

D. Longhiera - IJCLab 2021

LHCP2021

The Ninth Annual Conference on Large Hadron Collider Physics

Online

7-12 June 2021 ~~Paris (France), Sorbonne Université (IN2P3/CNRS, IRFU/CEA)~~

Experimental Highlights

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12 Jun 2021



SAPIENZA
UNIVERSITÀ DI ROMA



Istituto Nazionale di Fisica Nucleare



Disclaimer

- ▷ 33 plenary experimental talks
 - $O(10^2)$ parallel session talks
- ▷ Remarkable number of new results, ideas, upgrades despite challenging past 16 months



- ▷ A very *personal and non-comprehensive* narrative
 - apologies if your favorite result not included

Many thanks to all speakers for providing the material for this talk

*Name omissions and mistakes purely due to **sleep deprivation** and will be fixed in the public version on the conference website*

Executive Summary

- ▷ Flavor anomalies still alive and need further input
- ▷ Jet substructure tools widely used from rare searches to dense QGP
- ▷ Consolidation of Machine Learning for analysis and future detectors
- ▷ Rich program across energy and mass scales to detect rare processes
 - indirect search for New Physics
- ▷ Vibrant and diversified direct search program for New Particles
- ▷ Taking a stab at some of rarest processes already with Run 2
- ▷ Higgs, top, and vector bosons constraining effective theories with Standard Model as low-energy limit
 - SMEFT is here to stay

$$\mathcal{L}_{\text{eff}} = \frac{\Lambda^4}{g_*^2} \mathcal{L} \left(\frac{D_\mu}{\Lambda}, \frac{g_H H}{\Lambda}, \frac{g_{f_{L,R}} f_{L,R}}{\Lambda^{3/2}}, \frac{g F_{\mu\nu}}{\Lambda^2} \right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \dots$$

dimension-4 terms:

The SM

dimension-6 terms:

Leading deviations
from the SM

SMEFT

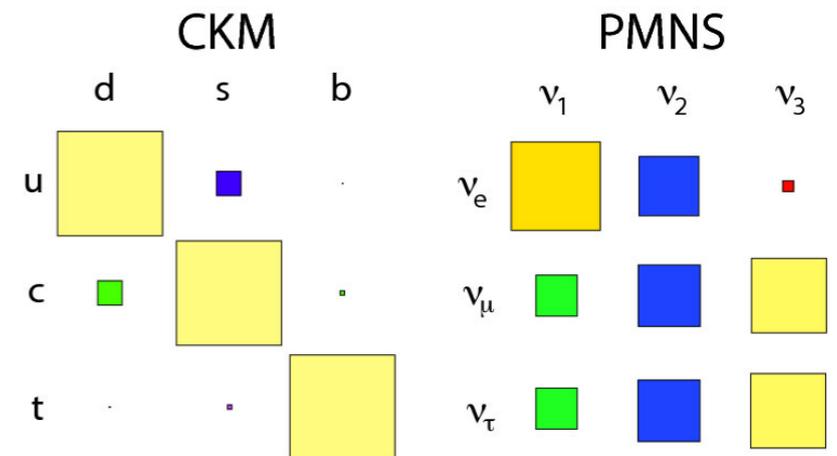
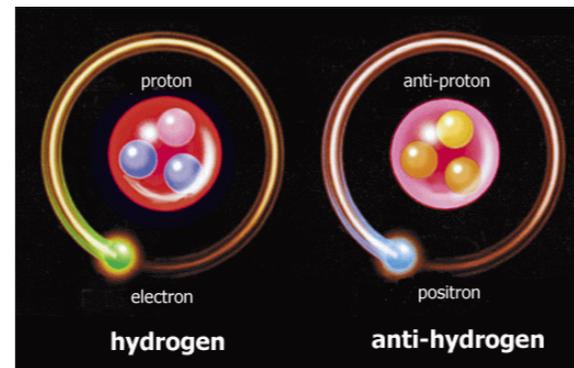
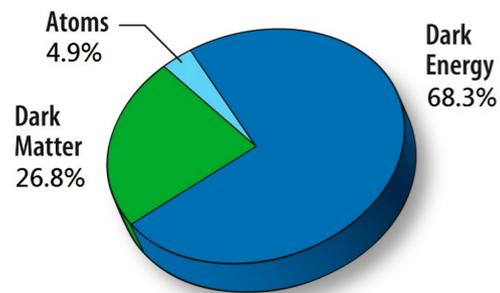
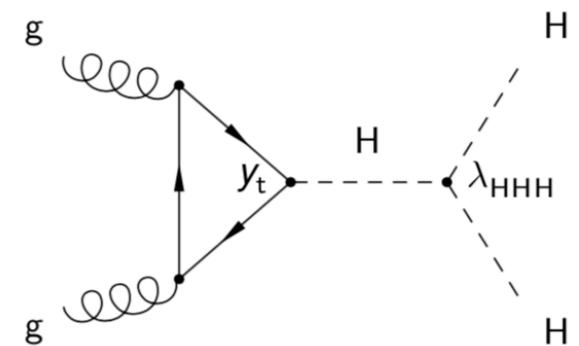
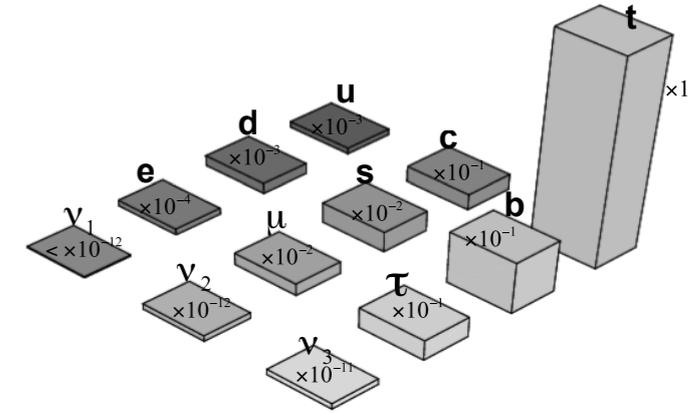


Standard Model

- ▷ Extremely predictive theory since its inception
- ▷ Last missing piece discovered just 9 years ago
 - Compare to gravitational waves and general relativity
- ▷ Has successfully resisted 50 years of falsification
- ▷ *We already know it is incomplete*
 - Neutrinos are massive
- ▷ It cannot address some basic curiosities and questions about *our* Universe

Questions and Curiosities

- ▷ What is the origin of mass?
- ▷ Have we found *the* Higgs boson?
- ▷ What is the origin of mass hierarchy?
- ▷ Do all leptons behave equally?
- ▷ Where is all the anti-matter in *our Universe*?
- ▷ What is Dark Matter?



LHC provides broad spectrum of measurements to tackle almost all these questions!

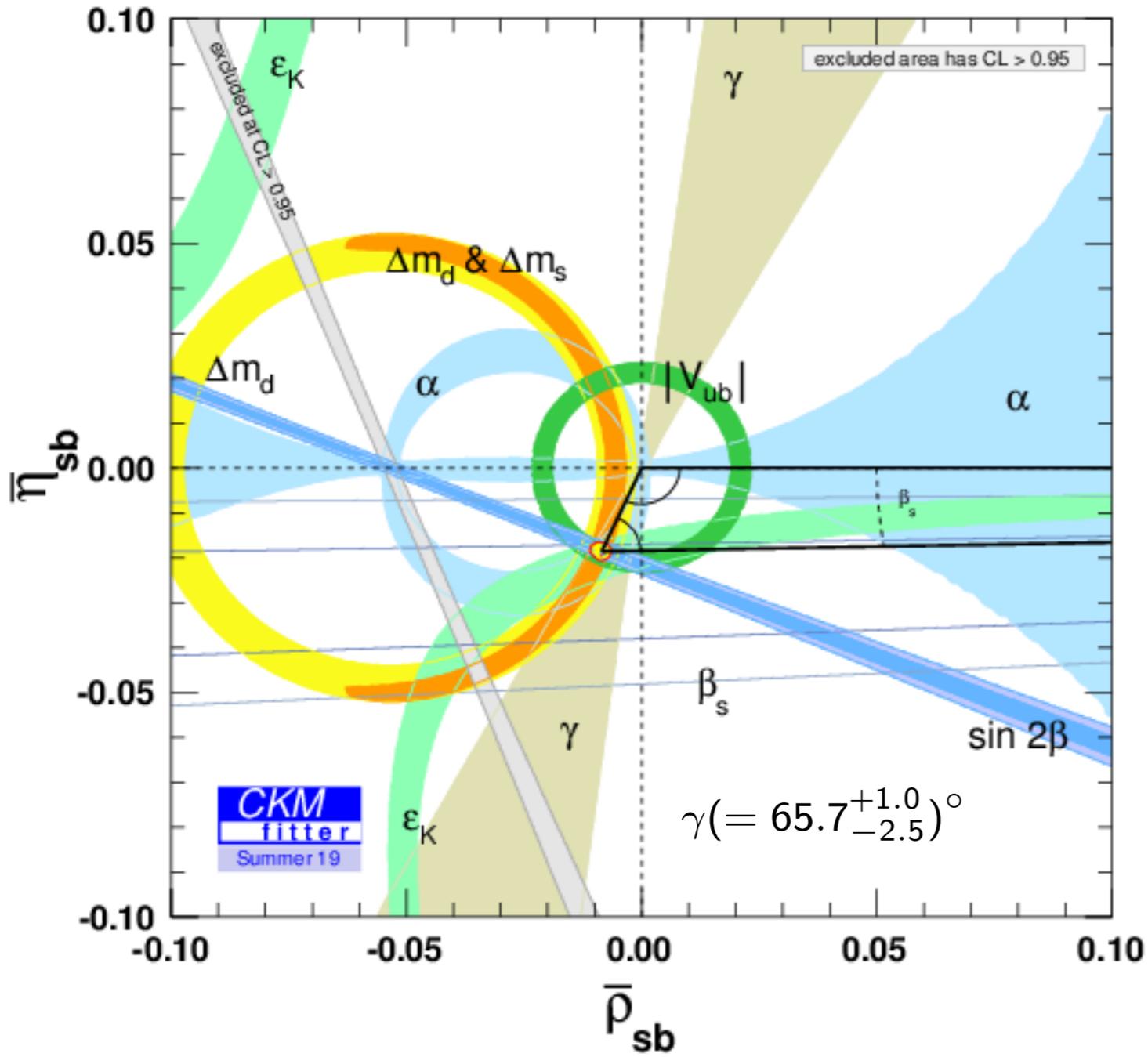
Means of Falsification

- ▷ Multiple and redundant measurements of well known quantities
 - different methods, contexts, technologies
 - differential and fiducial cross sections

The Known Knowns
- ▷ Measurement of very small and precise predictions
 - variety of such observables across the spectrum
 - typically referred to as indirect search for New Physics
 - At LHC now merging with standard Physics thanks to amount of data

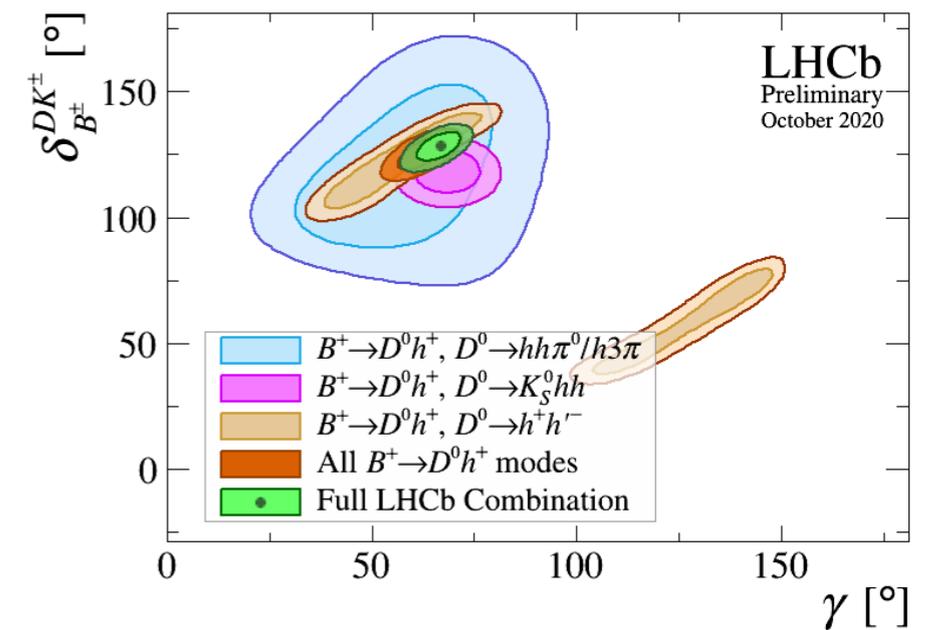
The Known Unknowns
- ▷ Search for the exotic
 - chasing more or less crazy ideas by theory friends
 - often motivated by some big question
 - Taking advantage of capabilities of detectors for unconventional signatures

The Unknown Unknowns
- ▷ New computational tools for more efficient data mining and increasing sensitivity
- ▷ New technologies to improve detection techniques and try new avenues



$$V_{\text{CKM}} \sim \begin{pmatrix} V_{ud} & V_{us} & |V_{ub}|, \gamma \\ V_{cd} & V_{cs} & |V_{cb}| \\ \Delta m_d, \beta & \Delta m_s, \beta_s & |V_{tb}| \end{pmatrix}$$

$$\gamma = (67 \pm 4)^\circ$$



CP Violation

Φ_s and $B_s^0 \rightarrow J/\Psi \phi$

▷ Golden mode for Bs

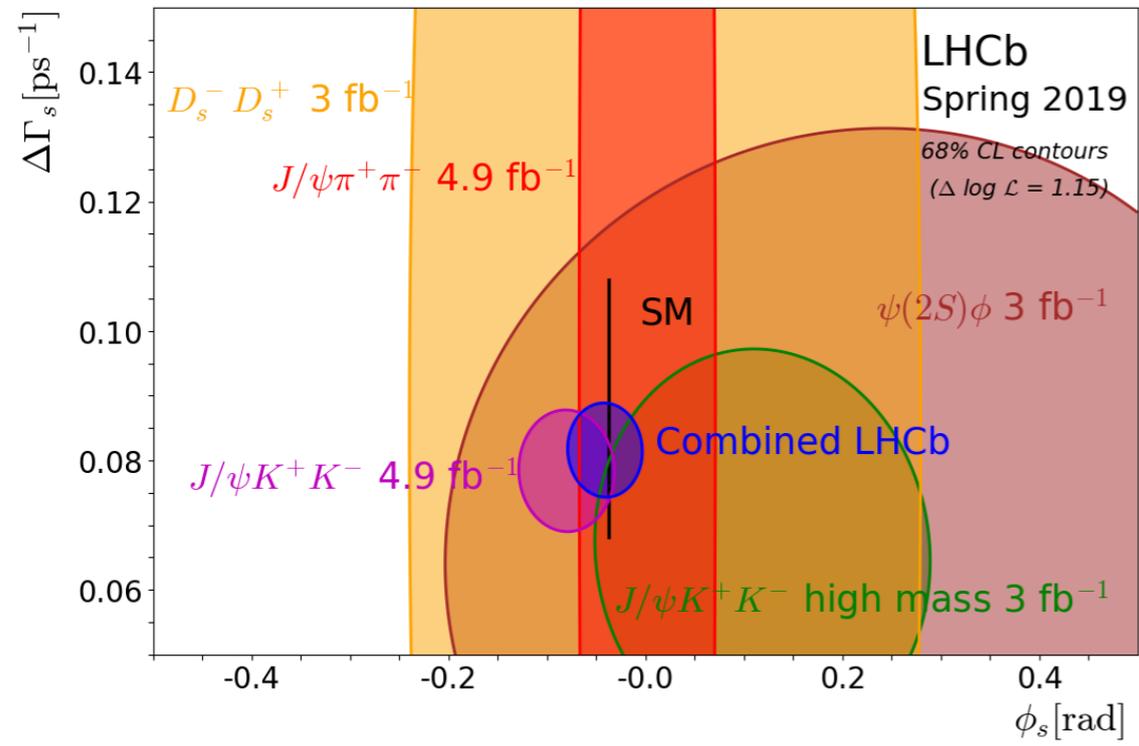
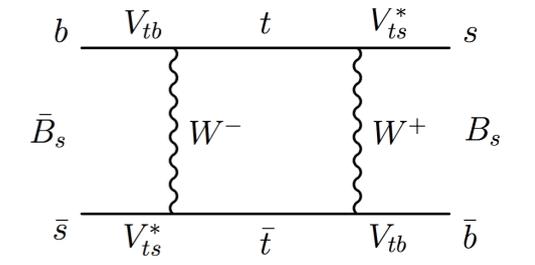
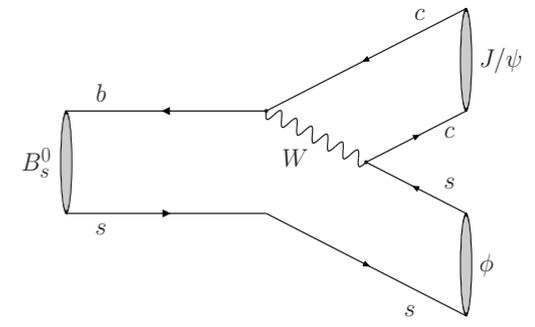
- clean experimental signature and theoretical prediction

$$\phi_s^{SM} \simeq -2\beta_s = -36.89_{-0.81}^{+0.70} \text{ rad [CKMfitter]}$$

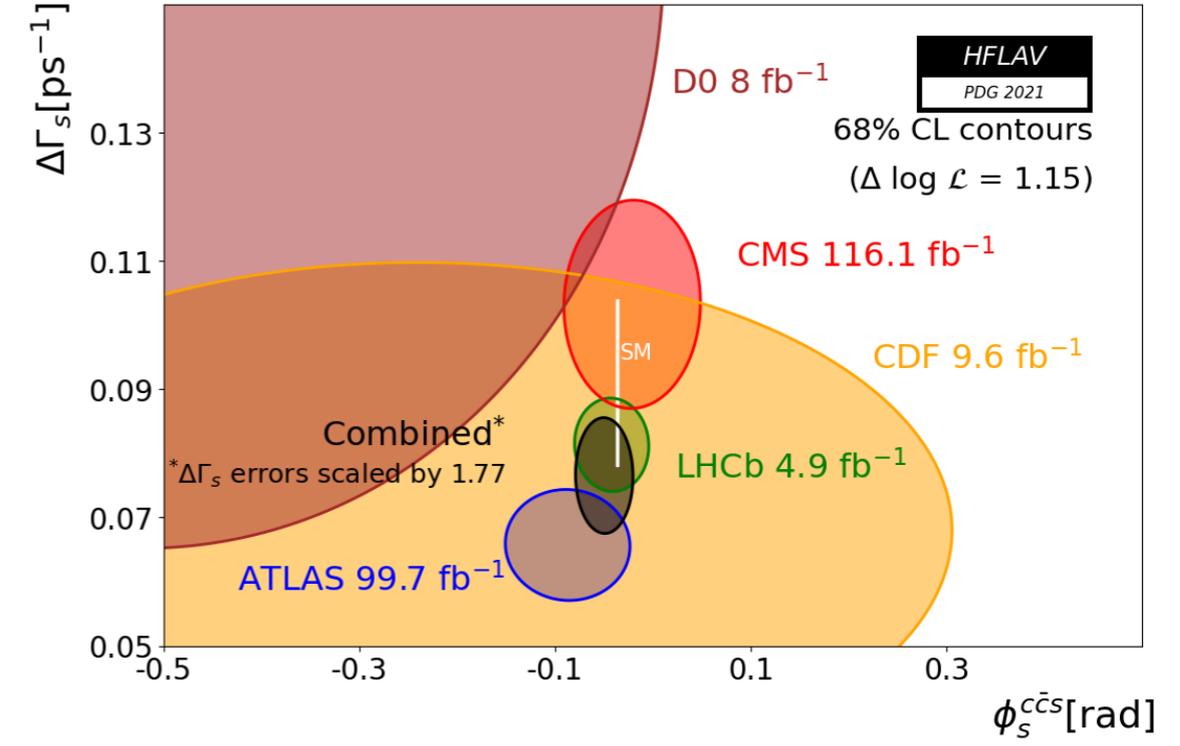
▷ Different trigger strategies for ATLAS and CMS

- uncertainties competitive with LHCb

▷ LHCb provides measurement with several channels



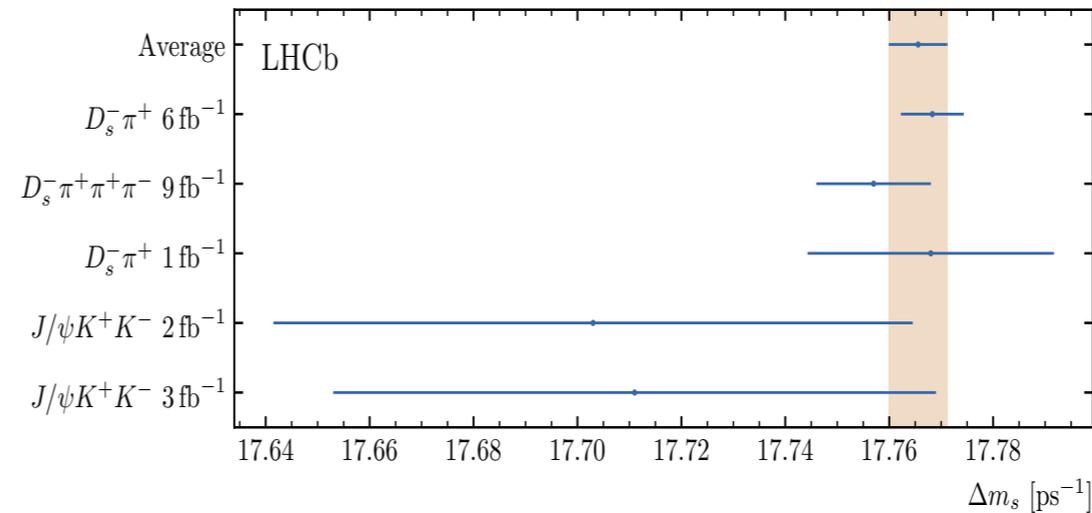
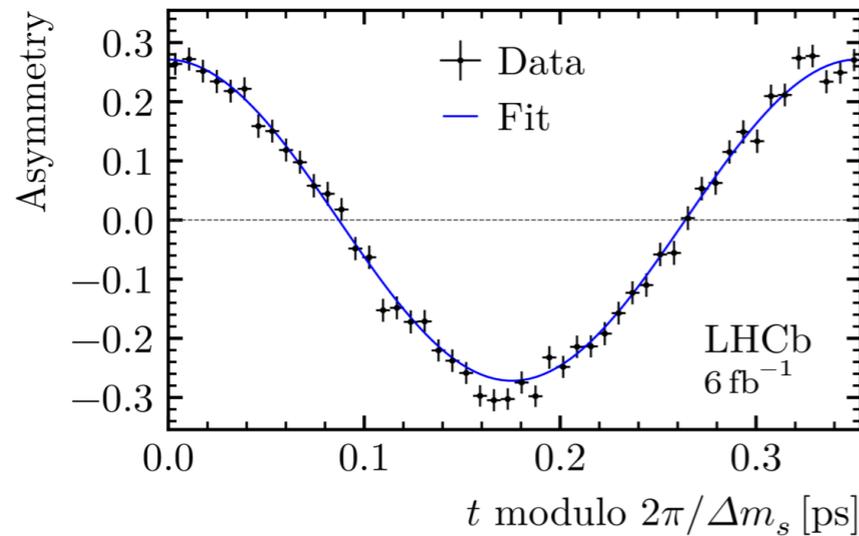
$$\phi_s = -0.041 \pm 0.025 \text{ rad}, \Delta\Gamma_s = 0.082 \pm 0.005 \text{ ps}^{-1}$$



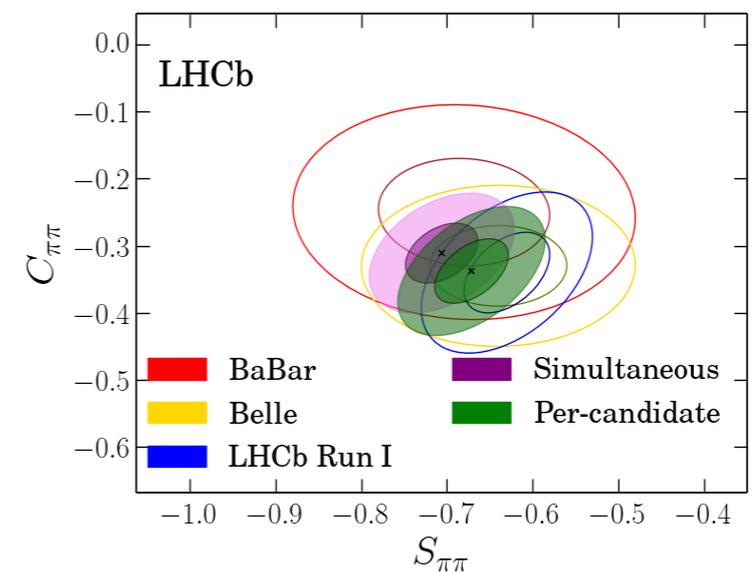
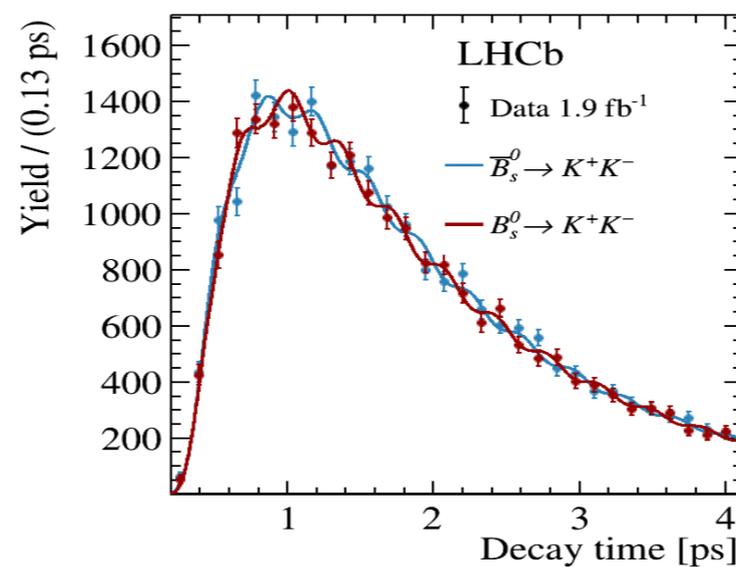
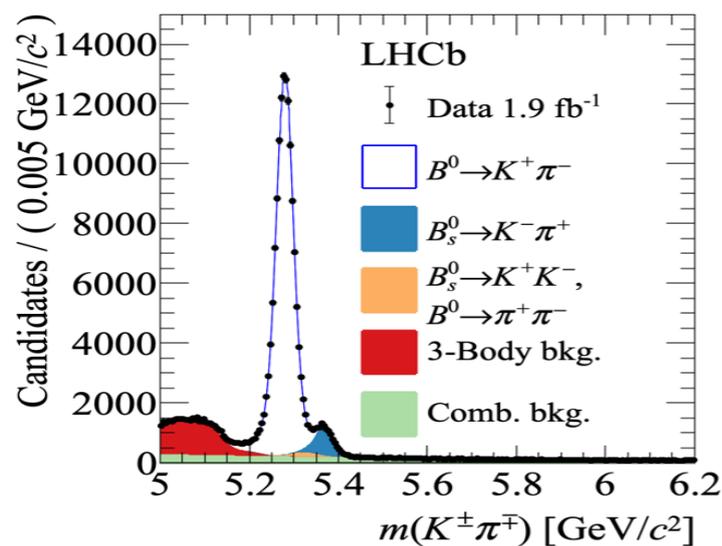
B_s^0 oscillation and time-dependent CPV

