Summary of Winter Conferences 2021

Séminaire DPhP
May 3, 2021

CEA - Saclay

Gautier Hamel de Monchenault ➡ SM, BSM and flavour
Sotiris Loucatos ➡ neutrinos and astroparticles
Maarten Boonekamp ➡ precision measurements

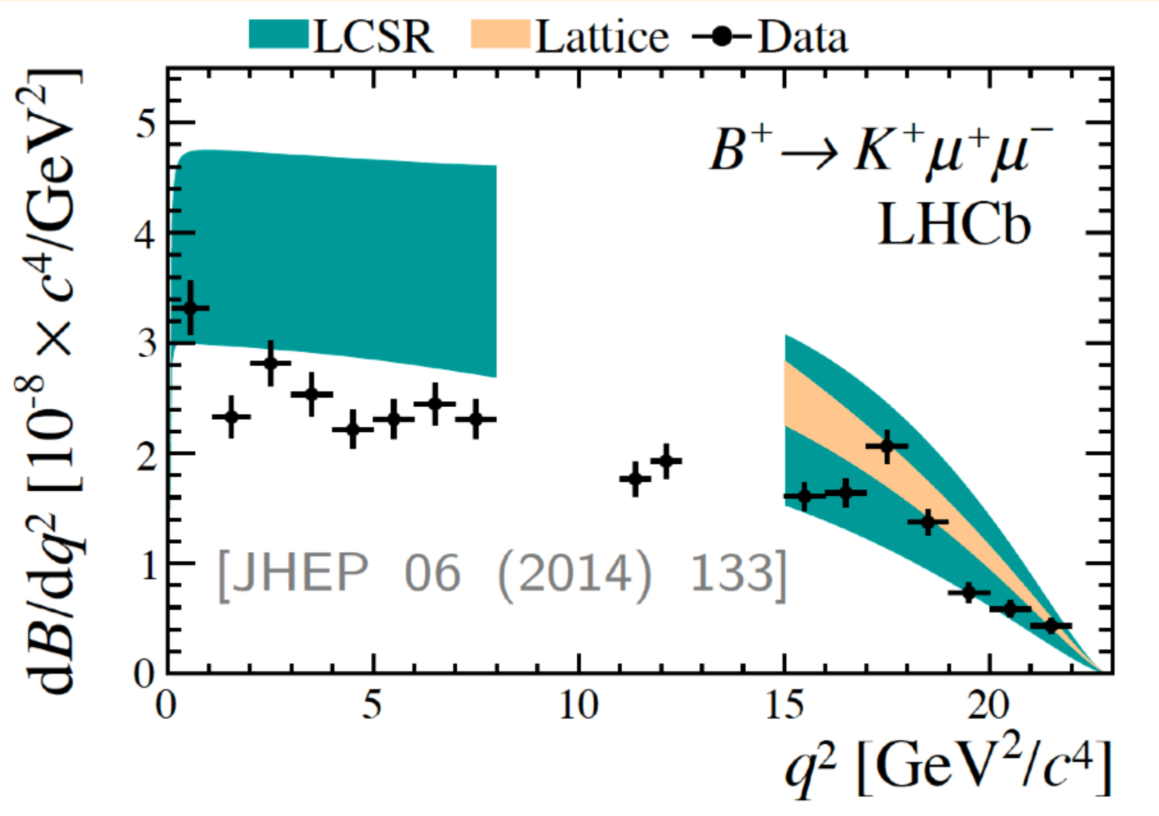
Tests of Lepton Flavour Universality

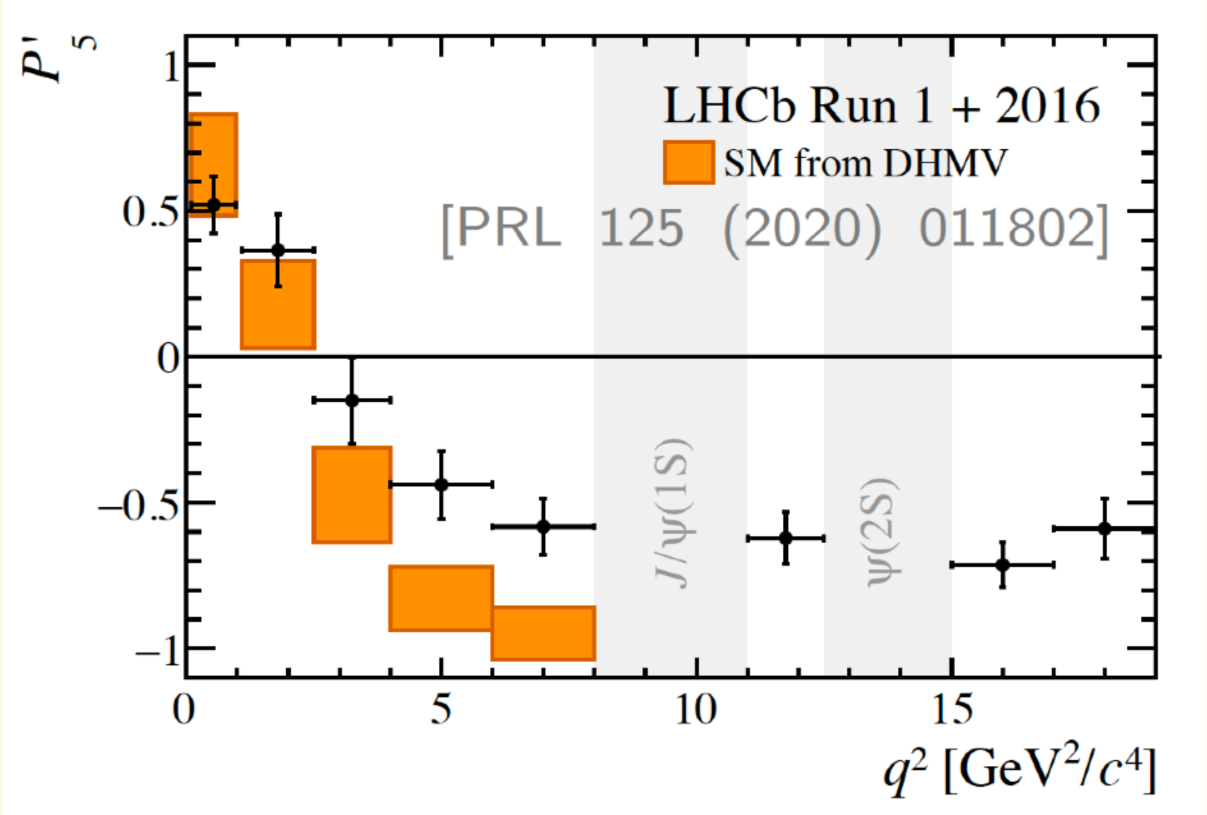
Over the years LHCb has reported or confirmed intriguing flavour anomalies, some of which hint at deviations from Lepton Flavour Universality (LFU)

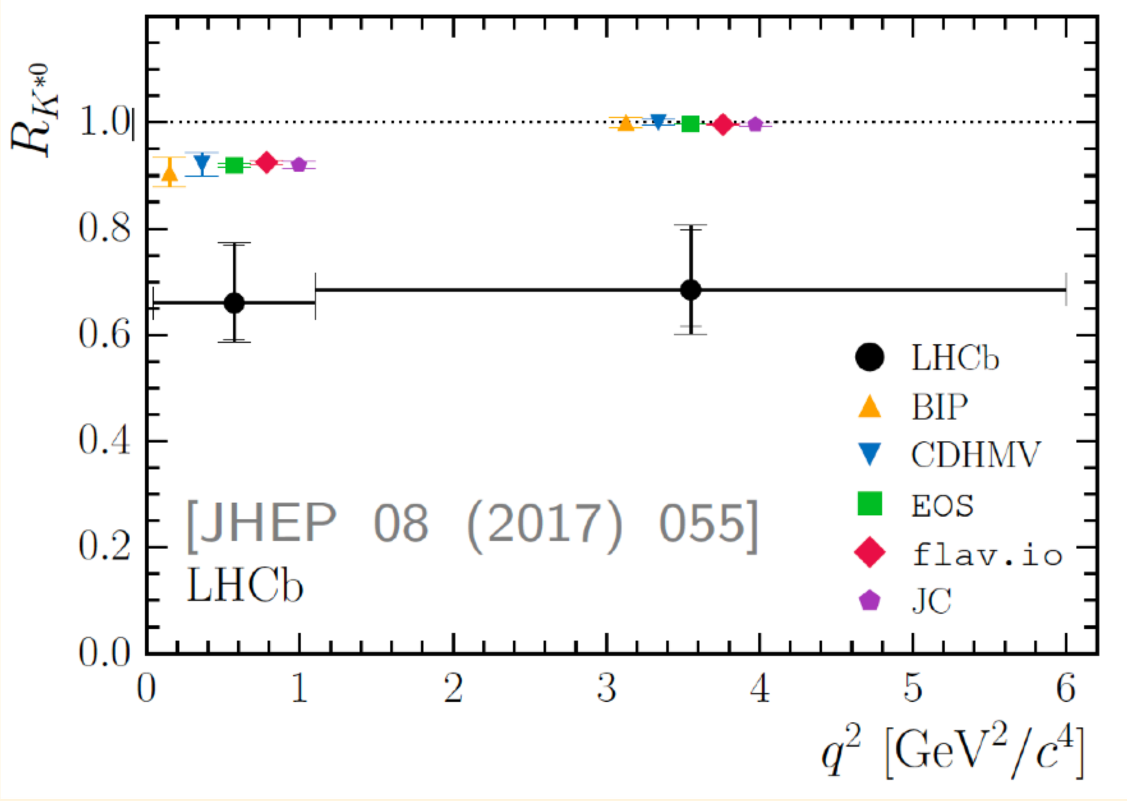
LFU in the SM: universal electroweak gauge interactions to e, μ and τ leptons

In $b \to s\ell^+\ell^-$ transitions

- Branching fractions
- Angular analyses
- Test of LFU involving μ/e ratios $R(K^{(*)})$: $B \to K^{(*)}\mu^+\mu^- / B \to K^{(*)}e^+e^-$

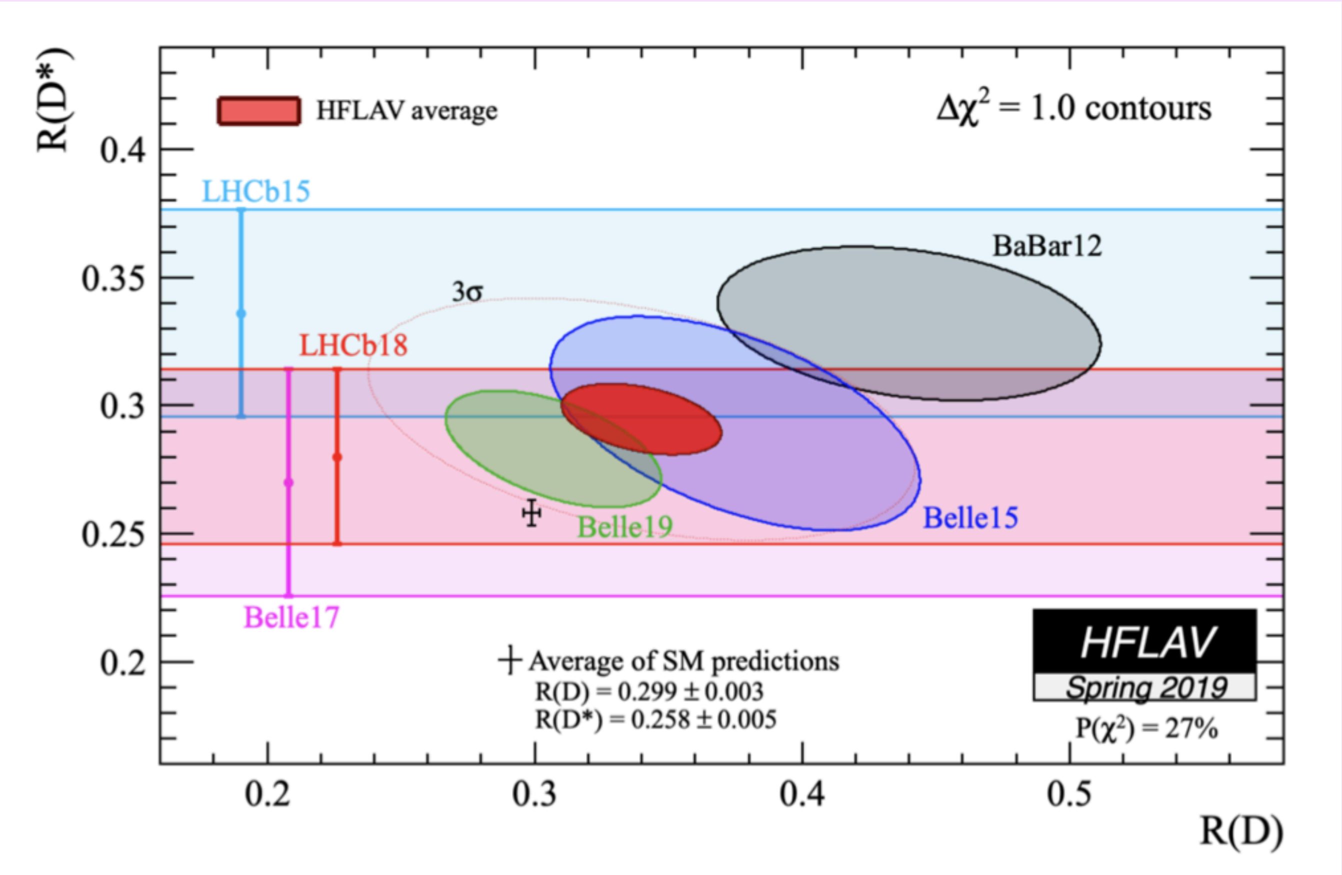






In $b \to c\ell\nu$ transitions

- tests of LFU involving τ/μ ratios $R(D^{(*)})$: $B \to D^{(*)}\tau\nu$ / $B \to D^{(*)}\mu\nu$



LHCb has presented several new results based on their full Run-2 dataset

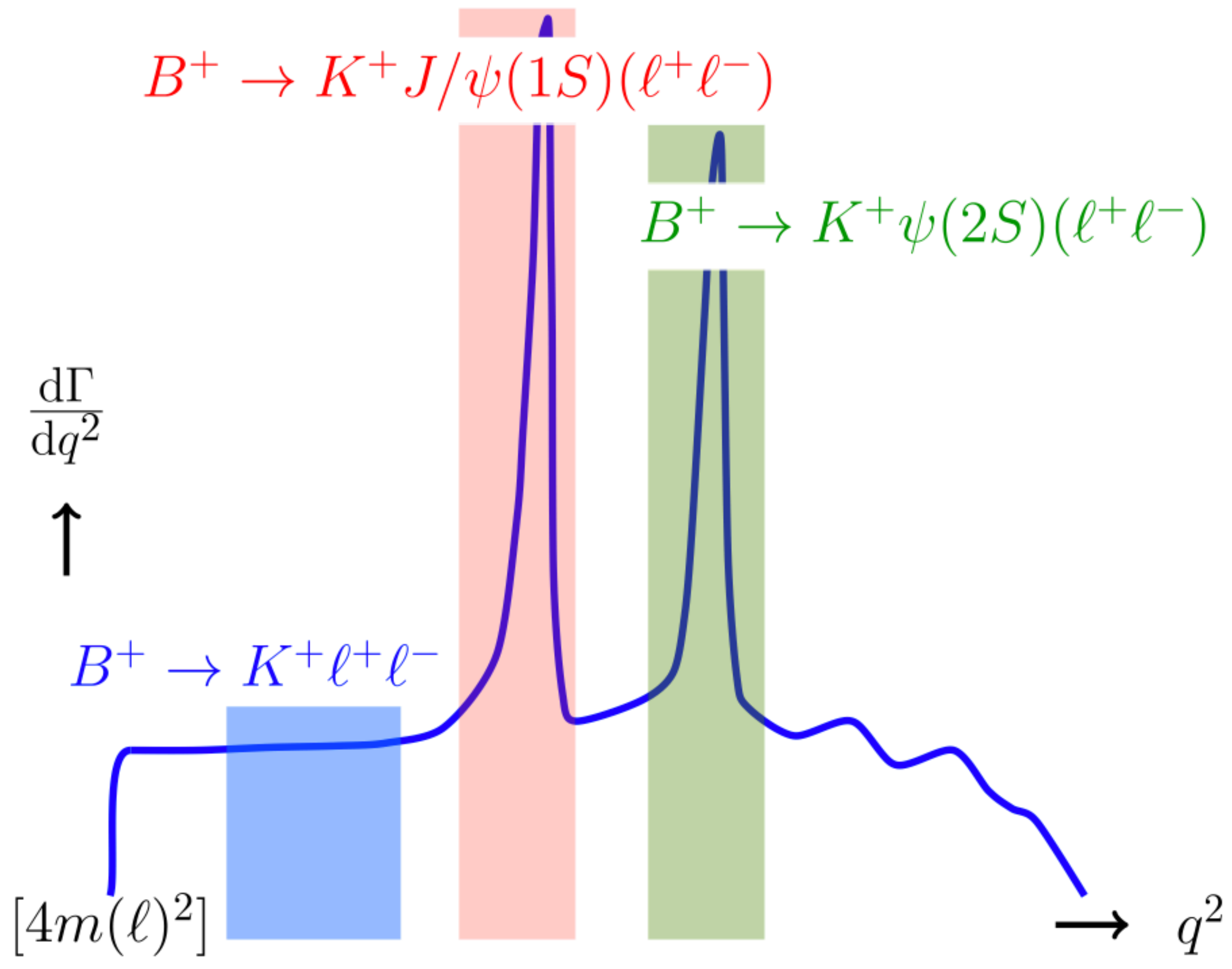
New Measurement of the LFU R(K) Ratio

LHCb 9 fb⁻¹ (full Run-2)

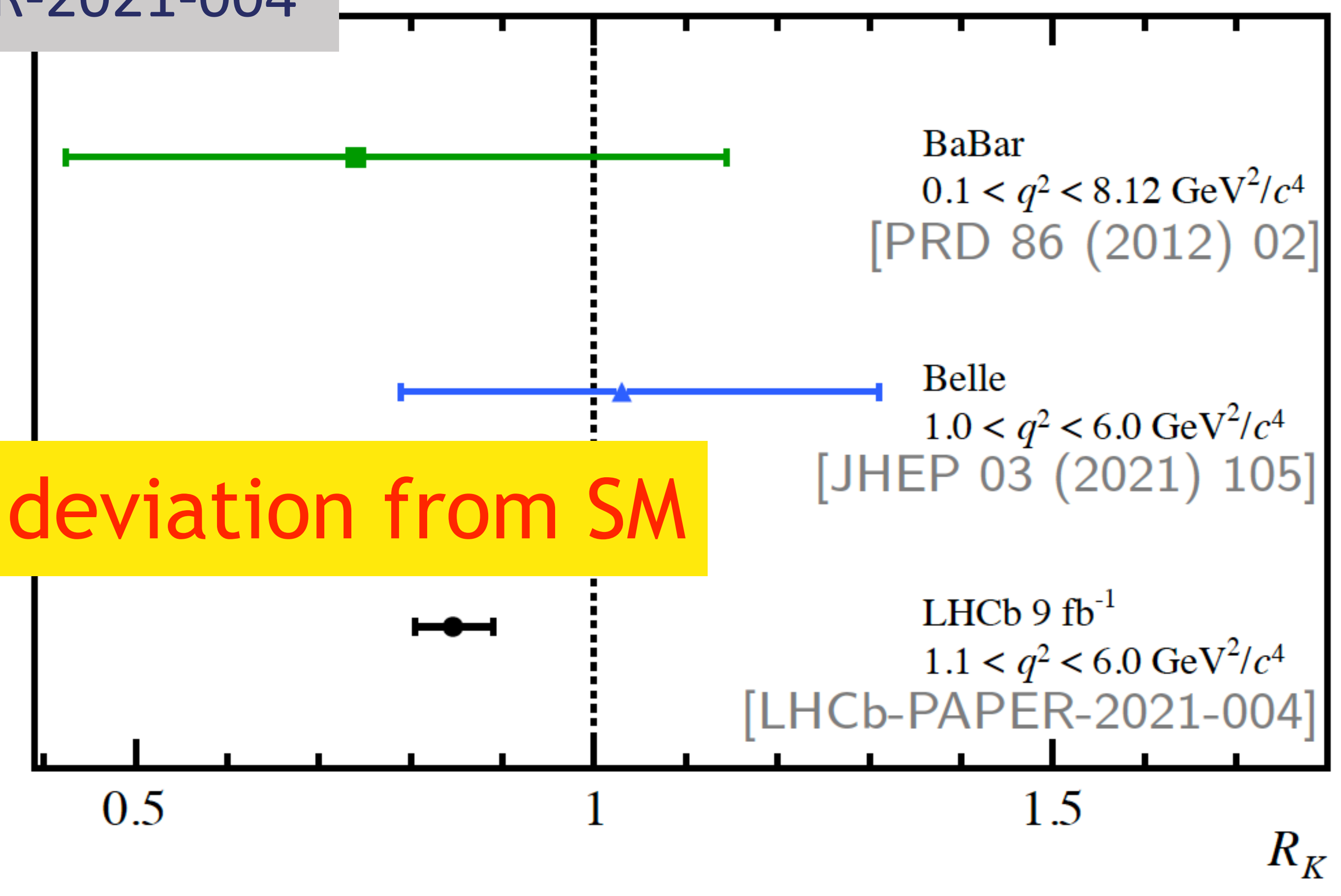
Measurement of
$R(K) = N(B^+ \to K^+\mu^+\mu^-) / N(B^+ \to K^+e^+e^-)$
in bin $1.1 < q^2 < 6.0$ GeV²

Expect $R(K) = 1$ in the SM

measured as a double ratio to cancel experimental uncertainties

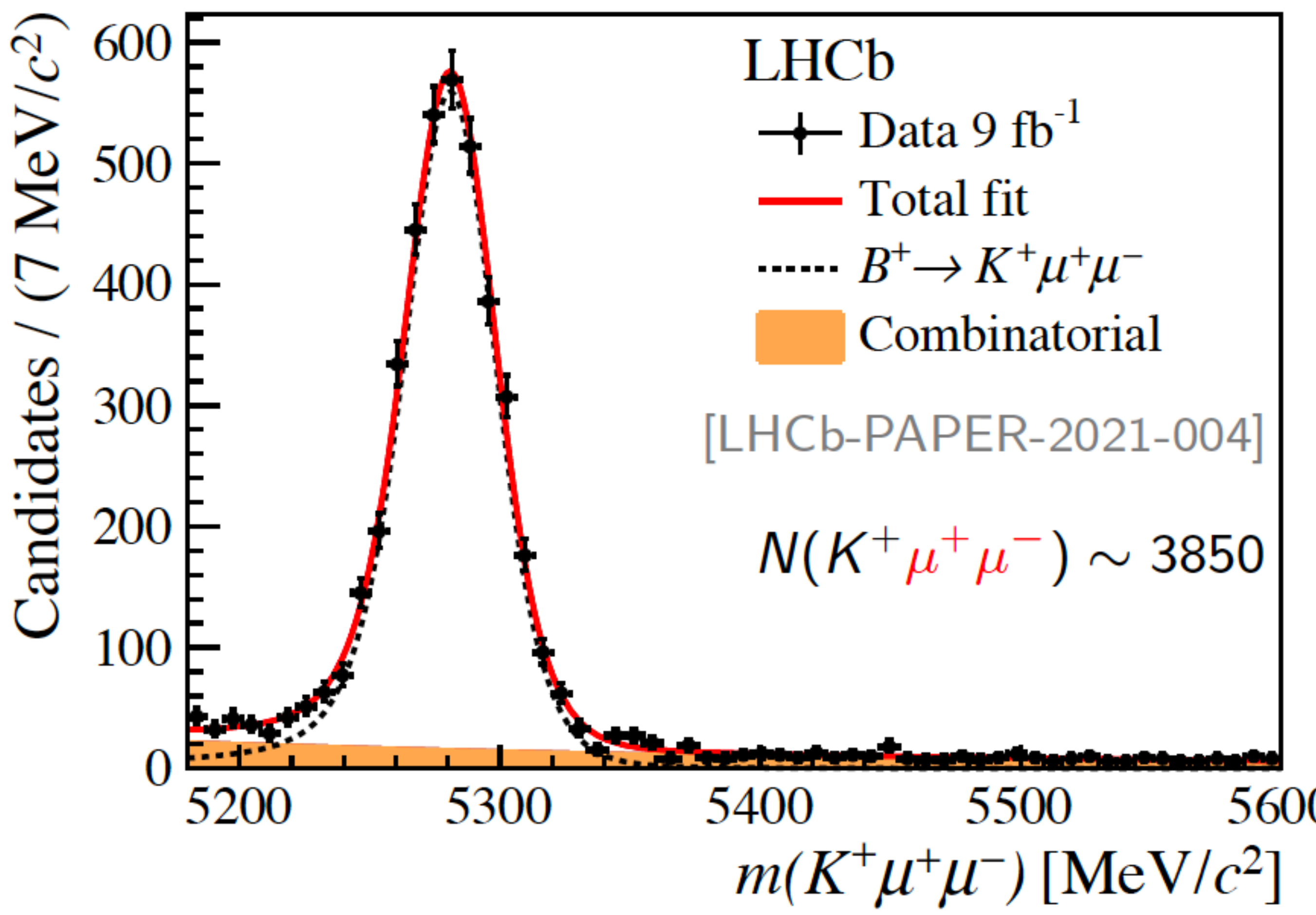


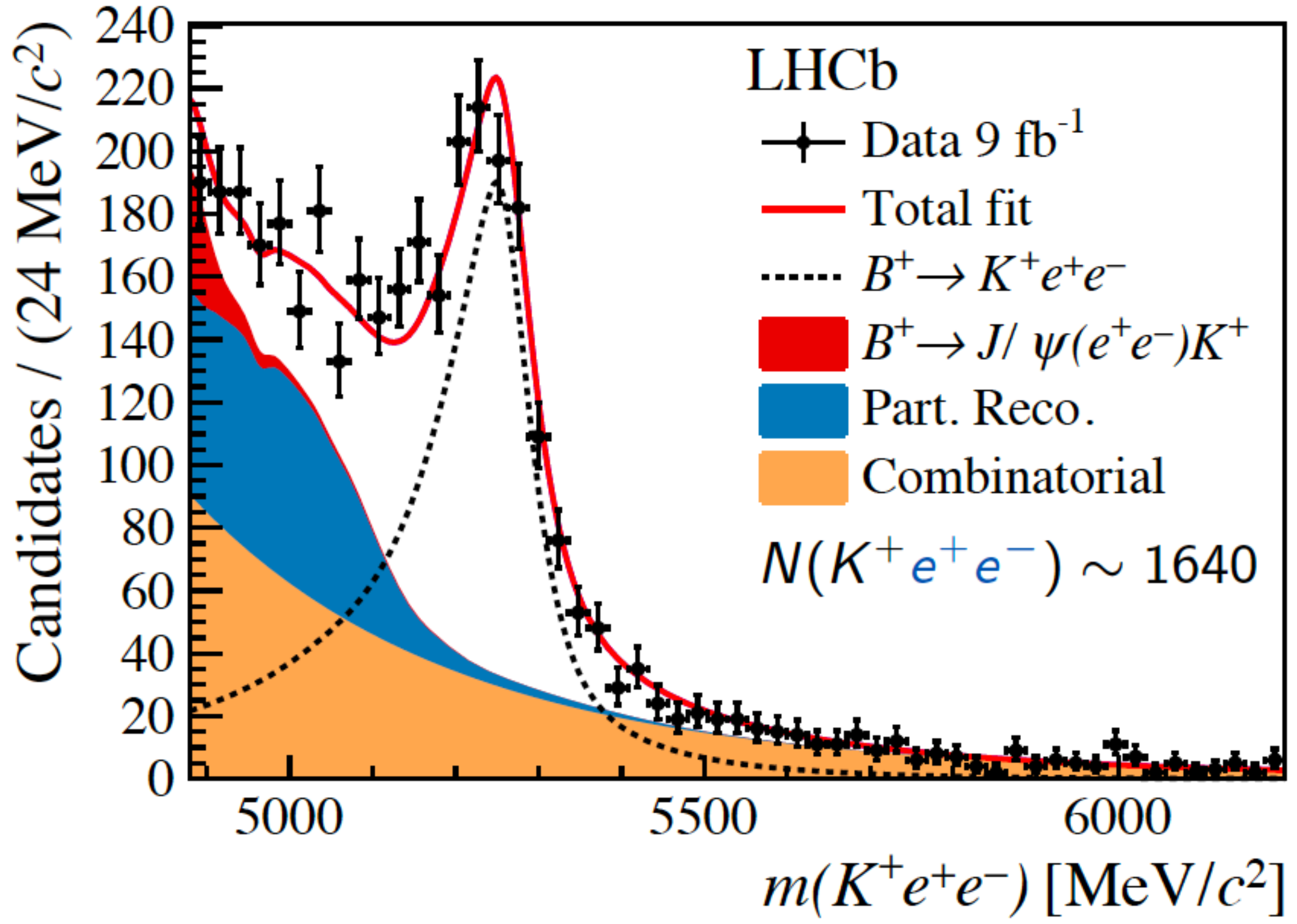
LHCb-PAPER-2021-004



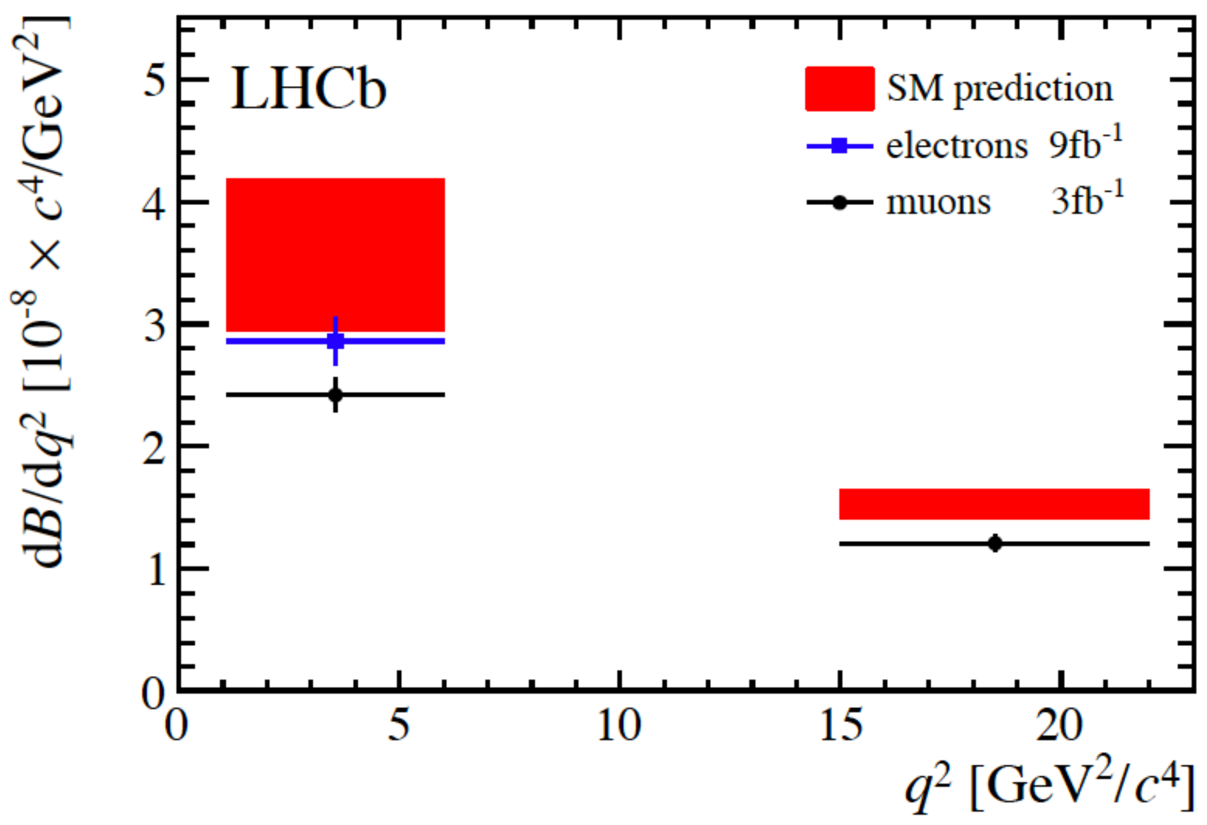
3.1σ deviation from SM

$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$





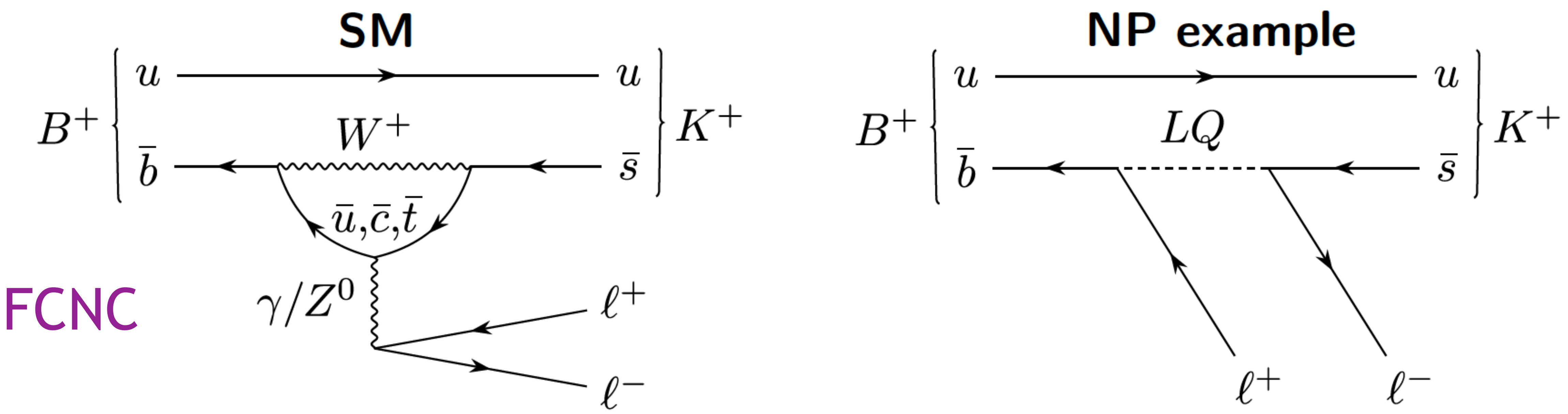
combining with measurement of $BF(B^+ \to K^+\mu^+\mu^-)$



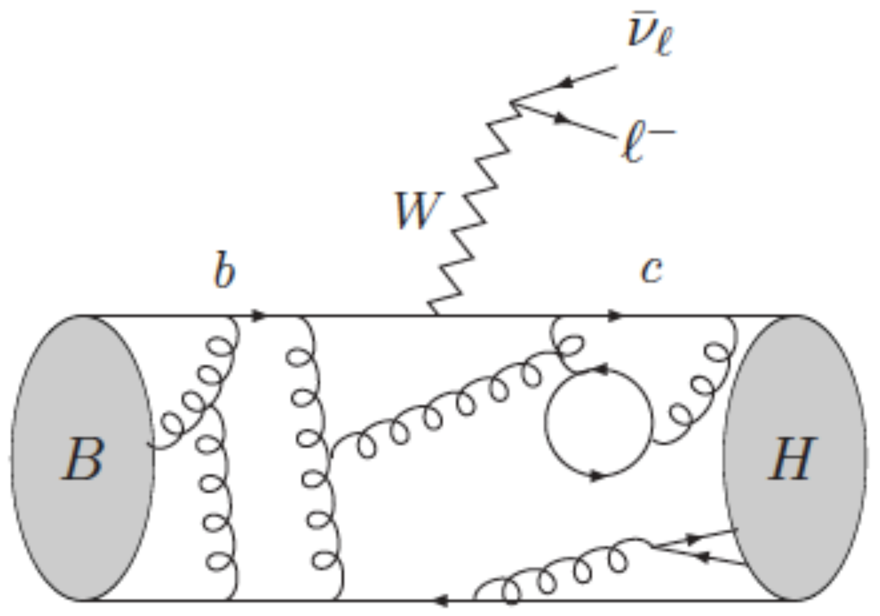
hint of NP coupled to μ?
is this related to (g-2) of the μ?

Theoretical Explanations?

