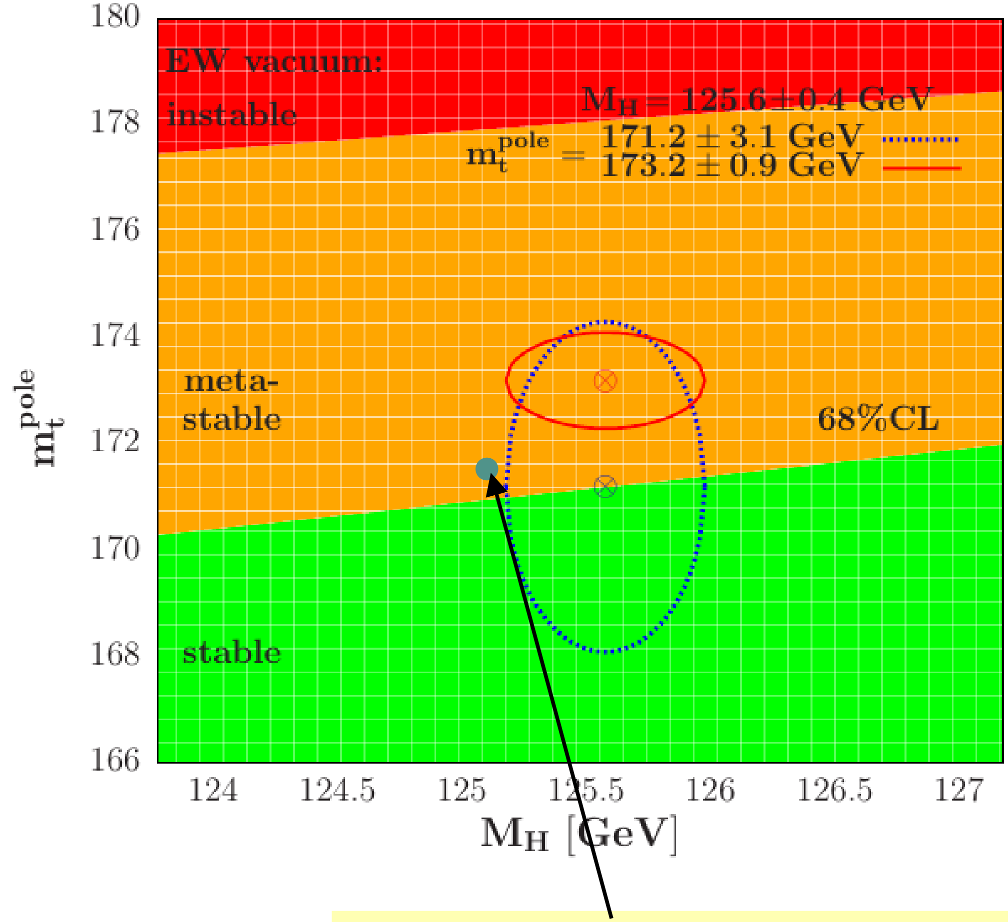
SM vacuum life time < age of the Universe
→ instable vacuum

Top and Higgs mass and vaccum stability

https://arxiv.org/abs/1205.6497

https://arxiv.org/abs/1207.0980





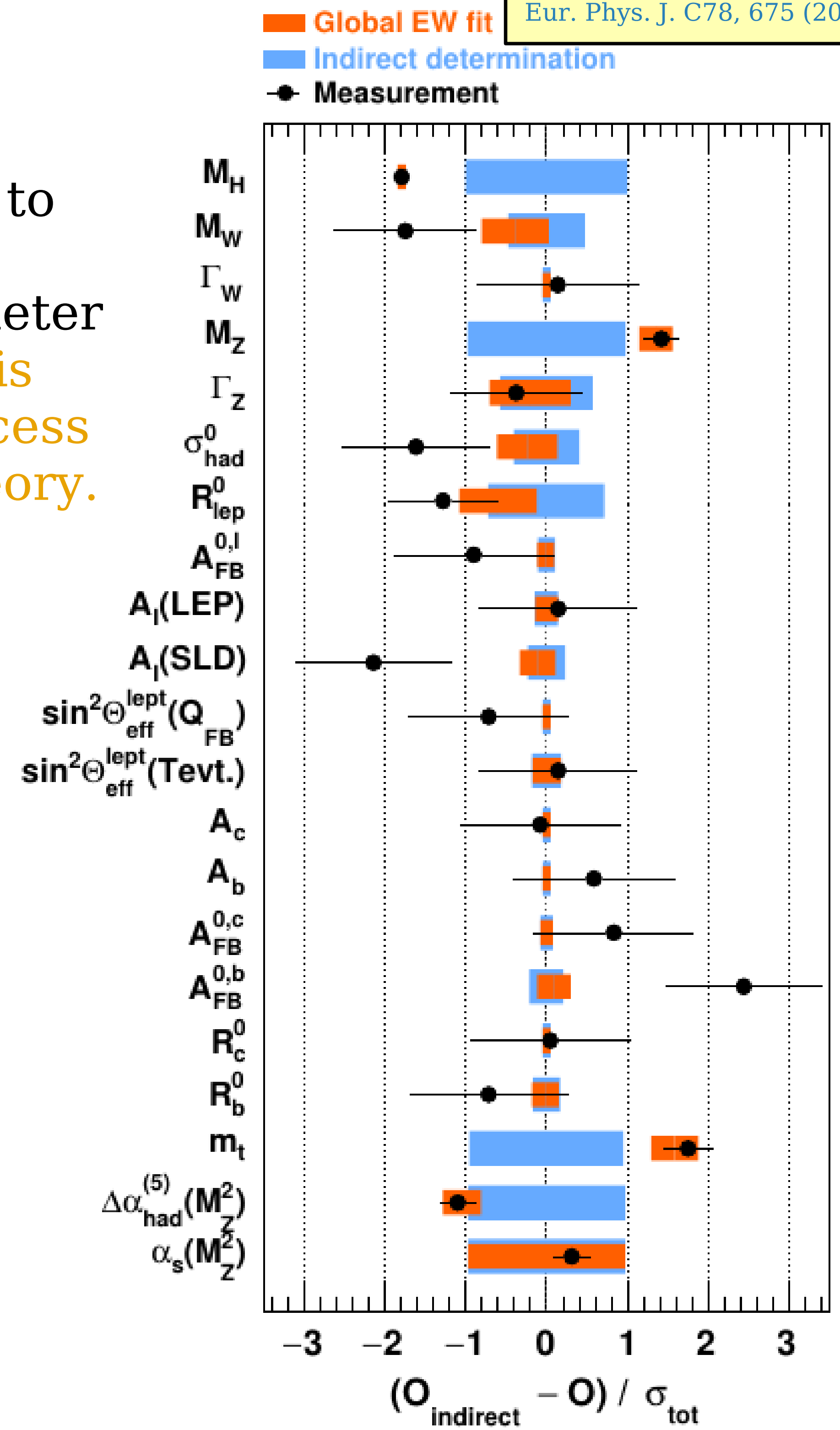
$m_H = 125.09\ GeV/c^2$
$m_{top} = 171.8\ GeV/c^2$