▷ Most precise measurement oscillation frequency in $B_s^0 \rightarrow D_s^- \pi^+$

$$\Delta m_s = 17.7656 \pm 0.0057 \text{ ps}^{-1}$$



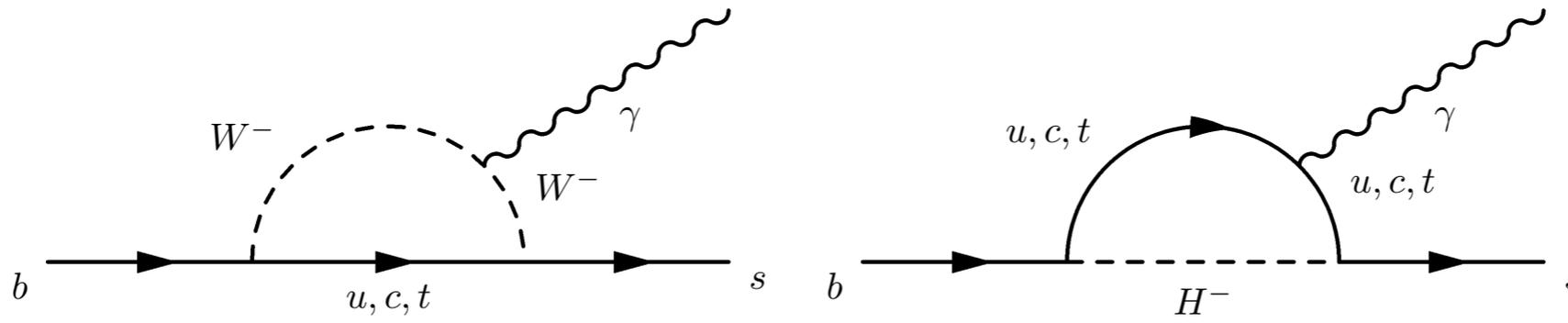
▷ First observation of time-dependent CP violation in $B_{s,d}^0 \rightarrow h^+ h^-$



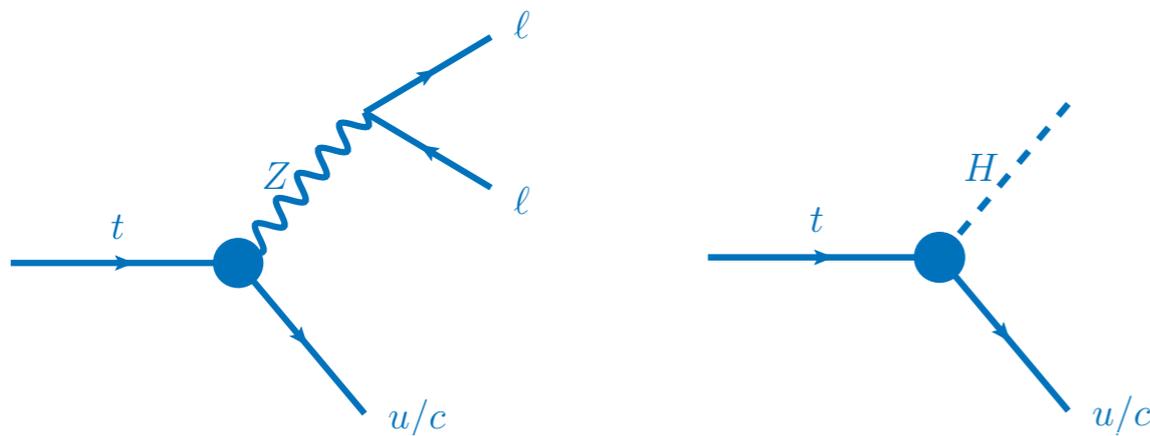
$$S_{\pi\pi} = -0.706 \pm 0.042 \pm 0.013, \quad S_{KK} = +0.123 \pm 0.034 \pm 0.015$$

$$A_{CP}^{B^0 \rightarrow K^+ \pi^-} = -0.082 \pm 0.003 \pm 0.003, \quad A_{CP}^{B_s^0 \rightarrow K^- \pi^+} = +0.236 \pm 0.013 \pm 0.011$$

Flavor Changing Neutral Currents



- ▷ Forbidden in Standard Model at tree level
- ▷ Typically small predicted rates and hence sensitive to new particles in strong and electroweak penguin loops
- ▷ Rich area of probe in b, c, s, and now also top decays



SM

$$\text{BR}(t \rightarrow qH) \sim 10^{-15}$$

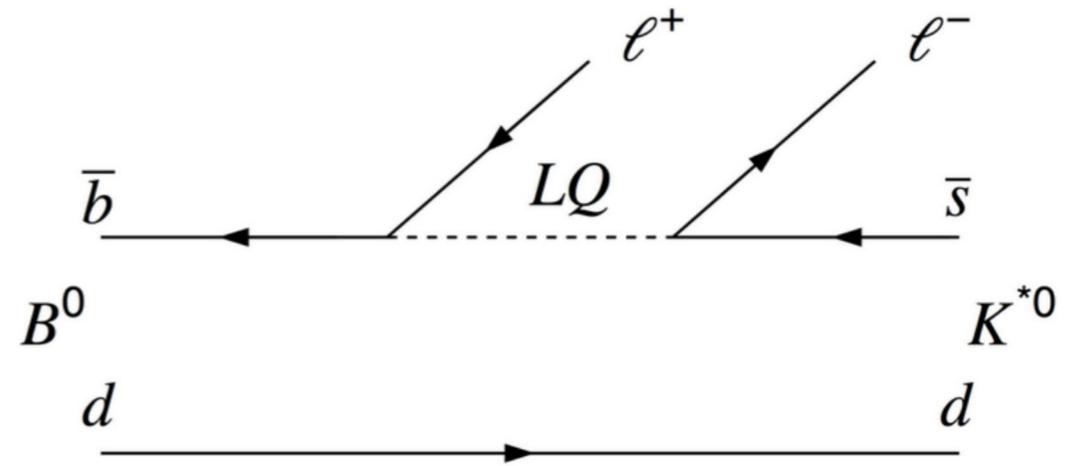
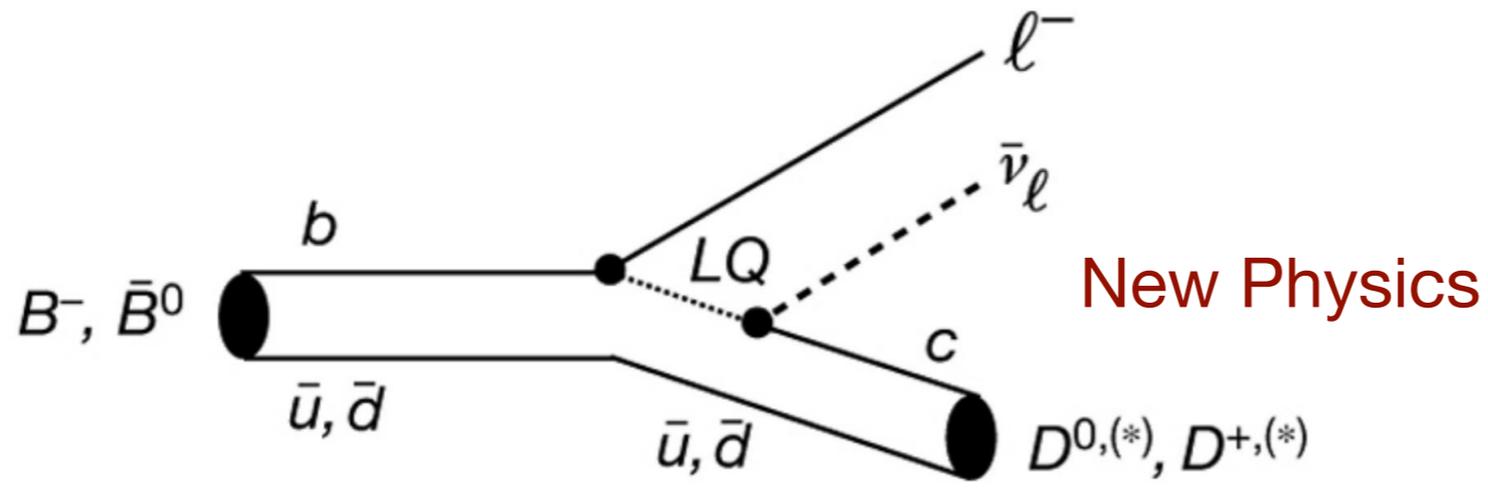
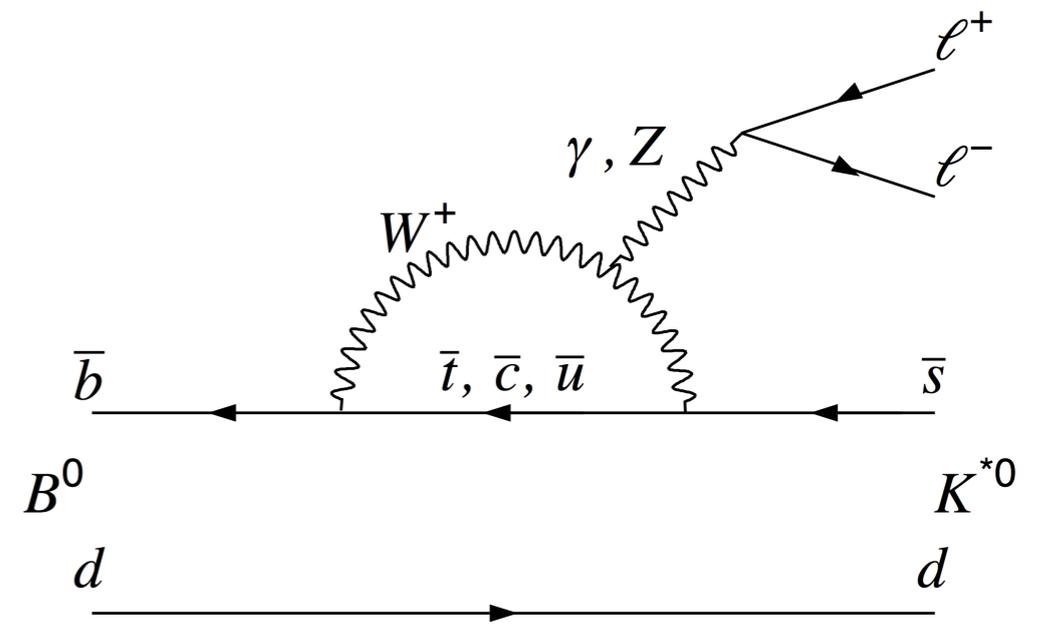
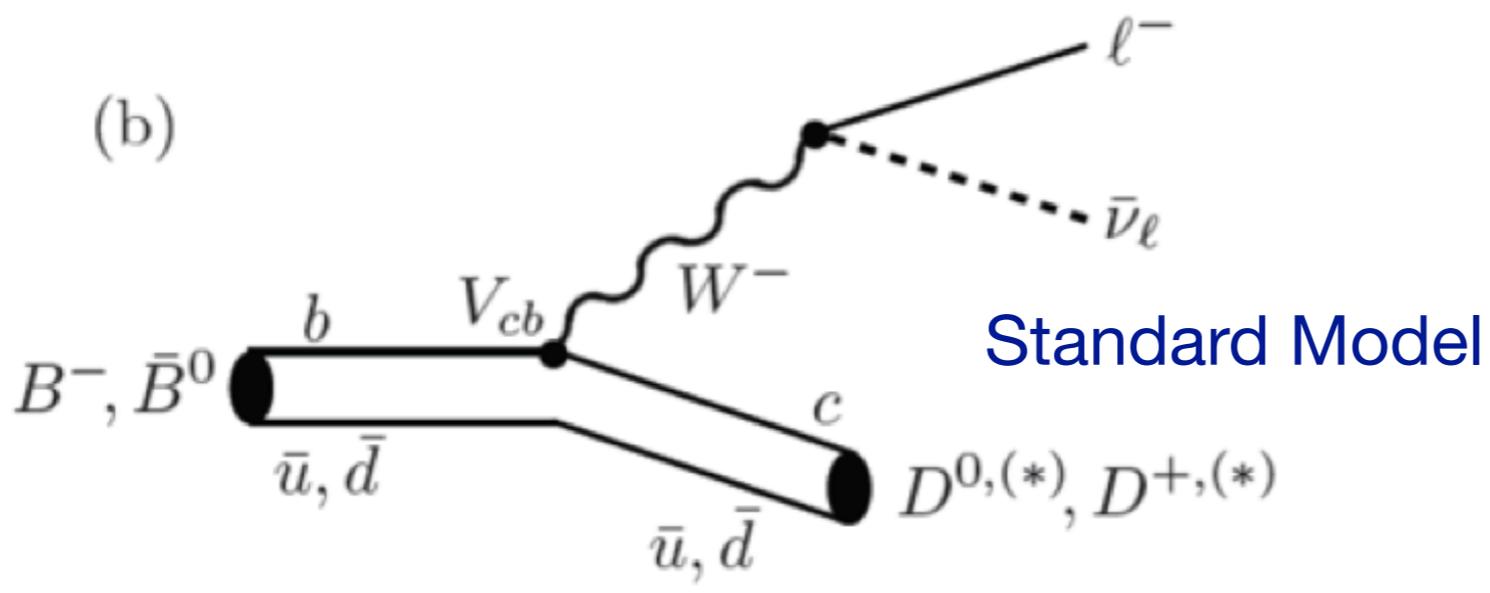
$$\text{BR}(t \rightarrow qZ) \sim 10^{-14}$$



New CMS-PAS-TOP-20-007

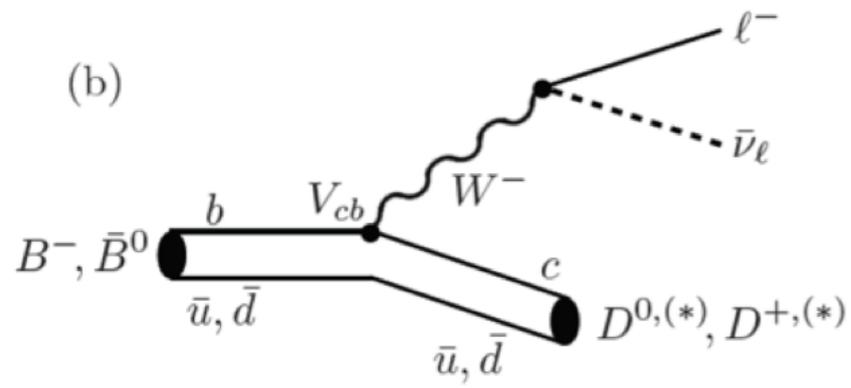
$$B(t \rightarrow Hu) < 1.9 \times 10^{-4}$$

$$B(t \rightarrow Hc) < 7.3 \times 10^{-4}$$

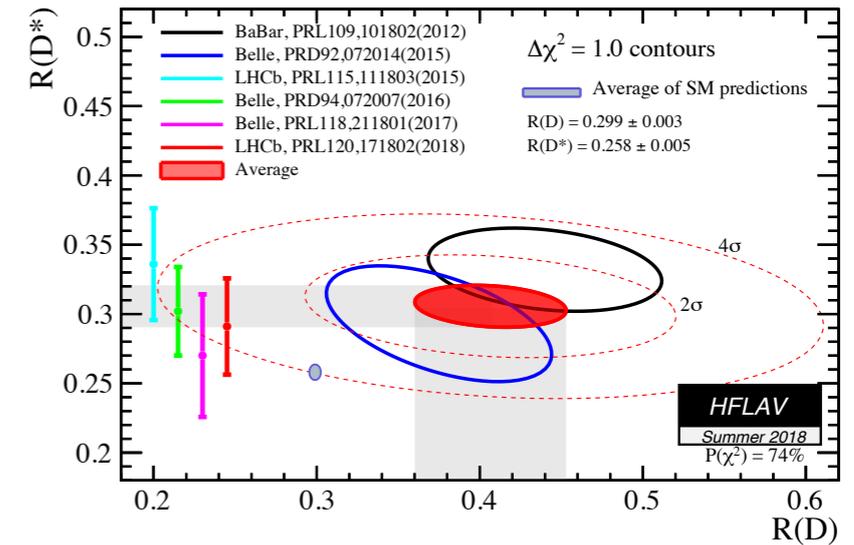


Lepton Flavor Universality

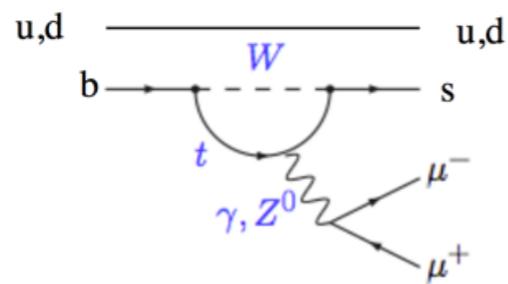
Long Standing Anomalies



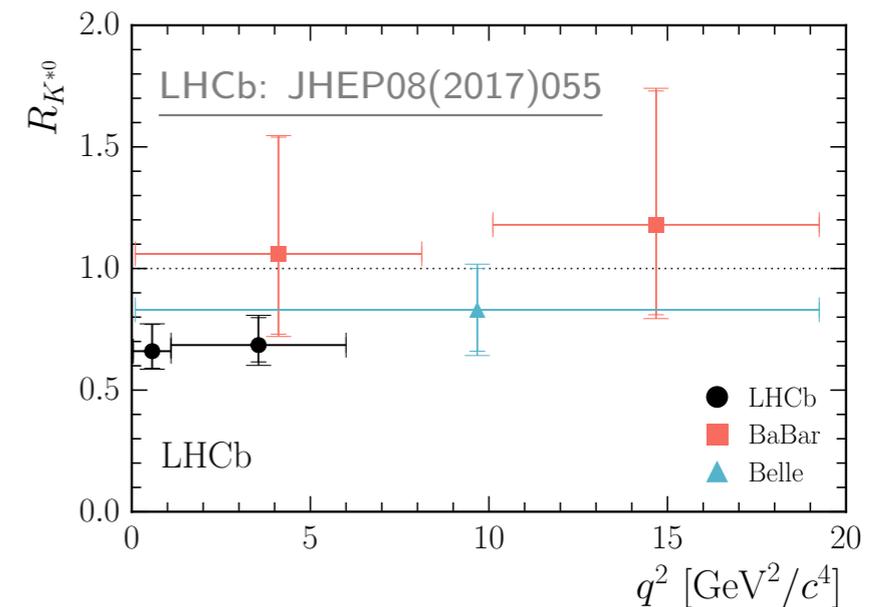
$$R(D^*) = \frac{BF(B \rightarrow D^* \tau \nu)}{BF(B \rightarrow D^* \mu \nu)}$$



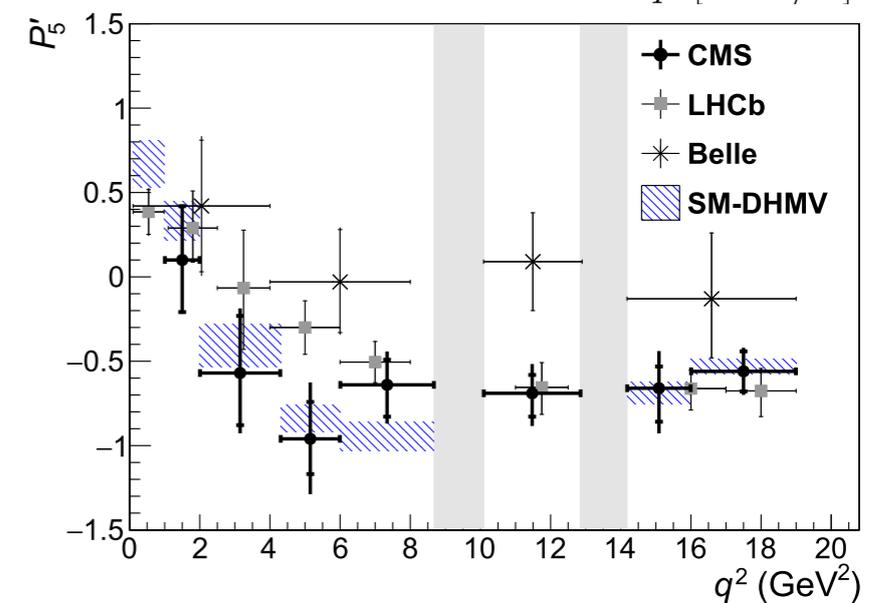
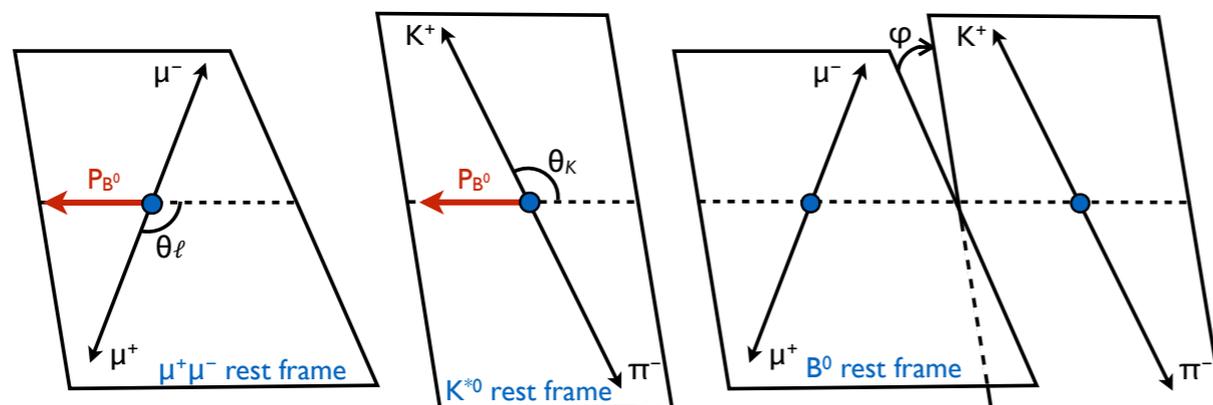
muons / electrons [b → s]



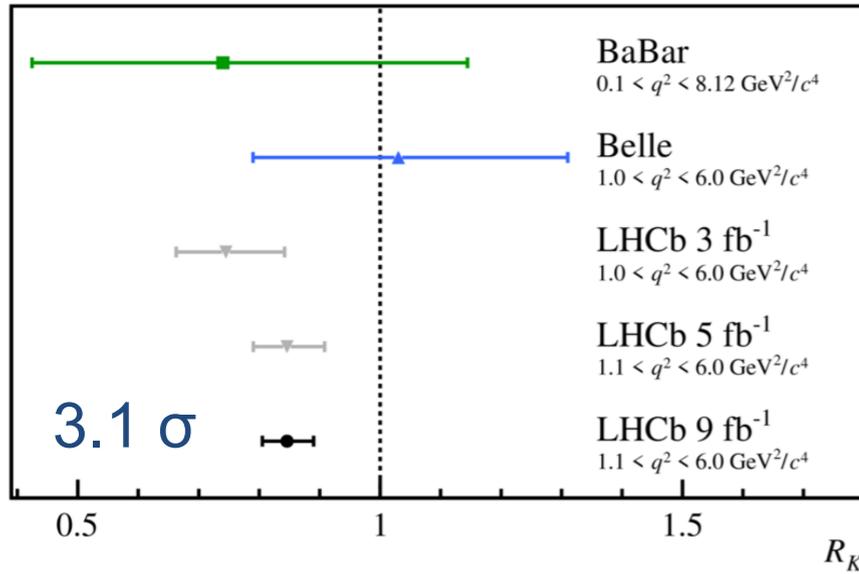
$$R_K = \frac{BR(B^+ \rightarrow K^+ \mu^+ \mu^-)}{BR(B^+ \rightarrow K^+ e^+ e^-)}$$



$$B^0 \rightarrow K^{*0}(K^+ \pi^-) \mu^+ \mu^-$$



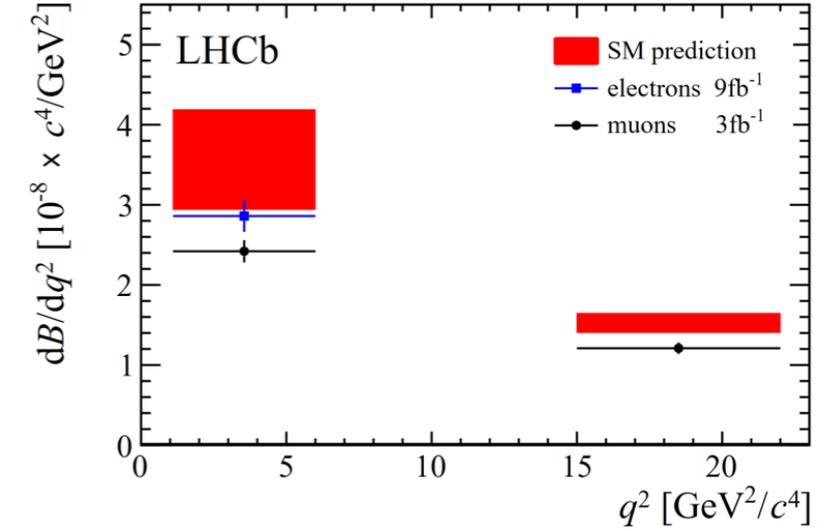
Anomaly stands still



$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu\mu) / \mathcal{B}(B^+ \rightarrow K^+ J/\psi(\mu\mu))}{\mathcal{B}(B^+ \rightarrow K^+ ee) / \mathcal{B}(B^+ \rightarrow K^+ J/\psi(ee))}$$

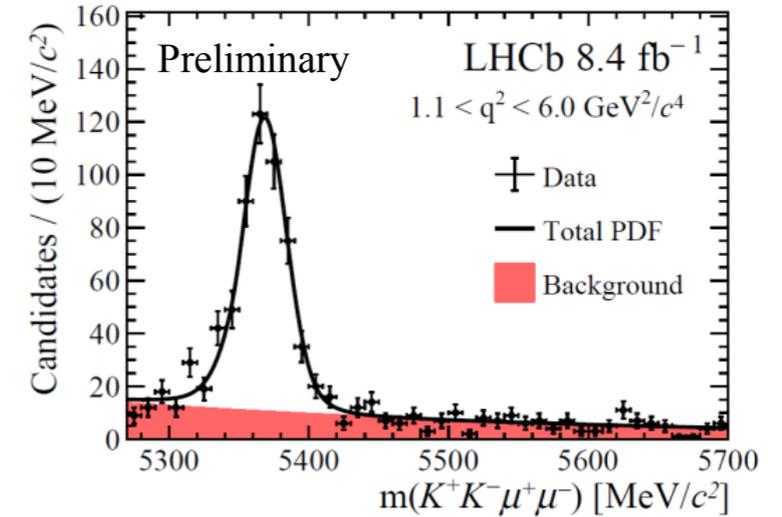
$$= \frac{N(K^+ \mu\mu)}{N(K^+ J/\psi(\mu\mu))} \cdot \frac{N(K^+ J/\psi(ee))}{N(K^+ ee)} \cdot \frac{\varepsilon(K^+ J/\psi(\mu\mu))}{\varepsilon(K^+ \mu\mu)} \cdot \frac{\varepsilon(K^+ ee)}{\varepsilon(K^+ J/\psi(ee))}$$

$$R_K = 0.846^{+0.044}_{-0.041}$$



▷ New angular analysis in $B_s^0 \rightarrow \phi \mu^+ \mu^-$

- Discrepancy wrt predictions similar to $K^{*0} \mu^+ \mu^-$
- CP Asymmetries and averages compatible with SM