$B^+ \to K^+\ell^+\ell^-$ and related decays occur through $b \to s\ell^+\ell^-$



$B \to D^*\ell\nu$ occurs through $b \to c\ell\nu$

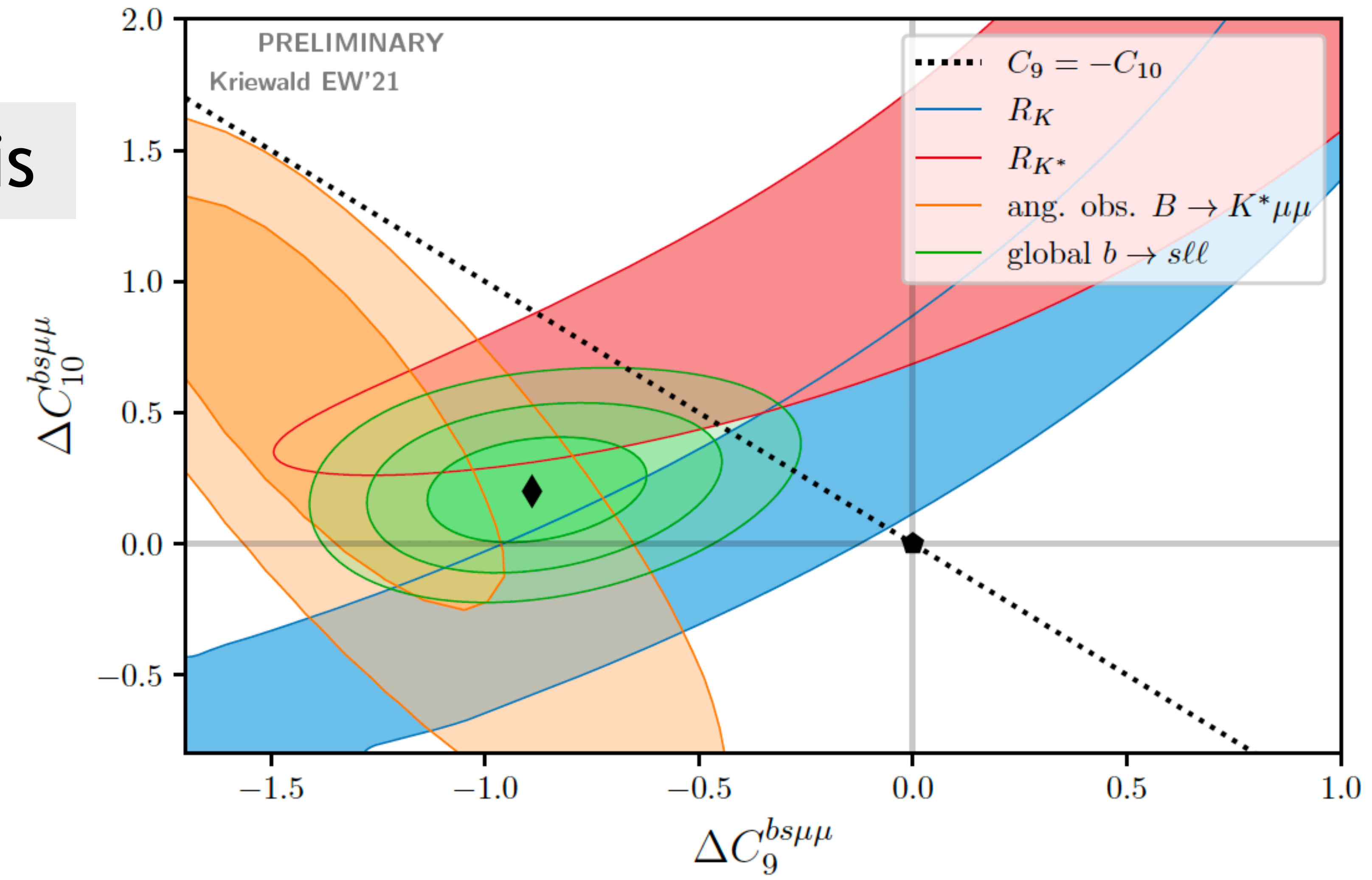


$b \to s\ell\ell$ e/μ anomalies suggest BSM at $\mathcal{O}$(10—30 TeV), e.g.:

- Z' (heavy Z-boson) connecting b to s
- Leptoquark (LQ) coupling quarks to leptons

$b \to c\ell\nu$ τ/μ anomalies suggest BSM at $\mathcal{O}$(1—3 TeV)

EFT analysis



$C^{bs\mu\mu}_{10}$: $L\otimes A$

$C^{bs\mu\mu}_{9}$: $L\otimes V$

A single-particle explanation would require very different couplings

JHEP 12 (2019) 006

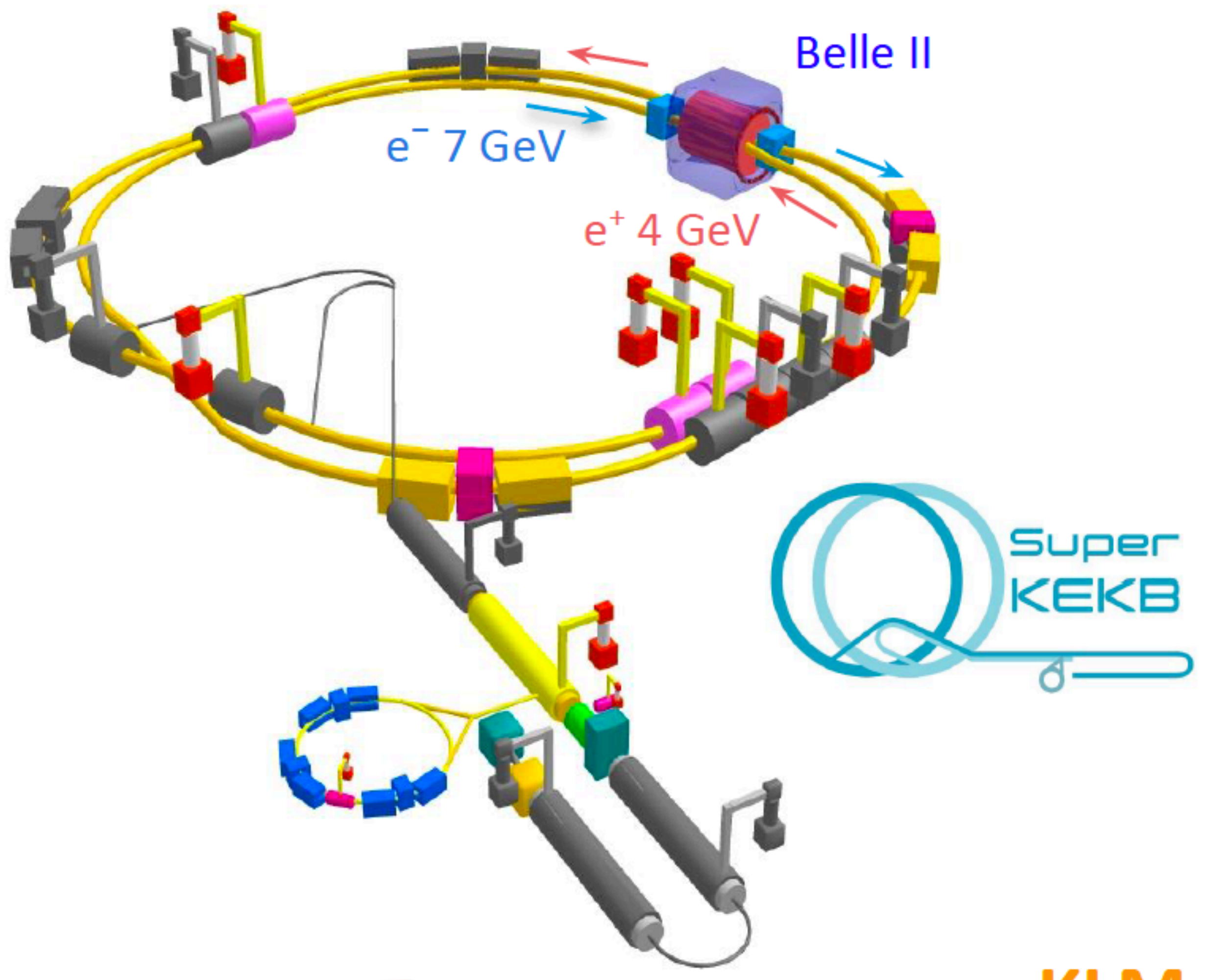
arXiv:2012.05883

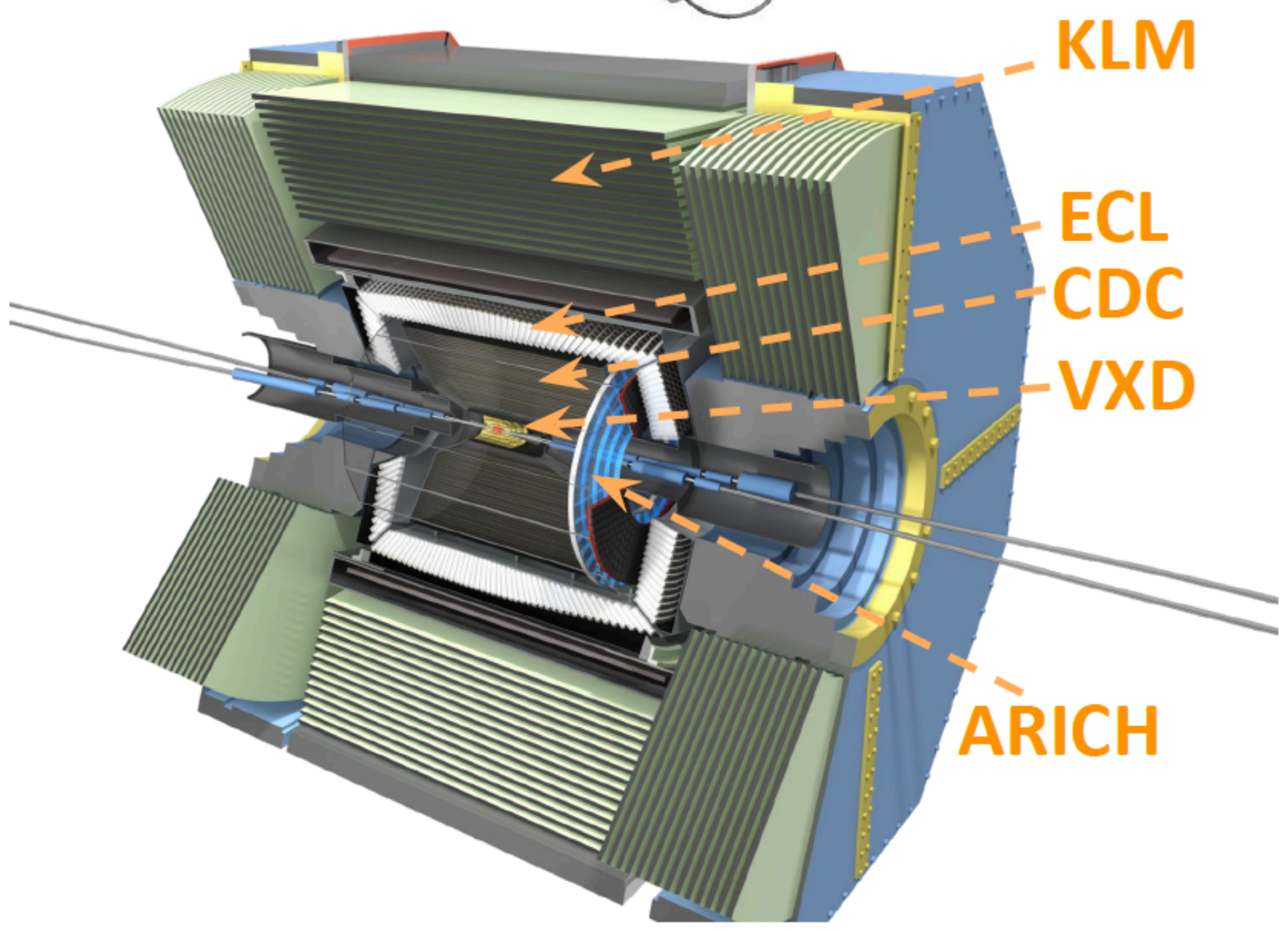
A viable BSM explanation for both anomalies:

- 3 generations of **Vector** LQ with non-unitary LQ-q-ℓ couplings

Expect strong constraints from B-meson and τ-lepton decays

News from BELLE-II





Super-KEKB, next-generation B factory

Target:

- $\mathscr{L}$ = 6×10^{35} cm^{-2}s^{-1} (=30×KEKB)
- $\int\mathscr{L}$ = 50 ab^{-1} (=50×KEKB)

since 2019:

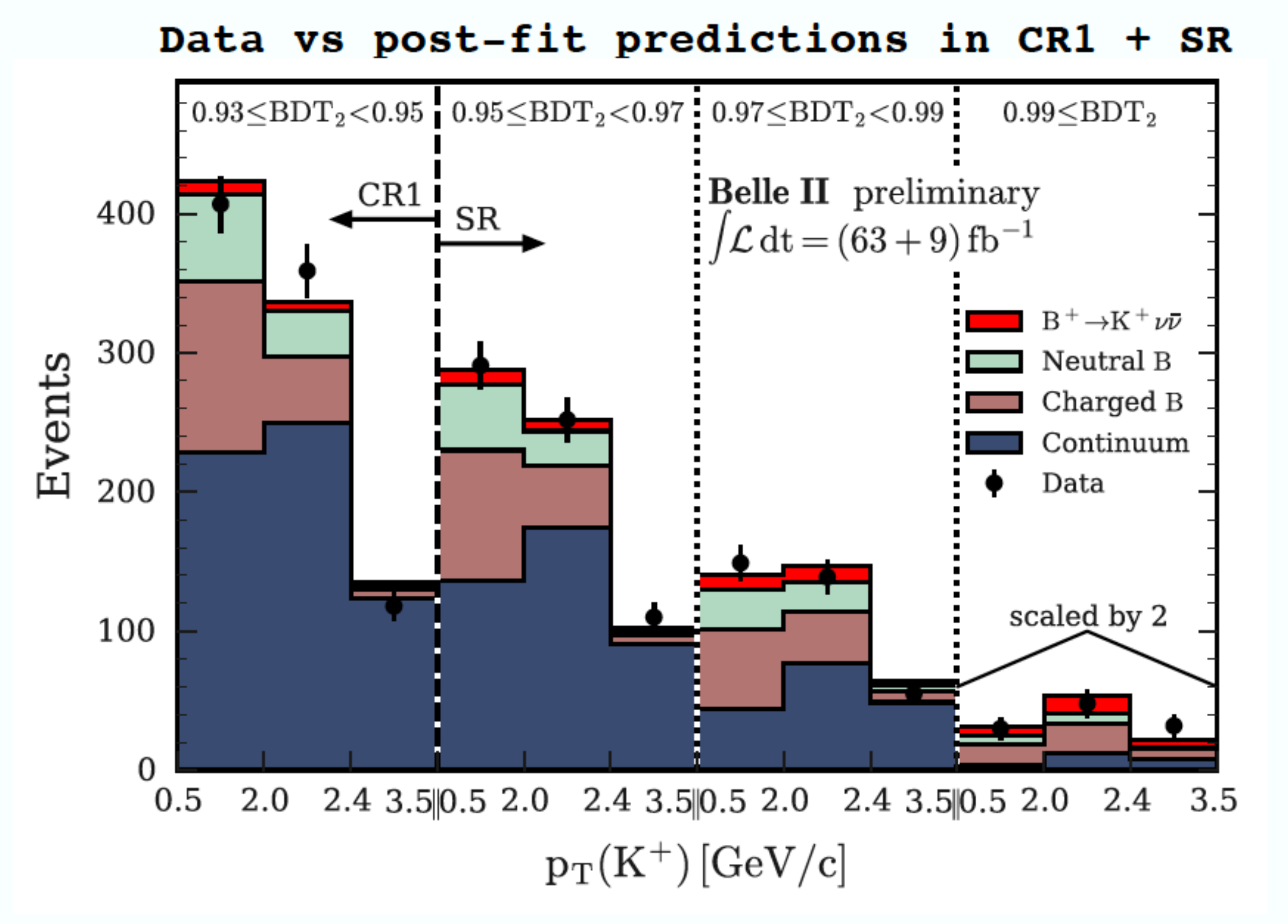
- $\int\mathscr{L}$ = 0.1 ab^{-1}

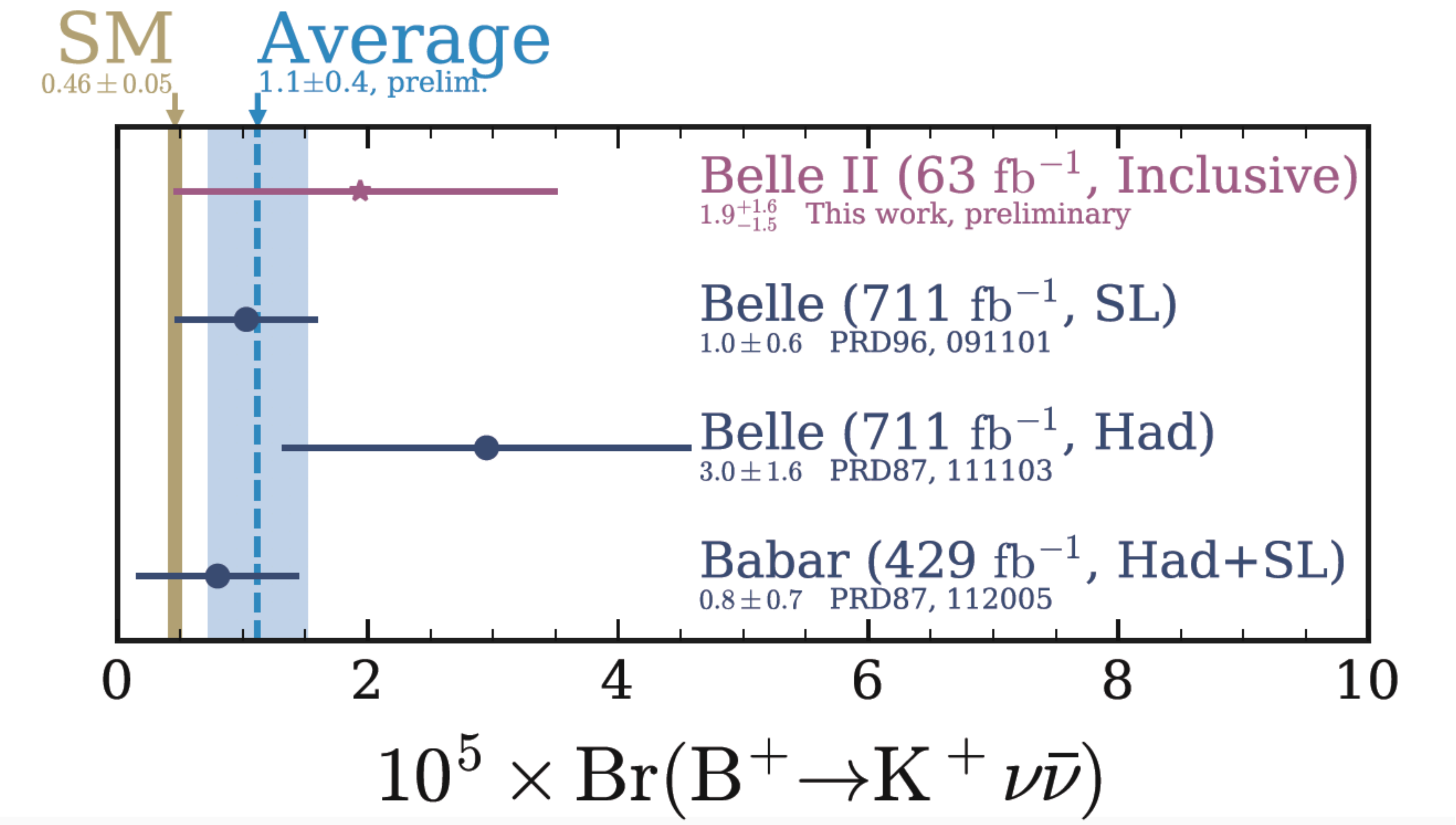
BELLE-II will greatly improve sensitivities in many rare B and τ decay channels

however still at a **very** early stage
some results ("rediscoveries"), but not yet competitive with BABAR, BELLE and LHCb

To be noted: a new method for B → K$\nu\bar{\nu}$:

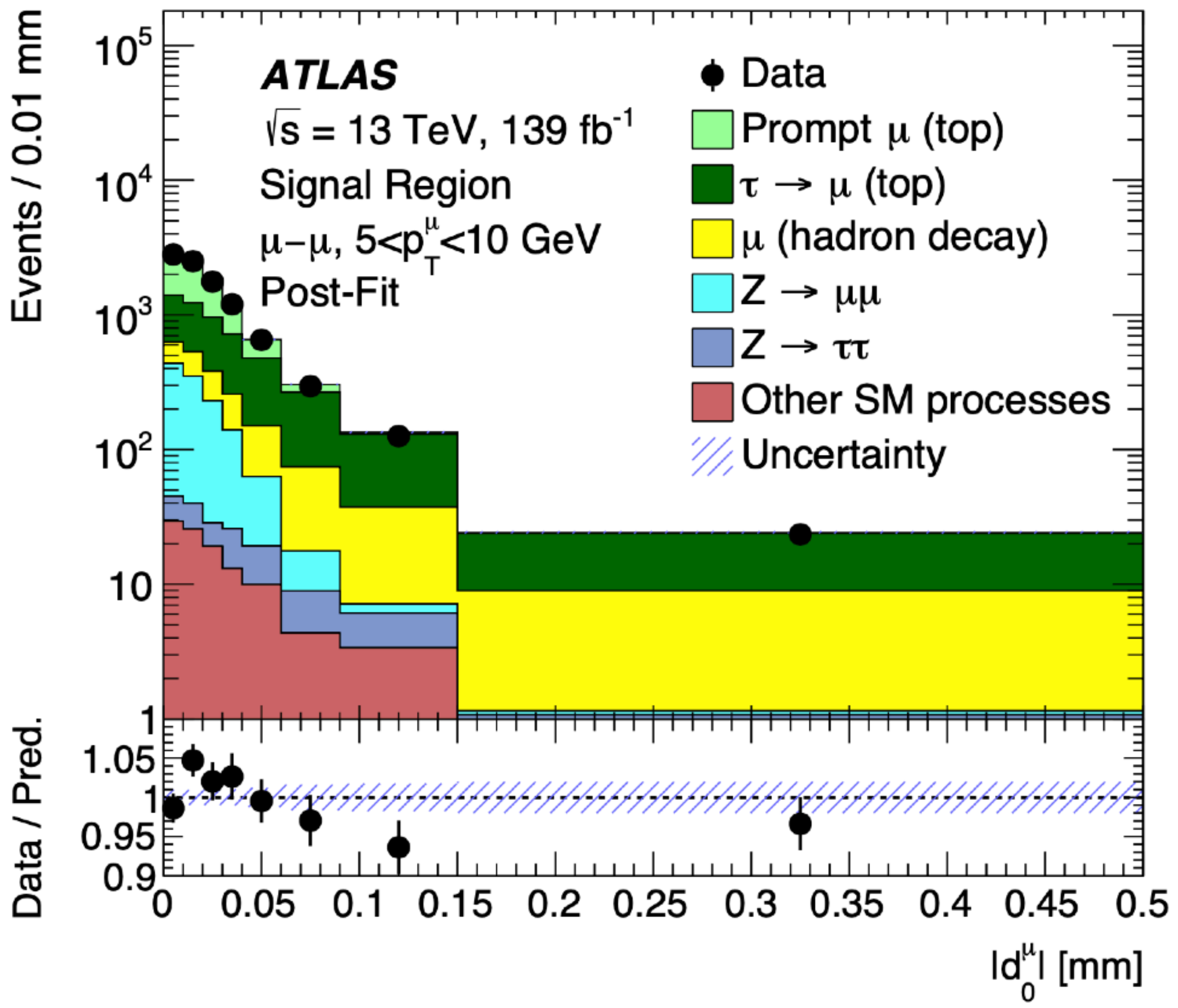
- inclusive tagging + ML
- already competitive despite small dataset



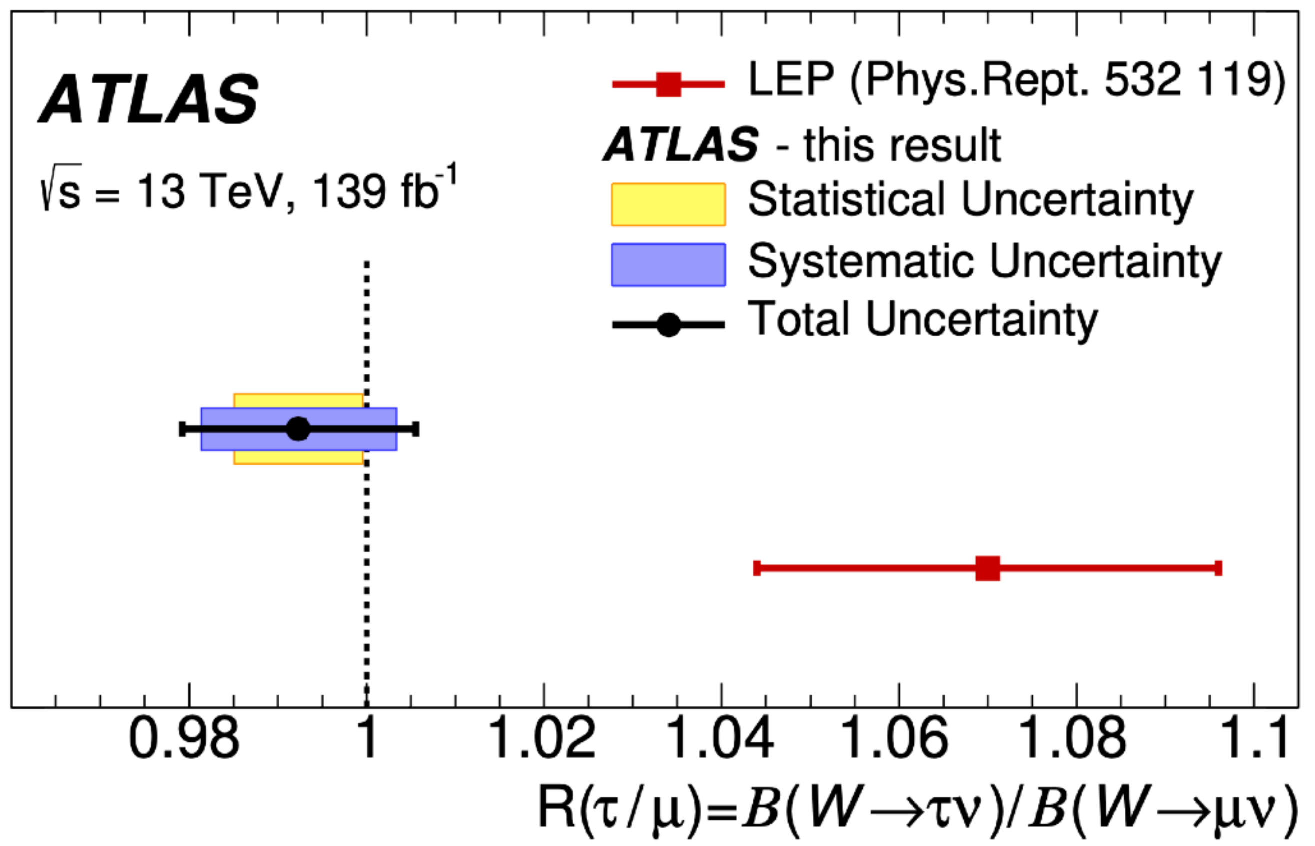


Test of τ/μ and τ/e Universality in W Decays

- Using $t\bar{t}$ events, ATLAS and CMS select relatively unbiased samples of on-shell W bosons

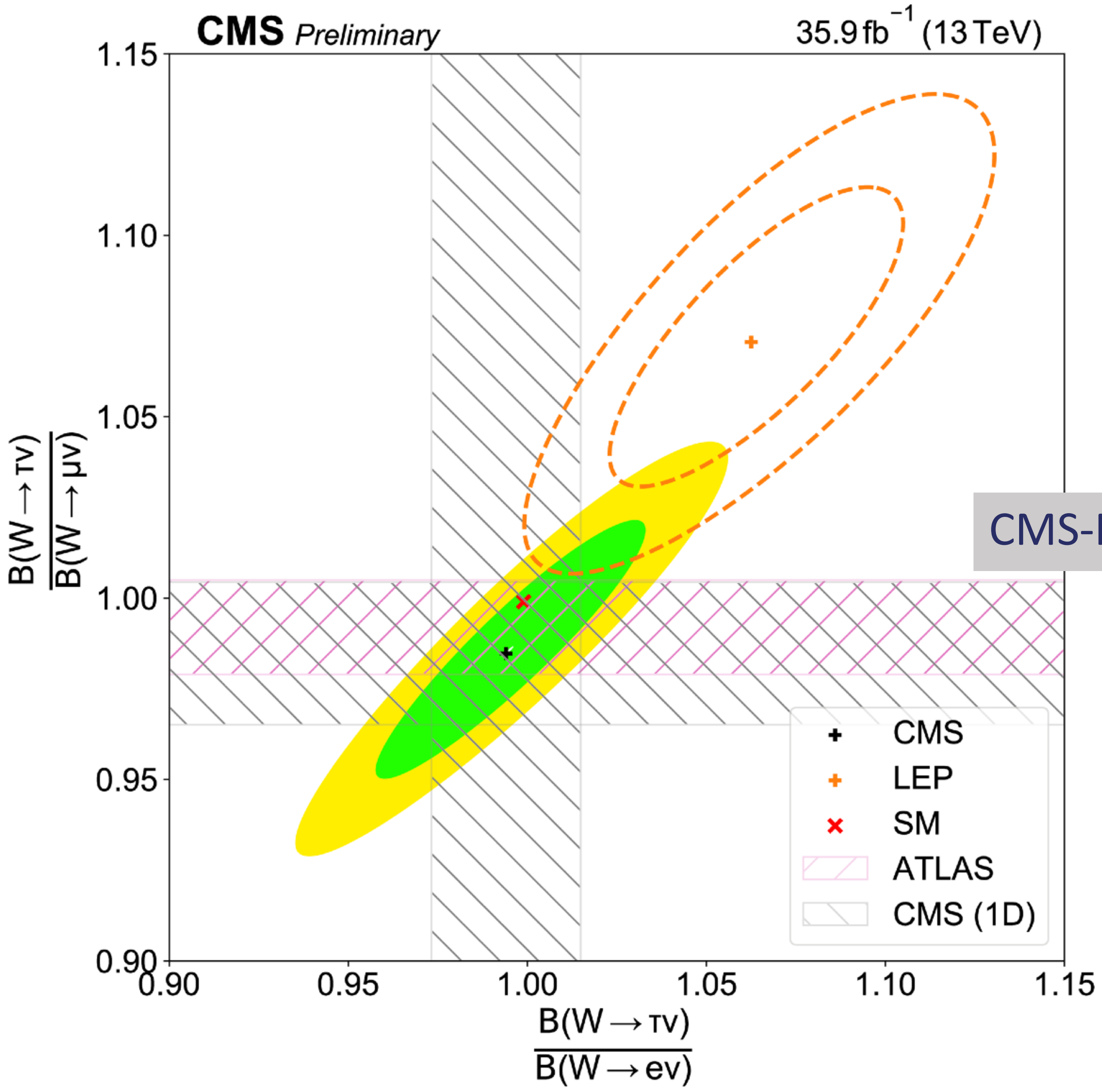


ATLAS: ratio determined from muon transverse impact parameter d_0 distribution



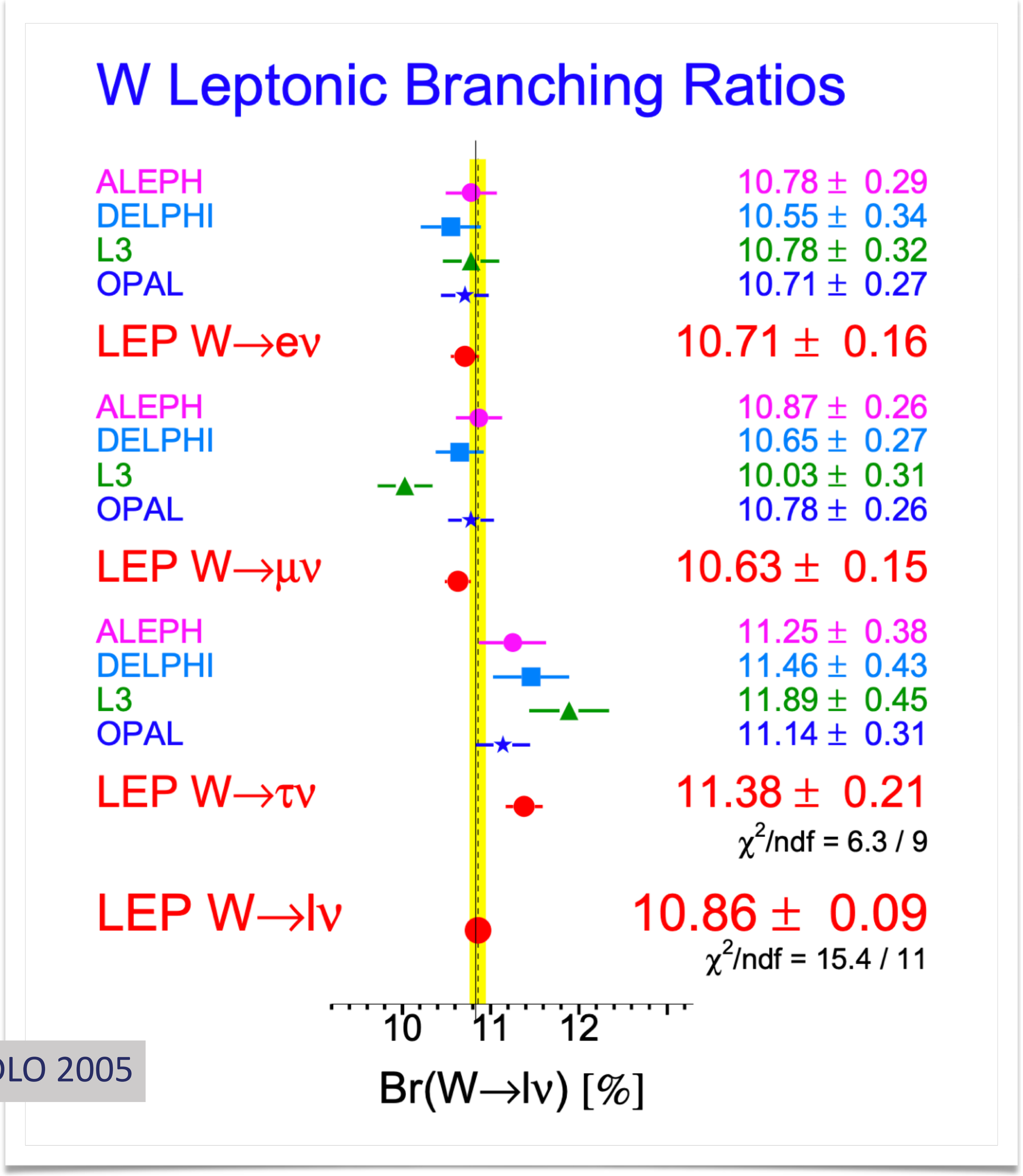
ATLAS-TOPQ-2018-29
Accepted by NP

CMS: Trailing lepton p_T used to discriminate between prompt W → e/μ decays from W → τ → e/μ decays in ee, μμ, and eμ events

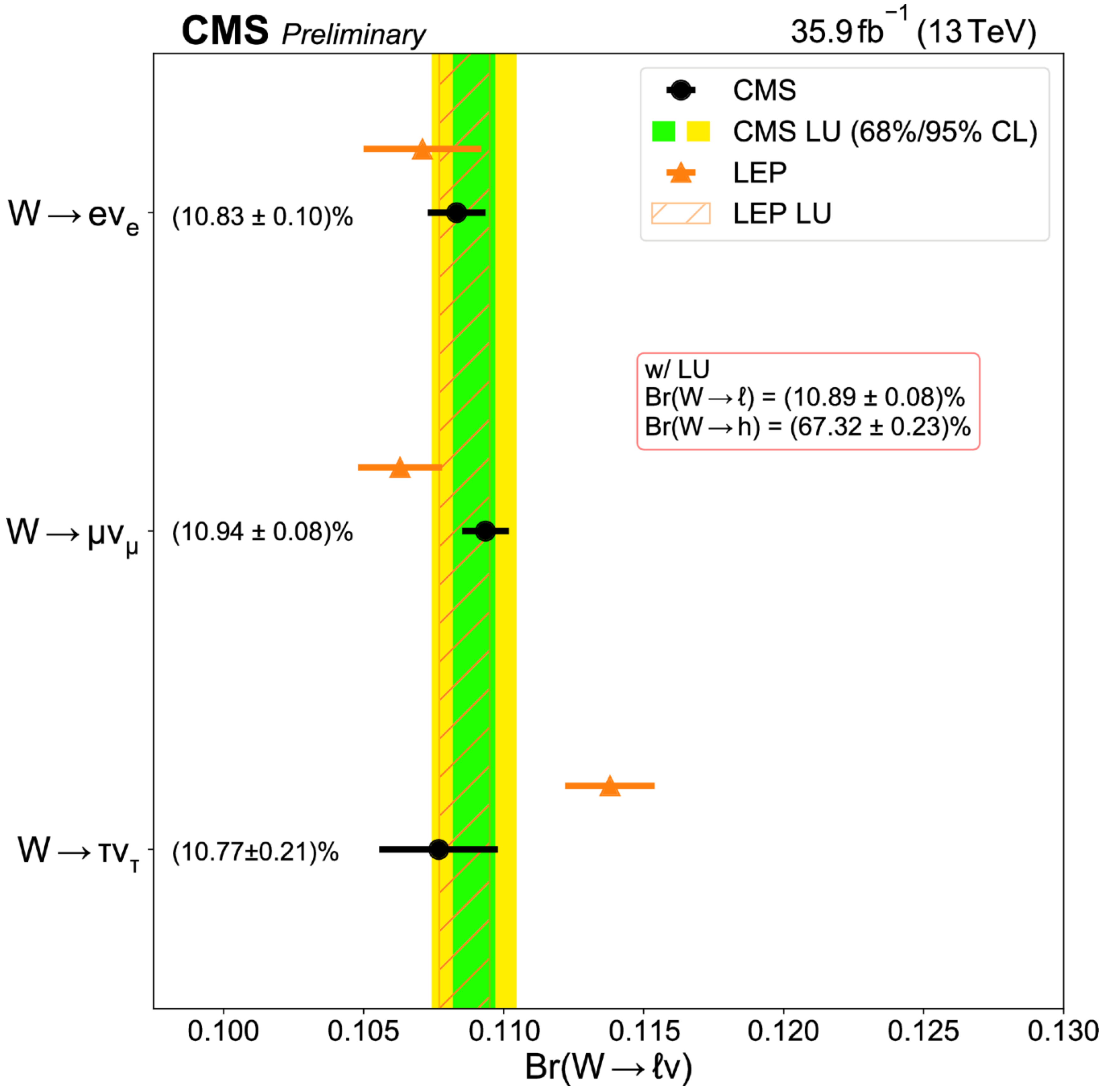


CMS-PAS-SMP-18-011

Universality of W Leptonic Decays



LEP ADLO 2005



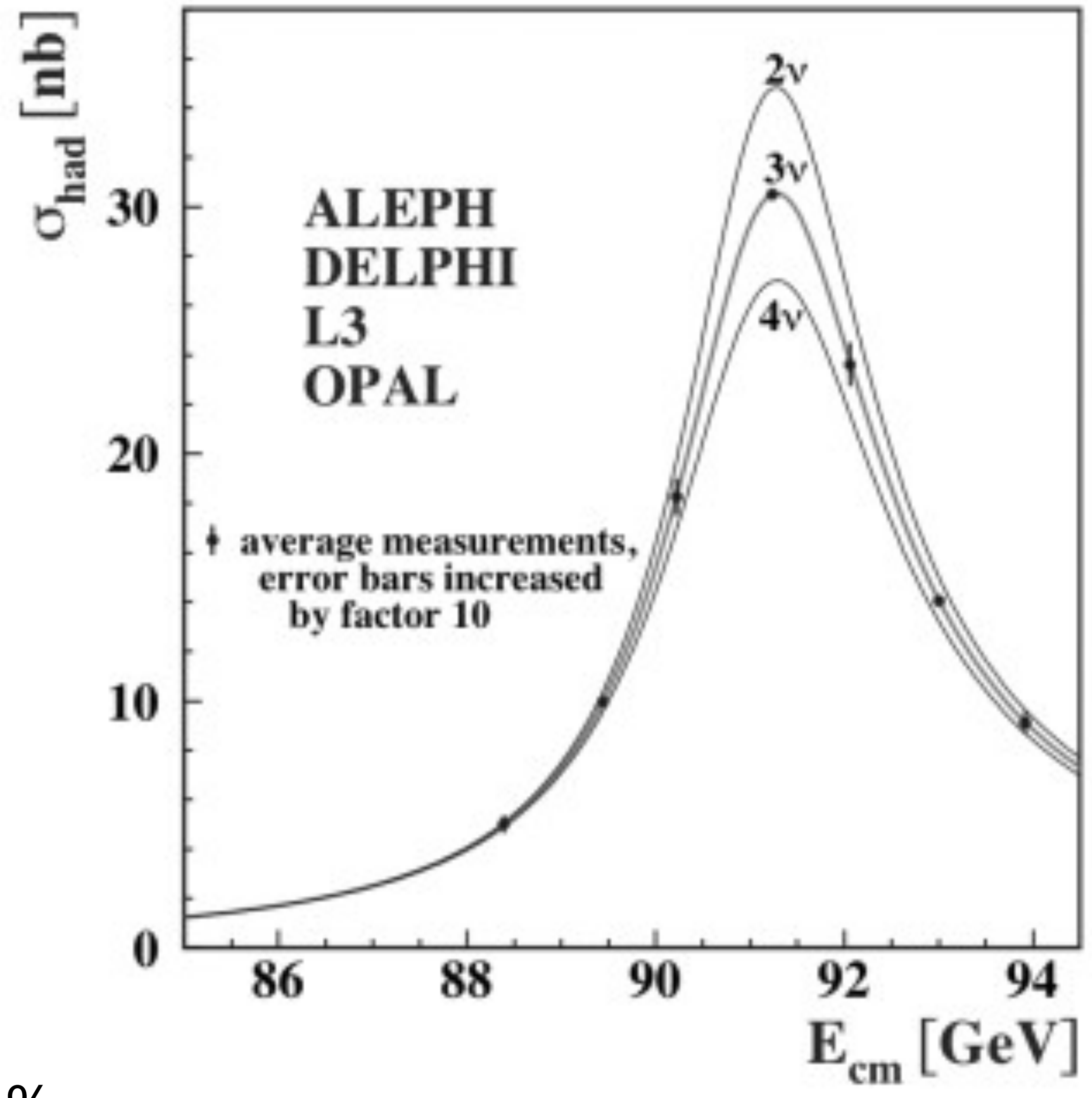
CMS-PAS-SMP-18-011

this is the end of a long-standing >2.5σ “tension”

recent ATLAS and CMS results are fully consistent with universality of charged currents

