The 10th Annual
Large Hadron Collider Physics Conference
May 16-21, 2022

2022 LHCP TAIPEI ONLINE

EXPERIMENTAL HIGHLIGHTS

10th Edition of the Large Hadron Collider Physics Conference

Monica Pepe Altarelli
CERN


This talk
Live from my
Office!

LHCP in numbers

- ~32 experimental plenary talks
- Well over 100 parallel sessions talks on EW, top, Higgs, BSM@TeV scale, BSM:Feebly interacting particles, Flavour, Heavy Ions, Performance&Tools, QCD, upgrades&future projects, Outreach, diversity &education
- Subject distribution broadly reflects that of the > 3000 papers published/submitted to refereed journals by the LHC experiments (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL) M. Mangano
  - ~10% on Higgs
  - ~30% on searches for new physics
  - ~60% on SM measurements (jets, EW, top, b, heavy ions,…)
- Impossible to cover/follow everything (up to 8 parallel sessions!) and I had to make choices certainly biased by my own personal judgment, “imperfect understanding” and simply …fatigue/saturation. In general I tried to privilege more recent results.

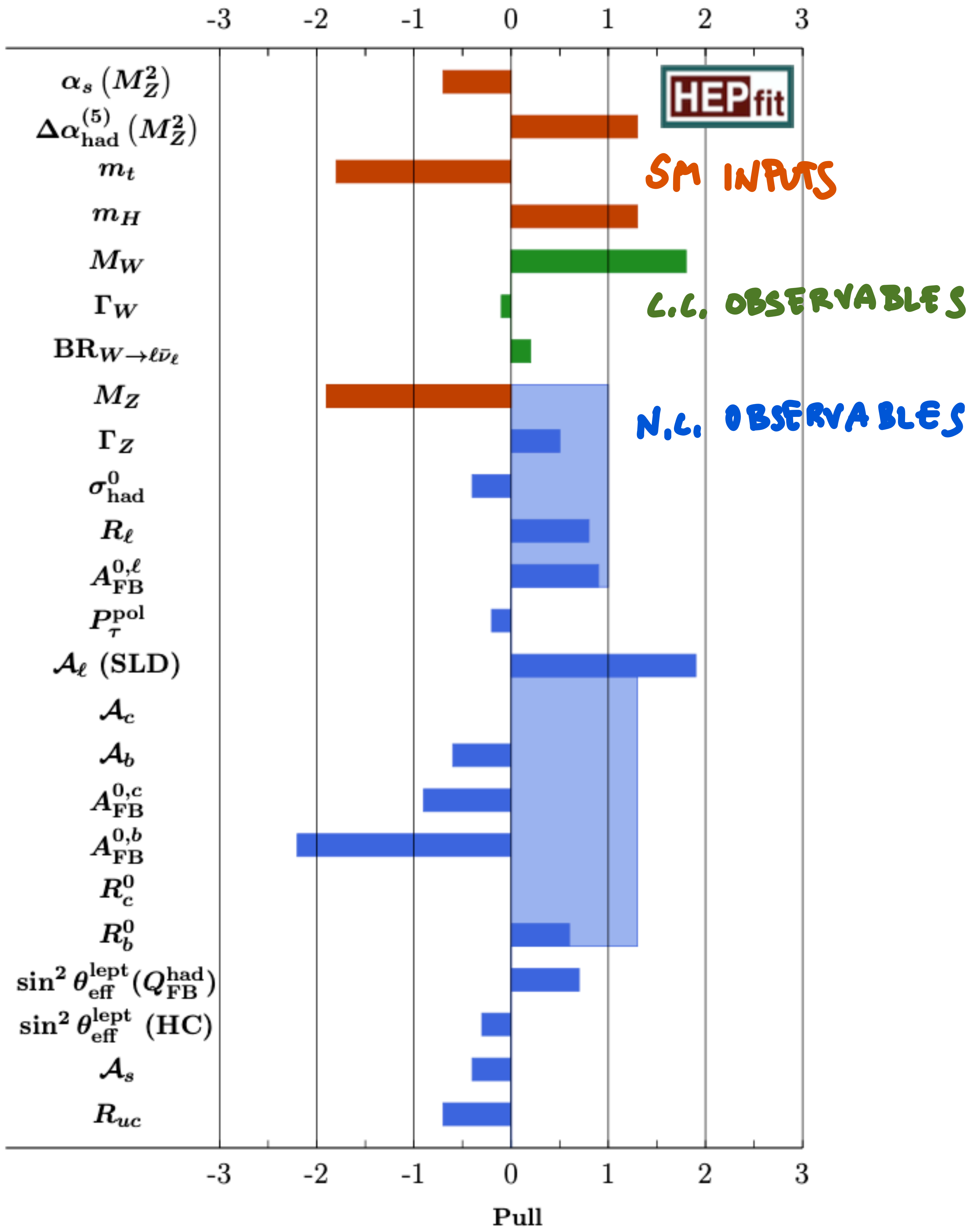
ELECTROWEAK PHYSICS

Precision! Precision!

- The quest for significant deviations of the measured parameters of the SM from their prediction is a mandatory plan
- Current measurements of EW observables are consistent with the SM predictions
- For many observables the indirect determinations are more precise than the experimental measurements → Increase the precision!

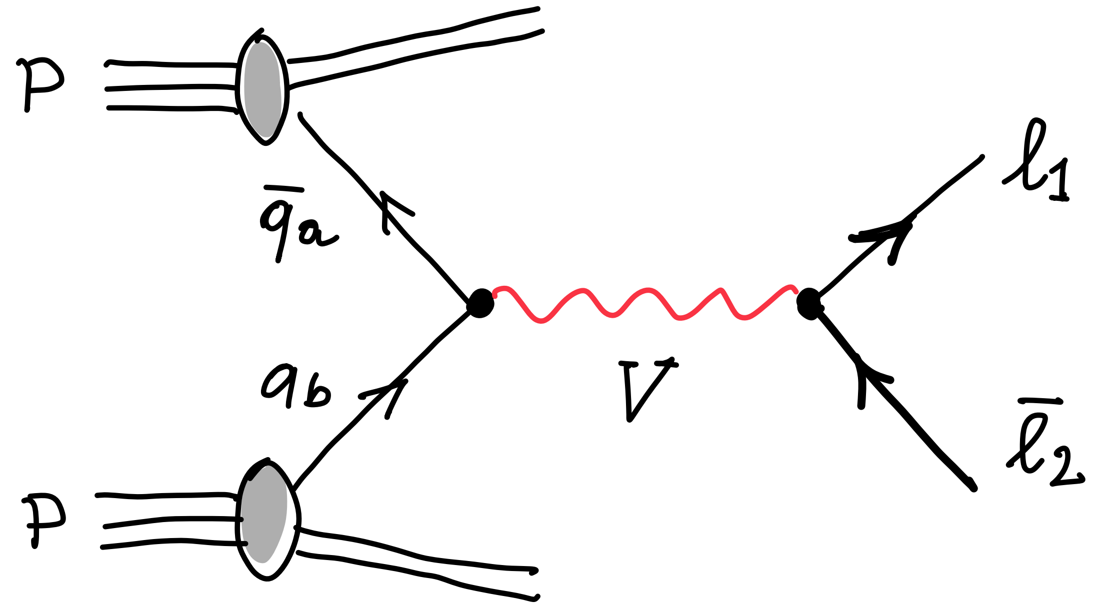
Global fit of EW data

[arXiv:2112.07274v1]



Inclusive $W^{\pm}$ & Z production

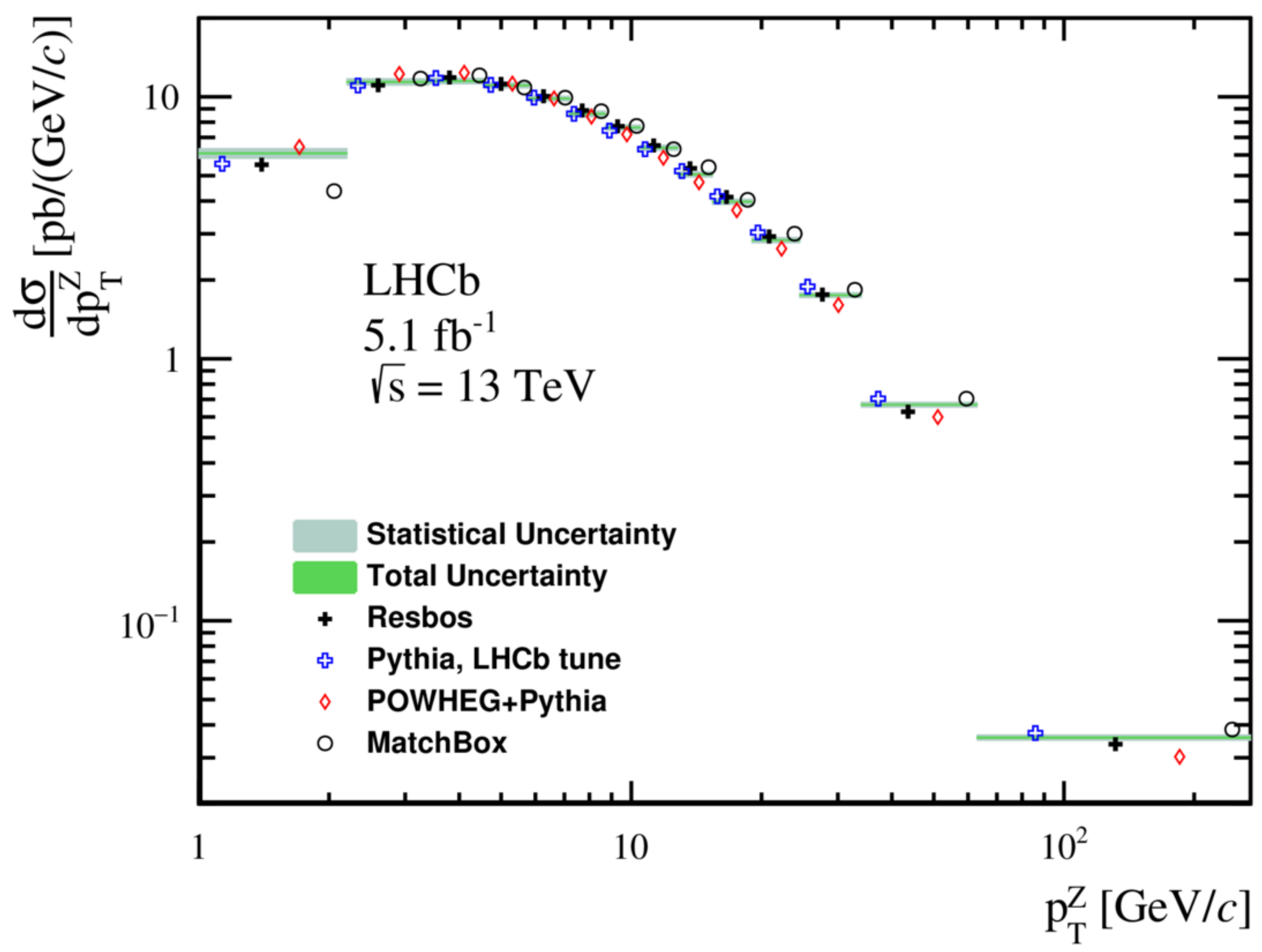
Menglin Xu



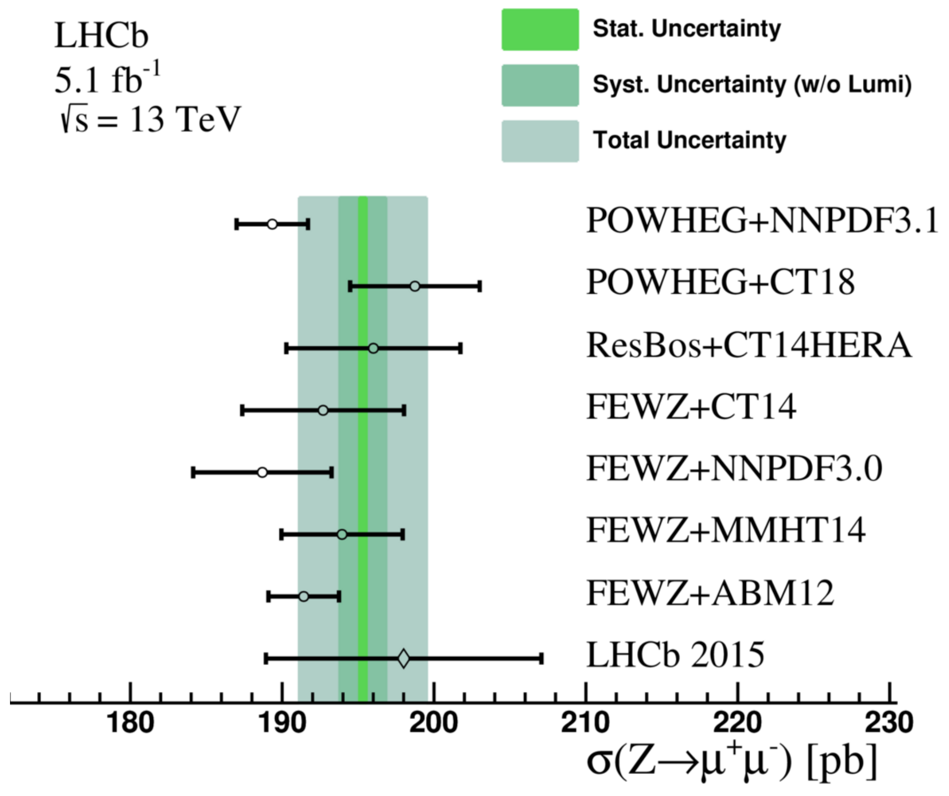
- Very well understood processes at hadron colliders
- $W \to \ell\nu$ and $Z \to \ell\ell$ $(\ell = e, \mu)$ are among the cleanest final states experimentally: many, many measurements → derive various EW parameters, probe QCD effects and put constraints on NP
- Two recent examples…

Precise measurement by LHCb of $\sigma(Z \to \mu^+\mu^-)$ in the forward region (integrated and differential) [arXiv:2122.07458]

Important information for the PDF determination

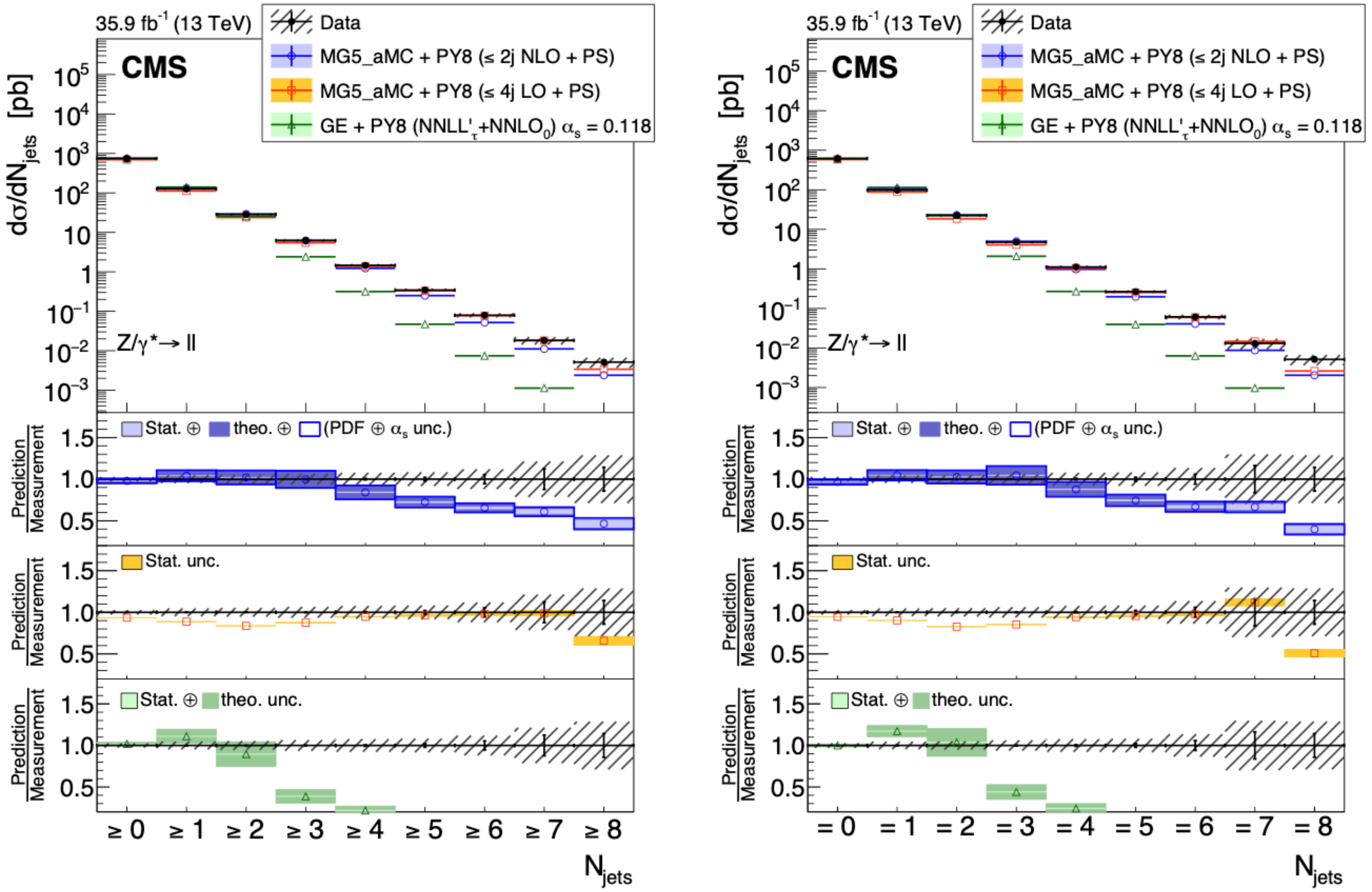


$\sigma_{Z\to\mu^+\mu^-} = 195.3 \pm 0.2_{stat} \pm 1.5_{syst} \pm 3.9_{Lumi}$ pb



Differential cross-section of Z+jets by CMS [arXiv:2202.12327]

Gain better theoretical understanding of both strong and EW physics in jet environment



W mass @ LHCb

M. VESTERINEN

- Measurement based on shape of p_T distribution of muons from W decay
- Simultaneous fit of q/p_T of muons from W and of ϕ^* of $Z \to \mu\mu$

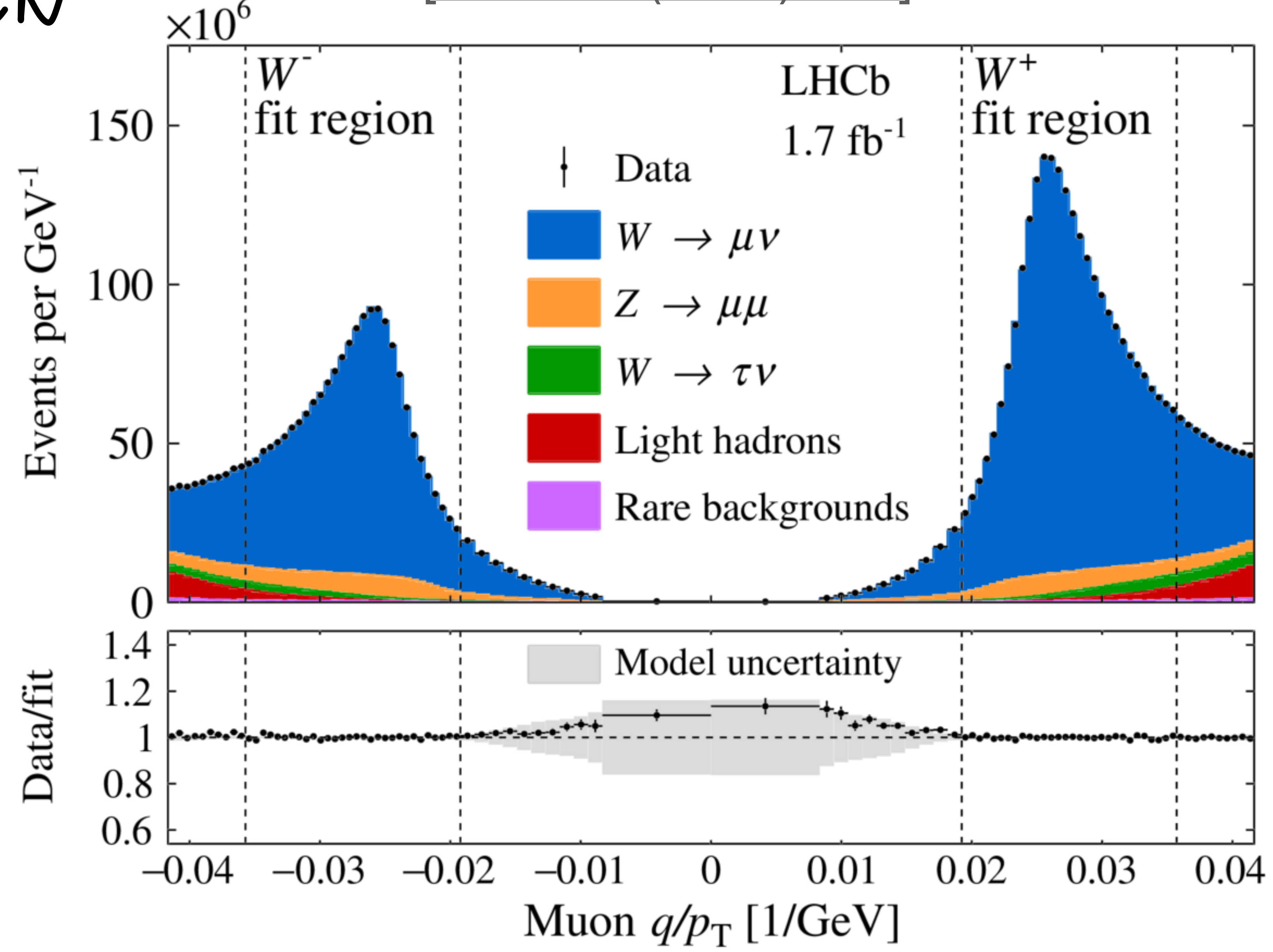
Proxy of p_T^Z

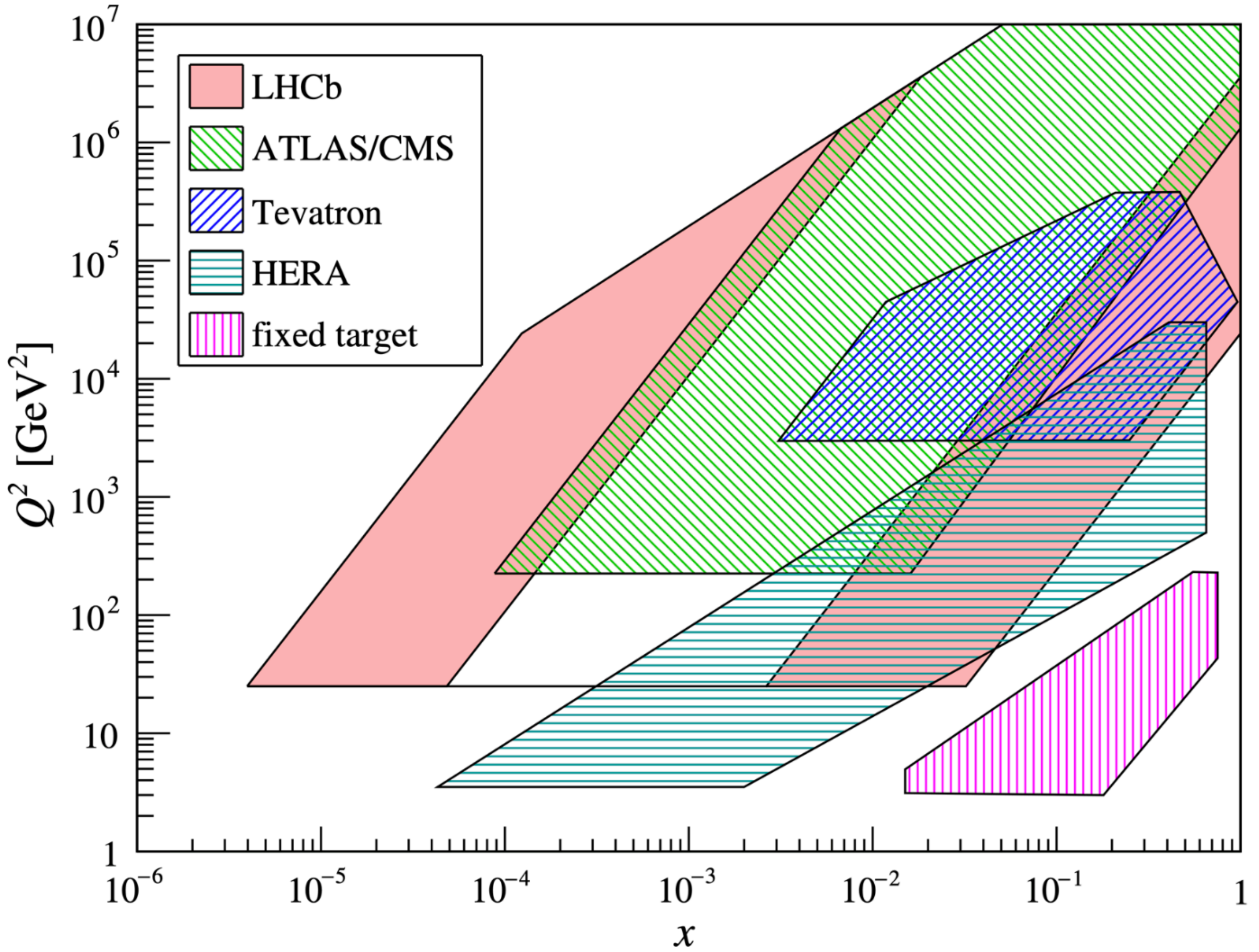
$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

~32 MeV total

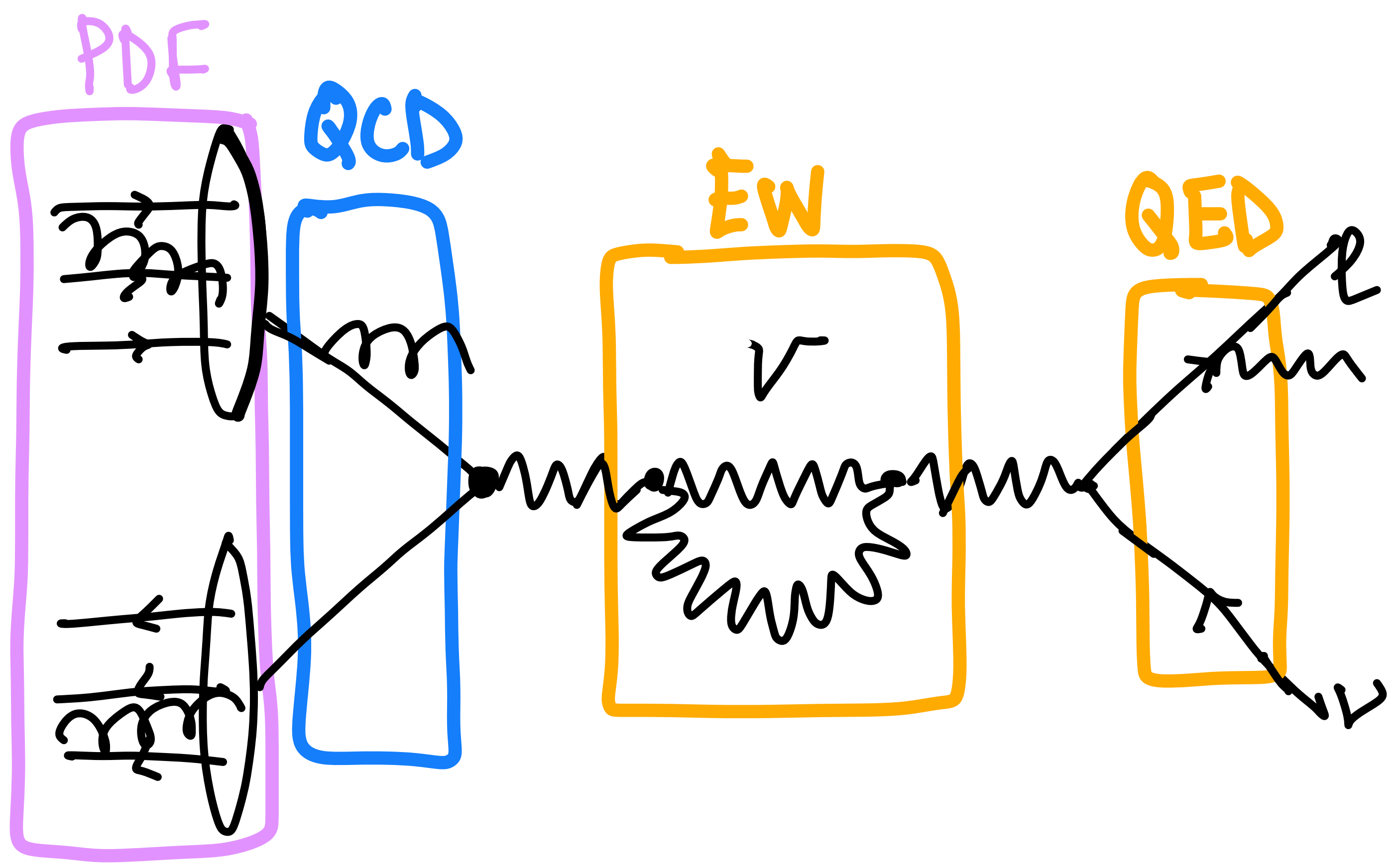
- Result based on $1.7\ \text{fb}^{-1}$ (3x more data on tape); effort now on improving the modelling and reducing the systematic uncertainties
- Important because LHCb probes an acceptance region complementary to that of ATLAS/CMS
- Exploit anticorrelation of PDF uncertainties to partially cancel uncertainties in M_W combination

[JHEP01 (2022) 036]





Current status of M_W



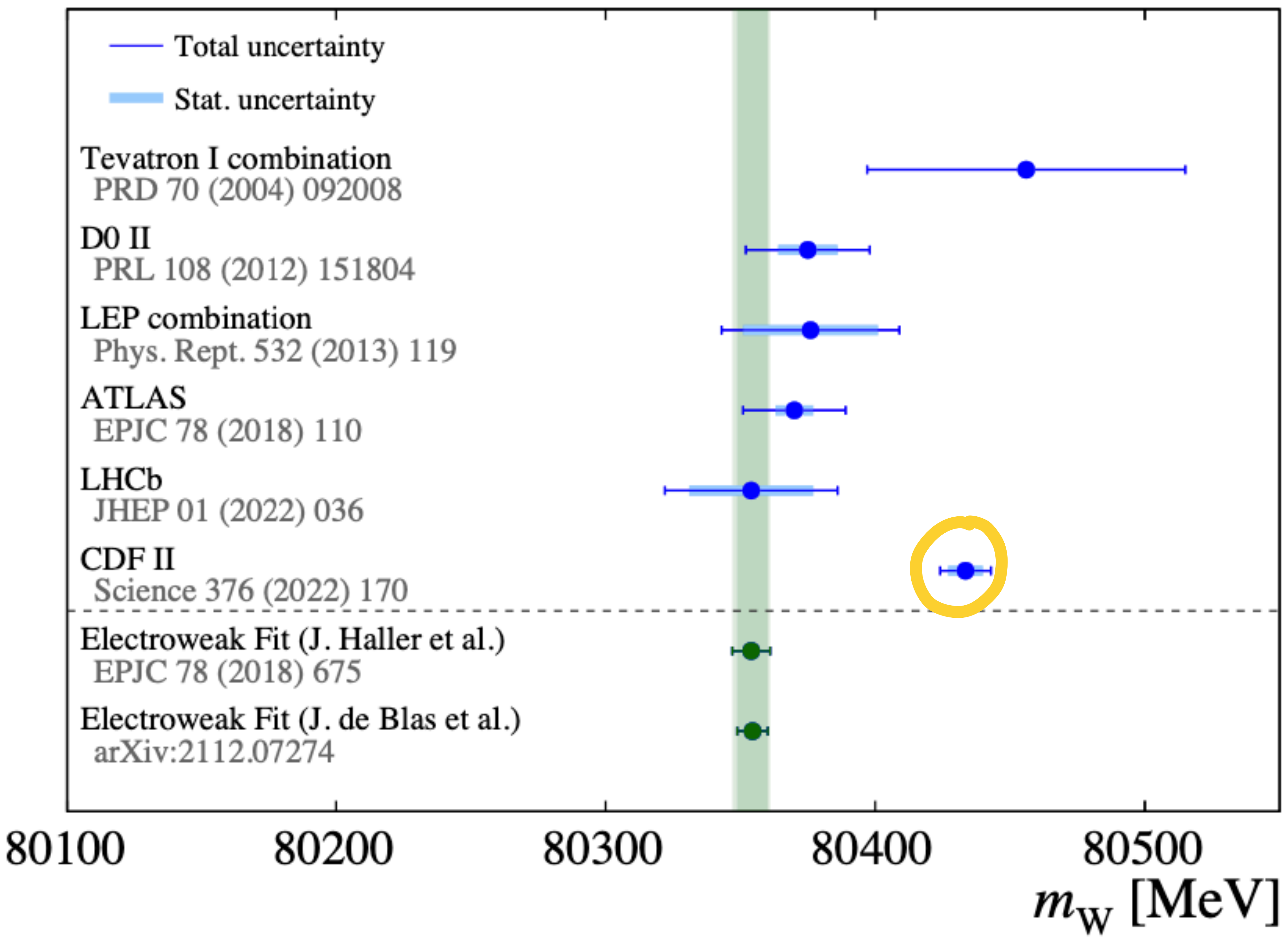
- Global EW fit provides prediction with 7 MeV precision
- Most precise measurement at LHC by ATLAS
  - 19 MeV, of which 7(stat),11(exp.syst),14(modelling syst) ← PDFs
- New, impressive result from CDF :

$$M_W = 80433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}}\ \text{MeV}$$
$$= 80433.5 \pm 9.4\ \text{MeV}$$

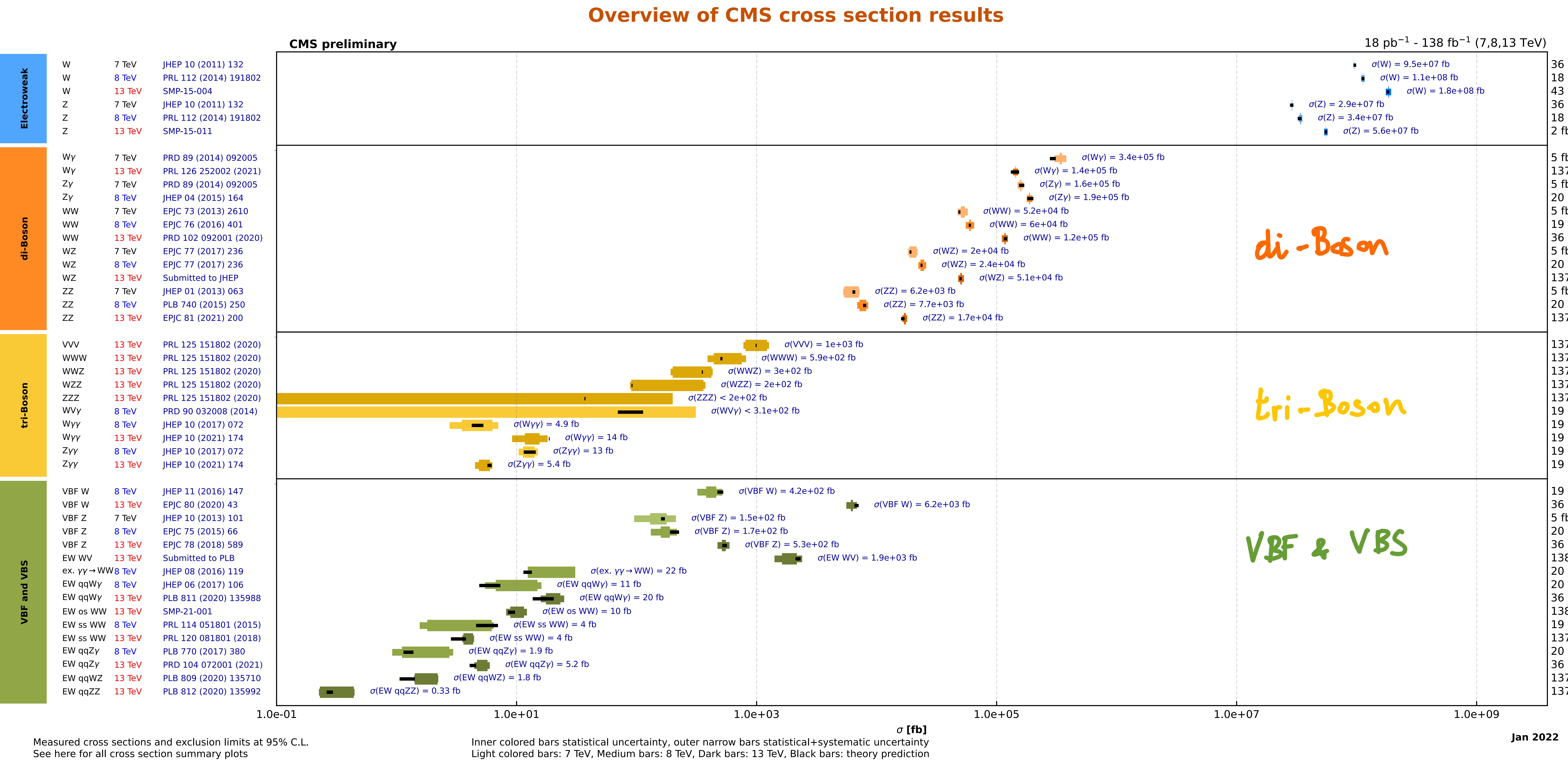
7σ from SM ! [Science 376 (2022) 170]