$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2 d\cos\theta_l d\cos\theta_K d\phi} \frac{d^3(\Gamma + \bar{\Gamma})}{d^3q^2} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K (1 + \frac{1}{3} \cos 2\theta_l) \right.$$

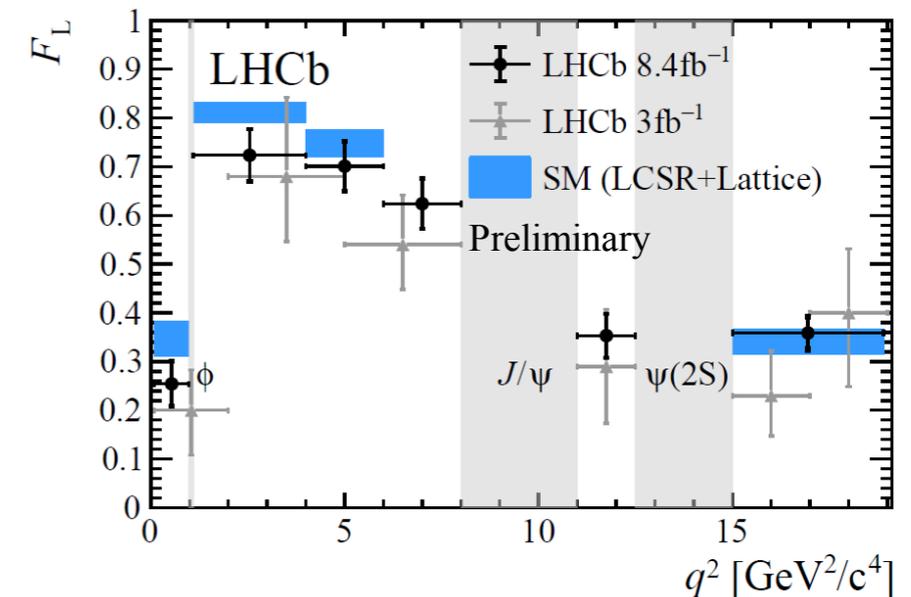
$$+ F_L \cos^2 \theta_K (1 - \cos 2\theta_l)$$

$$+ S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi$$

$$+ A_5 \sin 2\theta_K \sin \theta_l \cos \phi + \frac{4}{3} A_{FB}^{CP} \sin^2 \theta_K \cos \theta_l$$

$$+ S_7 \sin 2\theta_K \sin \theta_l \sin \phi + A_8 \sin 2\theta_K \sin 2\theta_l \sin \phi$$

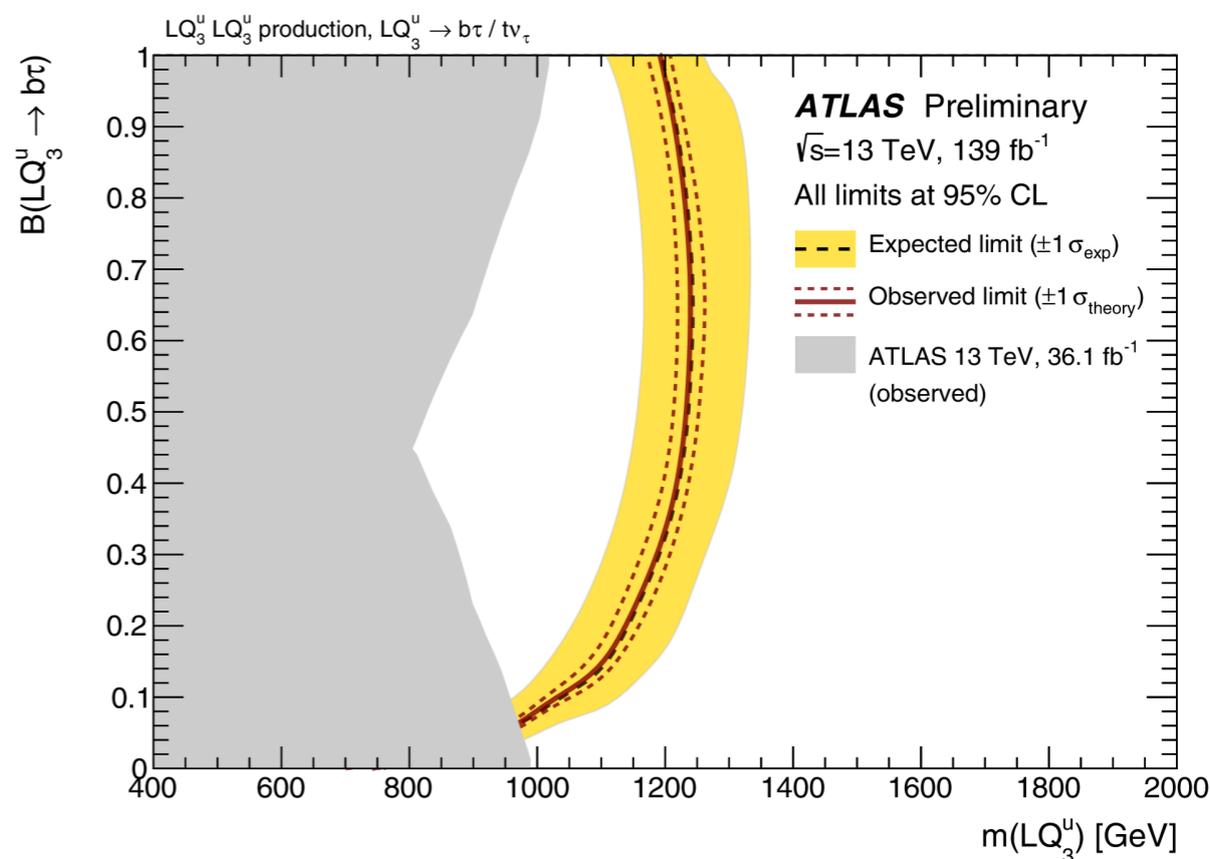
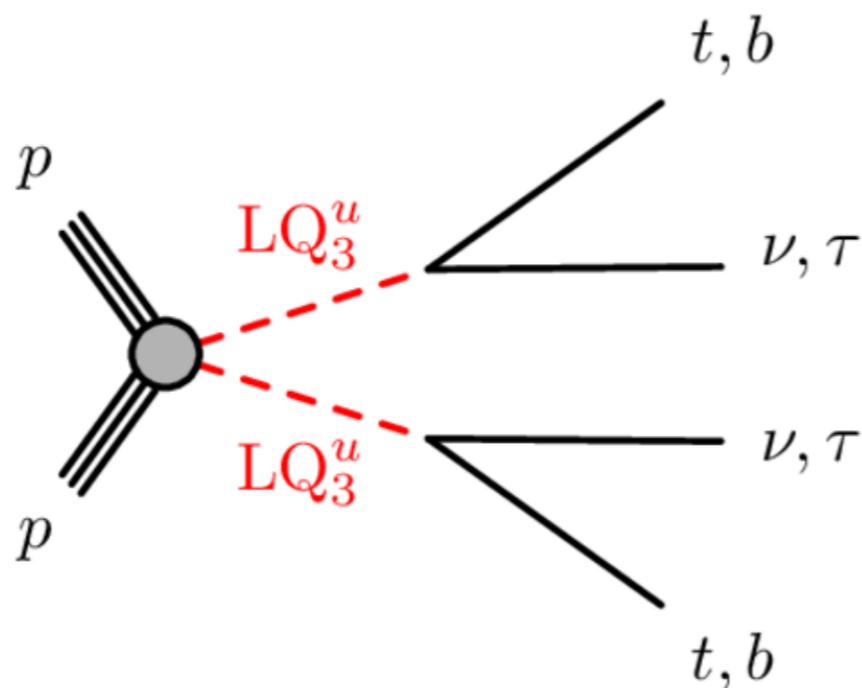
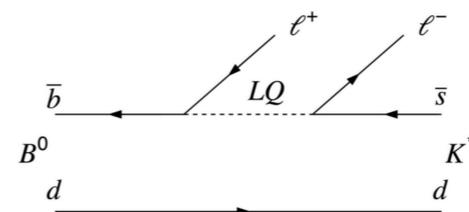
$$\left. + A_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$$



Tackling Anomalies at High Mass

▷ Tree-level explanation of B anomalies with preferred coupling to 2nd and 3rd generations

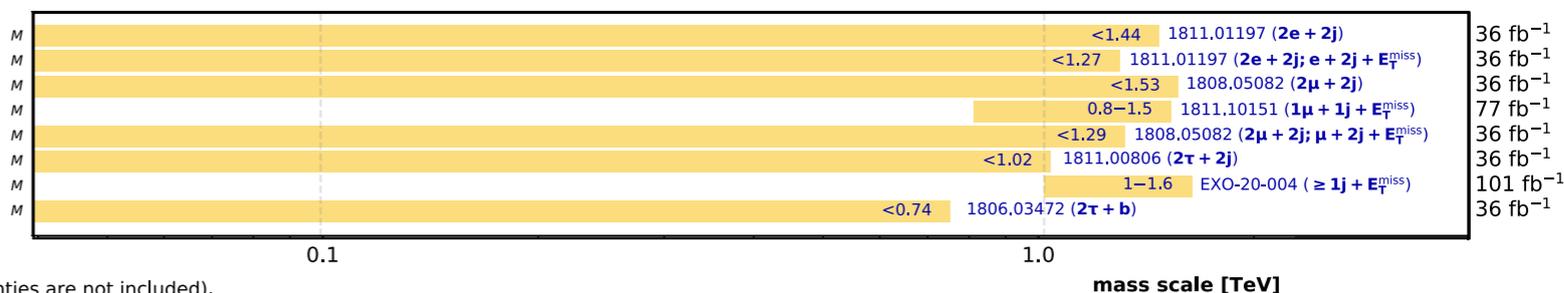
– Pair- and single-production of leptoquarks



CMS

Leptoquarks

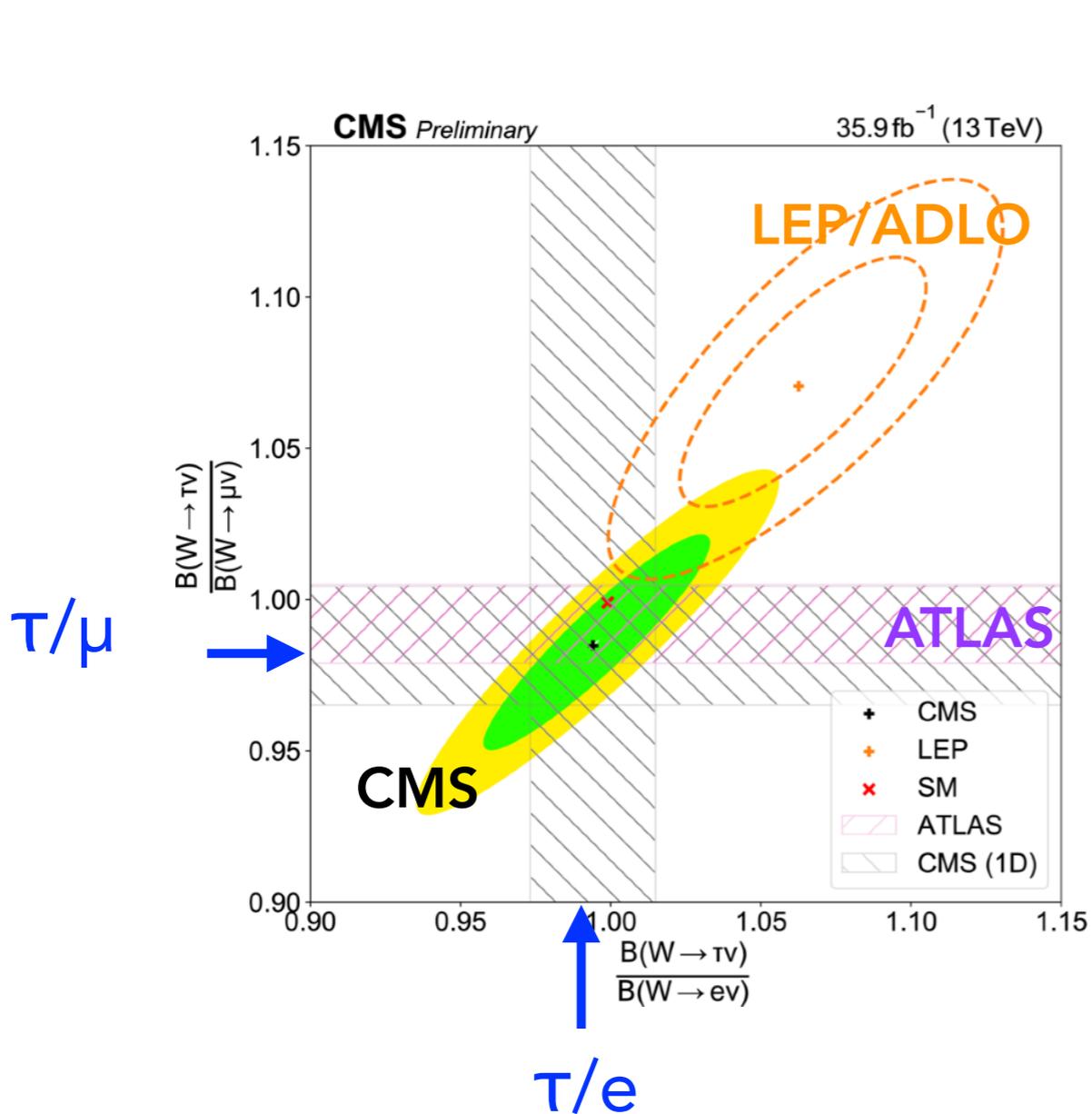
- scalar LQ (pair prod.), coupling to 1st gen. fermions, $\beta = 1$
- scalar LQ (pair prod.), coupling to 1st gen. fermions, $\beta = 0.5$
- scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 1$
- scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 1$
- scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 0.5$
- scalar LQ (pair prod.), coupling to 3rd gen. fermions, $\beta = 1$
- scalar LQ (single prod.), coupling to 1st gen. fermions, $\beta = 0, \lambda = 1$
- scalar LQ (single prod.), coupling to 3rd gen. fermions, $\beta = 1, \lambda = 1$



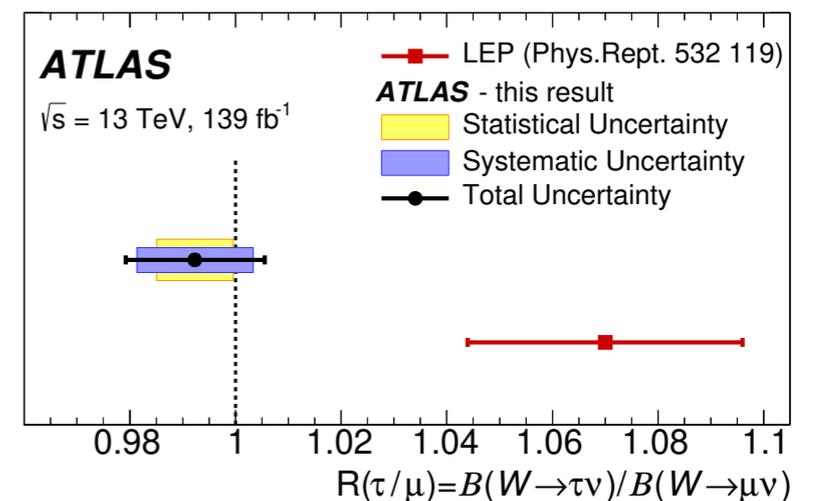
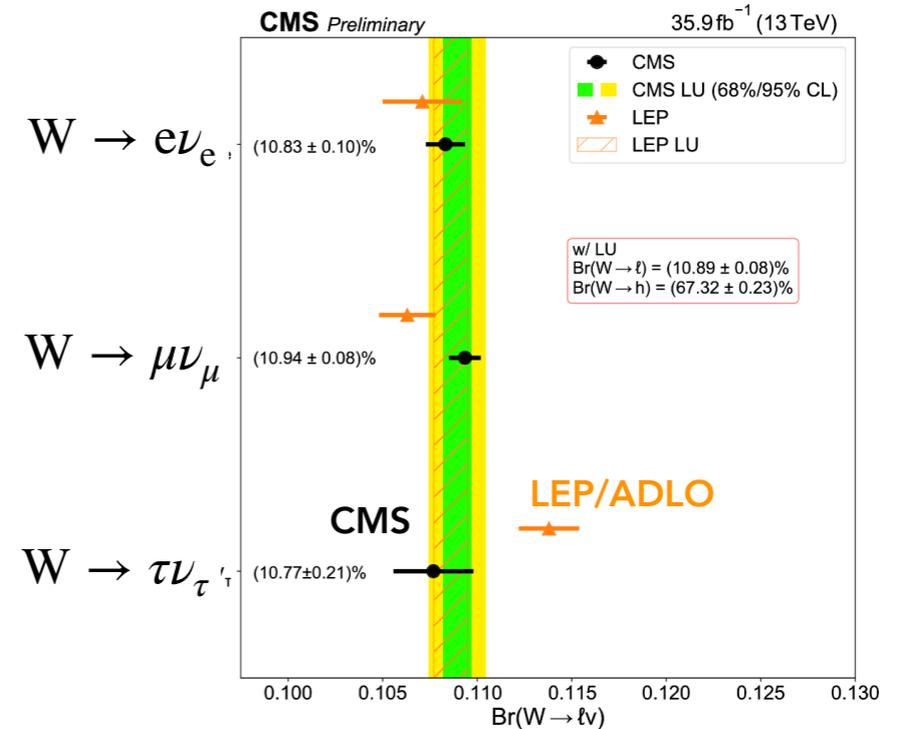
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Lepton Universality in W decays

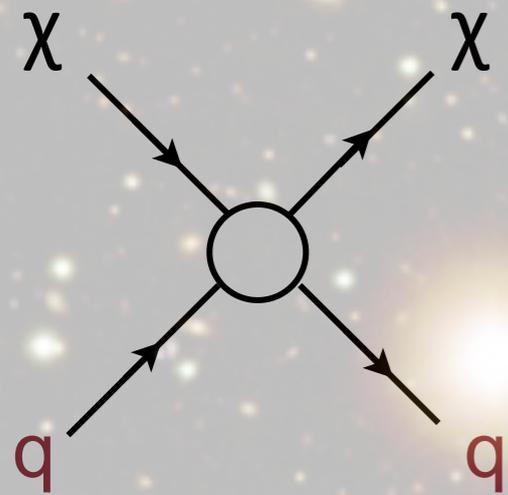
▷ Compare W branching fraction in e, μ, τ



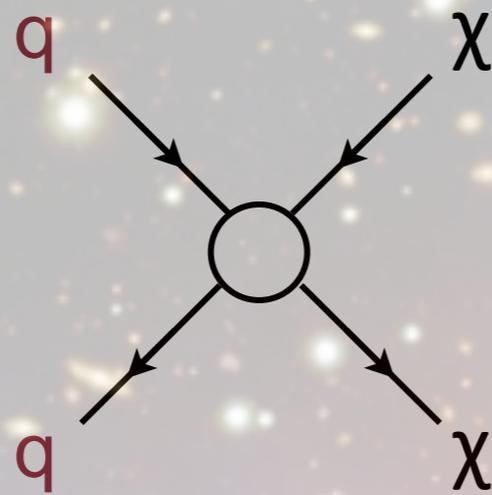
Branching fractions $W \rightarrow e, \mu, \tau$



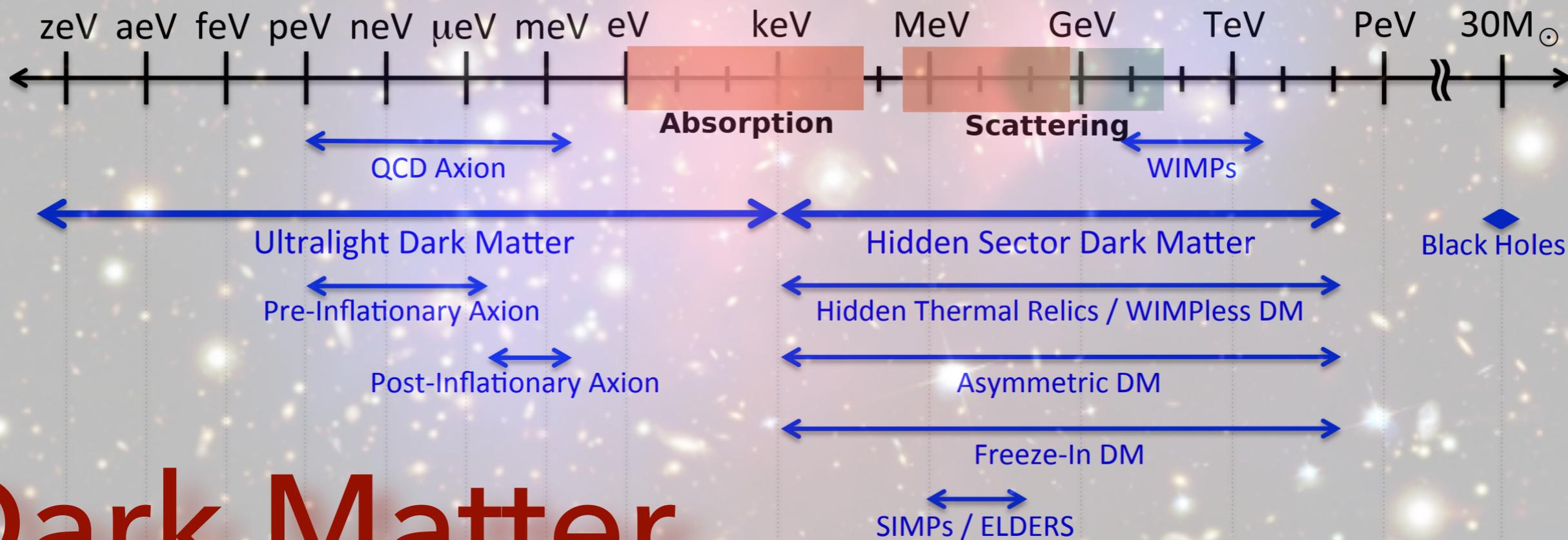
▷ Very good agreement between LHC and Standard Model



Direct Detection



Production at Colliders

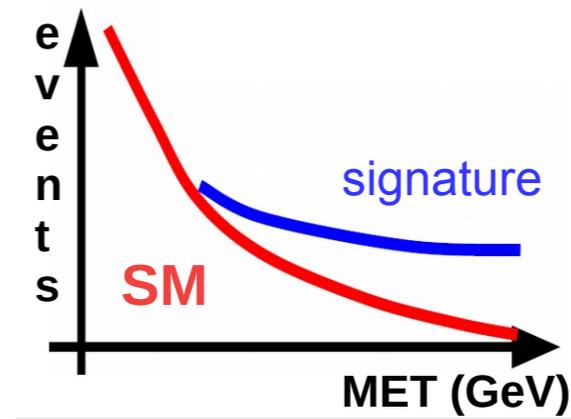
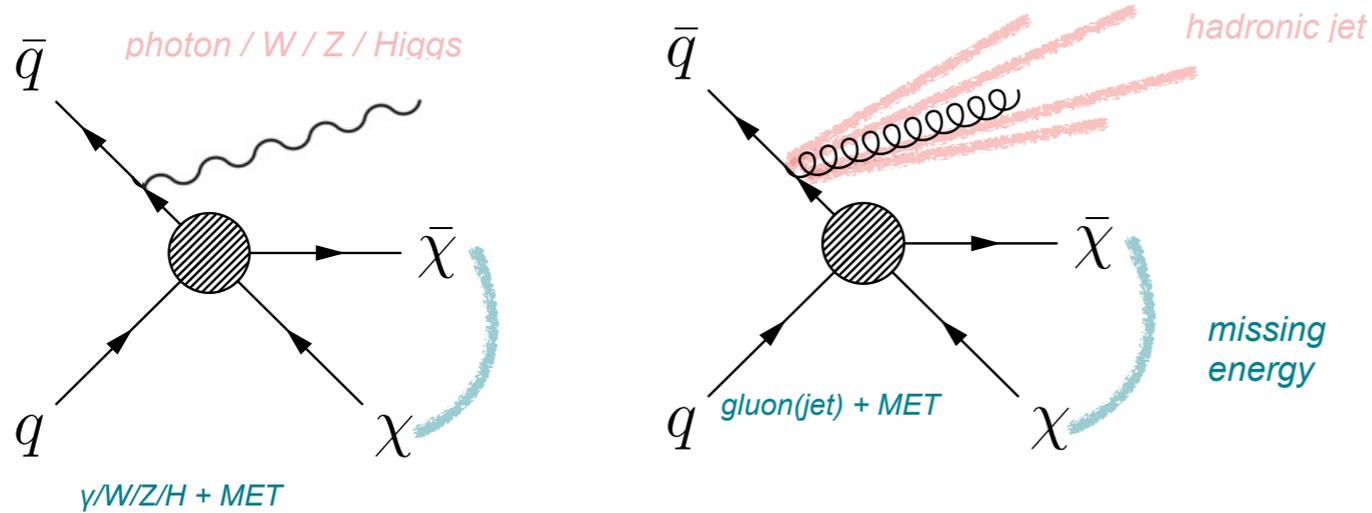