A By-Product of FCC-ee Studies

A recent LEP **luminosity update** confirms N_ν = 3 *active neutrinos*



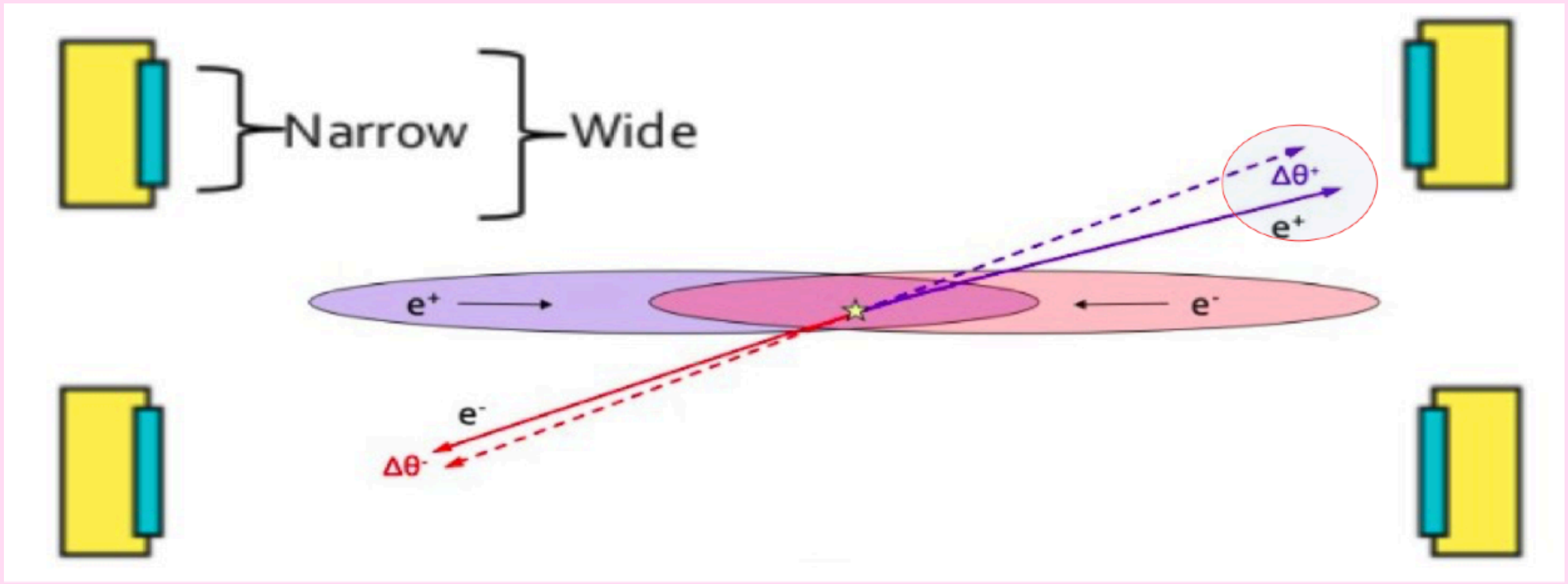
Including **corrections** due to the beam-beam effect, and updating theoretical calculation the Bhabha scattering cross-section, the long-standing LEP 2σ deficit is gone

from $N_\nu = 2.9840 \pm 0.0082$

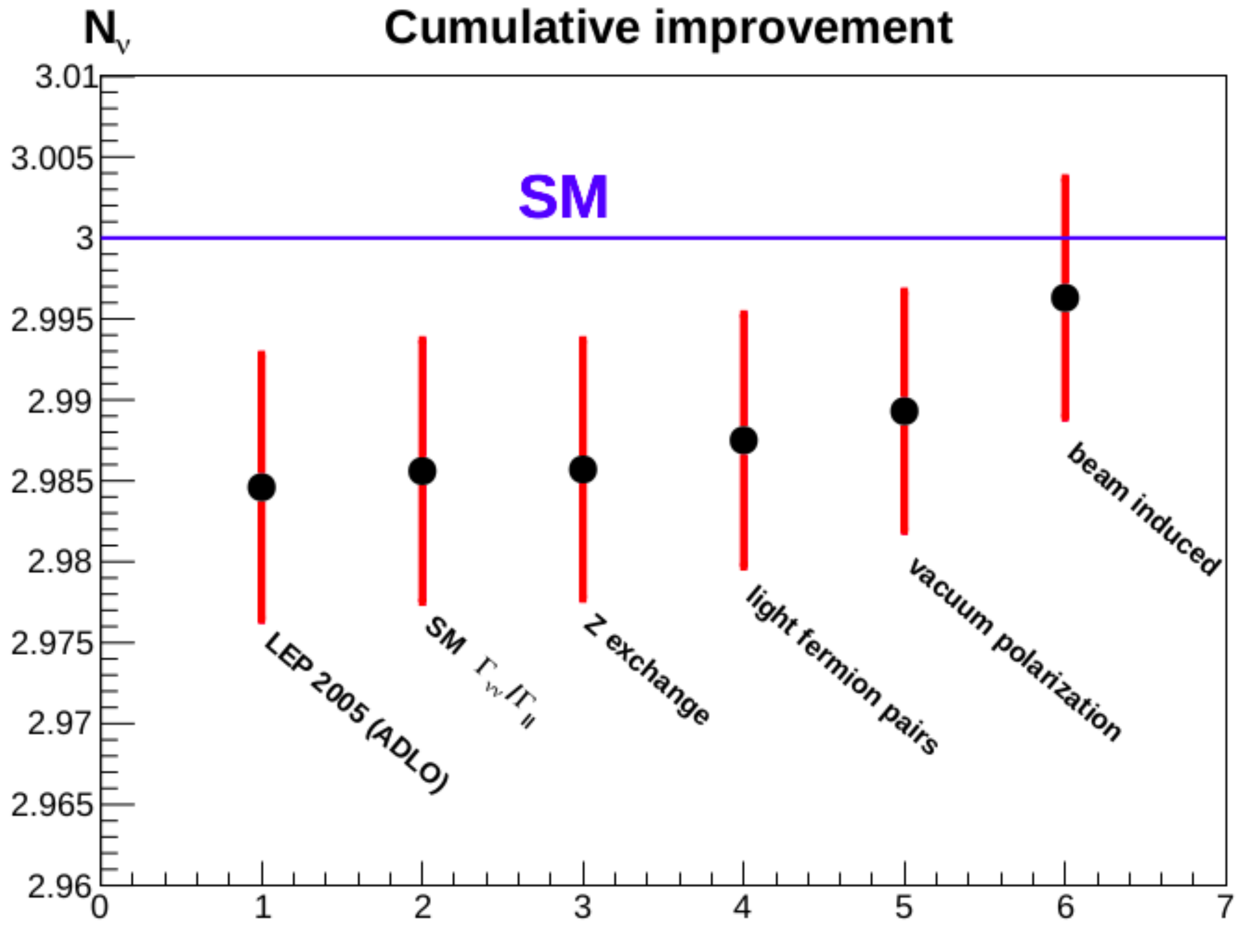
to $N_\nu = 2.9963 \pm 0.0074$

arXiv:1912.02067

Luminosity bias: −0.2%



scattered electrons are focused by the field of the opposite bunch



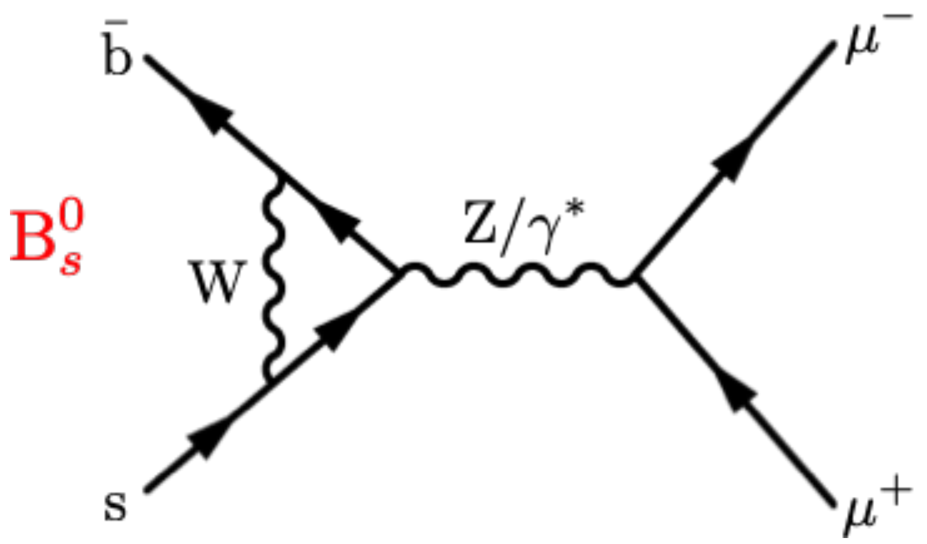
but α_s from Z pole now *somewhat puzzling*

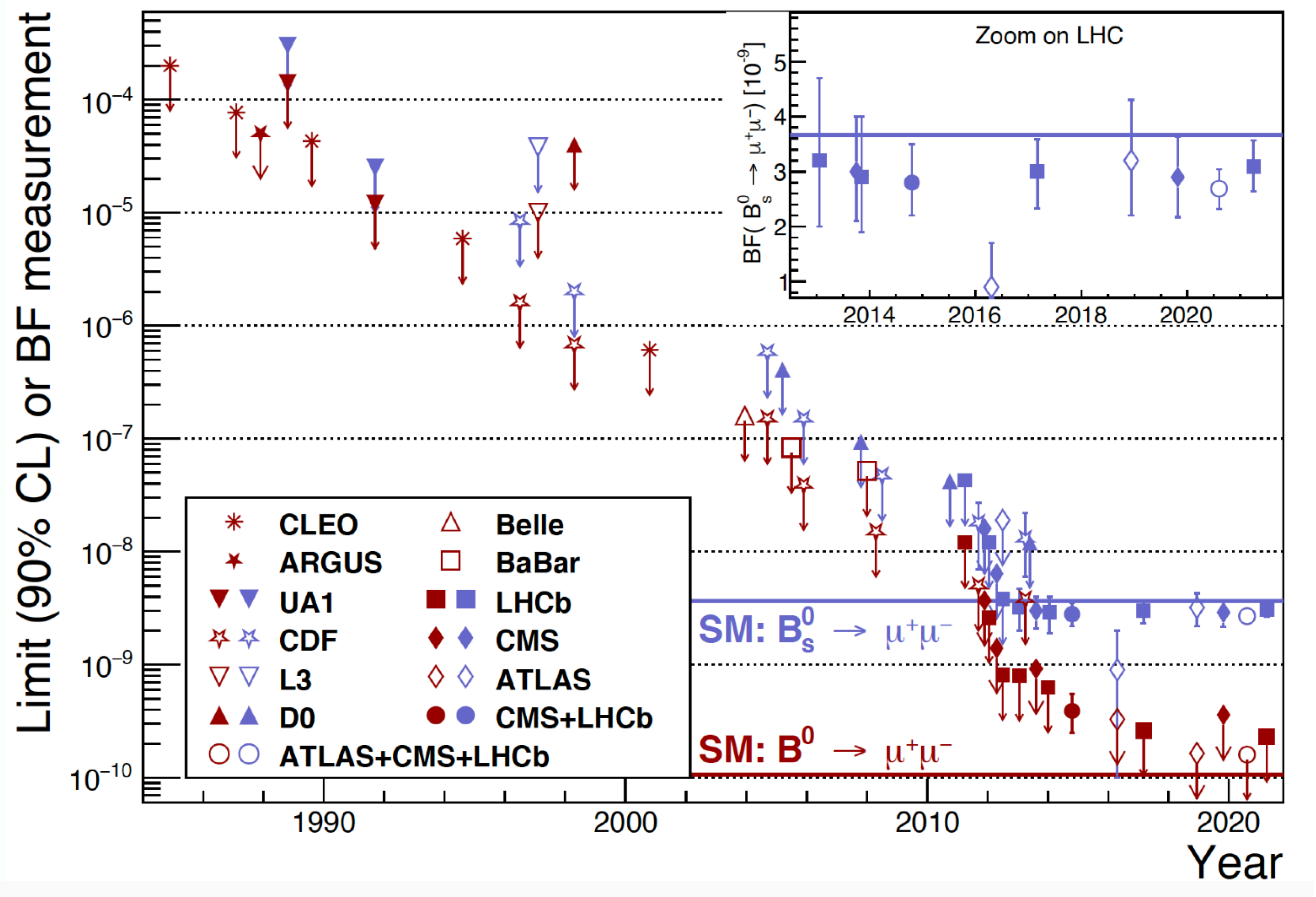
see Maarten's talk…

New results on $BF(B_{s,d}^0 \to \mu^+\mu^-)$

Clean theory predictions (limited by $|V_{cb}|$)

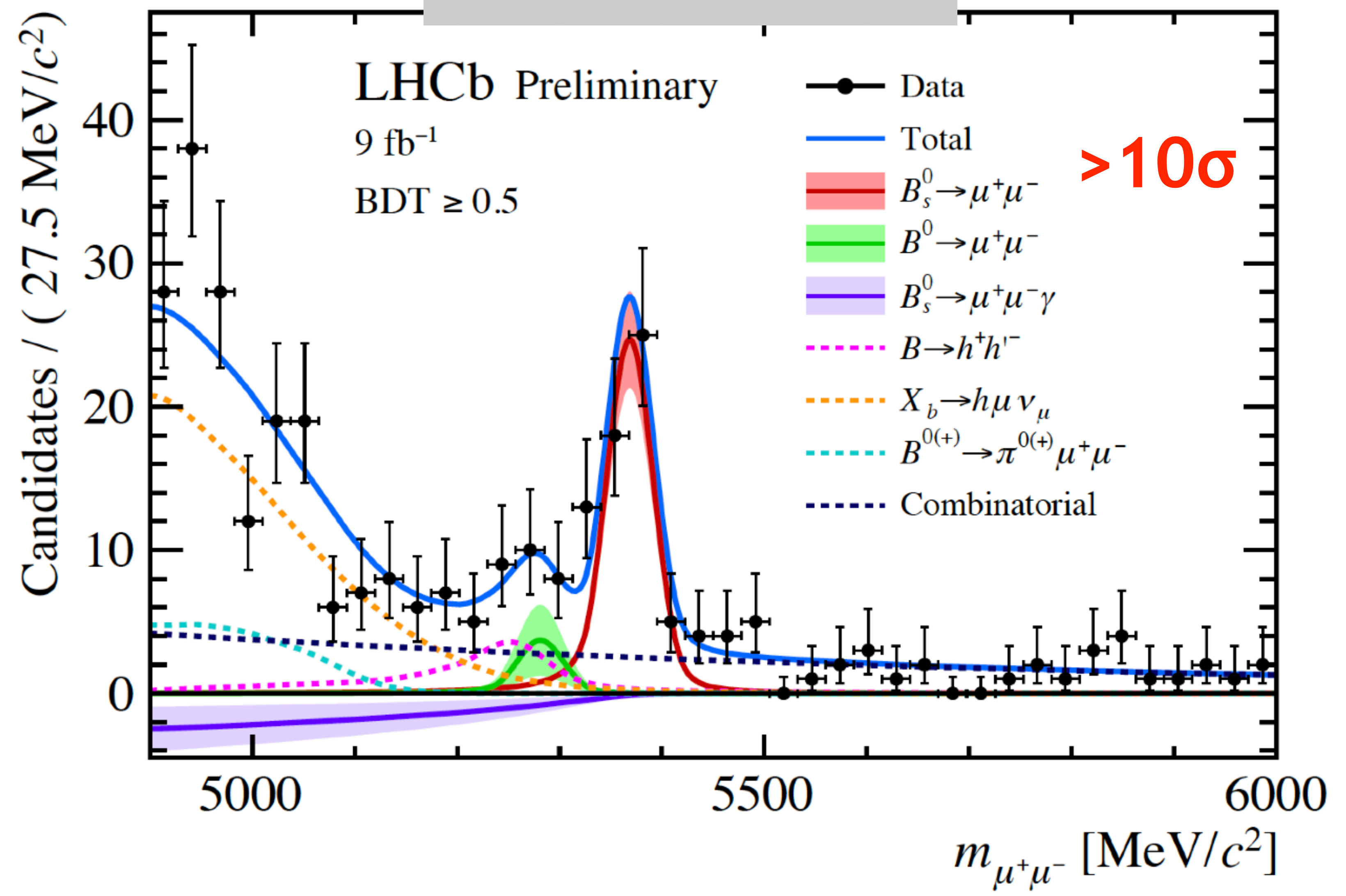
- $BF(B_s^0 \to \mu\mu) = (3.7 \pm 0.3) \times 10^{-9}$
- $BF(B_d^0 \to \mu\mu) = (1.1 \pm 0.1) \times 10^{-10}$





LHCb 9 fb^{-1} (full Run-2)

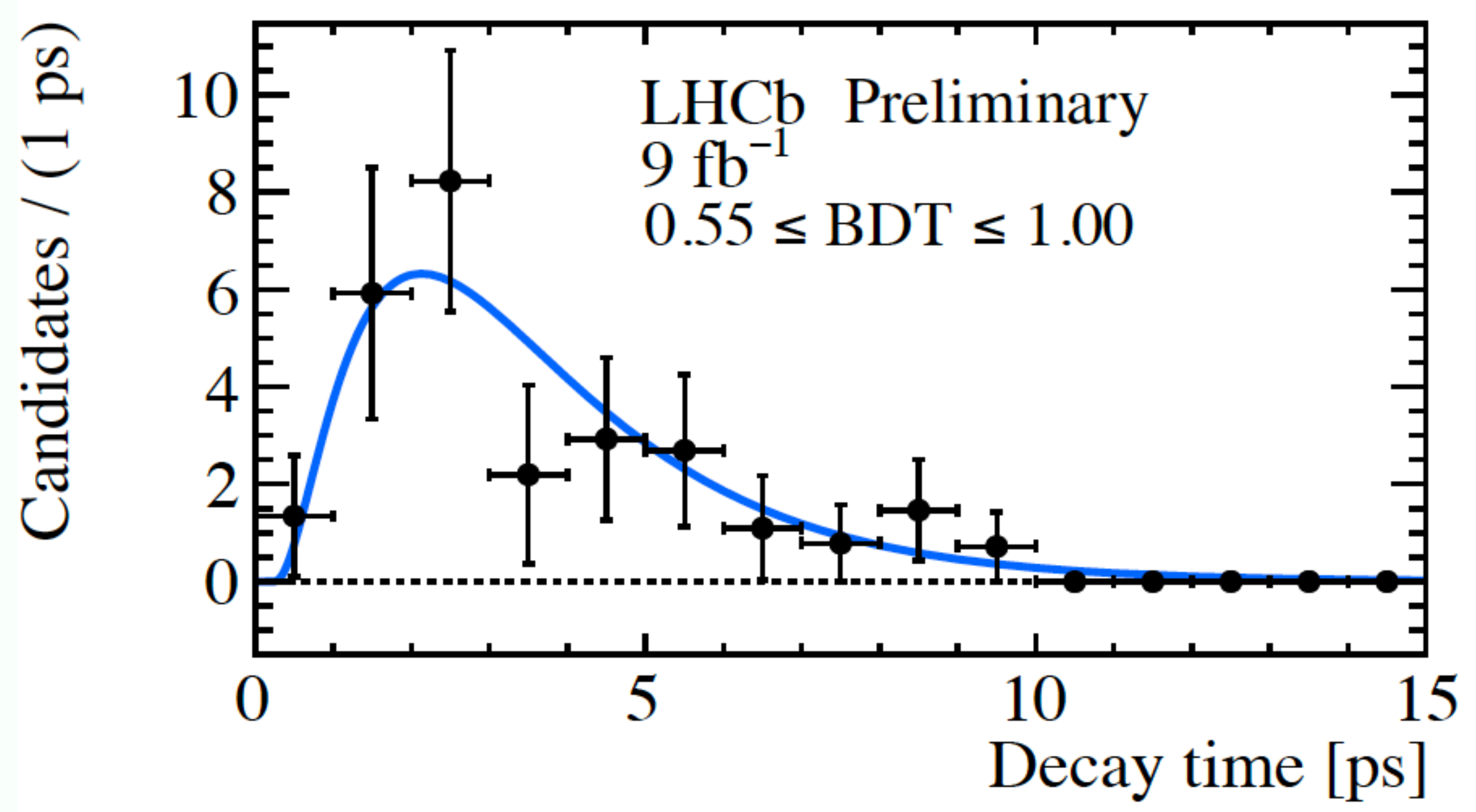
LHCb-PAPER-2021-007



in the SM, only the ***CP*-odd eigenstate** (B_{sH}) contributes to the $\mu^+\mu^-$ decay

$BF(B_s^0 \to \mu\mu) = (3.09 \pm 0.46 \pm 0.15) \times 10^{-9}$

$BF(B_d^0 \to \mu\mu) < 2.6 \times 10^{-10}$ at 95% CL



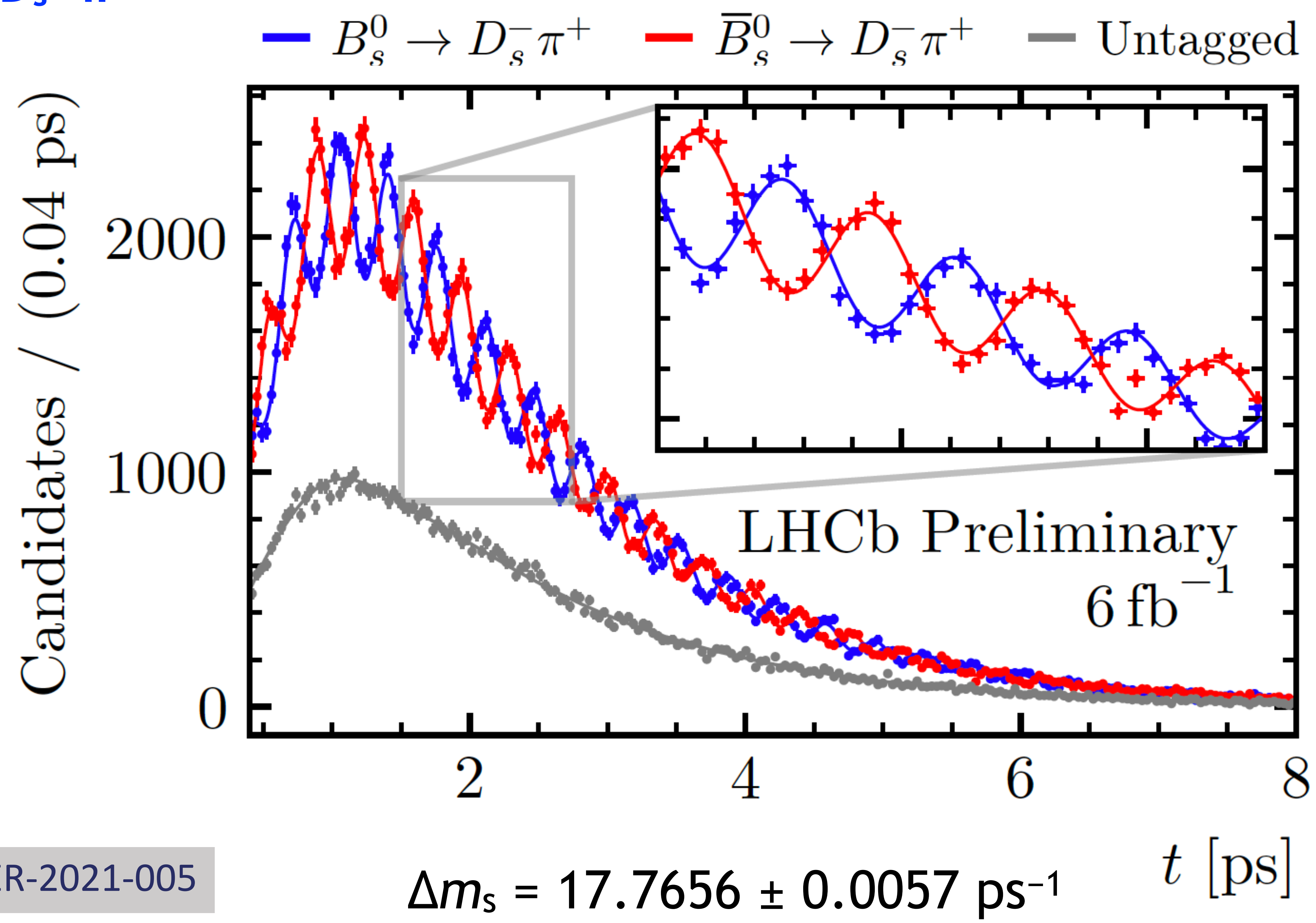
First meaningful measurement of the $B_s^0 \to \mu^+\mu^-$ mean decay time:

$$\tau_{\mu\mu} = (2.1 \pm 0.3) \text{ ps}$$

The $\tau_{\mu\mu}$ result is compatible with *CP*-odd (-even) at 1.5σ (2.2σ)

B_s mixing and TD-CP violation

TD-analysis of
$B_s^0 \to D_s^- \pi^+$



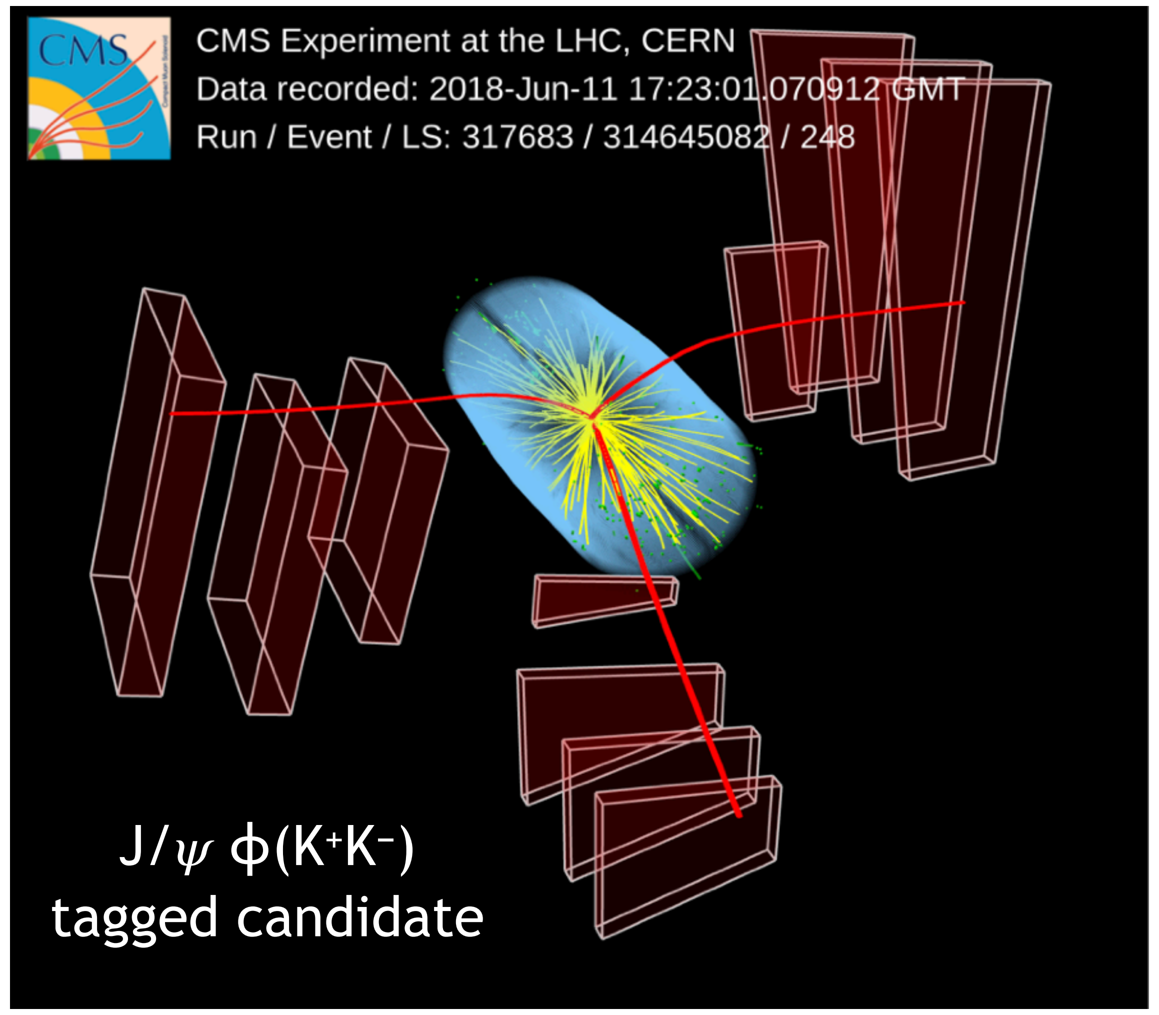
LHCb-PAPER-2021-005

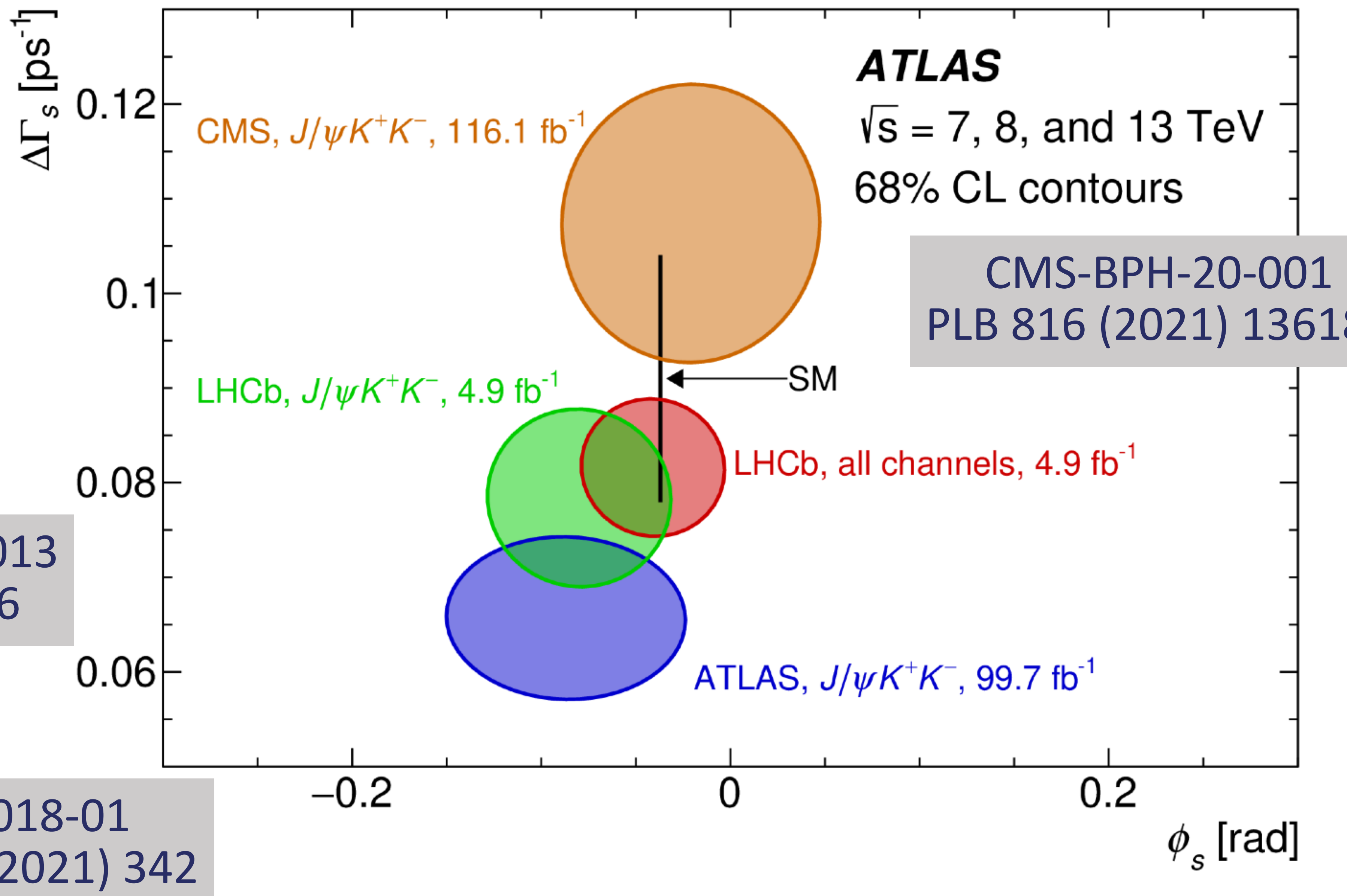
$\Delta m_s = 17.7656 \pm 0.0057\ \text{ps}^{-1}$
precision: 0.3‰ !

- sizeable difference in decay times
  $\Delta\Gamma_s/\Gamma_s = (12.9 \pm 0.6)\%$
  $\tau(B_{sL}) = 1.423 \pm 0.005$ ps
  $\tau(B_{sH}) = 1.620 \pm 0.007$ ps

TD-analysis of
$B_s^0 \to J/\psi\ \phi(K^+K^-)$

Measurement of
- CPV phase ϕ_s
- width difference $\Delta\Gamma_s$





CMS-BPH-20-001
PLB 816 (2021) 136188

LHCB-PAPER-2019-013
EPJC 79 (2019) 706

ATLAS-BPHY-2018-01
Eur. Phys. J. C 81 (2021) 342

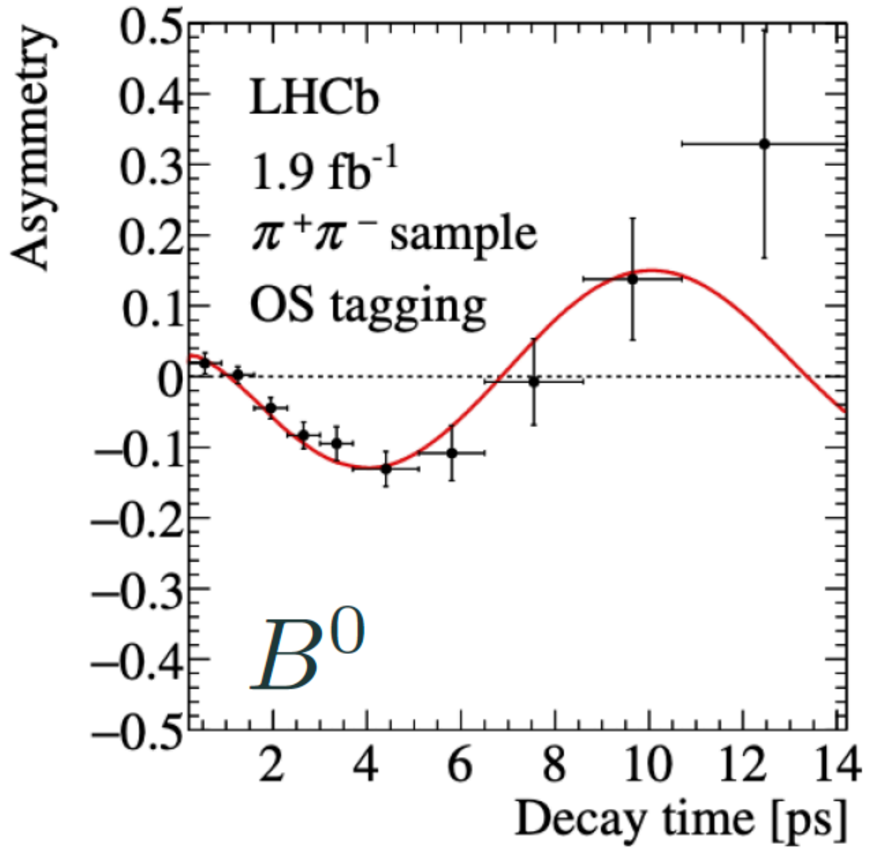
new results from ATLAS and CMS

Charmless Two-Body B Decays

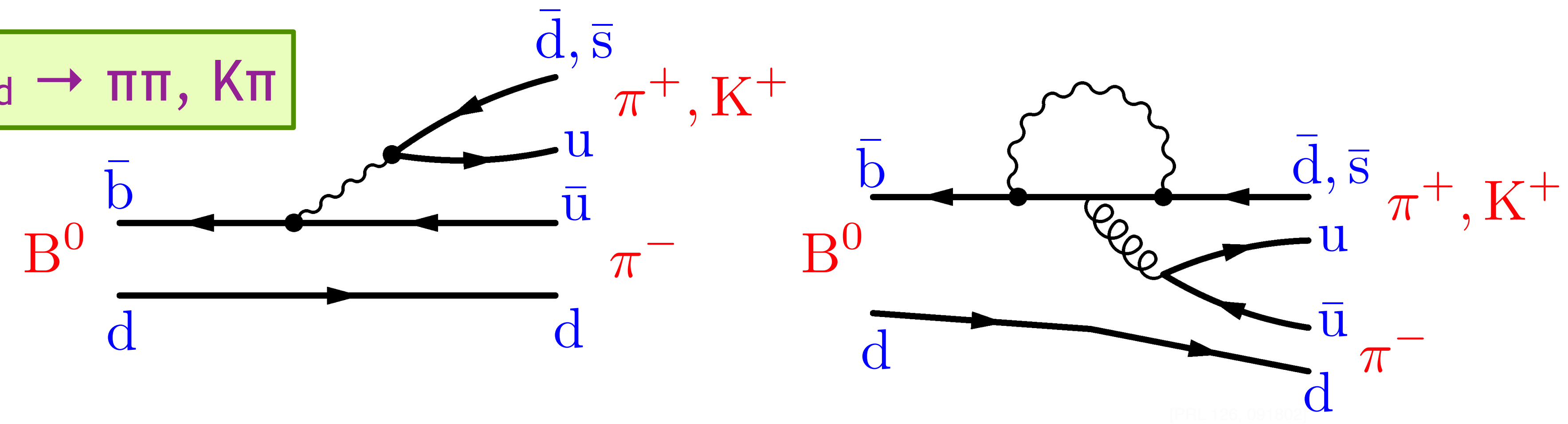
Two types of CP asymmetries are measured

- $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$: time-dependent
- $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$: time-integrated

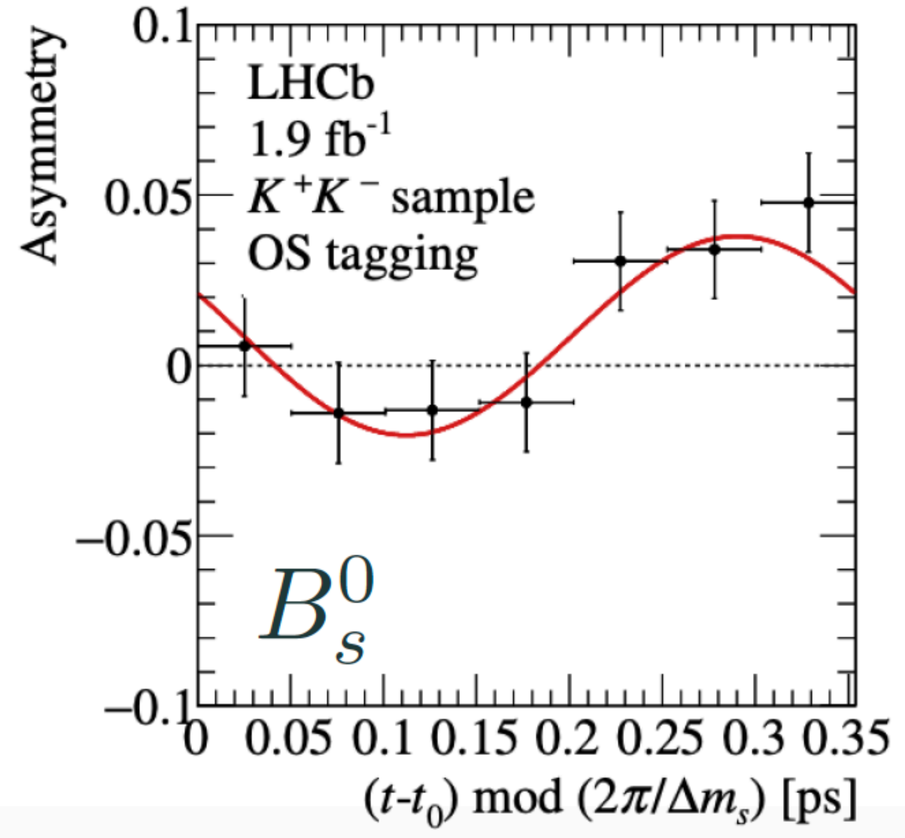
[arXiv:2012.05319]



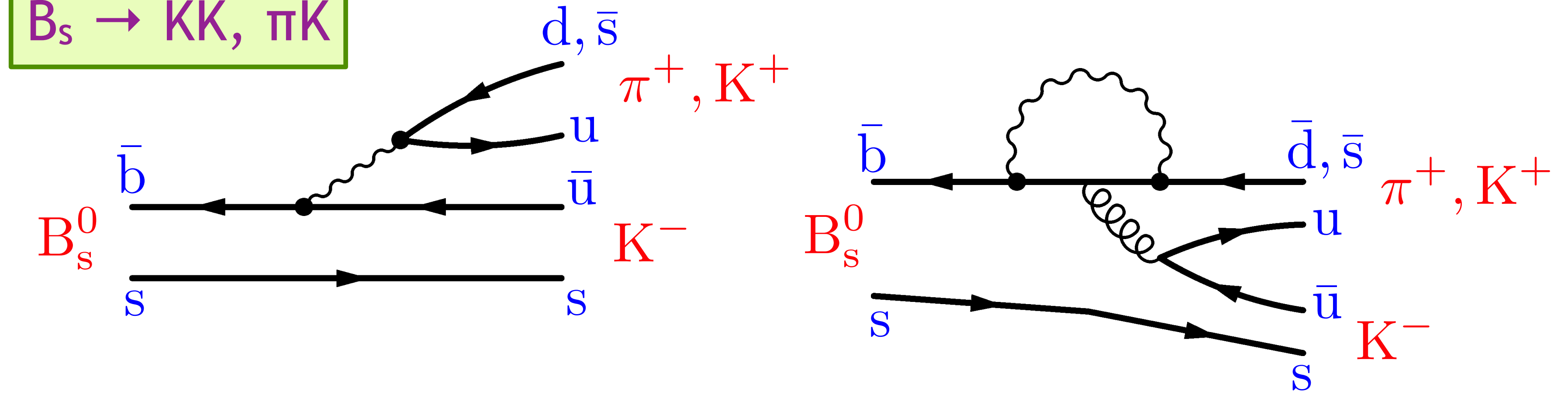
Bd → ππ, Kπ



mixing-induced and direct CPV: sensitivity to angles α and γ of the Unitarity Triangle

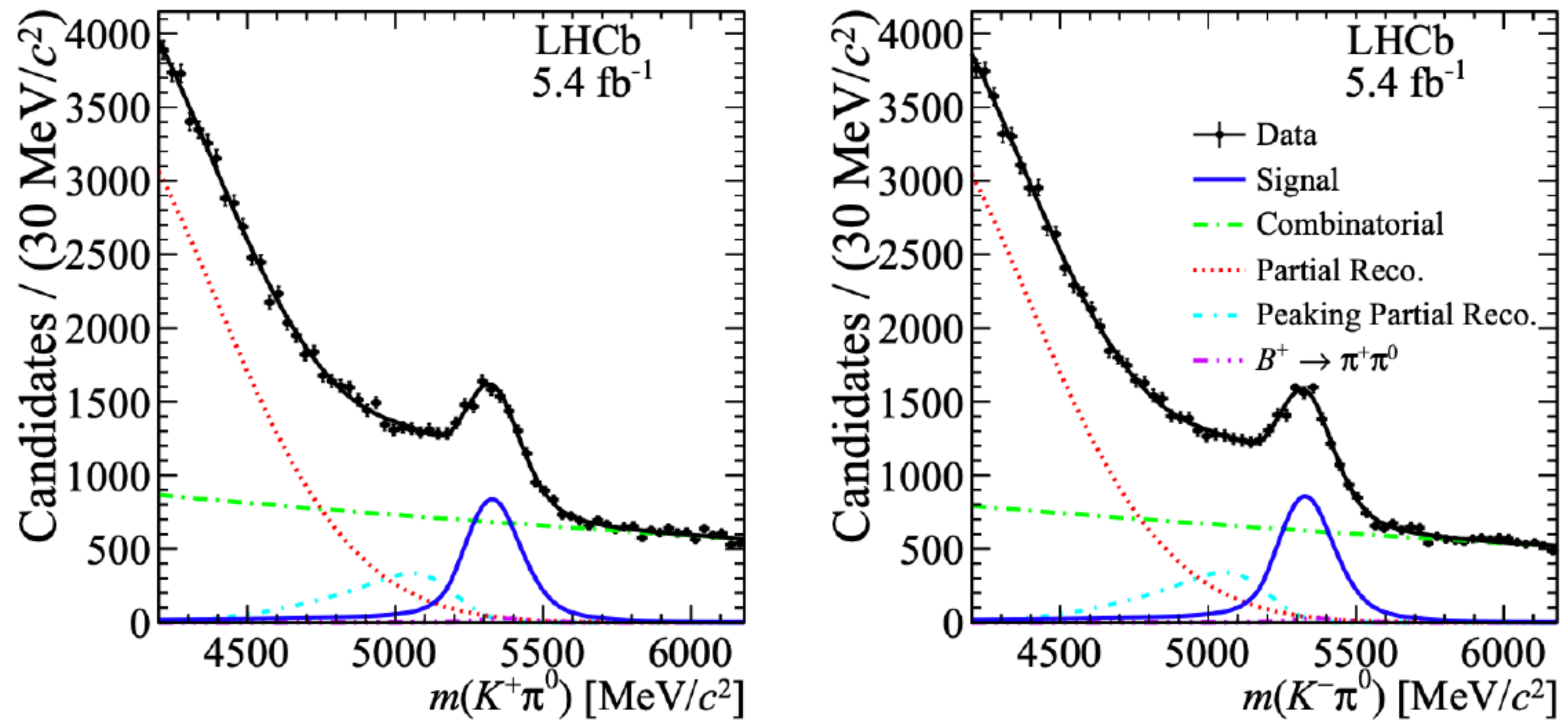


Bs → KK, πK



First observation of TD-CP asymmetry in the B_s system!