- @LHC larger signal and calibration samples (pp) but more challenging environment than Tevatron ($p\bar{p}$), eg
  - @Tevatron W production is charge symmetric and dominated by interactions with at least one valence quark, @LHC sea-quark PDFs play a larger role, including contributions from charm- and strange-quark PDFs
  - At higher c.m.energy, stronger dependence on modelling of p_T^W spectrum
- Priority is to understand tension between CDF and other experiments
- Eagerly waiting for CMS result

LHCB-FIGURE-2022-003



Multibosons

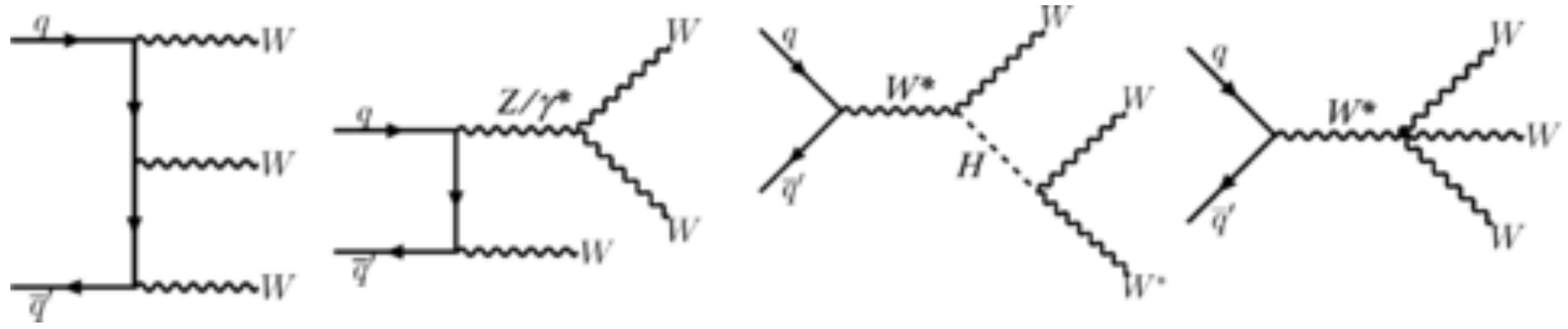


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

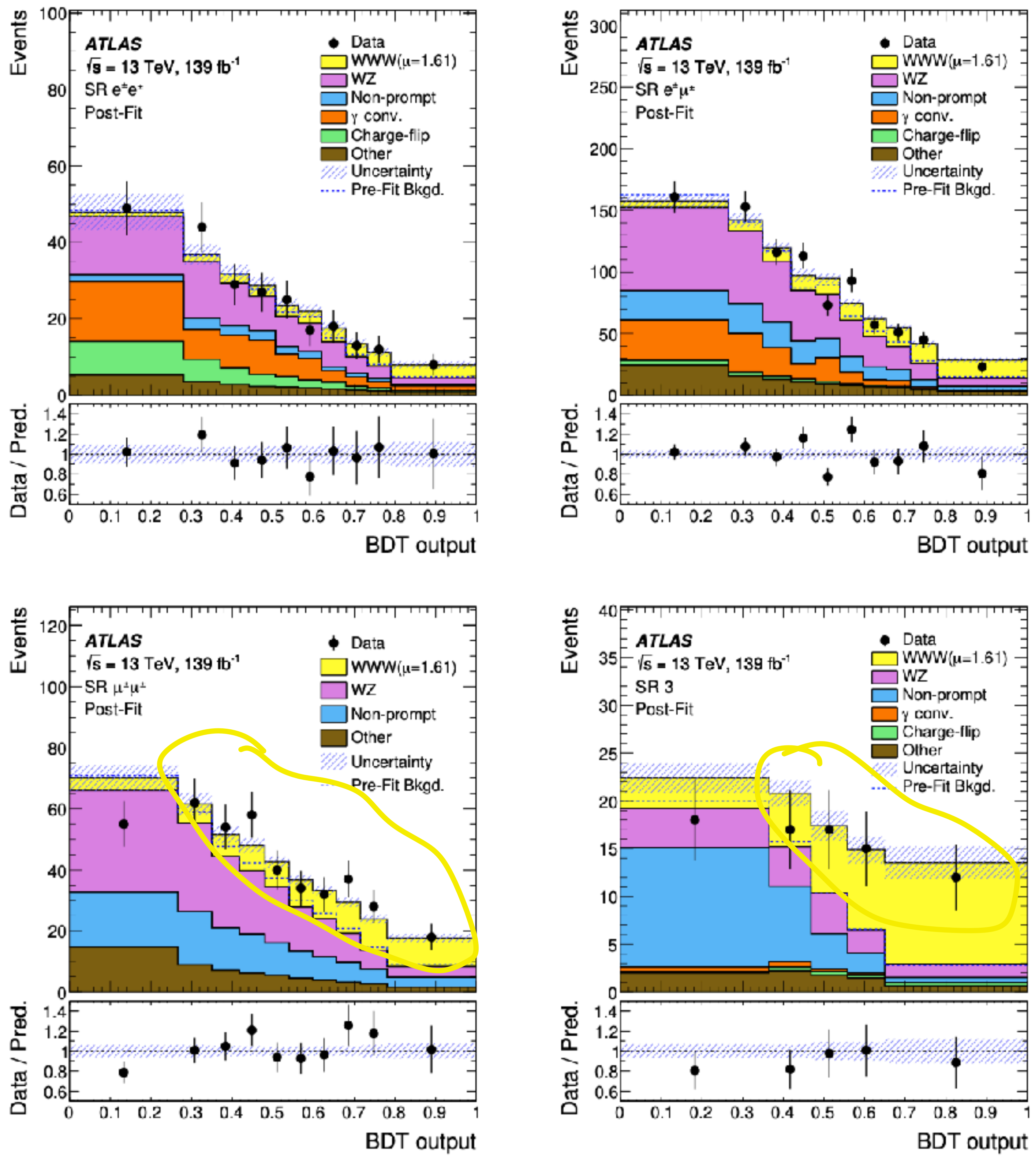
ATLAS first observation of WWW production

Ying An

- Measurements of triboson production are a direct test of SM gauge boson self-interactions, deviations would hint at NP
- Triboson final states are among the least-understood SM processes given the small production cross sections
- WWW production looked for by ATLAS in 2ℓ and 3ℓ final state



Fit	$\mu(WWW)$	Significance observed (expected)
$e^\pm e^\pm$	1.54 ± 0.76	$2.2\ (1.4)\ \sigma$
$e^\pm \mu^\pm$	1.44 ± 0.39	$4.1\ (3.0)\ \sigma$
$\mu^\pm \mu^\pm$	2.23 ± 0.46	$5.6\ (2.7)\ \sigma$
2ℓ	1.75 ± 0.30	$6.6\ (4.0)\ \sigma$
3ℓ	1.32 ± 0.37	$4.8\ (3.8)\ \sigma$
Combined	$\mathbf{1.61 \pm 0.25}$	$\mathbf{8.0\ (5.4)\ \sigma}$



[arXiv:2201.13045v1]

Observed for first time with a significance of 8.0 σ (5.4 expected)

$\sigma^{\text{incl}}_{WWW} = 820 \pm 100_{\text{stat}} \pm 80_{\text{syst}}$ fb

compatible with SM at $2.6\,\sigma$ (SM: 511 ± 18 fb)

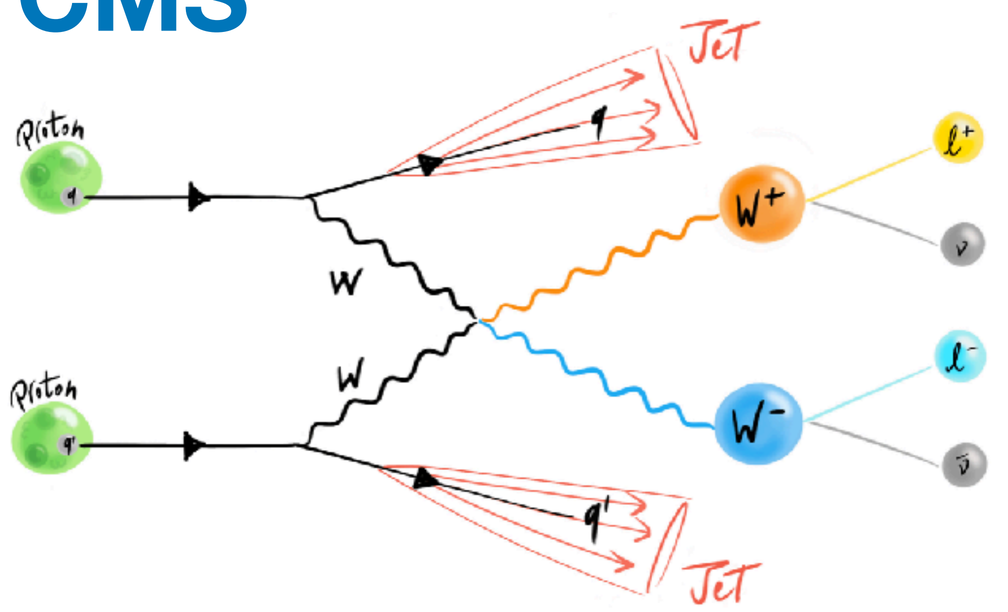
Vector Boson Scattering (VBS) @CMS

J. Nielsen
J. OLSEN
Jing Peng

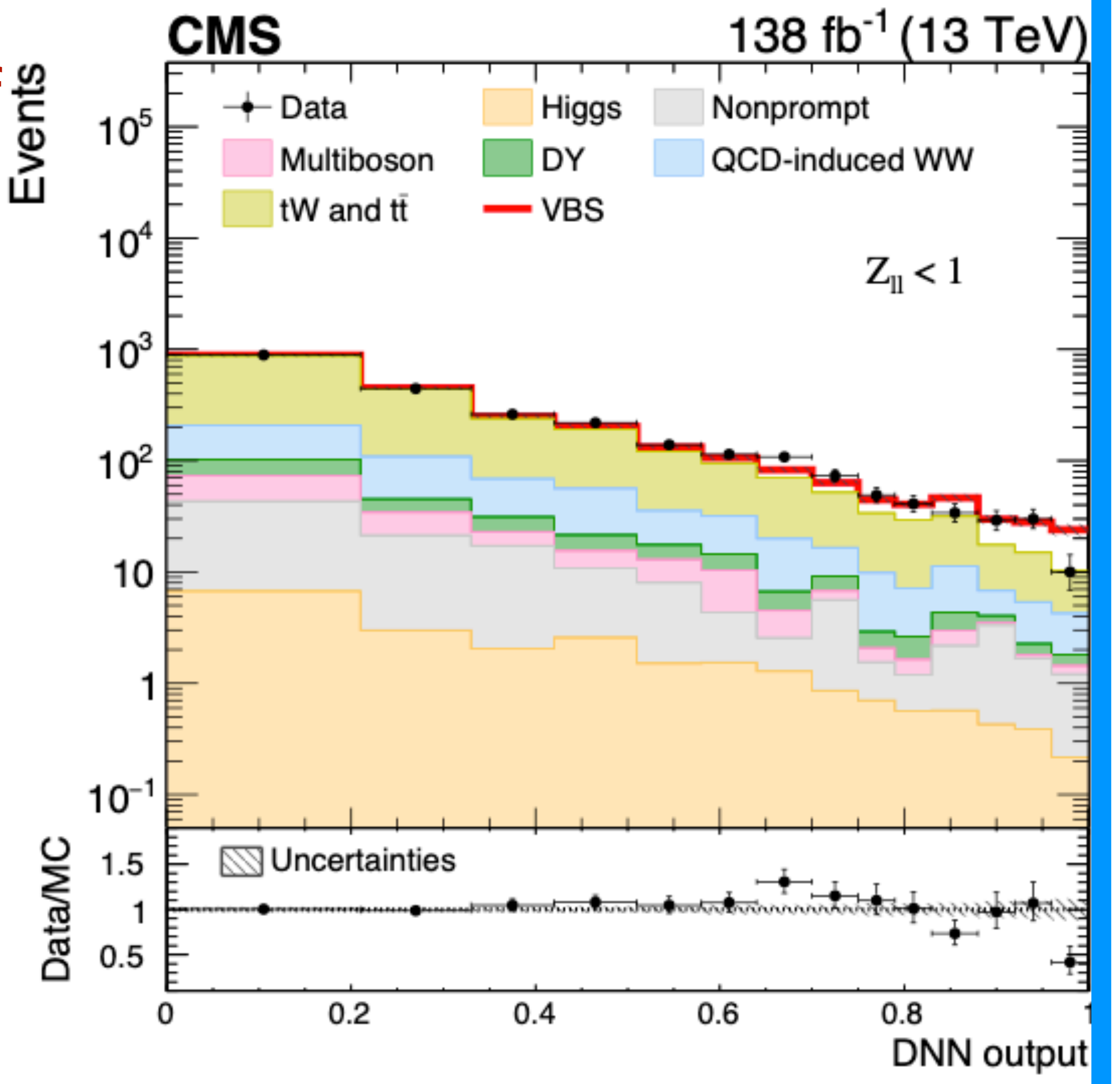
Study of VBS ($VV' \to VV'$) crucial to probe the nature of the Higgs sector →
The Higgs prevents unitarity violation in VBS by adding diagrams that cancel divergences

Observation of VBS in W^+W^- by CMS

- Experimentally challenging : very rare plus large $t\bar{t}$ background
- Experimental signature: two leptons (e or μ) and two jets with large pseudorapidity gap and large invariant mass
- W^+W^-jj signal observed with a significance of $5.6\,\sigma$ ($5.2\,\sigma$ expected). First observation in this channel



[arXiv:2205.05711]

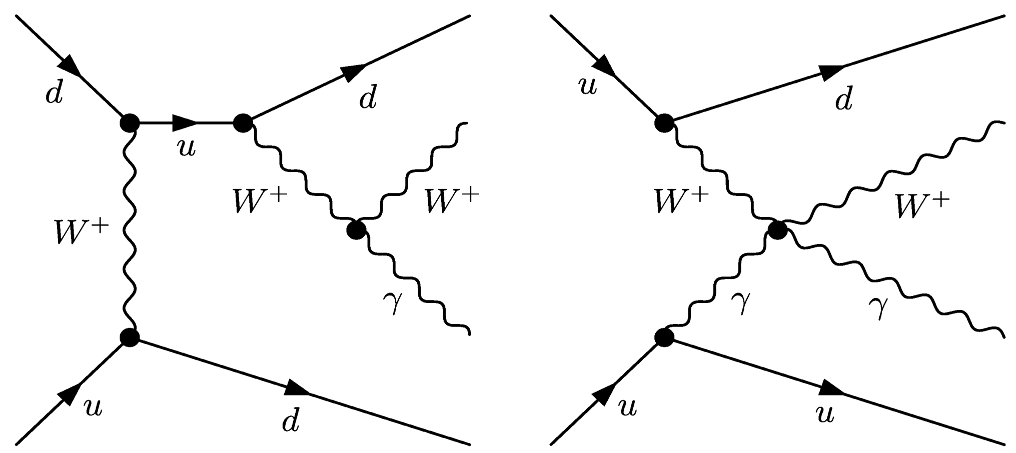


Fiducial cross section:

- **Measured = (10.2±2.0) fb**
- SM prediction = (9.1±0.6) fb

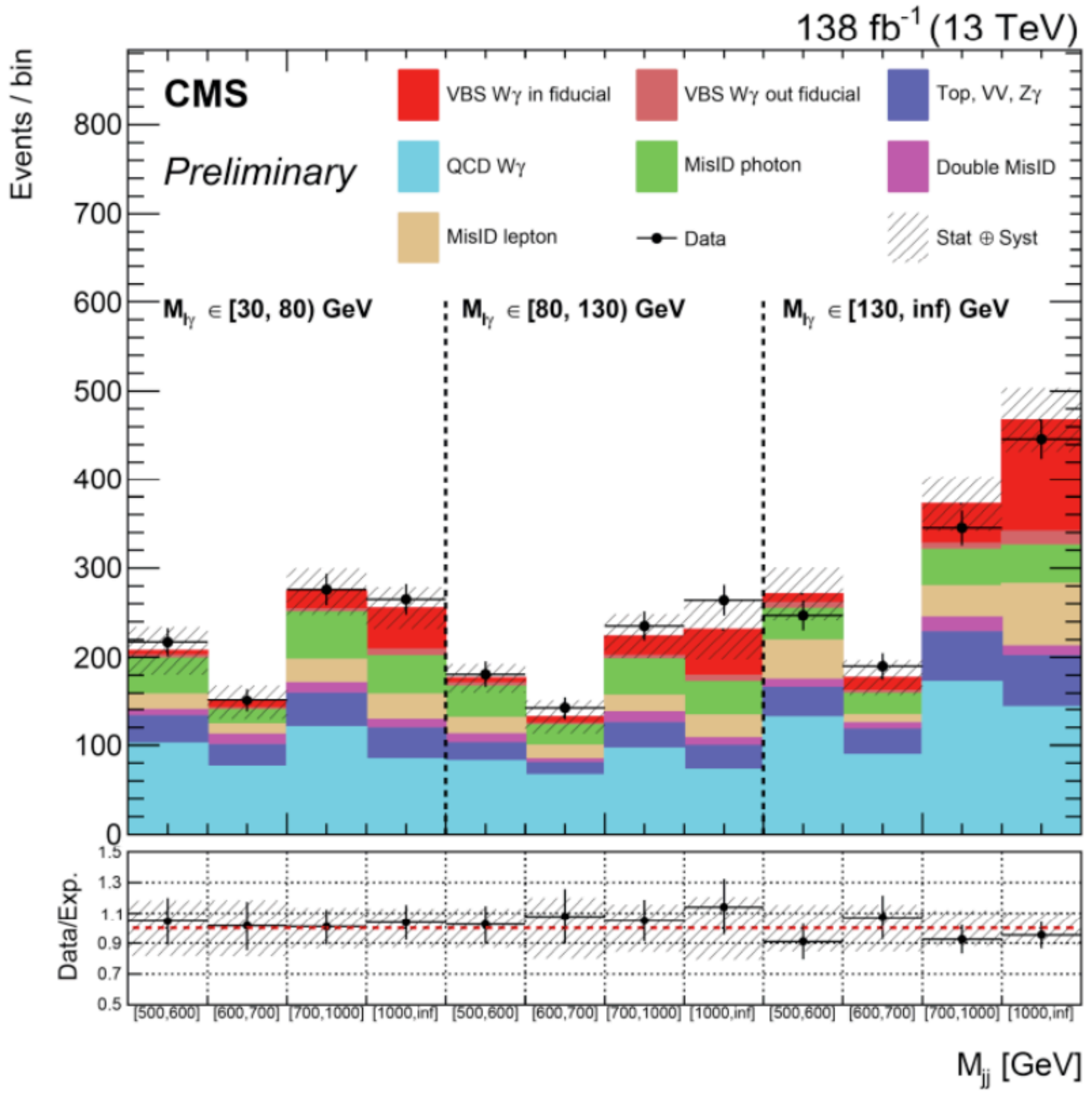
EW Production of $W\gamma jj$

NEW LHCP 2022



- Analysis update based on full statistics

[SMP-21-011]



- EW $W\gamma jj$ signal observed with a significance of $6.0\,\sigma$ ($6.8\,\sigma$ exp)
- Fiducial cross section :

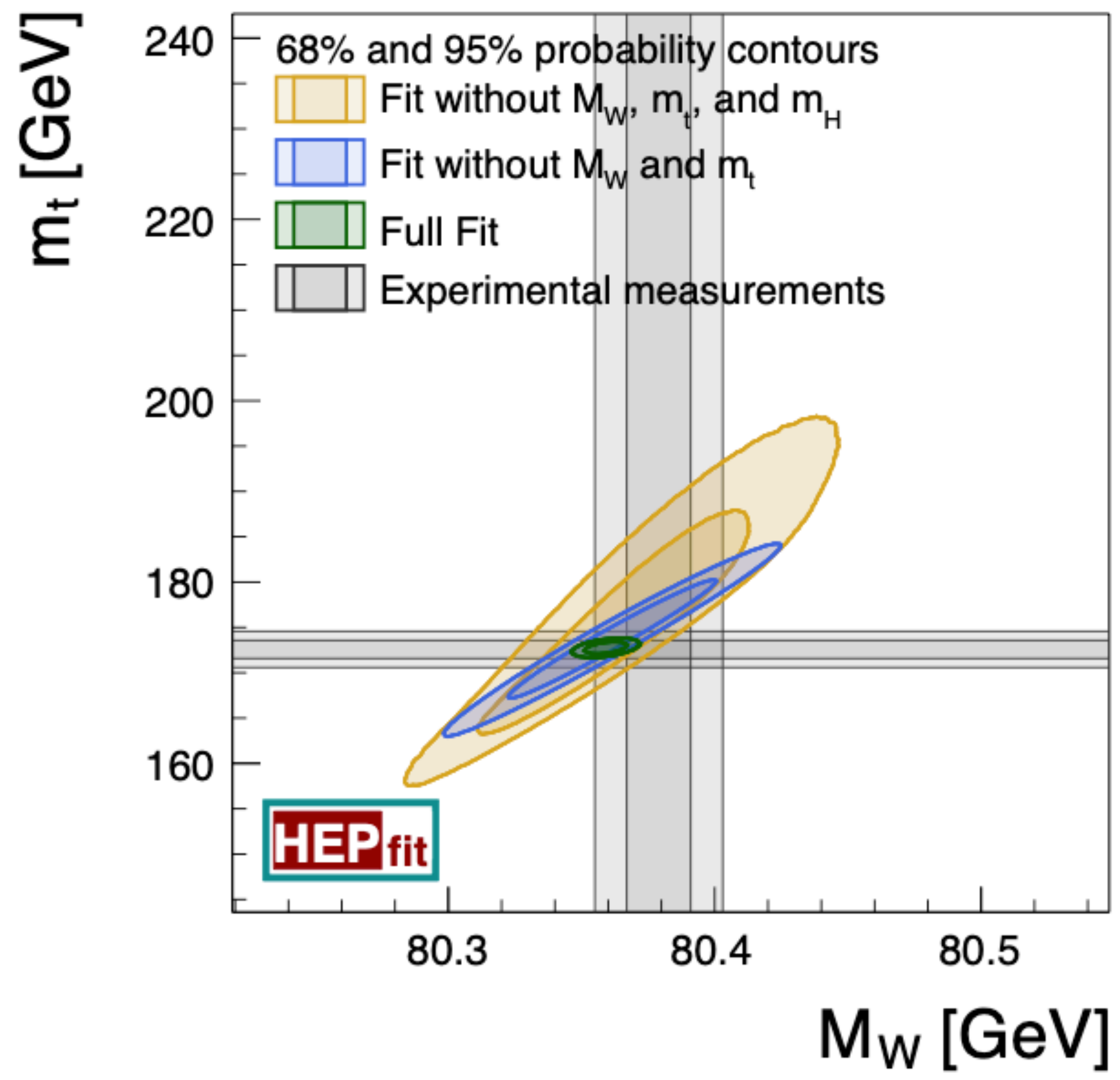
(19.2±4.0) fb

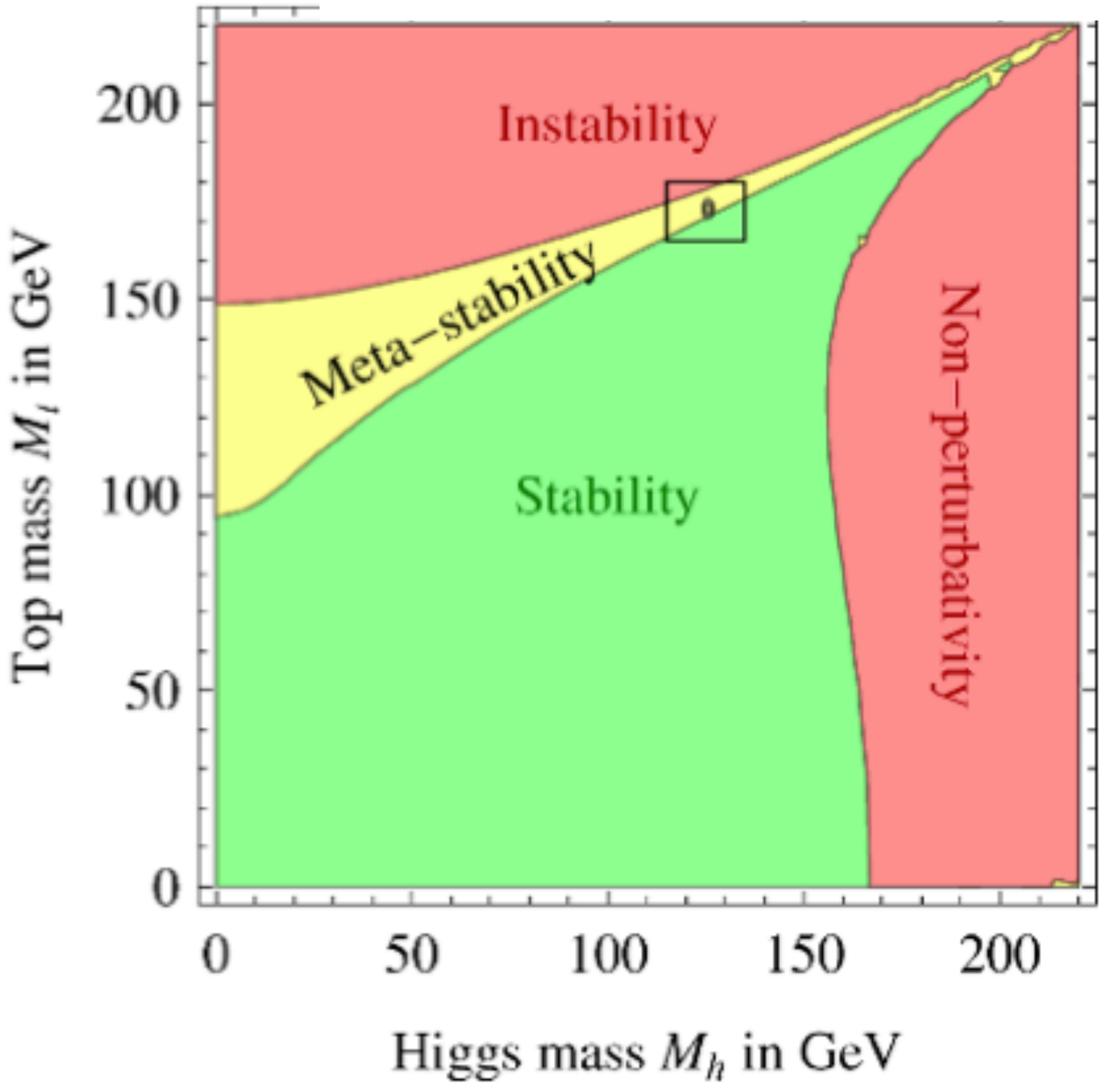
TOP

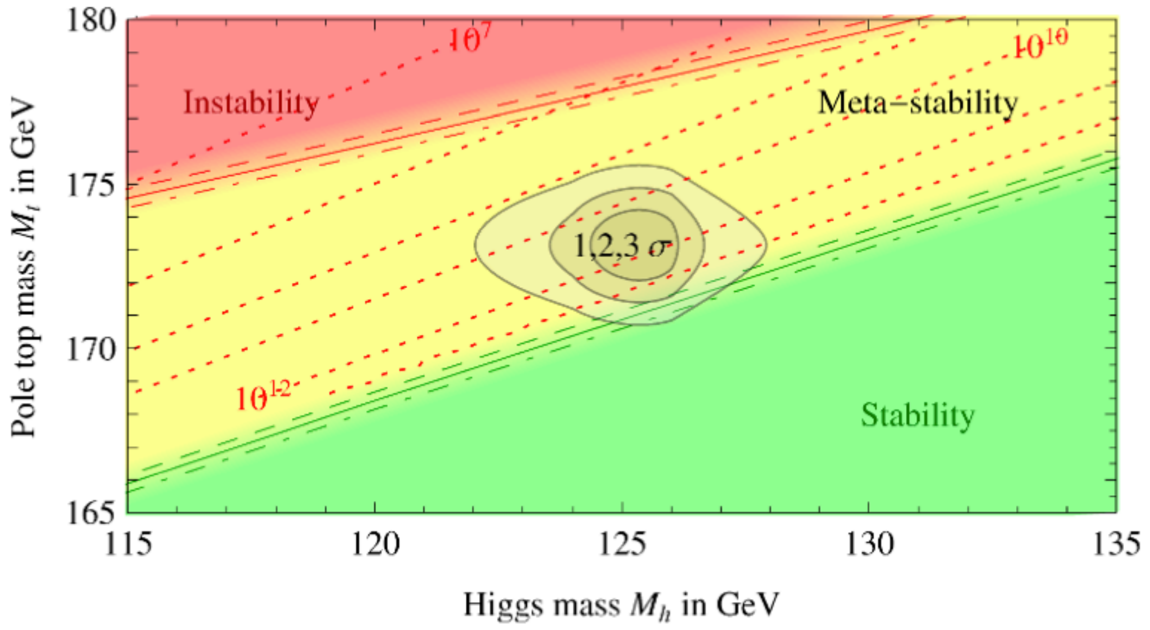
The top quark

- Heaviest fundamental particle observed
- Lifetime smaller than hadronization time, so bare quark properties can be measured
  - $\tau_{top} \sim 5\,10^{-25}\,\mathrm{s}$ $\qquad \tau \sim 1/(m^5 |V_{CKM}|^2)$
- Loops contribute to the Higgs boson and W mass: top quark mass is a prominent input for SM consistency checks
- Precise m_t determination allows strong constraints on the stability of the electroweak vacuum

[arXiv:2112.07274v1]





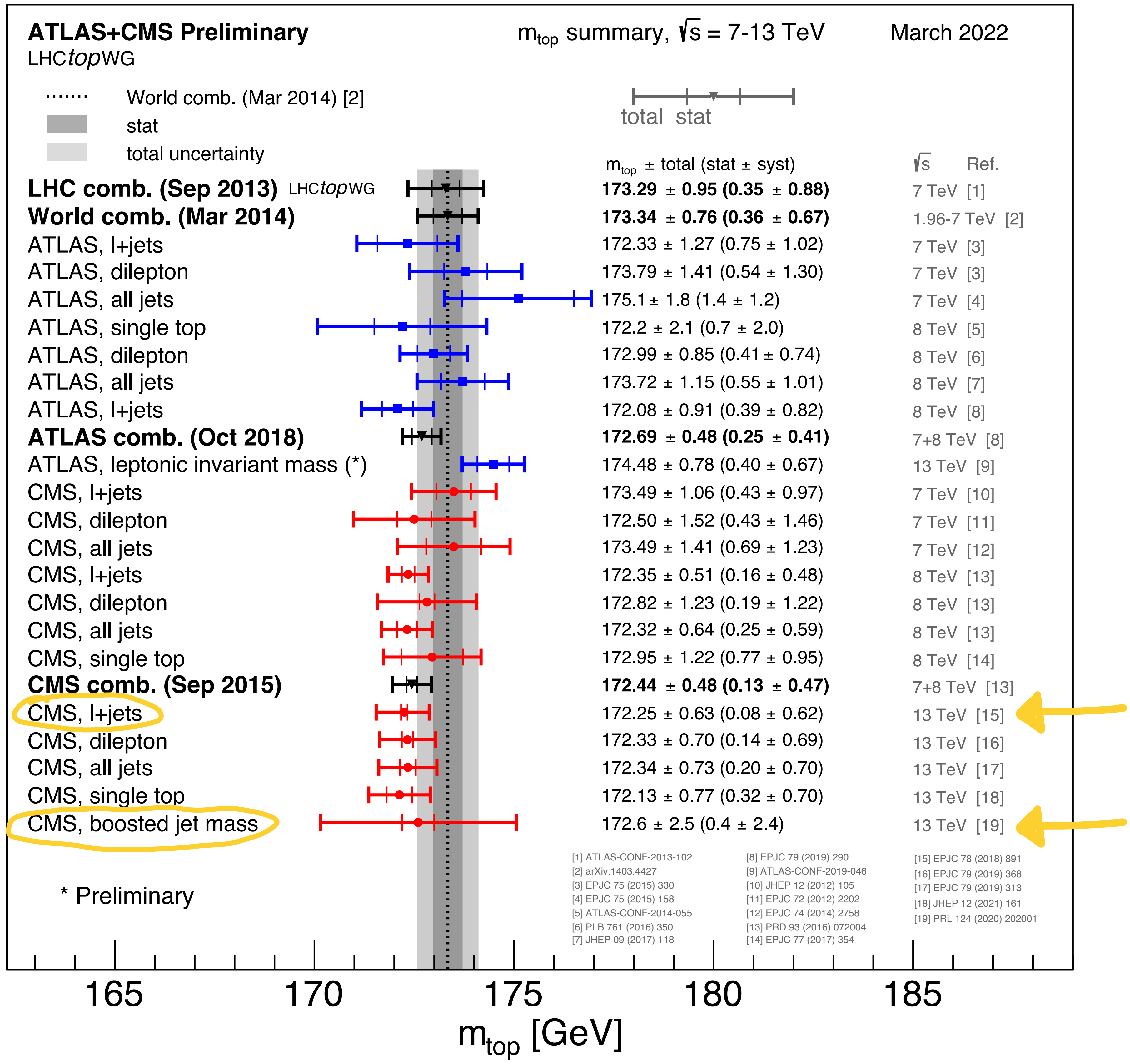


JHEP08(2012)098

The top mass

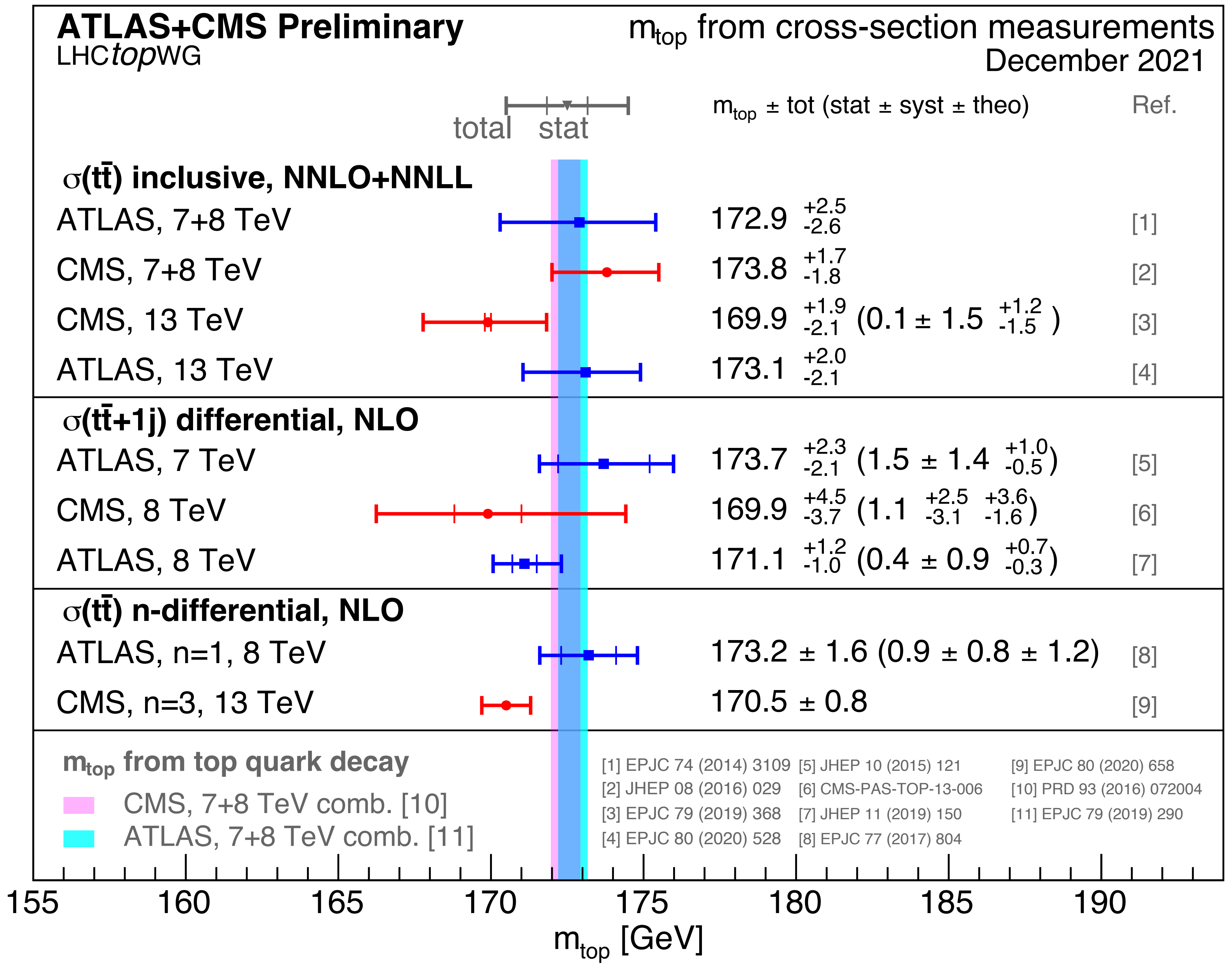
Direct mass measurements

- Measure m_t^{MC} from reconstructed decay products
- Very high exp. precision : ~0.5 GeV
- Uncertainty in relation to theoretically well-defined mass $\mathcal{O}$(0.1-1) GeV