Dark Matter

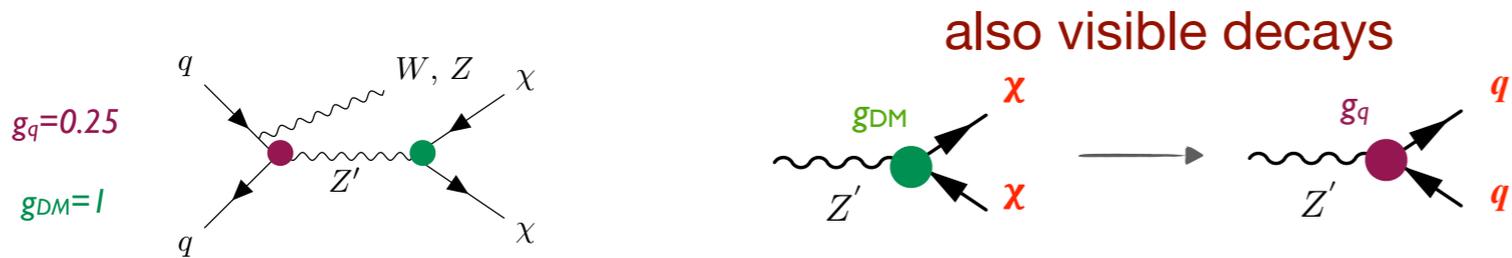
The known unknown

Dark candidates at LHC

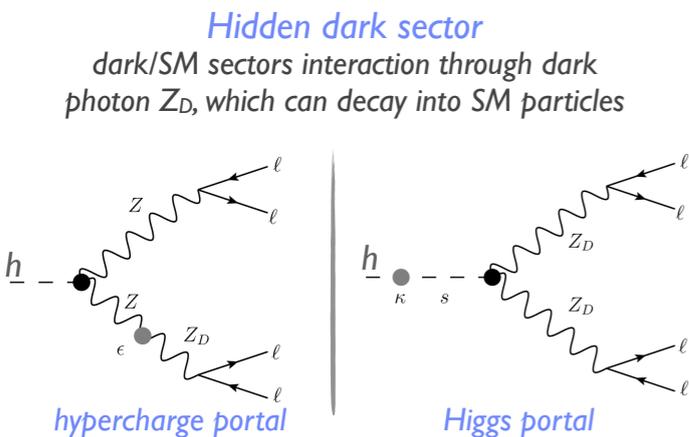
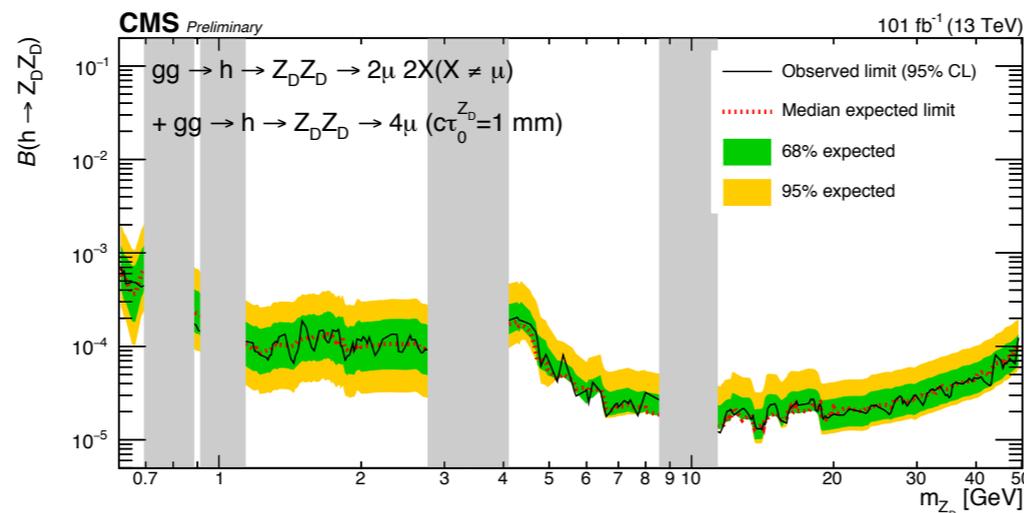
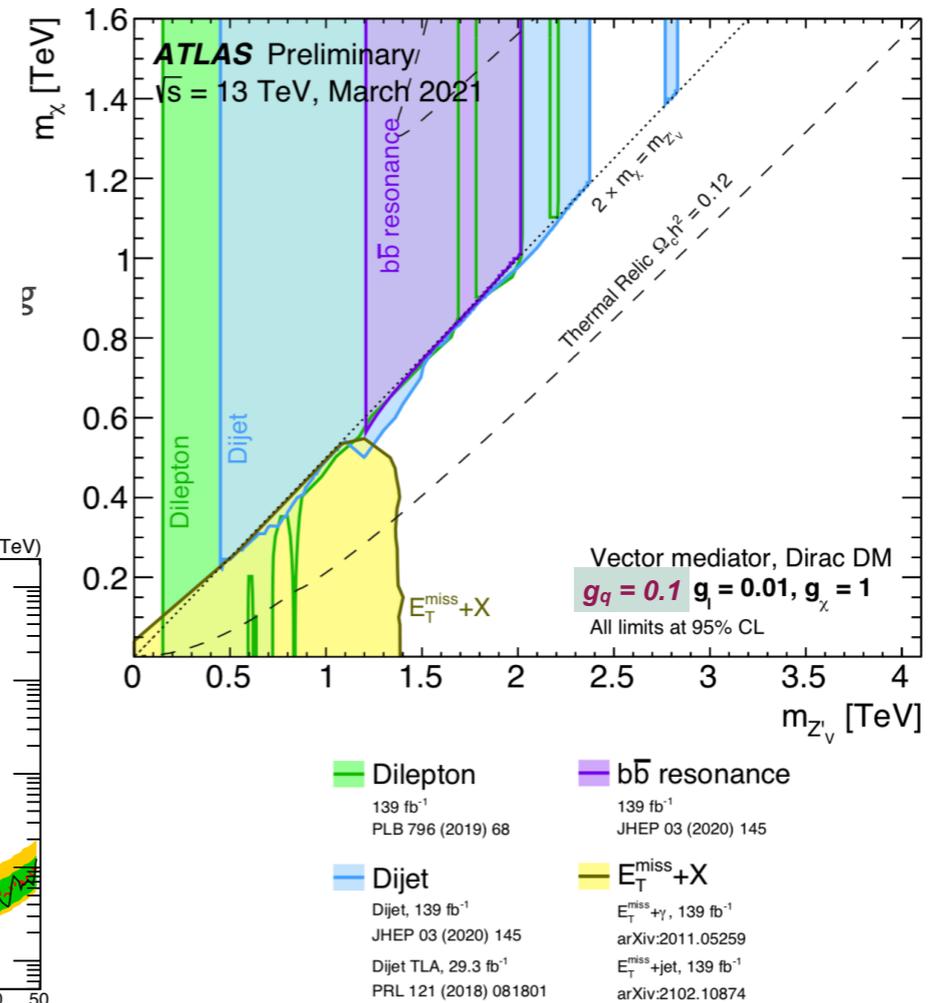
Deborah Pinna



► In addition to classic MET + SM-object(s) search, also constraining mediator mass and coupling in simplified models



► Search for hidden sector also at very low mass



LHC Physics Program

▷ Intense scrutiny of Higgs and Yukawa sector

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + |D_{\mu}\phi|^2 - V(H)$$

$$+ Y_{ij}\psi_i\psi_j\phi + \text{h.c.}$$

Precision Electroweak
QCD

Higgs properties
Higgs self interaction

Higgs coupling to bosons and fermions
CKM matrix and CP Violation

▷ While keeping a wide open eye on new phenomena

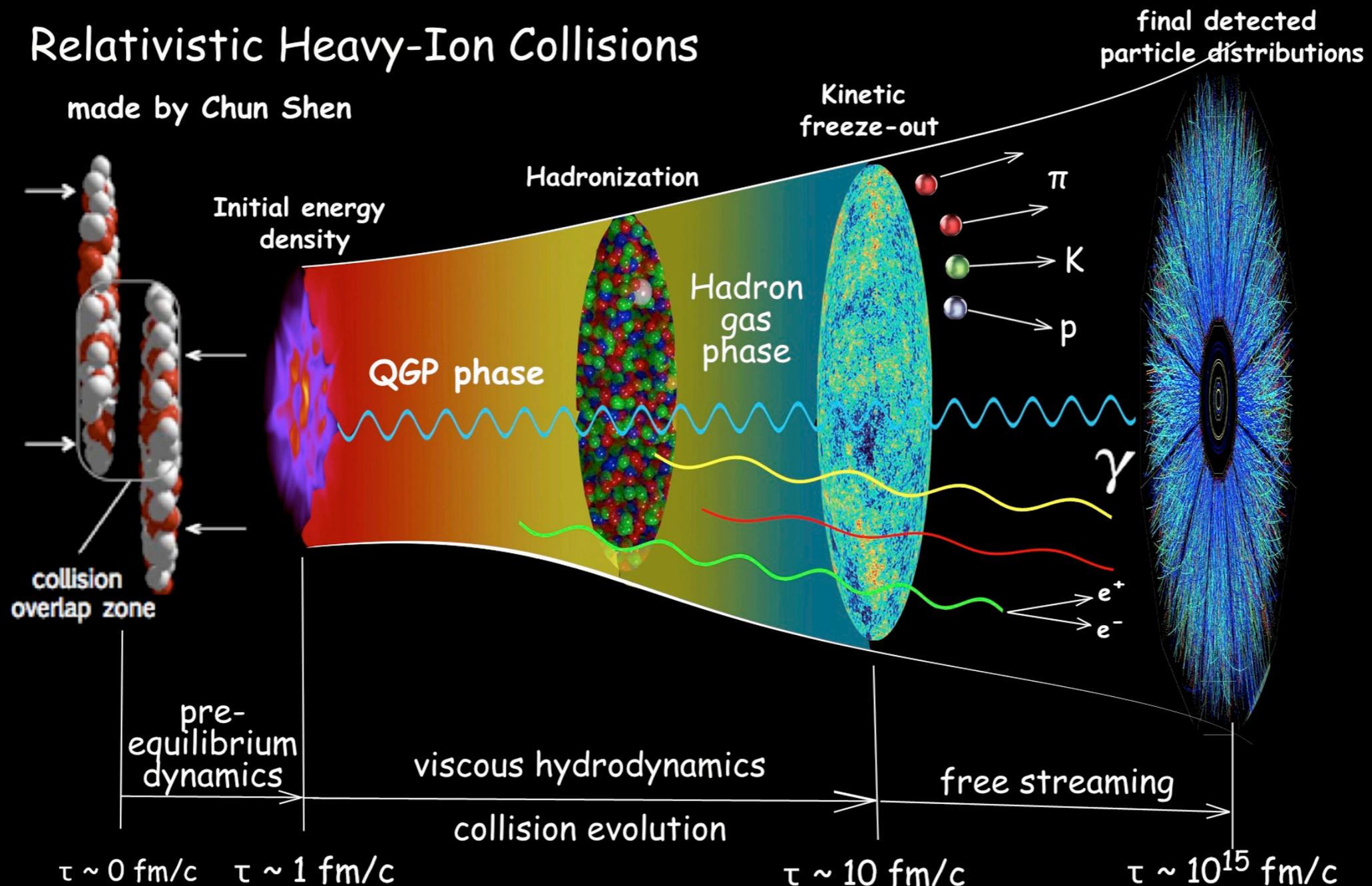
$$+ \mathcal{L}_{\text{New}}$$

New light and heavy particles
Lepton flavour universality violation
Leptoquarks
SUSY
Long-lived particles
Dark matter

Quantum Chromo Dynamics

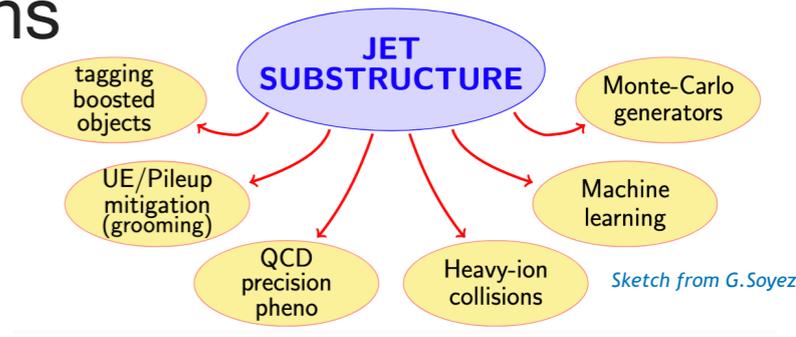
Quark-Gluon Plasma and Spectroscopy

Relativistic Heavy-Ion Collisions

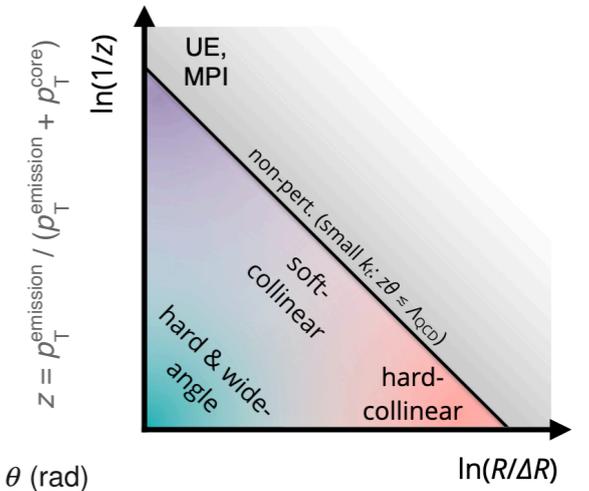


Jet substructure

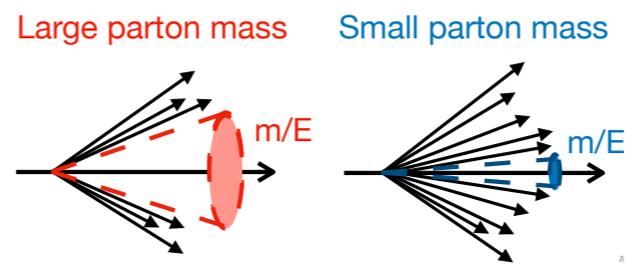
- Internal radiation pattern used in pp and ion-ion collisions
 - reliable predication
 - valuable probe in both high density matter and rare searches
 - distinguish QCD jets from W/Z/H



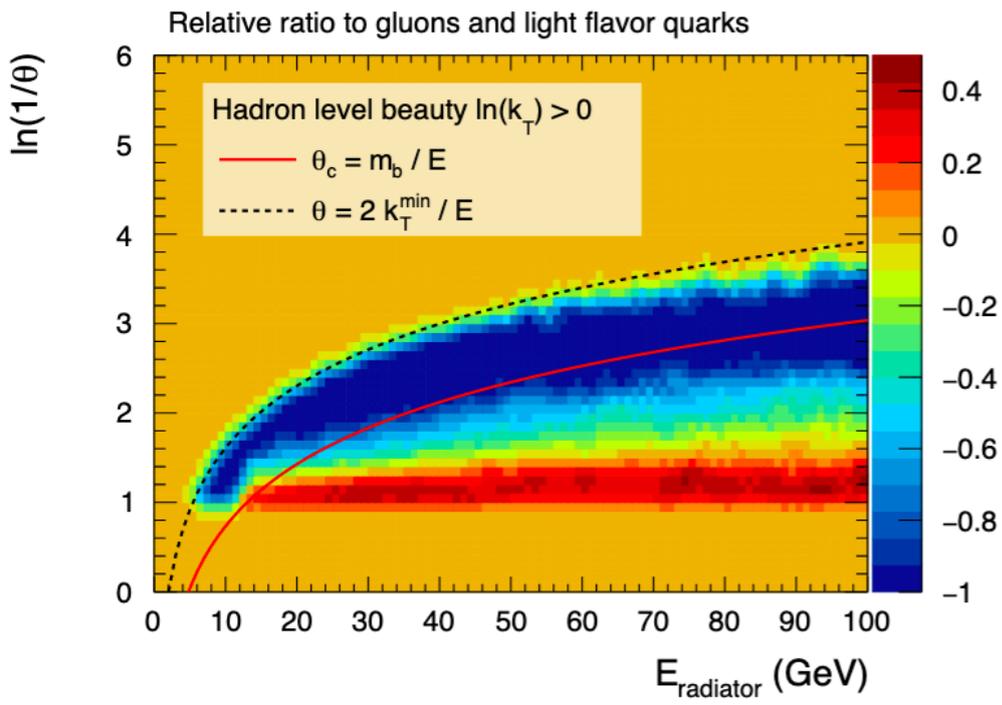
- Systematic study of radiation versus opening (Lund Plane)
 - complementary kinematic regions in ALICE and ATLAS+CMS



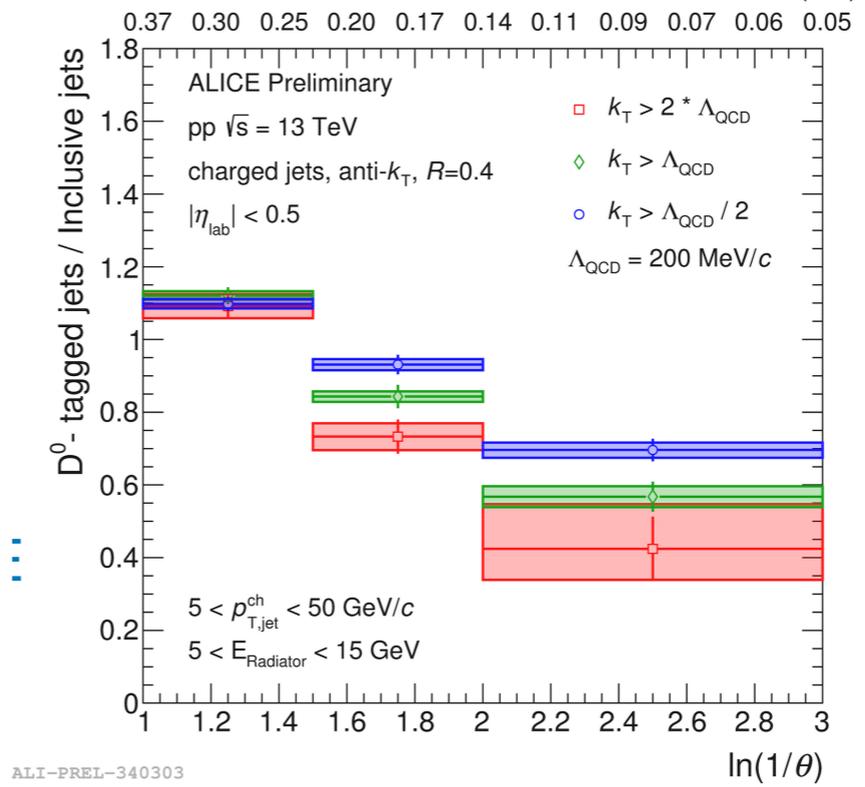
- Jets with heavy flavor to probe mass dependency



$$R(\theta) = \frac{1}{N^{D^0 \text{ jets}}} \frac{dn^{D^0 \text{ jets}}}{d \ln(1/\theta)} \bigg/ \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d \ln(1/\theta)} \bigg|_{k_T, E_{\text{Radiator}}}$$



Radiator: quark lead prong



ALI-PREL-340303

Large θ

Small θ

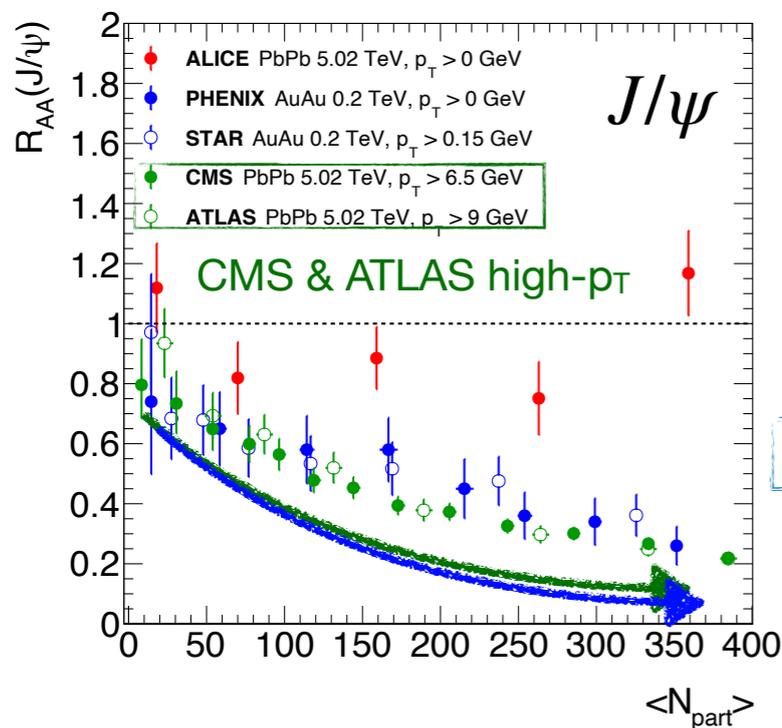
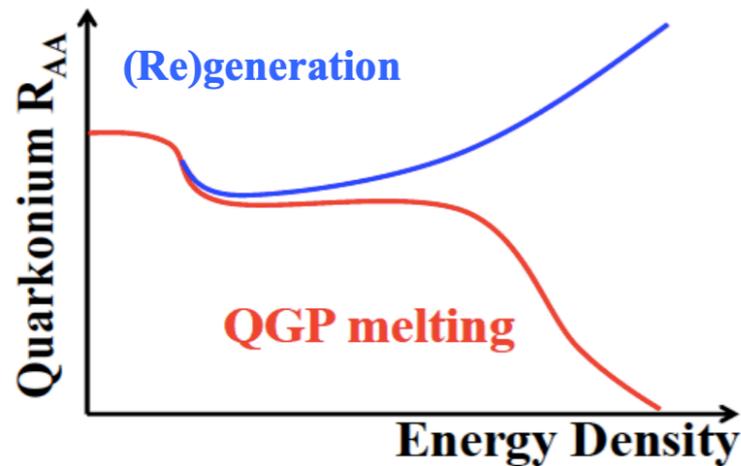
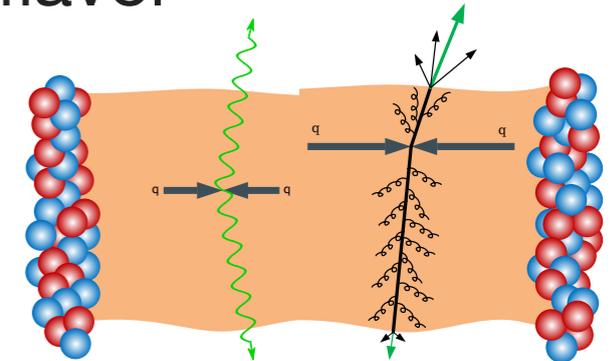
Interaction in QGP

Laura Havener
Sebastian Tapia

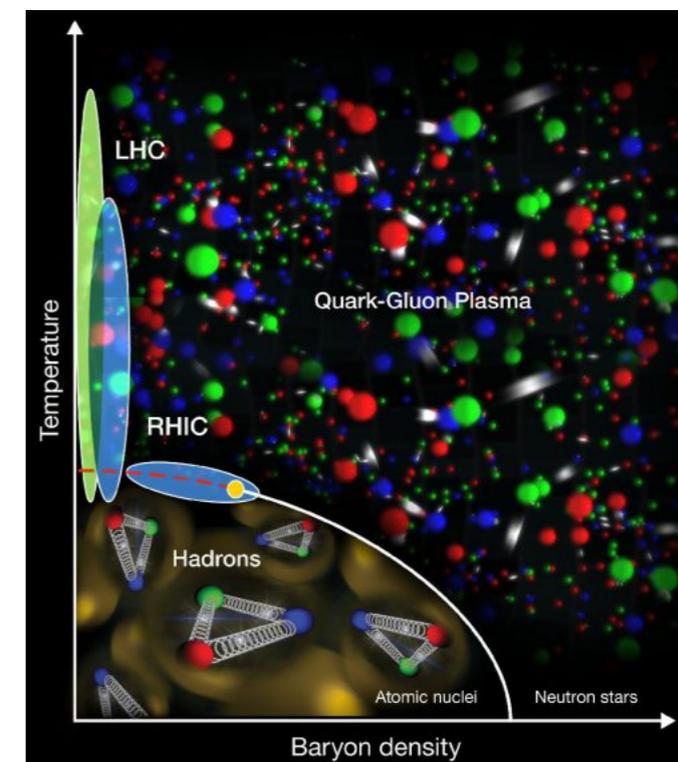
▷ Probing interactions with medium with W/Z, jets, and heavy flavor

- Use W/Z and p-p as reference
- measure energy loss and jet widening

$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled } \otimes \text{pp}}$$



Agreement between RHIC and high pT LHC despite different energy density



Observation of odderon

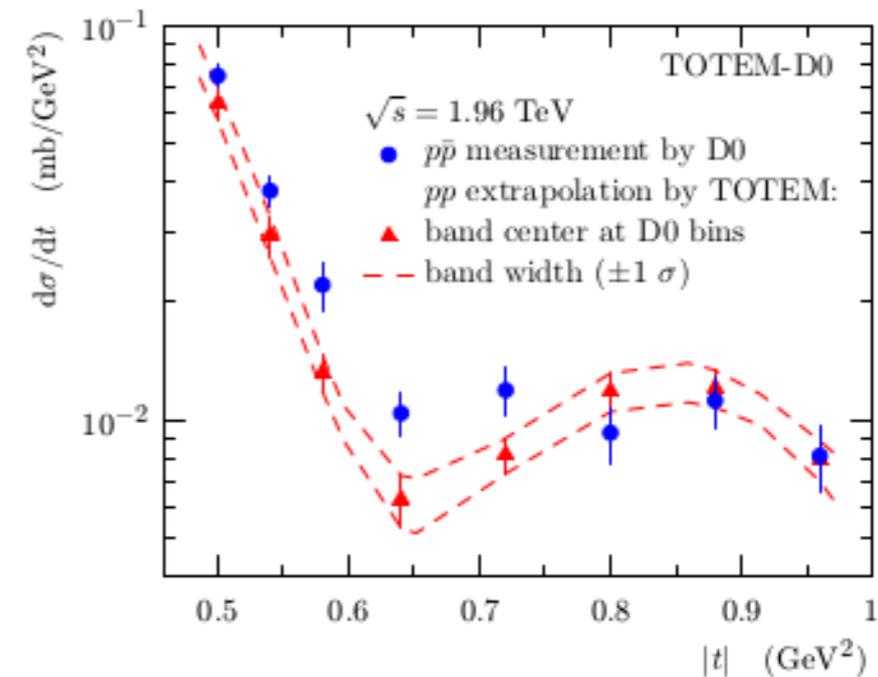
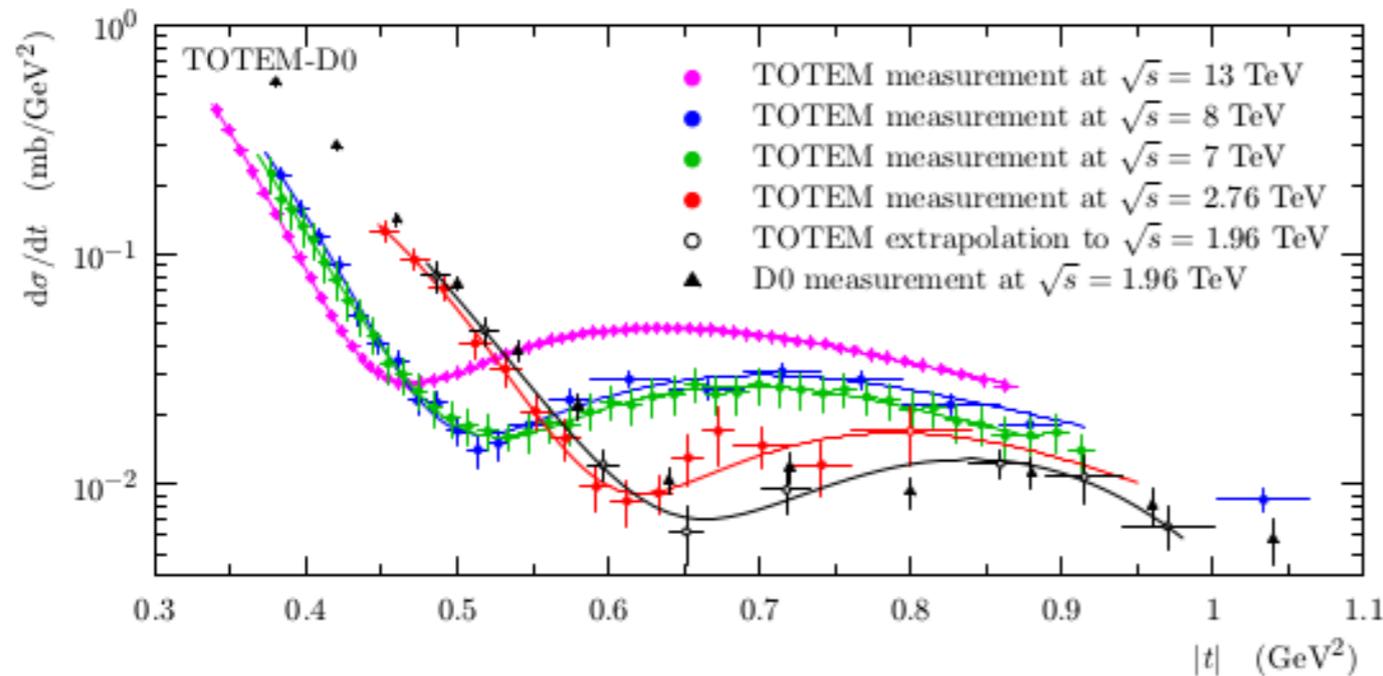
- ▷ Structure in differential cross section of elastic scattering

D0 measured elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV.