EWK fits

Electro-weak fit – fit a given parameter to existing data for electro-weak processes, excluding direct measurements of parameter in question. Once the Higgs boson mass is found the number of input parameter excess the number of free parameters of the theory.

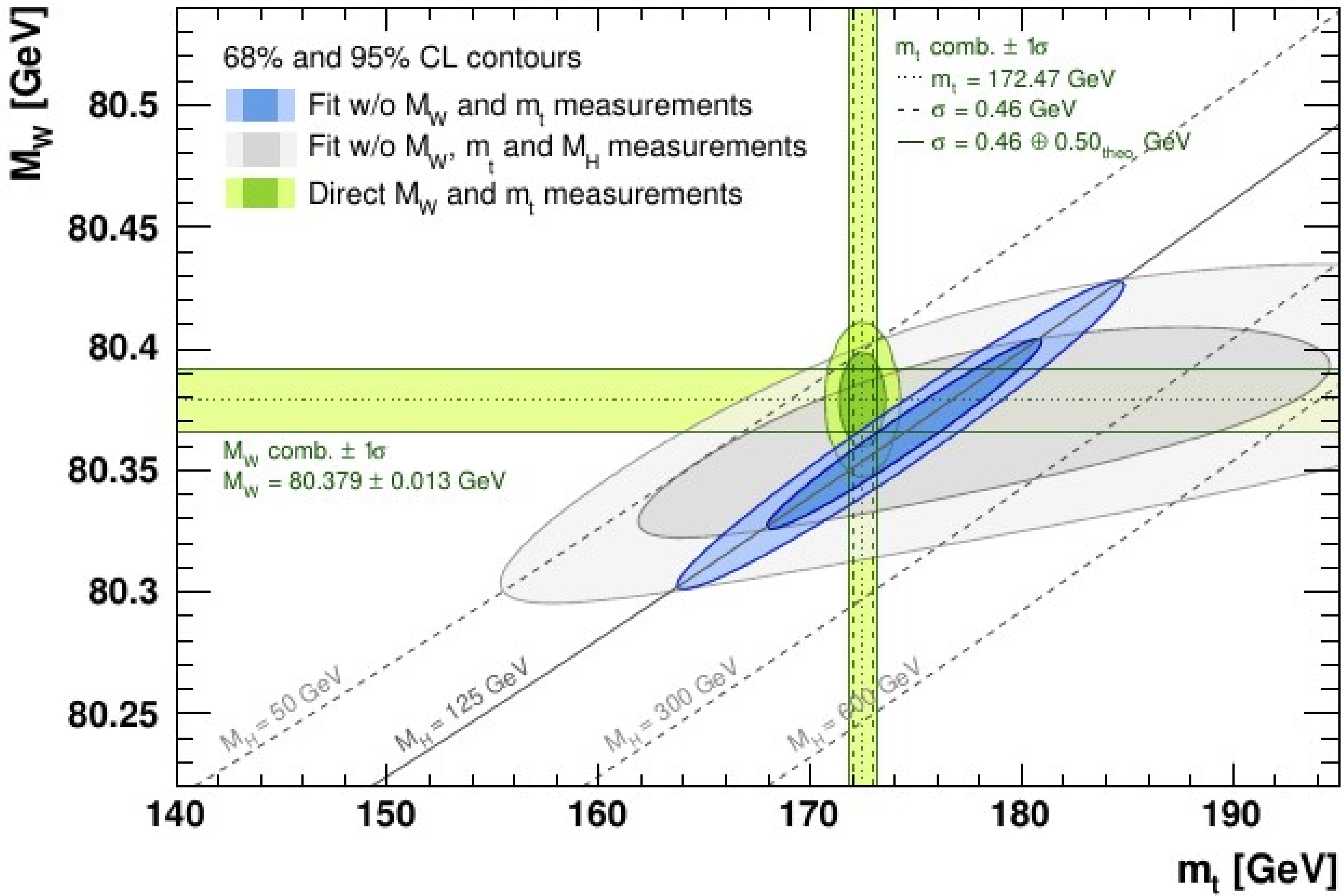
Parameter	Input value	Free in fit	Fit Result	Fit w/o exp. input in line
M_H [GeV]	125.1 ± 0.2	yes	125.1 ± 0.2	90^{+21}_{-18}
M_W [GeV]	80.379 ± 0.013	–	80.359 ± 0.006	80.354 ± 0.007
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1882 ± 0.0020	91.2013 ± 0.0095
m_t [GeV]$^{(\bigtriangledown)}$	172.47 ± 0.68	yes	172.83 ± 0.65	176.4 ± 2.1