Indirect mass measurements

- Extract m_t in well defined renormalisation scheme (pole, $\overline{\text{MS}}$)
- Measures cross section, either inclusive or differential, corrected for detector effects, and compare to analytical calculations.
- Unfolding of detector/hadronization effects typically yields bigger uncertainty : 1-2 GeV



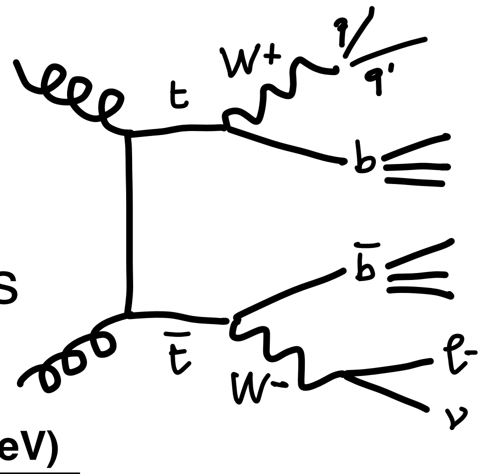
Top mass measurements @ CMS

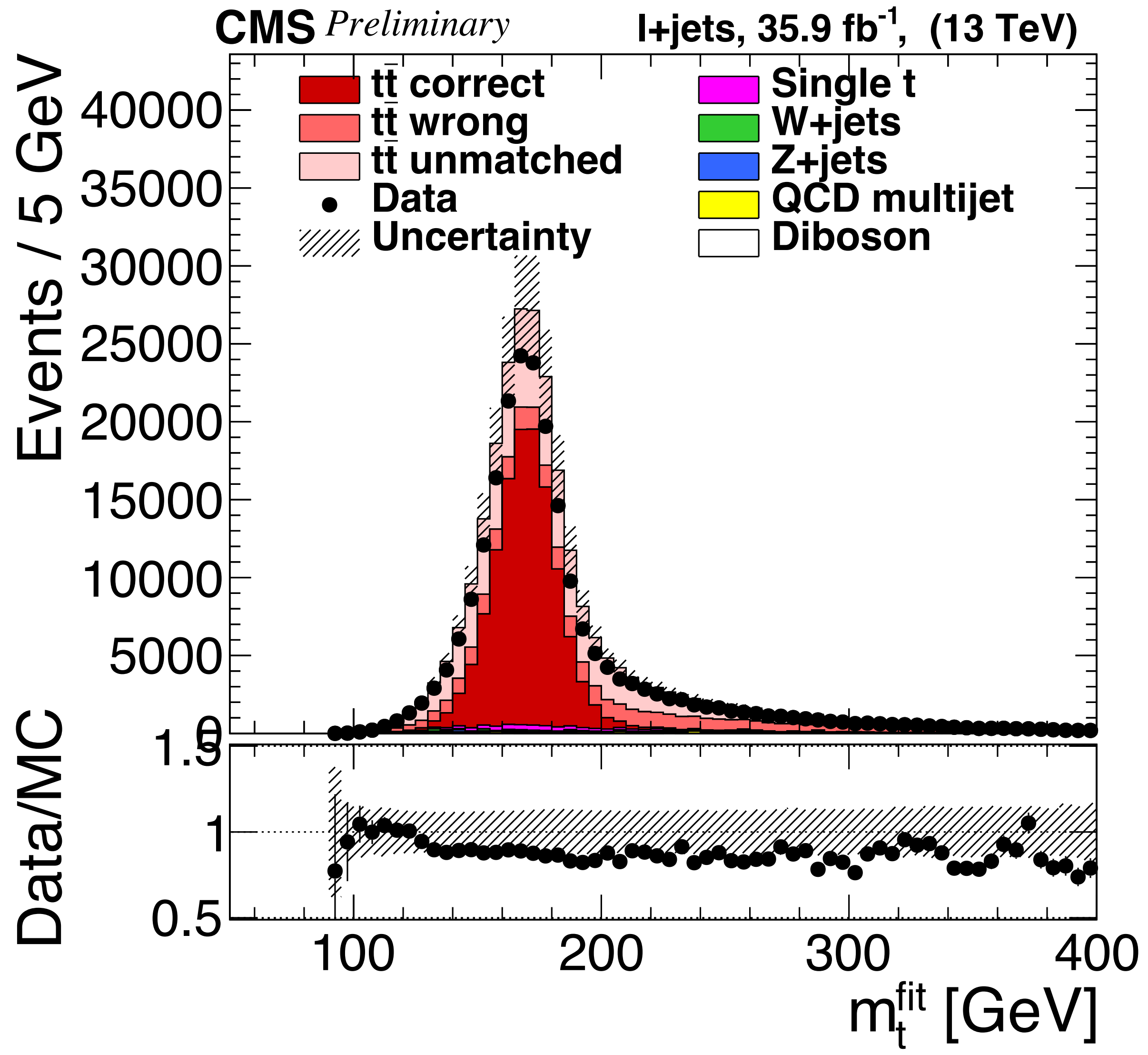
J. Olsen
M. Owen
S. Wuchterl

[CMS-TOP-20-008]

Direct mass measurement from profile likelihood method using lepton+≥4jets

- better b-jet tagging and other calibrations
- better $t\bar{t}$ modelling (updated tune)
- more events in simulation
- new fit setup with more observables





$m_t = 171.77 \pm 0.38$ GeV $\left(\frac{\sigma_{m_t}}{m_t} = 0.22\,\%\right)$

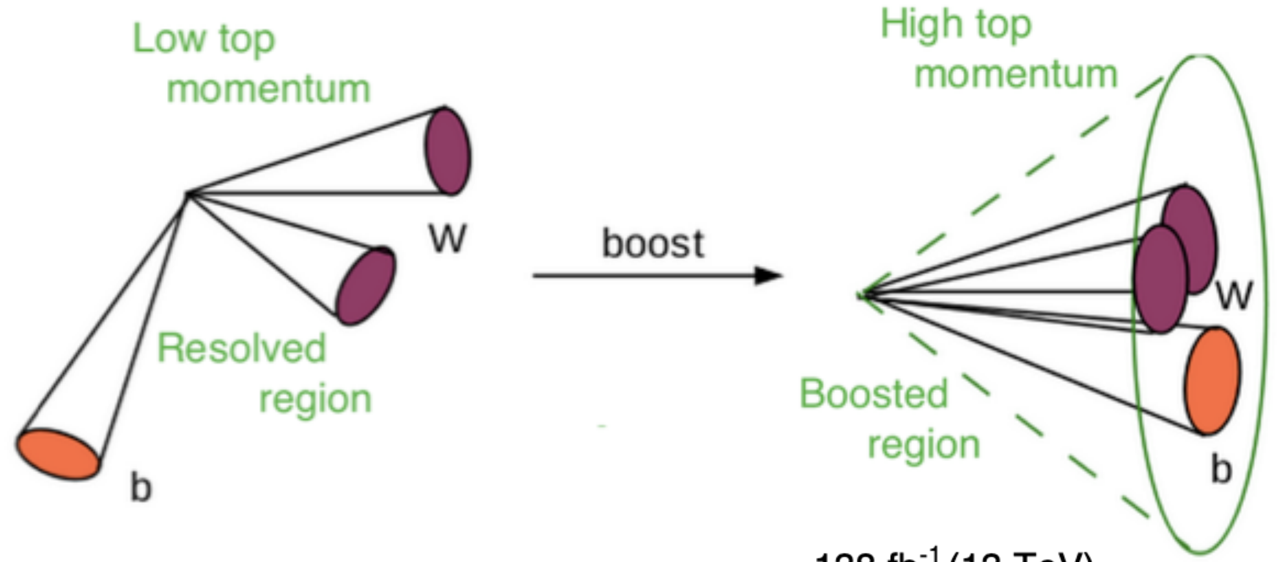
Most precise measurement to date

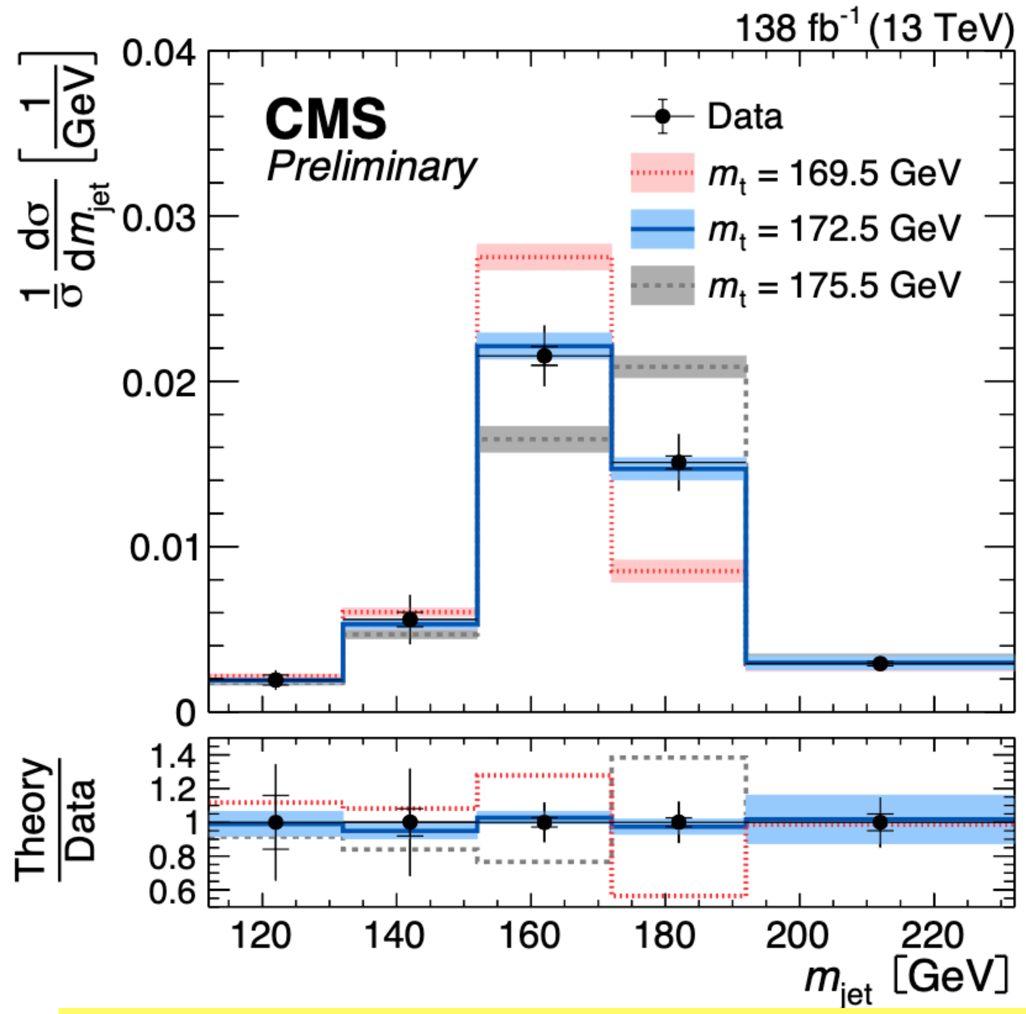
[CMS-TOP-21-012]

NEW LHCP 2022

m_t from differential $t\bar{t}$ cross section as a function of the jet mass m_{jet} in hadronic decays of boosted top

- dedicated calibration of jet mass scale
- study of effects of FSR inside large-radius jets
- 3.7 times more data

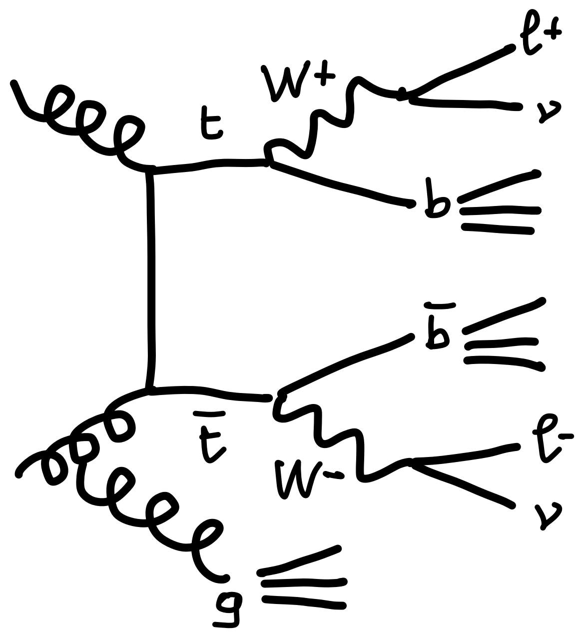




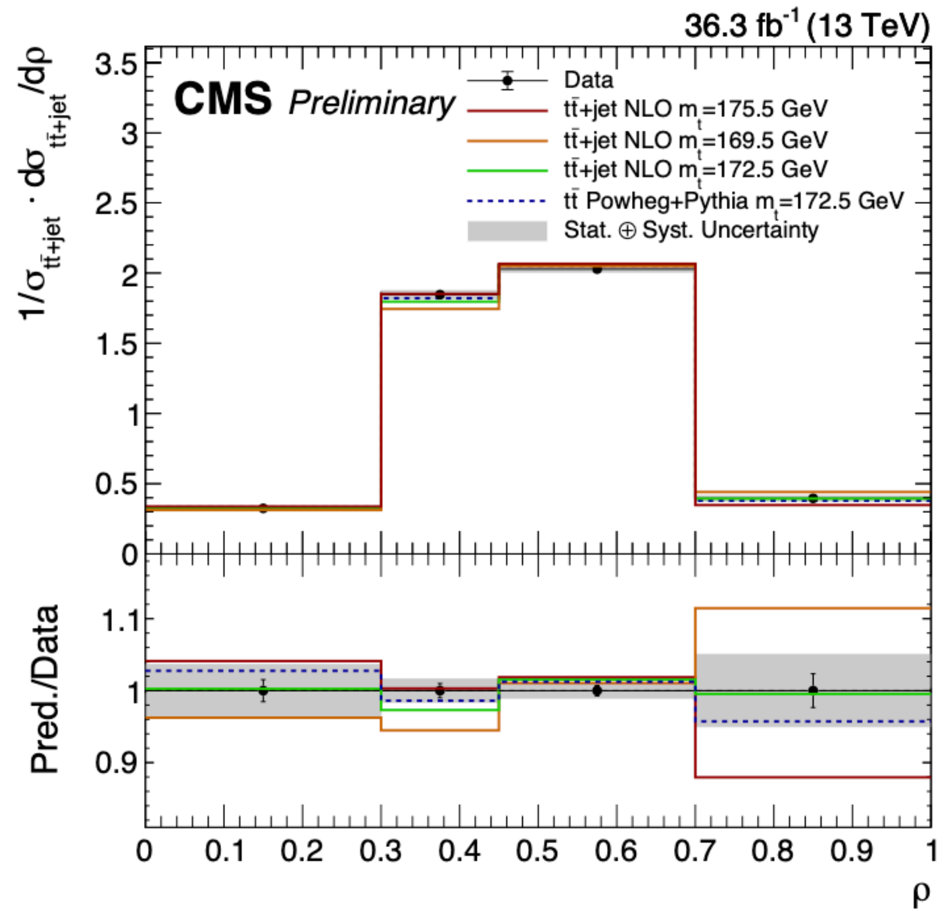
$m_t = 172.76 \pm 0.81$ GeV

[CMS-TOP-21-008]

m_t^{pole} from $t\bar{t}$+jet events in dilepton final state



- Measure $\frac{1}{\sigma_{t\bar{t}+\text{jet}}}\frac{d\sigma_{t\bar{t}+\text{jet}}}{d\rho}$, with $\rho = \frac{2m_0}{m_{t\bar{t}+\text{jet}}}$, $m_0 = 170\,\text{GeV}$



$m_t^{\text{pole}} = 172.94^{+1.37}_{-1.34}$ GeV $\left(\frac{\sigma_{m_t}}{m_t} = 0.8\,\%\right)$

using the ABMP16NLO PDF set

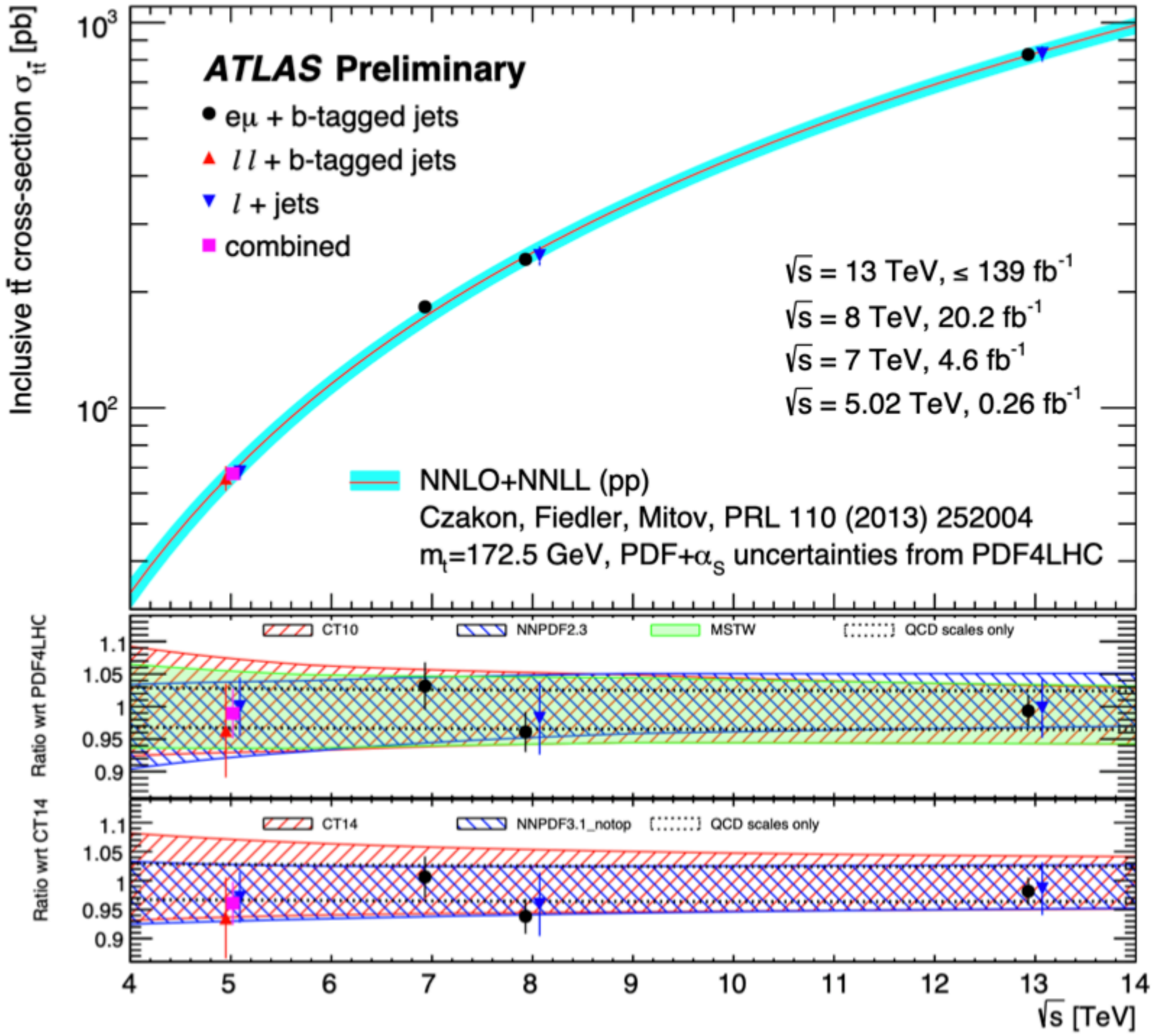
Top pair production at 5.02 TeV @ ATLAS

M. KADO
L. SERKIN

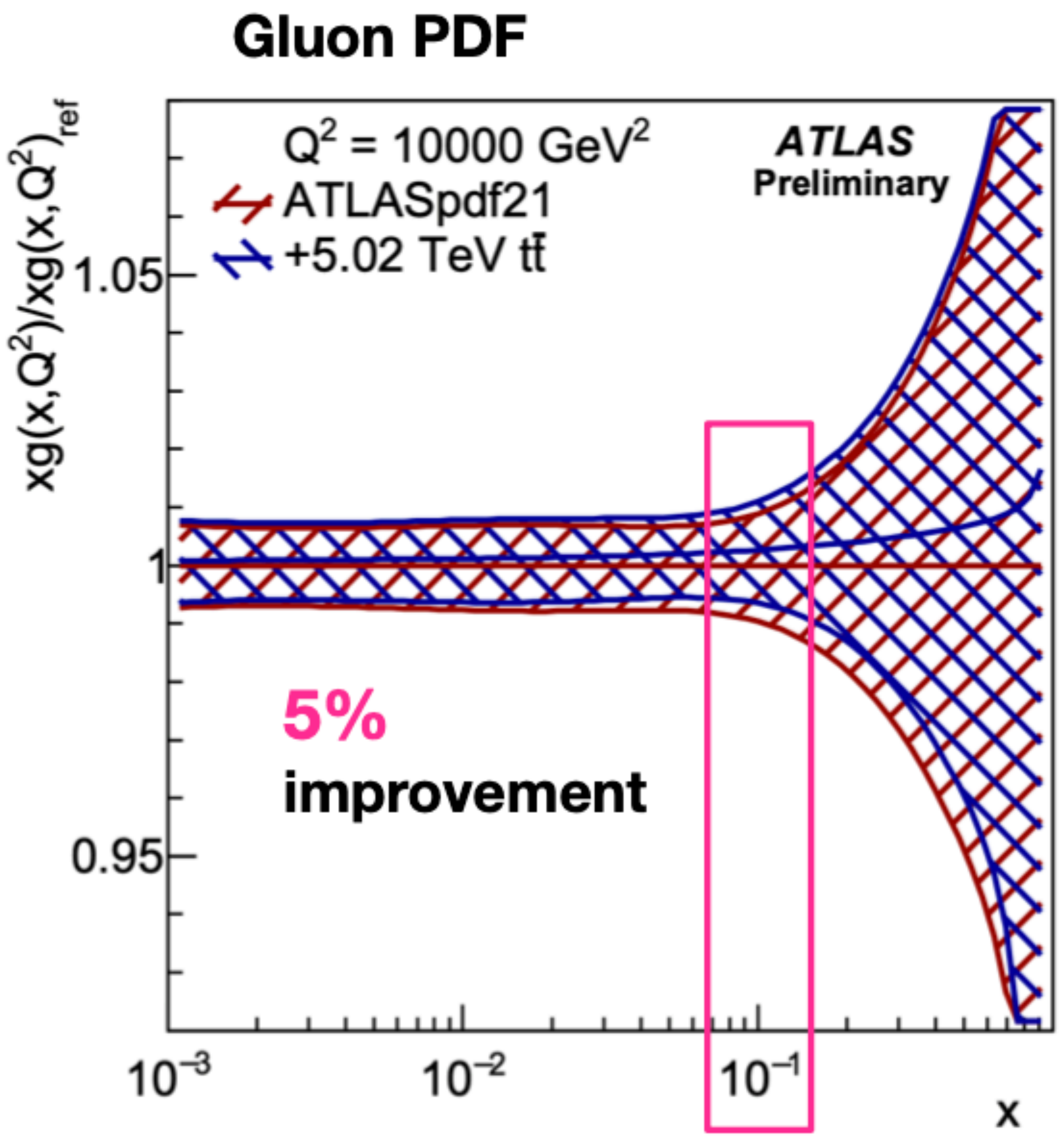
NEW LHCP 2022

- ATLAS measurement of $\sigma_{t\bar{t}}$ in single and di-lepton channel from low-pileup runs at 5.02 TeV (0.26 fb^{-1})
- $\sigma_{t\bar{t}} = 67.5 \pm 0.9_{\text{stat}} \pm 2.3_{\text{syst}} \pm 1.1_{\text{lumi}} \pm 0.2_{\text{beam}}$ pb (3.9%)

NNLO+NNLL prediction calculated with Top++ : $68.2 \pm 4.8^{+1.9}_{-2.3}$ pb



Additional constraints on PDFs

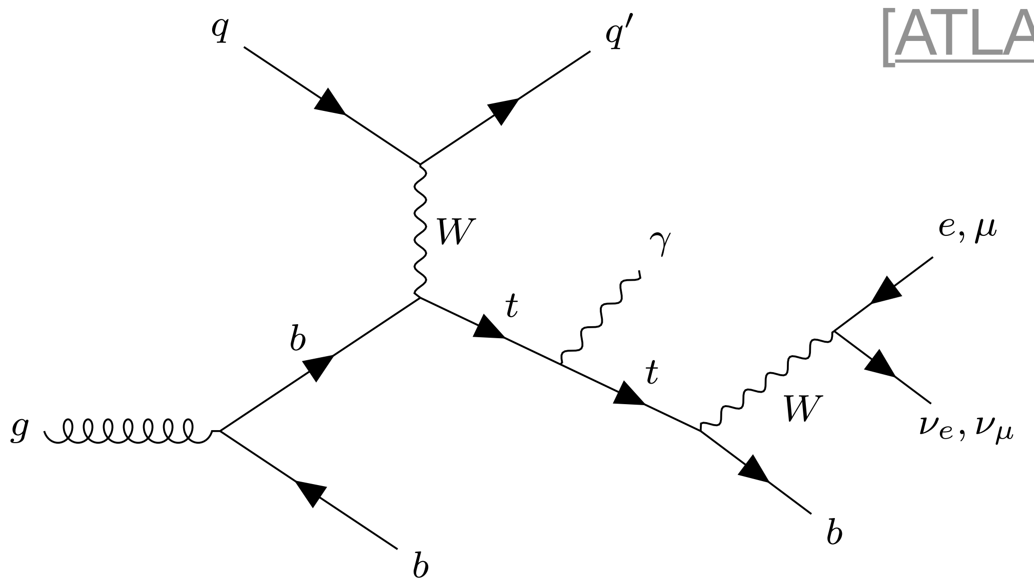


NUNO CASTRO
M. KADO
B. WENLAND

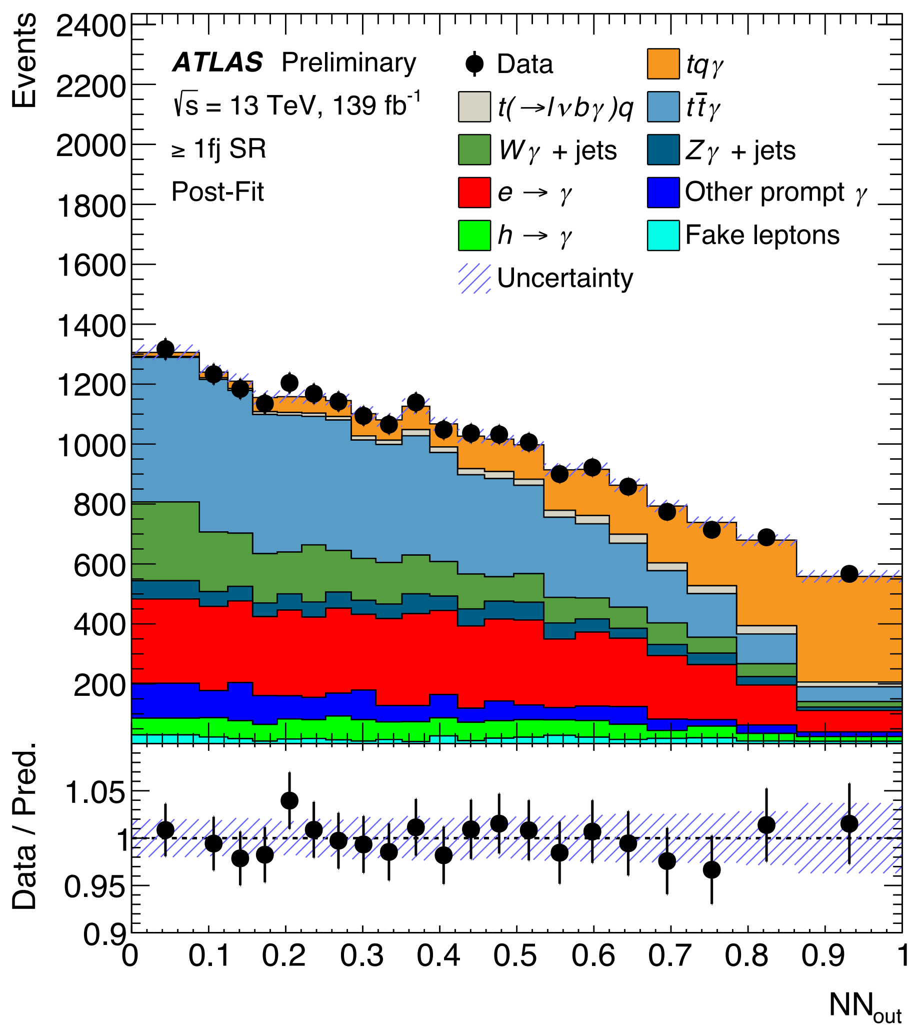
Rare single-top production with ATLAS

Observation of single top plus photon

[ATLAS-CONF-2022-013]



- One single lepton, missing p_t, well isolated γ, one b-jet



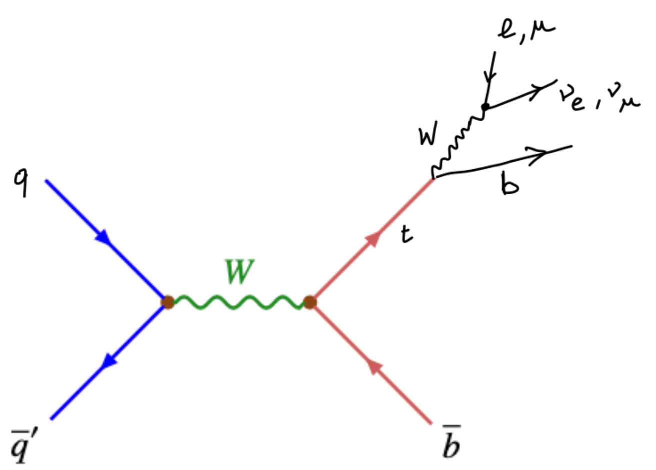
The measured $tq\gamma$ cross section plays a significant role in constraining the top-EW couplings in EFT fits

- Parton-level fiducial cross-section (≥1 photon with $p_t > 20\,\mathrm{GeV}$ in the acceptance): $\sigma_{tq\gamma} \times B(t \to \ell\nu b) = 580 \pm 19_{\mathrm{stat}} \pm 63_{\mathrm{syst}}\,\mathrm{fb}$, compatible with SM at $2.5\,\sigma$; observed signal significance is $9.1\,\sigma$ $(6.7\,\sigma$ expected)

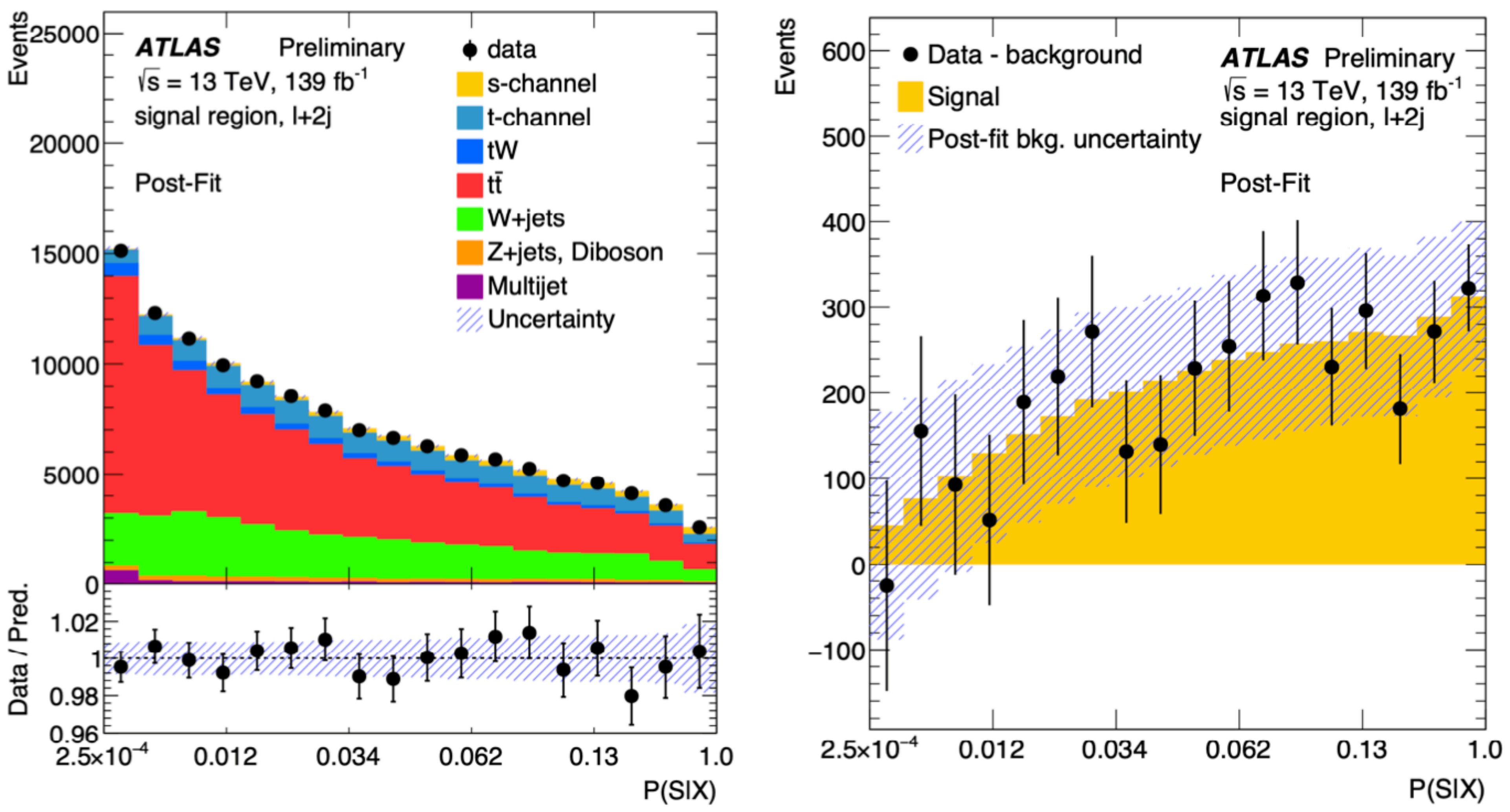
s-channel single top production

[ATLAS-CONF-2022-031]