TOTEM measured elastic pp $d\sigma/dt$ at: 2.76, 7, 8 and 13

– odderon: C-odd gluon compound

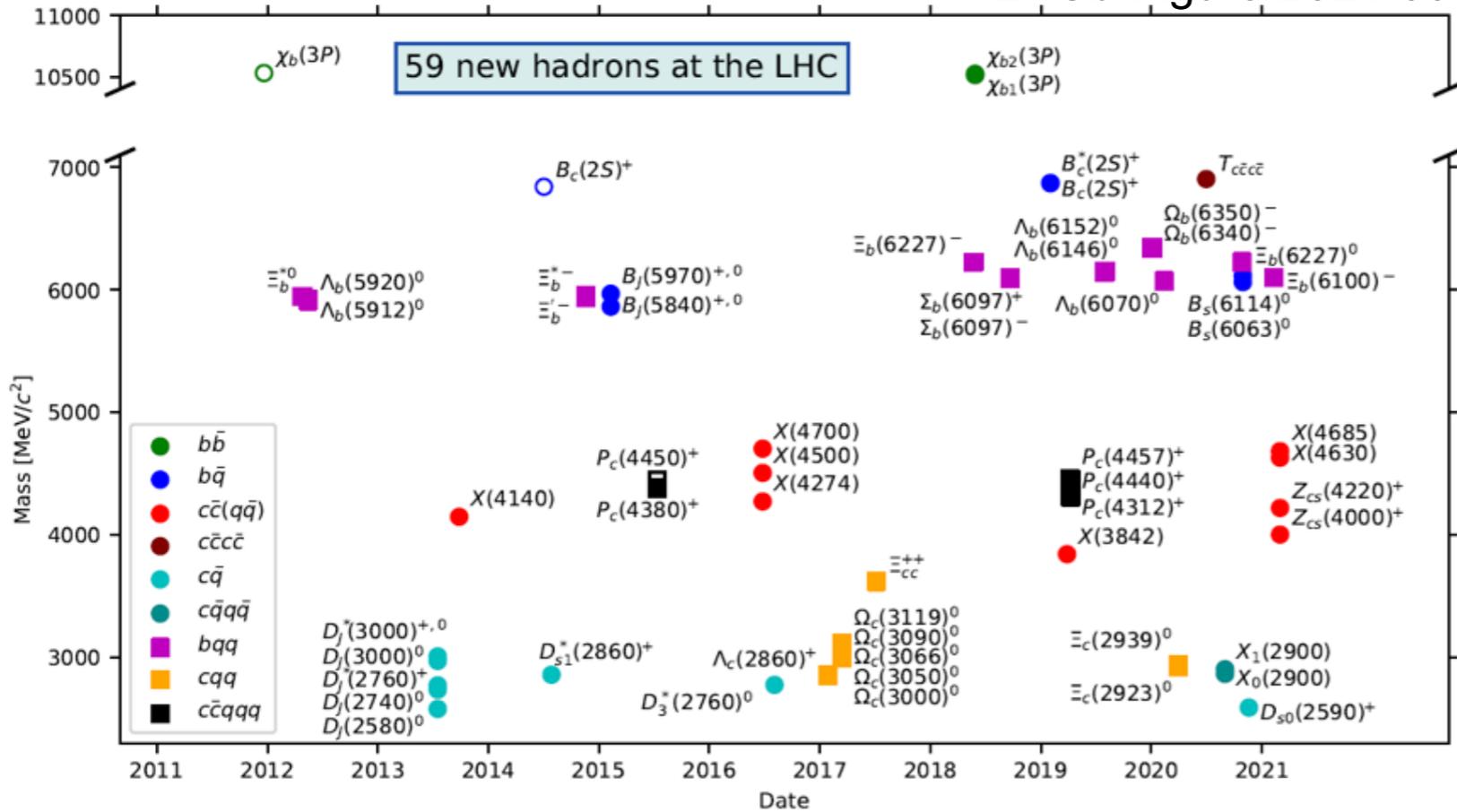
- ▷ Combination of TOTEM and D0 excludes models w/o odderon exchange



Spectroscopy

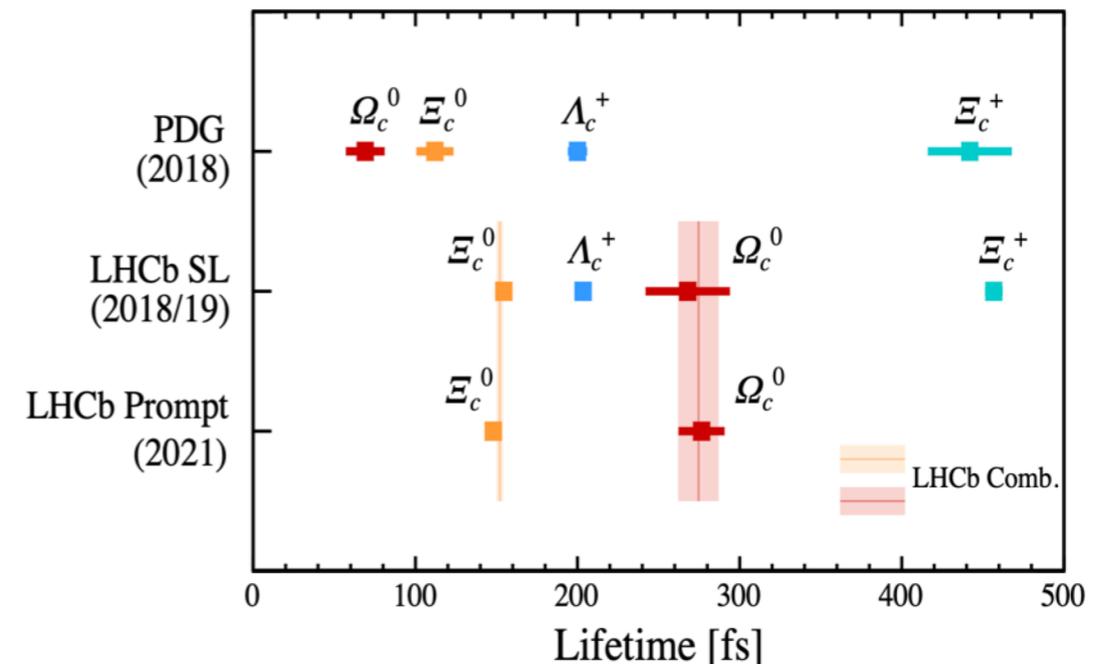
- ▷ New Age of spectroscopy and fruitful collaboration with theory
 - systematic study of tetra- and penta-quarks

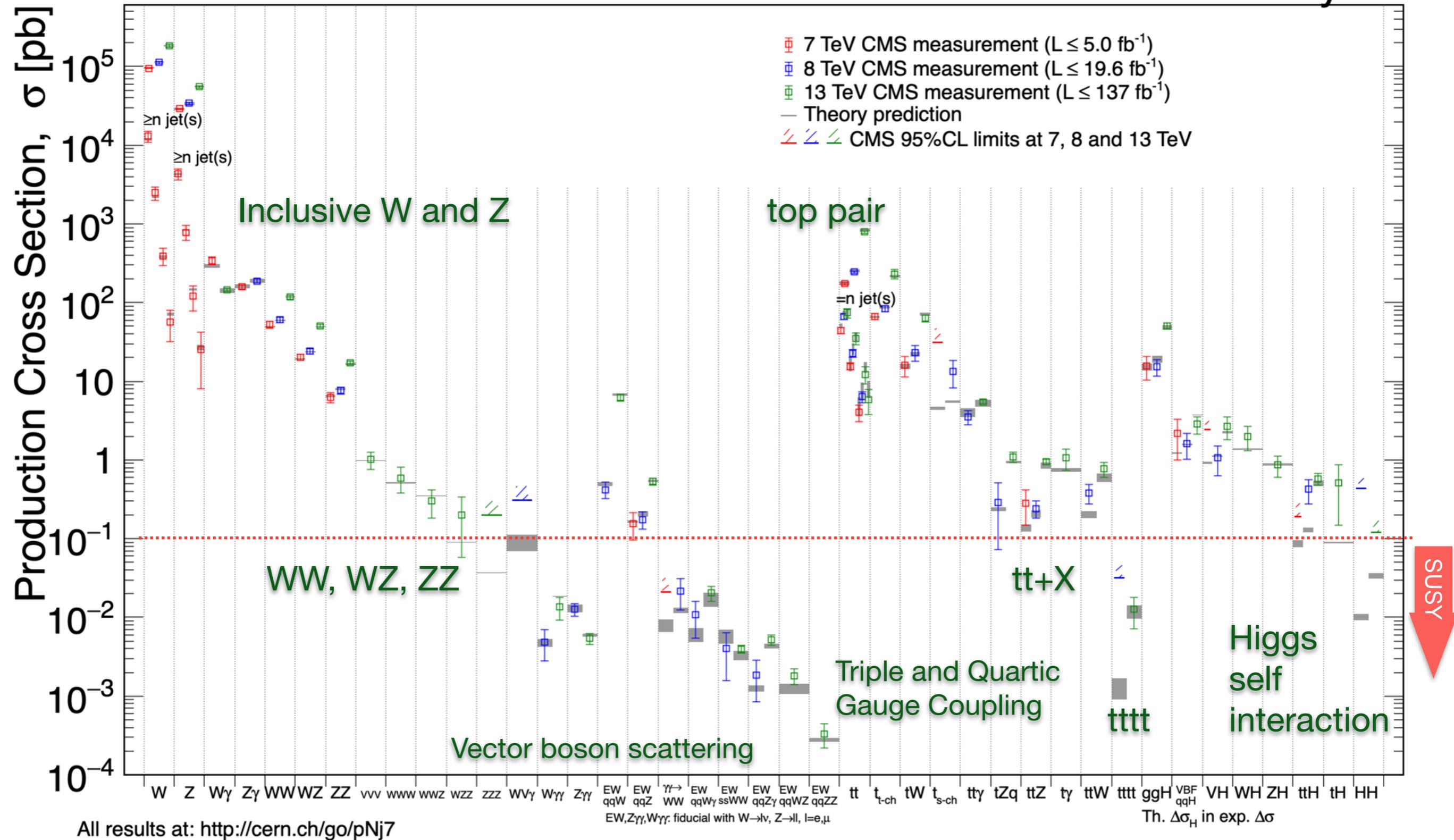
LHCb-Figure-2021-001



- ▷ Interesting discrepancy in baryon lifetimes confirmed

- interesting to see theory prediction and previous measurement





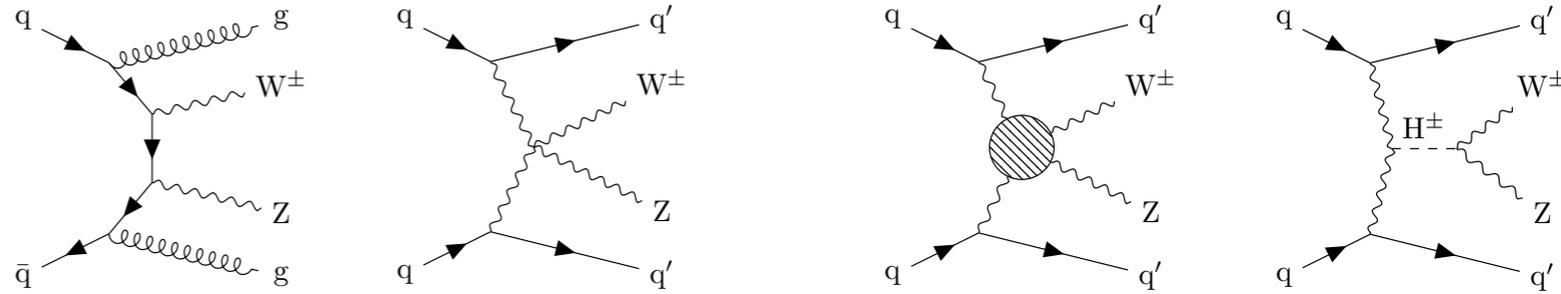
Electroweak Sector

New Physics through Precision

Vector Boson Scattering

▷ Quartic gauge couplings known exactly in SM and sensitive to new physics contributions

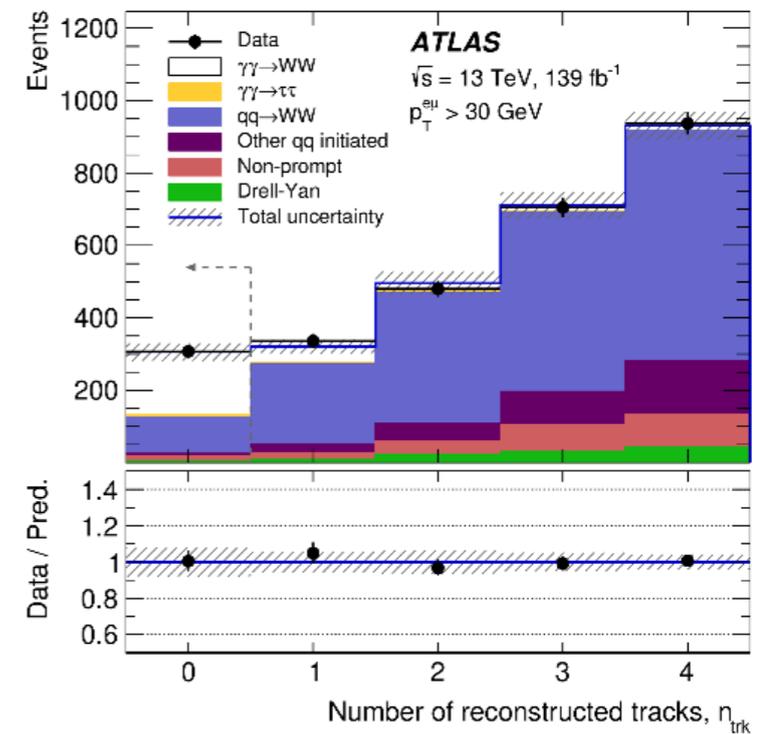
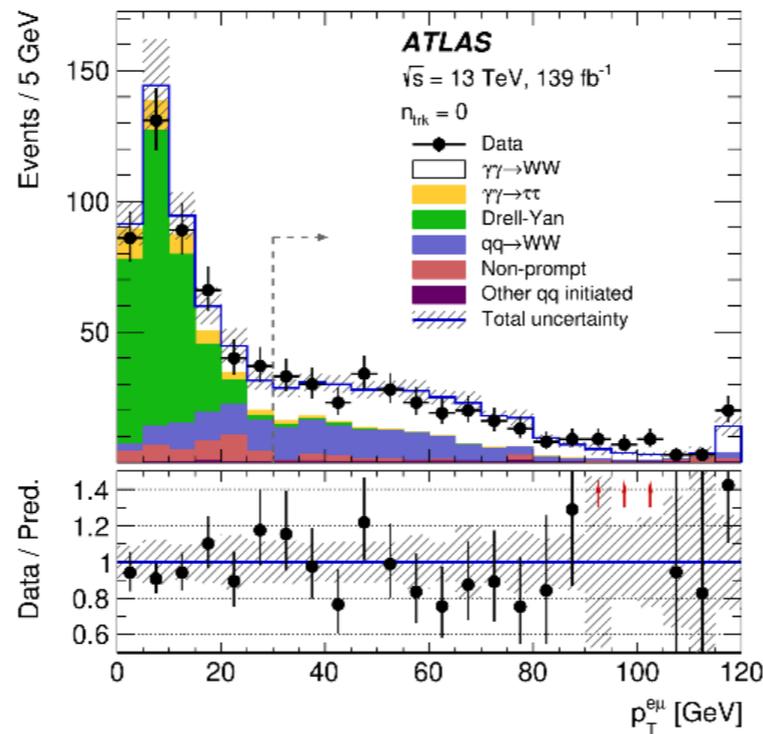
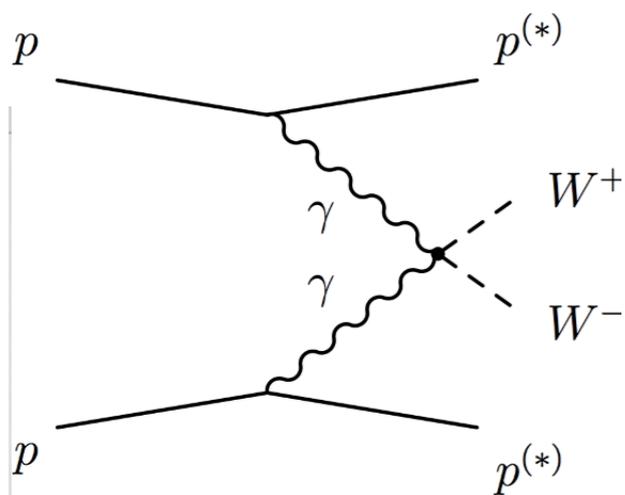
- Disentangle QCD and EW contribution through jet kinematics
- suppress QCD background with novel ML techniques



▷ Important milestone for longterm LHC program towards study of WW scattering

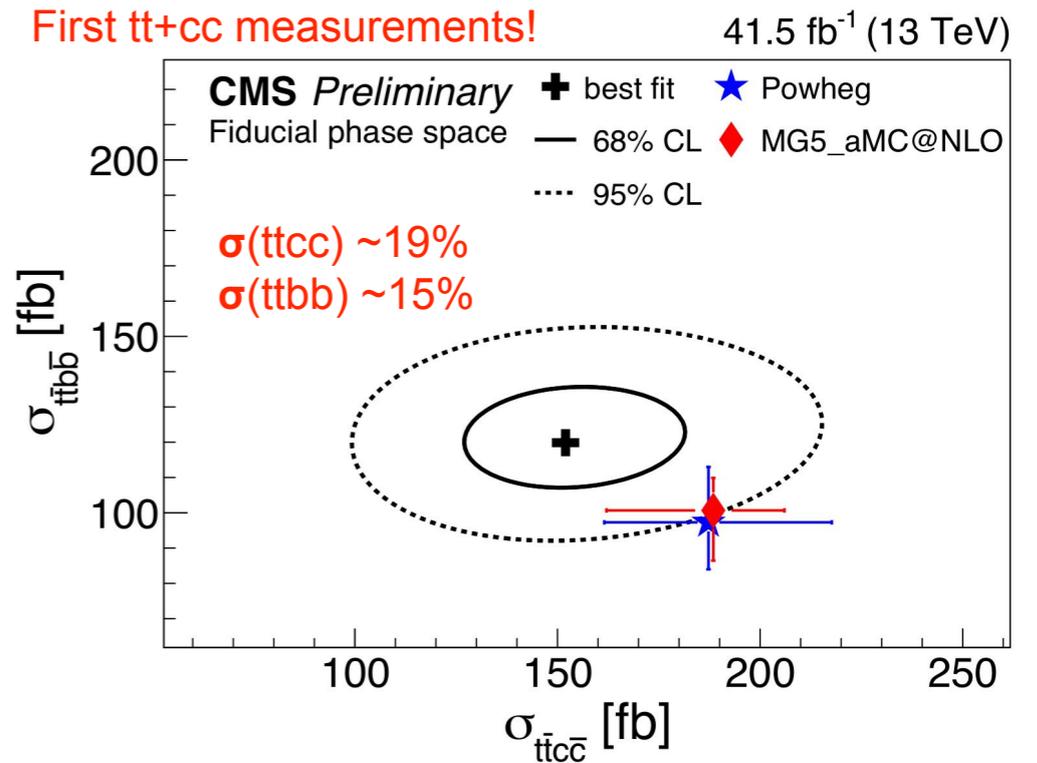
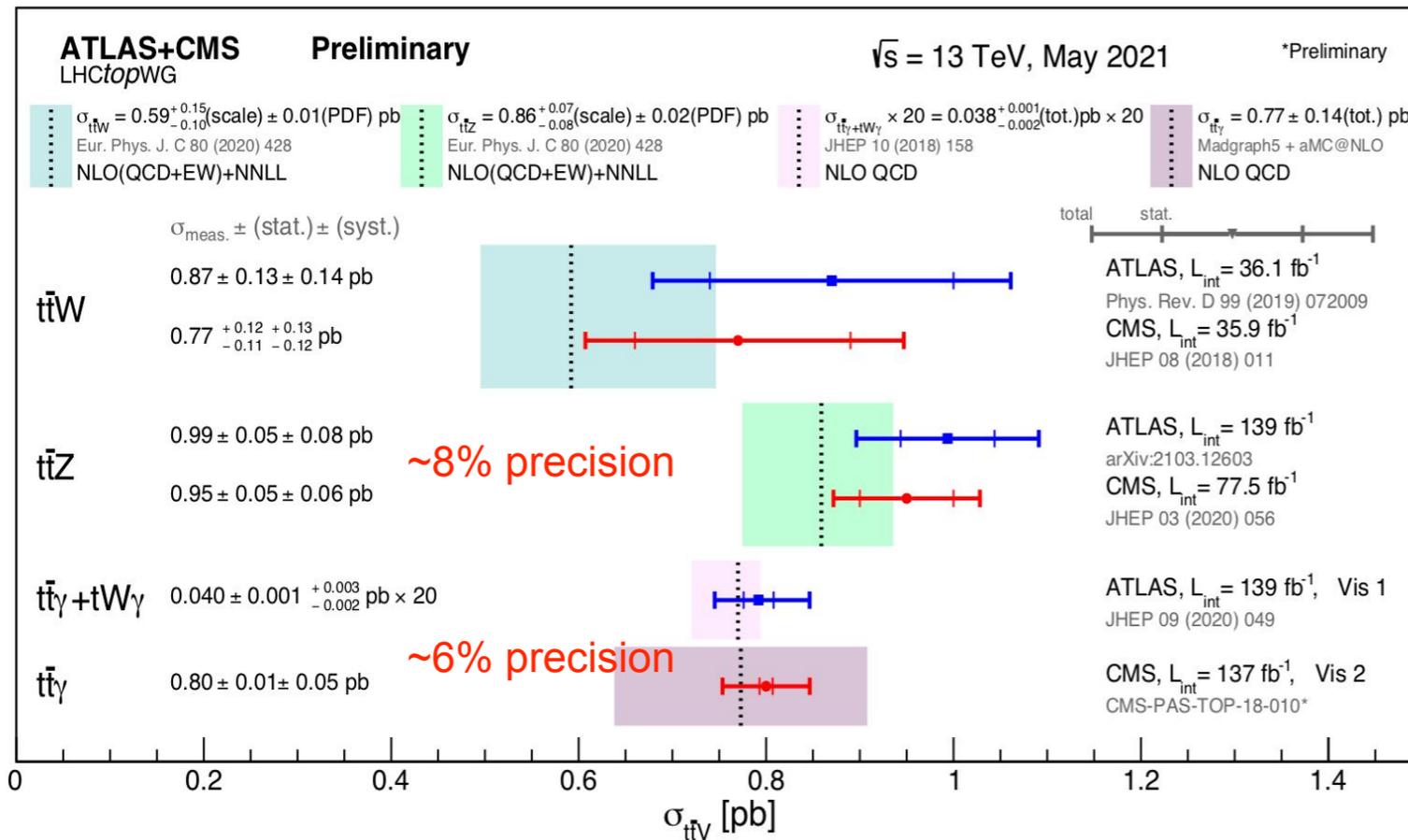
- Observation of Same-sign WW in 2017!