Eur. Phys. J. C78, 675 (2018)



W mass from the EWK fit

Eur. Phys. J. C78, 675 (2018)



W boson mass

Science 376 (2022) 6589, 170-176

Phys. Rev. D88, 052018 (2013)

LEP+ Tevatron: 80.385±15 MeV

Eur. Phys. J. C 78 (2018) 110

ATLAS: 80.370±19 MeV

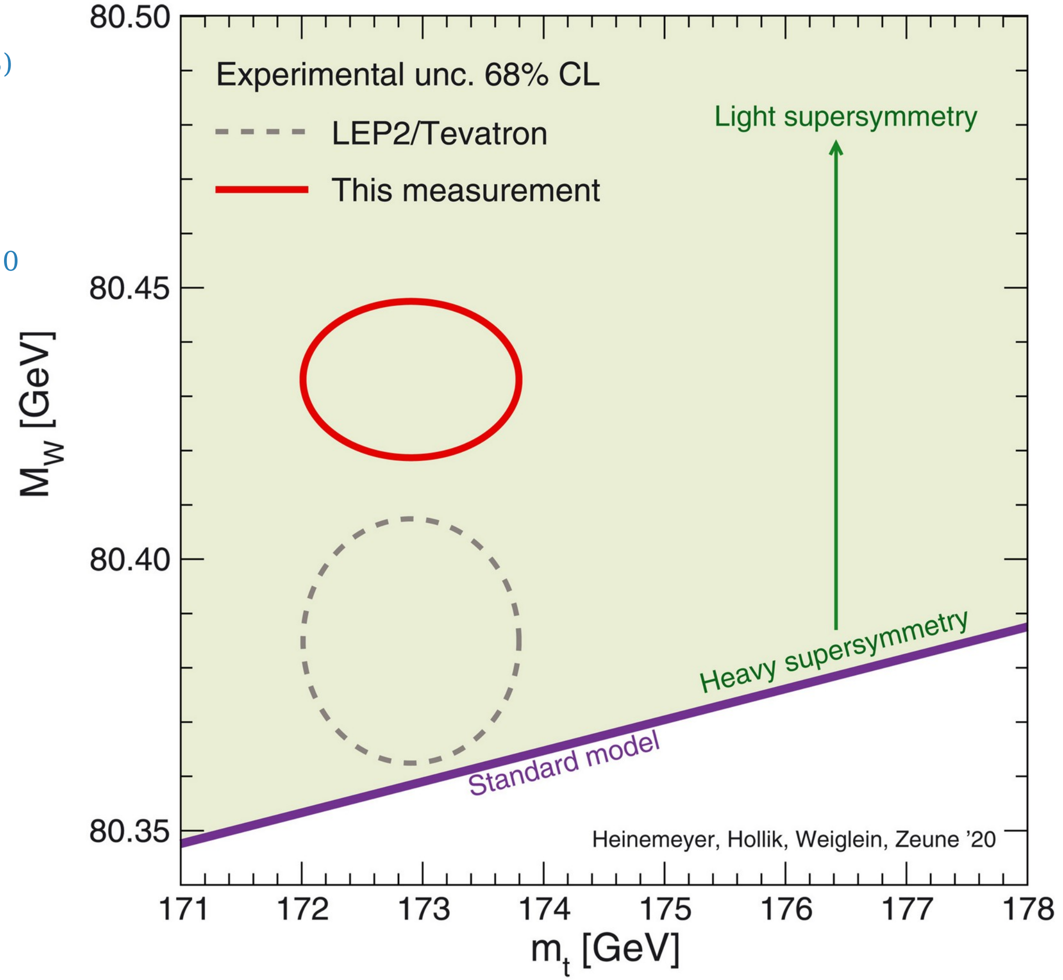
CMS: ---

JHEP 01 (2022) 036

LHCb: 80.354±32 MeV

Science 376 (2022) 6589, 170-176

CDF: 80.433±9 MeV



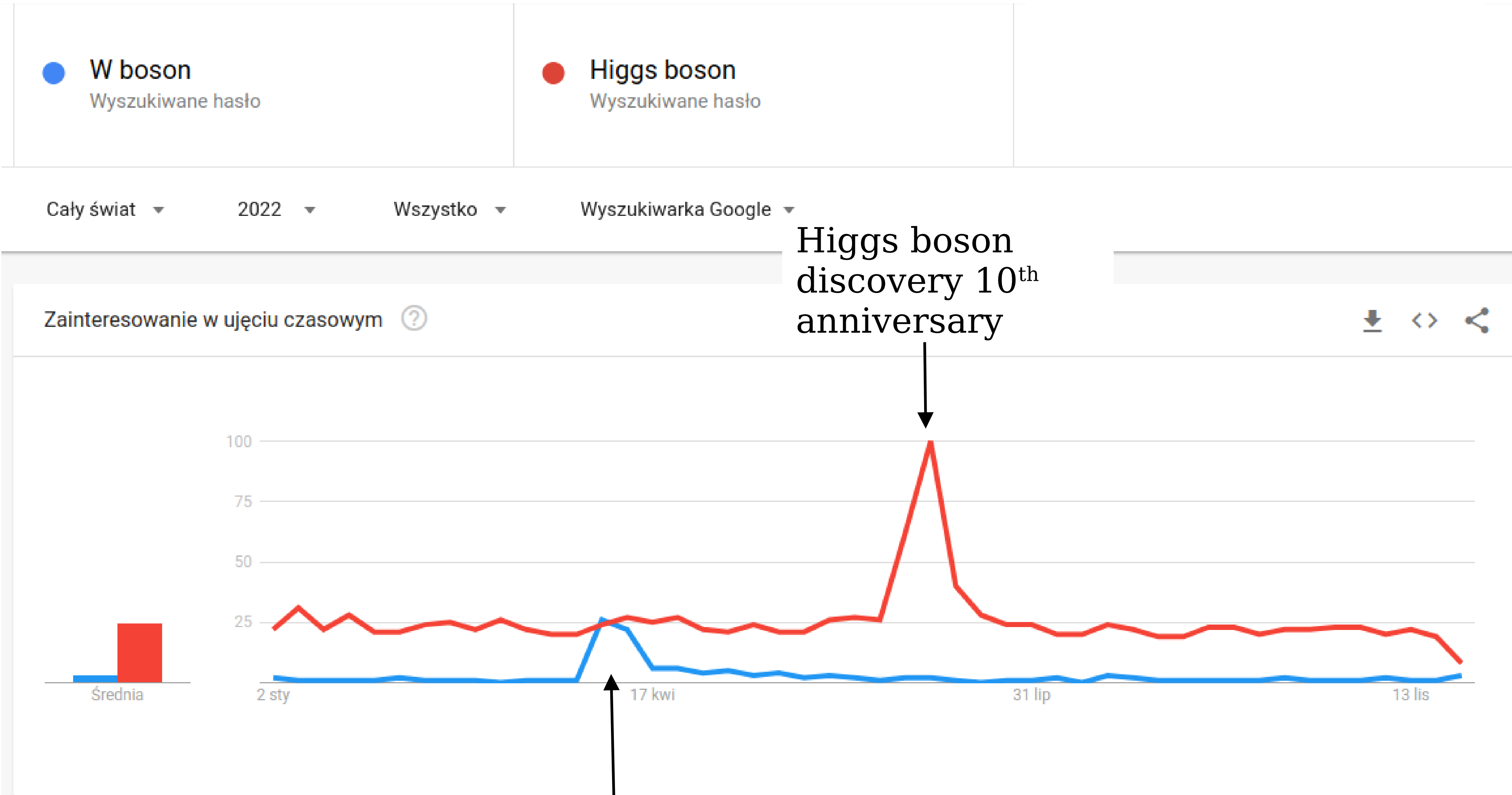
Conclusions

The CMS Collaboration has a plethora results on Standards Model physics, and:

- not every interesting measurement requires a lots of integrated luminosity

- precise measurements are still important for the global picture of the SM

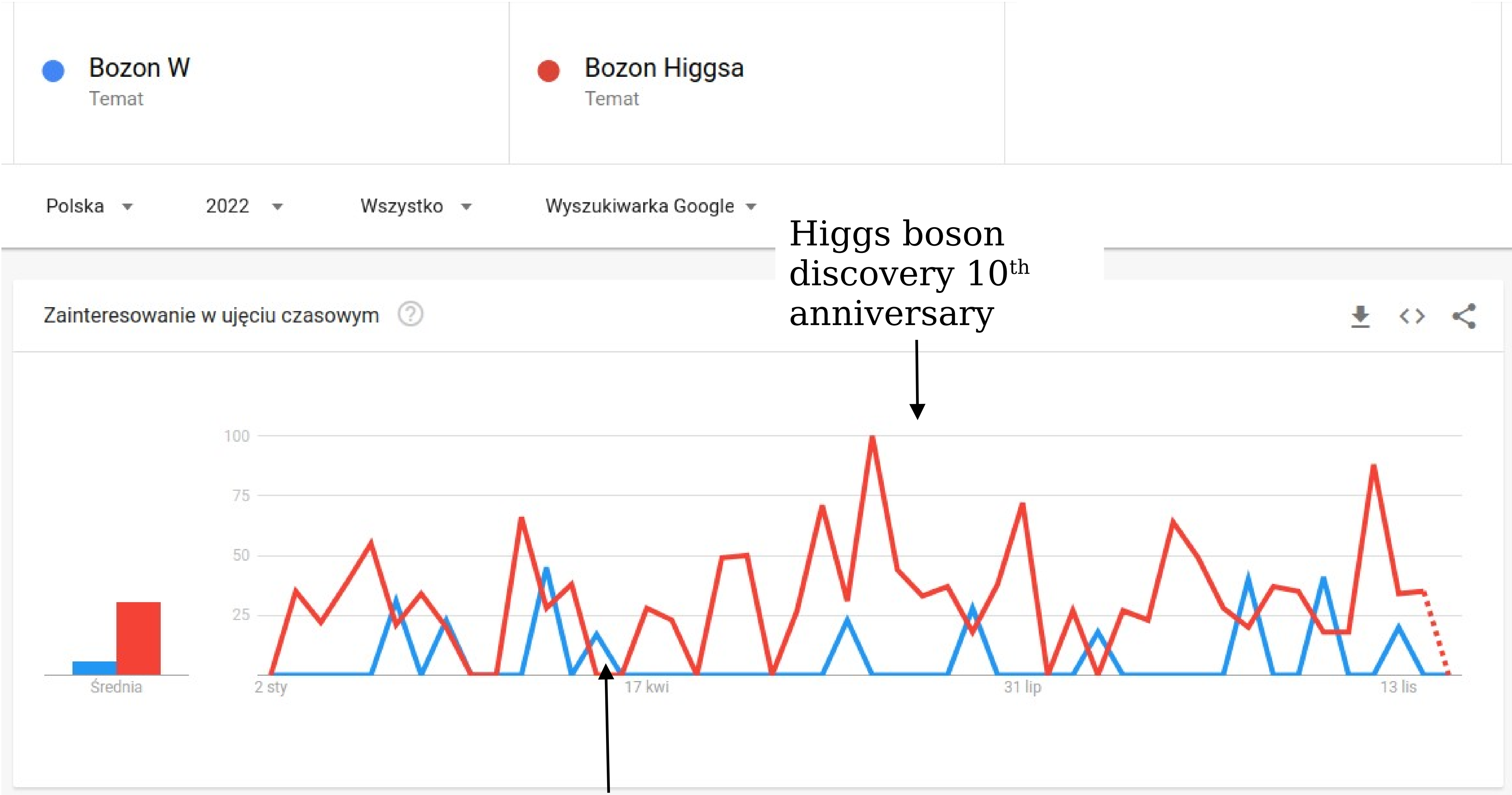
Google trends – whole world



Higgs boson discovery 10th anniversary