NEW LHCP 2022



- One single lepton, missing p_t, two b-jets



P(S|X) : Matrix Element Probability for a given event X to be a signal event S

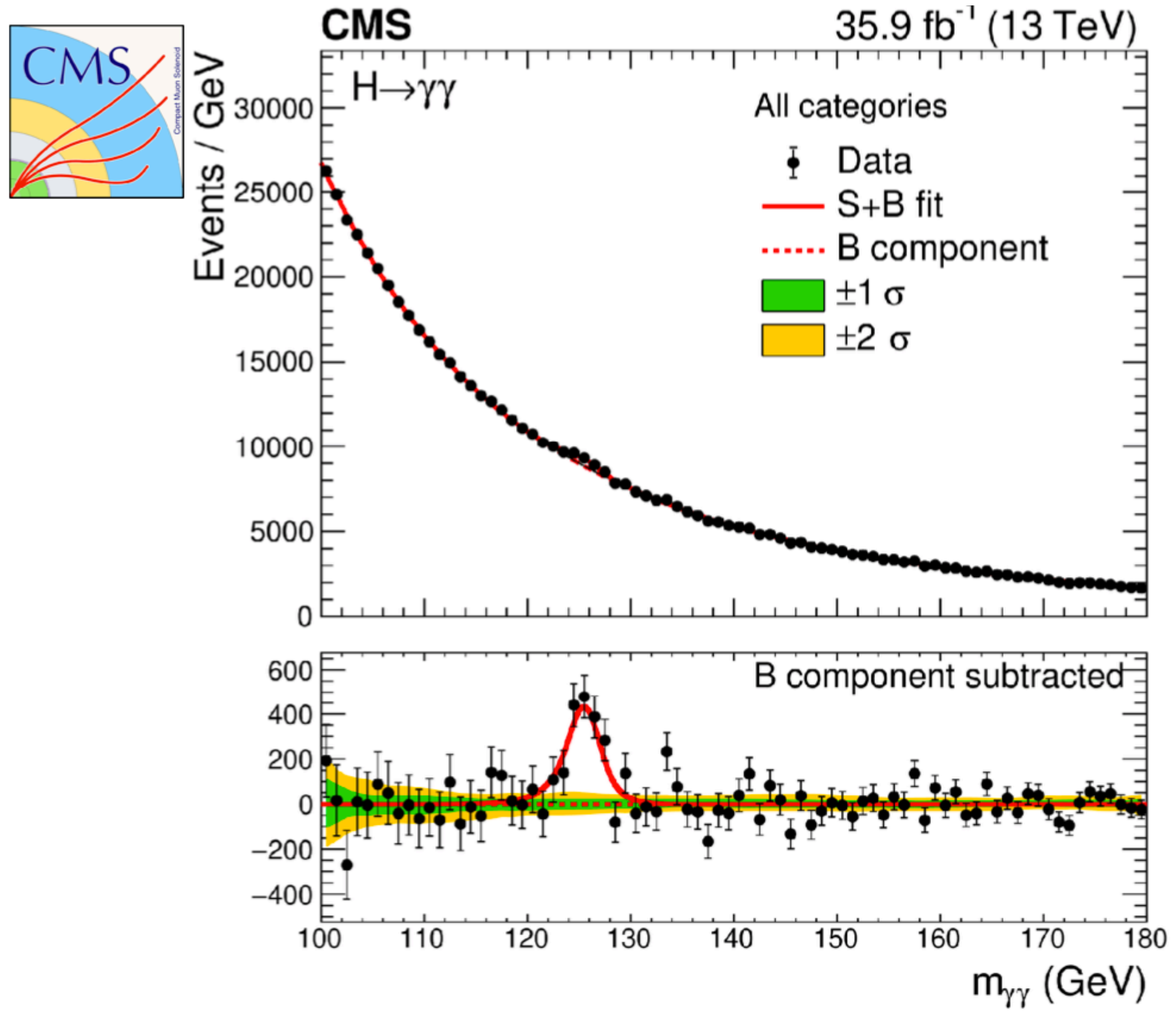
- Cross-section : $\sigma_s = 8.2^{+3.5}_{-2.9}\,\mathrm{pb}$, in agreement with SM: $\sigma_s^{\mathrm{SM}} = 10.3 \pm 0.4\,\mathrm{pb}$
  Observed signal significance is $3.3\,\sigma$ $(3.9\,\sigma$ expected)

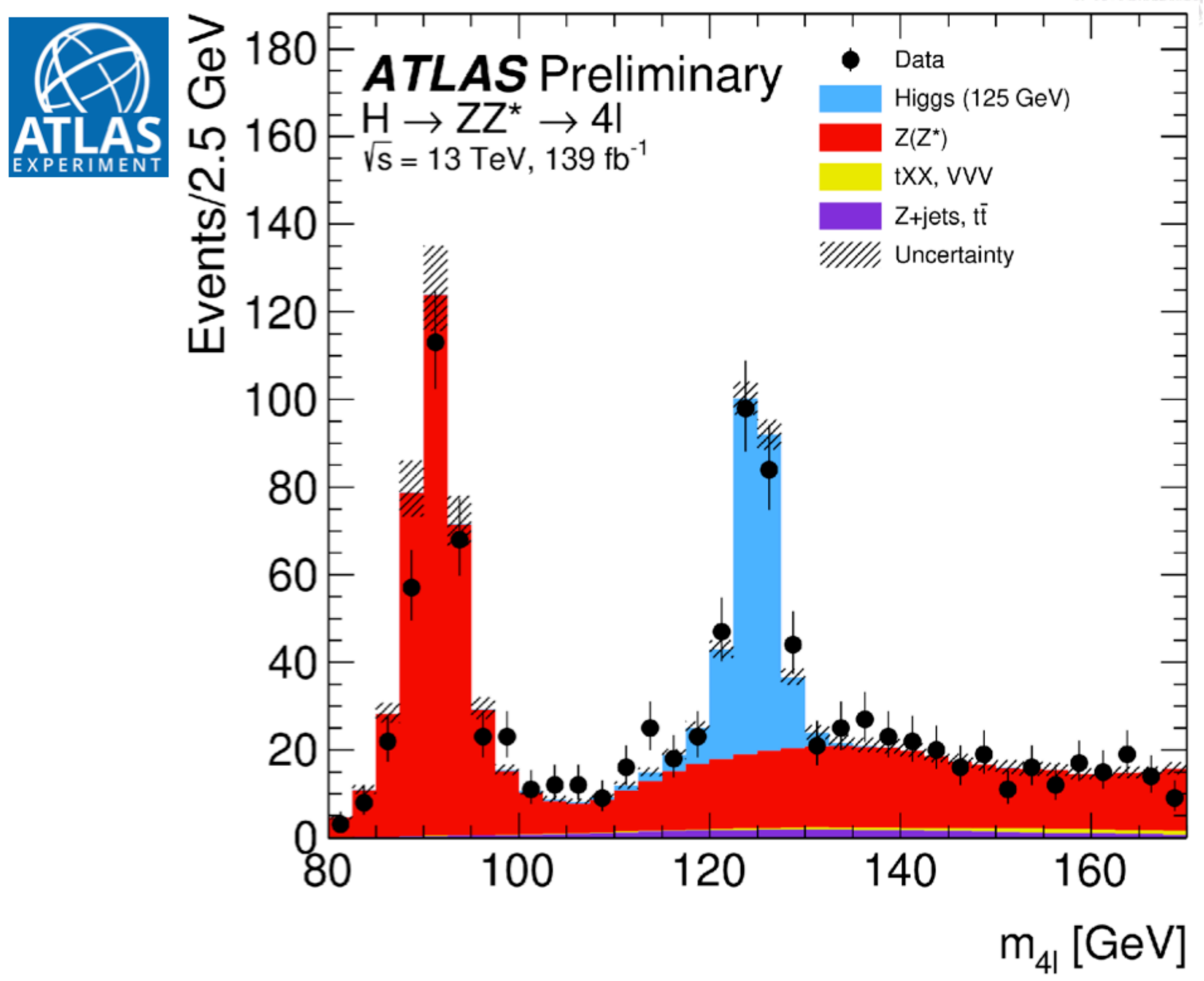
HIGGS BOSON

Enough data on the Higgs to start filling the PDG table!

K. Köneke

- Millions of Higgs bosons produced at the LHC, enabling
  - Measurement of m_H to nearly per mille precision
  - Observation of all third-generation couplings
  - Detailed measurements of H properties





H^0 $J = 0$

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.13 \pm 0.06$
$WW^* = 1.19 \pm 0.12$
$ZZ^* = 1.06 \pm 0.09$
$\gamma\gamma = 1.11^{+0.10}_{-0.09}$
$c\bar{c}$ Final State $= 37 \pm 20$
$b\bar{b} = 1.04 \pm 0.13$

J. DAVIES

From a combined measurement of on-shell and off-shell H production, using $H \to ZZ^{(*)} \to 4\ell$ and $2\ell 2\nu$, CMS finds

- $3.6\,\sigma$ evidence for off-shell Higgs production and
- $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV [arXiv:2202.06923]

$$\Gamma_H^{SM} = 4.1 \text{ MeV}$$

$$\Gamma_H \propto \frac{\sigma_{off}}{\sigma_{on}}$$

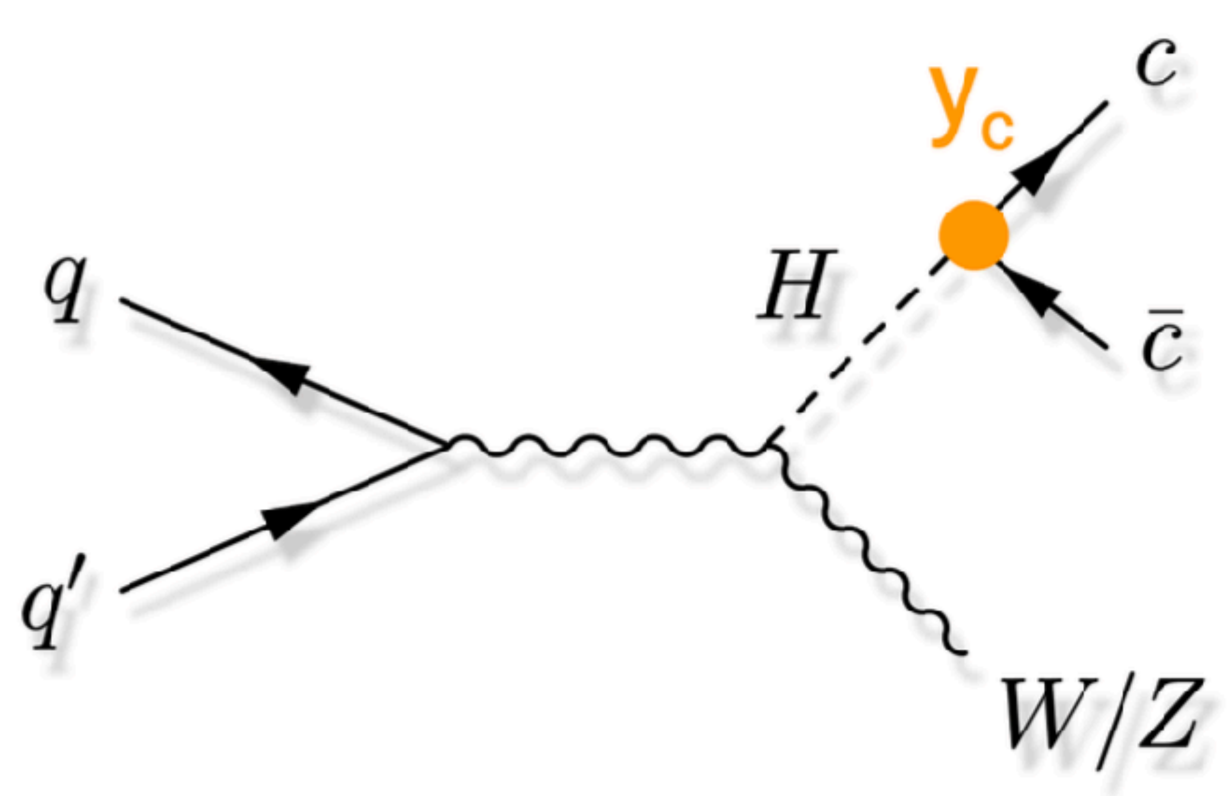
This unprecedented data set opens a new window in the exploration of the Higgs sector, e.g. rare H decays such as $H \to c\bar{c}$

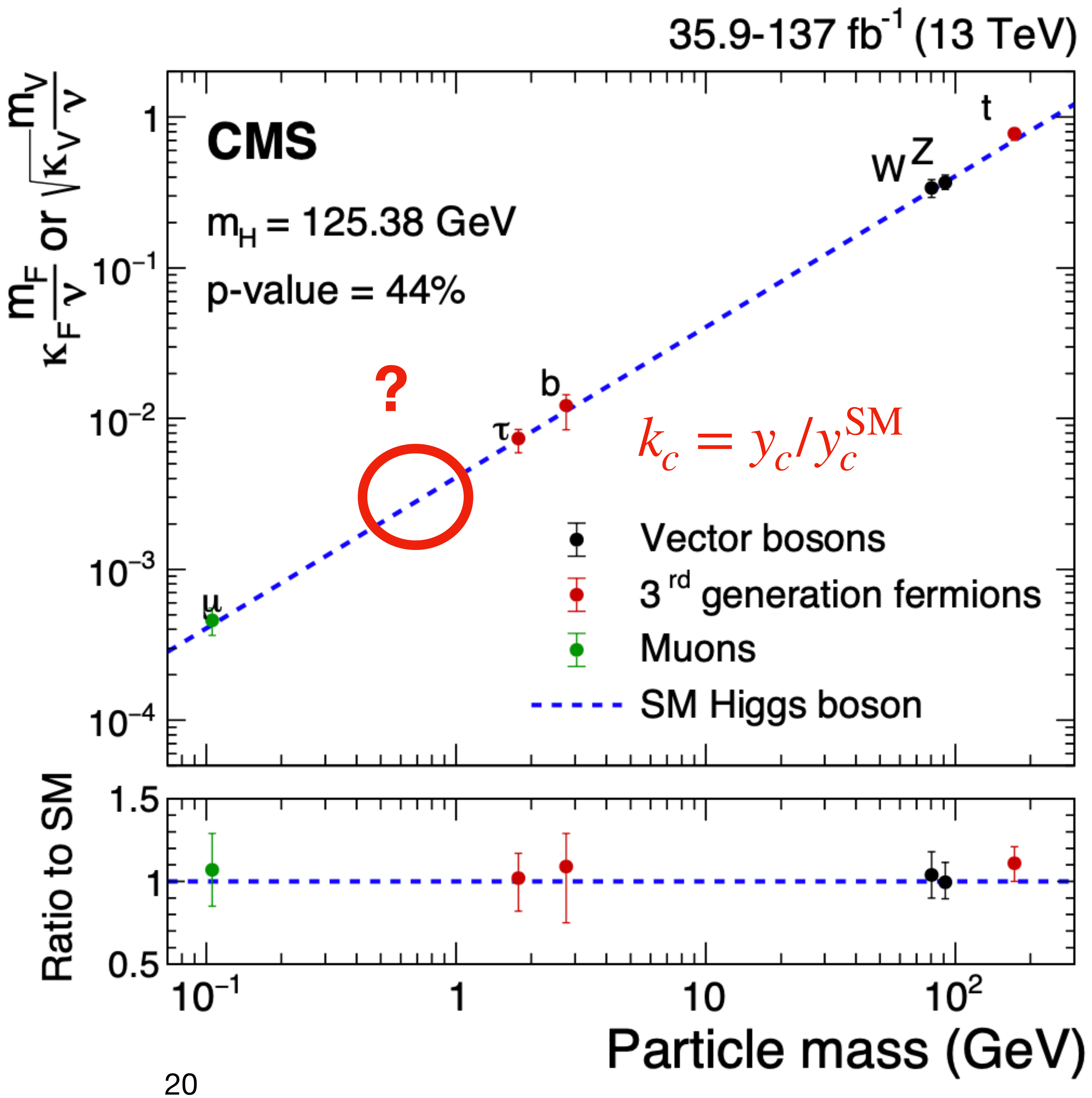
Higgs couplings

- Couplings are a powerful test of Higgs nature: SM or are there subtle differences??

- Higgs interactions with fermions are proportional to the fermion masses

- Yukawa coupling to charm is next important goal
(second-generation quark)





Constraining the Higgs-charm Yukawa

A. Novak
T. du Pree
J. OLSEN

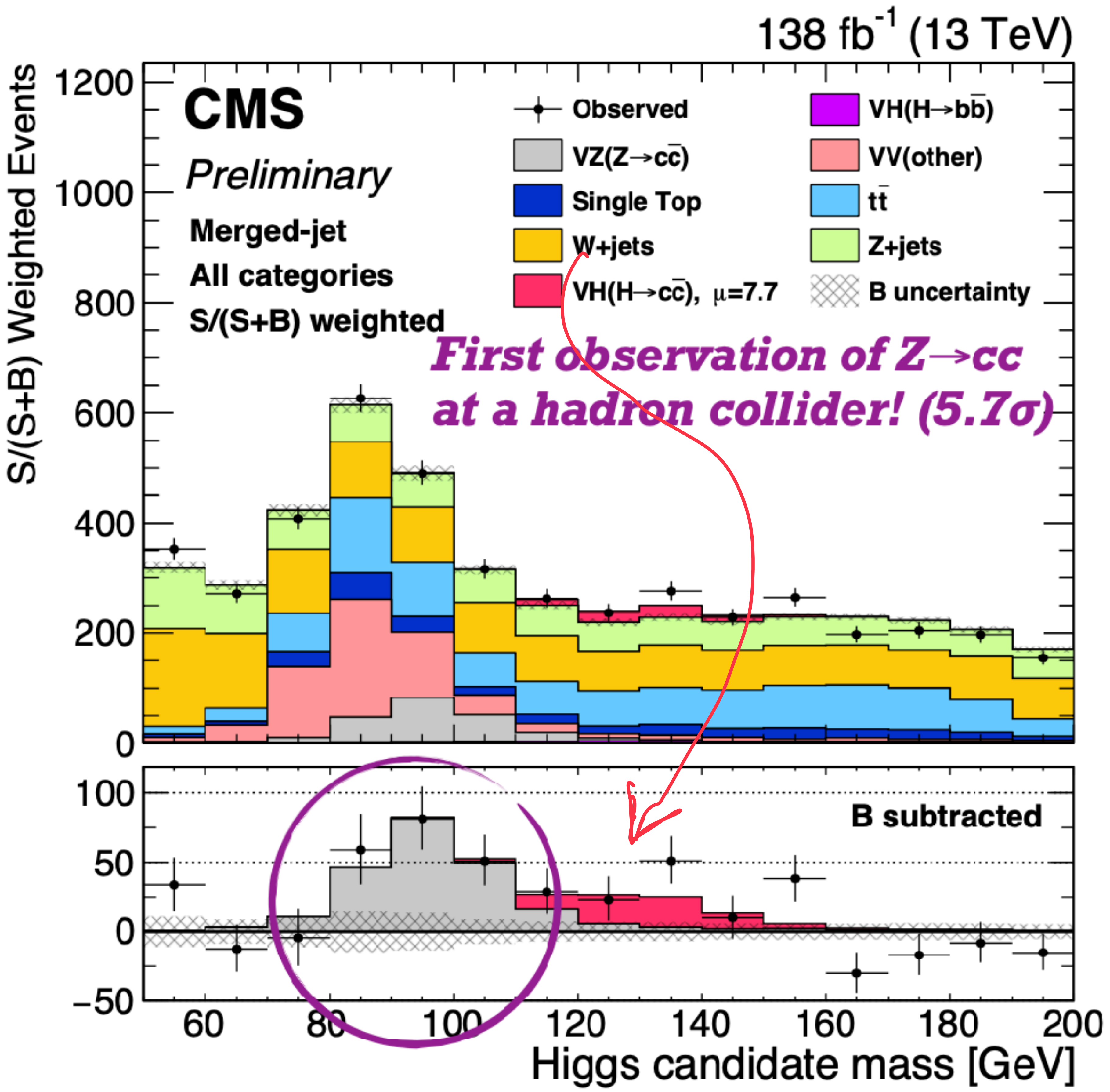
- Measuring $H \to c\bar{c}$ @LHC is extremely challenging
  - 20xsmaller BR than $H \to b\bar{b}$
  - Charm-jet tagging very difficult
  - Multijet background larger by 9 orders of magnitude

- However, very large improvement in CMS to c-tagging performance plus use of both "merged-jet" and "resolved-jet" topologies

- CMS constraints on k_c comparable to what had previously been expected at the end of HL-LHC!

$$1.1 < |k_c| < 5.5\ (< 3.4\ \text{exp.})\ @\ 95\,\%\ \text{CL}$$

[arXiv:2205.05550]



- First direct limit on k_c from ATLAS : [arXiv:2201.11428]

$$|k_c| < 8.5\ @\ 95\,\%\ \text{CL}$$ (exp. <12.4)

- Combination with $H \to b\bar{b}$ published analysis allows ATLAS to extract ratio of coupling modifiers

$$|k_c/k_b| < 4.5\ @\ 95\,\%\ \text{CL}$$ → Higgs boson coupling to charm quarks is smaller than Higgs boson coupling to b-quarks

CP properties in $H \to \tau^+\tau^-$ decays

M. KADO
K. KÖNEKE
J. DAVIES

NEW LHCP 2022

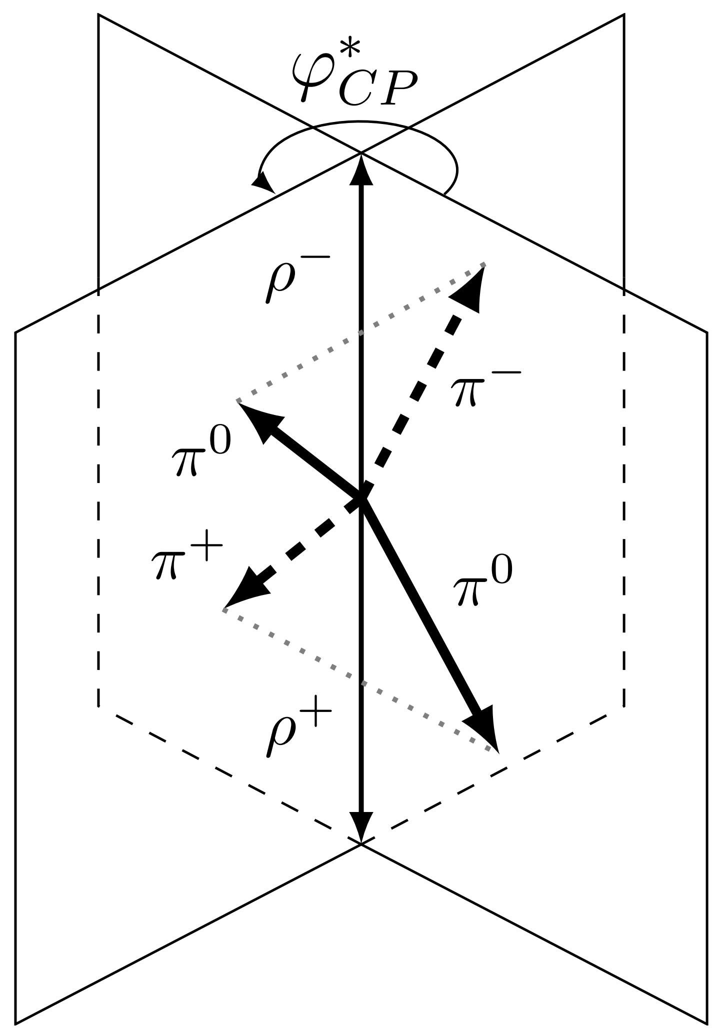
CP - even   CP - odd

- Parametrize Yukawa coupling as $\mathscr{L}_{H\tau\tau} \sim (\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i \gamma_5 \tau) H$

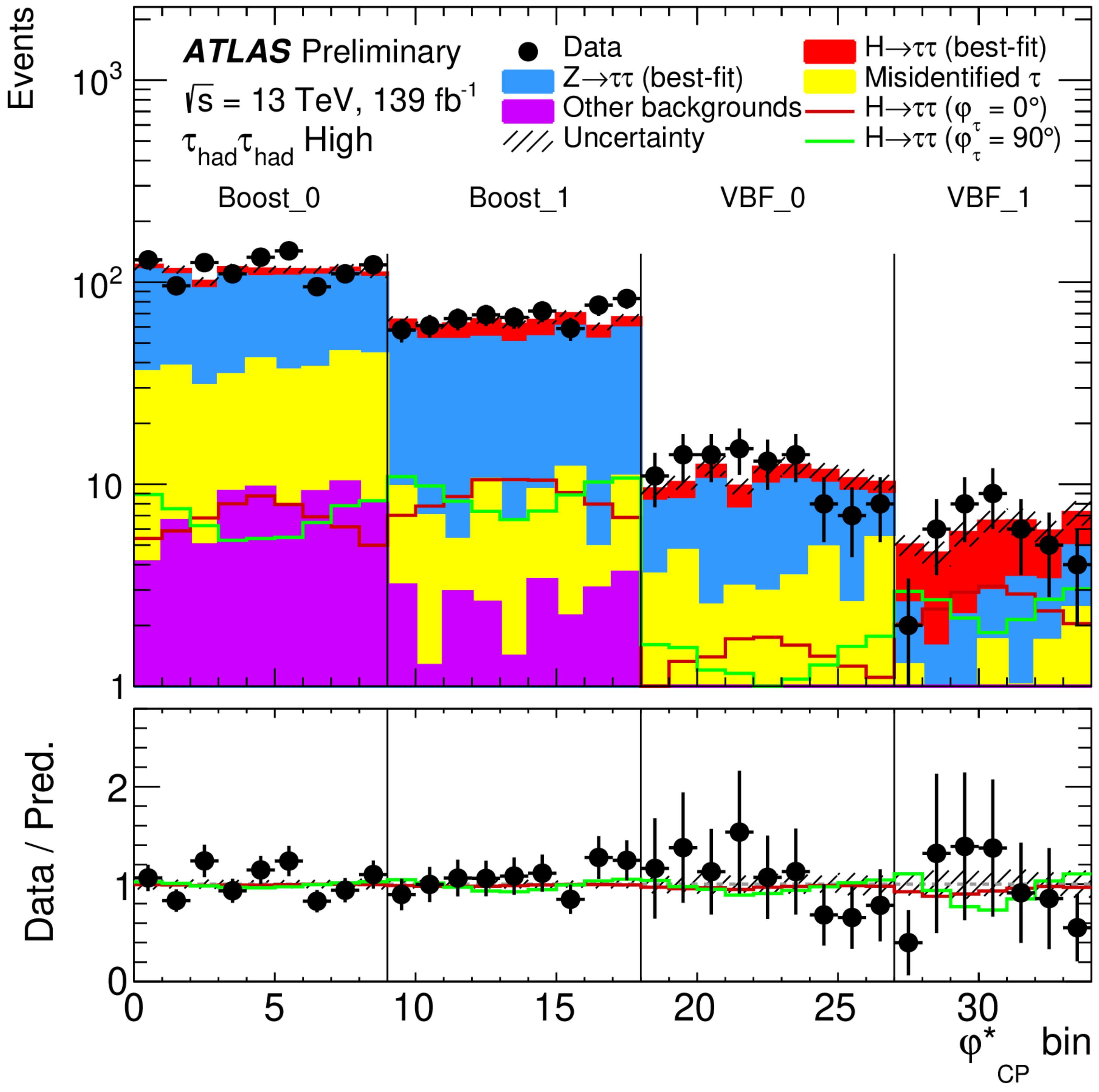
SM $H\tau\tau$ coupling: CP even ($\phi_\tau = 0°$)

- Reconstruct various τ decay modes (leptonic and hadronic)

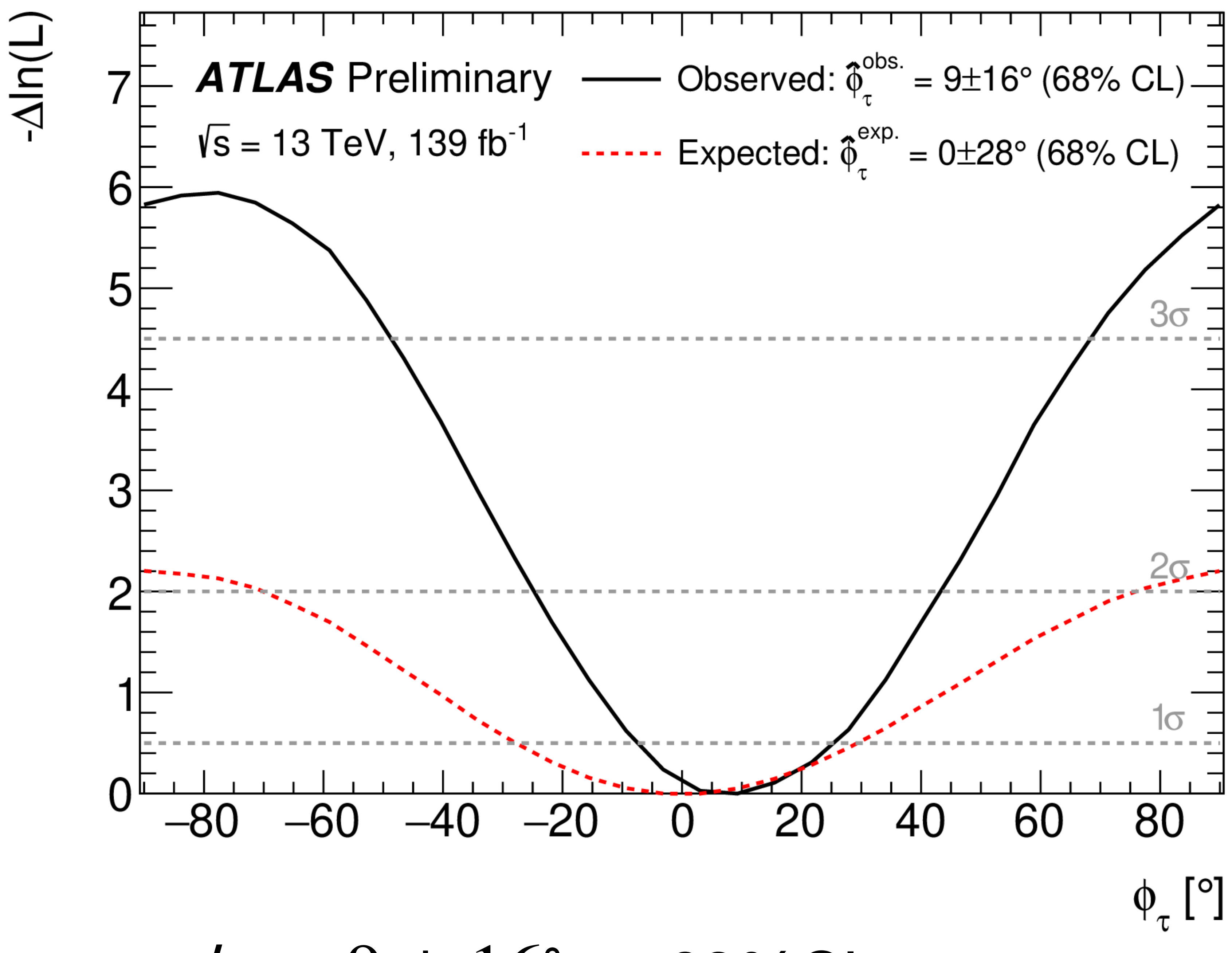
- Observable: signed acoplanarity angle between τ decay planes



[ATLAS-CONF-2022-032]



Pure CP odd ($\phi_\tau = \pm 90°$) disfavoured at 3.4σ



$\phi_\tau = 9 \pm 16°$ at 68%CL

Double Higgs production

K. Köneke
L. D'Eramo
D. Zuolo

- Gives access to the trilinear coupling λ_3 and to the shape of the Higgs potential

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + O(H^5)$$

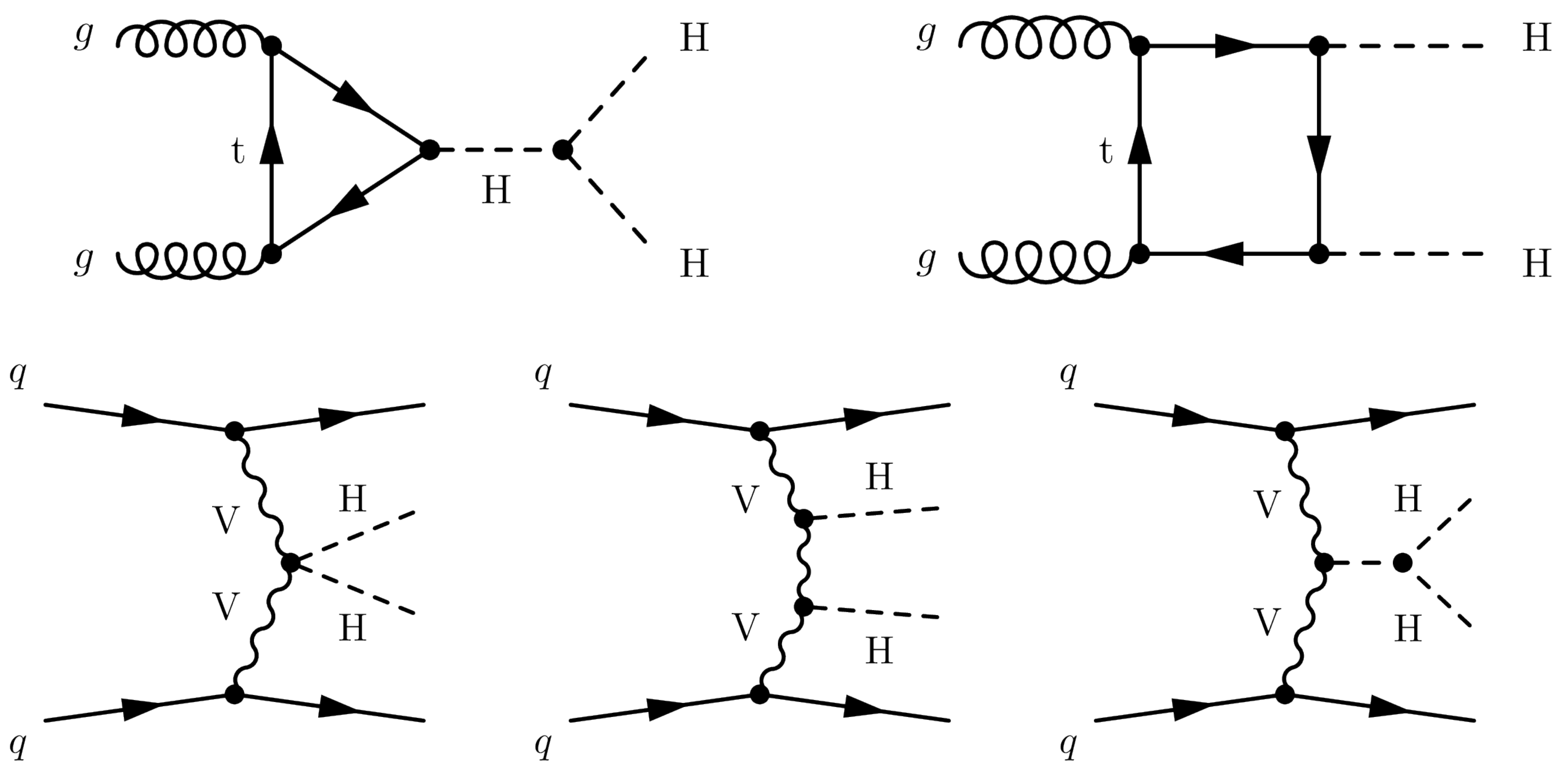
- HH x-section (ggF &VBF) too small, however nonresonant searches can be sensitive to BSM effects

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

$\sigma_{ggF} \simeq 31.05$ fb @ $\sqrt{s} = 13$ TeV

S. MANZONI
@ MORIOND EW '22

		$\sigma_{HH}/\sigma_{HH}^{SM}$ 95% CL			κ_λ 95% CL	
		Obs.	Exp.	Improvement wrt. 36 fb^{-1} tot. (w/o lumi)	Obs.	Exp.
$HH \to bb\gamma\gamma$	ATLAS	4.1	5.5	×5.1 (2.5)	[-1.5, 6.7]	[-2.4, 7.7]
	CMS	7.7	5.2	×3.9 (2)	[-3.3, 8.5]	[-2.5, 8.2]
$HH \to bb\tau\tau$	ATLAS	4.7	3.9	×3.8 (2)	[-2.4, 9.2]	[-2.0, 9.0]
	CMS	3.3	5.2	×4.8 (2.5)	[-1.8, 8.8]	[-3.0, 9.9]
$HH \to bbbb$	ATLAS	–	–	–	–	–
	CMS	3.9	7.8	×5.1 (2.6)	[-2.3, 9.4]	[-5.0, 12.0]
boosted	CMS	9.9	5.1	-	[-9.9, 16.9]	[-5.1, 12.1]
$HH \to bbZZ$	ATLAS	–	–	–	–	–
	CMS	30	37	–	[-9.0, 14.0]	[-10.5, 15.5]
Multilepton	ATLAS	–	–	–	–	–
	CMS	21.8	19.6	–	[-7.0, 11.7]	[-7.0, 11.2]
Combination	ATLAS	3.1	3.1	×3.5 (1.8)[a]	[-1.0, 6.6]	[-1.2, 7.2]
($bb\gamma\gamma$+$bb\tau\tau$)	CMS	–	–	–	–	–



$\sigma_{VBF} \simeq 1.73$ fb @ $\sqrt{s} = 13$ TeV

Improvement much bigger than what is expected for increased statistics !