▷ First observation of $\gamma\gamma \rightarrow W^+W^-$



▷ Comprehensive input with various VV modes to constrain EFT operators

Top agreement with theory

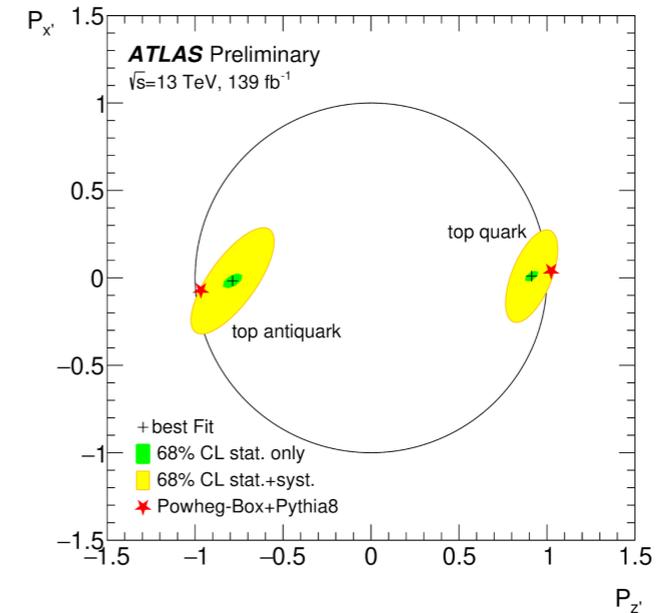
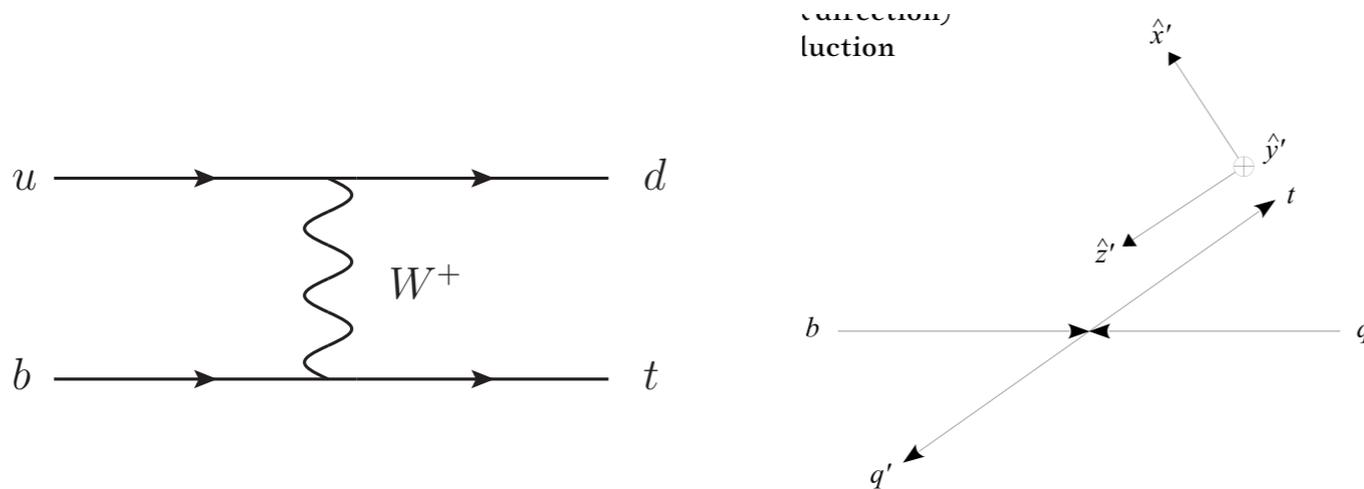


- ▷ Competing precision between theory and experiment in ttZ
- ▷ tt+bb production now exceeding theoretical knowledge!
 - Important background in study of top-Higgs Yukawa coupling
- ▷ Now also tt+cc with 19% precision
 - key role of c-tagging
- ▷ Precision theory input needed to reduce uncertainties
 - important ingredient for rare Higgs and other processes

top and W properties

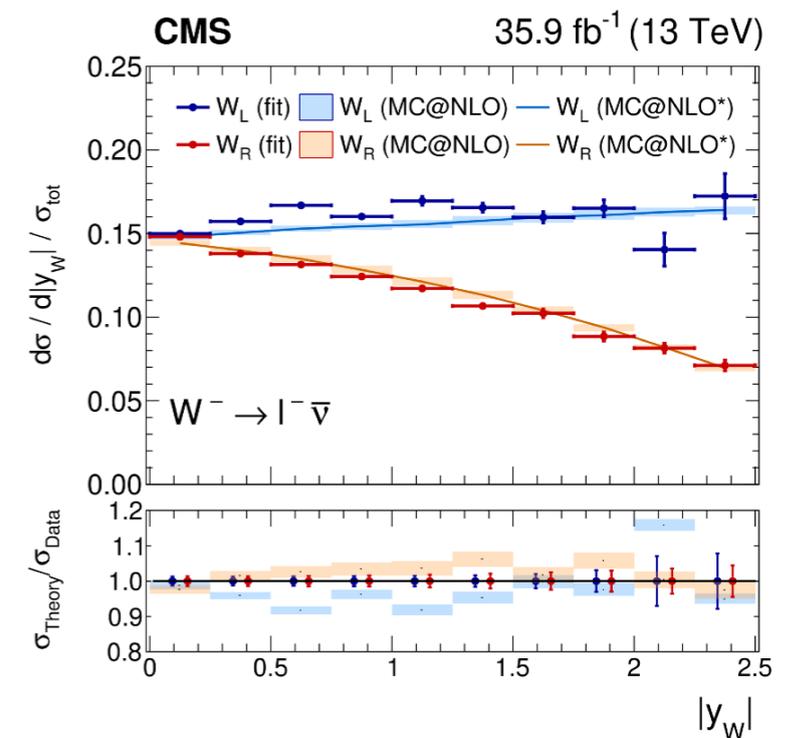
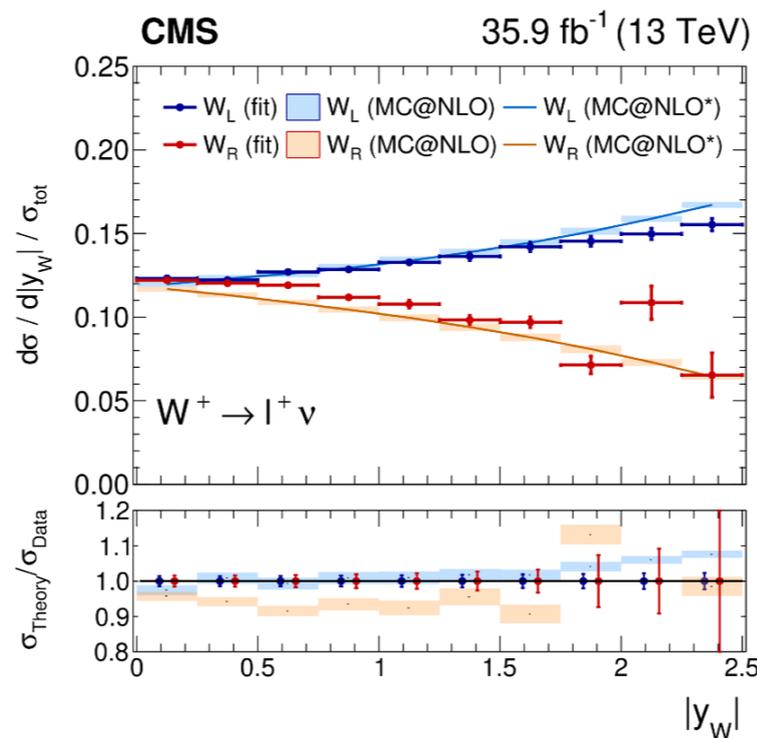
Sven Menke
I. Gorbunov

- ▷ Infer spin of weakly-produced single-top from angular analysis in $t \rightarrow bl\nu$
 - polarisation consistent with SM prediction and sensitive to new physics contributions

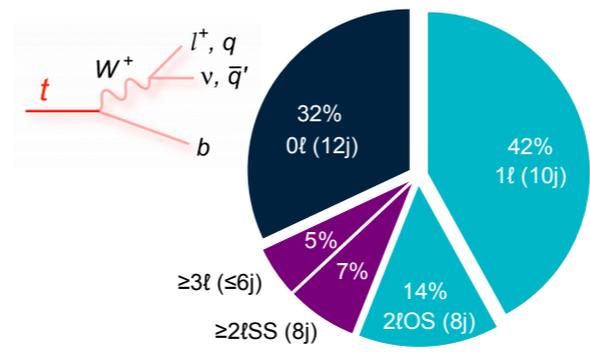
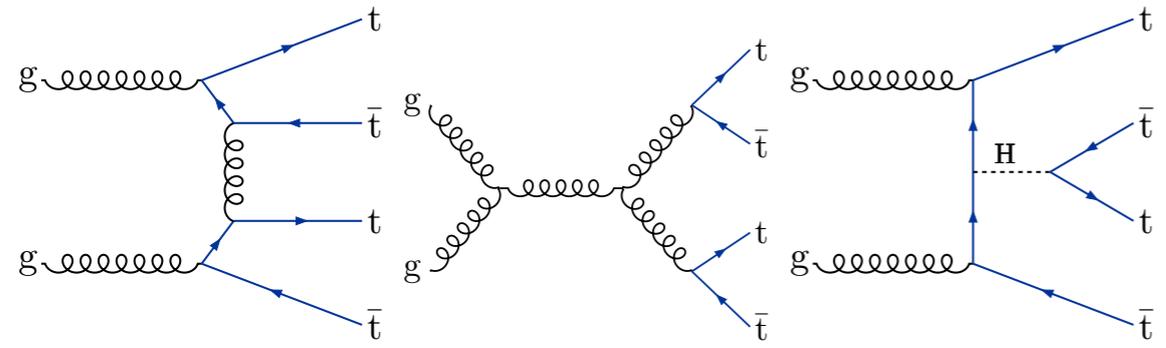


- ▷ Measurement of W helicity to approach W mass
 - differential cross section for W^+ and W^-
 - Aim at reduced uncertainty in W mass by constraining also PDFs

- correct and abundant simulation a key ingredient

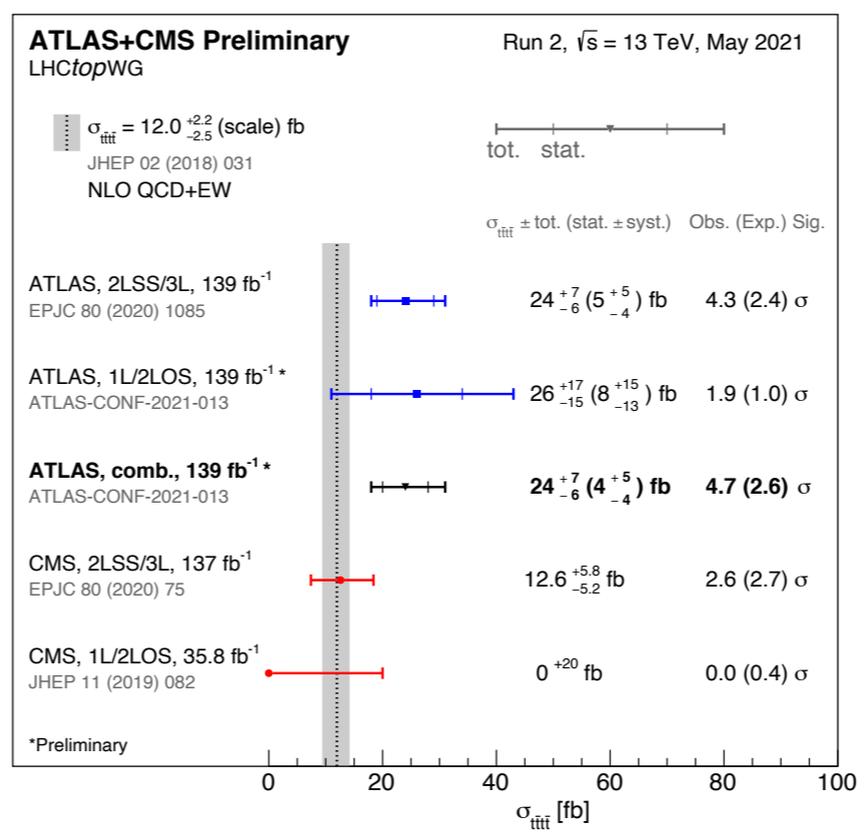
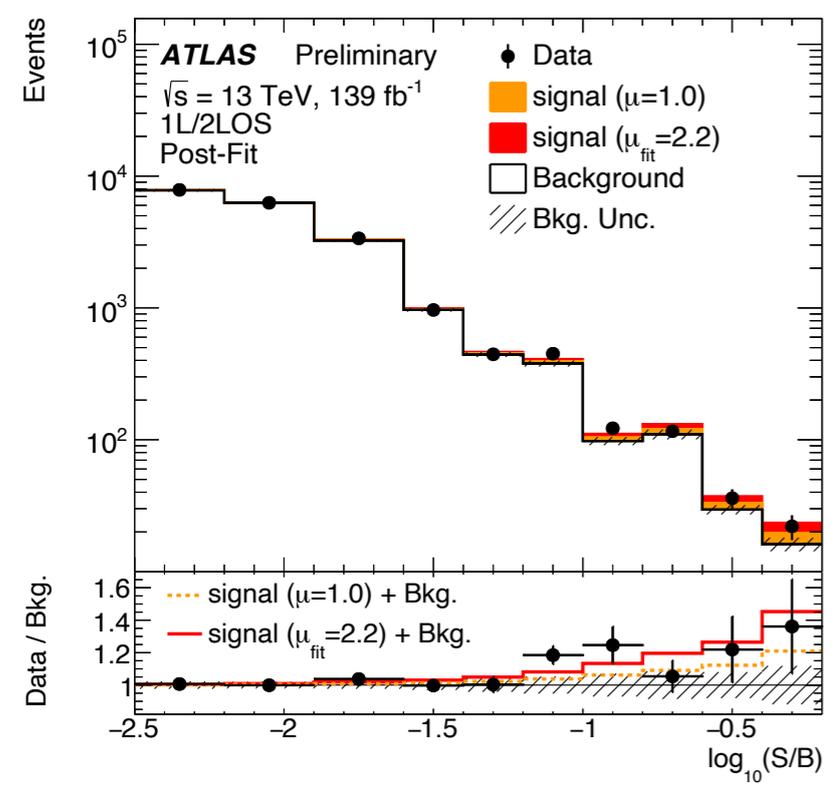
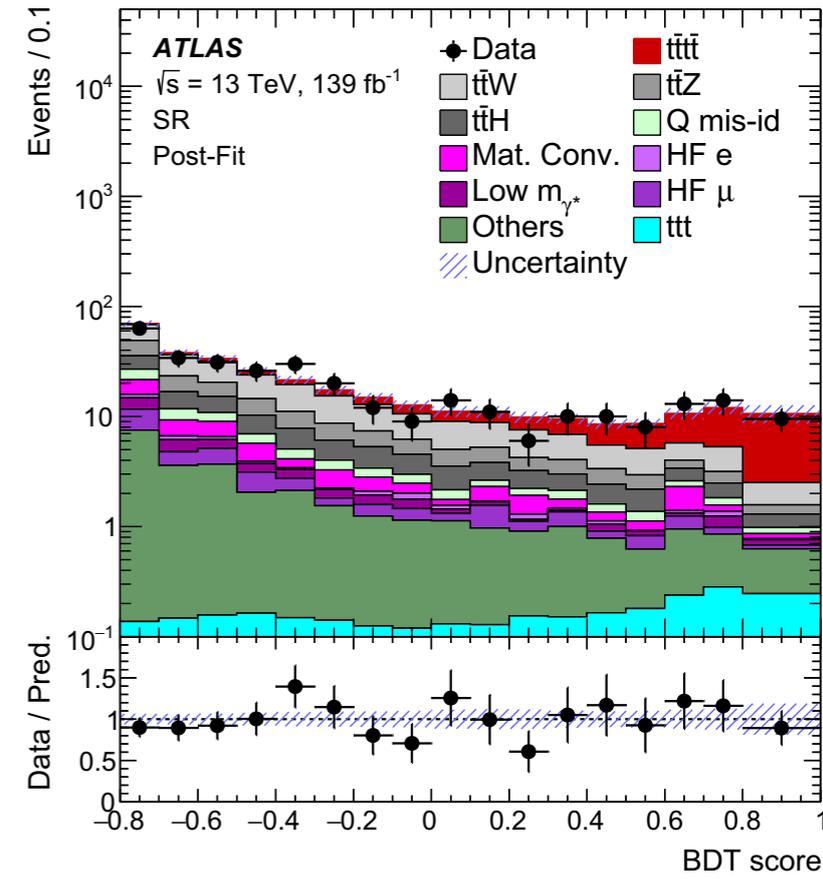


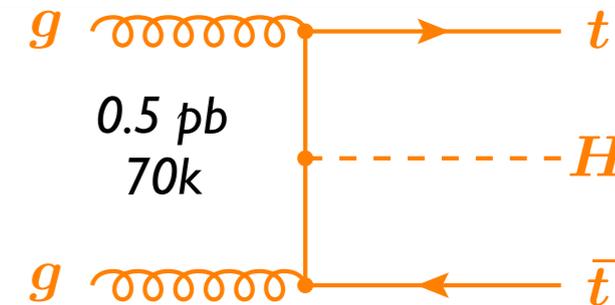
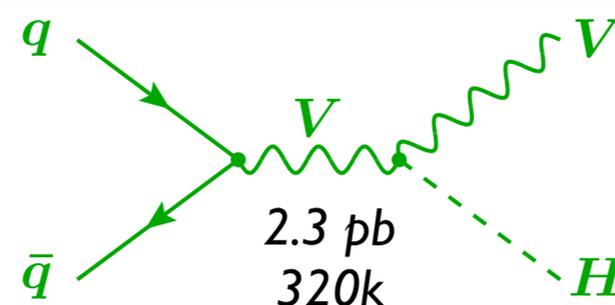
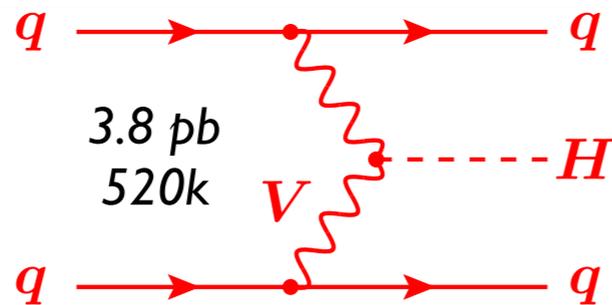
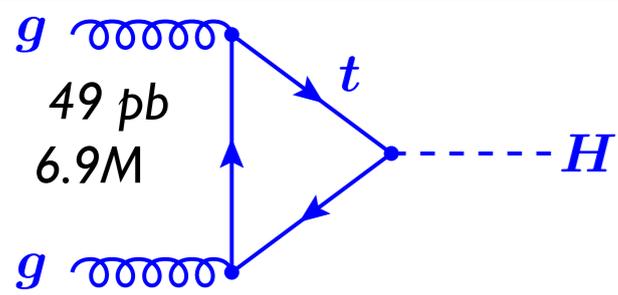
4-top production



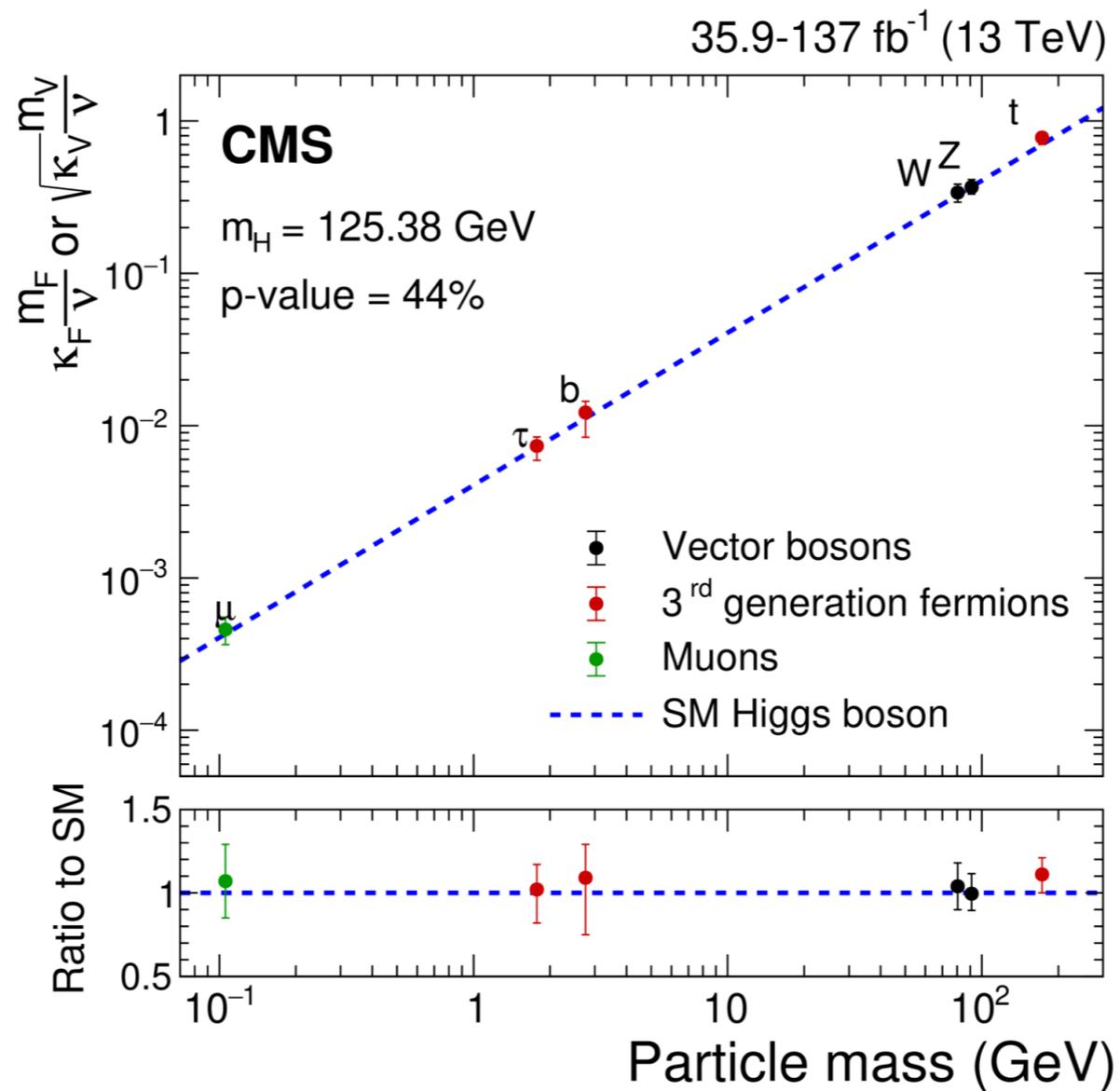
- ▷ SM cross section: 12 fb @ 13 TeV
- ▷ Several final states combined
 - key role of BDT discriminants in this search

Dominant uncertainties:
 $t\bar{t} + \geq 1b$ modelling, (± 8 fb), $t\bar{t} + \geq 1c$ cross-section (± 5 fb)





σ [pb]
#Higgs produced during
Run-2



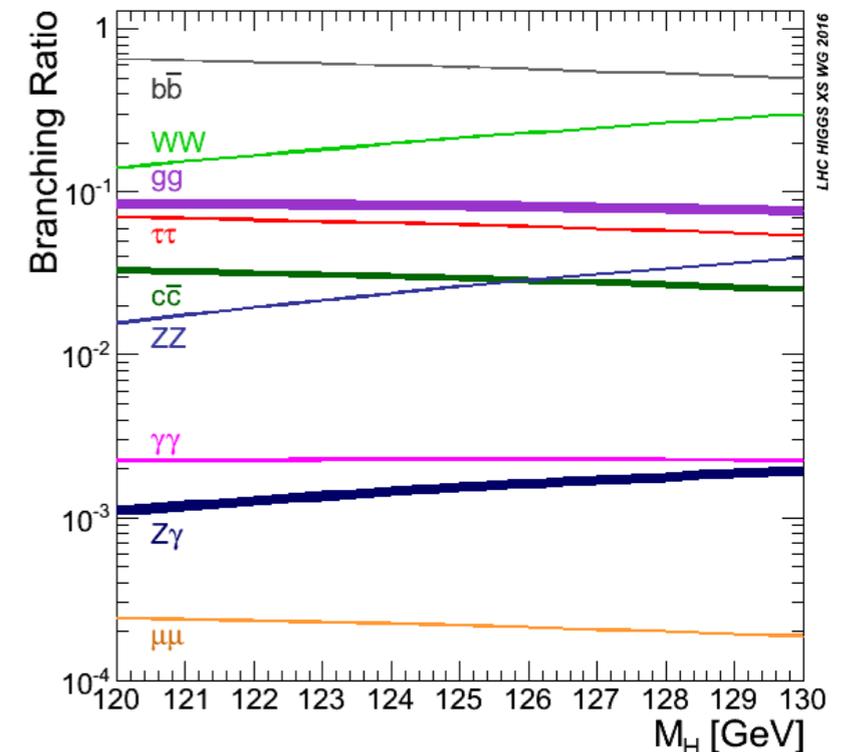
Higgs

From Discovery to Precision

$$Y_{ij}\psi_i\psi_j\phi$$

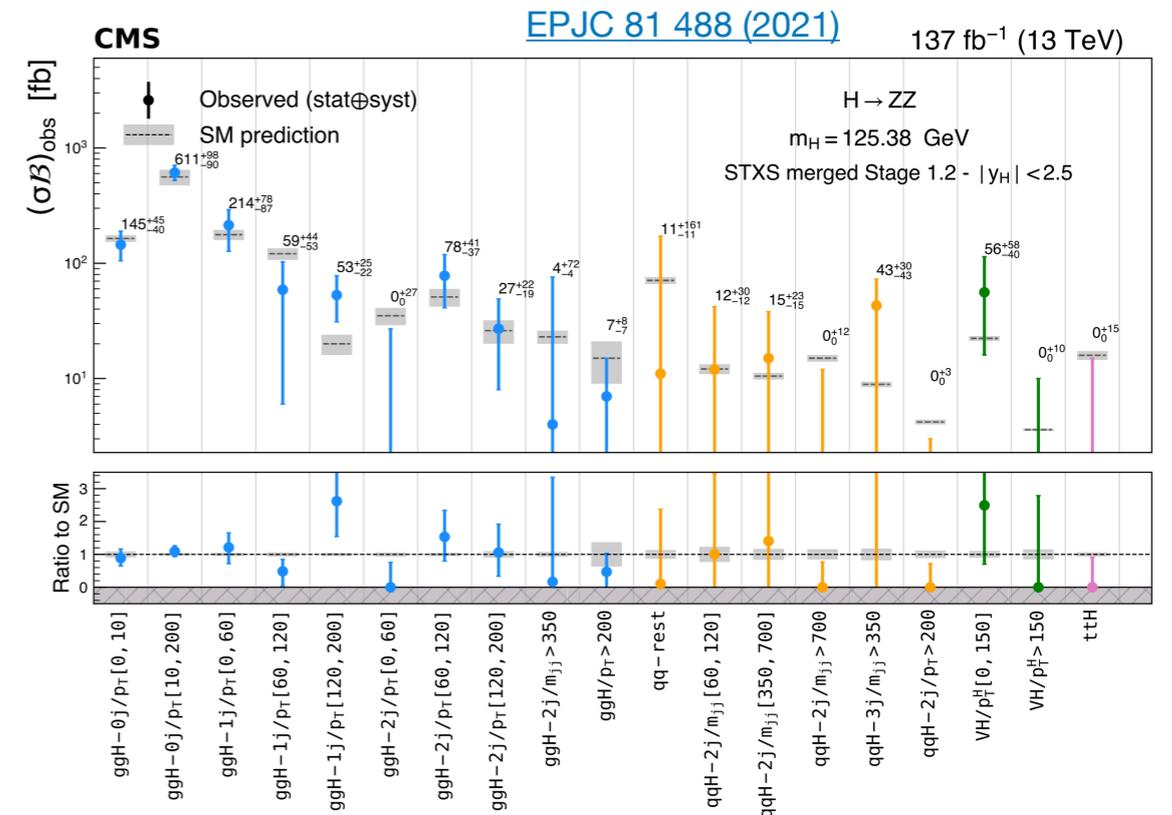
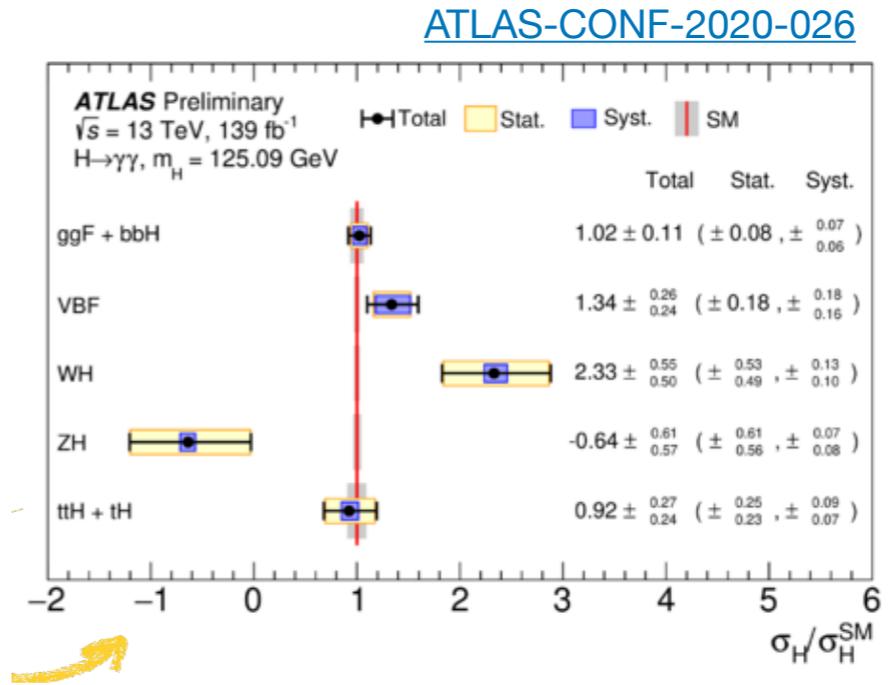
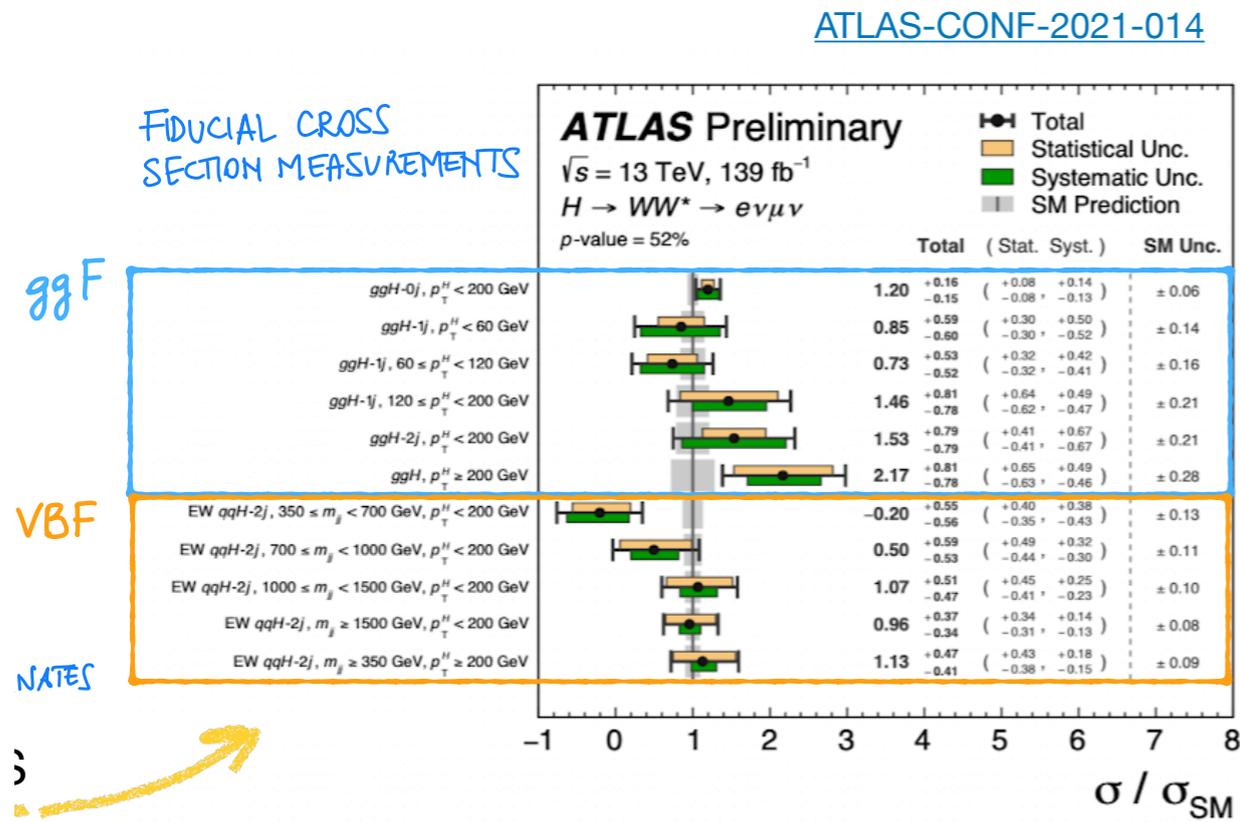
Higgs Physics