Direct CPV in $B^+ \to K^+\pi^0$



PRL 126, 091802

$A_{CP}(B^0 \to K^+\pi^-) = -0.082 \pm 0.003$

$A_{CP}(B^+ \to K^+\pi^0) = +0.024 \pm 0.016$

The "Kπ puzzle" deepens

The CP asymmetry difference

$A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-)$

is non-zero at the 8σ level (was 5.5σ)

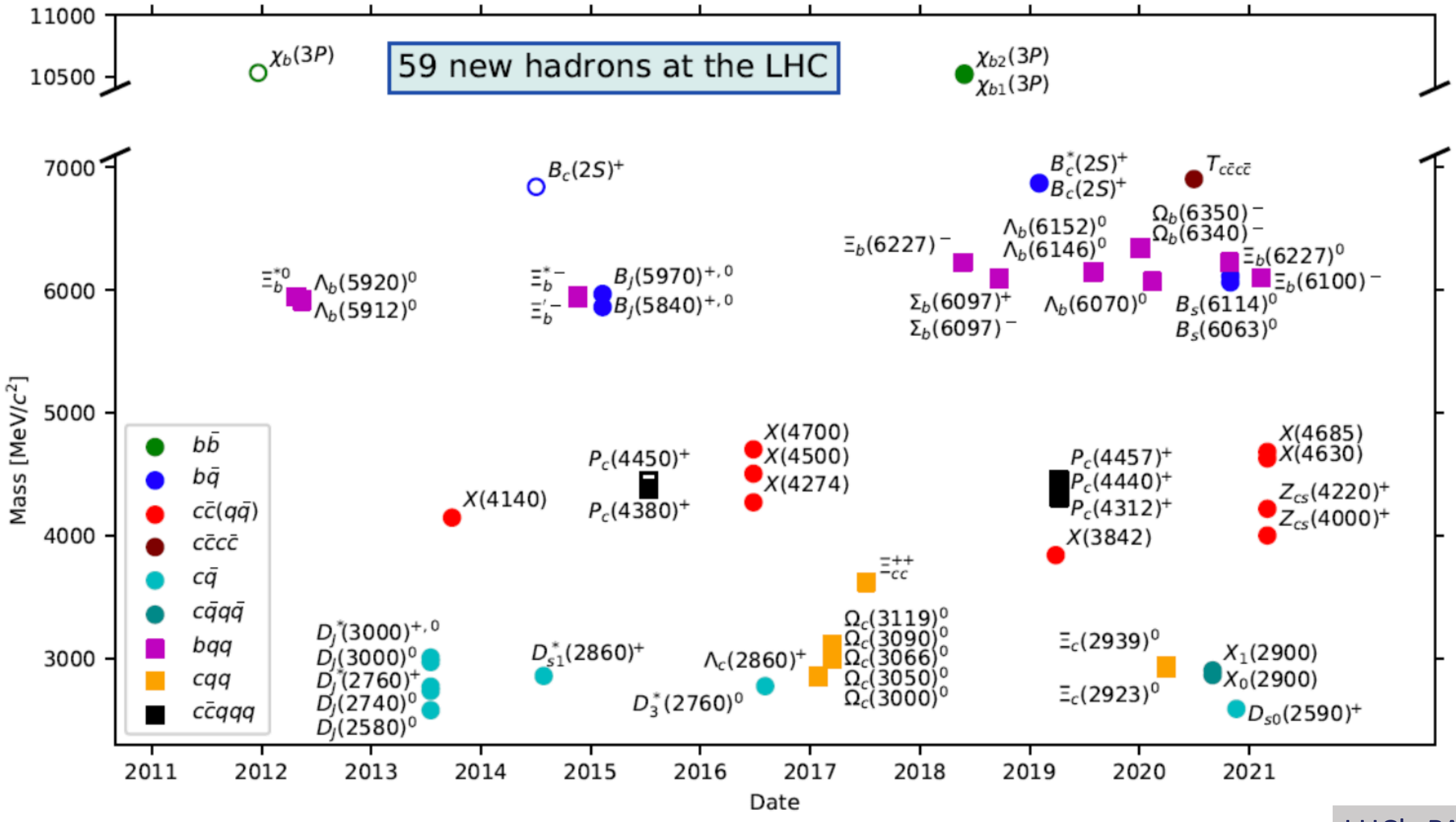
a violation of isospin relations still to be explained

60 Particles Discovered at the LHC

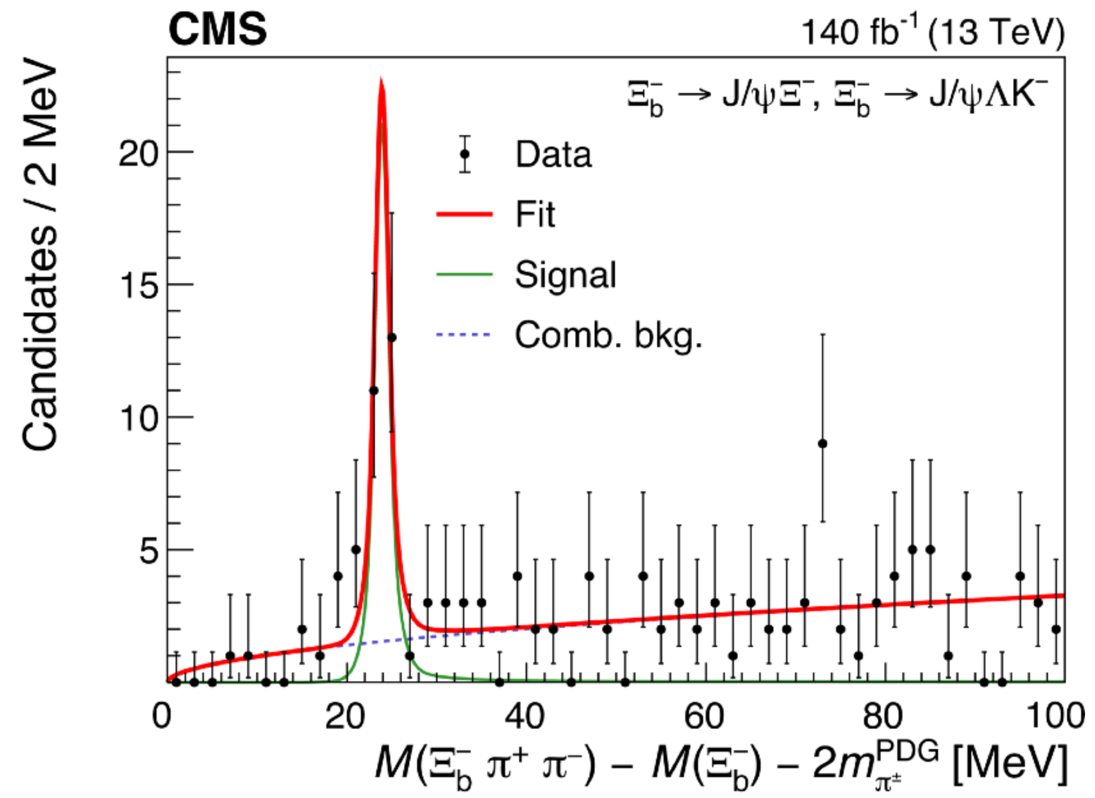
The **Higgs boson** in 2012 + …

59 hadrons discovered over the past 10 years

(mostly by LHCb, but also ATLAS and CMS)



CMS: New beauty strange baryon observed at a mass of 6100.3 ± 0.6 MeV

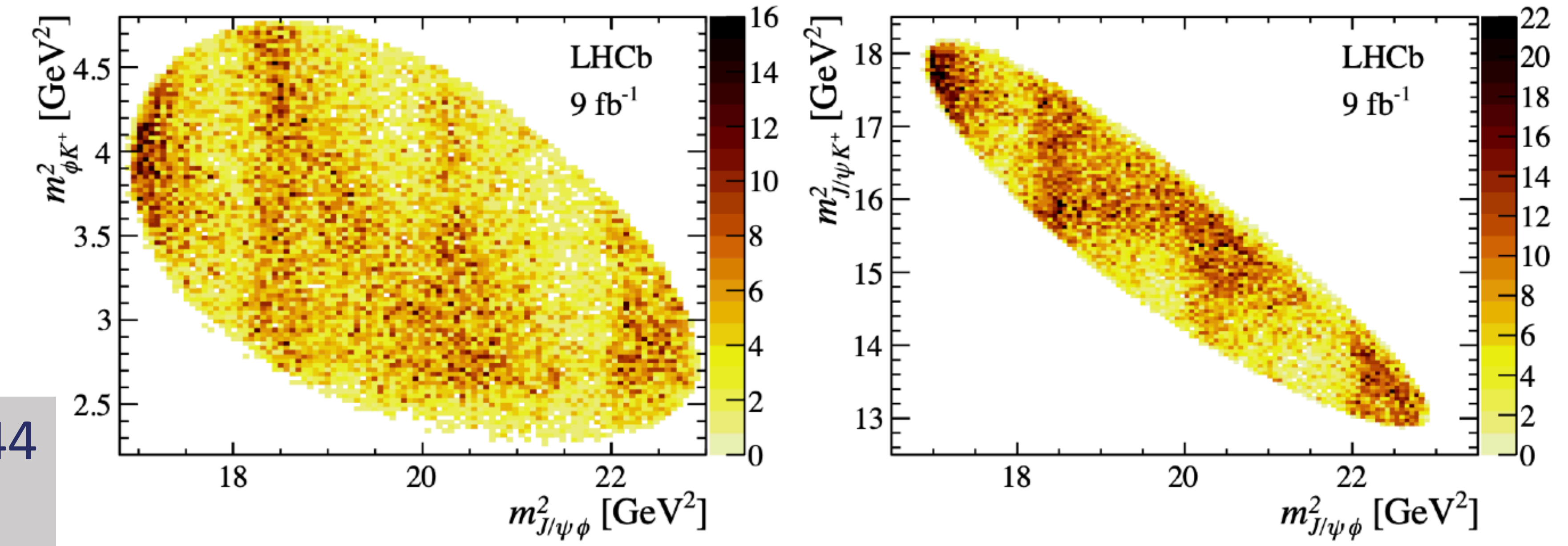


CMS-BPH-20-004 submitted to PRL

interpreted as lightest orbitally excited Ξ_b^- baryon $J^P = 3/2^-$

LHCb: Four new $X(\rightarrow J/\psi\phi)$ and $Z_{cs}^+(\rightarrow J/\psi K^+)$ states in the Dalitz analysis of $B^+ \rightarrow J/\psi\phi K^+$

LHCb-PAPER-2020-044 submitted to PRL

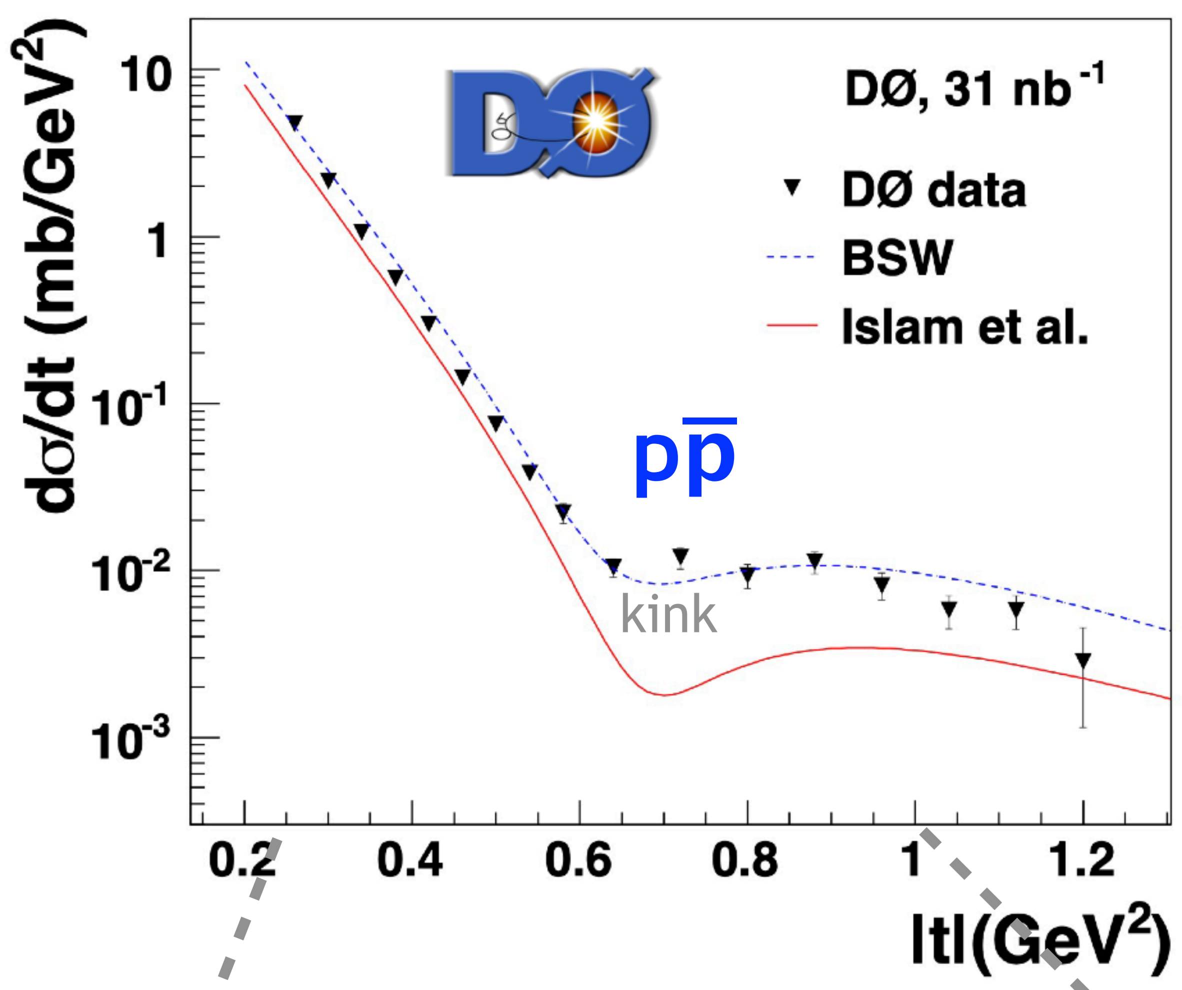


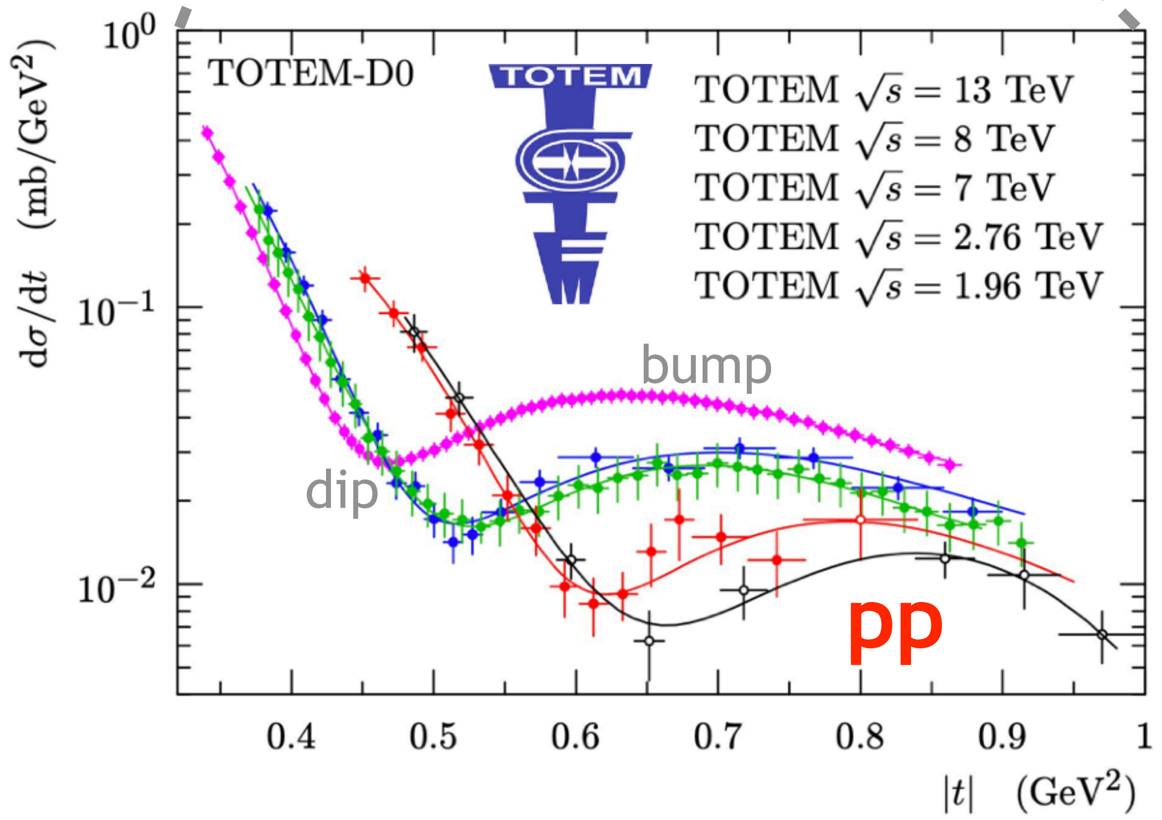
interpreted as tetraquarks

Confirmation of the Odderon

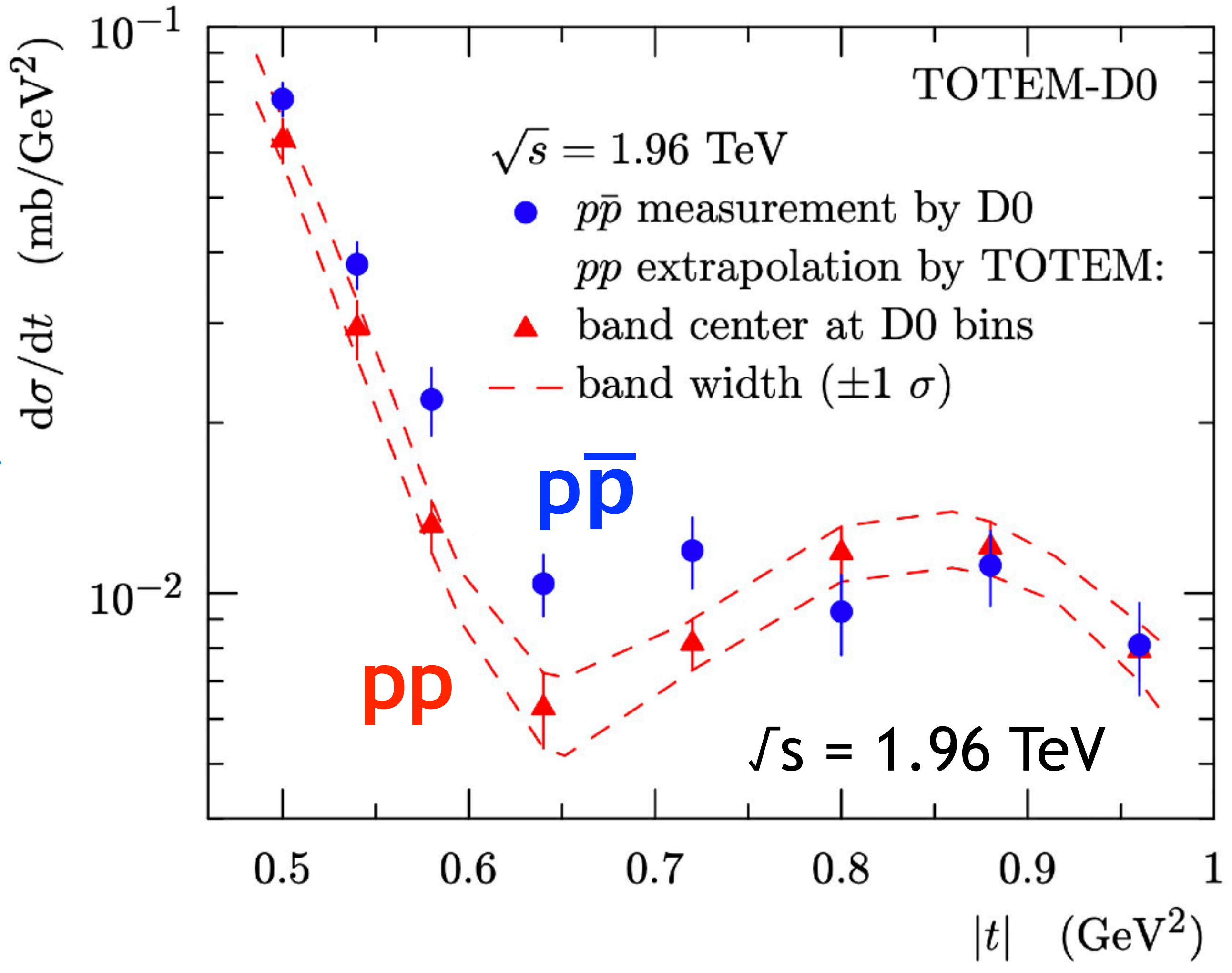
CERN-EP-2020-236, FERMILAB-PUB-20-568-E, arXiv:2012.03981

- at TeV energies pp/pp̄ differential elastic cross-sections are dominated by Pomeron exchange





- **Pomeron** = colourless **C-even** 2-gluon state
- **Odderon** = colourless **C-odd** 3-gluon state



Previous **4.7σ evidence for Odderon** by **TOTEM** from total cross section and study of the CNI region (< 0.05 GeV²)

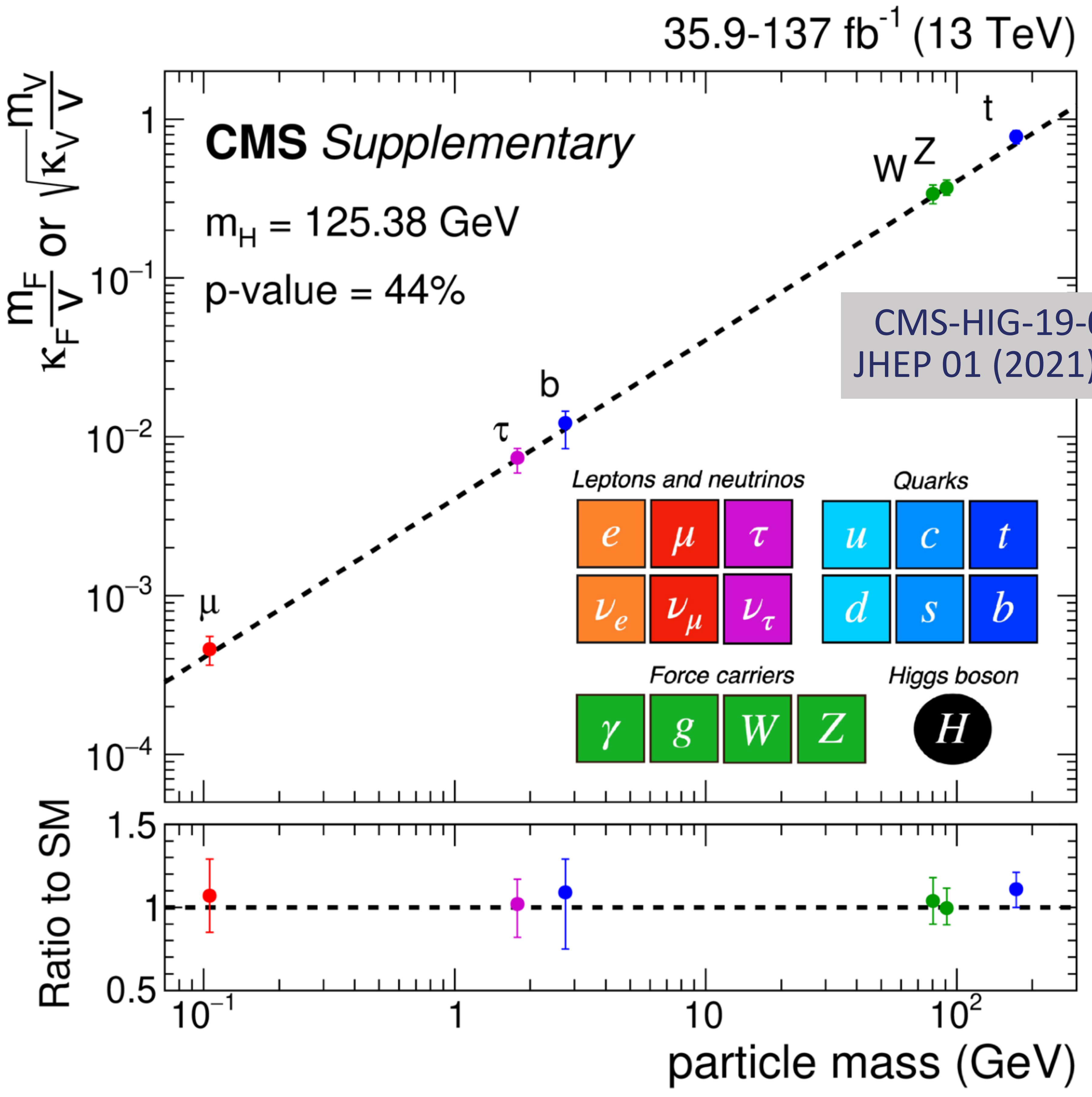
TOTEM-D0: quantify pp & pp̄ difference due to C-odd exchange near the diffractive minimum
➠ no “dip & bump” in pp̄

From comparison of D0 pp̄ data at √s = 1.96 TeV and TOTEM pp data extrapolated at the same energy, a **3.4σ significance difference** (*dip* in pp) around −t = 0.65 GeV²

Combination of results excludes a model without C-odd exchange at > 5.2σ

➠ *claim* for the *observation* of the Odderon

Higgs Boson Physics



CMS-HIG-19-006
JHEP 01 (2021) 148

The only *fundamental* particle of the SM discovered at the LHC is the Higgs boson

ATLAS and CMS

8M Higgs bosons produced per experiment in Run-2

- mass measurement at 1‰
- observation of $H \to b\bar{b}$
- observation of $t\bar{t}H$ production
- evidence for $H \to \mu^+\mu^-$

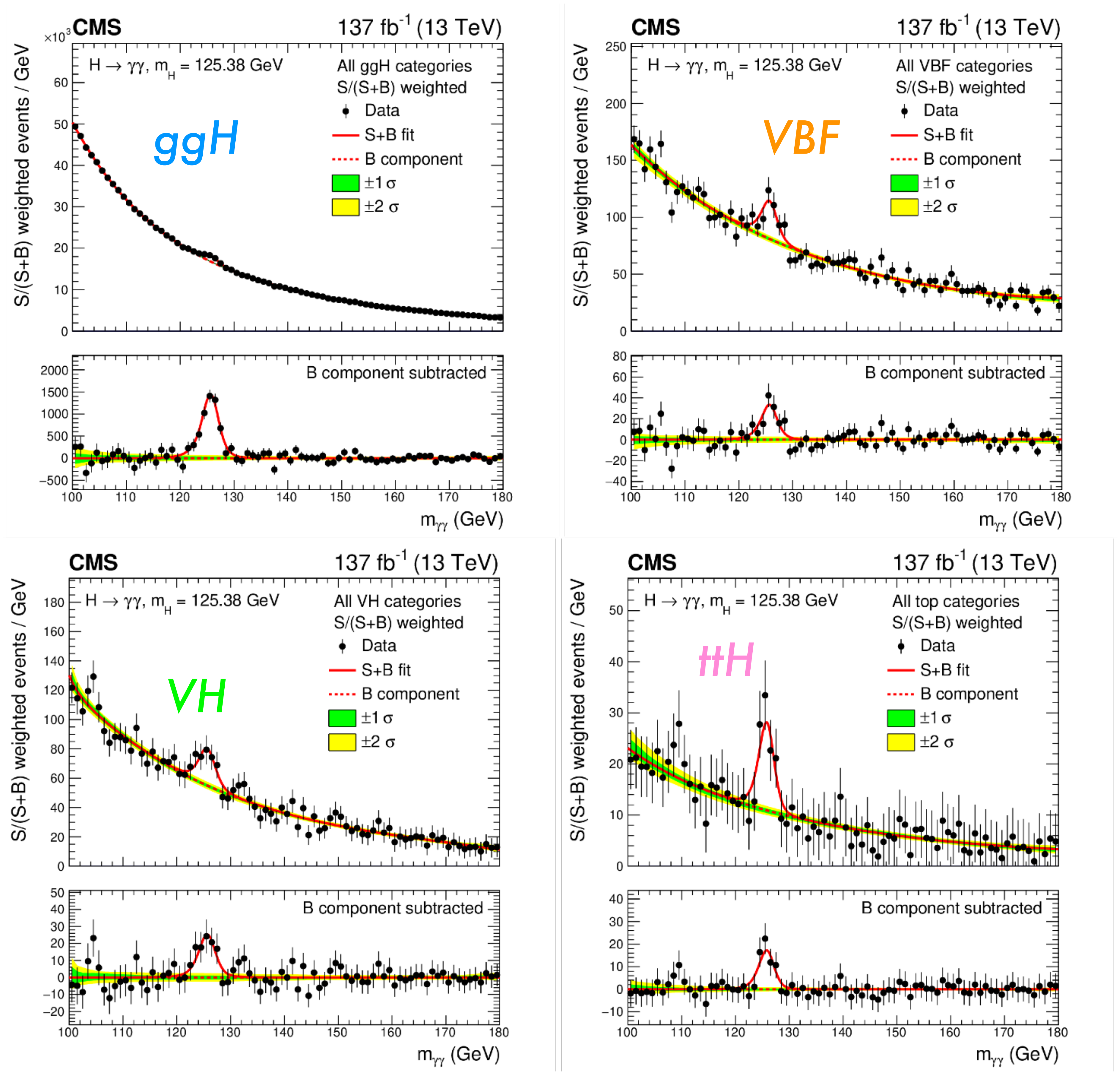
Next targets for Run-3

- observation and measurement of $H \to \mu^+\mu^-$
- evidence for $Z\gamma$
- search for anomalous HH production
- study of CP properties
- search for rare and non-SM decays

Evidence for $H \to \mu\mu$

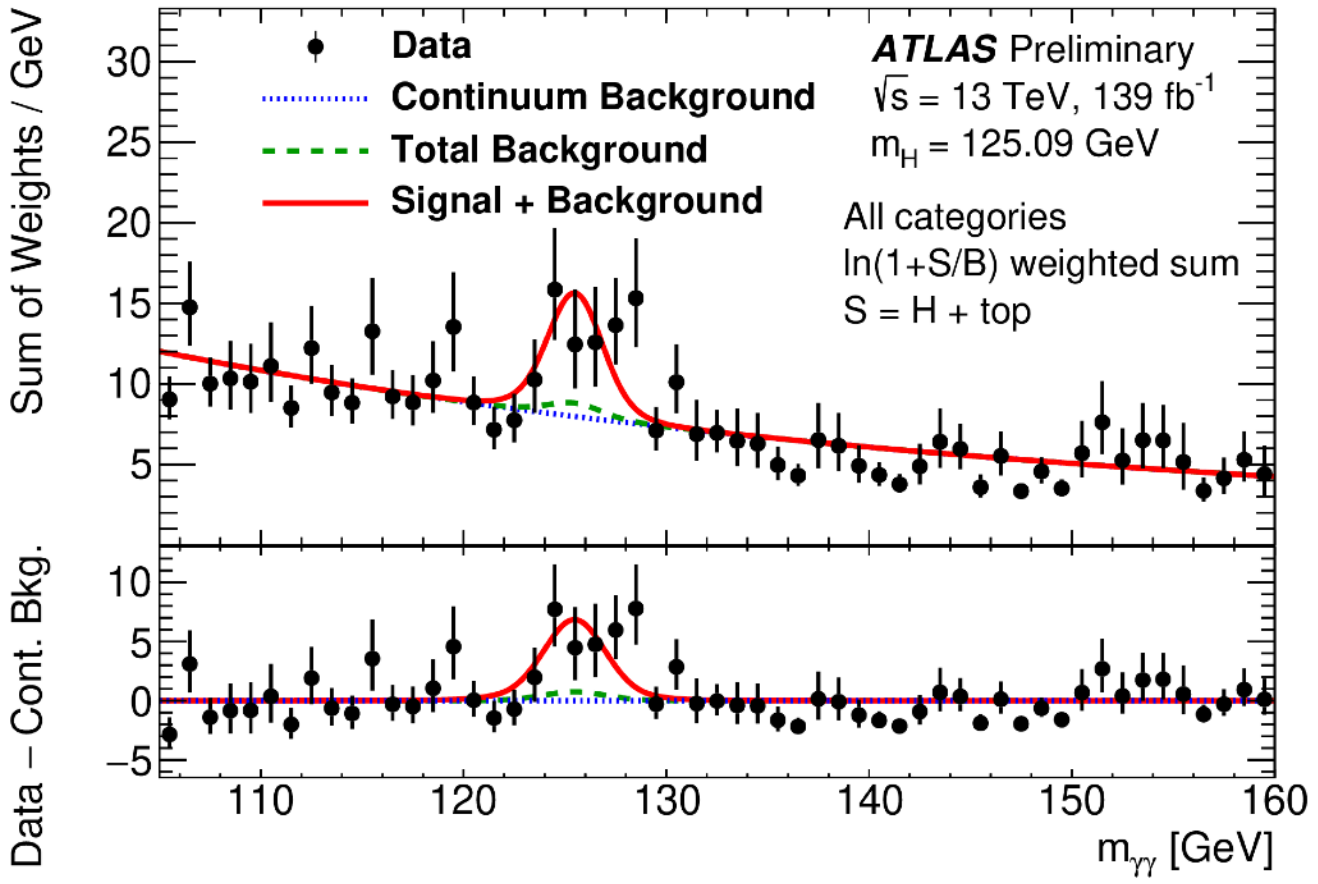
- CMS: obs. (exp.) significance **3.0σ** (2.5σ)
- ATLAS: obs. (exp.) significance **2.0σ** (1.7σ)

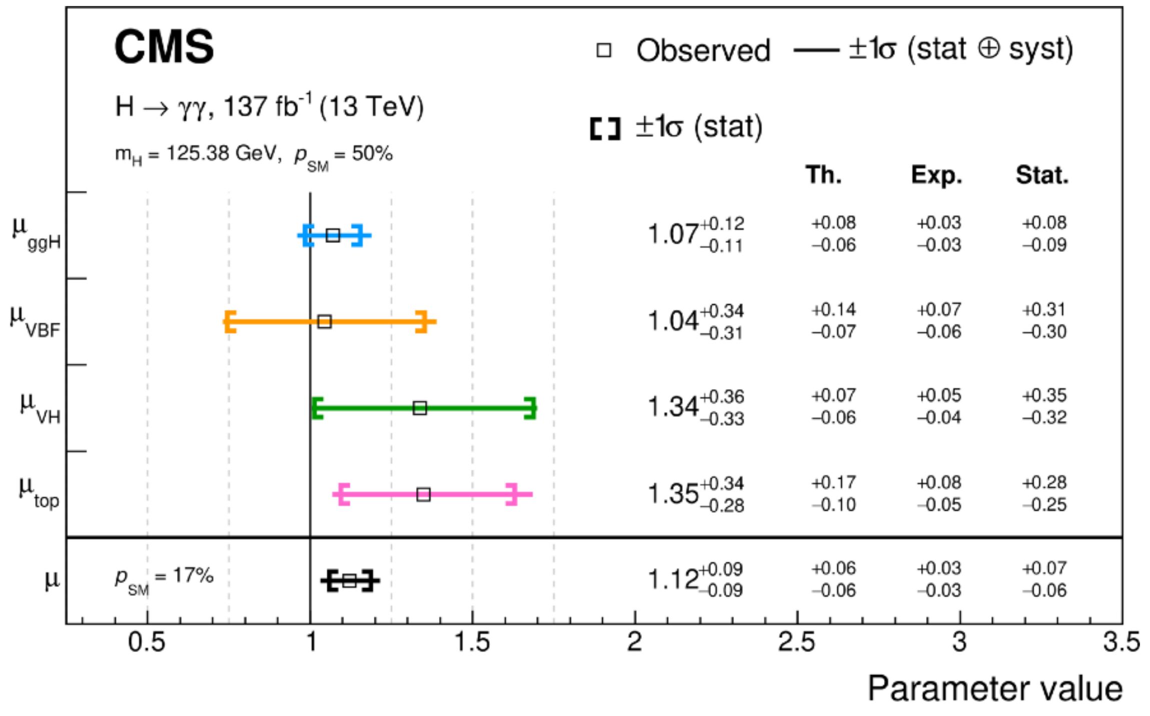
Production Modes in H → γγ and ttH Observation