BSM

Searches @ATLAS/CMS

- Heavy-resonance searches

  S. Chekanov

  - ~100 decay channels studied for various models that predict certain production rate(extra dimensions, gauge bosons, contact interactions, dark matter, heavy quarks, excited fermions, leptoquarks etc)
  - Commonly excluded masses ~ **0.4 – 12 TeV**

K. Hatakeyama

- Non-resonance searches
  - SUSY, leptoquarks, heavy leptons, axions, new dynamics/couplings….
  - eg, **gluino limit ~2 TeV, stop/sbottom ~1 TeV**….

H.Murayana : “SUSY idea should still be taken seriously”
J.Ellis : “Better late than never”

- Null search results at EW/TeV scale → growing interest in lower scales with very weak couplings (feebly interacting prticles, FIPs) with prompt and displaced topologies
  - New experimental ideas and a worldwide program of experiments to look for dark photons, dark Higgs, axions/ALPs, heavy neutral leptons …

Yusheng Wu
A. Escalante Del Valle
B. Thomas Datell

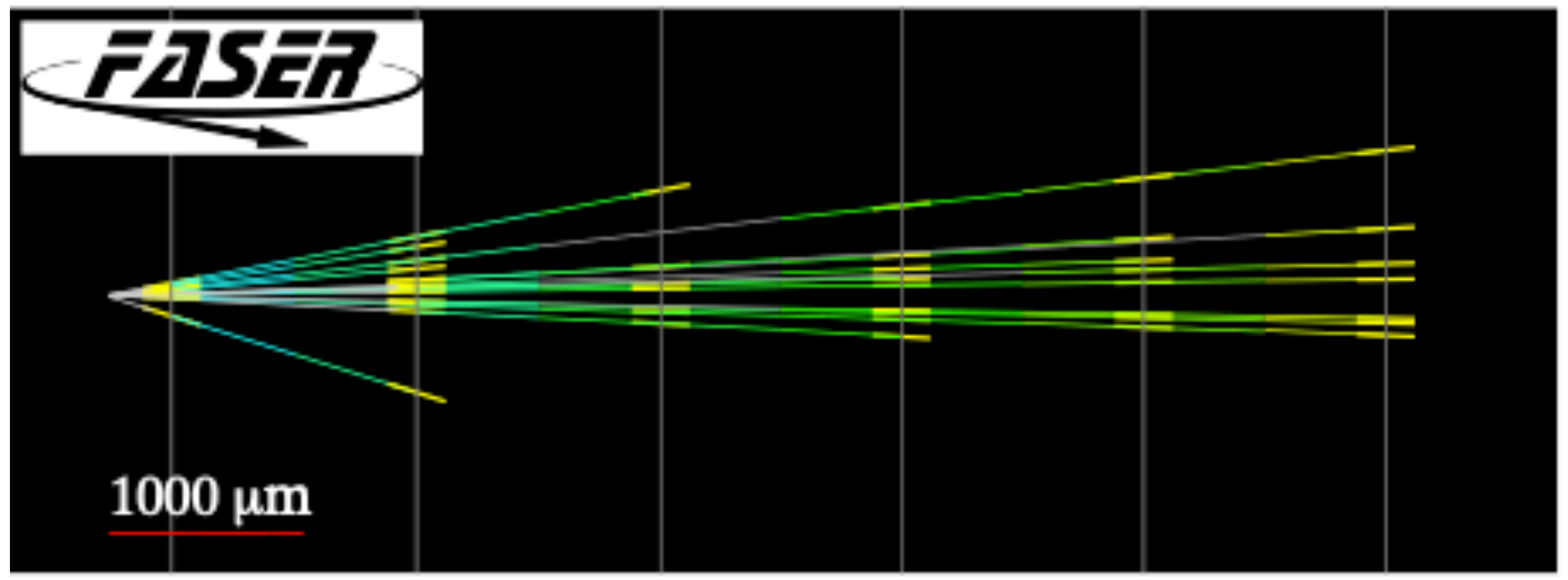
First observed neutrinos in FASER-ν!

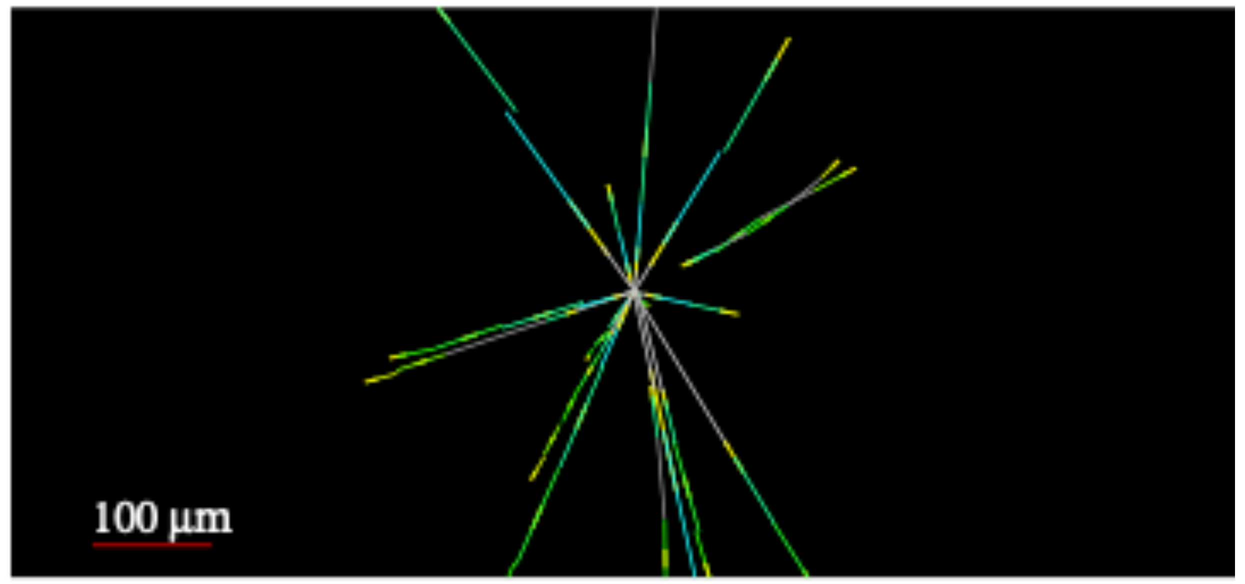
Ke Li

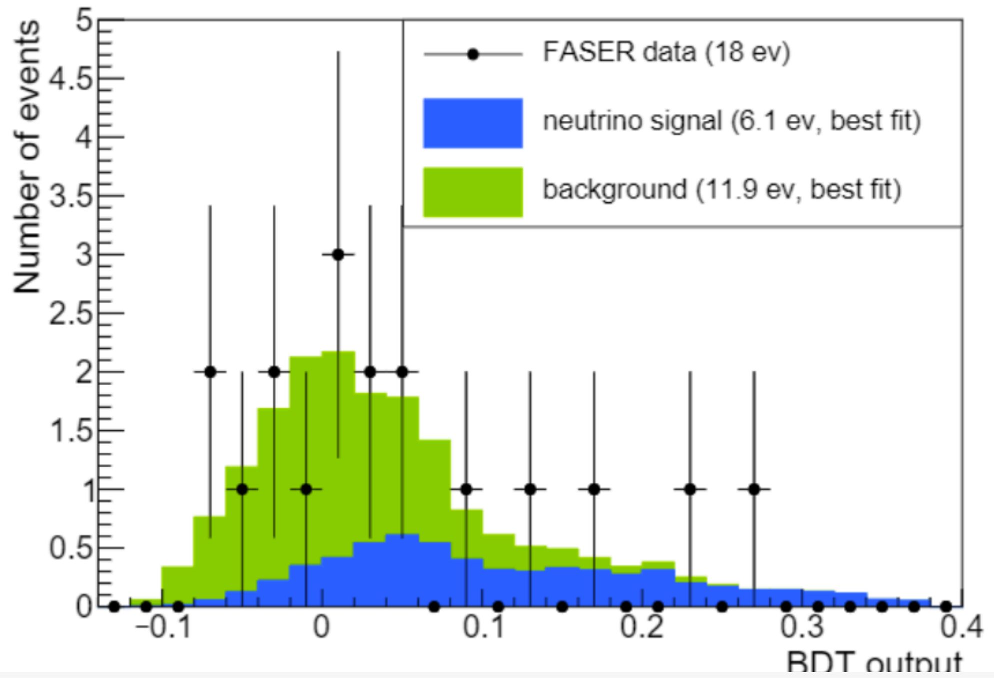
Ch. Betancourt

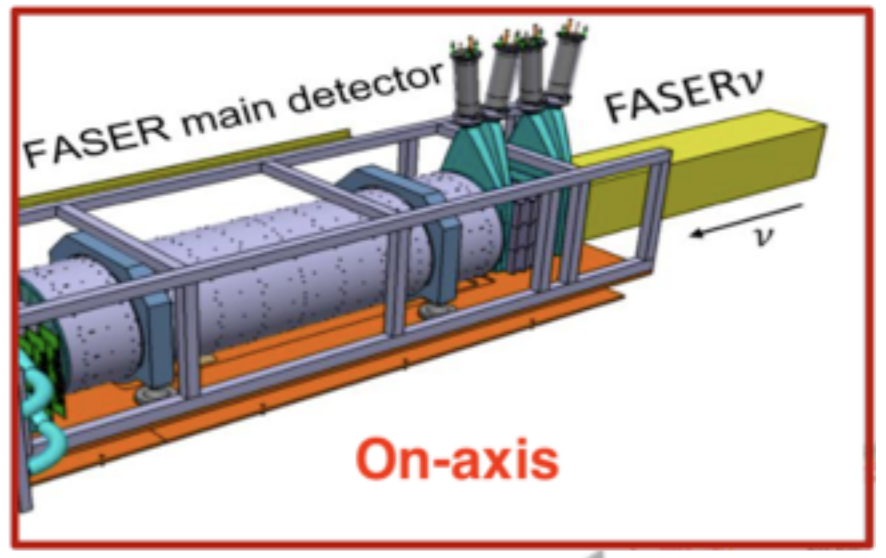
- These are the first ever directly observed neutrinos @ the LHC!!

Neutrino interaction candidates from pilot run with small emulsion detector

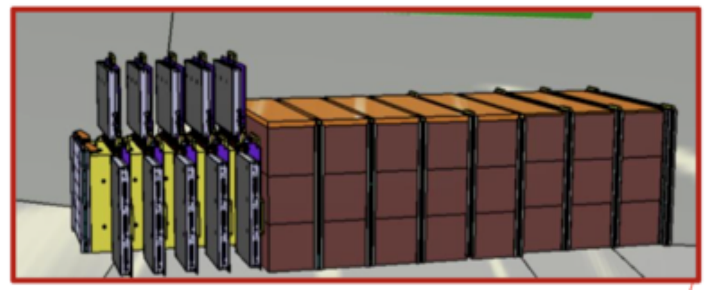


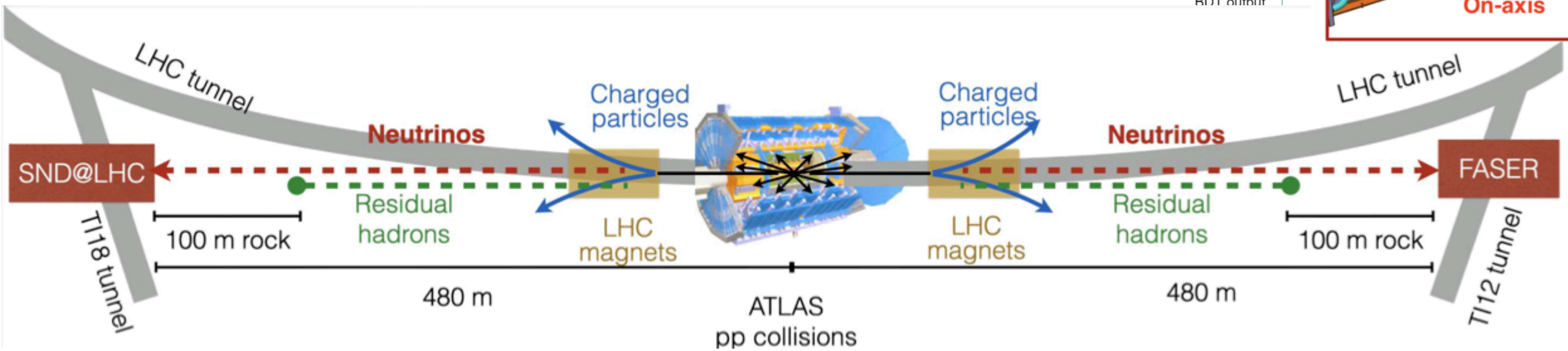




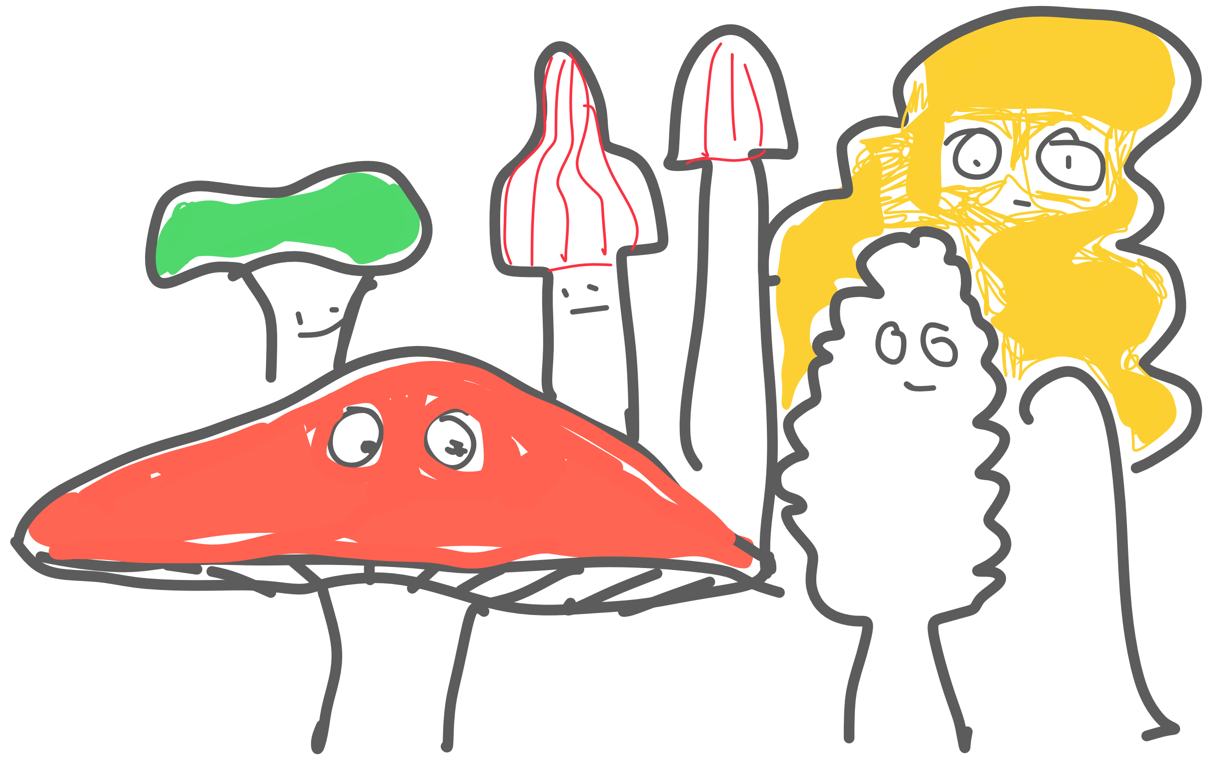


Off-axis





- FASER and SND are two forward experiments designed to study light dark-sector particles from SM meson decays (symmetric and complementary)
- They also profit from the large neutrino flux in the forward direction@LHC and study neutrino cross sections at TeV energies, where no such measurements exist
- Also proposal for Forward Physics Facility (FPF) at the HL-LHC



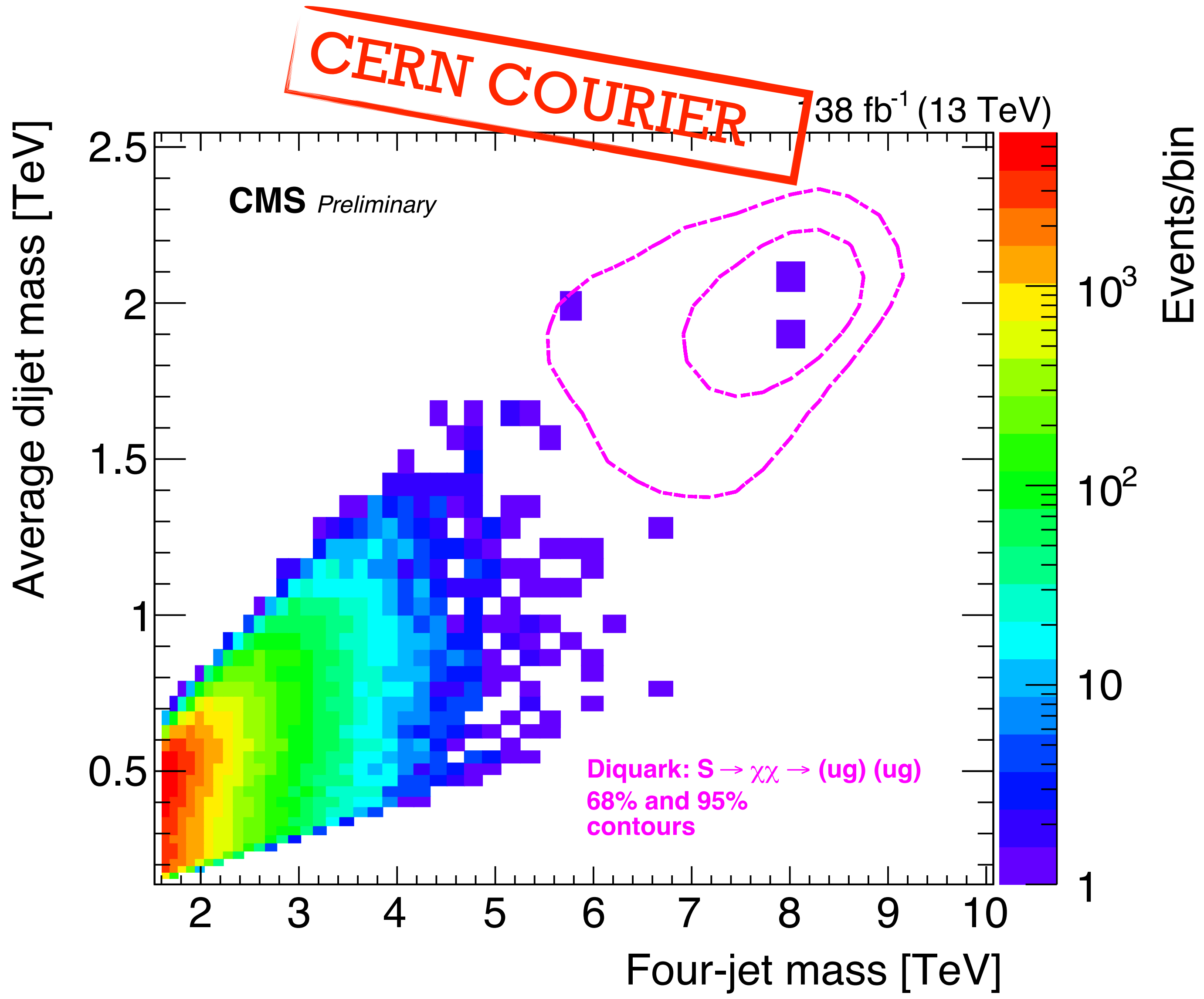
"Pick your favourite bump"

(while waiting for Run 3)

- Several new results with $> 3\sigma$ excesses, $\sim 2\sigma$ considering LEE
- Intriguing, but we need more data

Y→XX→(jj)(jj)

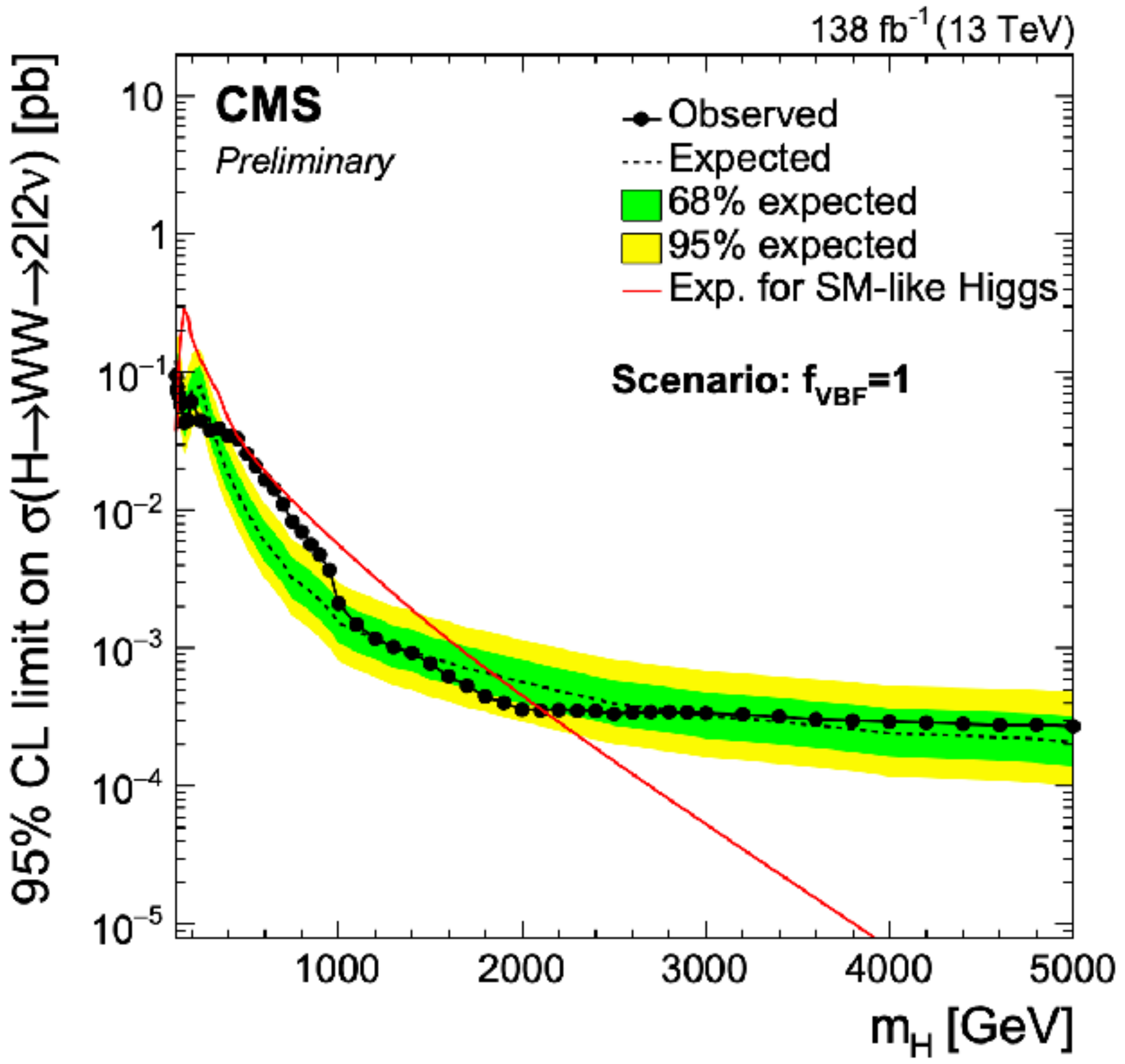
3.9σ (1.6σ global) at 8 TeV in four-jet mass



CMS-PAS-EXO-21-010

VBF H→WW

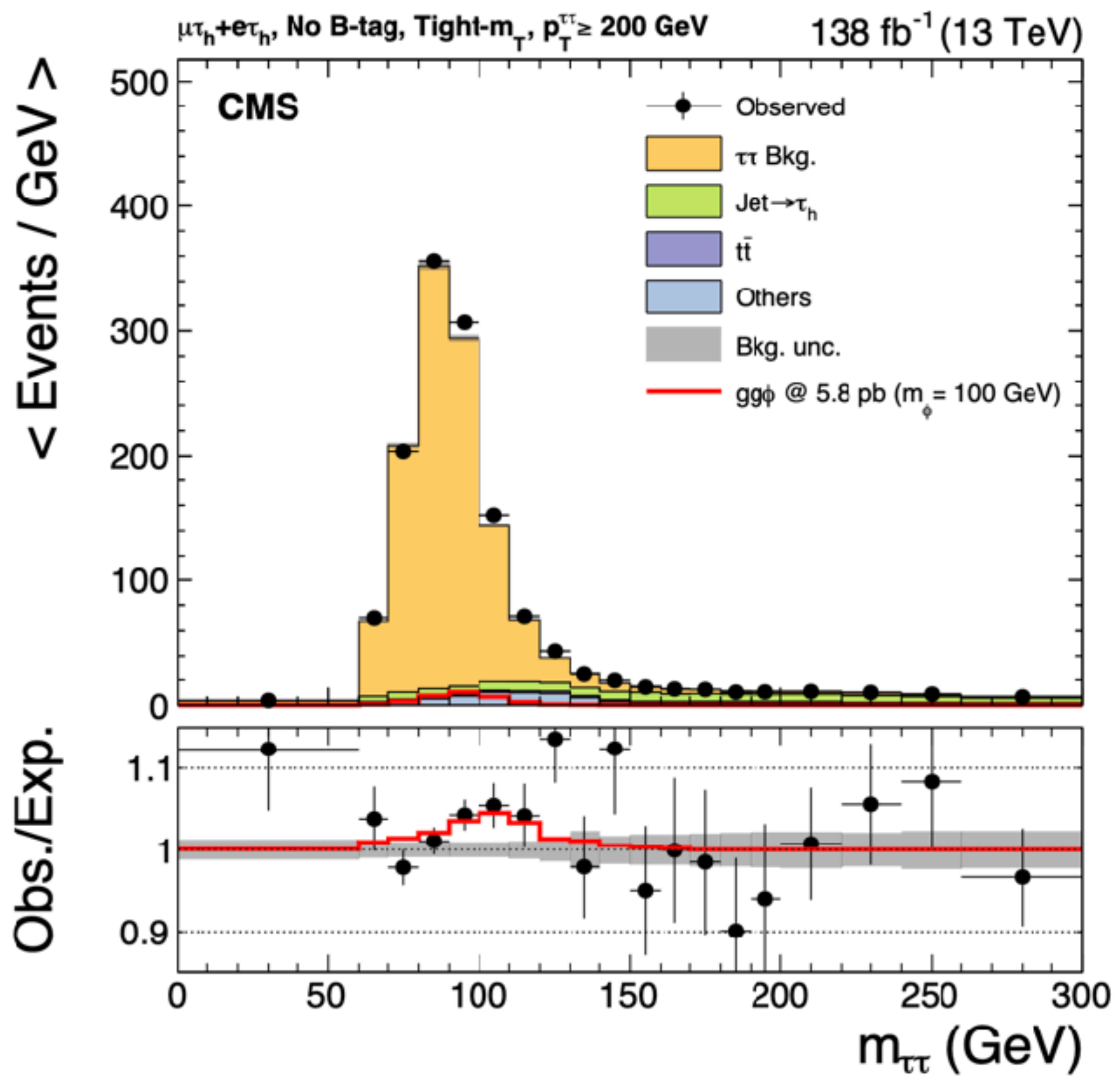
3.8σ (2.6σ global) in VBF WW broadly in mass ~700 GeV



CMS-PAS-HIG-20-016

ϕ→ττ

3.1σ local excess for $m_{\tau\tau}$ ~100 GeV



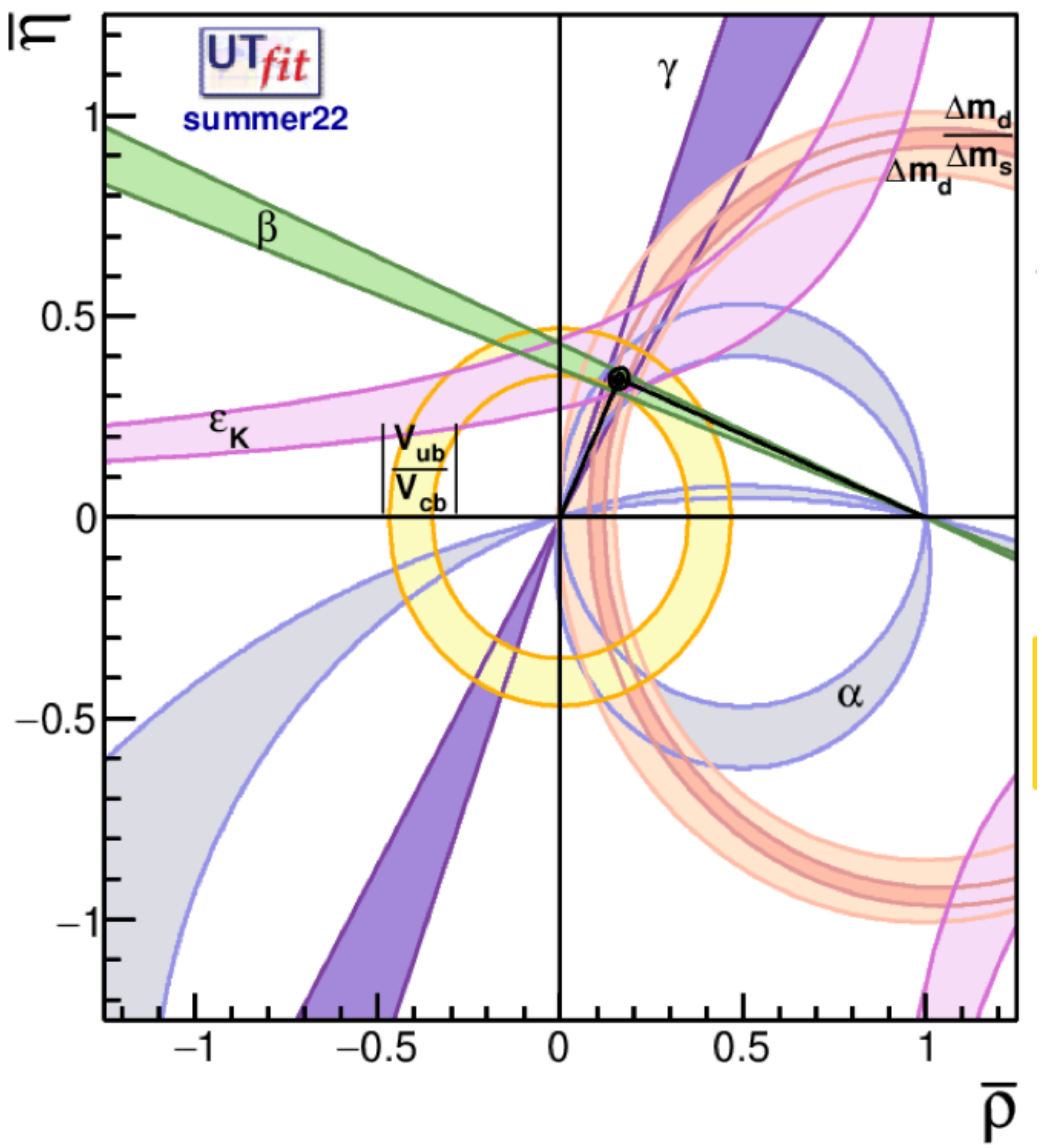
CMS-PAS-HIG-21-001

CREDIT S. Cooperstein

FLAVOUR

Consistency of CKM fits

M. BONA



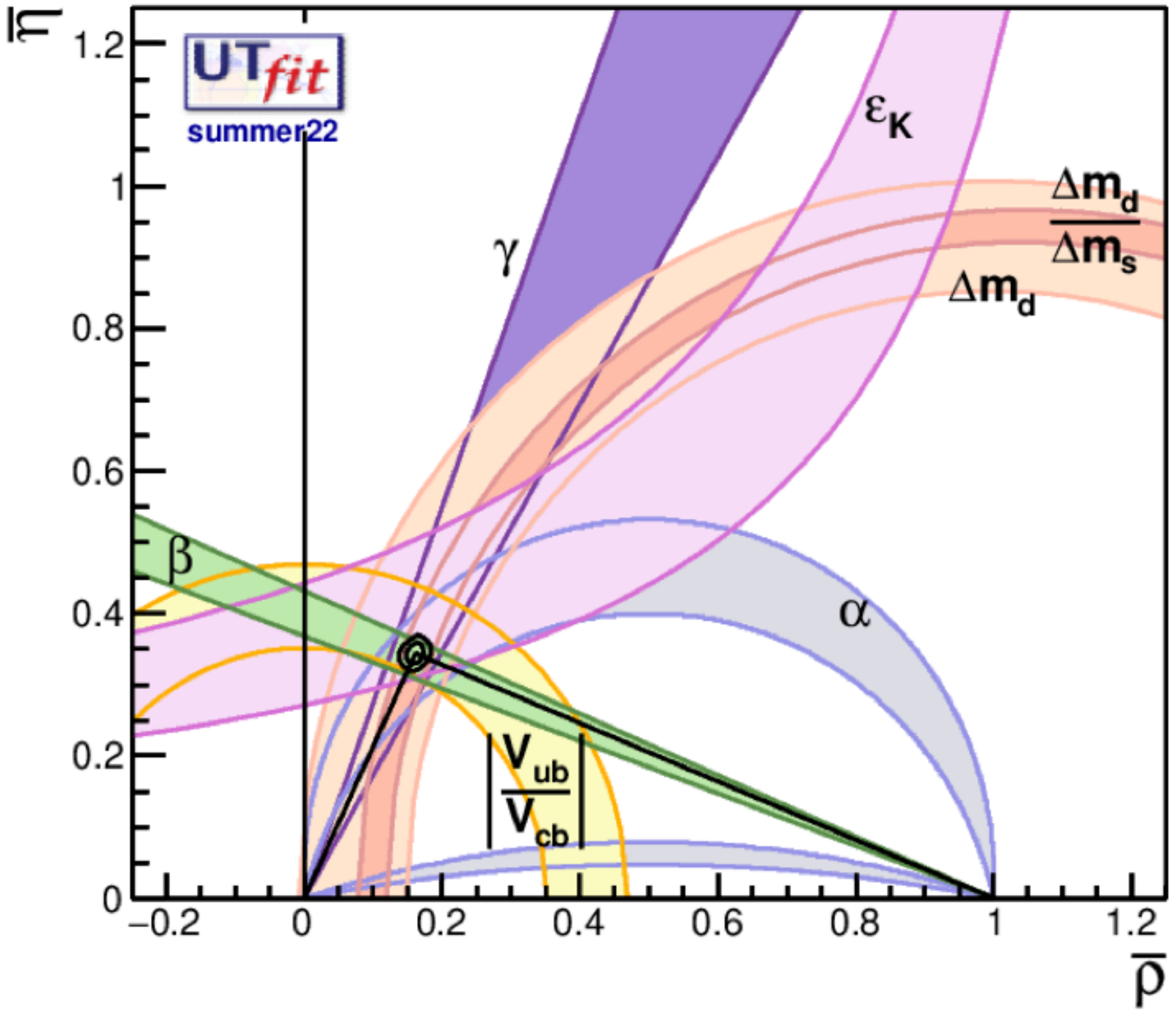
$\bar{\rho} = 0.161 \pm 0.009$ ~6%

$\bar{\eta} = 0.344 \pm 0.010$ ~3%

- Impressive effort from community and tremendous success of CKM paradigm!
- At the current level of precision, all measurements are consistent and intersect in the apex of the UT
- New Physics effects (if there) are small!