- ▷ A standard candle of Standard Model in just a decade since its discovery
 - compare to top, W, and Z
- ▷ Higgs now used as a probe in searches for new phenomena
 - FCNC in top decays
 - Search for Supersymmetry
 - Search for Dark Matter WIMP candidates
 - Decay of heavy new particles to H+X
- ▷ Couplings to 3rd generation established
 - taus in 2017, top and b in 2018
- ▷ Coupling to 2nd generation under way!
 - evidence for muons, tackling also charm
- ▷ So far it **walks** and **talks** like the Standard Model Higgs
- ▷ *Falsification of the Higgs mechanism a critical component of High Energy Frontier program*



Higgs precision studies

- Extensive measurement of differential and fiducial cross sections
 - STXS framework as the basis for reporting results



- Study of spin and CP also in agreement so far with Standard Model precisions
- Theory and experimental uncertainties now comparable
 - fruitful collaboration with theory

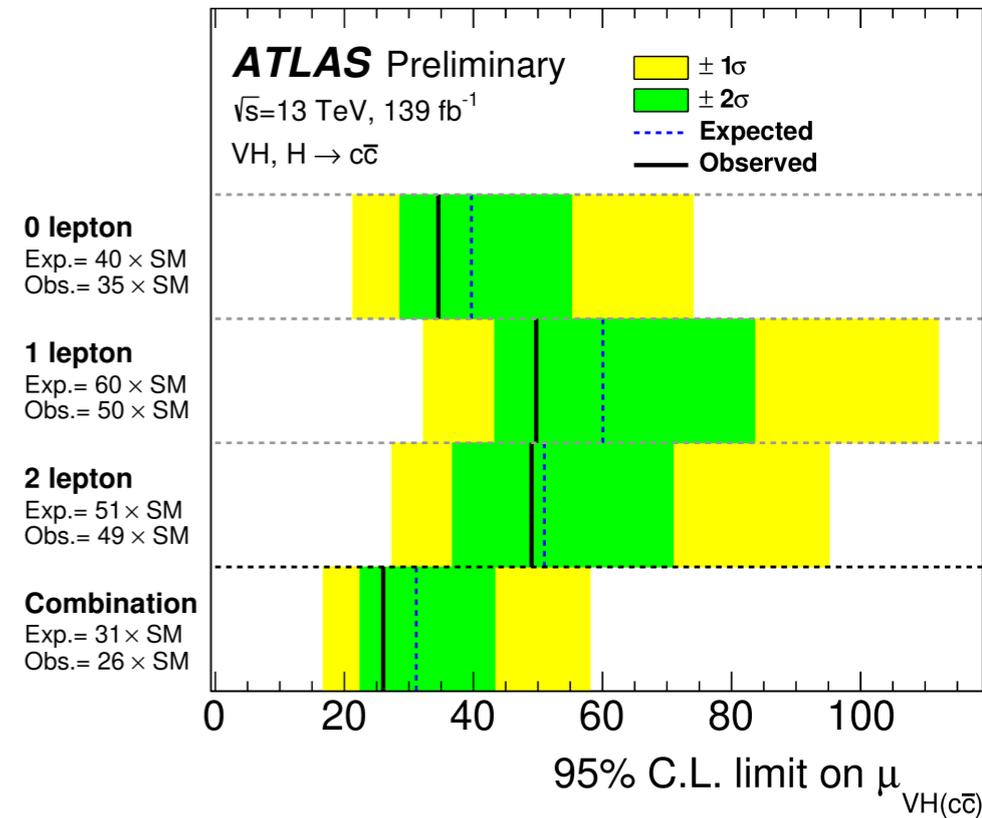
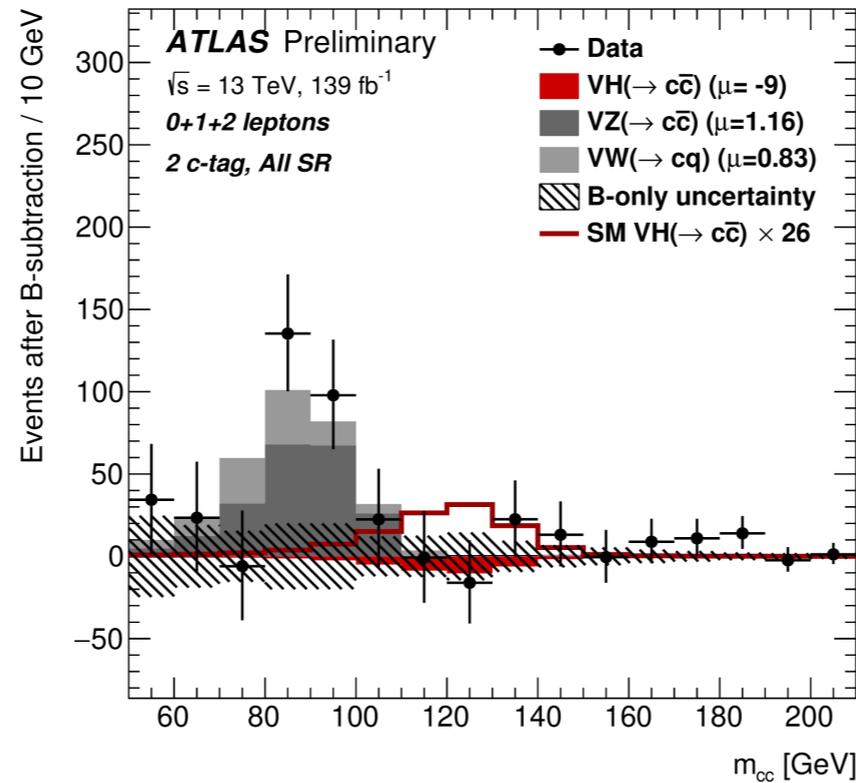
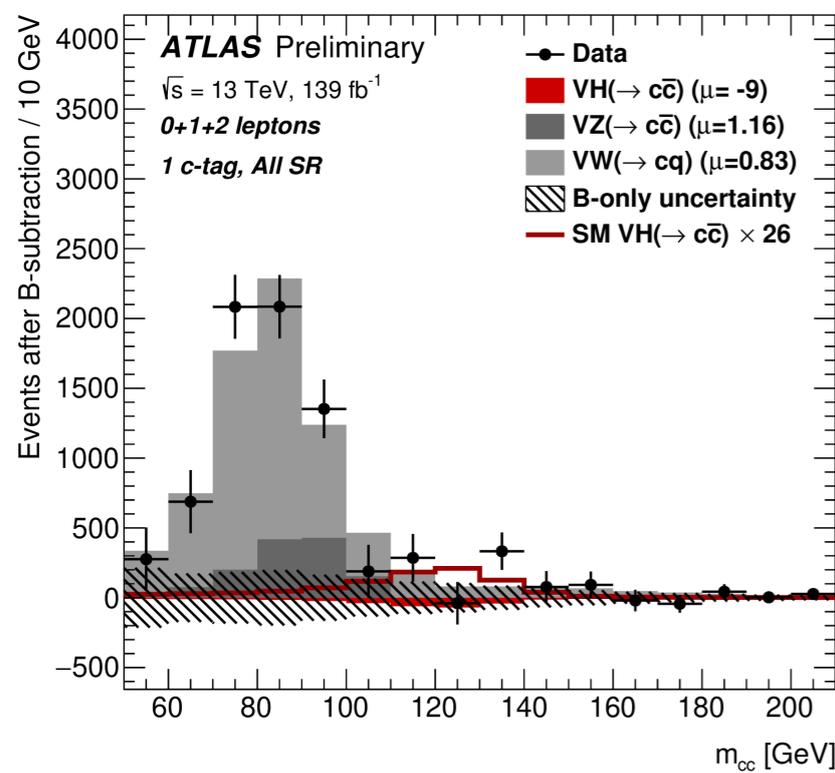
$H \rightarrow c\bar{c}$

▷ Higgs produced together with vector bosons

Manuella Vicer

1 c-tag

2 c-tags



▷ Remarkable achievement thanks to novel tagging techniques

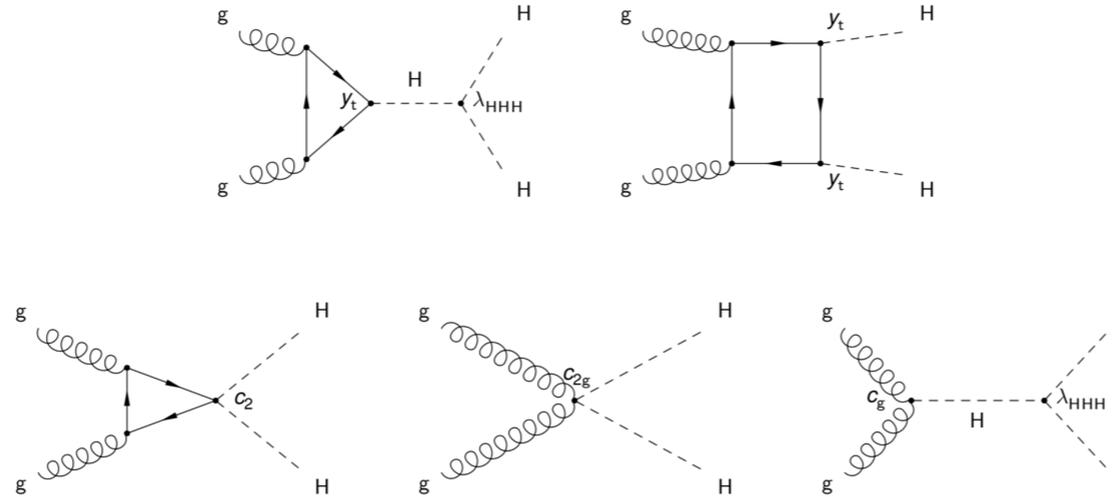
– Higgs Branching fraction 3% !

▷ Within reach with future improvements and copious data at HL-LHC

Higgs Self-Interaction

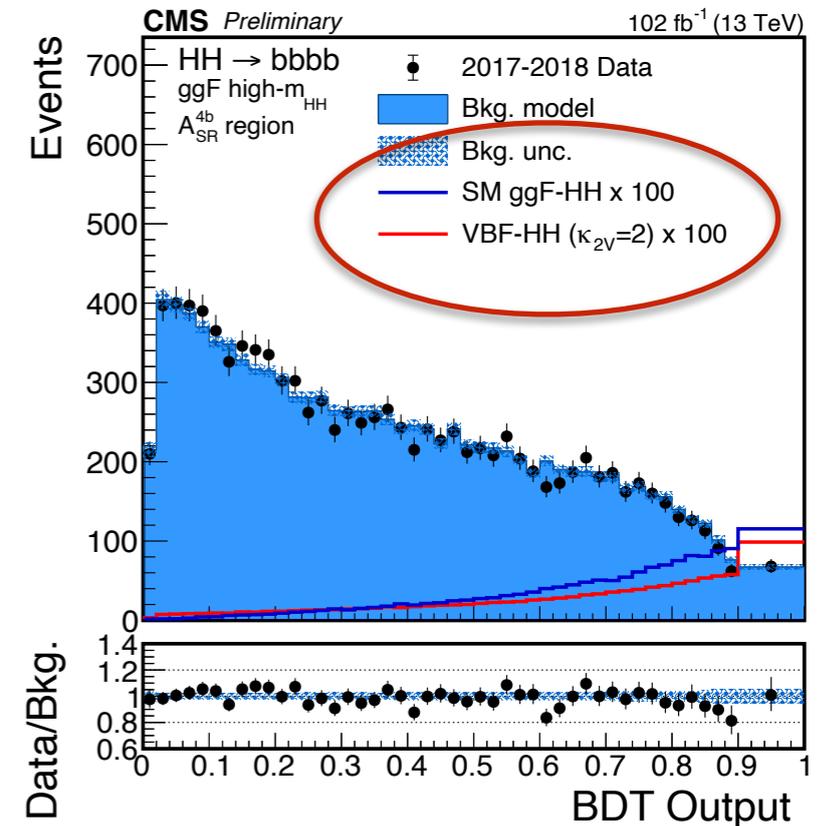
► Understanding Higgs sector requires **measurement** of its **self-interaction**

Standard Model



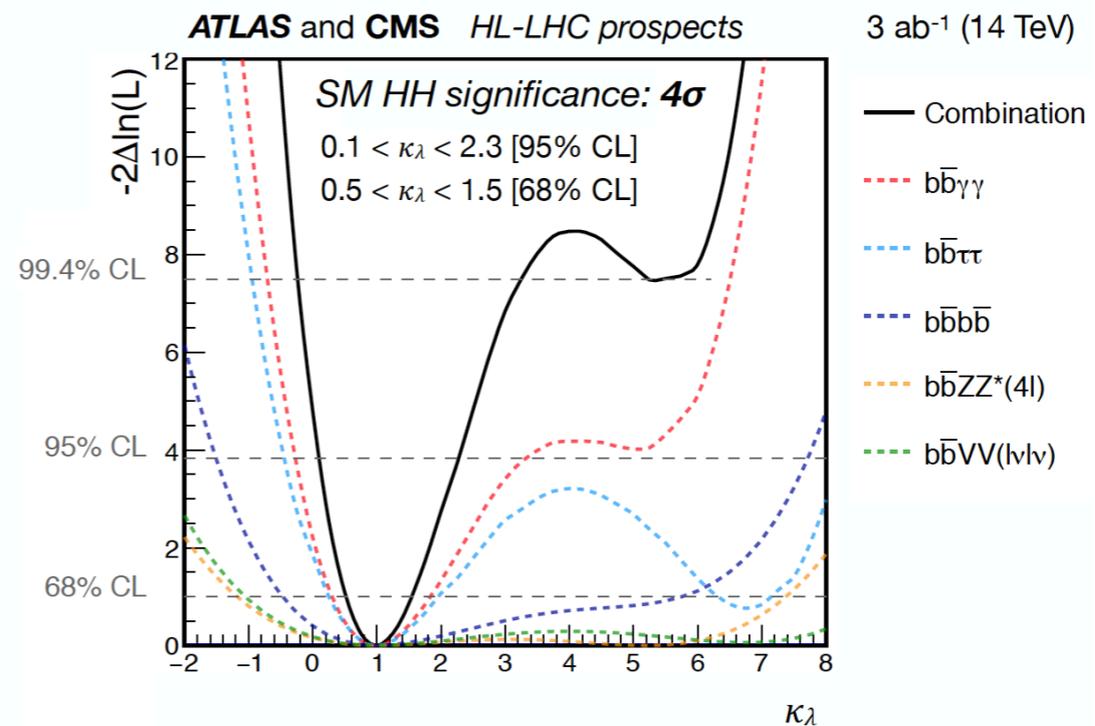
New Physics

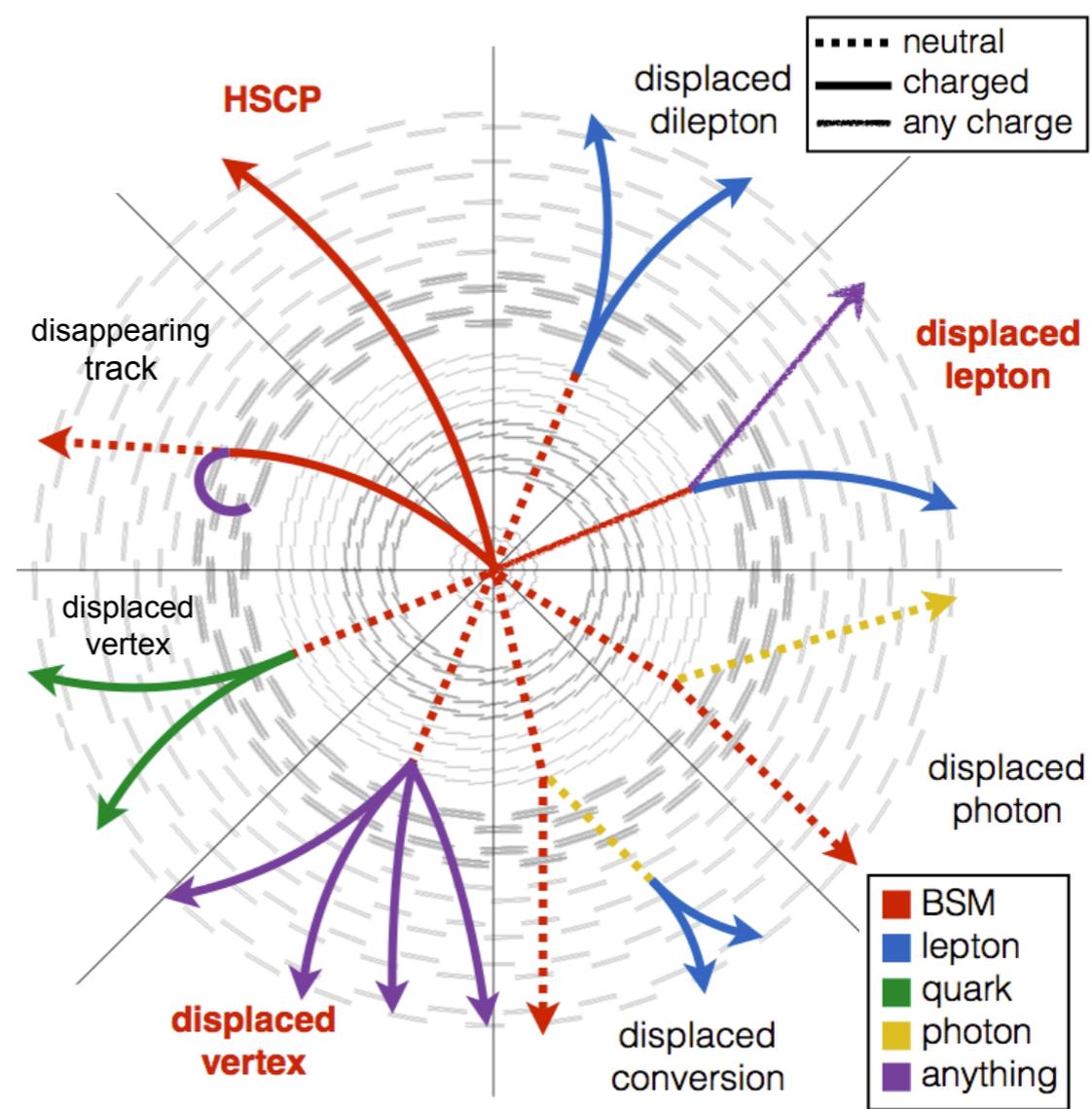
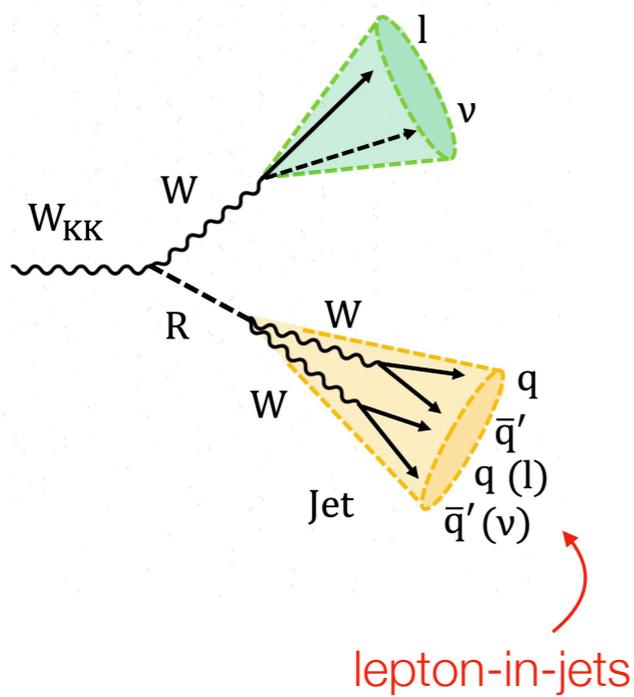
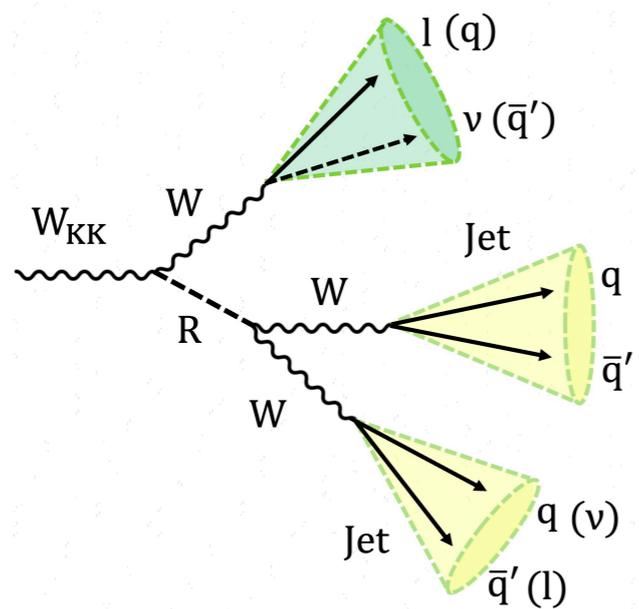
► Updated search in $bbbb$ now excluding $x4$ SM (expected $x7$ SM)



► Cornerstone of Run3 and HL-LHC

- currently limited by statistics
- room for even more sophisticated analysis techniques





Credits: J. Antonelli

Exotic Phenomena

The Higgs or A Higgs?

- ▷ In BSM models with more Higgs bosons, some can resemble *the* Higgs
- ▷ Direct search for additional light and heavy Higgs bosons

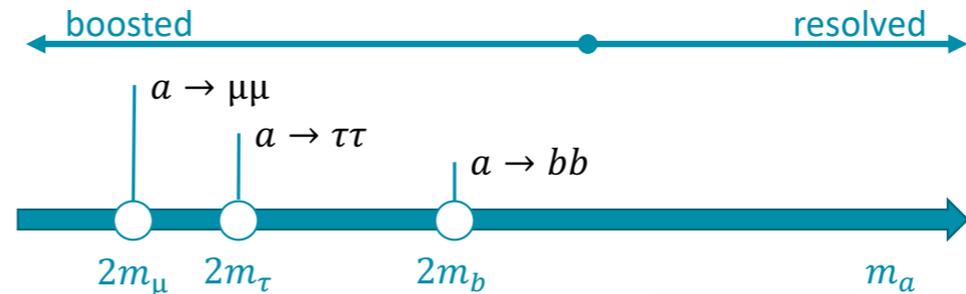
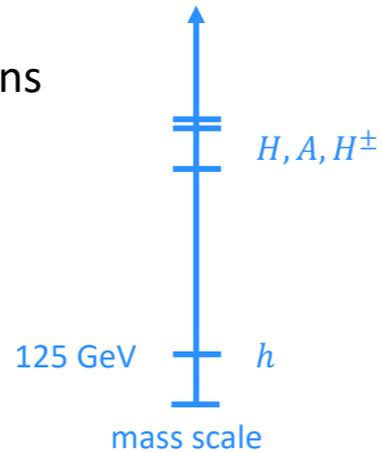
2HDM has 5 Higgs bosons

h : "SM" Higgs

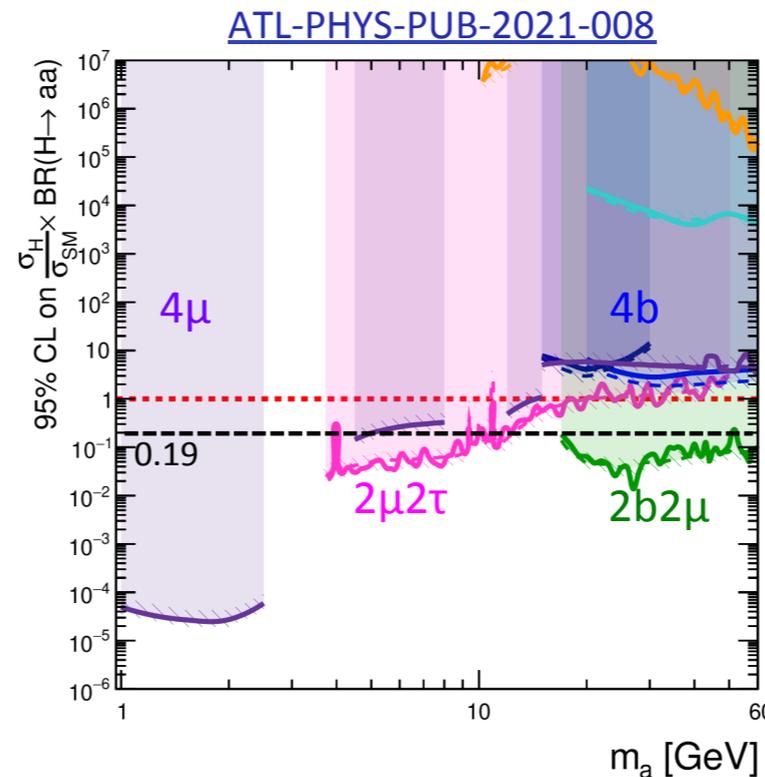
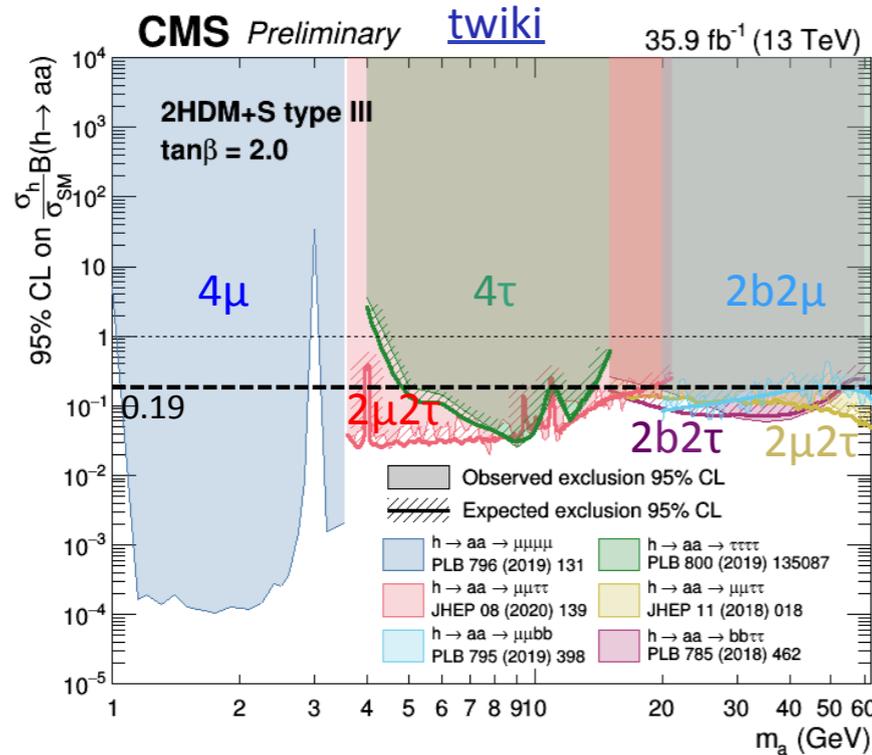
H : heavy Higgs