new publication on the W mass measurement

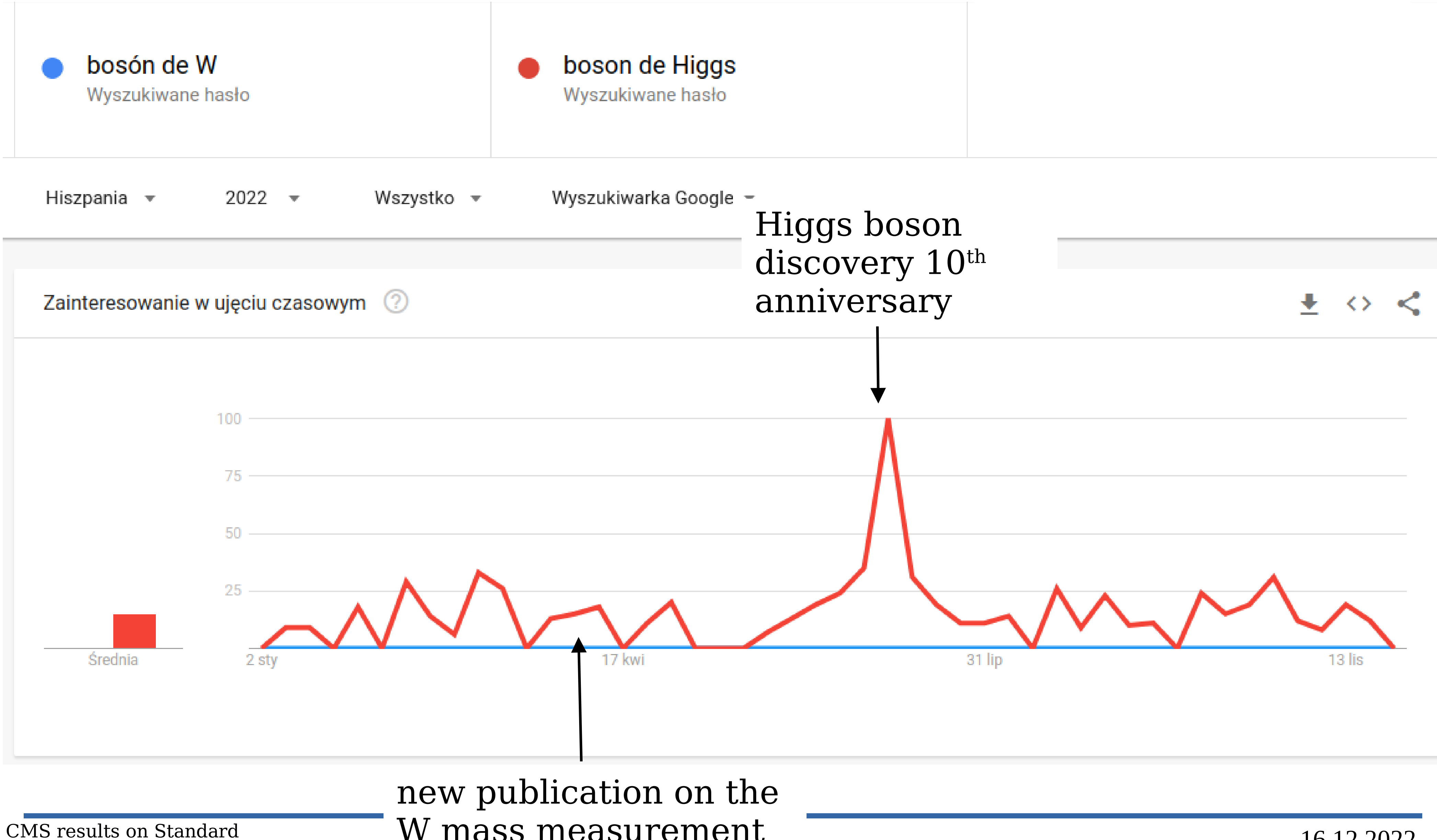
Google trends – Poland



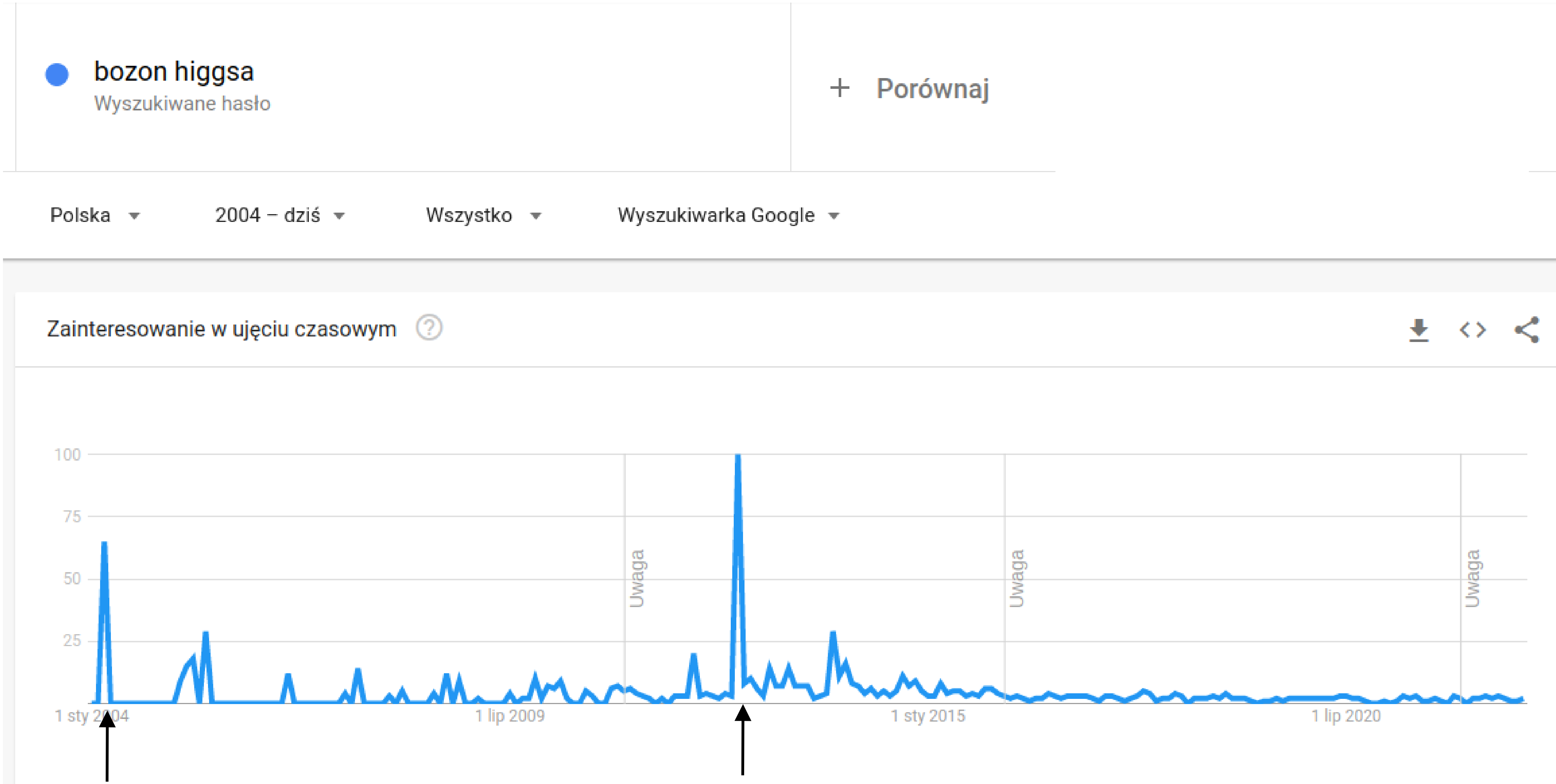
Higgs boson discovery 10th anniversary

new publication on the W mass measurement

Google trends – Spain



Google trends – Poland