Consistency of CKM fits

M. BONA



Zoomed in!

$\bar{\rho} = 0.161 \pm 0.009$ ~6%

$\bar{\eta} = 0.344 \pm 0.010$ ~3%

- Impressive effort from community and tremendous success of CKM paradigm!
- At the current level of precision, all measurements are consistent and intersect in the apex of the UT
- New Physics effects (if there) are small!

Improving precision of CKM consistency checks : Measuring γ at LHCb

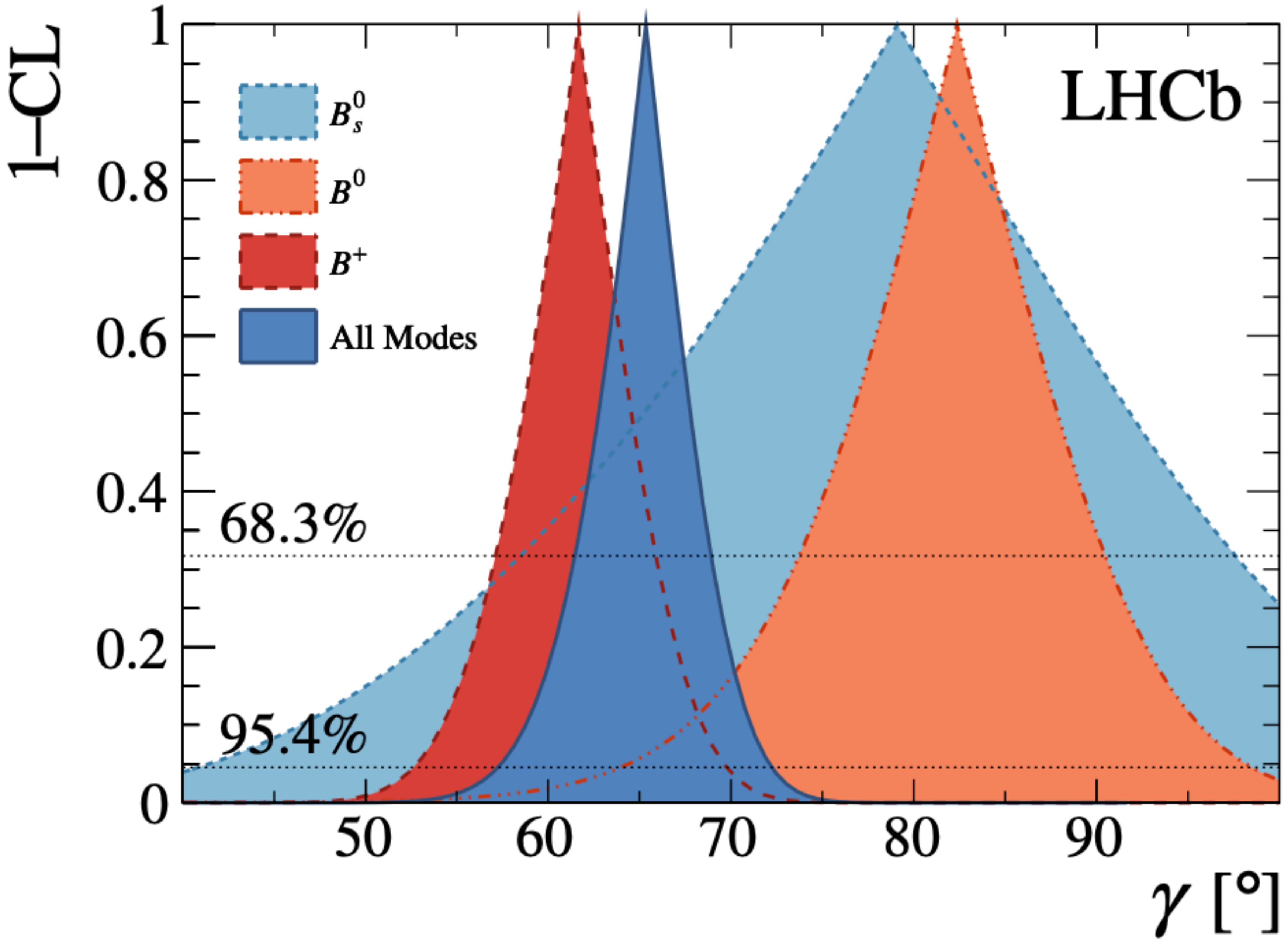
O. Ozcelik
M. Palutan

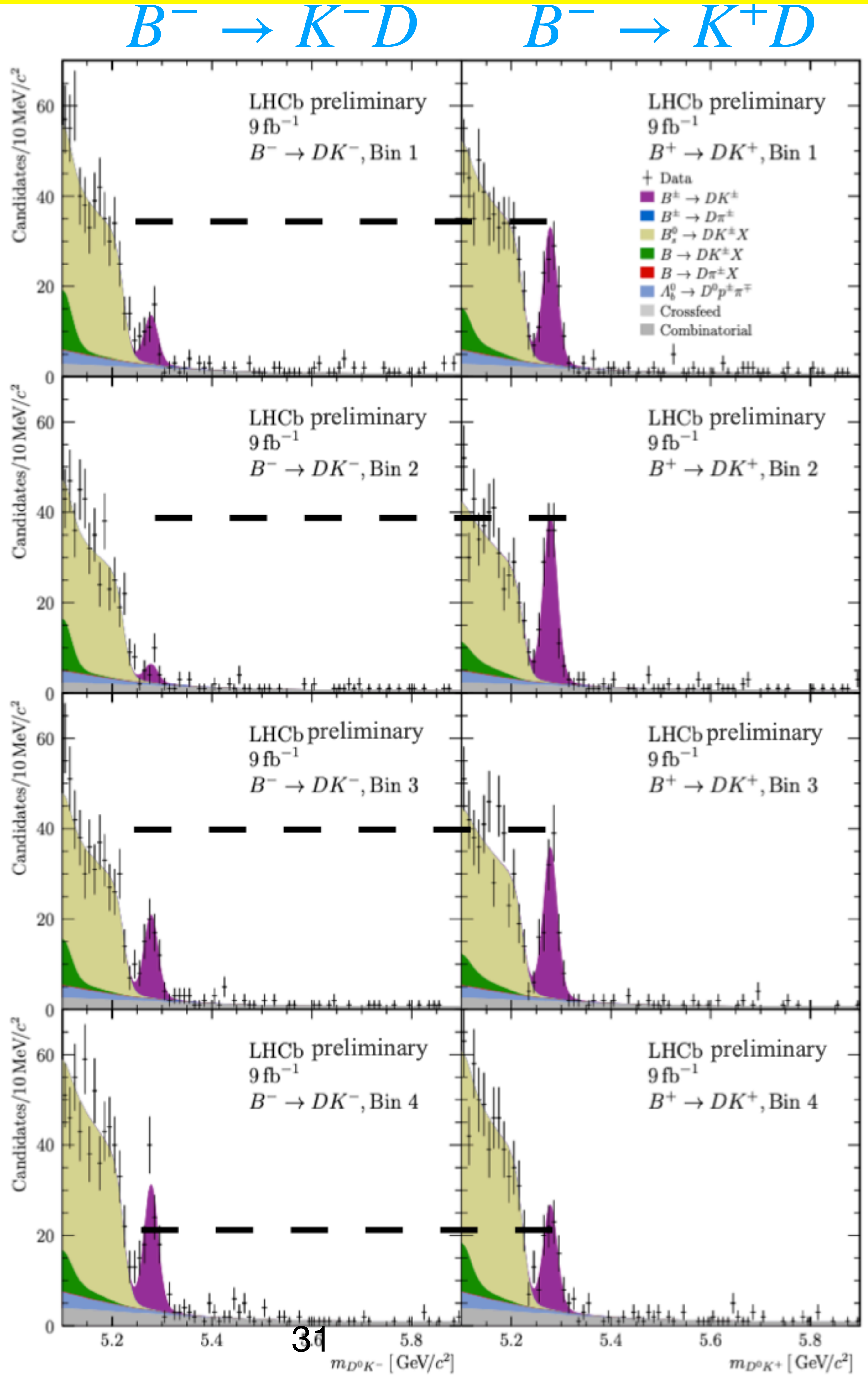
- γ is the only angle of the unitarity triangle that can be determined using only tree-level decays (standard candle)

- LHCb has provided most precise determination by a single experiment (which combines a multitude of channels) to be compared with $\gamma = (64.8 \pm 1.4)^\circ$ from CKM fits (UTfit) : ← M. BONA

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

[arXiv:2110.02350]





NEW LHCP 2022

- Measurement of γ from $B^\pm \to D[K^\mp\pi^\pm\pi^\pm\pi^\mp]h, \ (h = K, \pi)$
- CP asymmetry measured in 4 bins of D decay phase space (hadronic parameters of D decay constrained from results from BESIII and CLEO-c)

$$\gamma = (54.8^{+6.0}_{-5.8}(\text{stat}) \pm 0.6(\text{syst})^{+6.7}_{-4.3}(\text{ext}))^\circ$$

2nd best result from single mode (best result from $D \to K_s^0\pi^+\pi^-$)

[LHCb-PAPER-2022-017] in preparation

Lifetime of light B_s^0 mass eigenstate

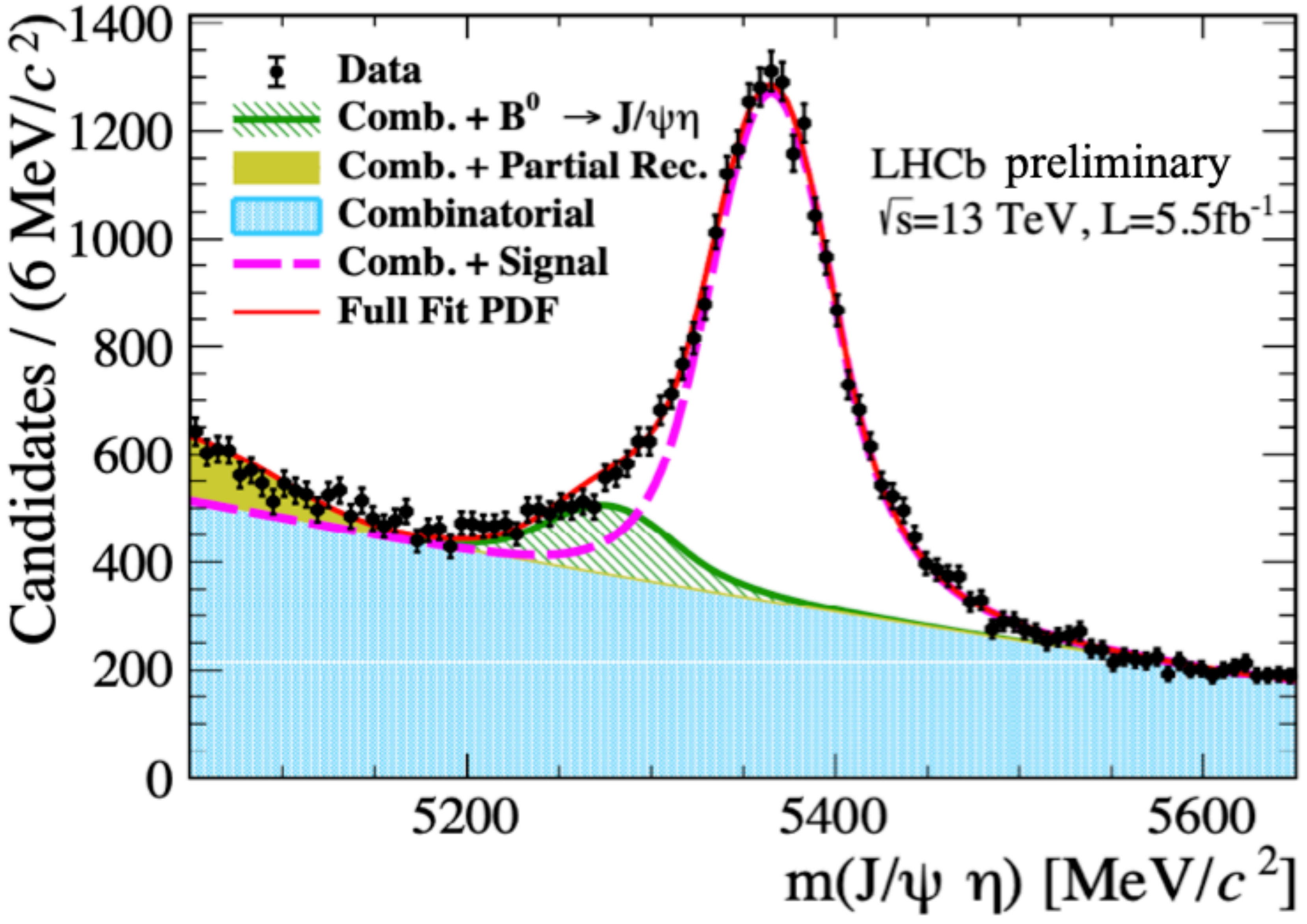
NEW LHCP 2022

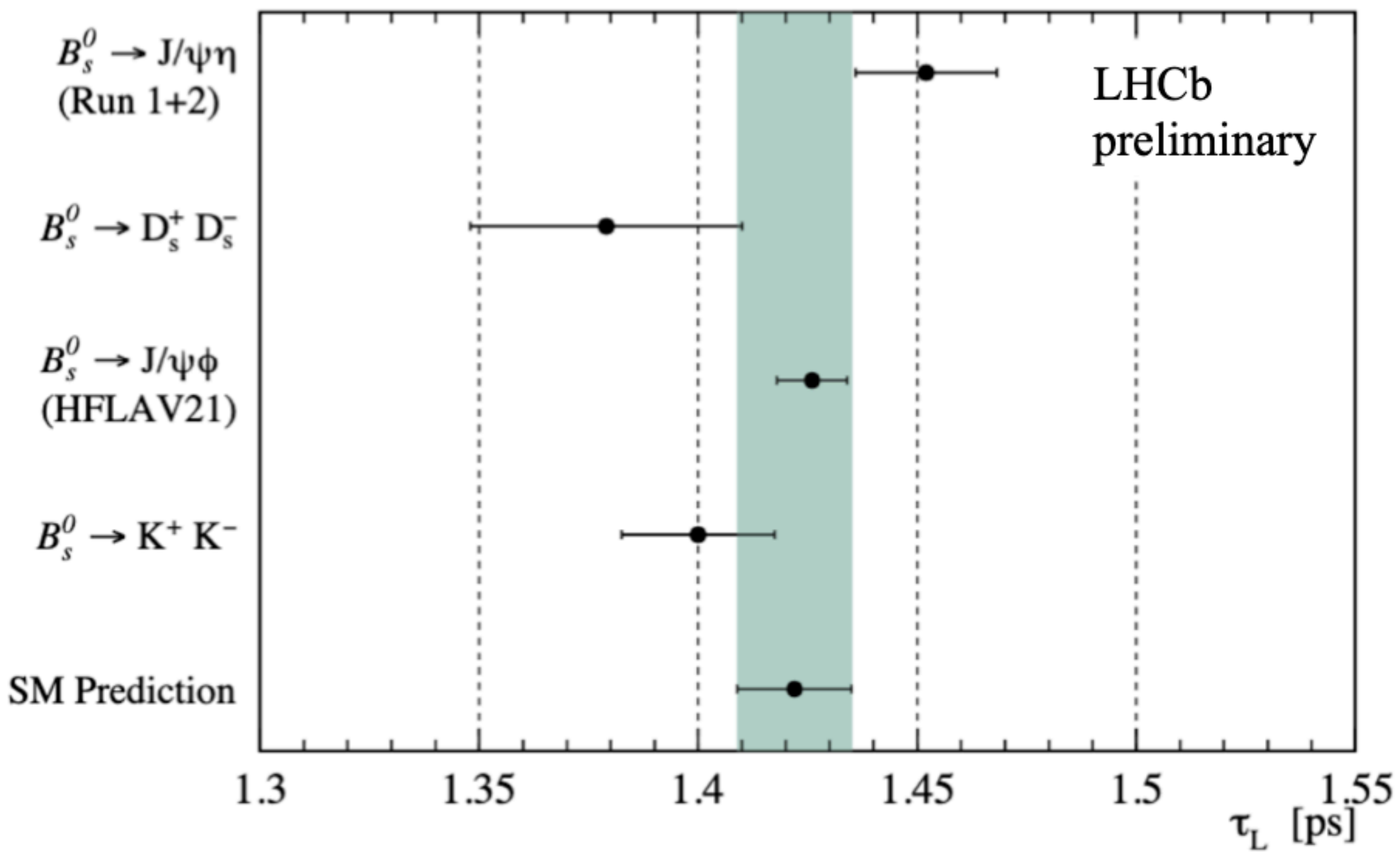
O. Ozcelik
M. Palutan

- Direct measurements of lifetimes of heavy (H) and light (L) B_s^0 mass (and ~CP) eigenstates can be compared with SM expectations and/or what is obtained from $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$ in $B_s^0 \to J/\psi\phi$
- New lifetime measurement using $B_s^0 \to J/\psi\eta$ decays
- CP-even final state, determines τ_L (lifetime of light (L) B_s^0 mass eigenstate)

[LHCb-PAPER-2022-010]
in preparation

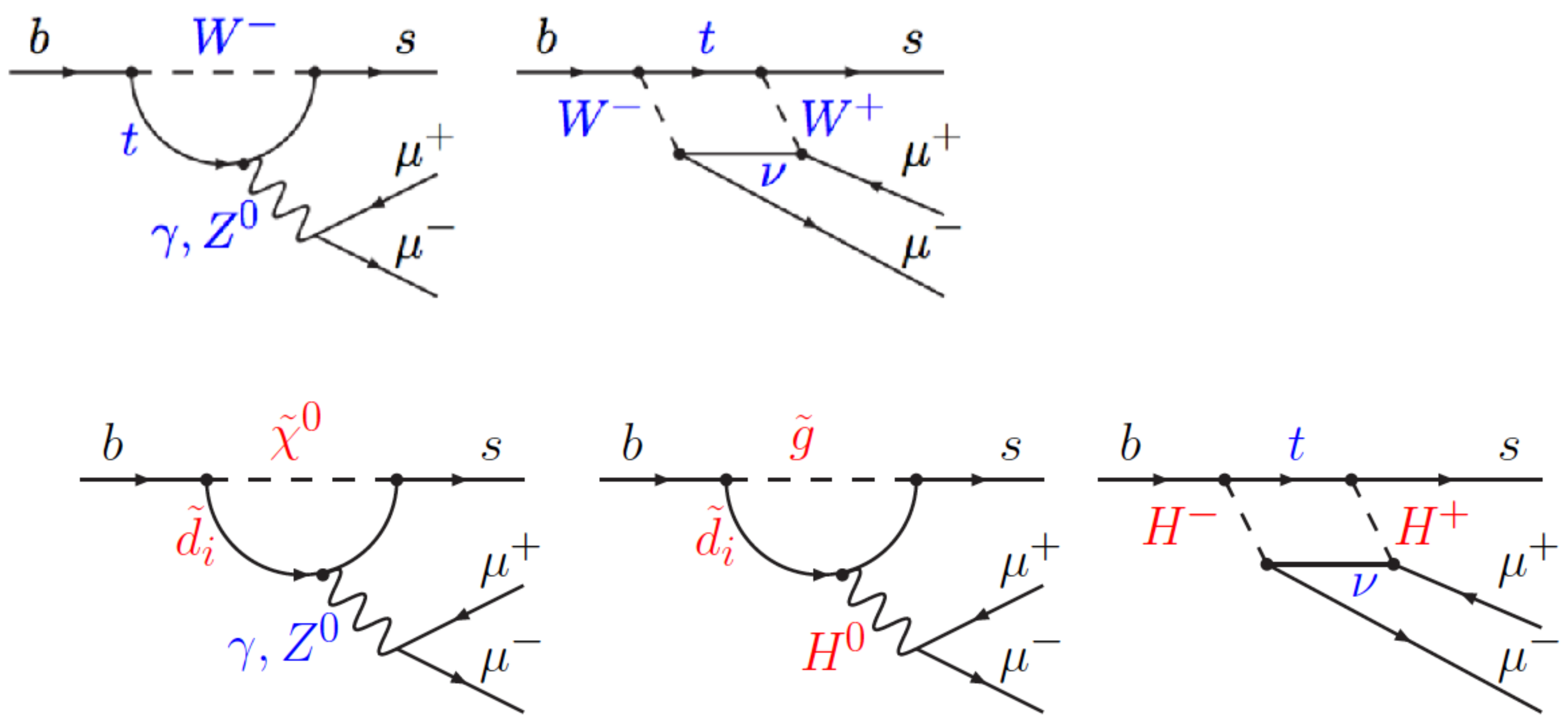
$\tau_L = (1.452 \pm 0.014_{stat} \pm 0.007_{syst-uncorr} \pm 0.002_{syst-corr})$ ps





Lepton Flavour Universality (LFU)

- In the SM the only flavour non-universal terms are the three lepton masses: $m_\tau, m_\mu, m_e \leftrightarrow$ 3477 / 207/ 1
- The SM quantum numbers of the three families could be an “accidental” low-energy property: the different families may well have a very different behaviour at high energies, as signalled by their different mass
- If NP couples in a non-universal way to the three lepton families, then we can discover it by comparing classes of rare decays involving different lepton pairs (e.g. μ/e or μ/τ)
- Test LFU in $b \to s\ell^+\ell^-$ transitions, i.e. flavour-changing neutral currents with amplitudes involving loop diagrams where NP could enter



A very intriguing pattern…

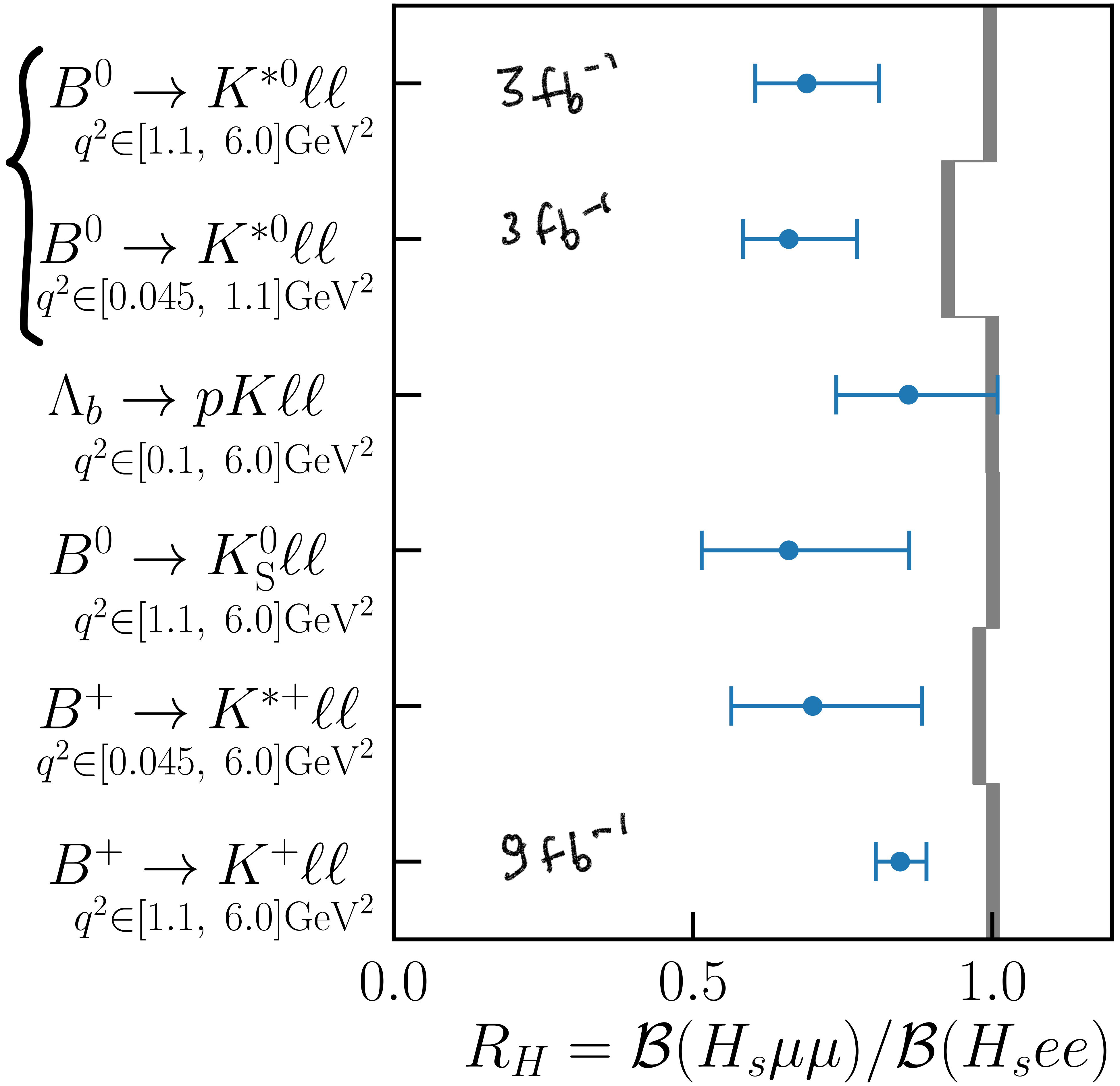
.. triggering flourishing model building directions

M. PALUTAN
G. SIMI

Summary of R_H @ LHCb

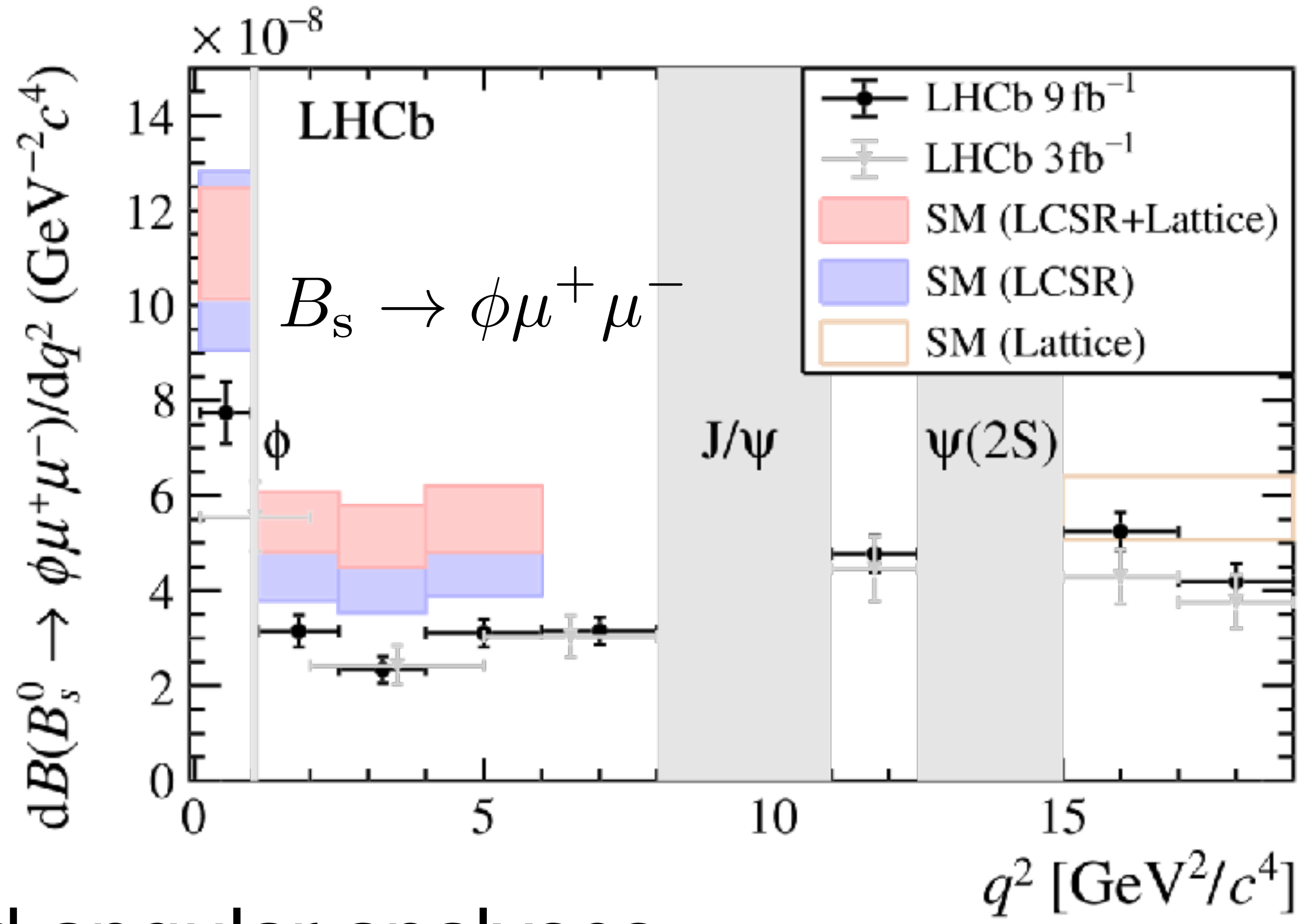
CREDIT M. BORSATO

To be updated with full statistics

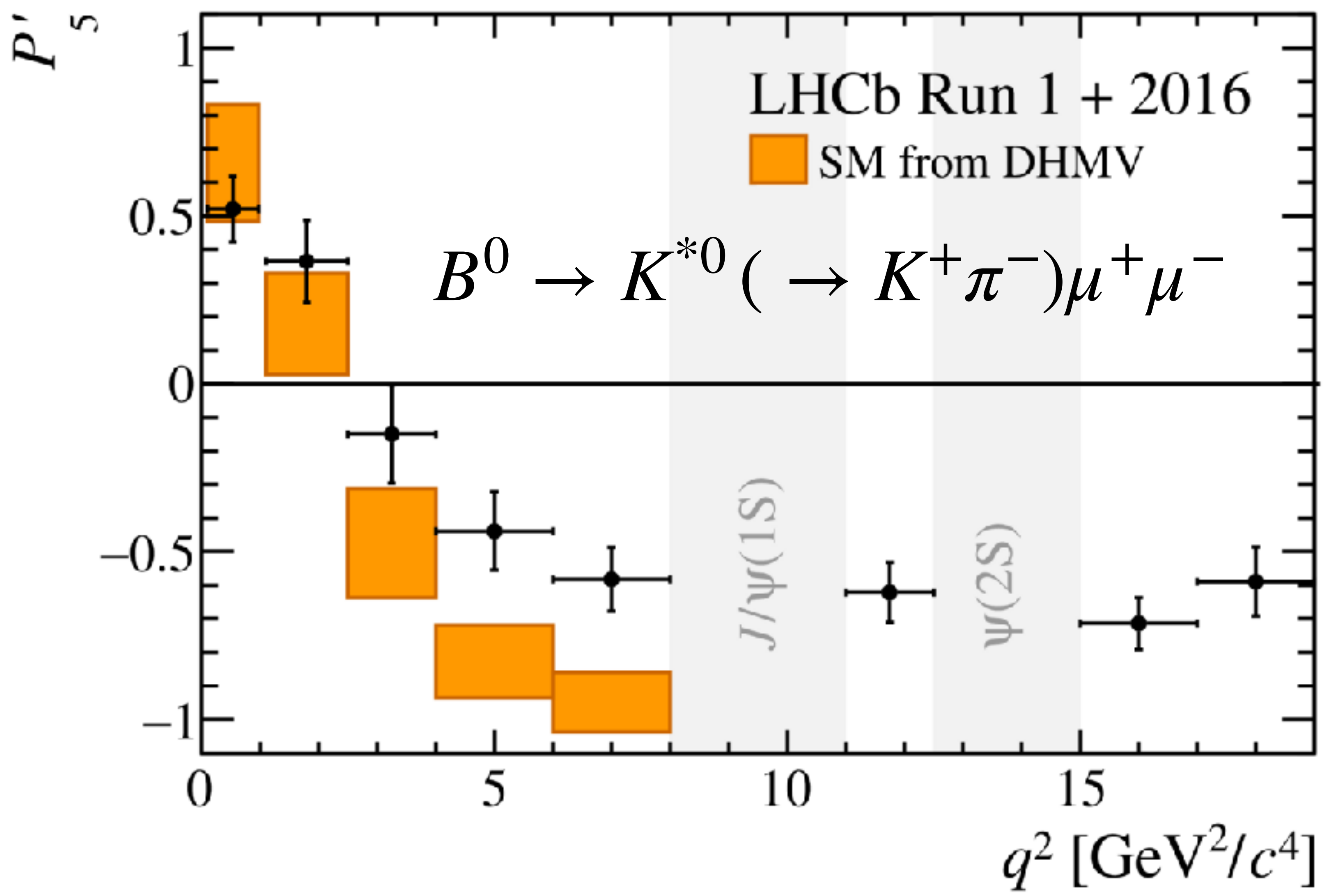


Theory calculated with flavio

- Coherent set of $b \to s\ell\ell$ tensions in BFs
  $B^+ \to K^+\mu^+\mu^-, B^0 \to K^{(*)0}\mu^+\mu^-, B_s \to \phi\mu^+\mu^-$ ..