A : pseudoscalar

H^\pm : charged Higgs



2HDM+S



ATLAS Preliminary

March 2021

Run 1: $\sqrt{s} = 8$ TeV

Run 2: $\sqrt{s} = 13$ TeV

2HDM+S Type-III, $\tan\beta = 2$

--- expected $\pm 1 \sigma$

— observed

Run 1 20.3 fb⁻¹ $H \rightarrow aa \rightarrow \mu\mu\tau\tau$
PRD 92 (2015) 052002

Run 1 20.3 fb⁻¹ $H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$
EPJC 76 (2016) 210

Run 2 36.1 fb⁻¹ $H \rightarrow aa \rightarrow \mu\mu\mu\mu$
JHEP 06 (2018) 166

Run 2 36.1 fb⁻¹ $H \rightarrow aa \rightarrow bbbb$
JHEP 10 (2018) 031

Run 2 36.1 fb⁻¹ $H \rightarrow aa \rightarrow bb\tau\tau$
PRD 102 (2020) 112006

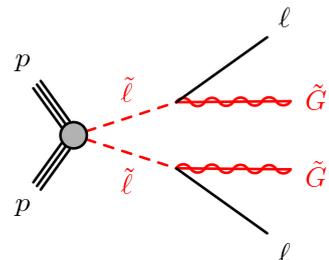
Run 2 36.7 fb⁻¹ $H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$
PLB 782 (2018) 750

Run 2 139 fb⁻¹ $H \rightarrow aa \rightarrow b\mu\mu\mu$
ATLAS-CONF-2021-009

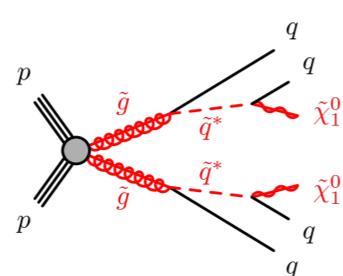
- ▷ So far no excess or evidence and only exclusion in theory parameter space
- ▷ High-Luminosity LHC two provide x20 increase in statistics

Long-Lived Particles

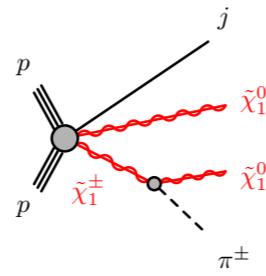
Elodie Resseguie
Lawrence Lee



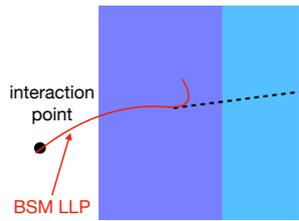
small coupling
e.g. coupling to gravitino



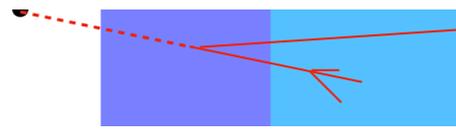
off-shell decays
e.g. squark mass > 10 TeV



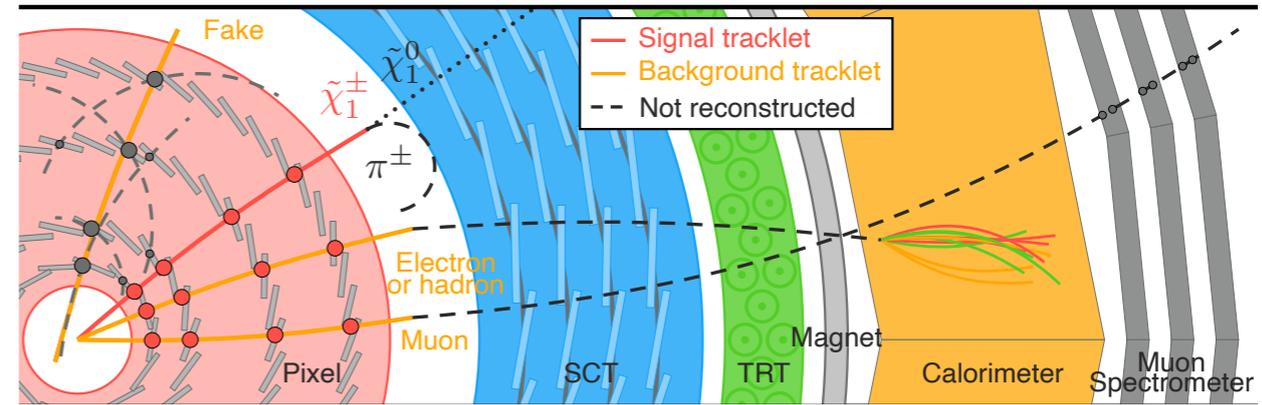
phase space
e.g. small mass splitting



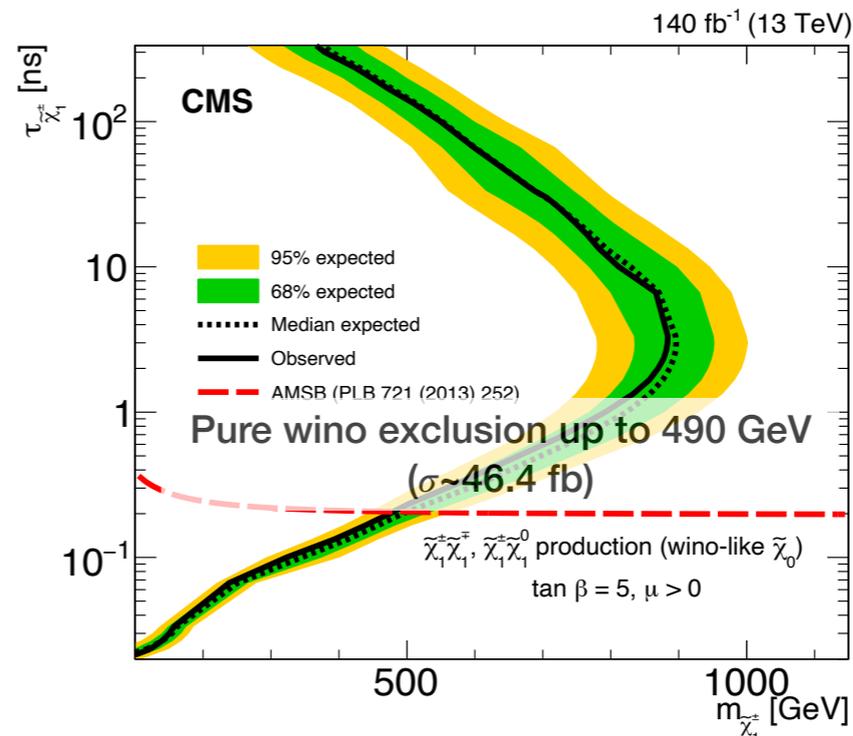
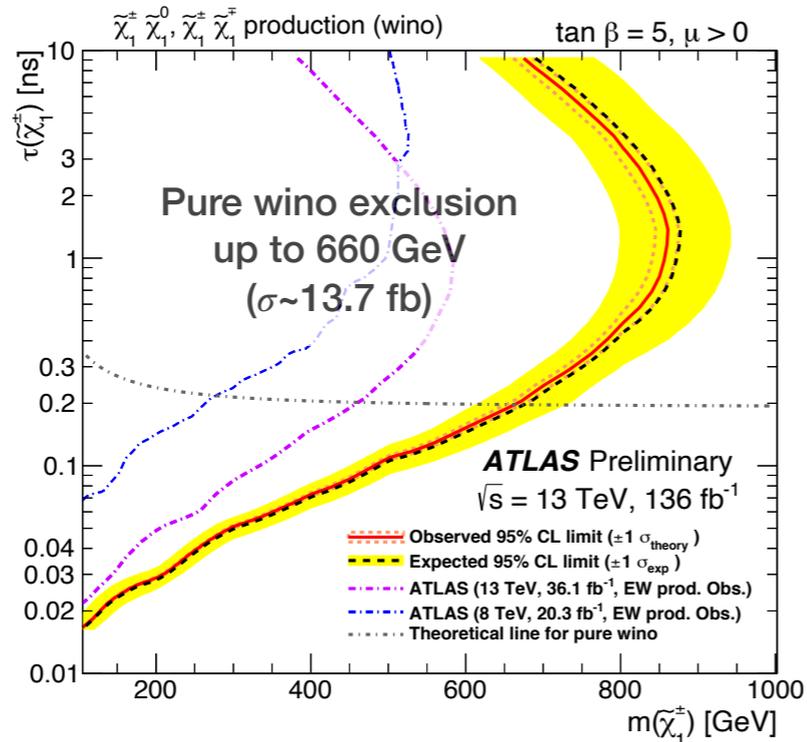
direct LLP detection
observable track



indirect LLP detection
observe decay products



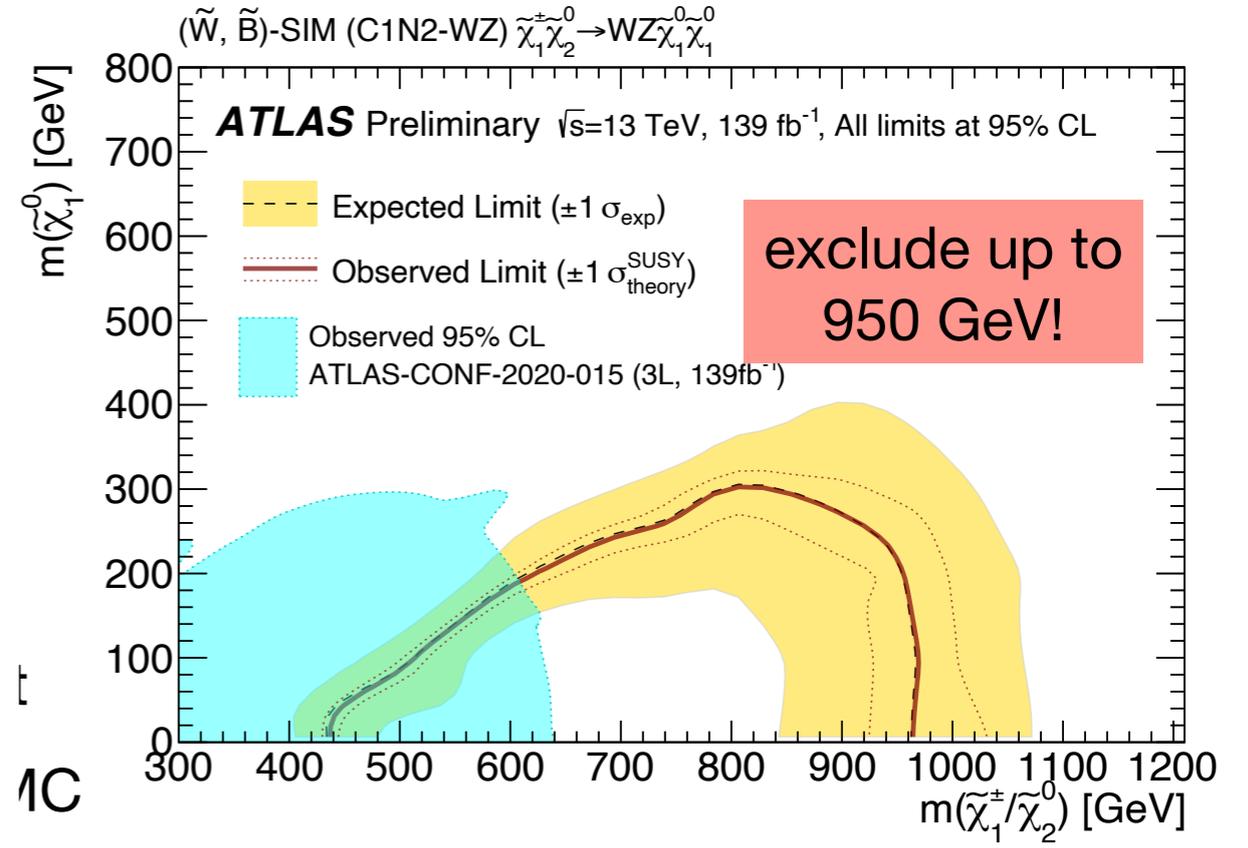
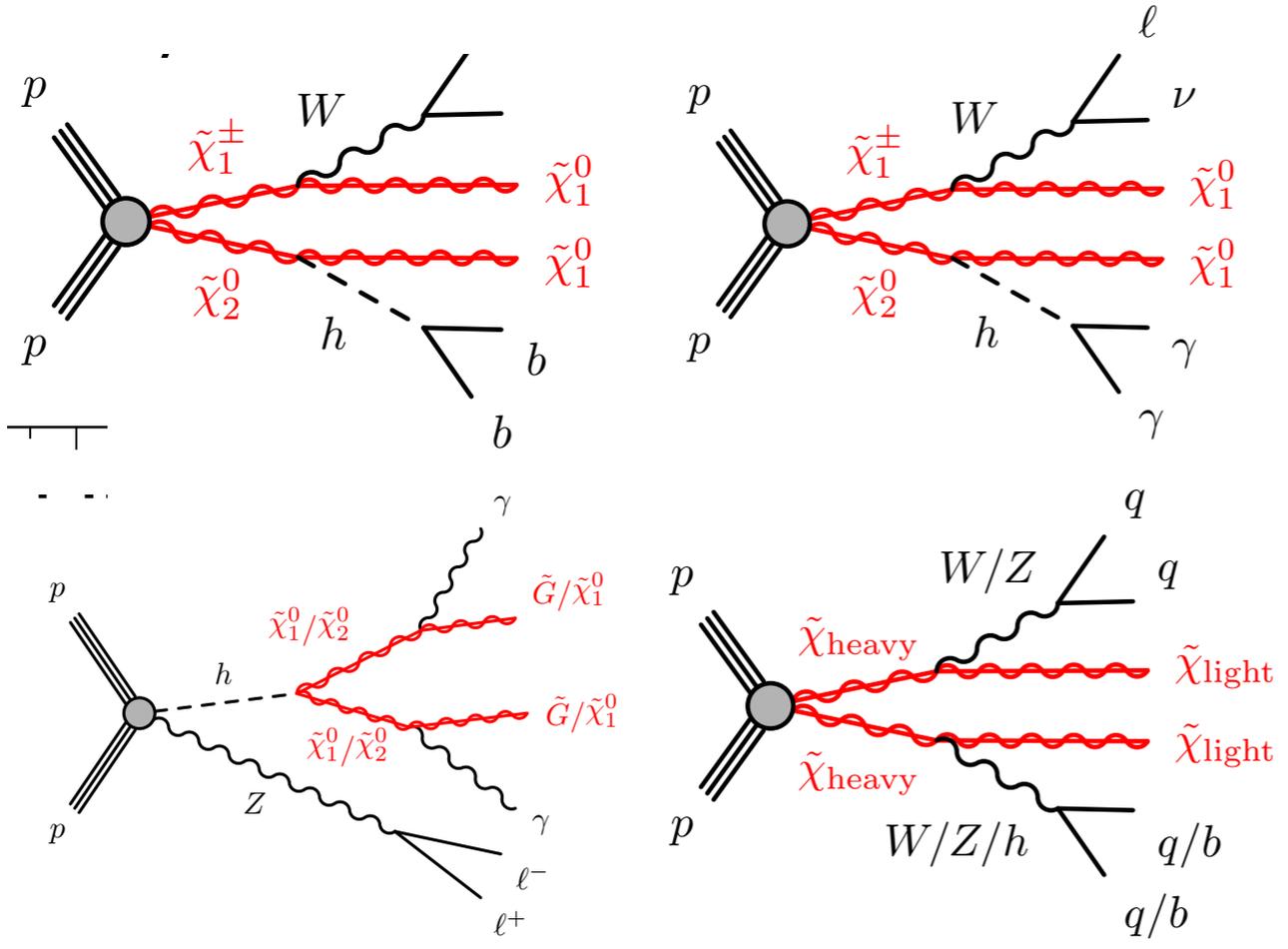
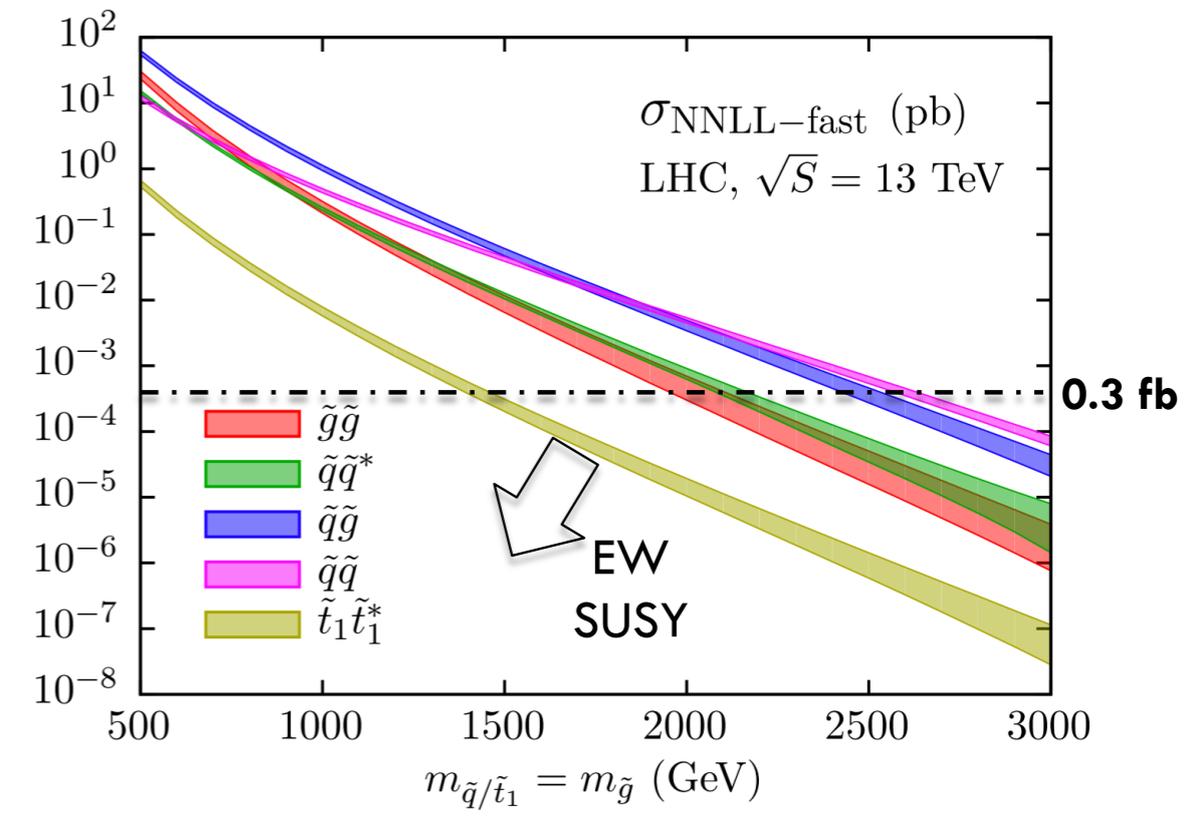
▷ Tracks only in inner tracker and possible calorimetric veto



Supersymmetry

Elodie Resseguie

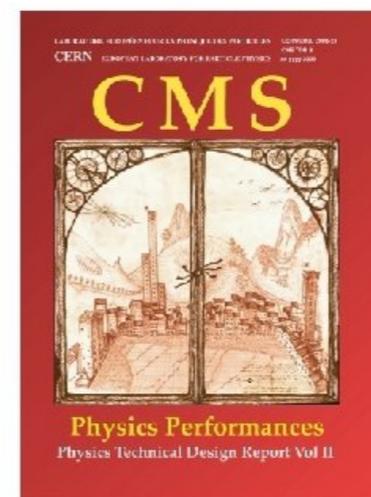
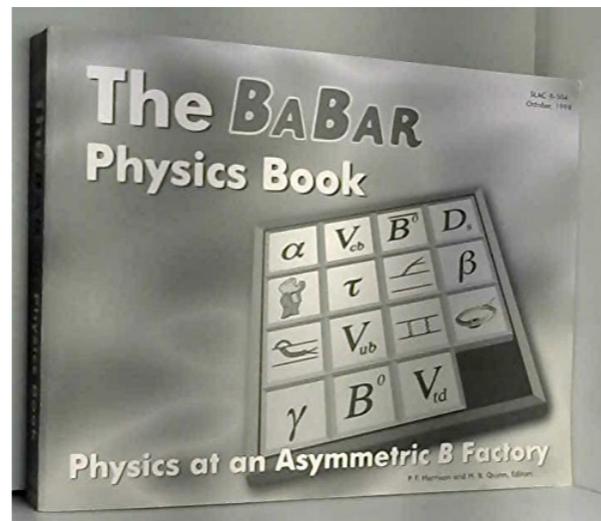
- ▶ Many new searches targeting both strong and electroweak production
 - No significant excess observed so far
- ▶ Strong SUSY searches targeting masses ~ 2 TeV
- ▶ Searches now using also $H \rightarrow \gamma\gamma$ and exotic Higgs decays in electroweak production



Advanced b-tagging and jet sub-structure

Machine-Assisted Intelligence

- ▷ Machine-Learning methods percolating not-only data analysis at fast rate
- ▷ Several processes already accessible in Run 2 thanks to advance techniques
 - flavor tagging for both b and c with deep learning
 - Boosted Decision Trees a crucial ingredient in top, Higgs, and electroweak sector
 - Significant impact also in direct searches
- ▷ Highest pay-off for deployment at low level to better understand detector response and particle or event identification
 - Upgraded detectors to rely on ML for low-level reconstruction
- ▷ Appropriate use of these tools and our experience with Run2 lay the foundations for improved sensitivity in Run 3 and HL-LHC
- ▷ Past experience tells us we always do better than $1/\sqrt{\mathcal{L}}$ in our projections
 - just pick any physics book from LHC or B factories

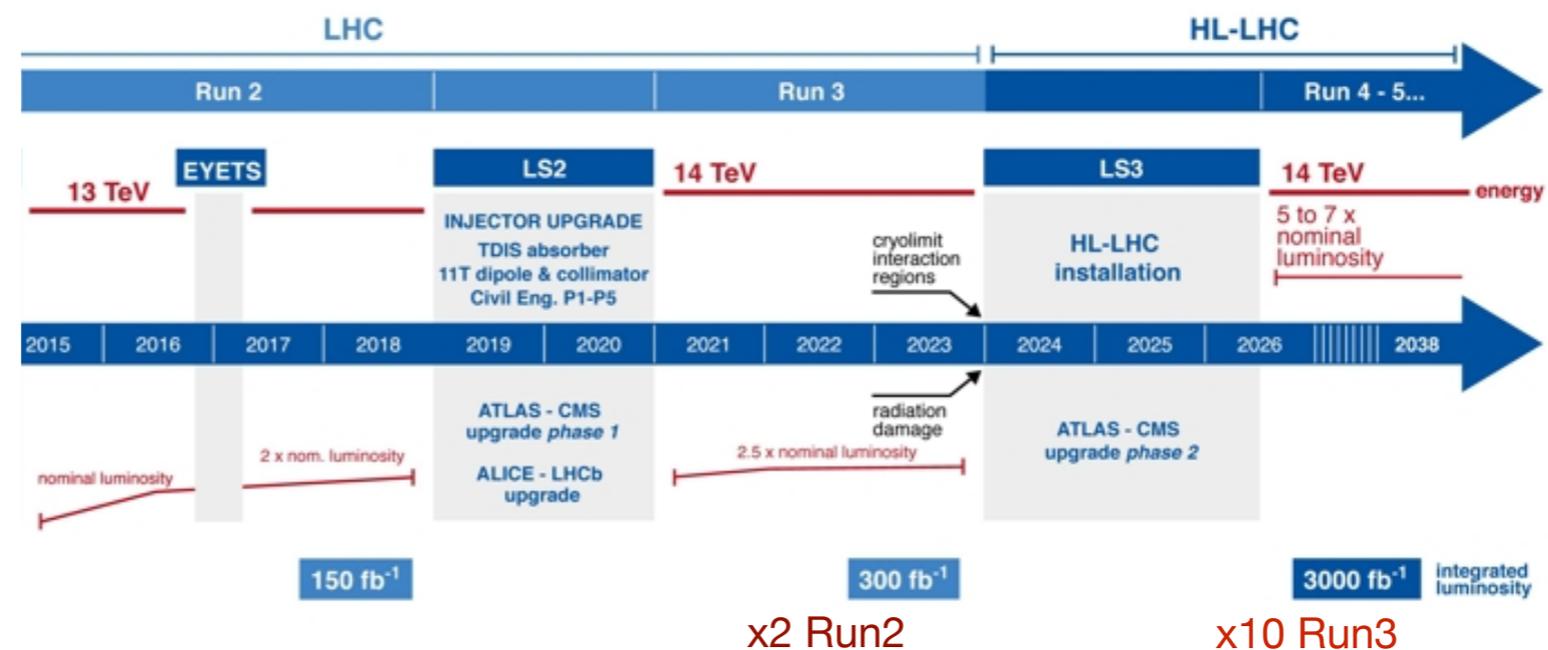


Outlook



- ▷ Standard Model continues to stand strong in **this Universe**
- ▷ Flavor anomaly still there and to be pursued at low and high mass
 - Redundant measurements and revamped interest for Z' and LQ
- ▷ Higgs coupling to 2nd generation fermion ahead of schedule
 - Take a look at physics TDRs released 15 years ago
- ▷ Top, W, Z, Higgs entering **precision era in pp** and constraining new physics
 - Maximise impact through concerted effort with EFT approach to SM
- ▷ Expected increase in ion-ion collisions Run 3 to allow differential studies
 - order of magnitude increase in statistics in addition to powerful ML techniques
- ▷ Human ingenuity assisted by Artificial Intelligence is putting us *further* ahead of statistics-only pace

Nice overview by
Sergo Jindariani



LHC in 2021

▷ Life during Run 1 of LHC



▷ In Run 2/3 day-to-day life can be challenging

- harvesting copious data
- upgrading magnificent detectors
- produce copious high quality results



▷ Do not forget the 30'000 feet view

- 90% of data yet to be delivered and collected
- room for novel ideas and techniques