CERN 50th anniversary

Higgs boson discovery

Backup slides

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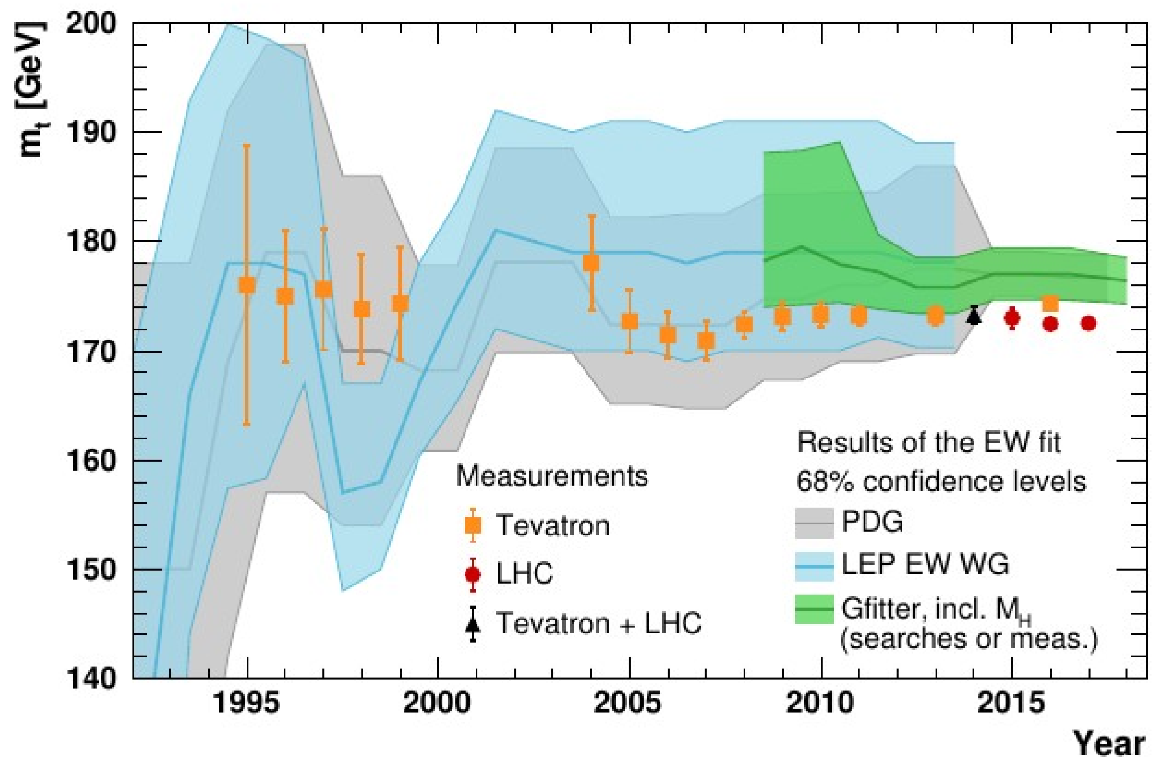
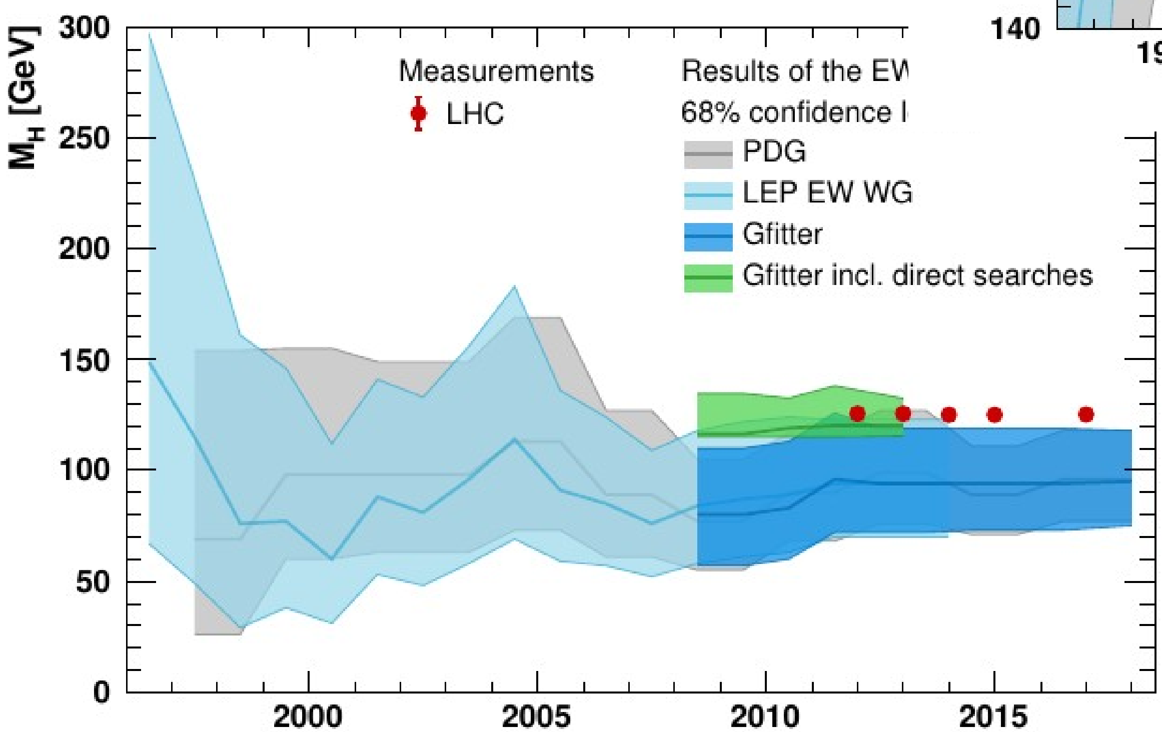
EWK fits – historical plots





Eur. Phys. J. C78, 675 (2018)