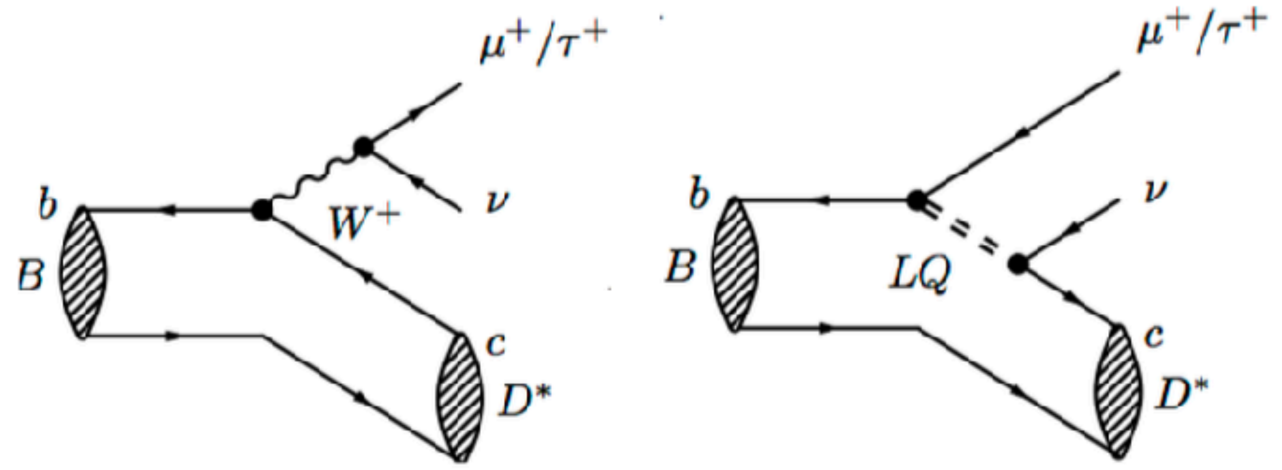
- and angular analyses



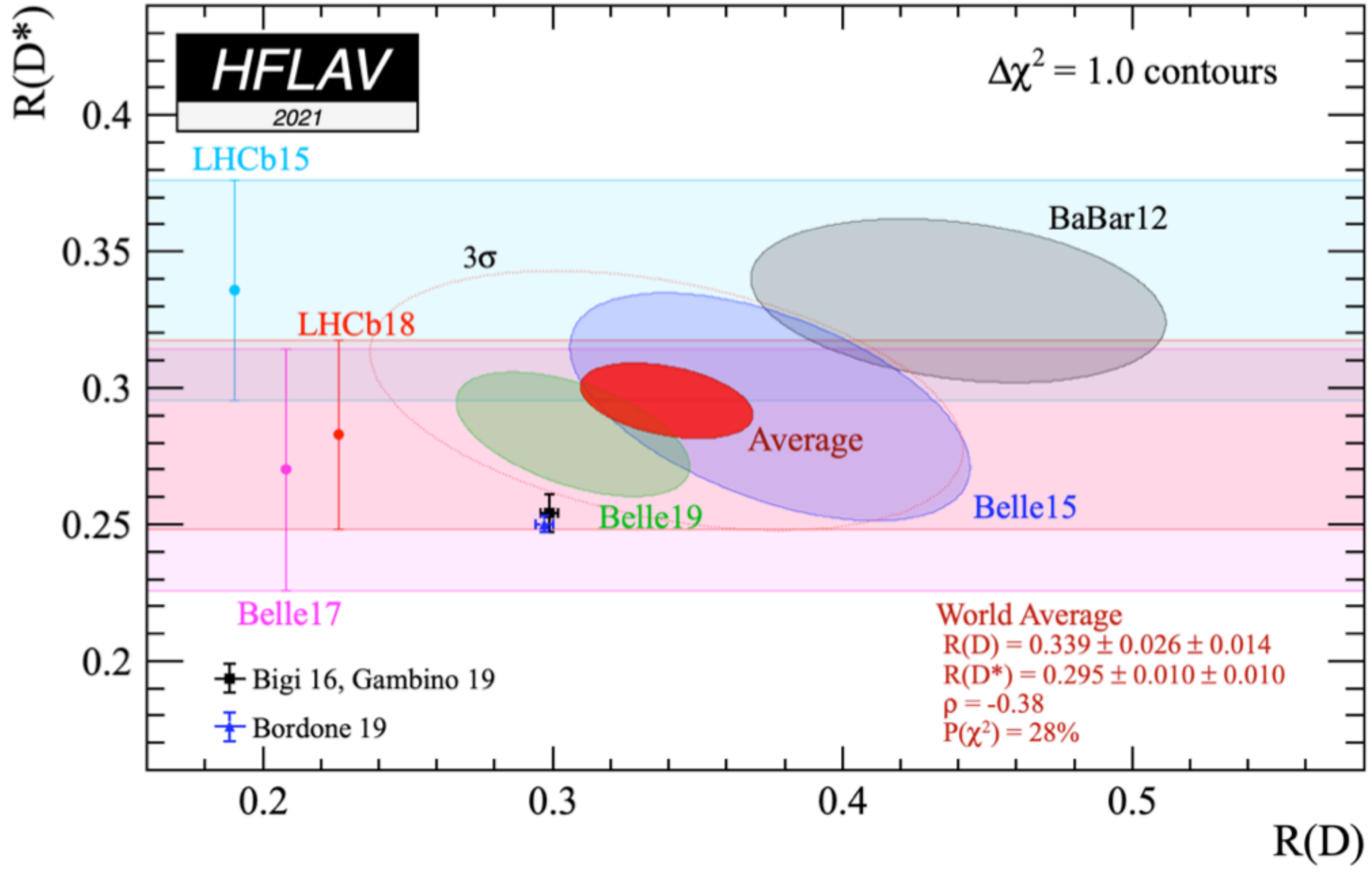
LFU in $B \to D^{(*)}\tau\nu$ decays

- Tree-level charged current with V_{cb} suppression

$$R(D^{(*)}) \equiv \frac{B(\overline{B} \to D^{*}\tau^{-}\overline{\nu}_{\tau})}{B(\overline{B} \to D^{(*)}\mu^{-}\overline{\nu}_{\mu})}$$



- All experiments see an excess wrt SM predictions
- $\sim 3.4\sigma$ tension, intriguing as it occurs in a tree-level SM process ($\Lambda_{NP} \lesssim 3\,\mathrm{TeV}$)



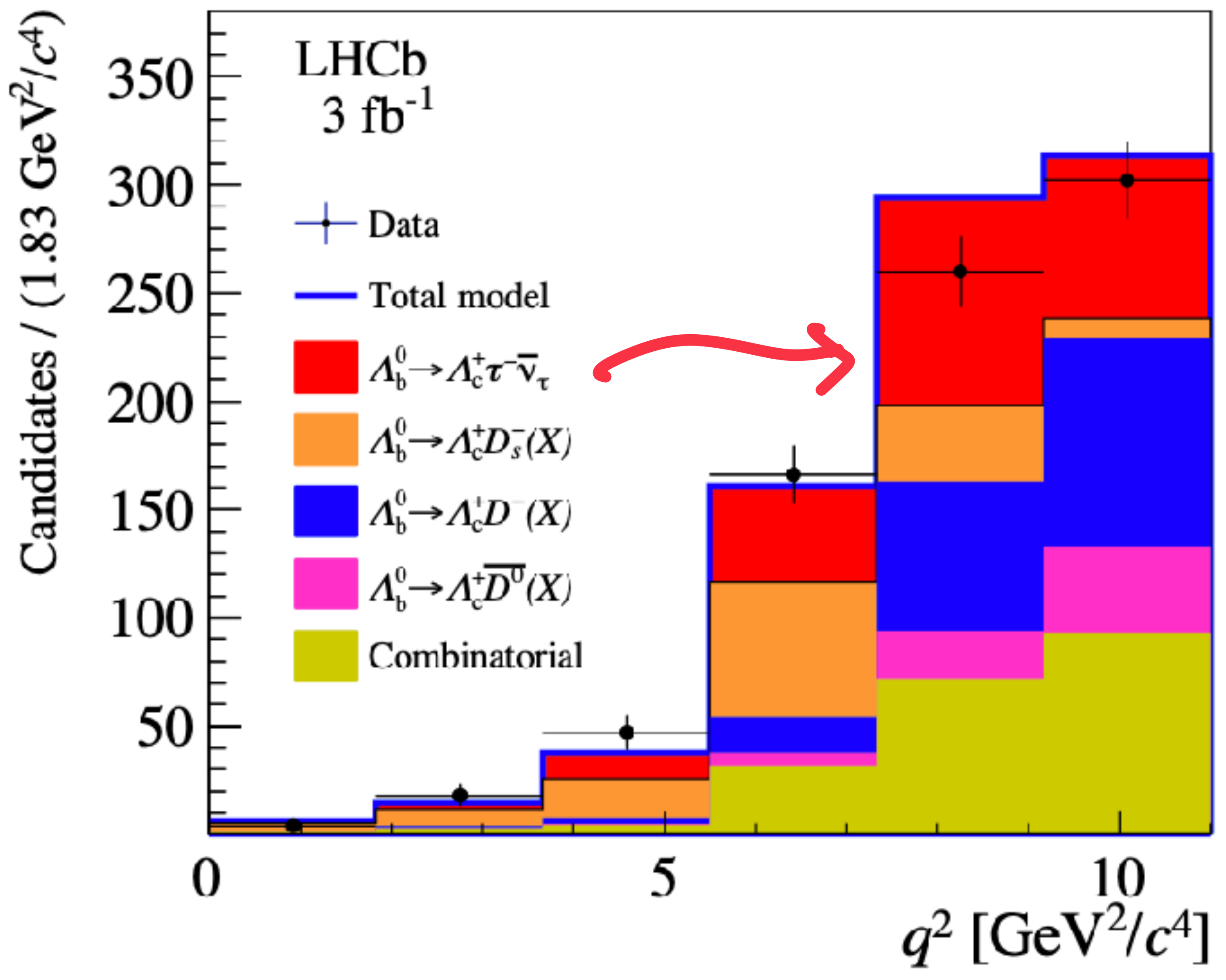
BABAR to deliver another precise measurement of $R(D^{(*)})$ after a decade, more data-driven

Measurement of $B(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)$ and $R(\Lambda_c)$ with τ three-prong decays

M. PALUTAN
G. SIMI

- Decay observed for the first time with 6.1σ significance

$$R(\Lambda_c^+) = \underbrace{\frac{B(\Lambda_b^0 \to \Lambda_c^+ \tau^- \nu_\tau)}{B(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}}_{\text{MEASURED}} \times \underbrace{\frac{B(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}{B(\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu_\mu)}}_{\text{EXT}}$$



[arXiv:2201.03497]

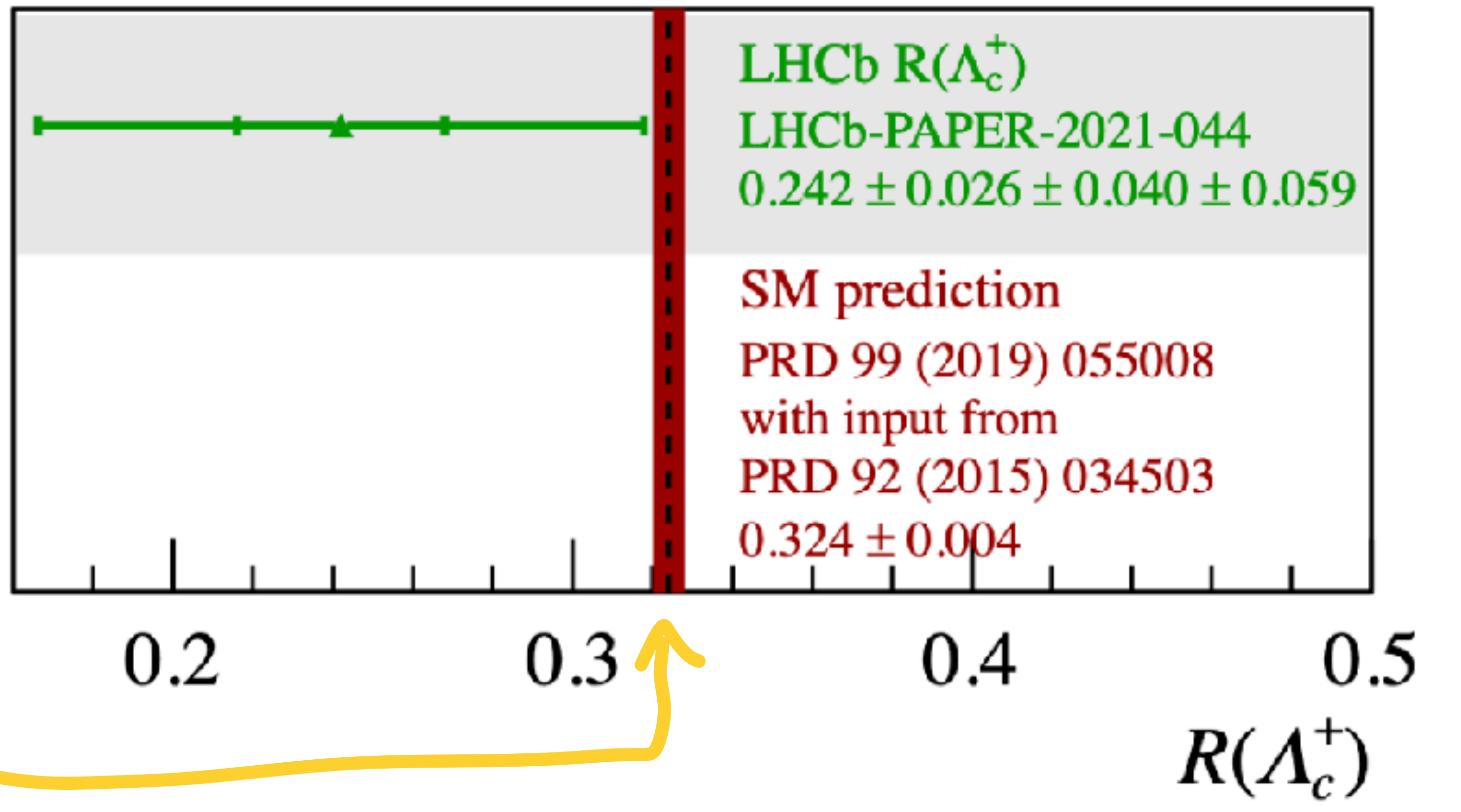
- Input from CDF+LHCb on $B(\Lambda_b^0 \to \Lambda_c^+ 3\pi)$ gives
  $B(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau) = (1.50 \pm 0.16 \pm 0.25 \pm 0.23)\,\%$

- Input from DELPHI on $B(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)$ gives

$$R(\Lambda_c^+) \equiv \frac{B(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{B(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)} = 0.242 \pm 0.026_{\text{stat}} \pm 0.040_{\text{syst}} \pm 0.059_{\text{ext}}$$

M. BLANKE

in agreement with SM

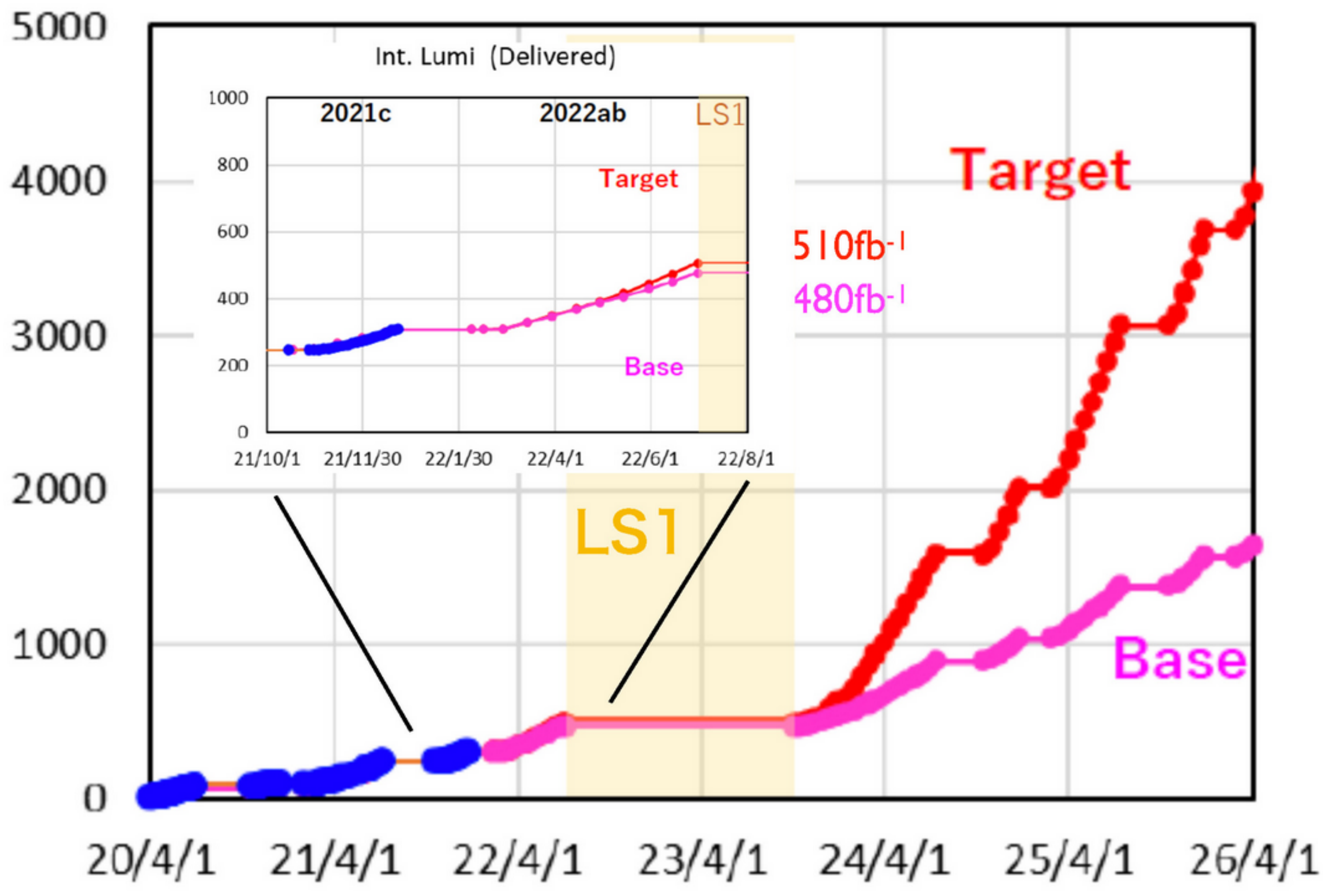


However, from approximate sum rule relating $R(D^*)$ and $R(\Lambda_c)$:
enhancement of $R(D^*)$ implies $R(\Lambda_c) > R_{\text{SM}}(\Lambda_c)$ BLANKE, CRIVELLIN et al.
(consistent with expectations from heavy-quark symmetry)

Many nice results from Belle II!

S.NISHIDA

- SuperKEKB performance below expectations, but $\mathscr{L}_{\text{inst}}$ exceeding KEKB by ~a factor 2 (goal is factor 10)
- $\mathscr{L}_{\text{int}}$ ~ 380 fb^{-1}, ie 1/3 full Belle dataset (goal is 50 ab^{-1})
- Long shutdown1 (LS1) starting summer 22



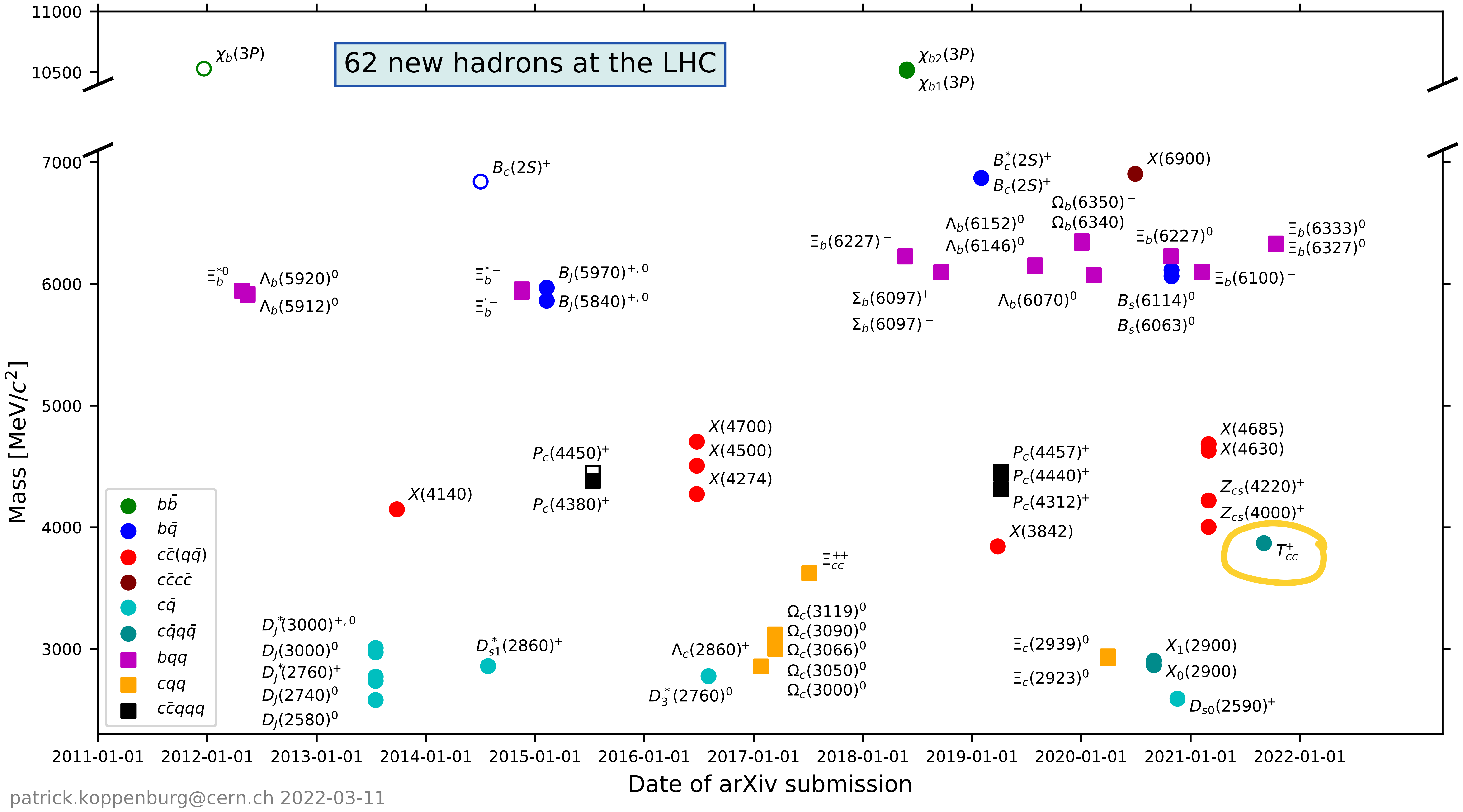
- Detector performance already mostly exceeding that of Belle
  - Tracking and vertexing, neutrals, muon-ID, flavour tagger (ϵ_{tag}~30%)…
- World's most precise measurements of D^0, D^+, Λ_c lifetimes
- Measurement of γ from a combined analysis of Belle and BelleII (expect $\lesssim 3°$ with 10 ab^{-1})
- B^0 lifetime and mixing frequency
- $|V_{\text{ub}}|, |V_{\text{cb}}|$
- BF for EW penguin diagrams with similar performance for e, μ and BF for radiative decays

SPECTROSCOPY

62 new hadrons @the LHC!

E.SPADARO NORELLA

https://www.nikhef.nl/~pkoppenb/particles.html



- Including many exotic states with minimal quark content different from $q\bar{q}$ and qqq
- A lot of interest from the theory community and many models based on eg, compact tetraquark/petraquark, hadronic molecules…

First observation of doubly charmed tetraquark : $T_{cc}^{+}(3875)$

P. GANDINI
E. SPADARO NORELLA

[arXiv:2109.01038]
[arXiv:2109.01056]

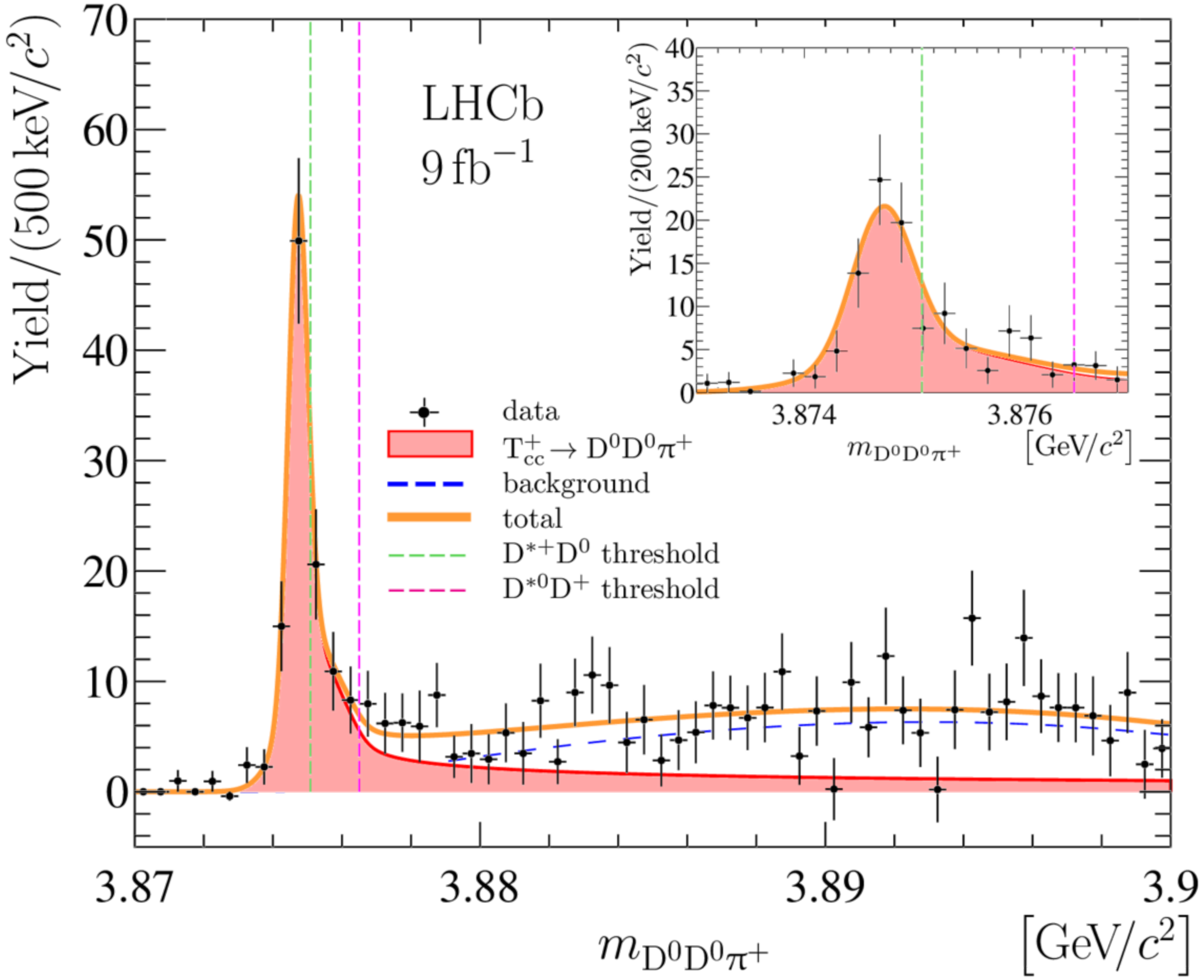
- Observed in $D^0D^0\pi^+$ mass spectrum
- State consistent with quark content $cc\bar{u}\bar{d}$ and $J^P = 1^+$
- Very narrow state, slightly below $D^{*+}D^0$ threshold

m ~ 3875 MeV

$$\delta m_{\rm BW} \equiv m_{\rm BW} - (m_{D^{*+}} + m_{D^0}) = -273 \pm 61 \pm 5^{+11}_{-14}\ \text{keV}$$

$$\Gamma_{\rm BW} = -410 \pm 165 \pm 43^{+18}_{-38}\ \text{keV}$$

- It is expected that the b quark is heavy enough to sustain the existence of a stable $bb\bar{u}\bar{d}$ state



HEAVY IONS

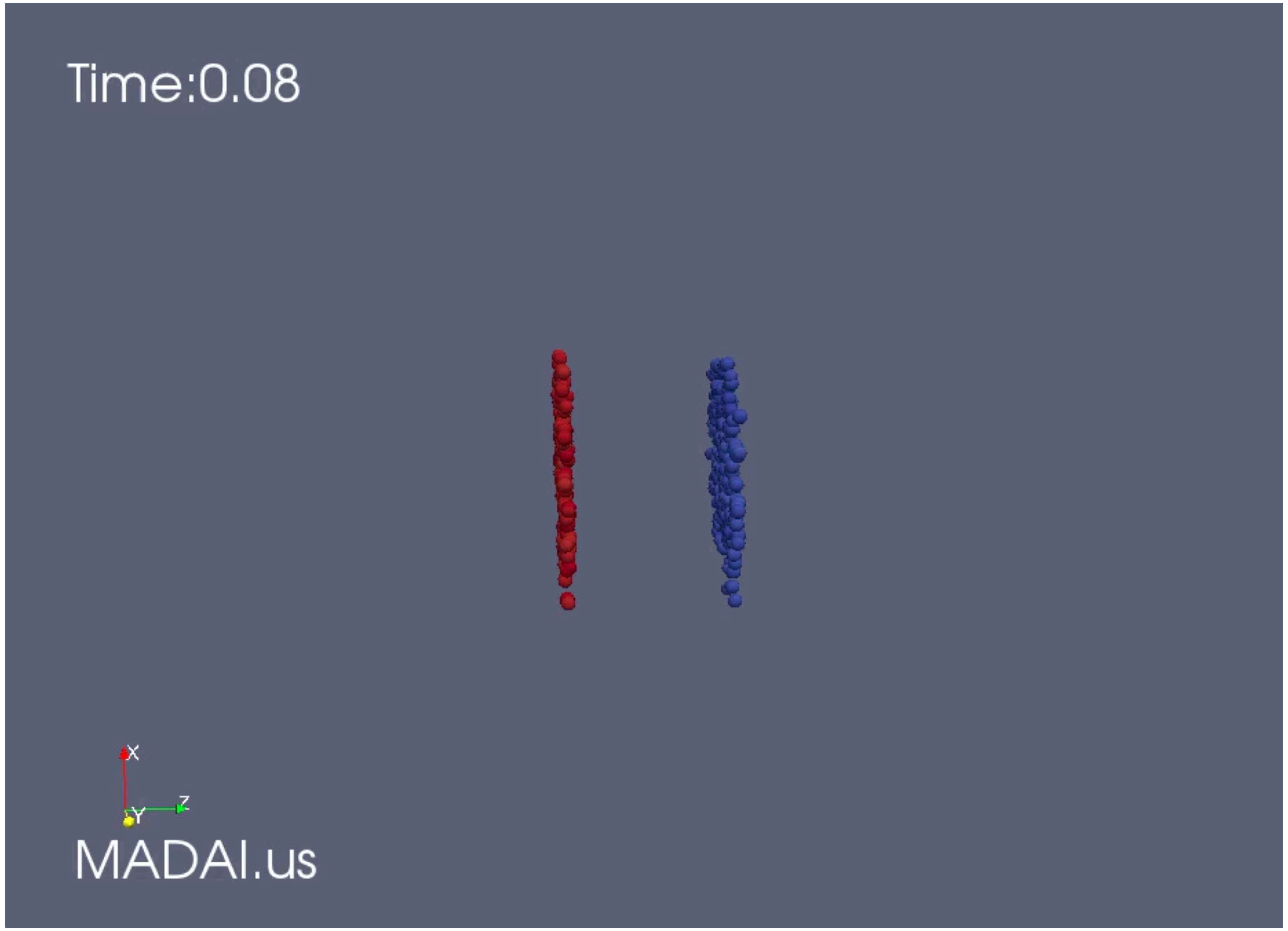
What happens in heavy-ion collisions?

J. NORONHA-HOSTLER

- What is the smallest droplet of Quark Gluon Plasma?
- What are the similarities (and differences) across collisions of different size?

K. Křížková Gajdošová

- What is the correct description of relativistic viscous fluid dynamics?
- What remnants of the initial state can be observed from experimental observables?



Evolution of heavy-ion collisions

K. Křížková Gajdošová

Collectively expanding

Signatures :
modification of momentum and angular distributions

Measurements :
anisotropic flow

Thermalised medium

Signatures :
modification of hadronisation
thermal photon radiation

Measurements :
particle yields
particle spectra

Dense & deconfined medium

Signatures :
parton energy loss
quarkonia dissociation

Measurements :
nuclear modification factor

QCD evolution via photon studies @ALICE

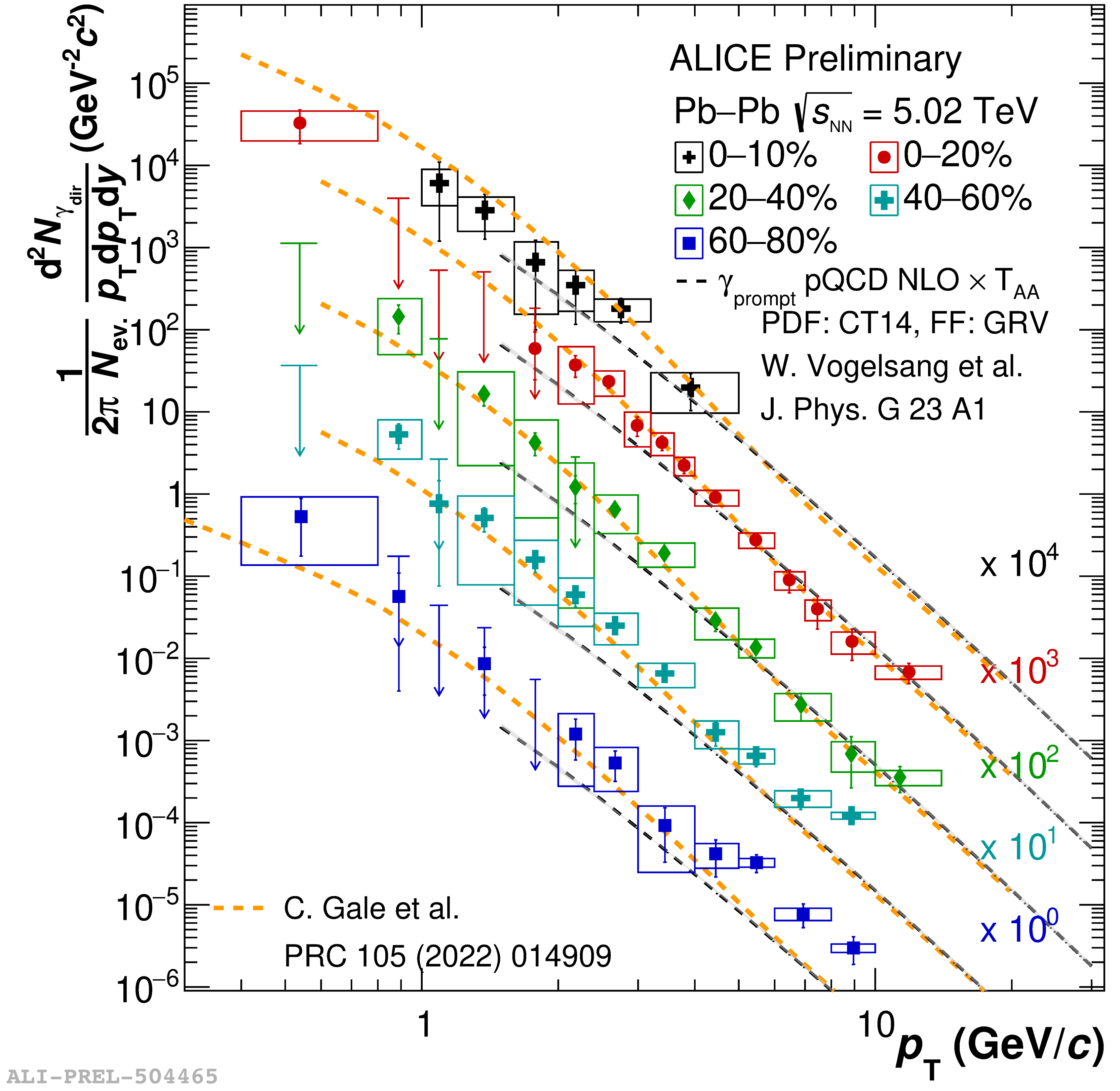
F. COLAMARIA
L. MUSA

t

- Prompt direct photons produced in initial hard-parton scatterings, prior to the formation of the QGP ($p_T \gtrsim 5$ GeV)
- Thermal photons from QGP phase
- Thermal photons from hadron gas