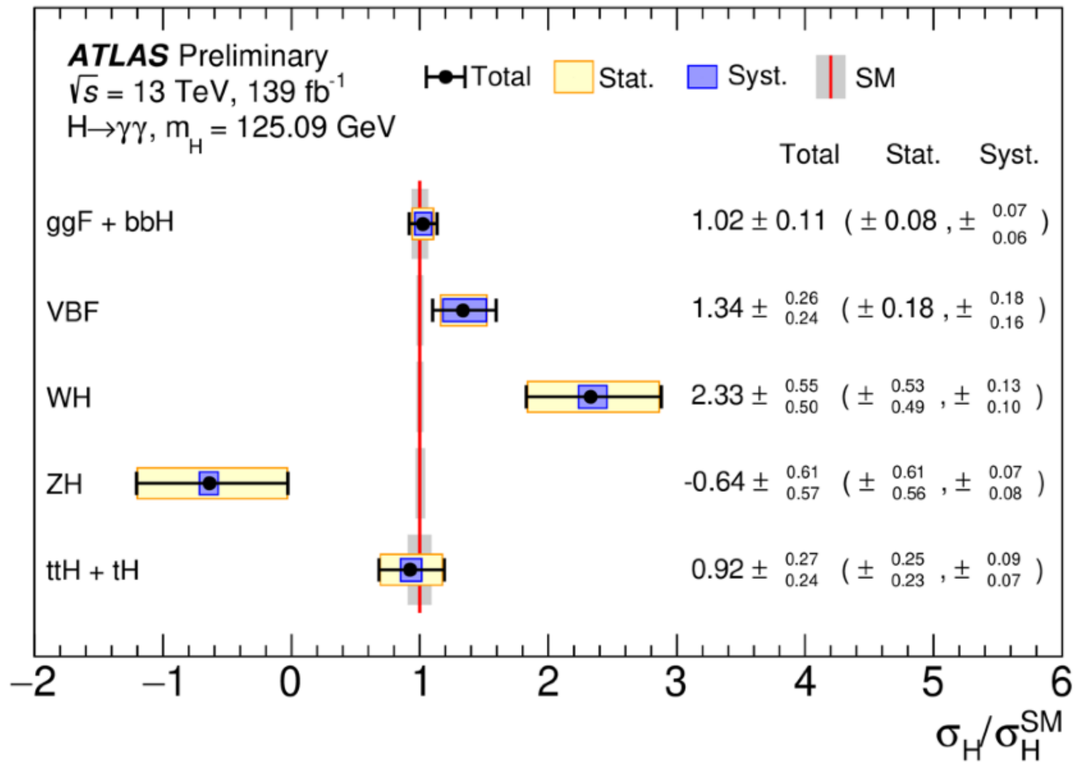


H → γγ gives access to the four main Higgs production modes

The $t\bar{t}H$ production mode, recently observed by ATLAS and CMS, is now measured

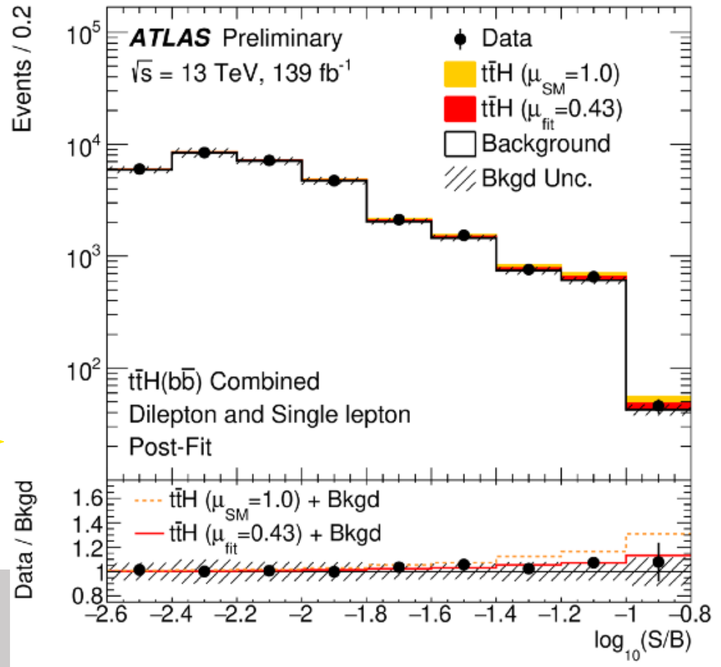






also $t\bar{t}H(\to b\bar{b})$

μ = 0.43 ± 0.36



CMS-HIG-19-015
subm. to JHEP

DPhP

ATLAS-CONF-2020-026

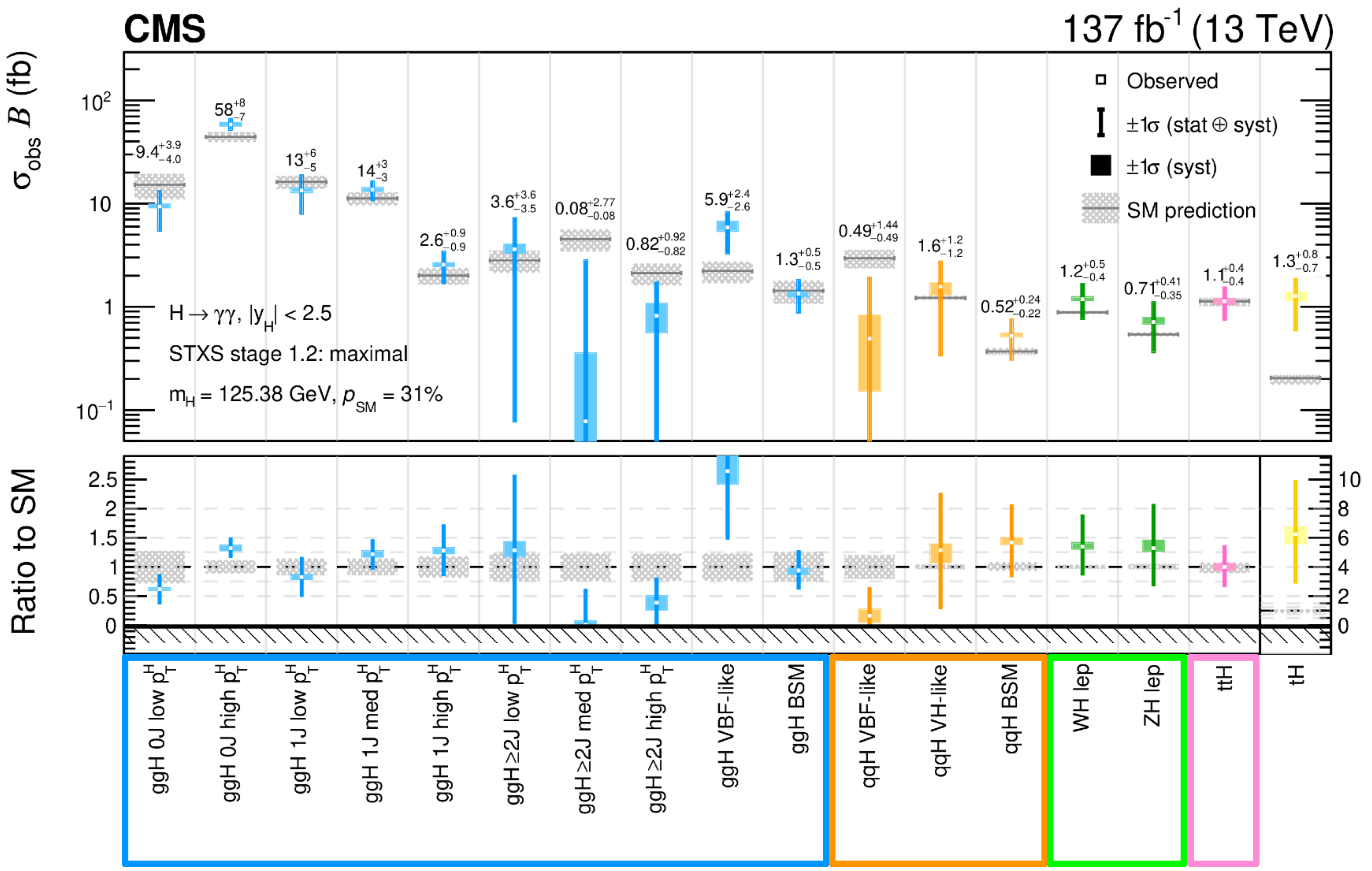
ATLAS-CONF-2020-026

DPhP

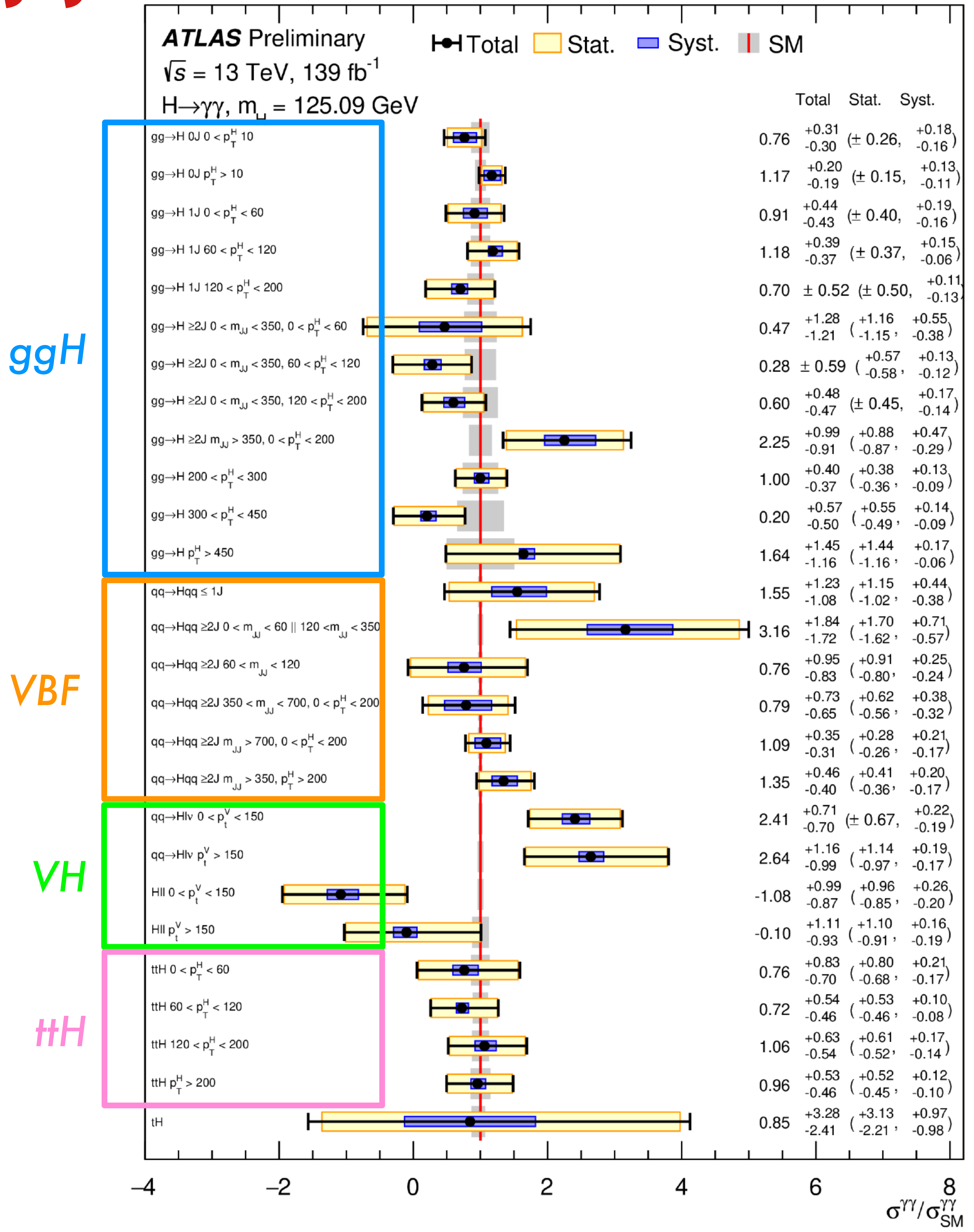
ATLAS-CONF-2020-058

Fiducial Cross Sections in H → γγ

Measurements by production mode in various kinematic regions (STXS = Simplified Template Cross Sections)



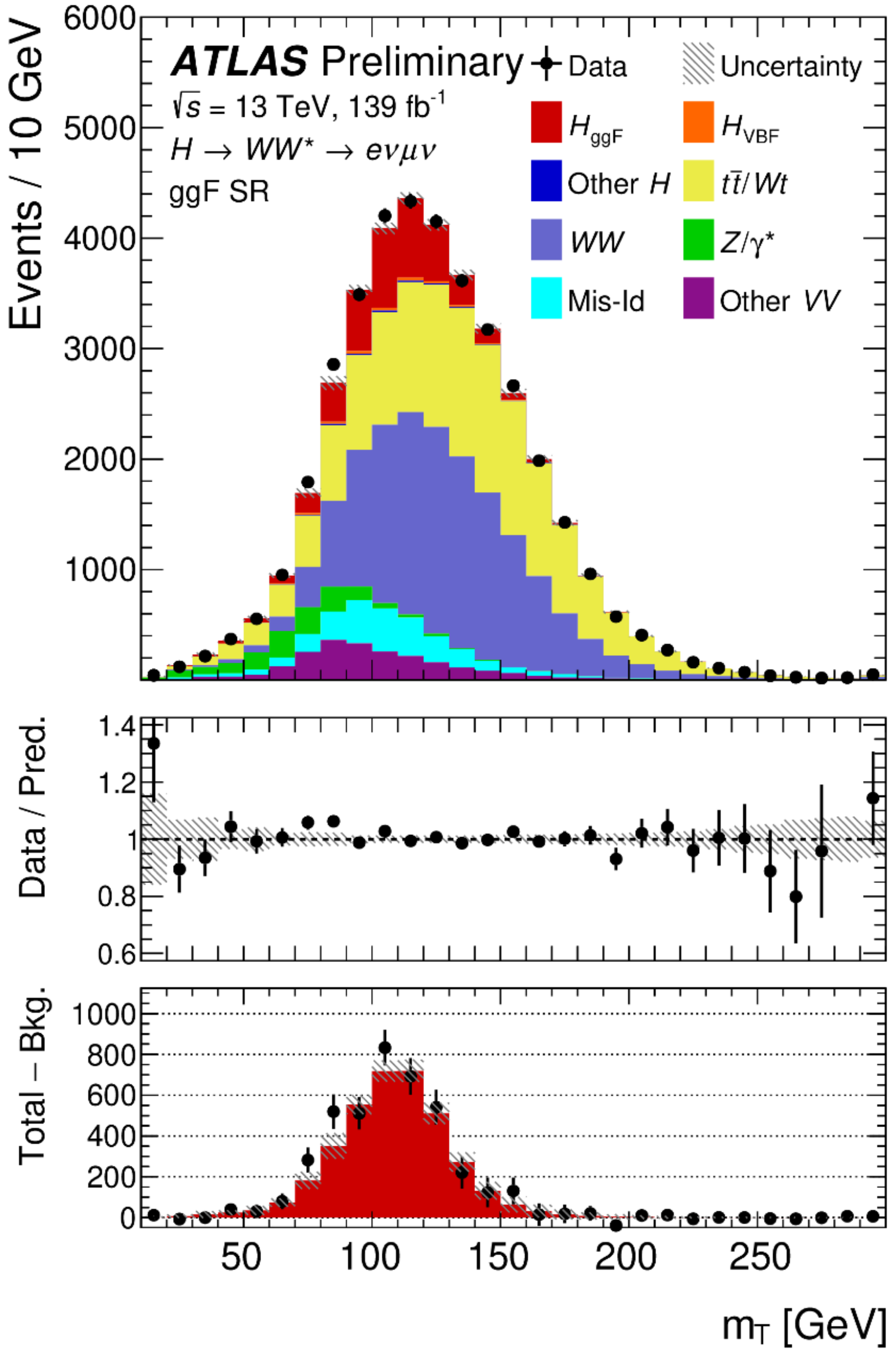
also, differential cross-sections



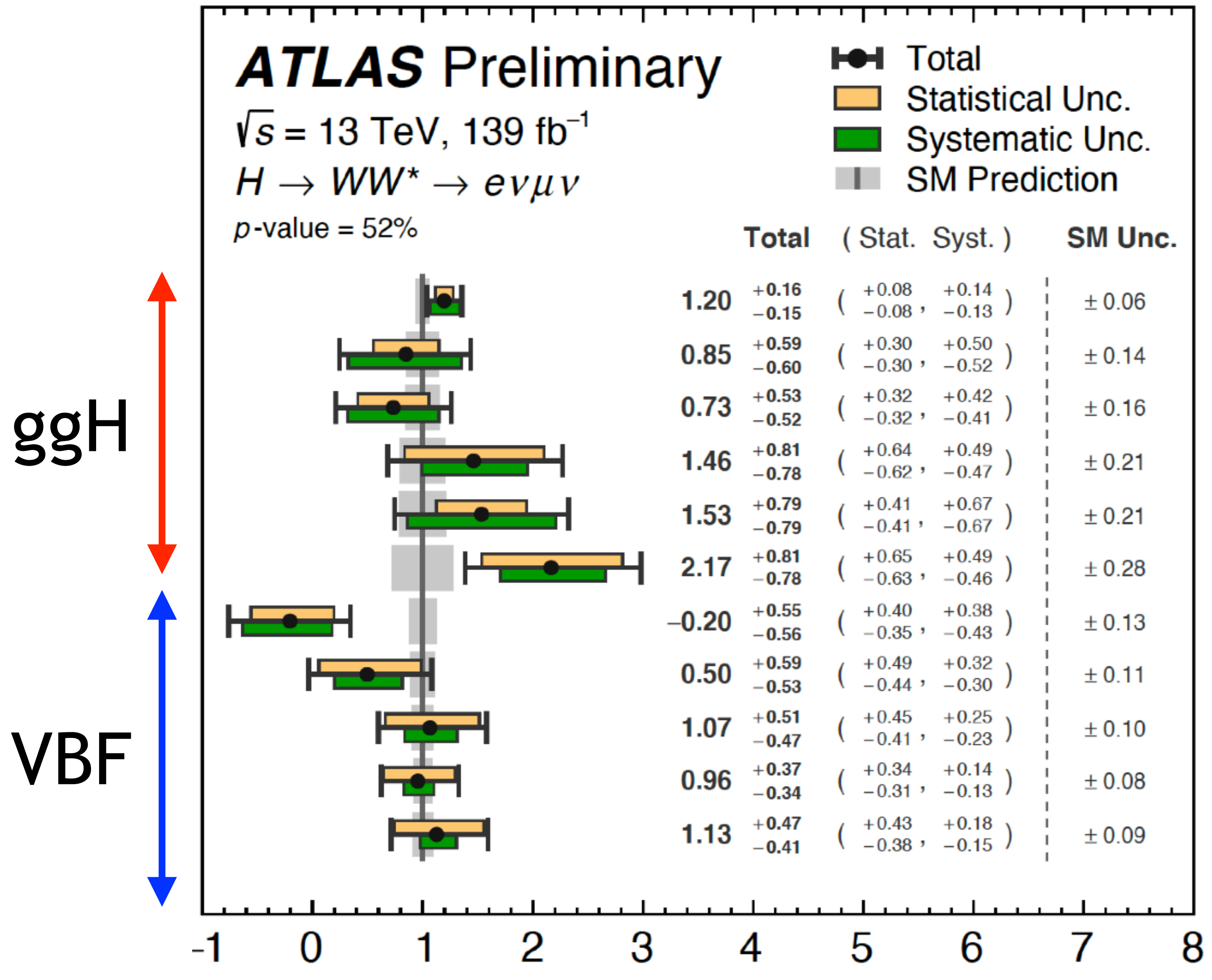
Fiducial Cross Sections in H → WW*

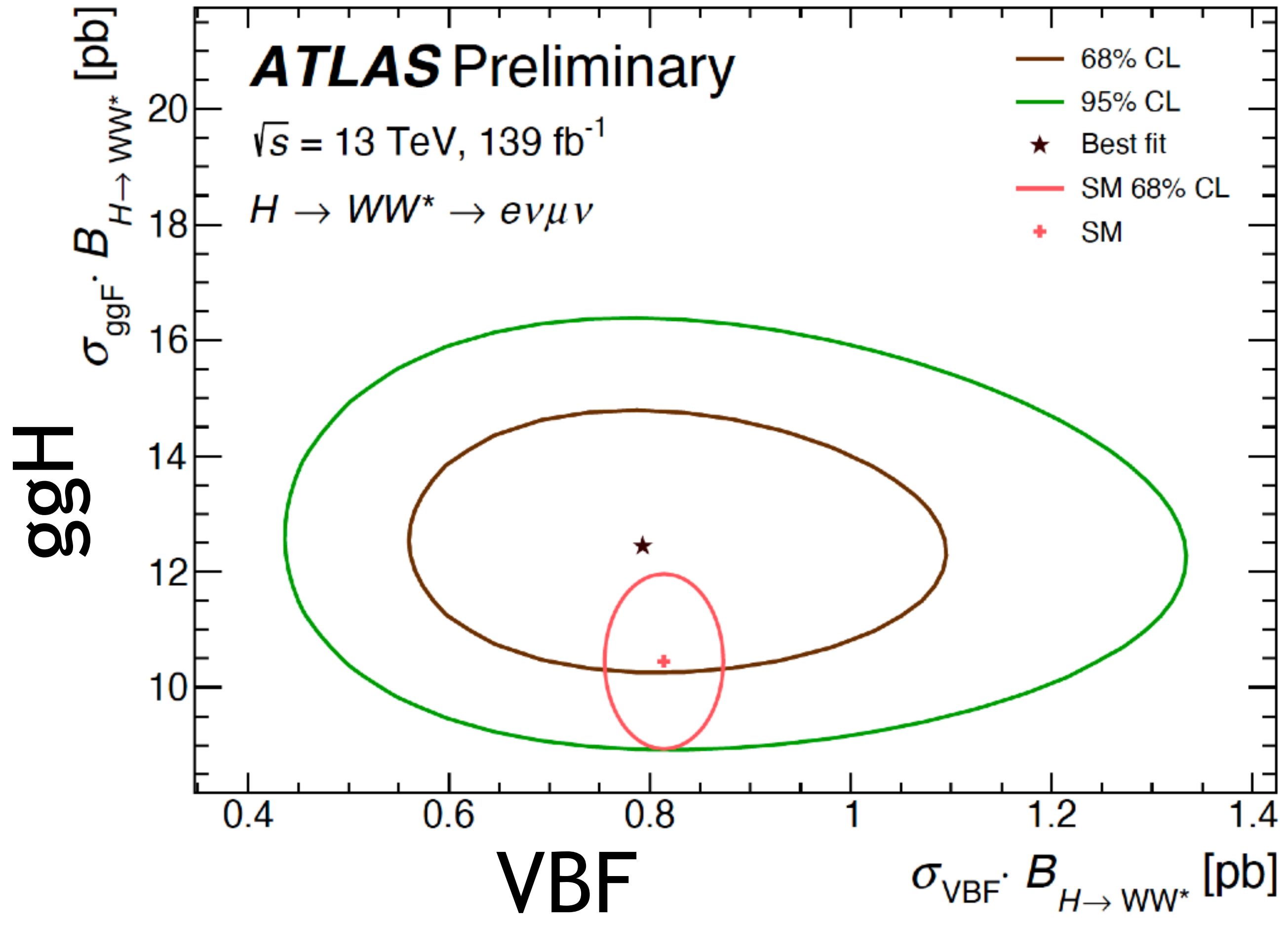
- an abundant decay, key for coupling measurements

ATLAS-CONF-2021-014

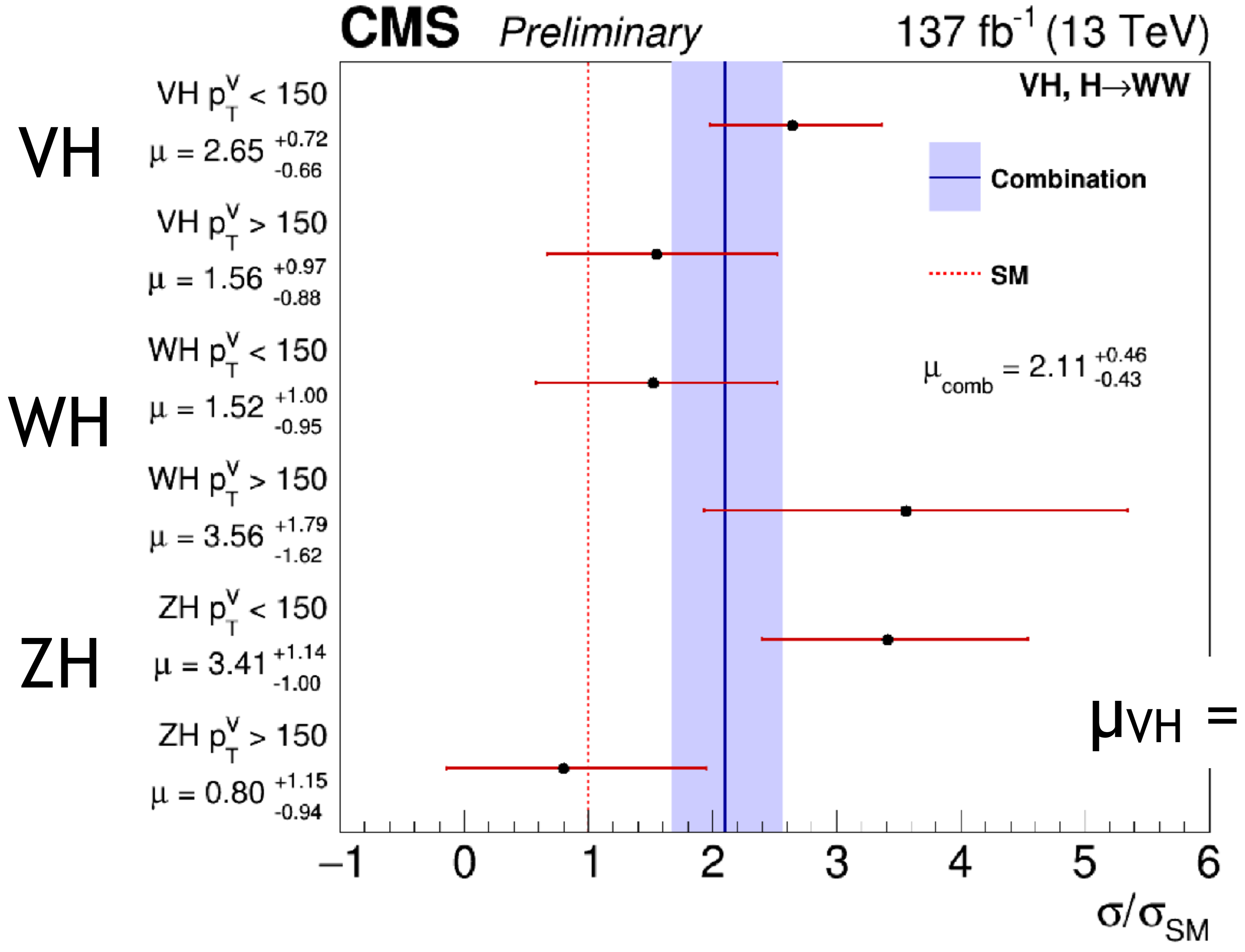


Agreement with SM in the **ggH and VBF modes**

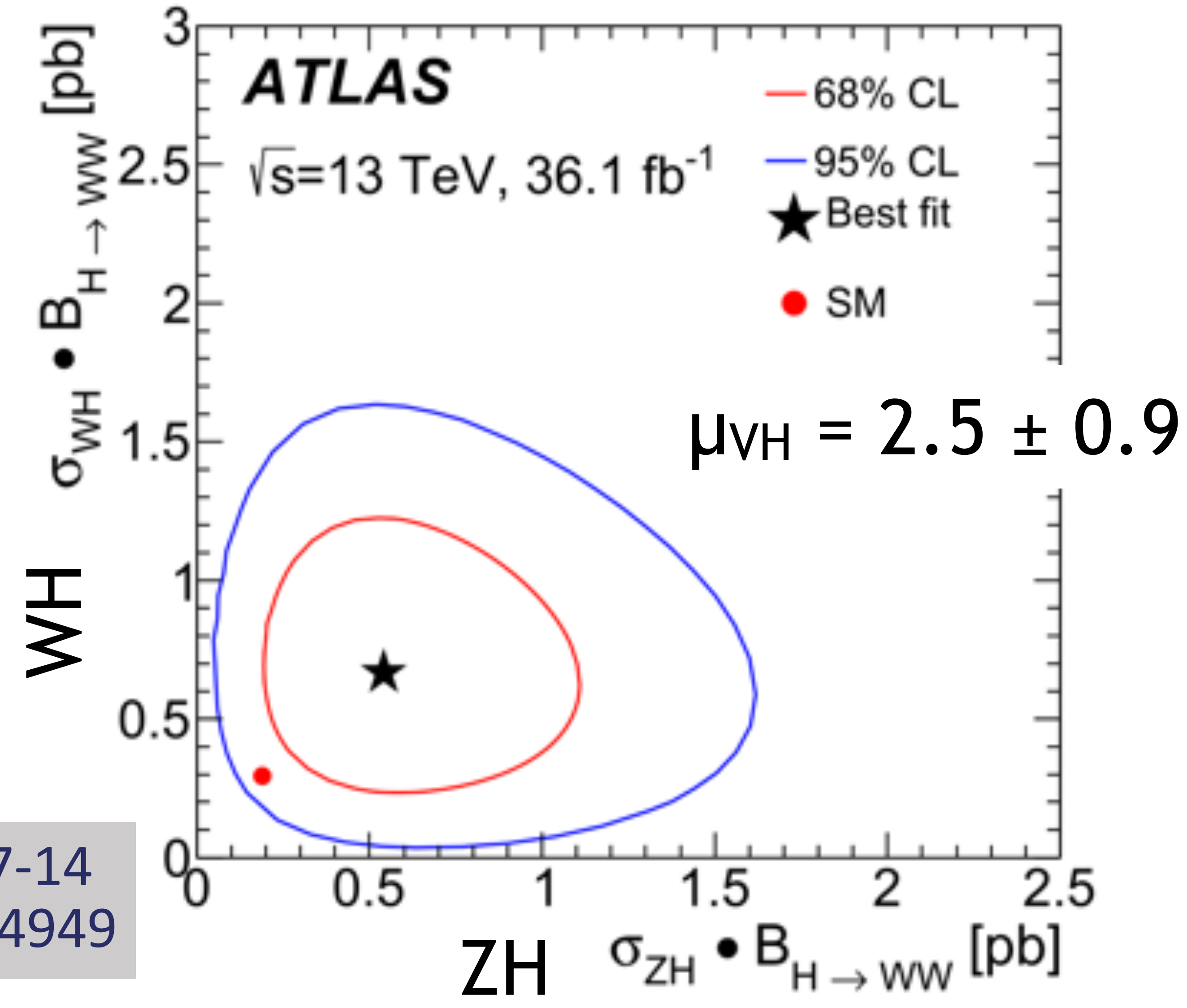




CMS-PAS-HIG-19-017



A **slight excess** (2σ) reported by **CMS** in the **VH mode**, consistent with an earlier result by **ATLAS (2016 data)**



ATLAS-HIGG-2017-14
PLB 798 (2019) 134949


ATLAS
EXPERIMENT
Run: 339387
Event: 812083095
2017-10-28 09:47:43 CEST
Jet
Photon
Merged - ee pair
H → γe⁺e⁻ candidate
(VBF topology)

Evidence for H → ℓℓγ and Search for H → Zγ

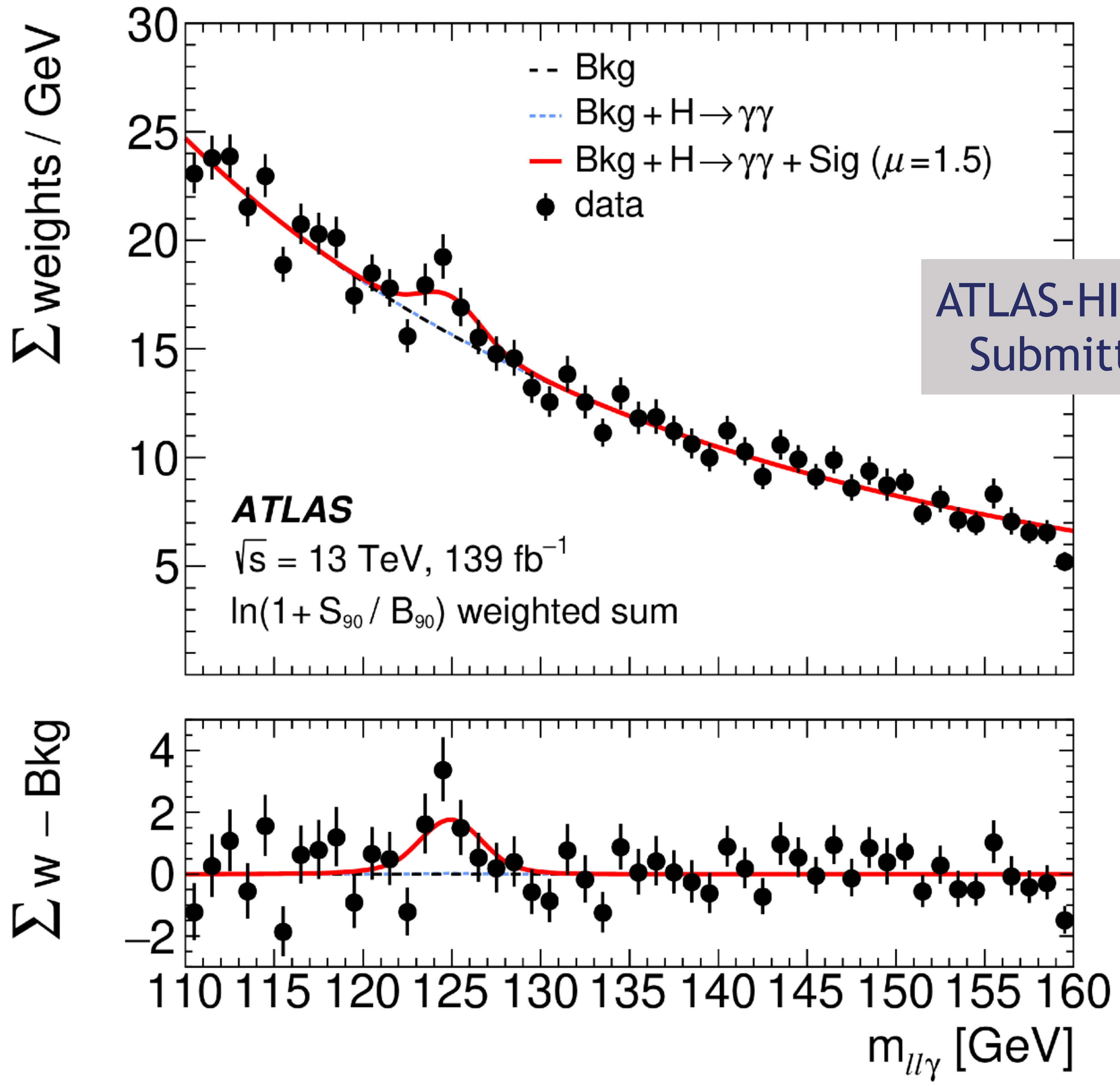
A very rare decay mode seen by ATLAS

H → ℓℓγ

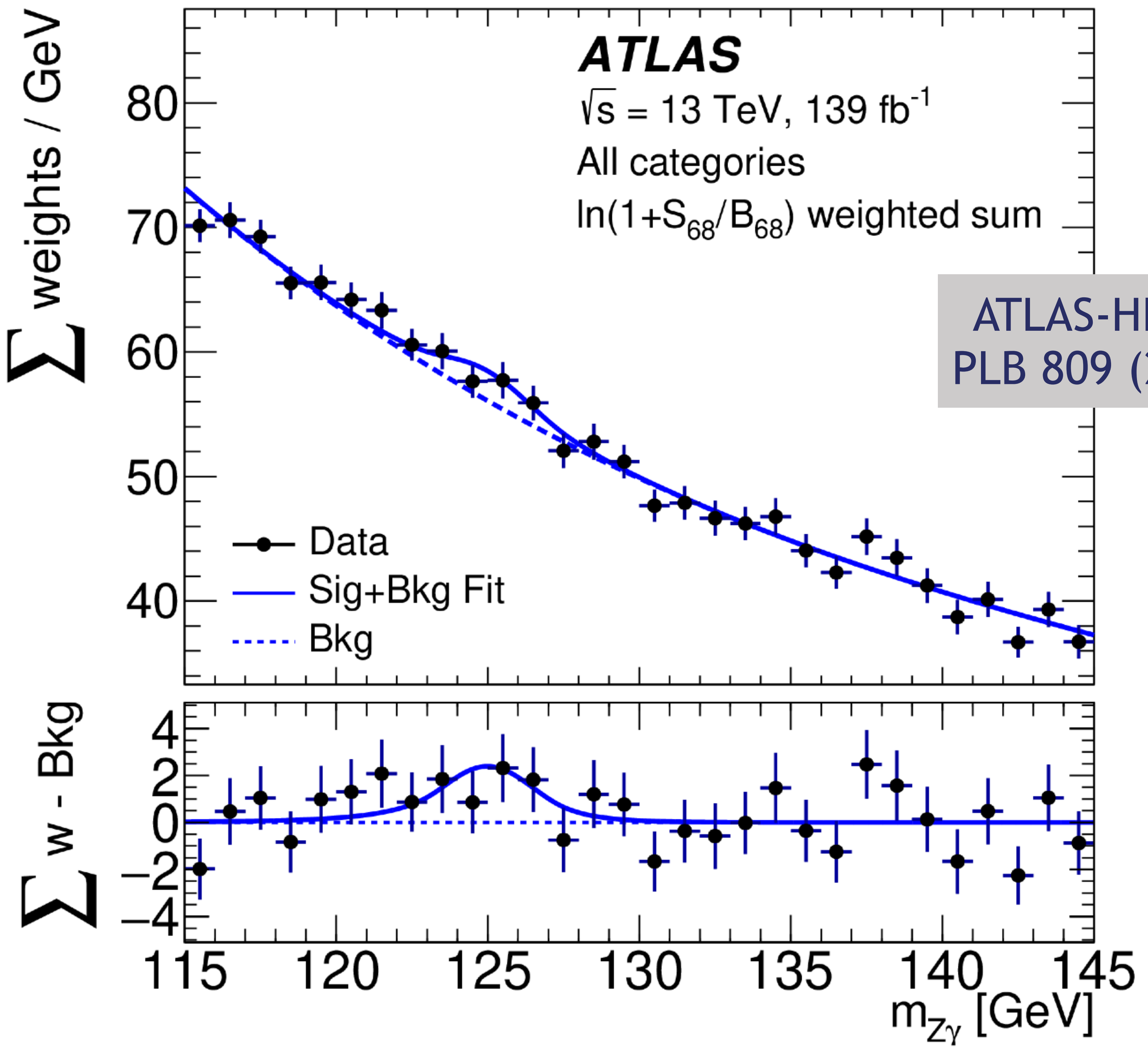
- signal strength: μ = *1.5 ± 0.5*
- Obs. (exp.) significance: *3.2σ (2.5σ)*