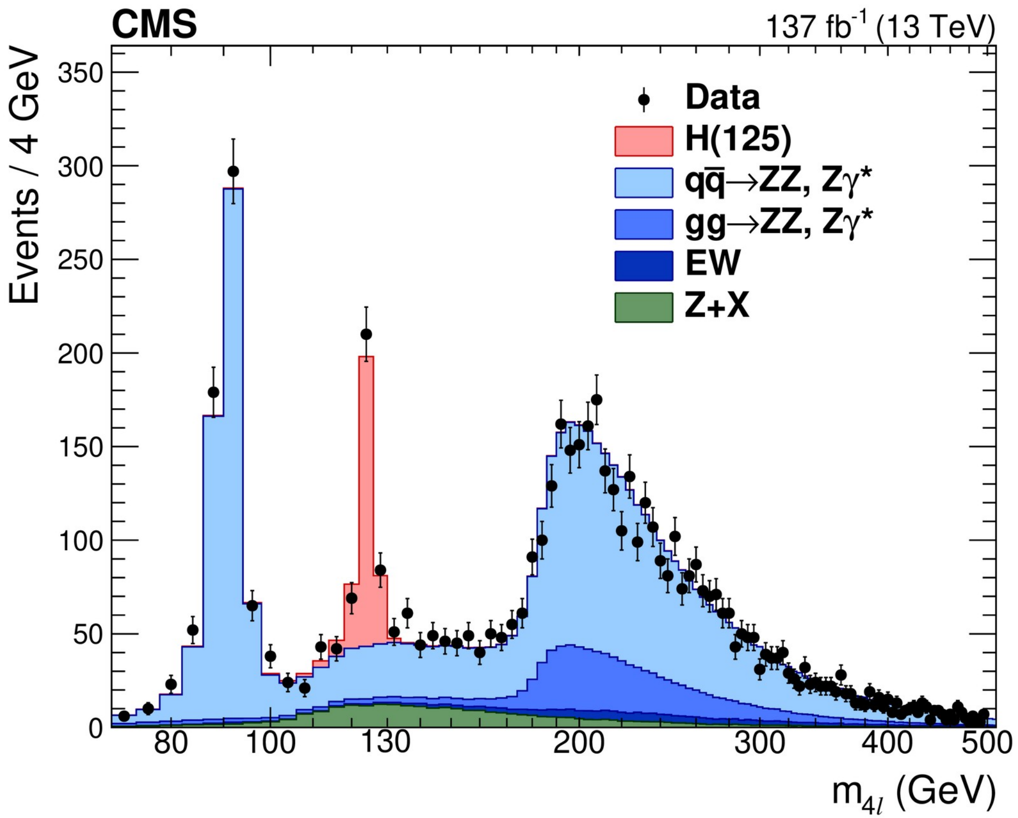
Higgs boson mass

Phys. Lett. B 805 (2020) 135425

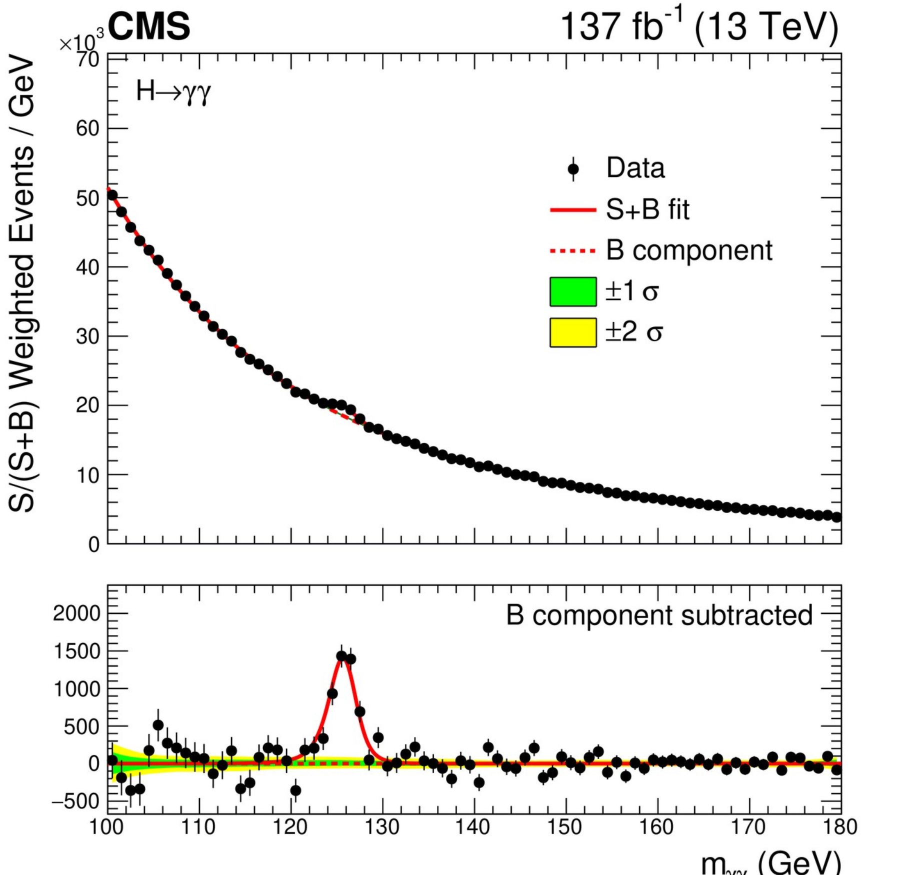
$$H \rightarrow ZZ, \gamma\gamma, \text{Run-1+2016}: \quad m_H = 125.38 \pm 0.14\,\text{GeV}$$

$$H \rightarrow ZZ \text{ only Runs-1,2}: \quad m_H = 125.09 \pm 0.15\,\text{GeV}$$

Eur. Phys. J. C 81 (2021) 488



Eur. Phys. J. C 81 (2021) 488



arXiv:2208.12279 [hep-ex]

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EWK fit input parameters

CMS

Eur. Phys. J. C78, 675 (2018)

Parameter	Input value	Free in fit	Fit Result	Fit w/o exp. input in line	Fit w/o exp. input in line, no theo. unc.
M_H [GeV]	125.1 ± 0.2	yes	125.1 ± 0.2	$90\,^{+21}_{-18}$	$89\,^{+20}_{-17}$
M_W [GeV]	80.379 ± 0.013	–	80.359 ± 0.006	80.354 ± 0.007	80.354 ± 0.005
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1882 ± 0.0020	91.2013 ± 0.0095	91.2017 ± 0.0089
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4947 ± 0.0014	2.4941 ± 0.0016	2.4940 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.475 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.742 ± 0.017	20.721 ± 0.026	20.719 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01620 ± 0.0001	0.01619 ± 0.0001	0.01619 ± 0.0001