$p_T \lesssim 3$ GeV

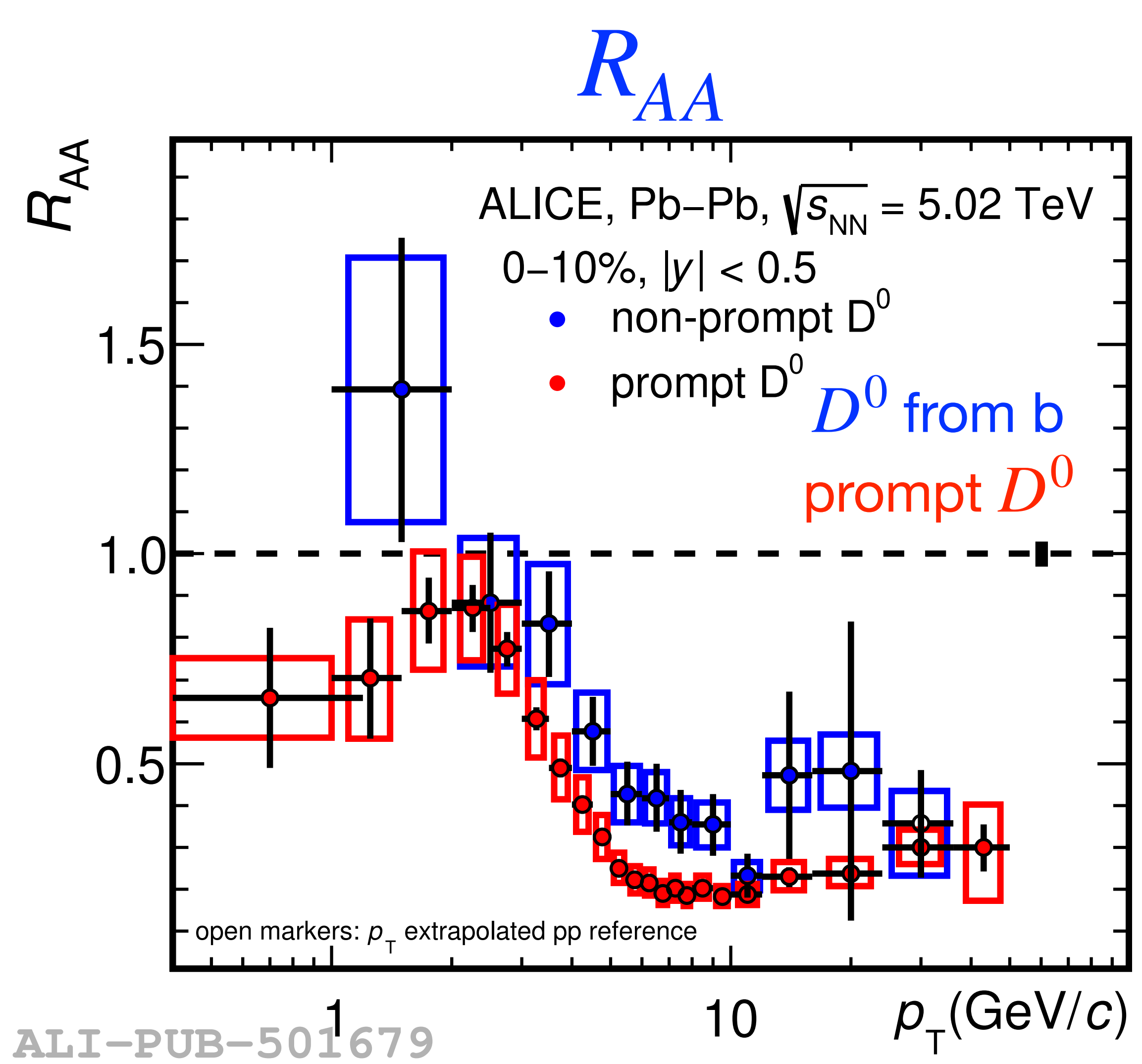
- Thermal photons excellent probe for QGP temperature
  - Extract effective temperature from slope of exponential photon p_T spectrum: $$\frac{d^2N}{p_T dp_T dy} \sim e^{-p_T/T_{\mathrm{eff}}}$$

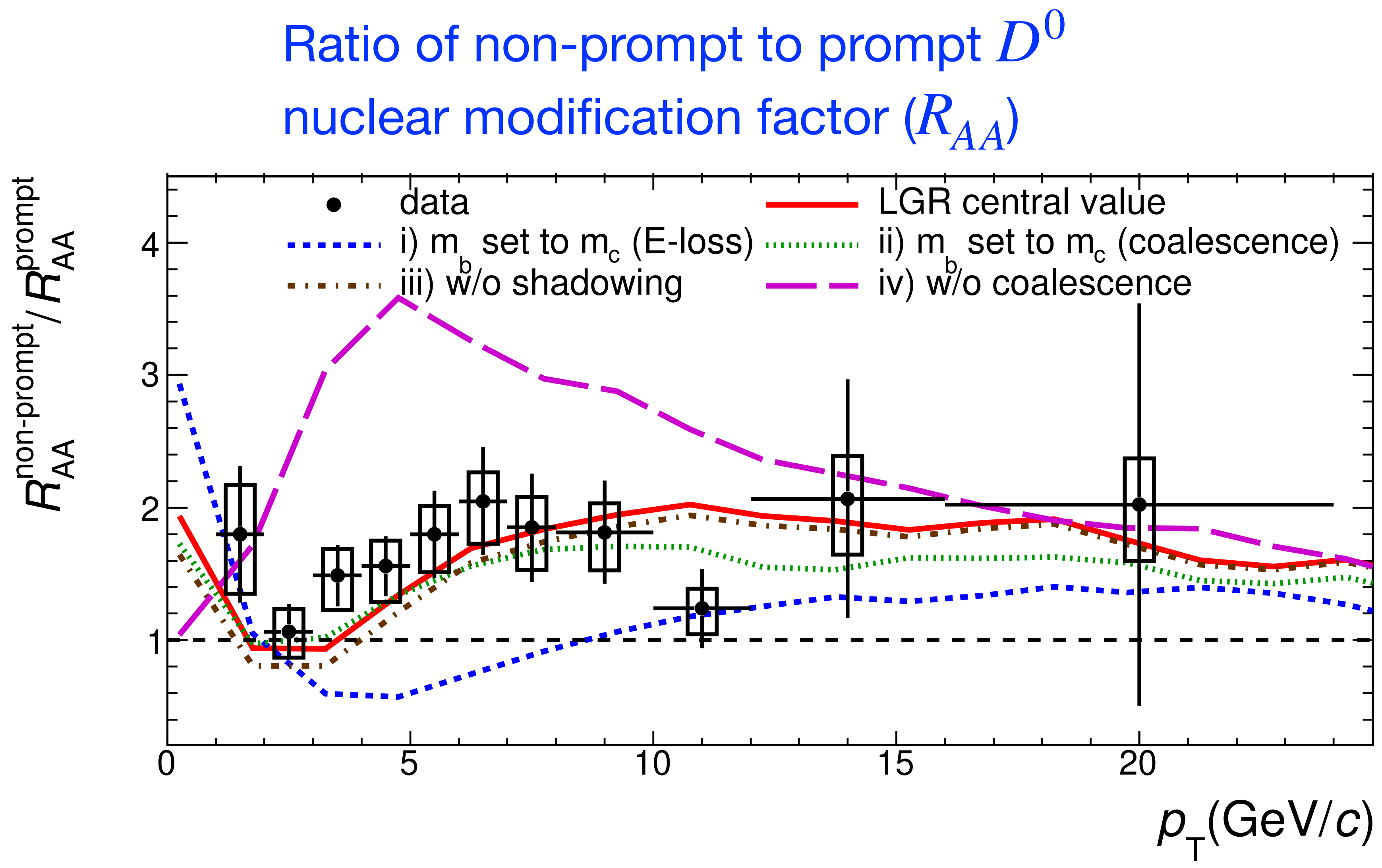


- Photon spectrum well described by calculations that include prompt pQCD photons from hard scatterings and thermal photons. These calculations suggest a dominance of thermal photons at $p_T \lesssim 3$ GeV.

Energy loss of charm and beauty quarks in the QGP@ALICE

L. MUSA
F. COLAMARIA

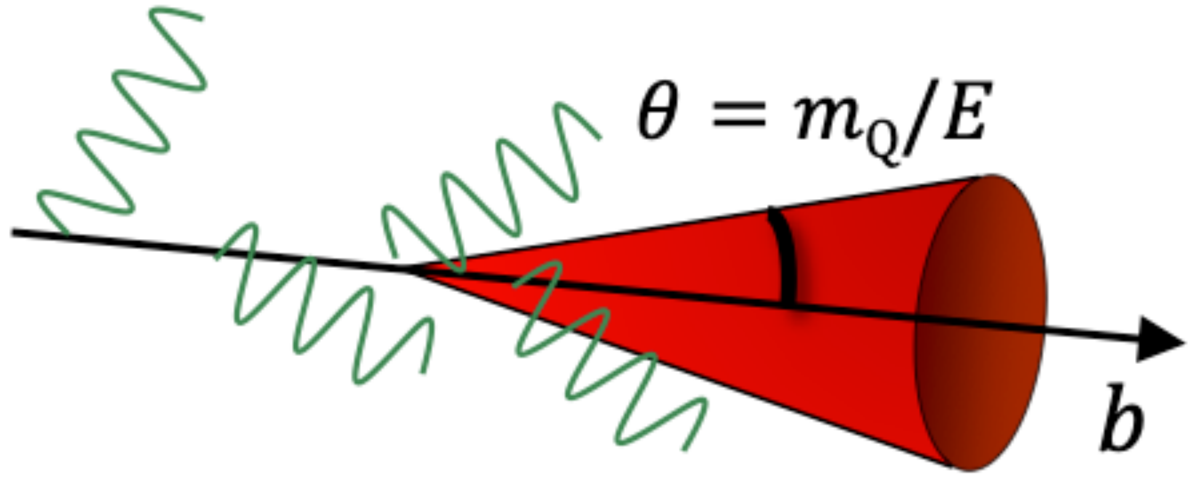




$$R_{AA} = \frac{dN^D}{dp_T}\Bigg|_{Pb-Pb} \Bigg/ \langle T_{AA}\rangle \cdot \frac{d\sigma^D}{dp_T}\Bigg|_{pp}$$

[Nature 605, 440 (2022)]

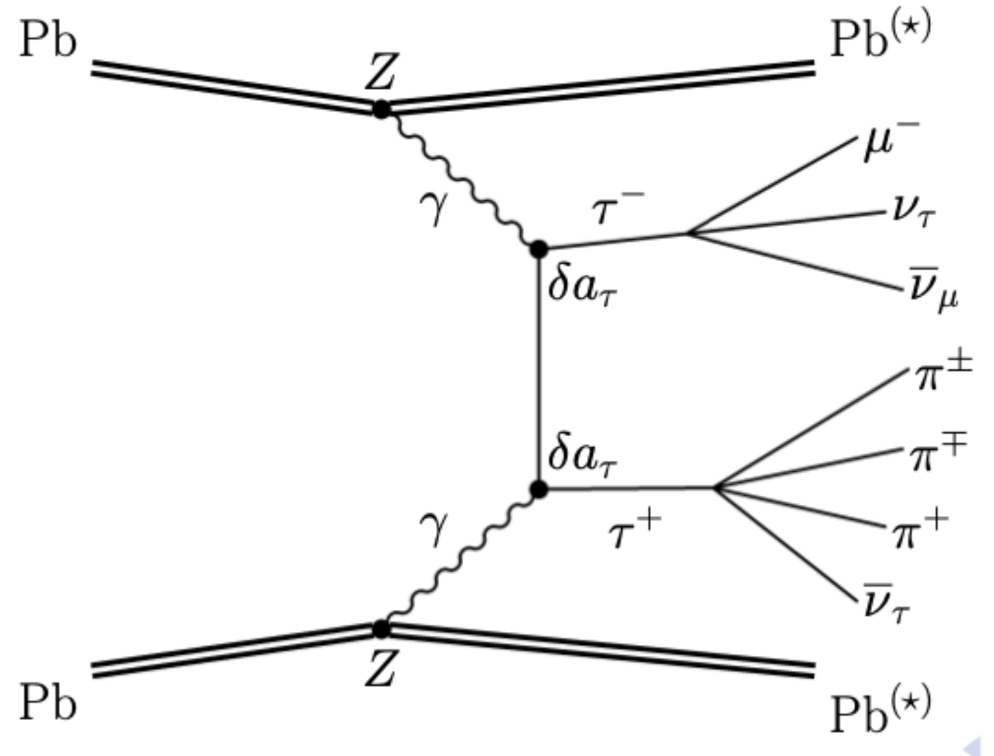
- Beauty R_{AA} measured down to $p_T = 1$GeV for the first time ; large suppression for $p_T > 5$GeV
- Data well described by models that include collisional and radiative energy loss and quark recombination, in addition to fragmentation as a hadronization mechanism
- Ratio of non-prompt to prompt D^0 R_{AA} is measured to be >1 for $p_T \gtrsim 4$ GeV as predicted by models in which b quarks lose less energy than c quarks in the QGP because of their larger mass



“Dead-cone” effect suppresses gluon radiation for $\theta < m_Q/E$ at high p_T, when energy loss is caused mainly by radiative processes

Test electromagnetic properties of the τ-lepton from ultraperipheral heavy ion collisions at $\sqrt{s_{NN}} = 5.02$ TeV

G.K. Krintiras
M. DYNDAL

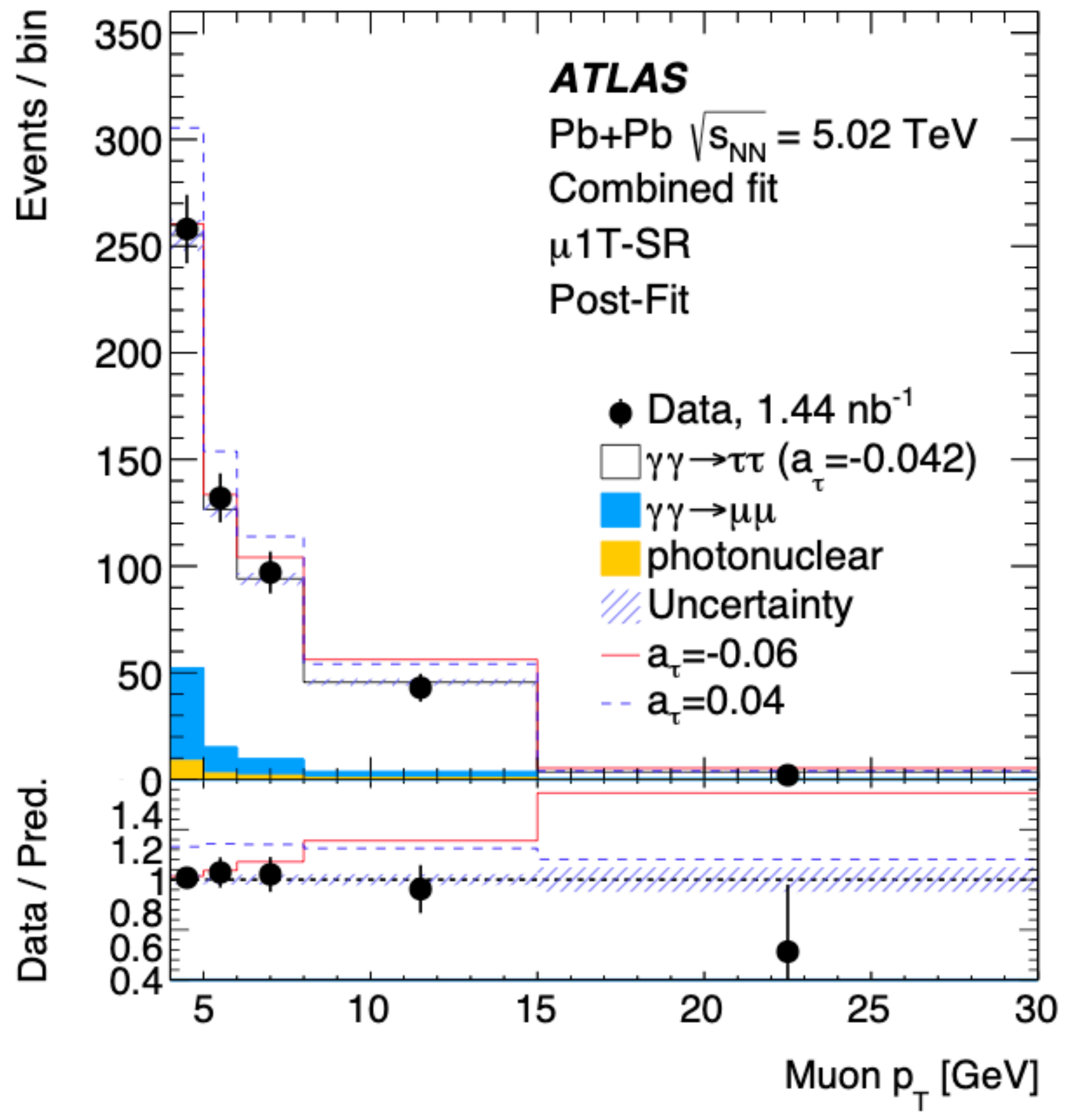


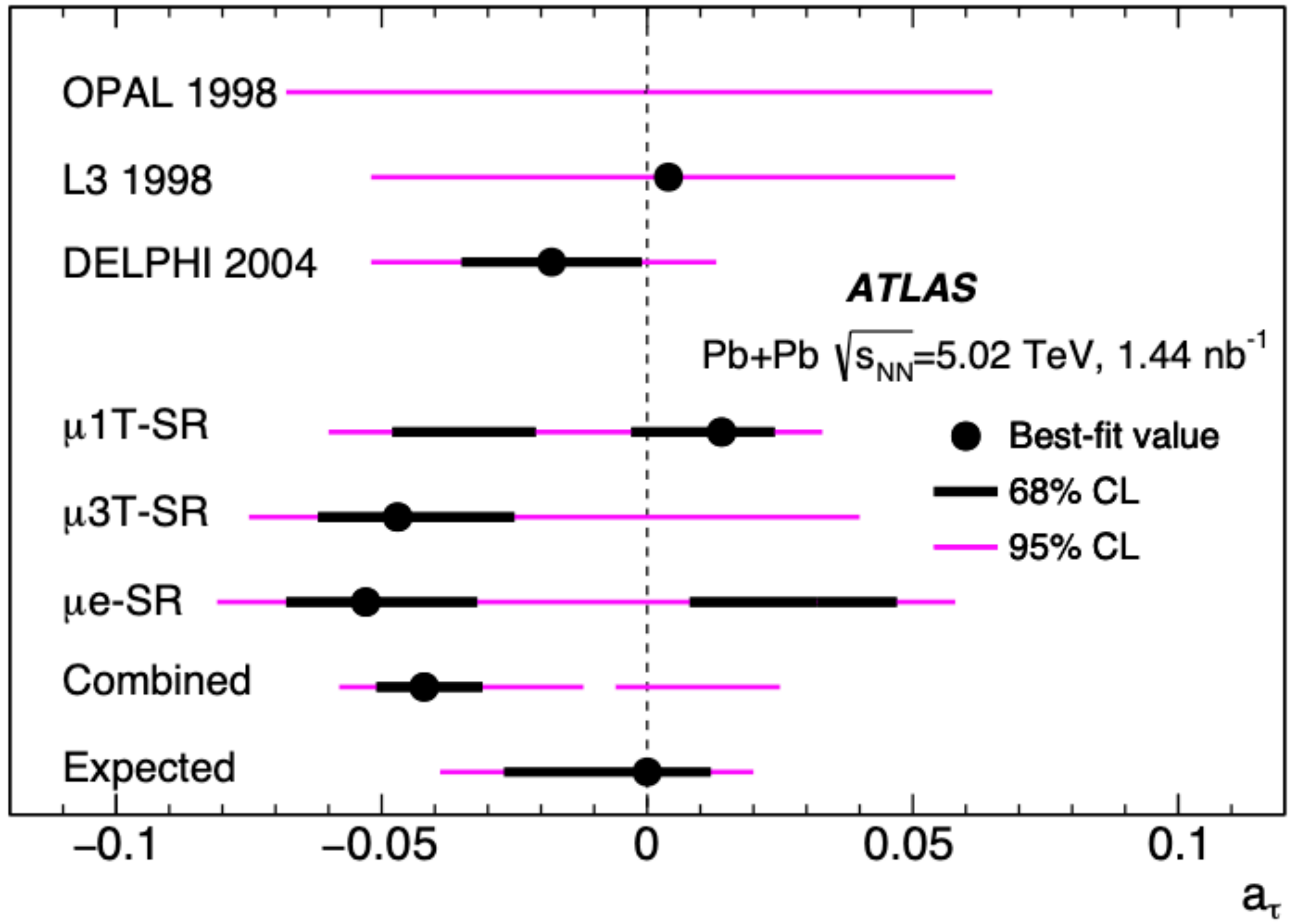
- Observation of exclusive $\gamma\gamma \to \tau\tau$ in ultraperipheral heavy ion collisions and constraints on a_τ
  - When colliding relativistic ions, photon-induced events due to large EM fields ($\sigma \sim Z^4$) - for impact parameter larger than ~2 ion radius EM interactions dominant
  - Cross-section and τ kinematics sensitive to anomalous magnetic moment $a_\tau = \frac{(g-2)_\tau}{2}$
  - From fiducial cross-section extract a model dependent limit on a_τ

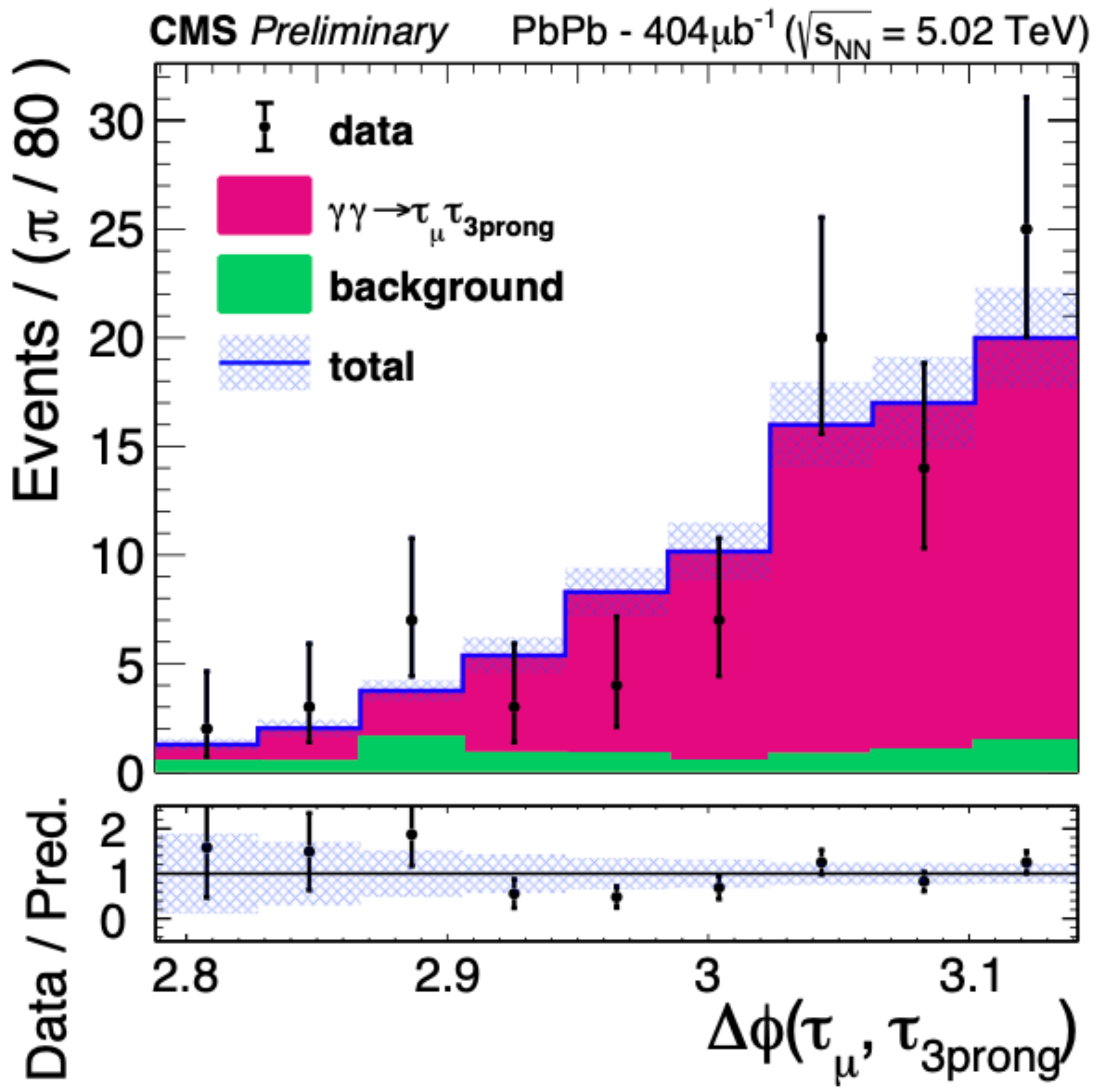
[arXiv:2204.13478]

Results competitive with those of lepton colliders!

[CMS PAS HIN-21-009]







- Measurement precision limited by statistical uncertainties

SOME FINAL REMARKS

Enormous and impressive wealth of results by the LHC experiments, well reflected at this conference

Not only Higgs and and countless searches for BSM! But innovative analyses with unprecedented precision on:

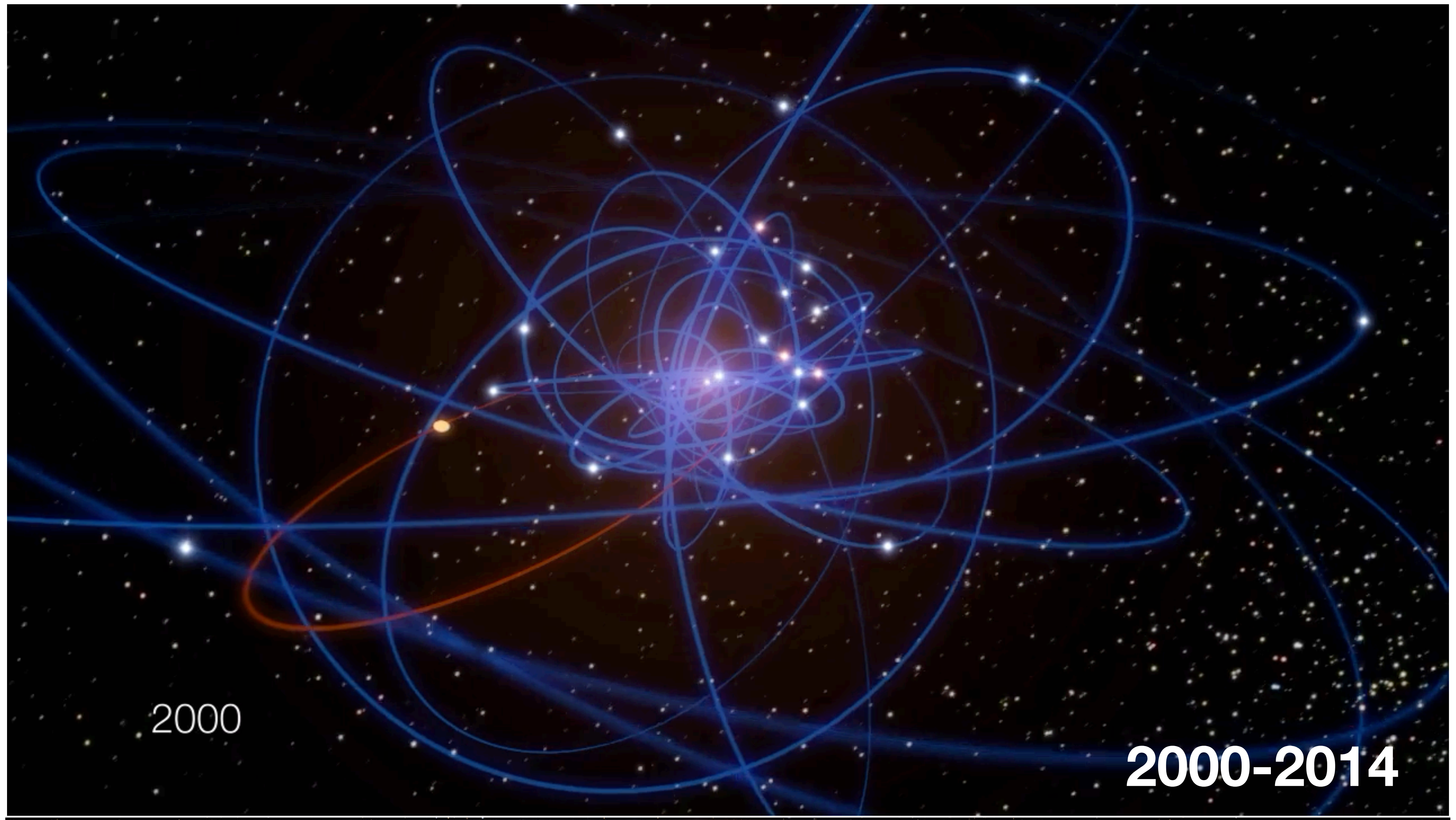
- EW parameters and dynamics
  - $m_W, m_t, \sin^2\theta_W$, EW interactions at the TeV scale (DY,VV,VVV,VBS,VBF,Higgs…)
- QCD dynamics
  - Countless precise measurements of hard cross sections, and improved determinations of the proton PDF; measurement of total, elastic, inelastic pp cross sections at different energies; exotic spectroscopy: discovery and study of new tetra- and penta-quarks, doubly heavy baryons; discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement, ...) in “small” systems (pA and pp)
- Flavour physics
  - $B_{(s)} \to \mu\mu$, neutral meson oscillation, CPV in charm, measurement of γ angle, CPV phase ϕ_s, LFU in charged and neutral currents: anomalies?

On each of these topics the LHC experiments are advancing the knowledge previously acquired by dedicated facilities (HERA, B-factories, RHIC, LEP/SLD,….) In a sense, NP is emerging every day at the LHC!

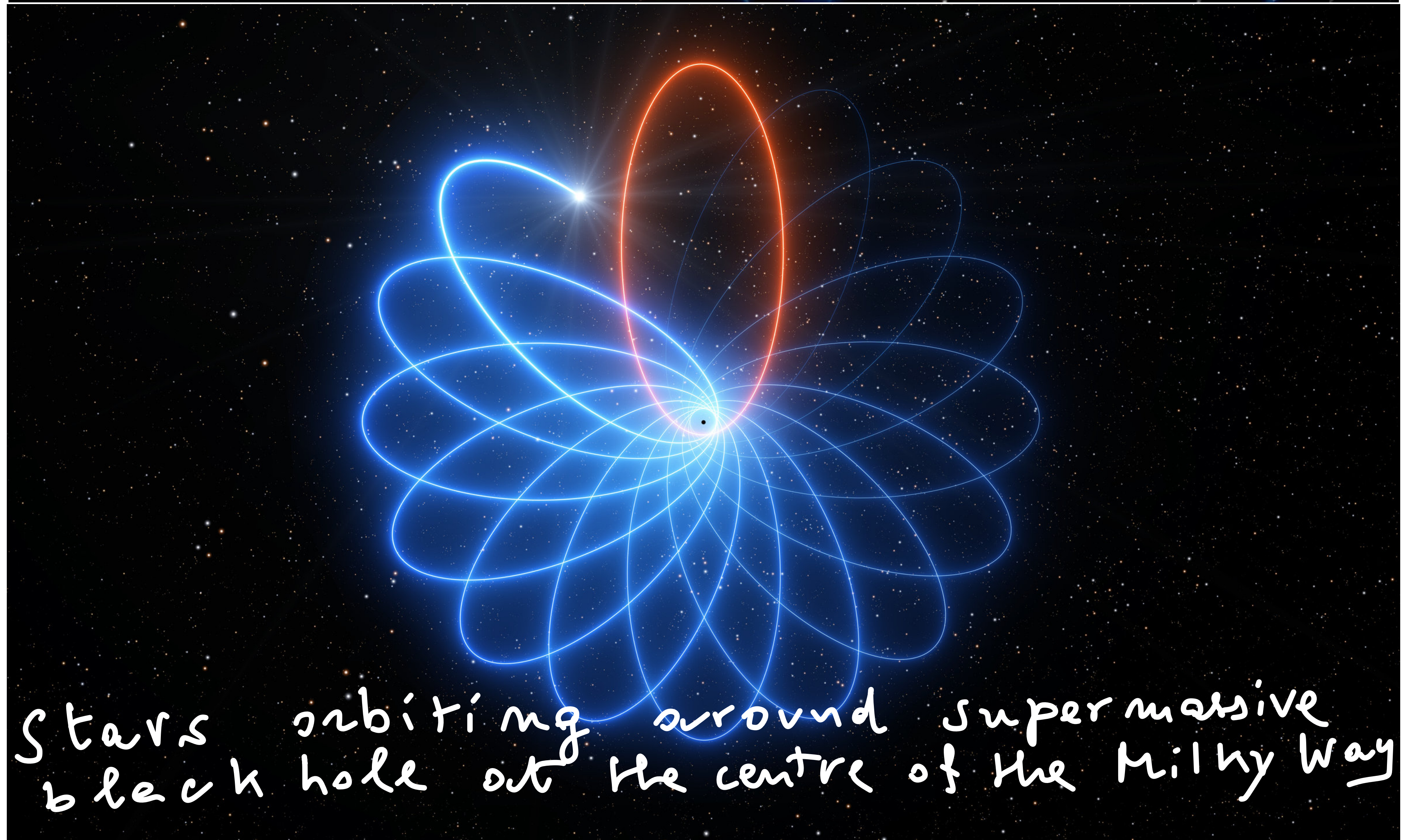
M. Mangano


STANDARD
MODEL
Photo by Mike Struik

From Indirect to Direct Observations



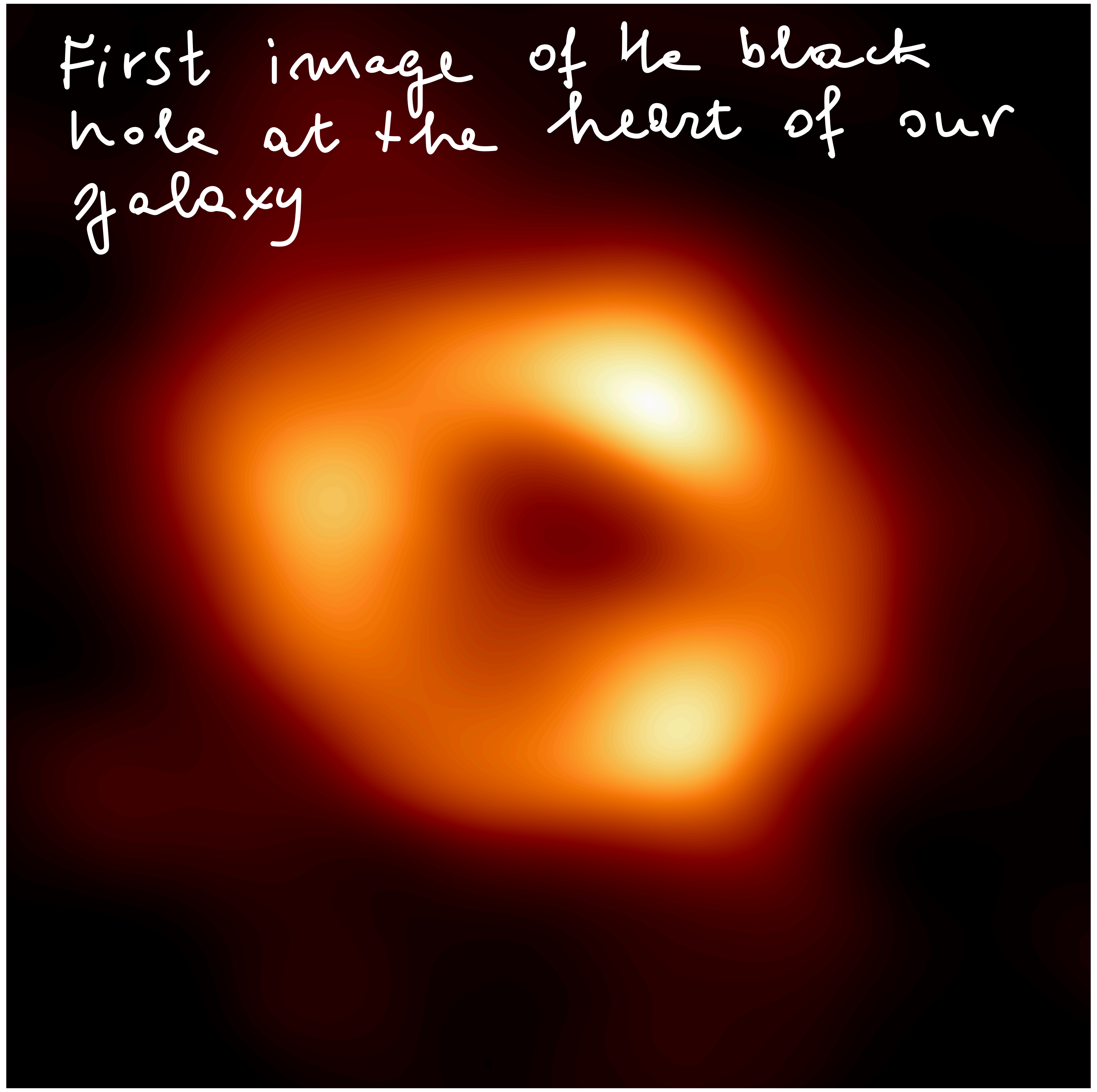
Genzel & Ghez (with Penrose) : Nobel Prize 2020



Genzel (MPE) 2020

→

Event Horizon Telescope 2022




time to pass the baton to Marcela