H → Zγ

- Obs. (exp.) μ < *3.2 (2.6)* at 95%CL

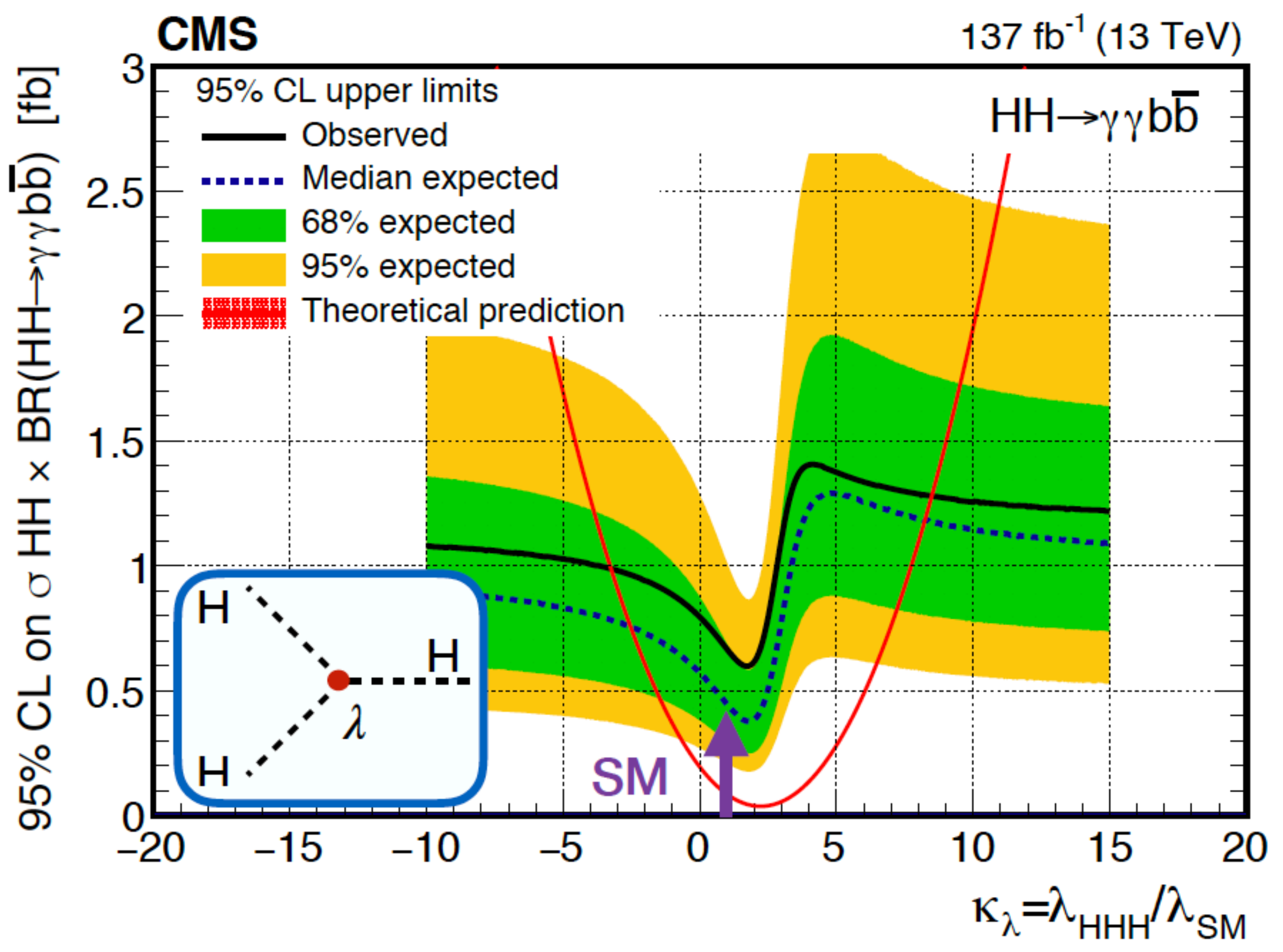


ATLAS-HIGG-2018-43
Submitted to PLB



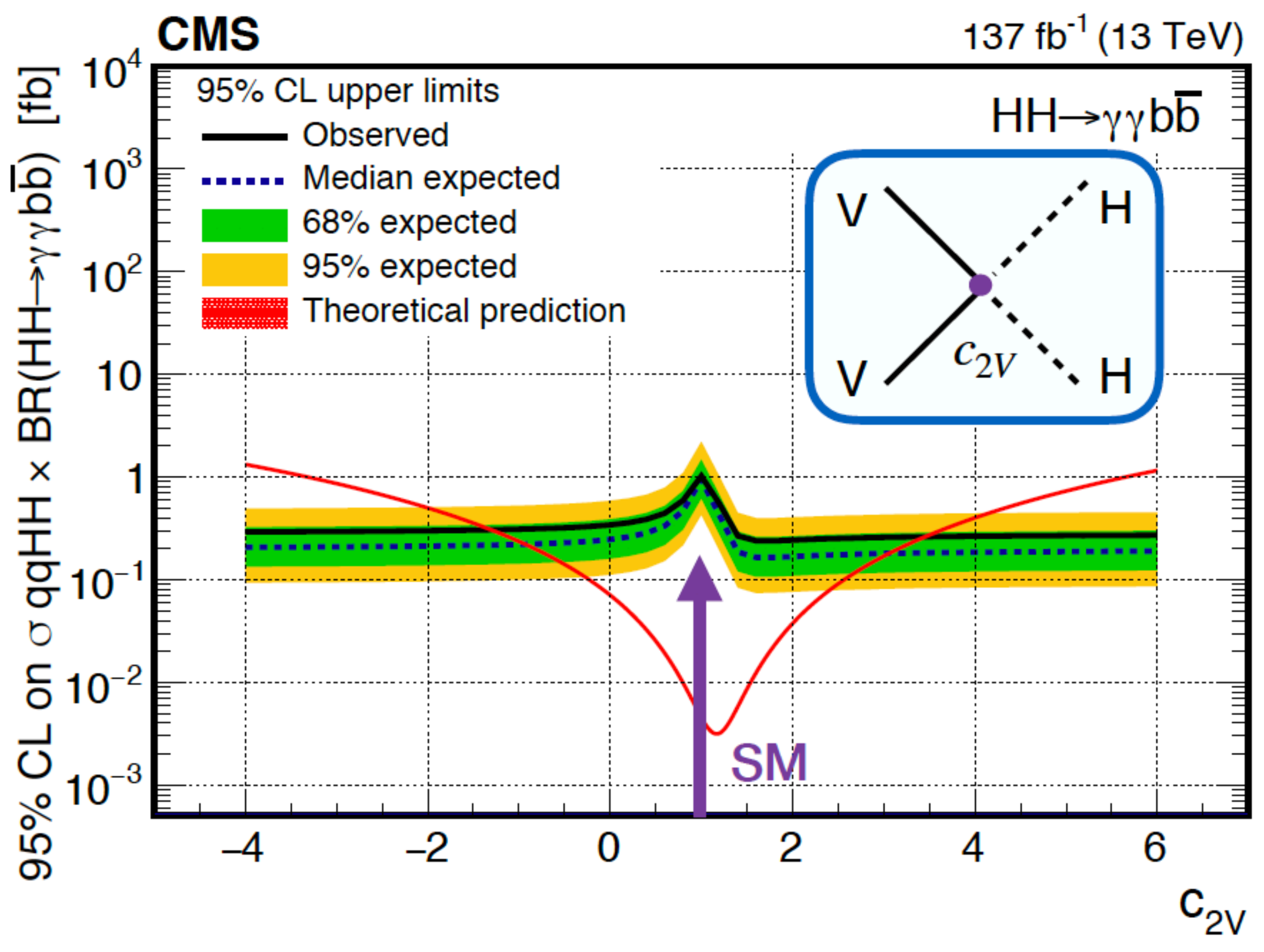
ATLAS-HIGG-2018-42
PLB 809 (2020) 135754

Search for Double Higgs Production



Driven by ggF categories

CMS Incl. HH → bb̄γγ:
σ/σ_{SM} < 7.7 (5.2) at 95% CL



Driven by VBF categories

CMS VBH HH → bb̄γγ:
σ/σ_{SM} < 225 (208) at 95% CL

CMS-HIG-19-018
JHEP 03 (2021) 257

DPhP

Constraints on anomalous HHH (κ_λ) and VVHH (c_{2V}) couplings

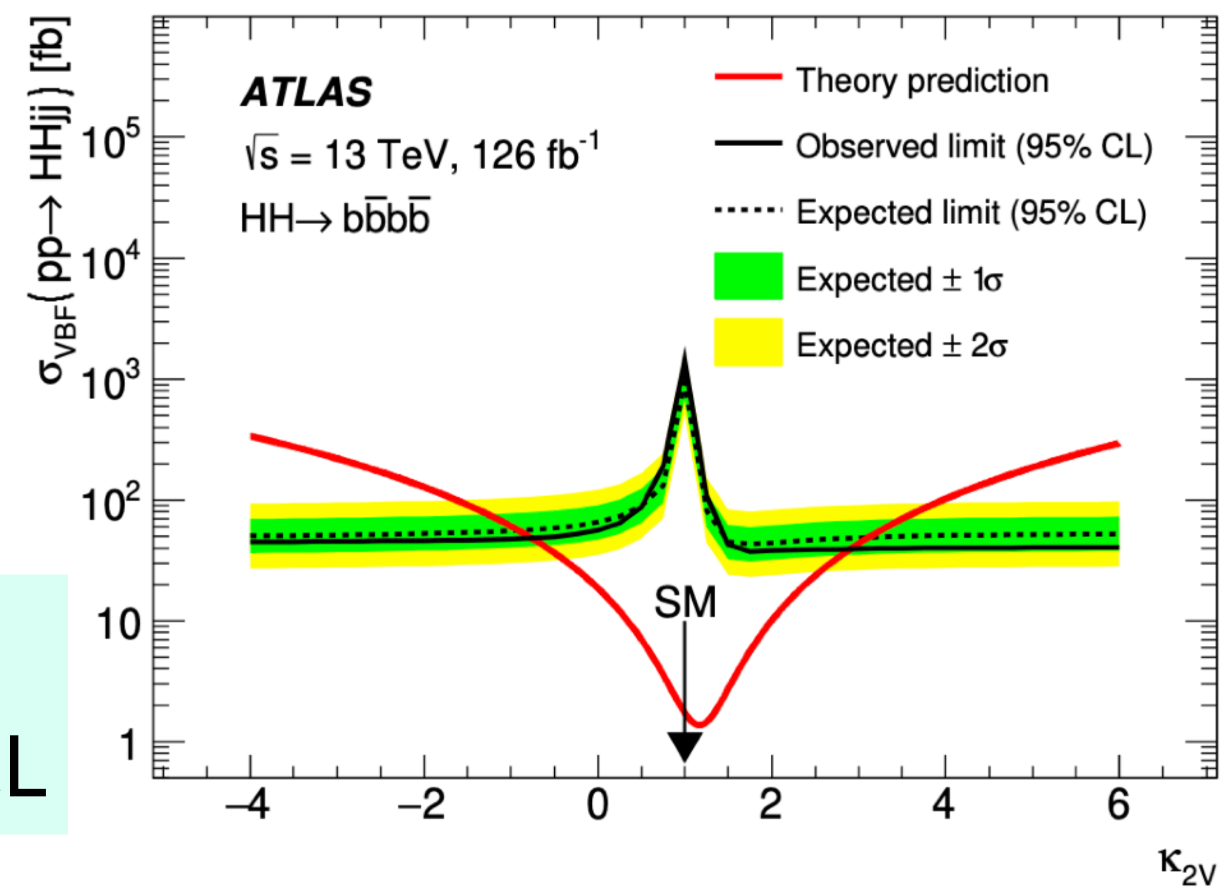
The observation of double Higgs production is one of the main goals of HL-LHC

A very active field
still far from reaching sensitivity to SM double-HIggs production, but getting closer

Run-2 + Run-3: Combining all channels expect "measurement" with 100% uncertainty per experiment

ATLAS-HDBS-2018-18
JHEP 07 (2020) 108

ATLAS VBH HH → bb̄bb̄:
σ/σ_{SM} < 840 (550) at 95% CL

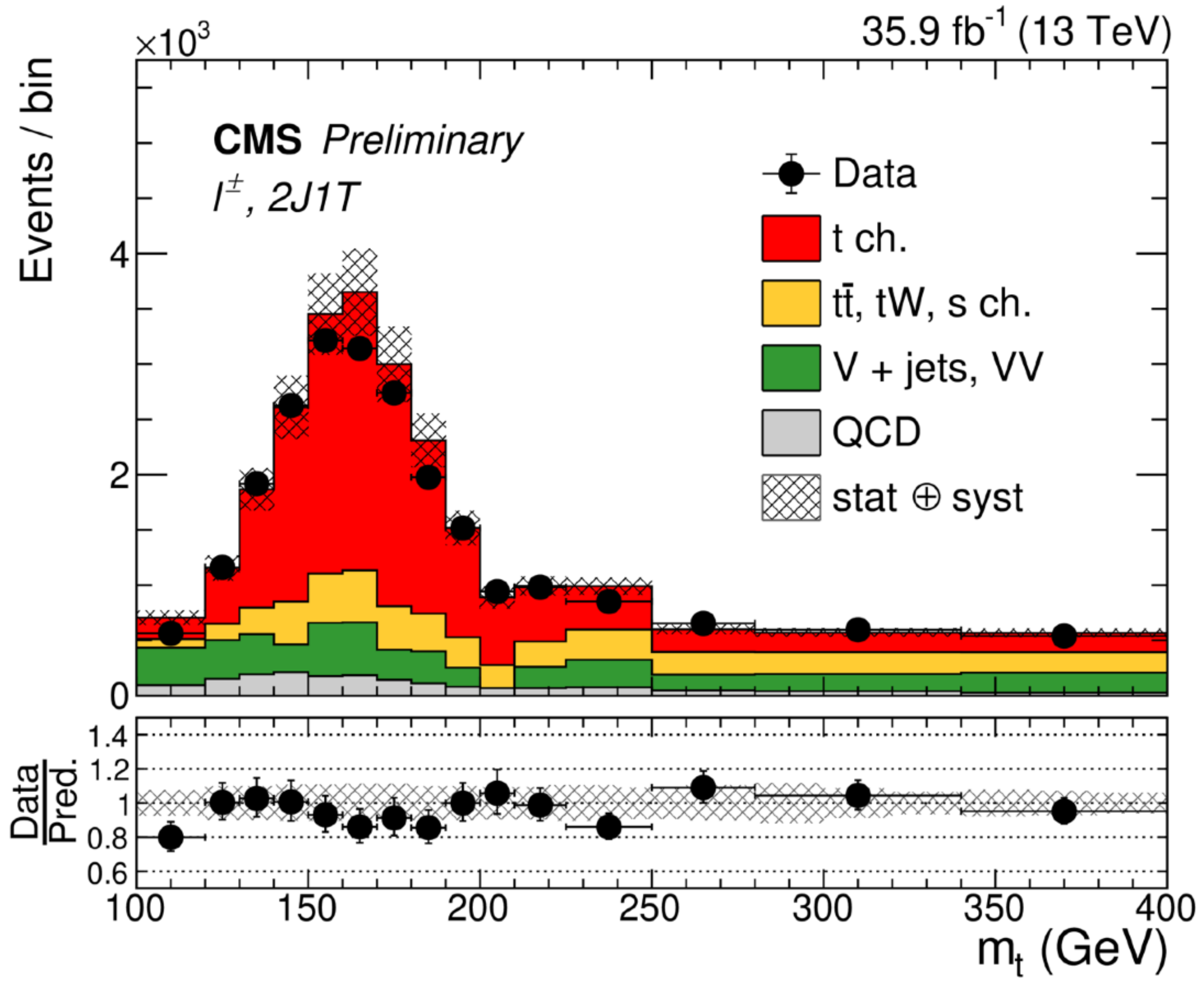


New Top Mass Measurements

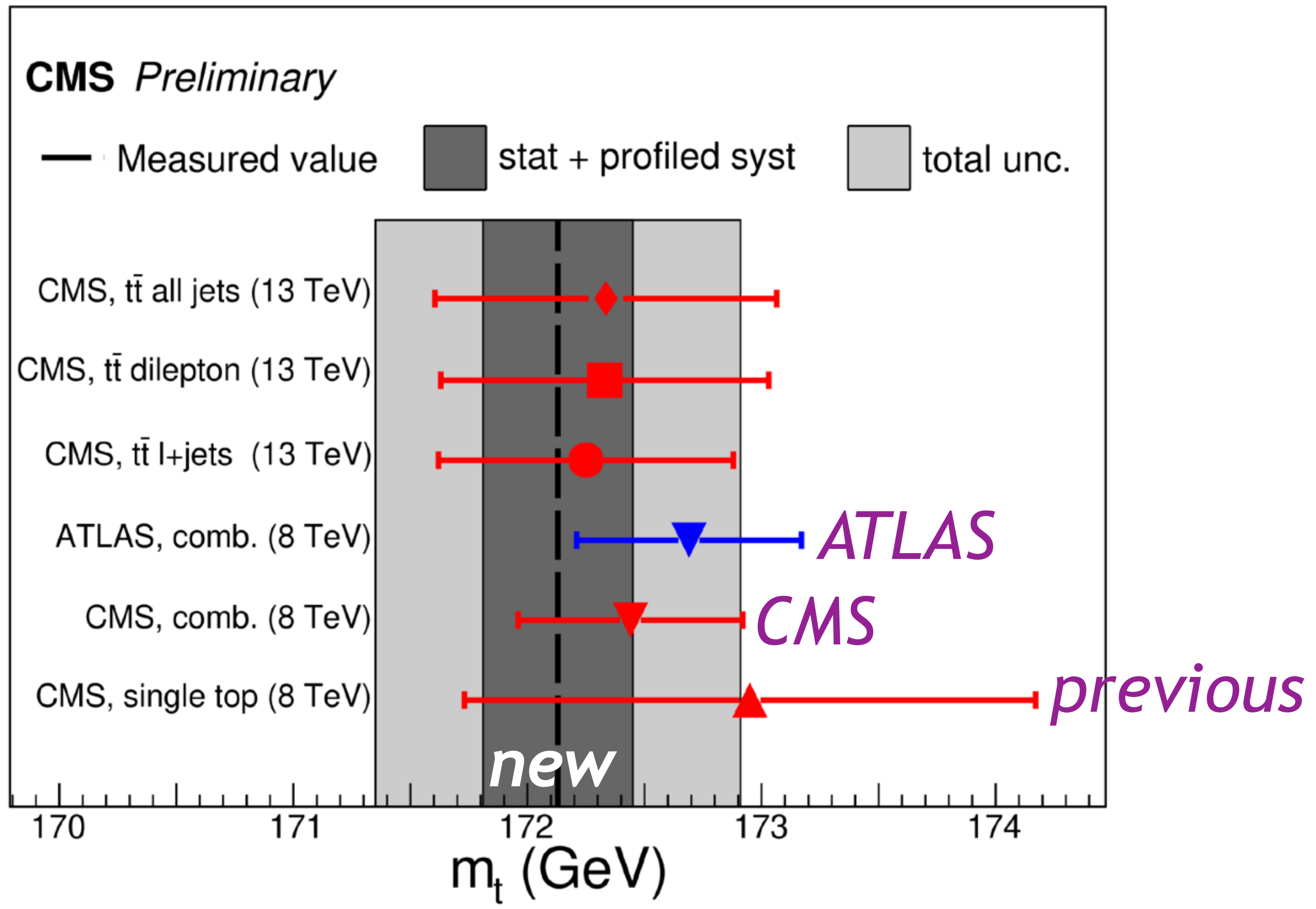
With single top events

Different phase space, different kinematics, and separate measurements of top and anti-top:

- m_t = 172.13 ± 0.77 GeV
- $m_{\bar{t}}/m_t$ = 0.995 ± 0.006
- $m_{\bar{t}} - m_t$ = $0.83^{+0.77}_{-1.01}$ GeV



CMS-PAS-TOP-19-009

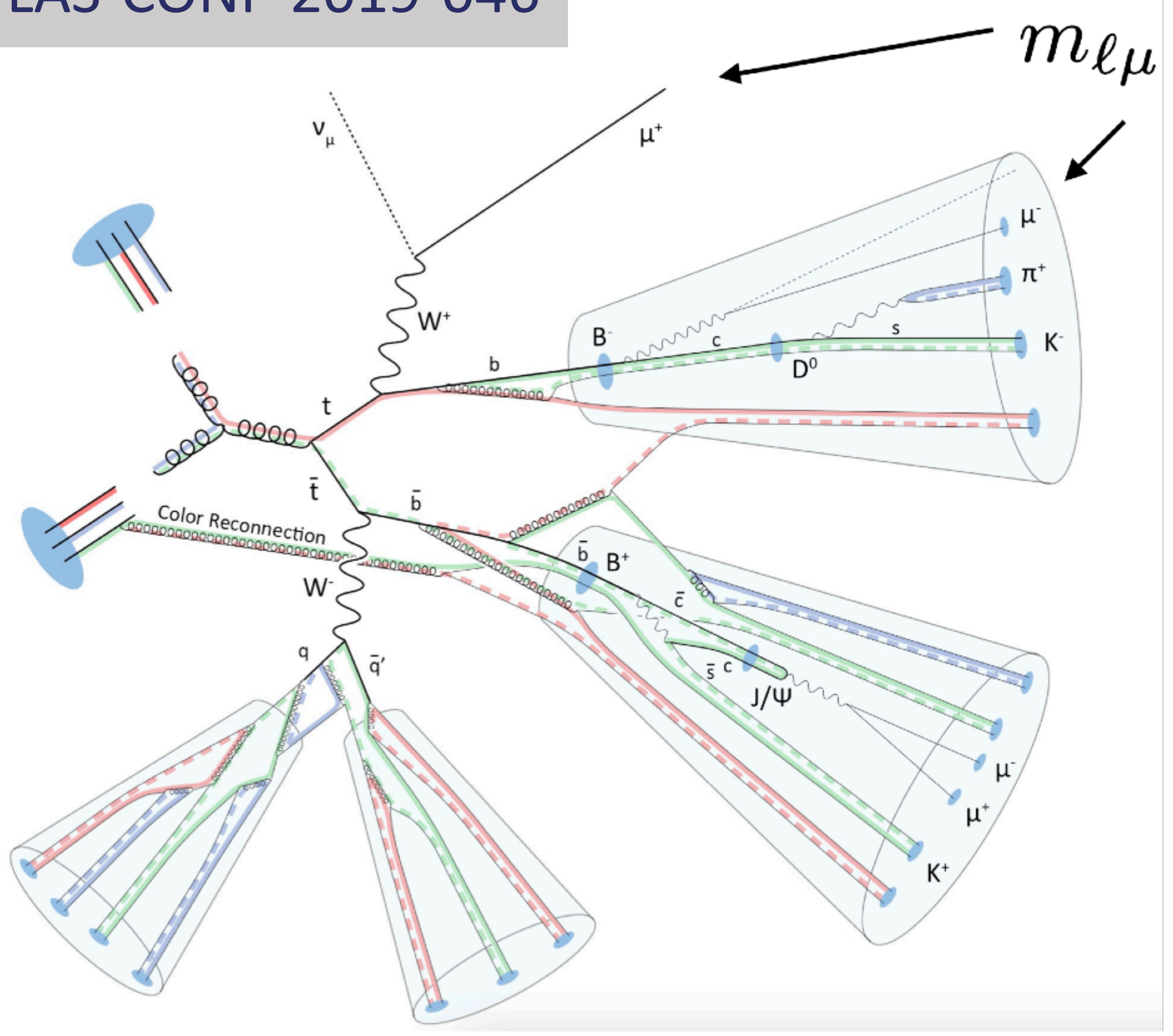


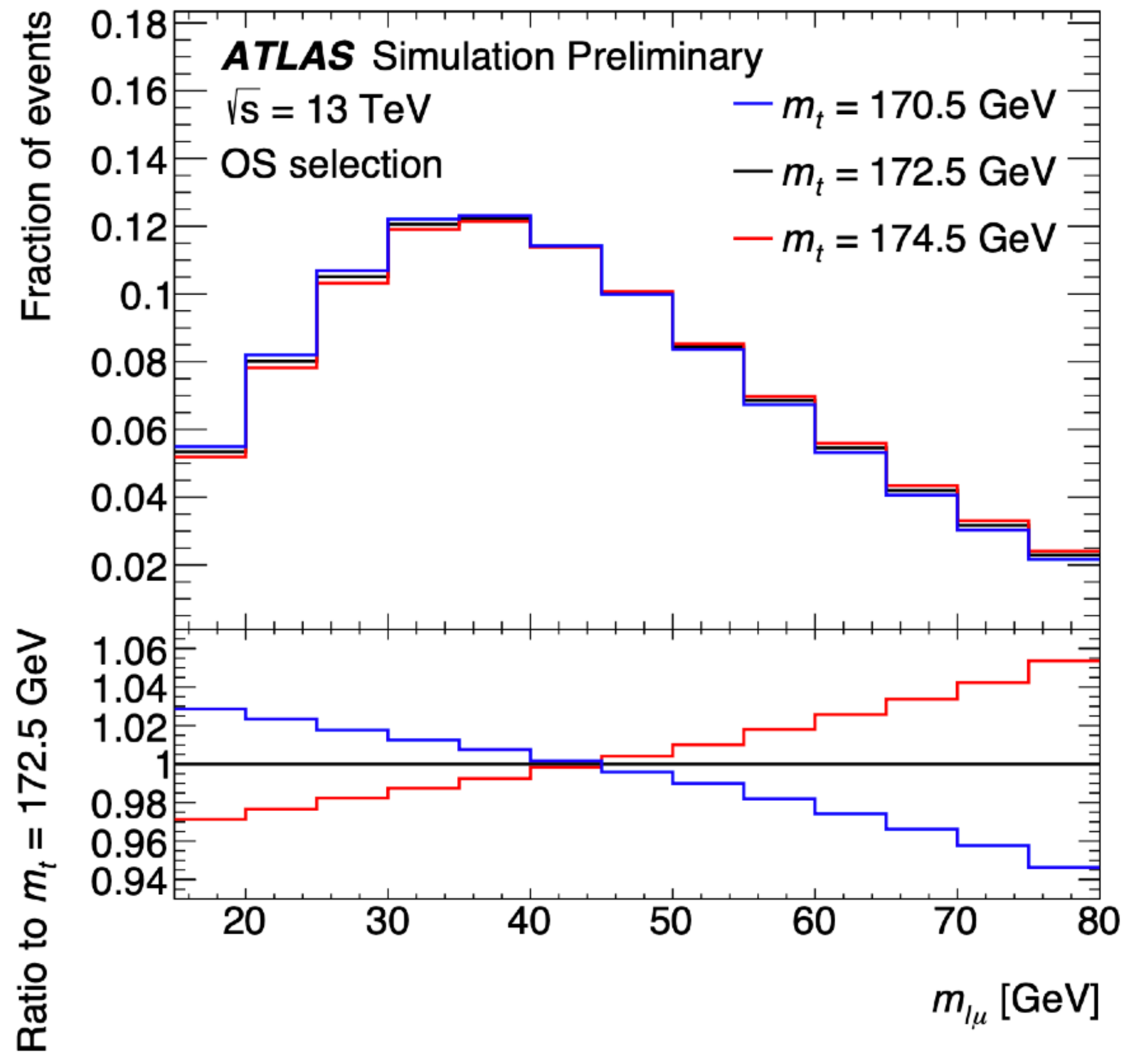
With soft muons

Less dependance on top quark production modelling

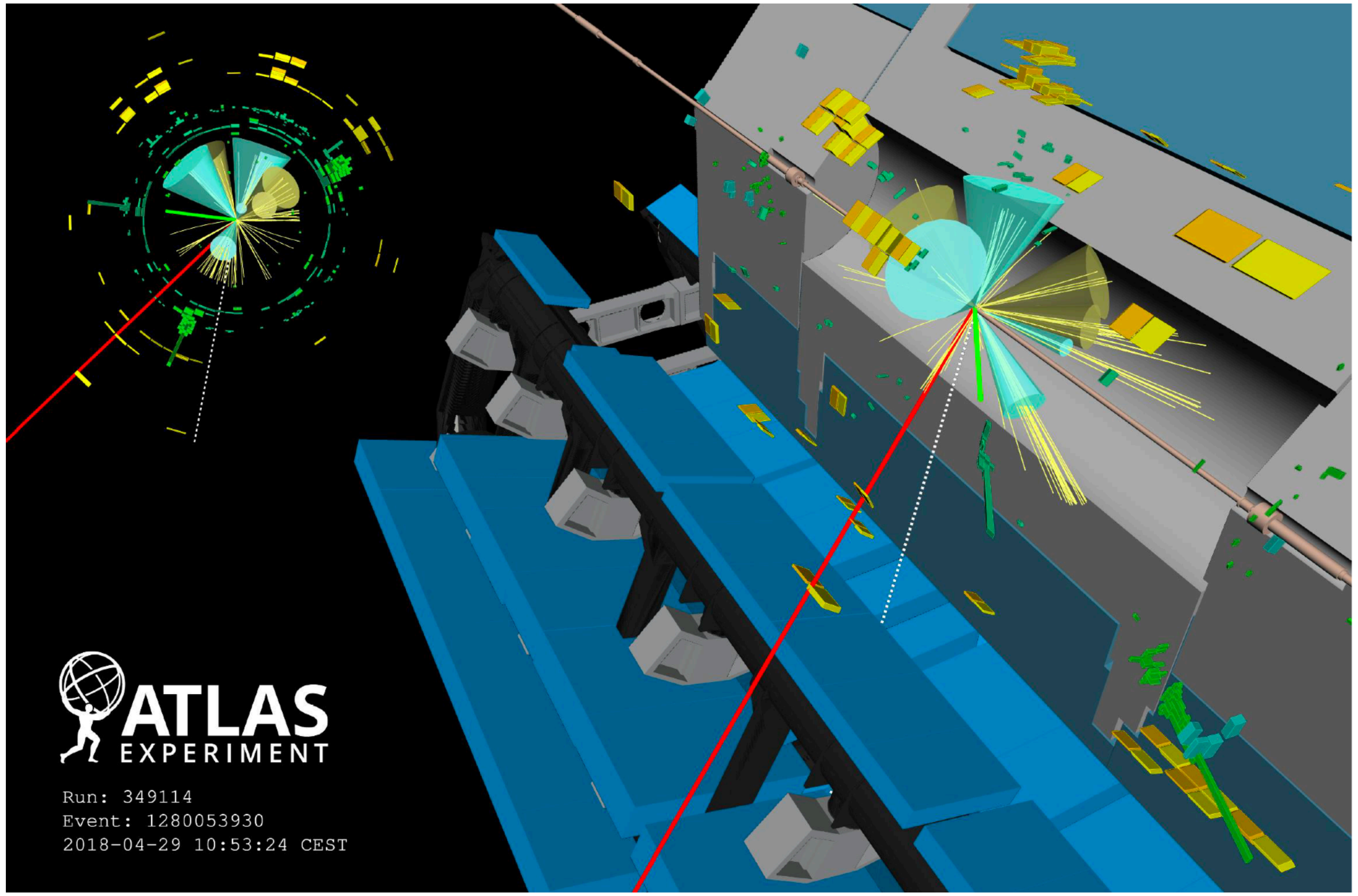
- B-fragmentation from LEP and SLD
- m_t = 174.48 ± 0.40 (stat) ± 0.67 (syst) GeV
- precision 0.45%
- main uncertainty: HF-hadron decay modelling

ATLAS-CONF-2019-046





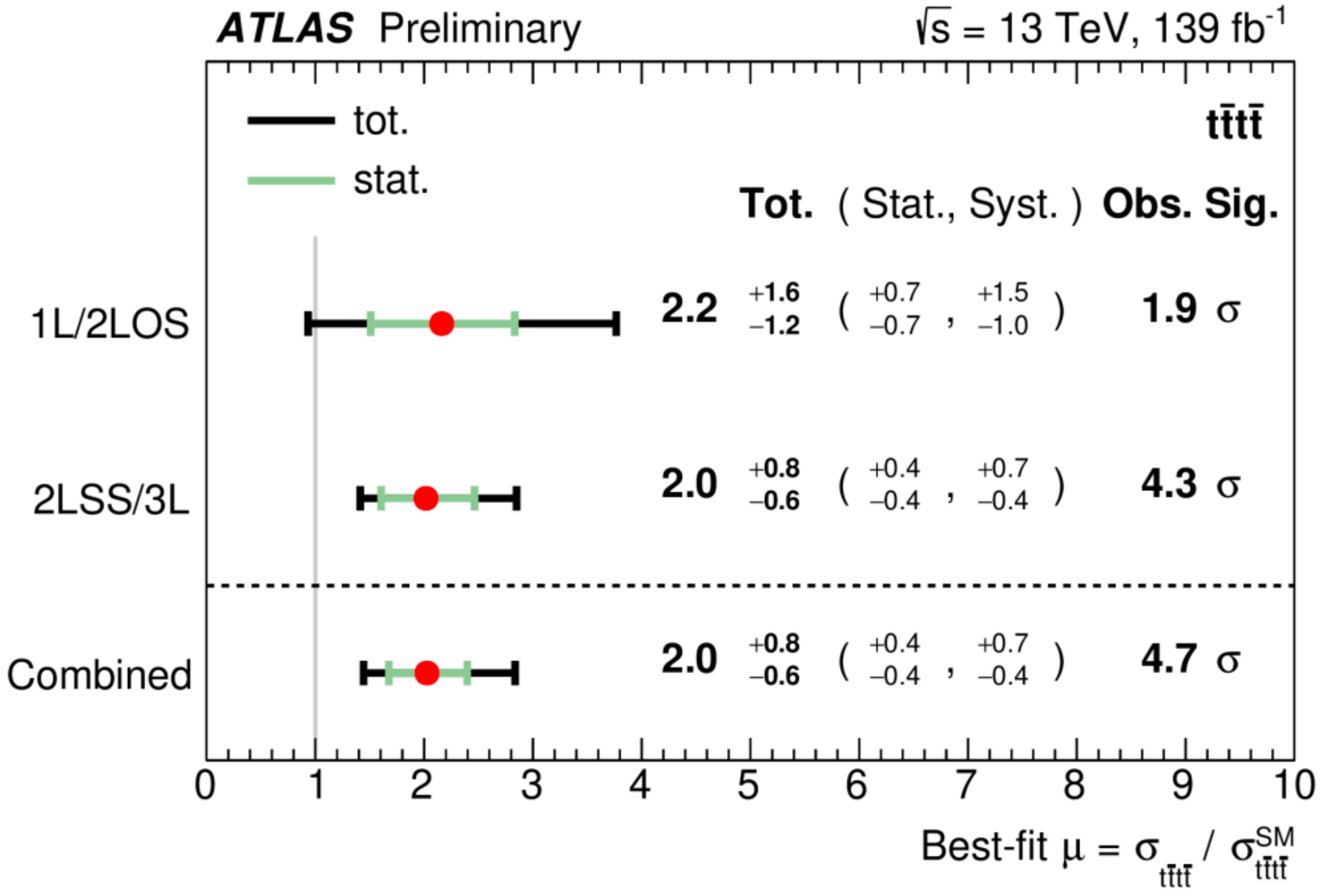
Four-Top Production



Compatible within 2σ with SM prediction

ATLAS-CONF-2021-013

First evidence of an ultra-rare process
(σ^{SM}_{tttt} = 12.0 ± 2.4 fb)



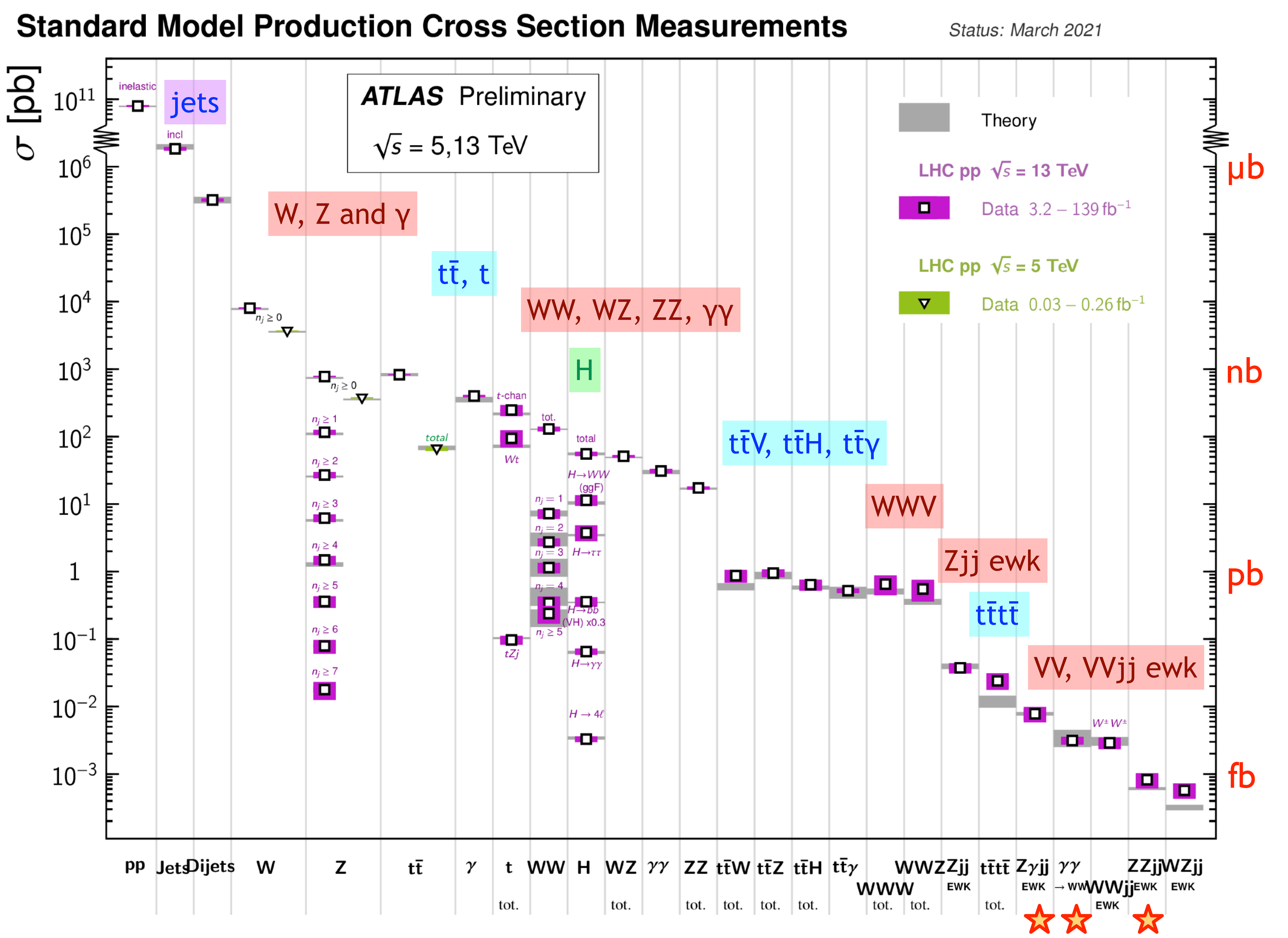
DPhP

Obs. (exp.) significance

- ATLAS: 4.7σ (2.6σ)
- CMS: 2.6σ (2.7σ)

Very high energy scale production
Sensitive to top-Higgs Yukawa coupling

Cross-Section Measurements



Production cross-section for many processes over more than 10 orders of magnitude