$A_\ell\ ^{(\star)}$	0.1499 ± 0.0018	–	0.1470 ± 0.0005	0.1470 ± 0.0005	0.1469 ± 0.0003
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
$\sin^2\theta^\ell_{\rm eff}(\rm Tevt.)$	0.23148 ± 0.00033	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
A_c	0.670 ± 0.027	–	0.6679 ± 0.00021	0.6679 ± 0.00021	0.6679 ± 0.00014
A_b	0.923 ± 0.020	–	0.93475 ± 0.00004	0.93475 ± 0.00004	0.93475 ± 0.00002
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0736 ± 0.0003	0.0736 ± 0.0003	0.0736 ± 0.0002
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1030 ± 0.0003	0.1032 ± 0.0003	0.1031 ± 0.0002
R^0_c	0.1721 ± 0.0030	–	0.17224 ± 0.00008	0.17224 ± 0.00008	0.17224 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21582 ± 0.00011	0.21581 ± 0.00011	0.21581 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	yes	$1.27\,^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	yes	$4.20\,^{+0.17}_{-0.07}$	–	–
m_t [GeV]$^{(\nabla)}$	172.47 ± 0.68	yes	172.83 ± 0.65	176.4 ± 2.1	176.4 ± 2.0
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)\ ^{(\dagger\triangle)}$	2760 ± 9	yes	2758 ± 9	2716 ± 39	2715 ± 37
$\alpha_s(M_Z^2)$	–	yes	0.1194 ± 0.0029	0.1194 ± 0.0029	0.1194 ± 0.0028

W boson mass

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