Studying **vector boson scattering** is a major goal of Run-3 and beyond

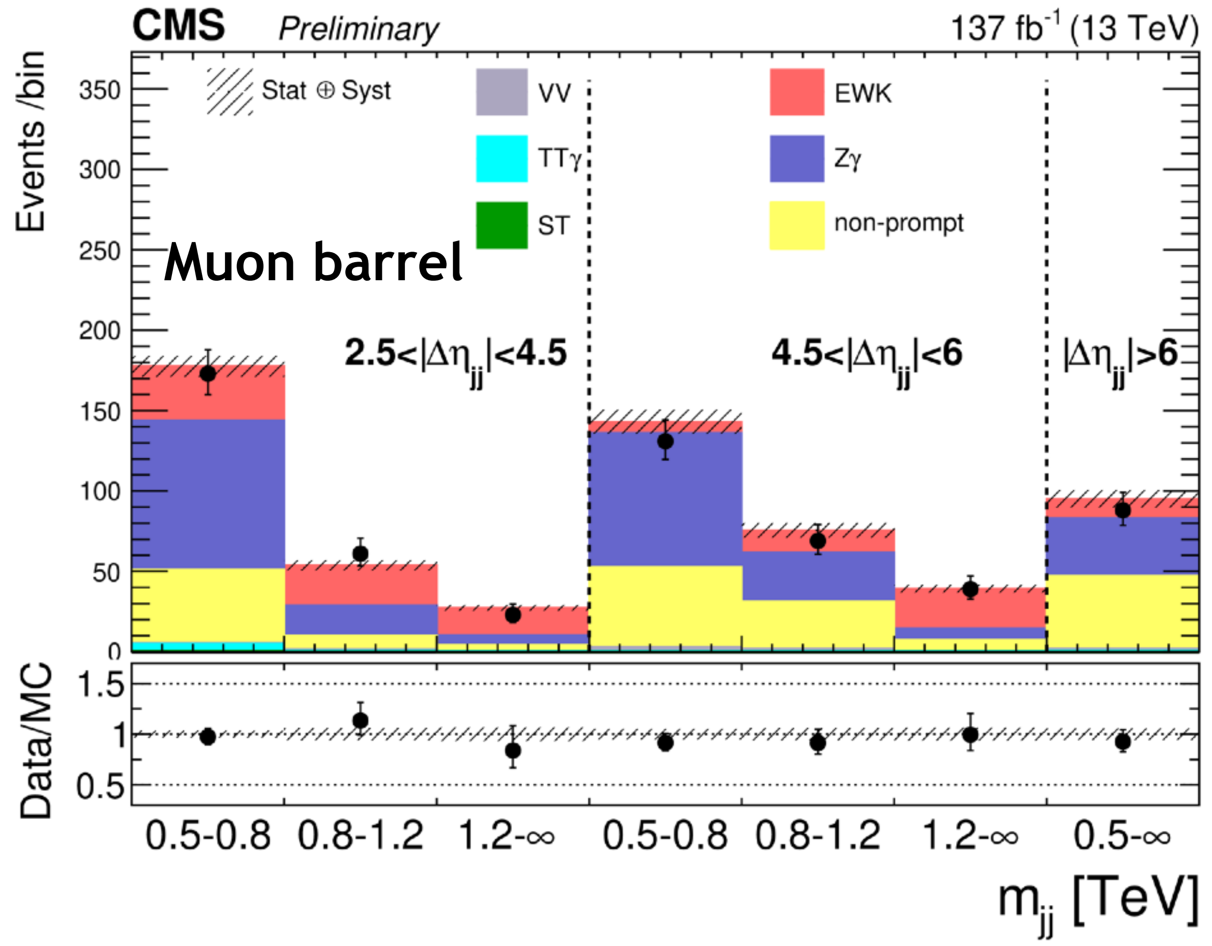
Vector Boson Scattering

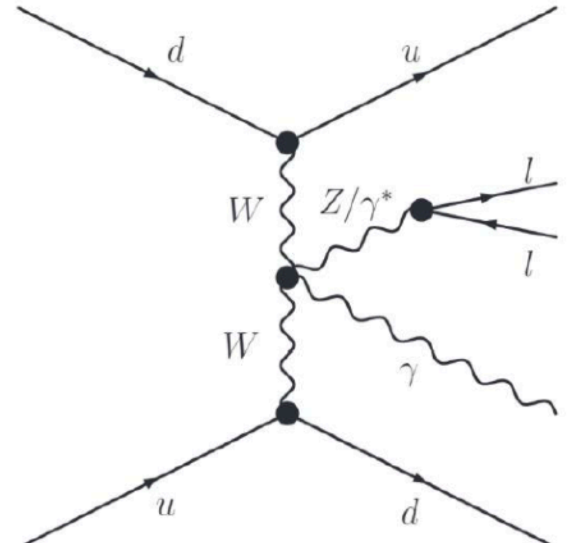
VBS signature: two jets with large rapidity separation and dijet mass

***Wγ* and *Zγ* scattering** observed with more than 5σ significance

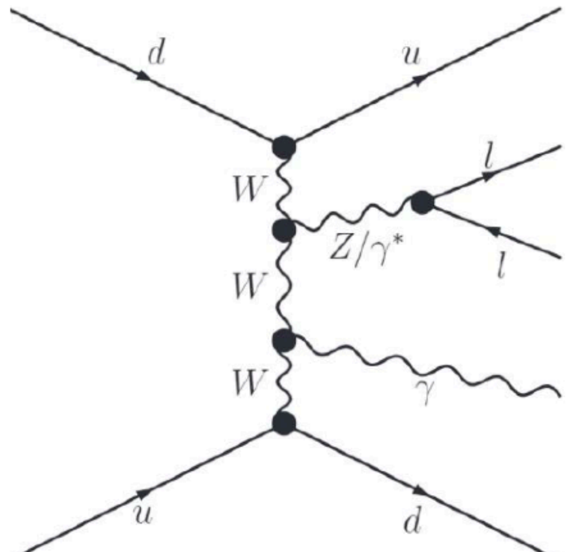
CMS-SMP-19-008
PLB 811 (2020) 135988

CMS-PAS-SMP-20-016





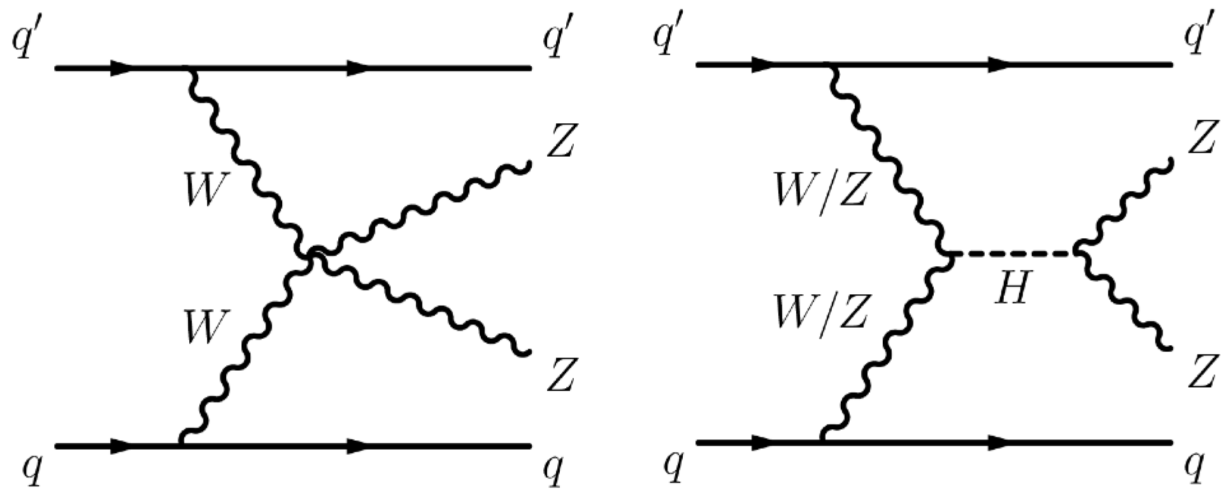
Quartic gauge coupling



Triple gauge coupling

Also evidence for Wγγ (3.1σ) and Zγγ (4.8σ)

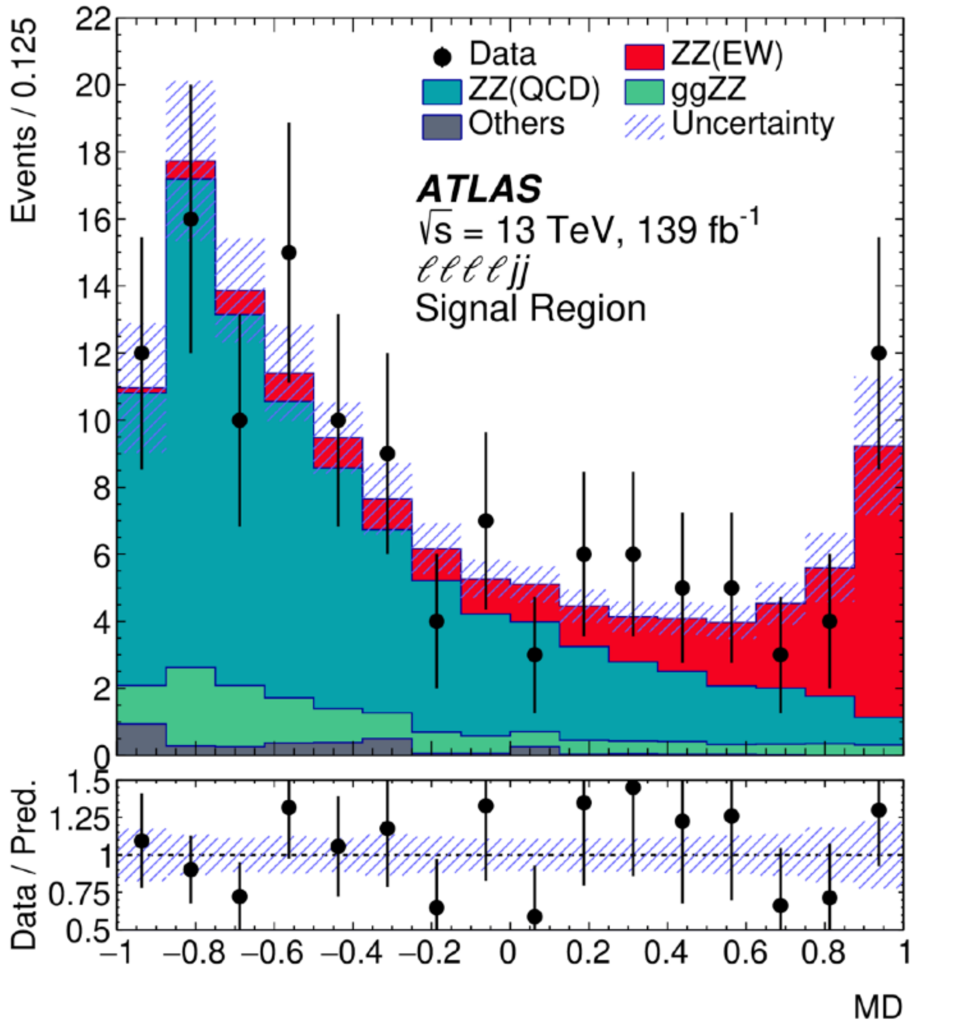
CMS-PAS-SMP-19-013



All **VBS VV channels** are observed by ATLAS

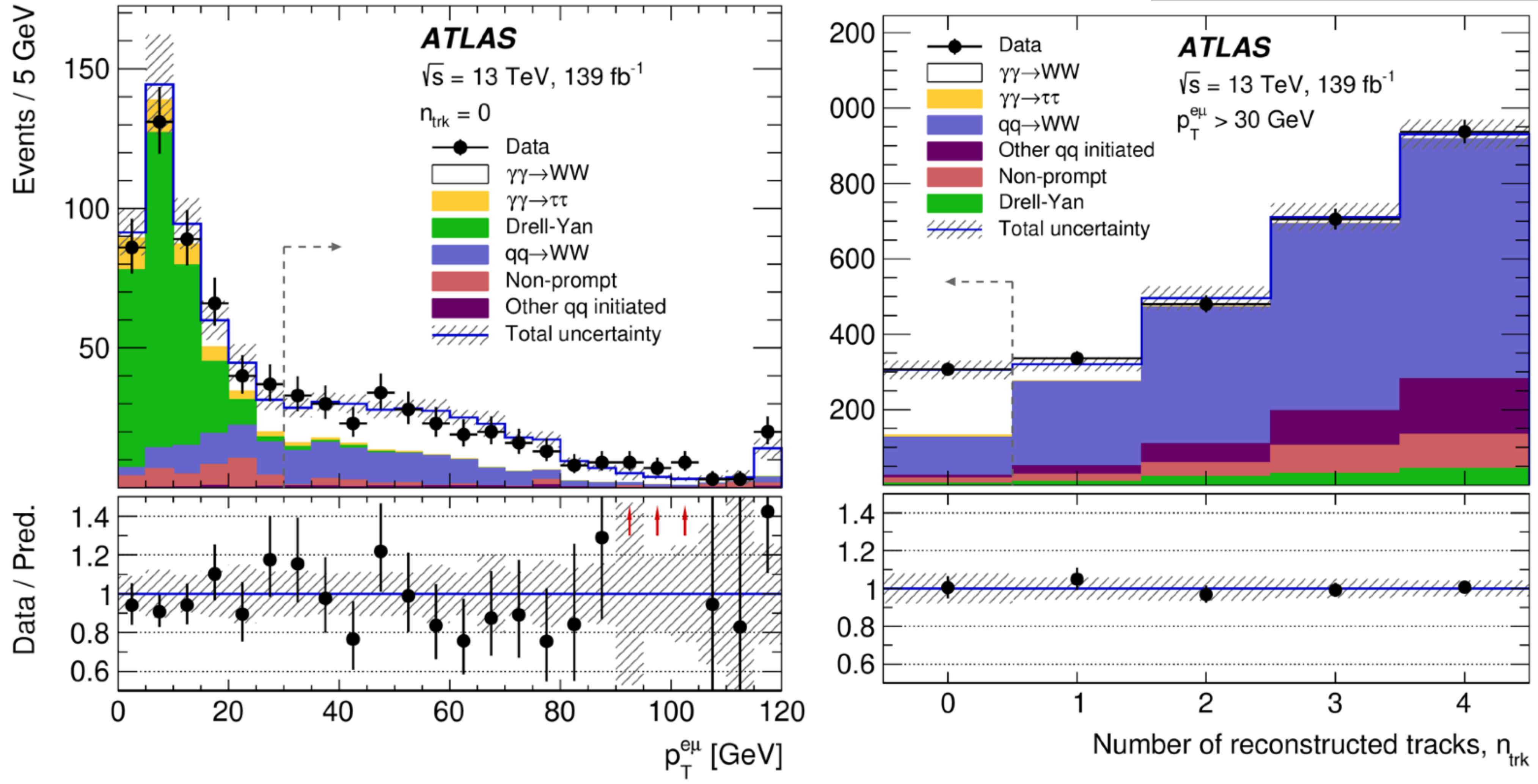
- same-sign WW (6.9σ)
- **ZZ** (5.5σ)
- WZ (5.3σ)

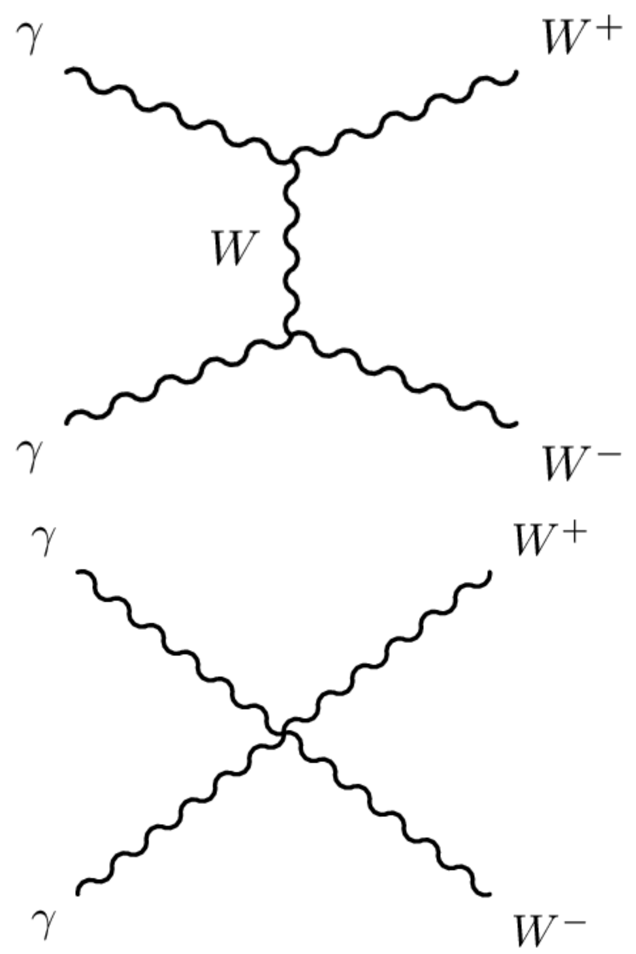
(similar results in CMS)



Photon-induced WW production

ATLAS-STDM-2017-21
PLB 816 (2021) 136190



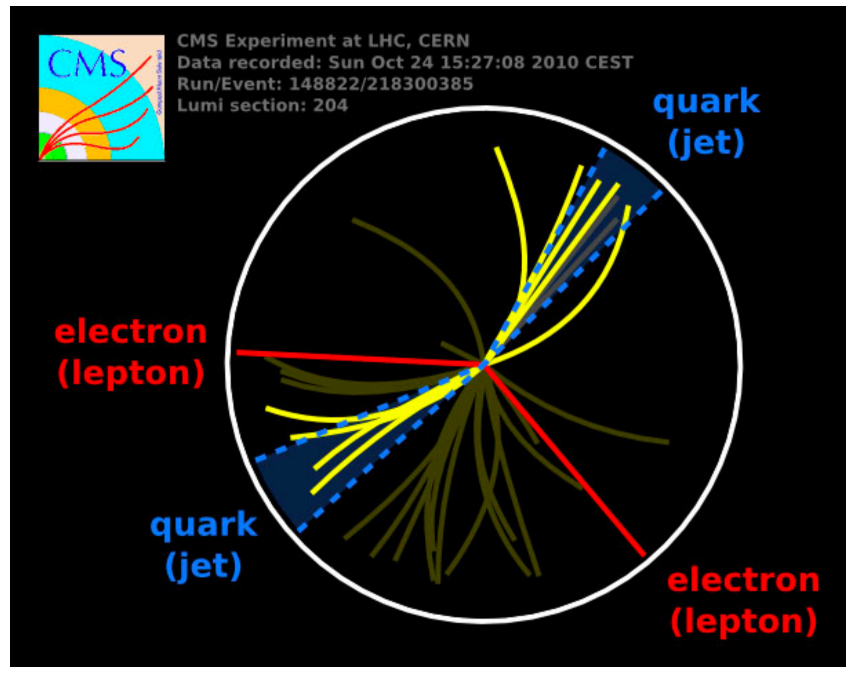


Observed significance 8.4σ (6.7σ expected)

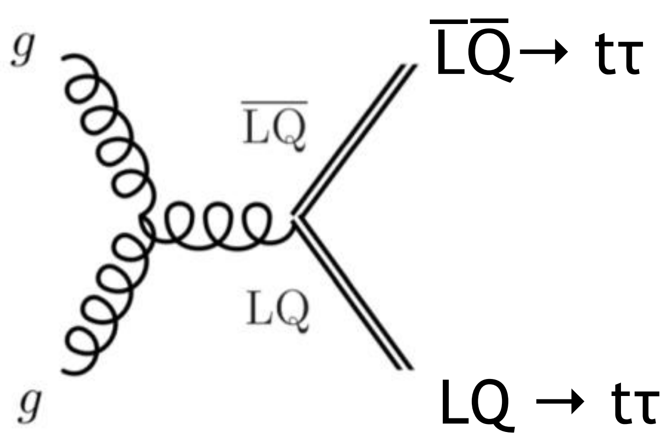
Direct Searches for NP in ATLAS and CMS

Search for Leptoquarks (LQ)

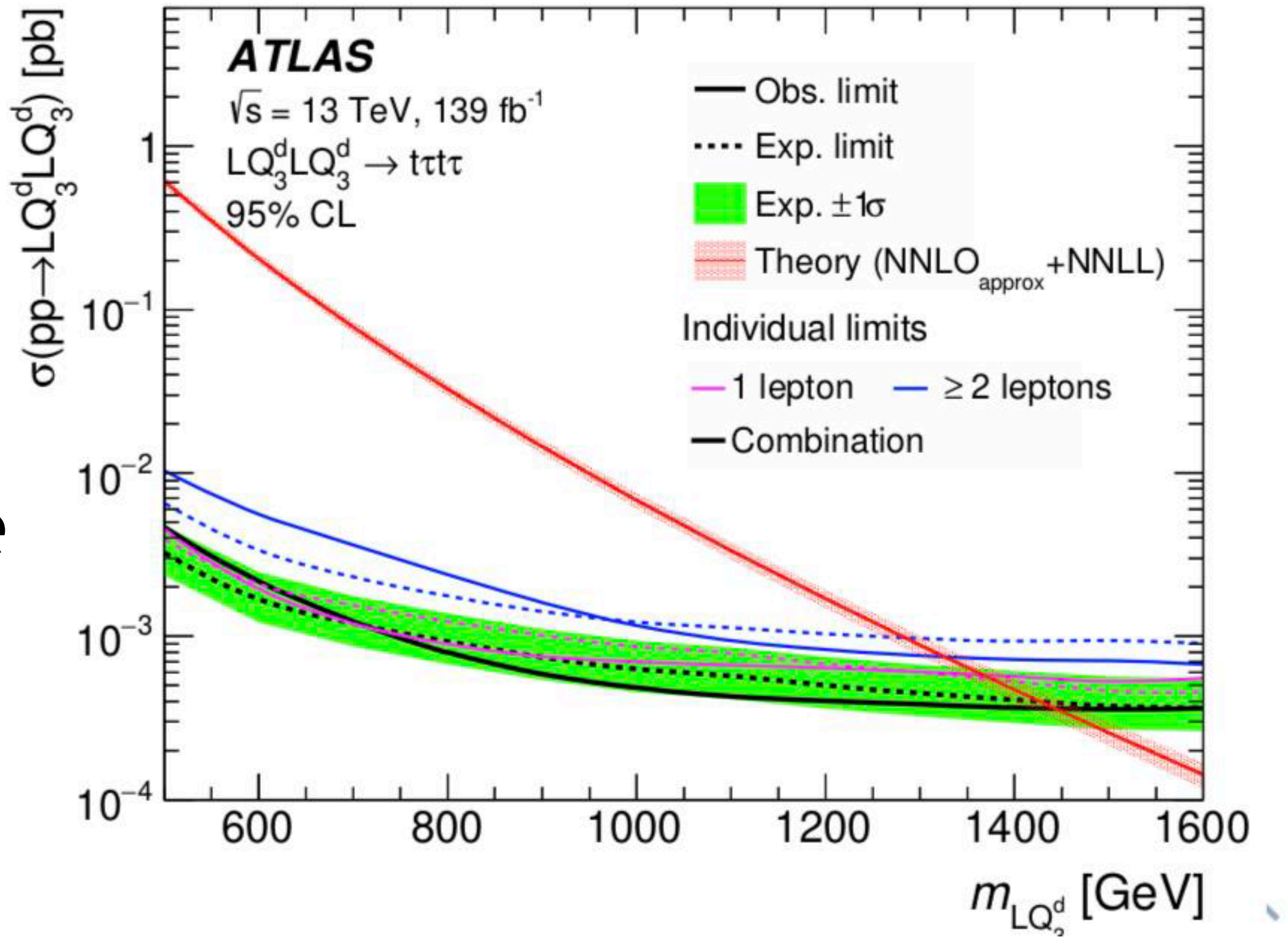
LQ carry non-zero baryon and lepton numbers, they can be produced in pair and decay into a quark and a lepton



ATLAS-EXOT-2019-015
Submitted to JHEP

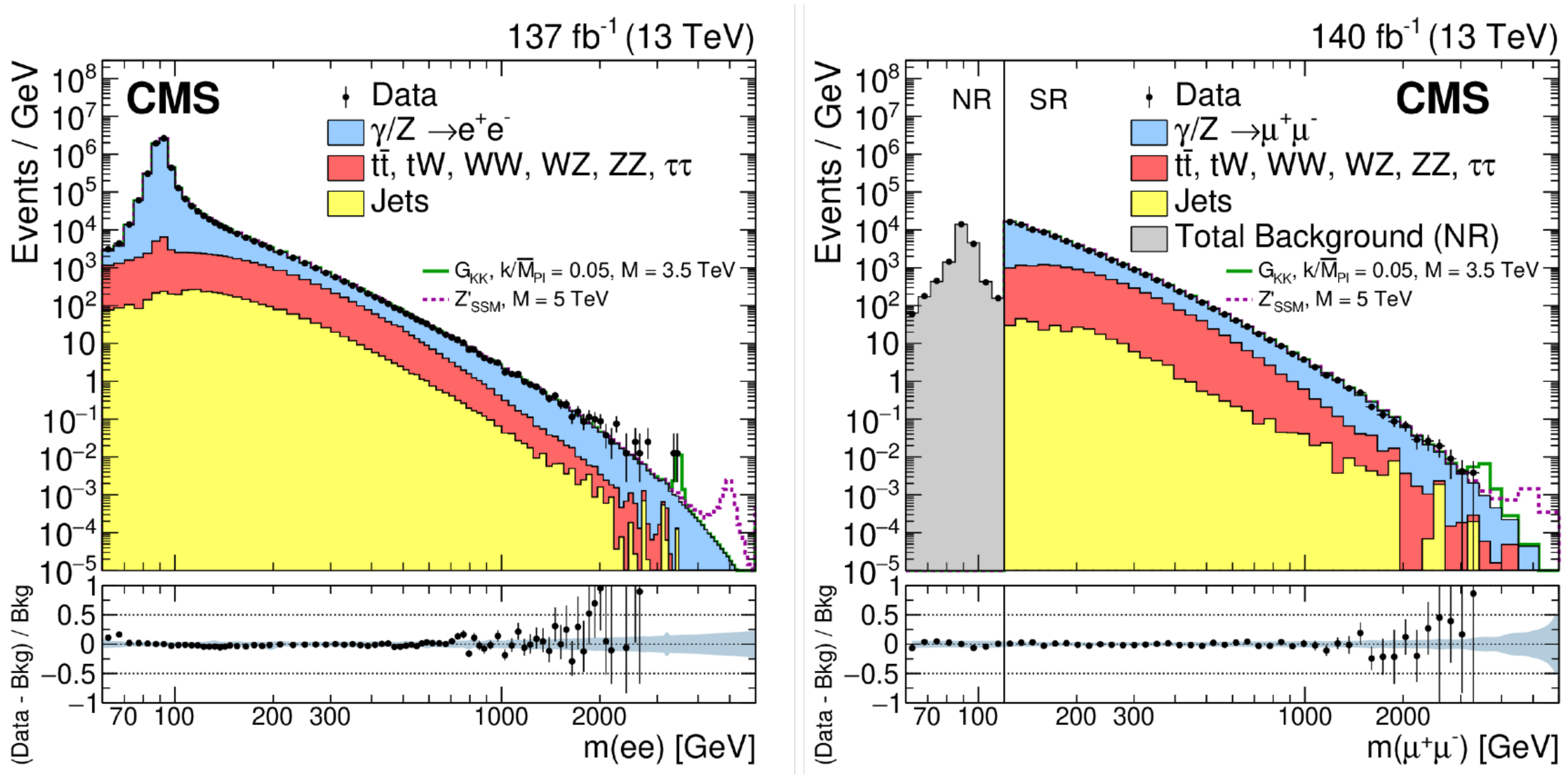


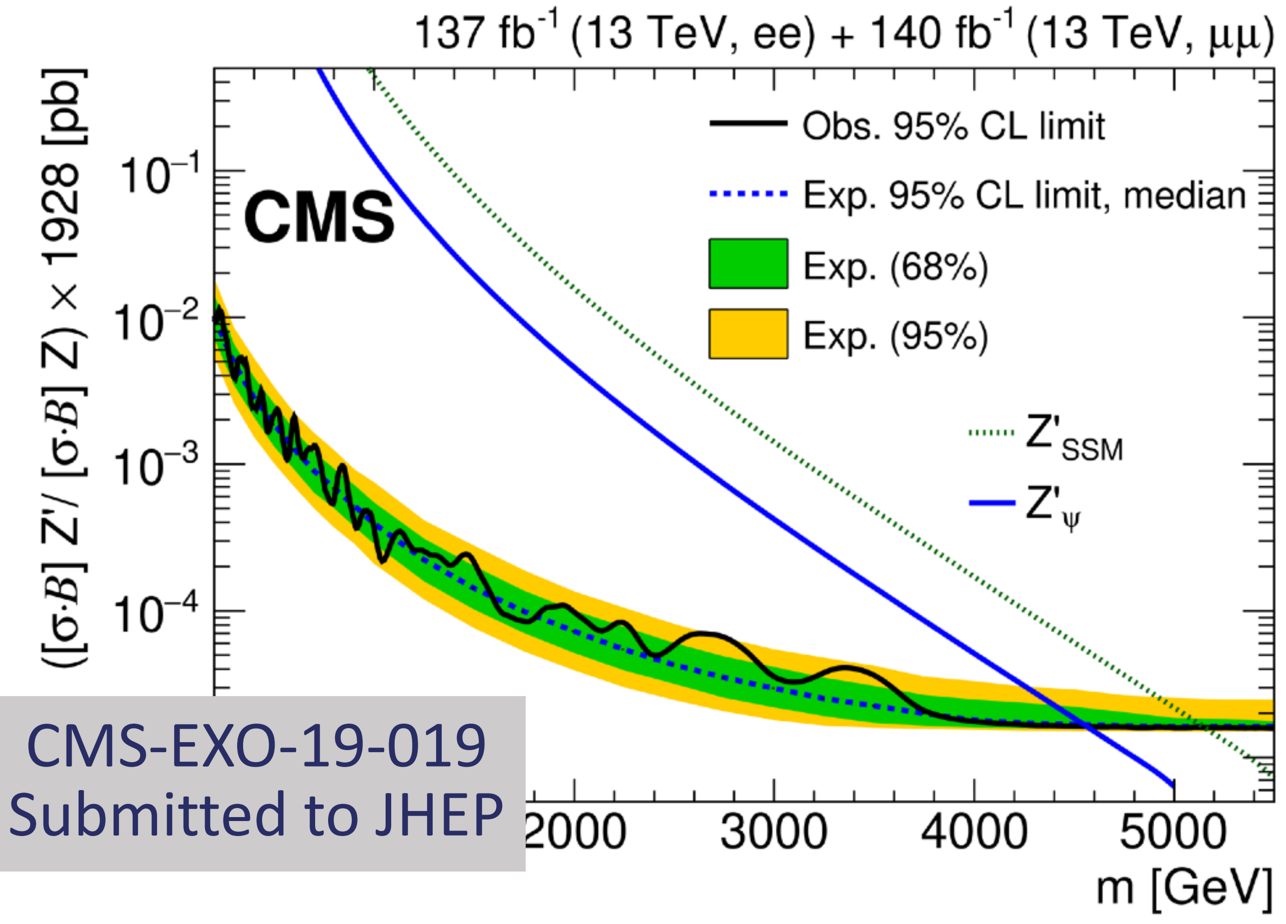
Limits on LQ in the range 1—2 TeV depending on their spin and couplings to leptons and quarks



Still far from masses and couplings that could explain the LFU μ/e anomalies

Search for dilepton resonances





CMS-EXO-19-019
Submitted to JHEP

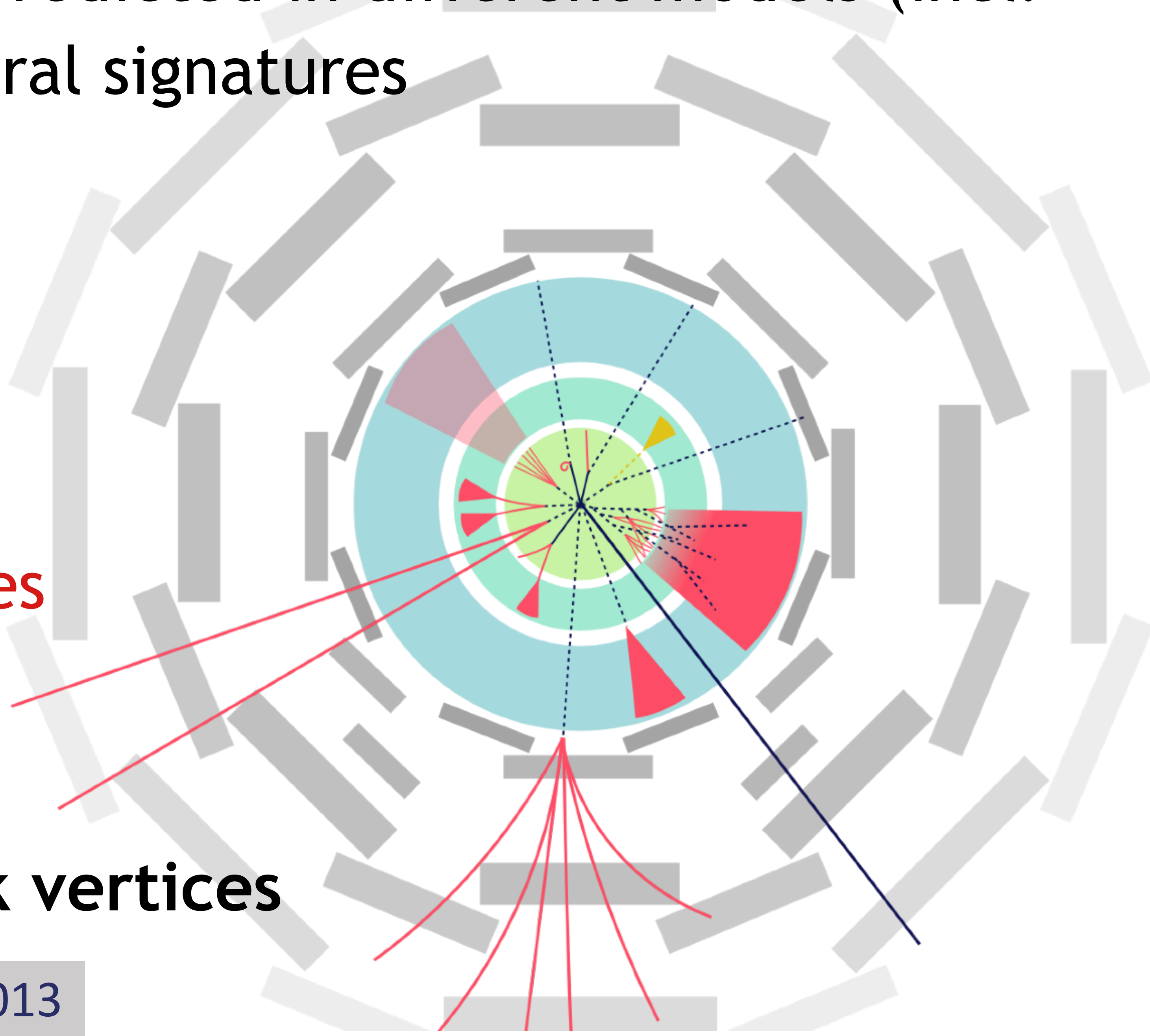
Limits on Z' in the range 4.5—5 TeV

Most standard searches have now been completed. Now consider for new signatures and models which have not yet been covered

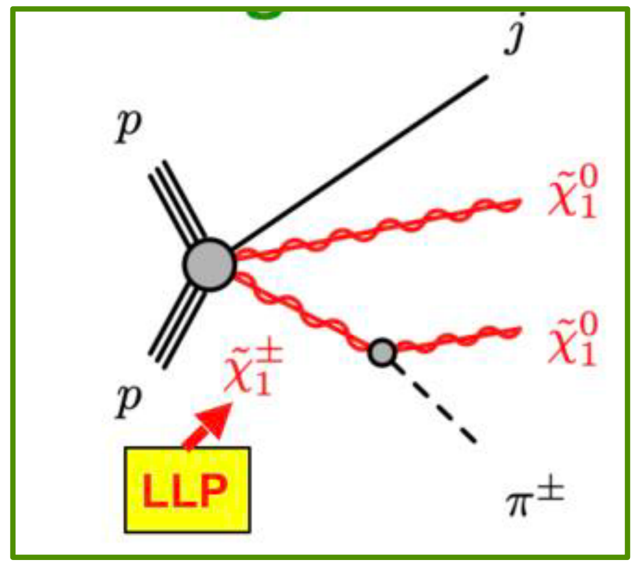
Unconventional Signatures of NP

Long-lived particles (LLP) are predicted in different models (incl. SUSY models) and present several signatures

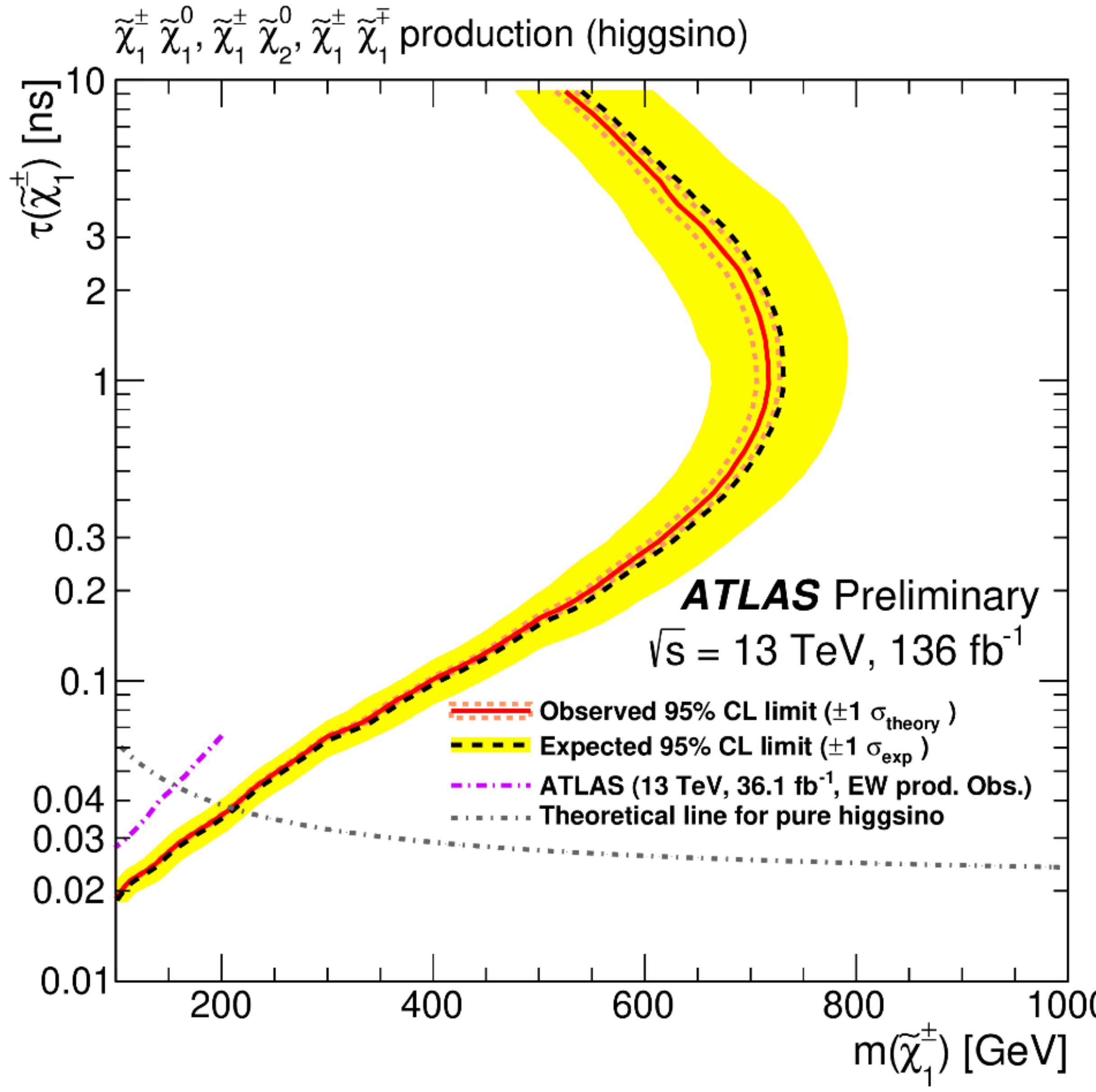
- disappearing tacks
- late photons
- emerging jets
- displaced leptons
- displaced multitrack vertices

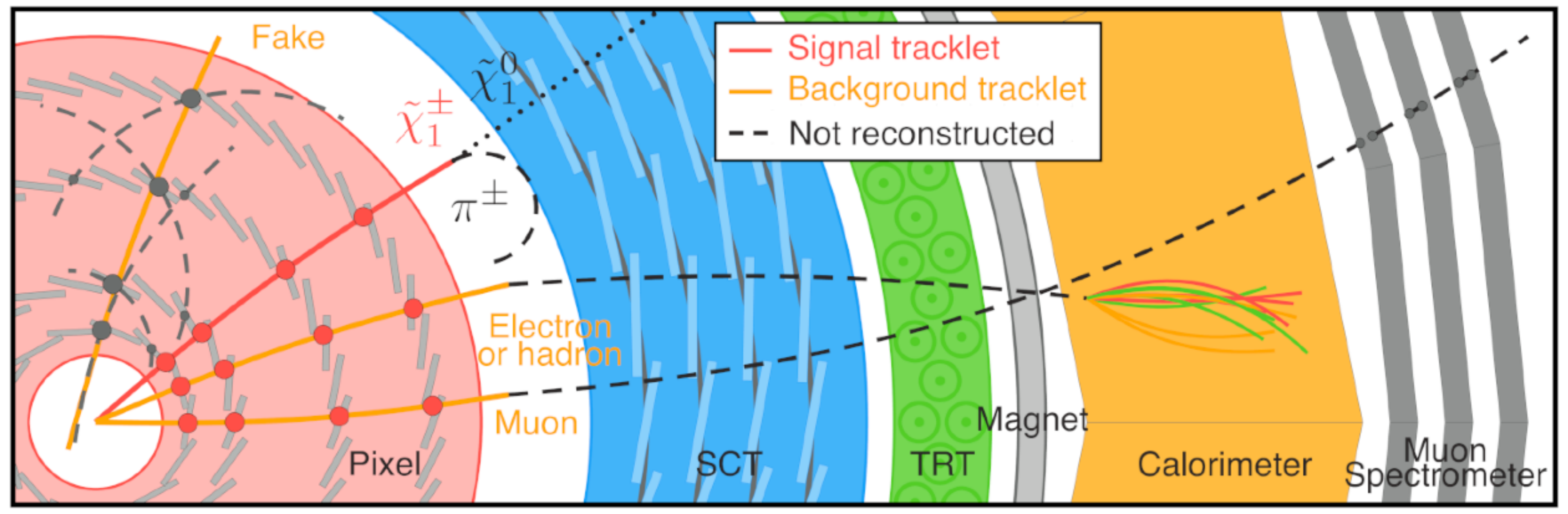


Search for disappearing tracks



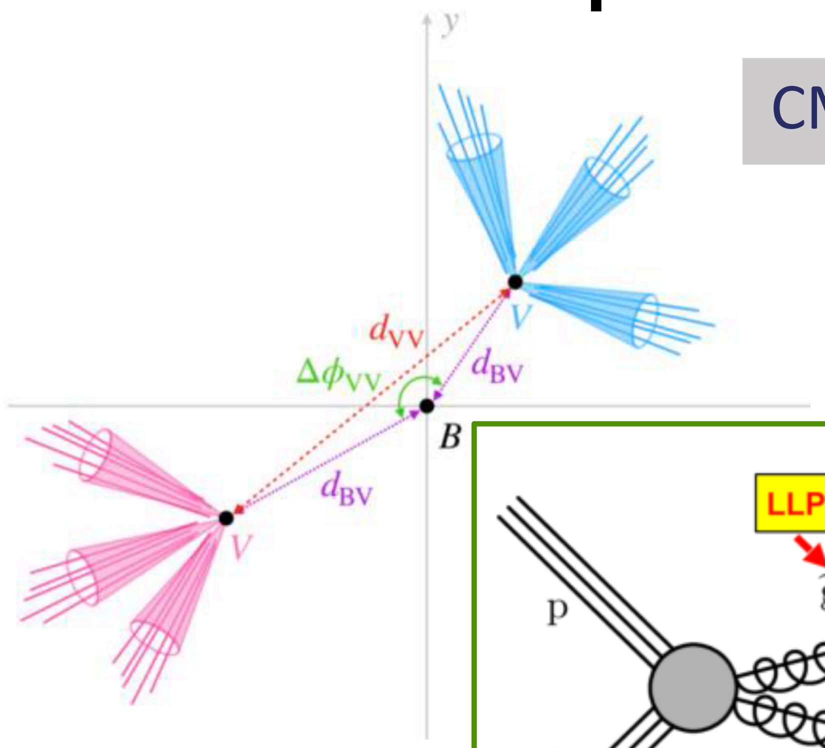
ATLAS-CONF-2021-015

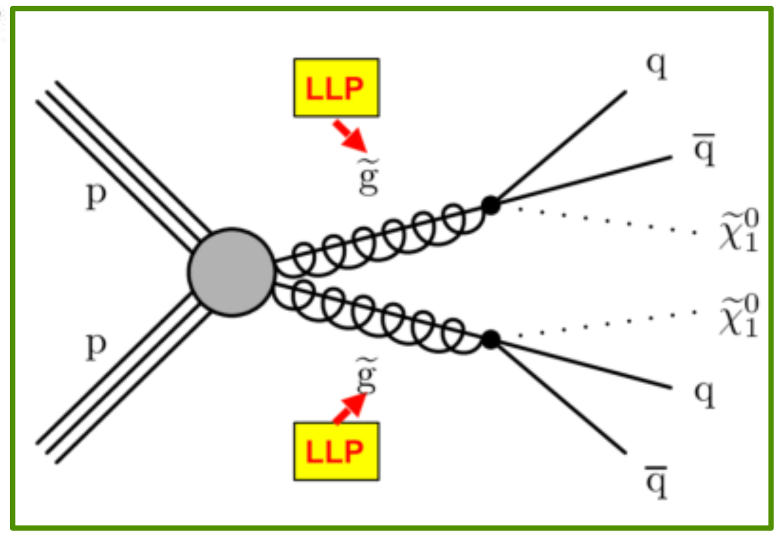




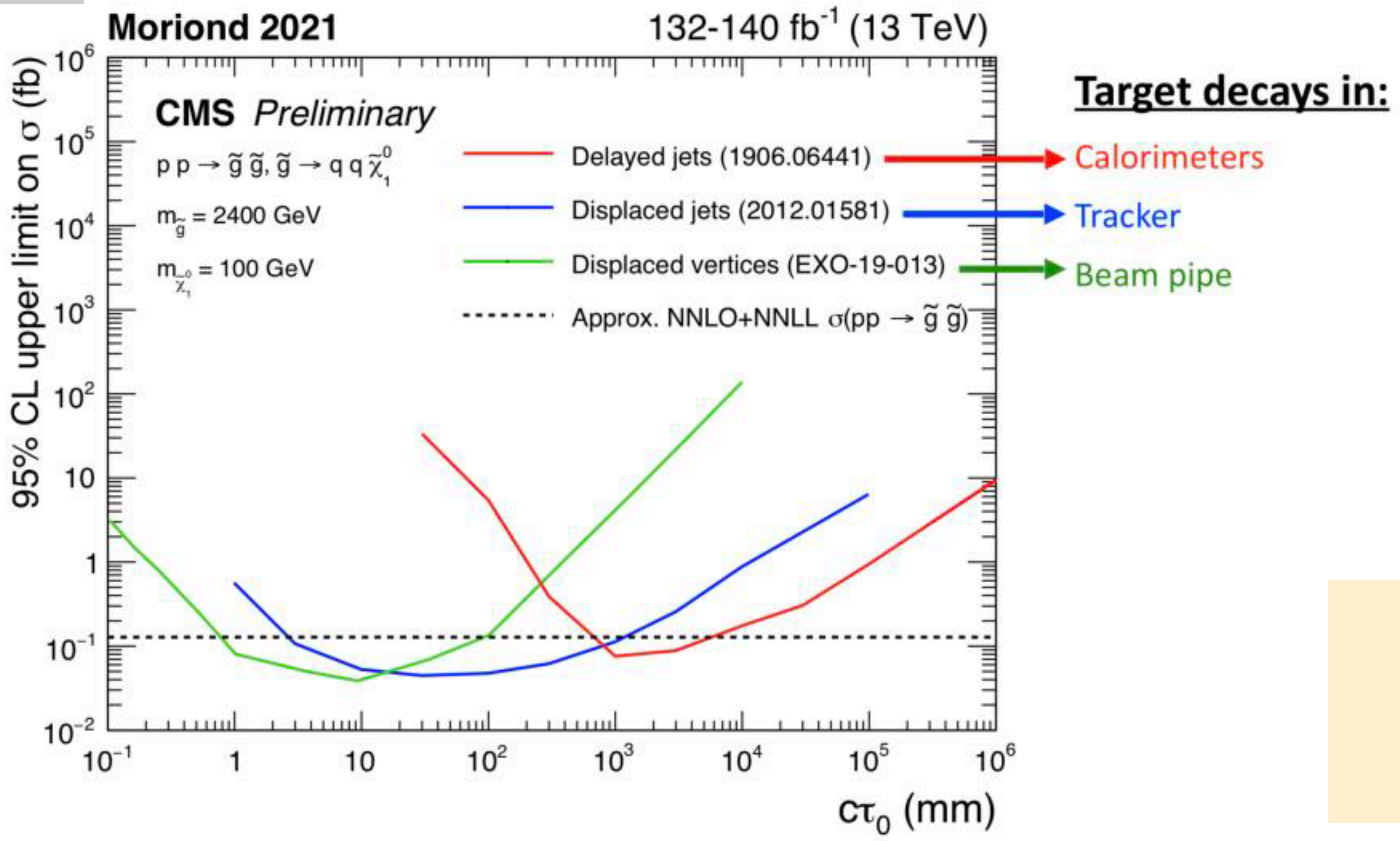
Search for displaced multitrack vertices

CMS-PAS-EXO-19-013





RPV SUSY benchmark



Special triggers are being developed to improve sensitivity to unconventional signatures in Run-3

Summary of Winter Conferences 2021

Séminaire DPhP

May 3, 2021

CEA - Saclay

Gautier Hamel de Monchenault ➡ SM, BSM and flavour

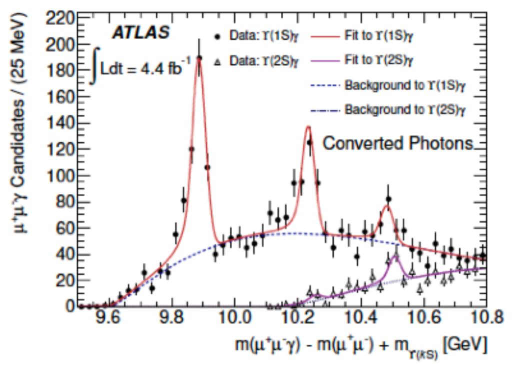
Sotiris Loucatos ➡ neutrinos and astroparticles

Maarten Boonekamp ➡ precision measurements

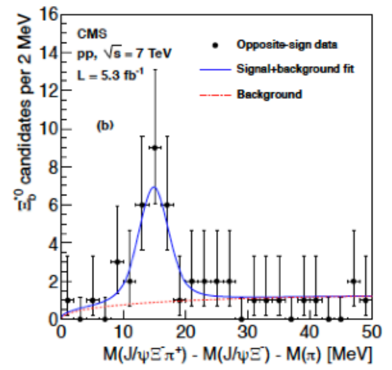
Particles Discovered at the LHC

Over the past 10 years the LHC has discovered

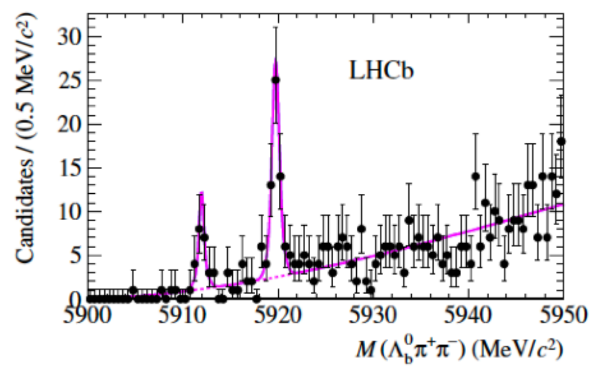
59 new hadrons



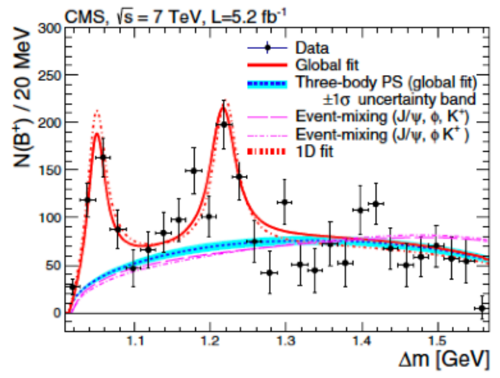
(a) $\chi_b(3P)$ [1]



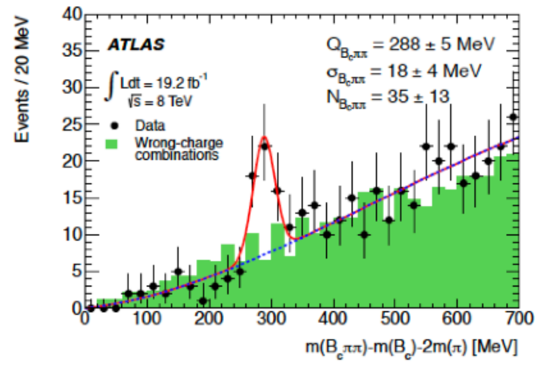
(b) Ξ_b^{*0} [2]



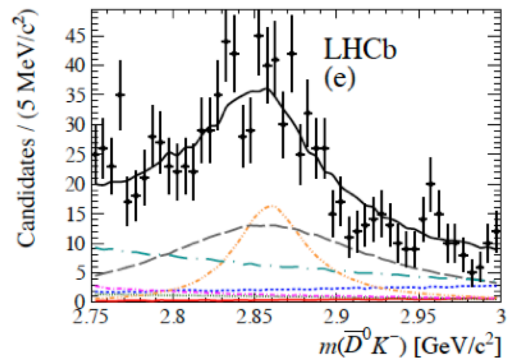
(c) $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$ [3]



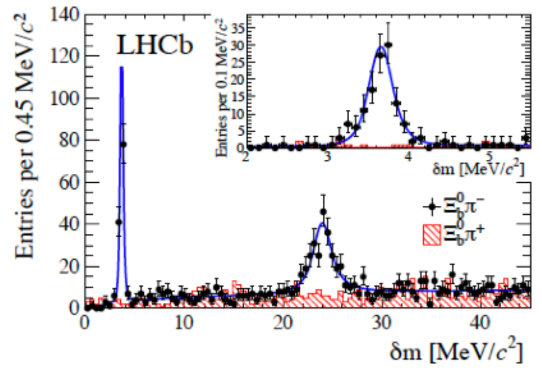
(d) $X(4140)$ [4]



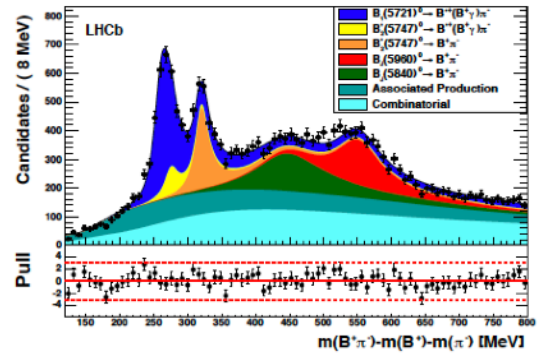
(e) $B_c(2S)^+$ [5]



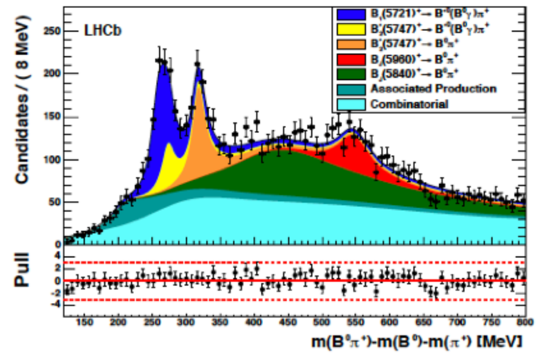
(f) $D_{s1}^*(2860)^-$ [6]



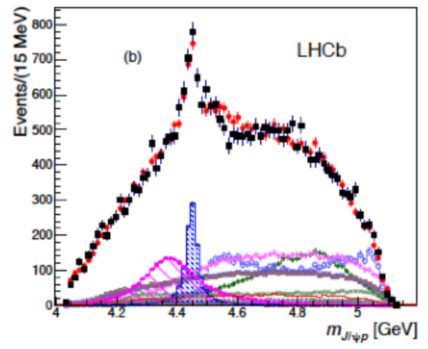
(g) Ξ_b^{*-}, $\Xi_b^{'-}$ [7]



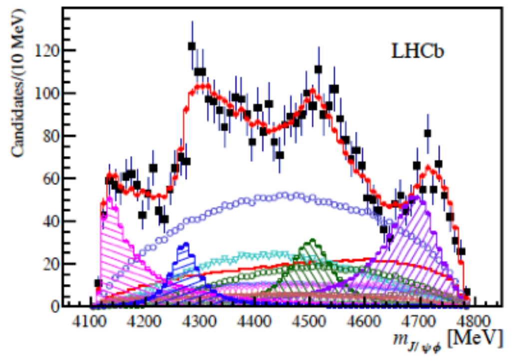
(h) $B_J(5840)^0$, $B_J(5970)^0$ [8]



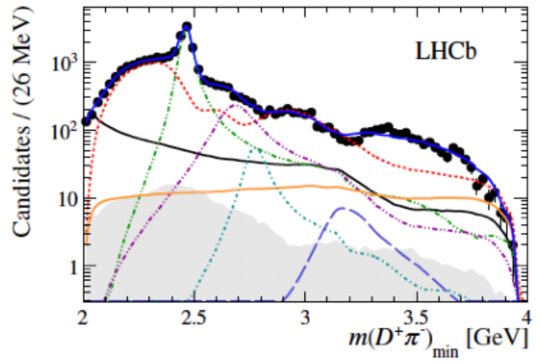
(i) $B_J(5840)^+$, $B_J(5970)^+$ [8]



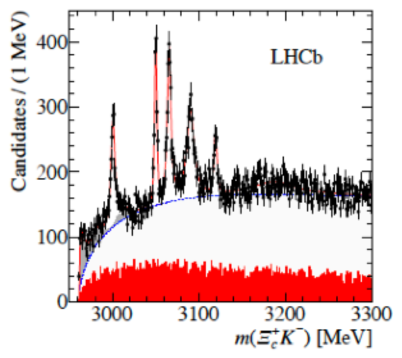
(j) $P_c(4380)^+$, $P_c(4450)^+$ [9]



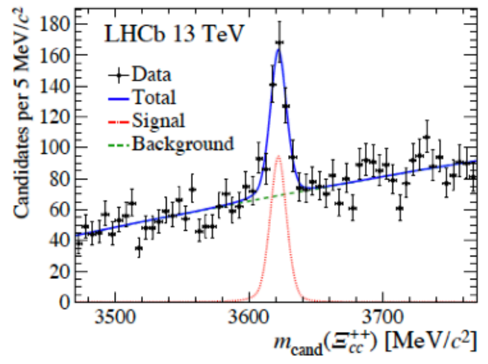
(k) $X(4274)$, $X(4500)$, $X(4700)$ [10]



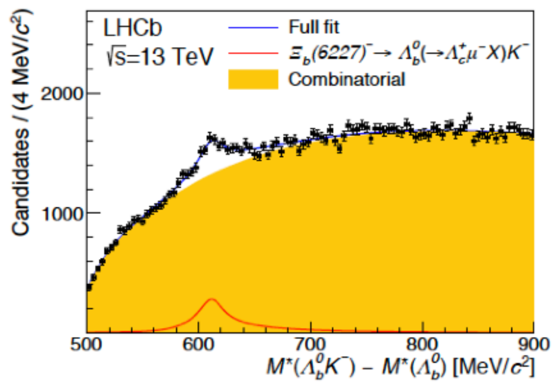
(l) $D_3^*(2760)^0$, $D_2^*(3000)^0$ [11]



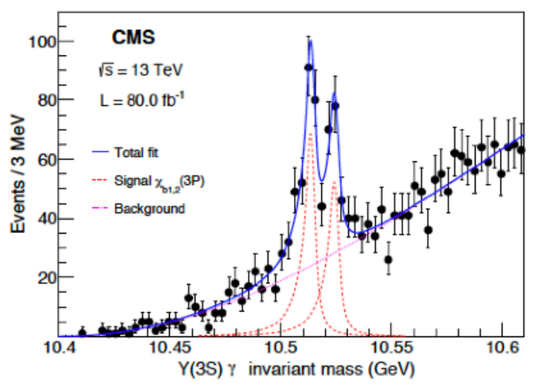
(m) Five Ω_c^0 [12]



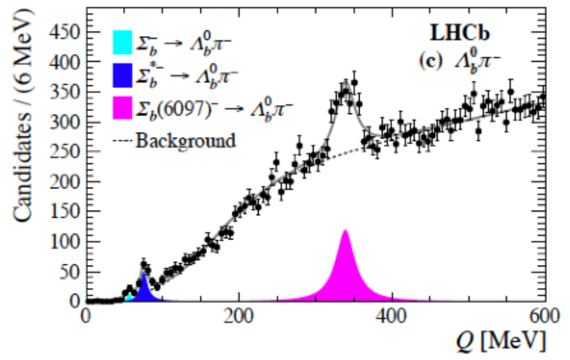
(n) Ξ_{cc}^{++} [13]



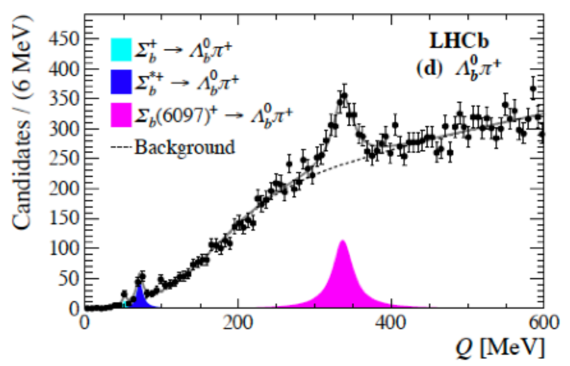
(o) $\Xi_b(6227)^-$ [14]



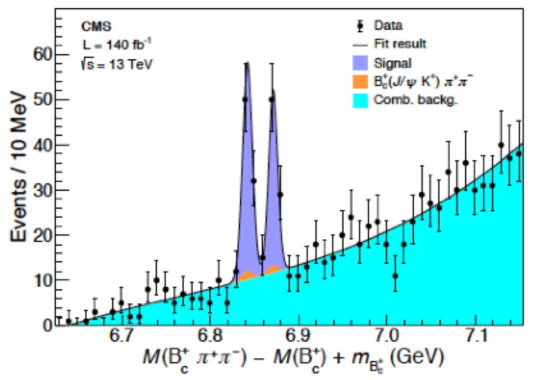
(p) $\chi_{b1}(3P)$, $\chi_{b2}(3P)$



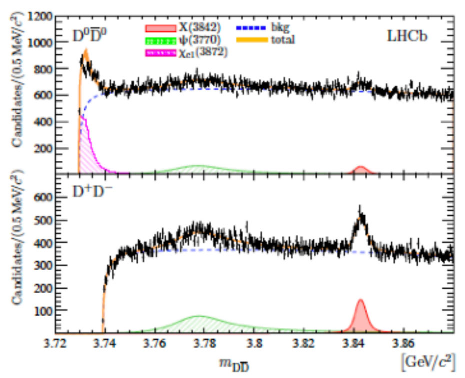
(q) $\Sigma_b(6097)^-$ [16]



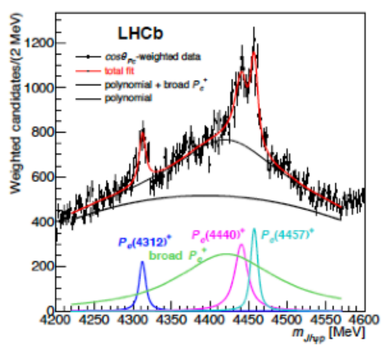
(r) $\Sigma_b(6097)^+$ [16]



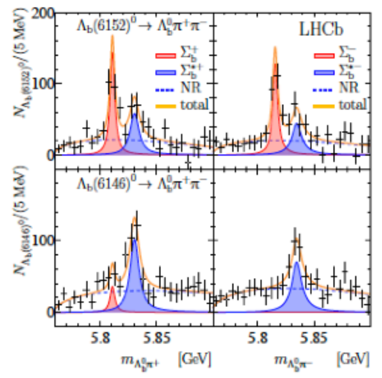
(s) $B_c(2S)^+$, $B_c^*(2S)^+$



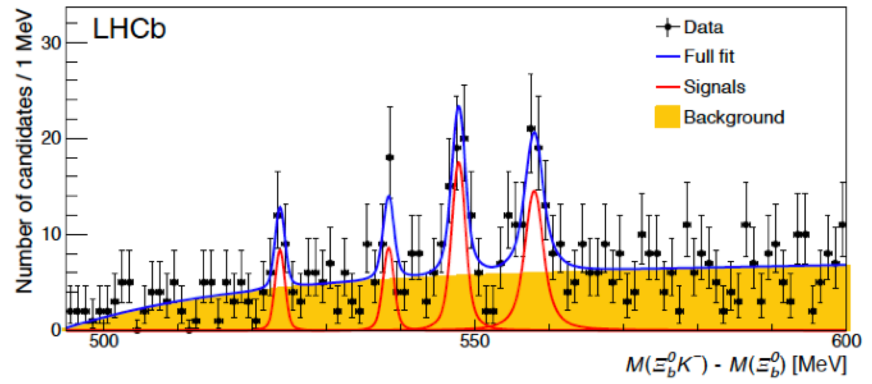
(t) $X(3842)$ [18]



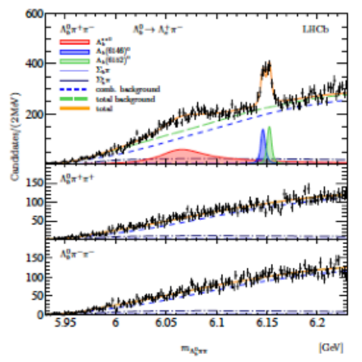
(u) $P_c(4440)^+$, [19]



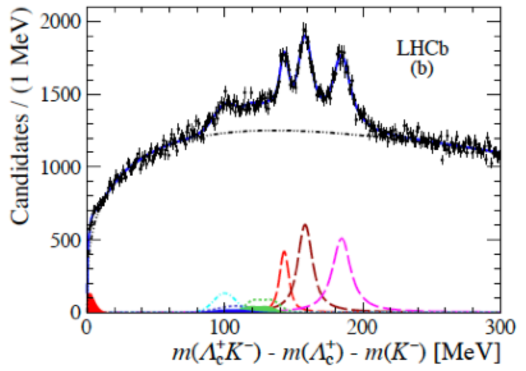
(v) $\Lambda_b(6146)^0$, $\Lambda_b(6152)^0$ [20]



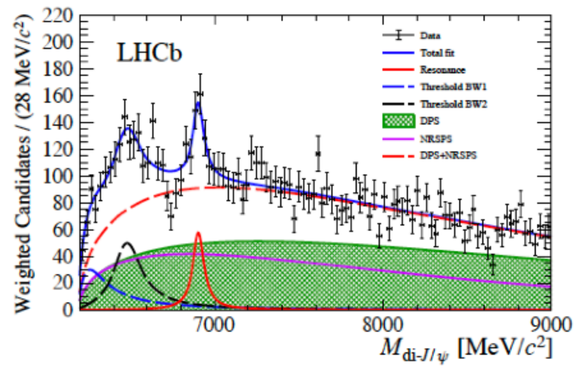
(w) $\Omega_b(6340)^-$, $\Omega_b(6350)^-$ [21]



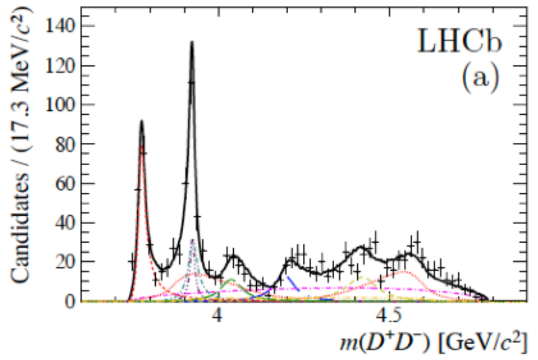
(x) $\Lambda_b(6070)^0$ [22]



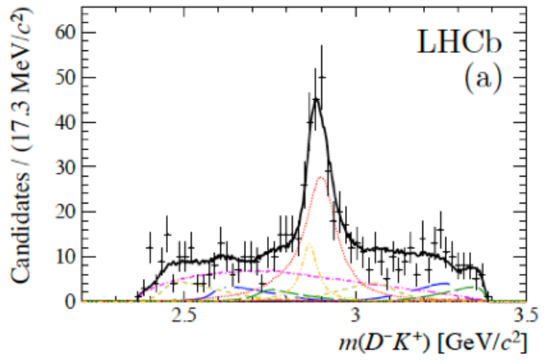
(y) $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ [23]



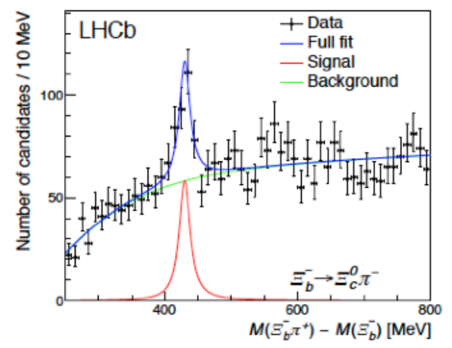
(z) $T_{c\bar{c}c\bar{c}}$ [24]



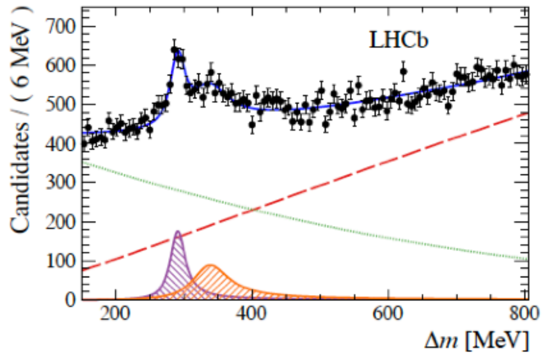
(aa) $\chi_{c0}(3930)$ [25]



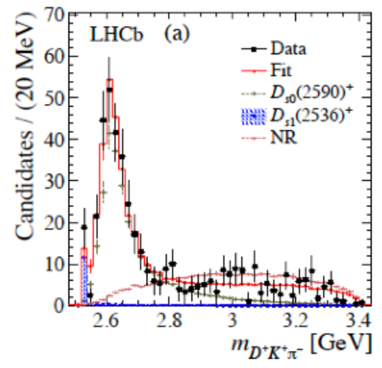
(ab) $X_0(2900)$, $X_1(2900)$ [25]



(ac) $\Xi_b(6227)^0$ [26]



(ad) $B_s(6063)^0$, $B_s(6114)^0$ [27]



(ae) $D_{s0}(2590)^+$ [28]

tt+Z and tt+γ

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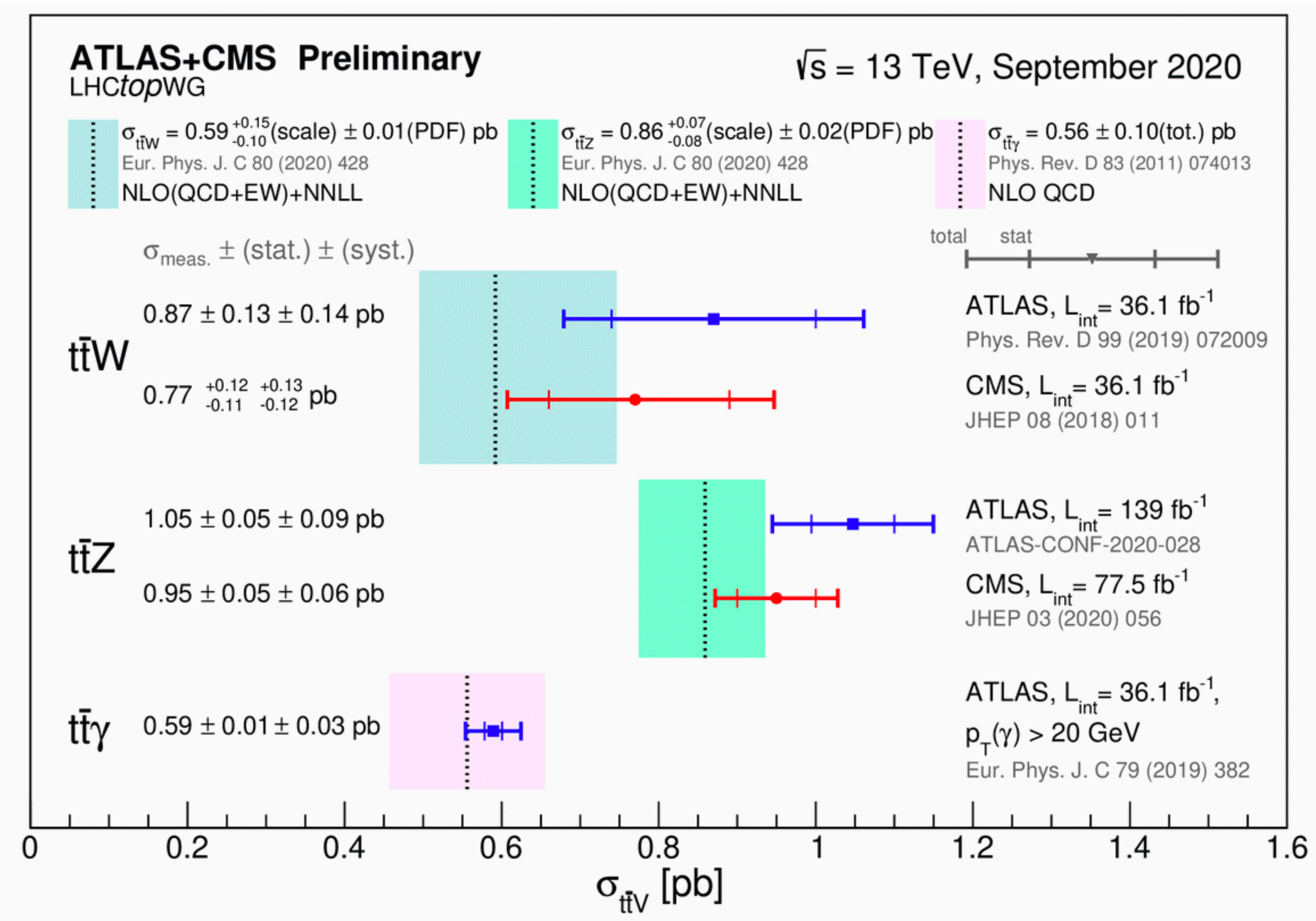
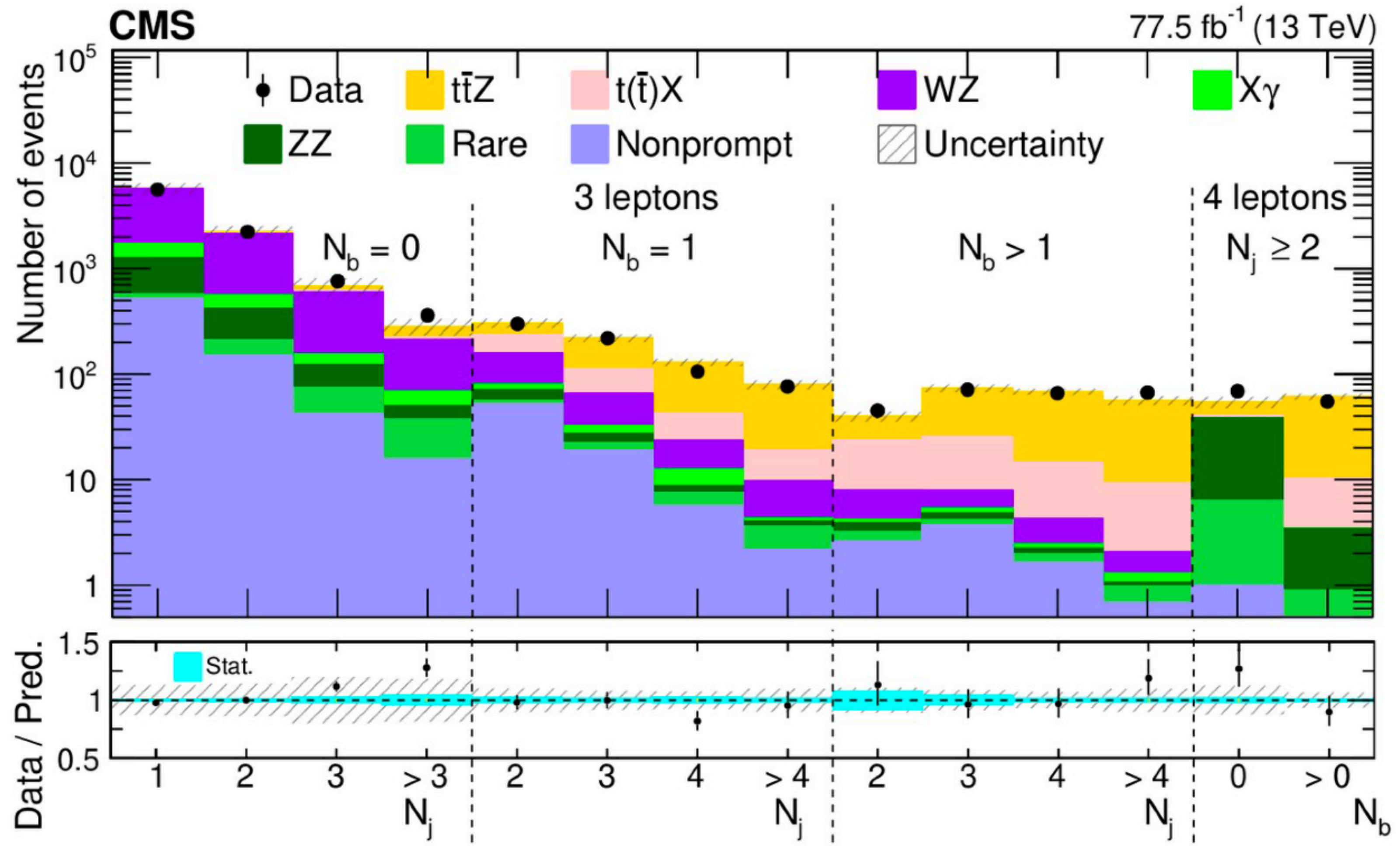


in agreement with NLO+NNLL predictions



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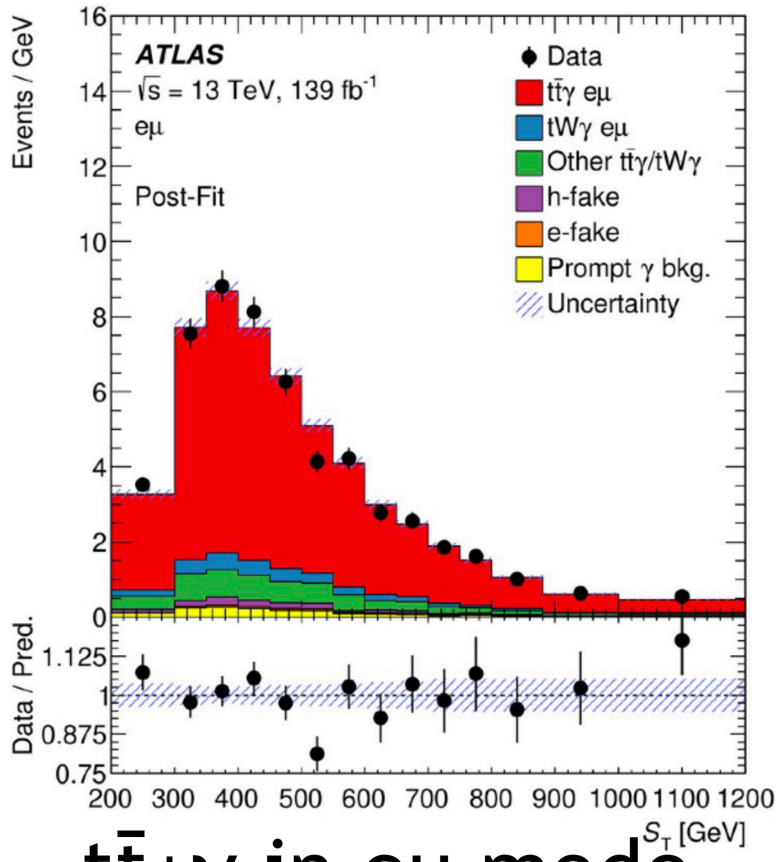

tt̄+γ in eμ mode

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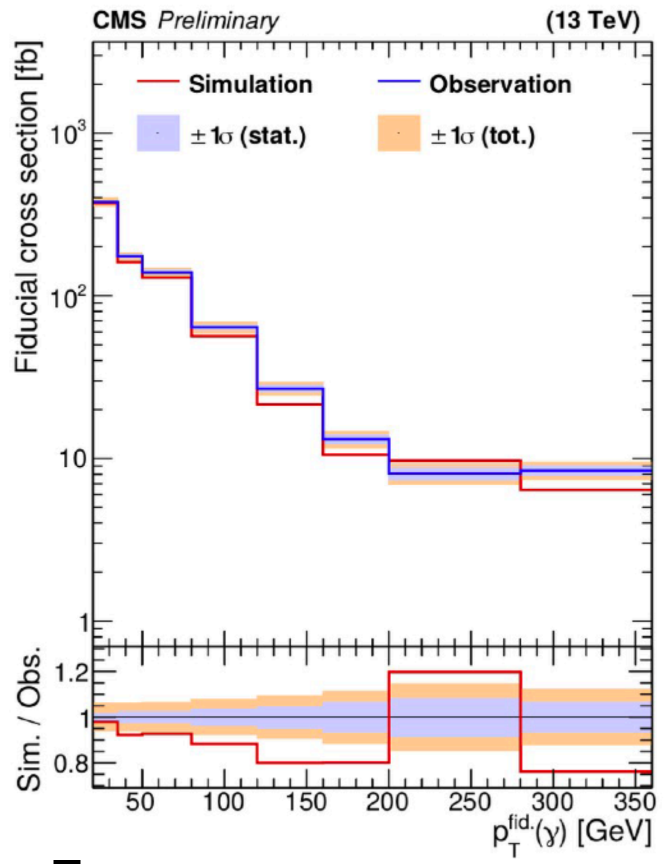

tt̄+γ in ℓ+jets mode