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

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

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

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

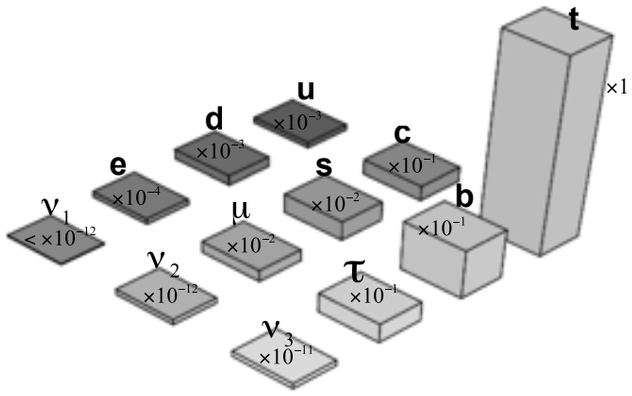
- Has successfully resisted 50 years of falsification

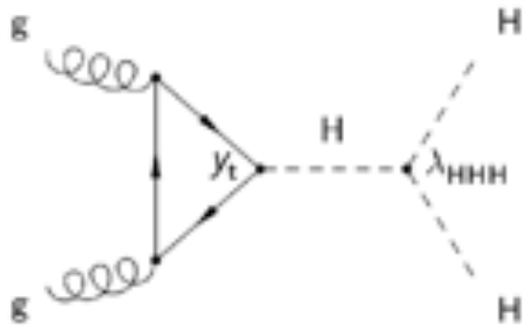
- *We already know it is incomplete*
  - Neutrinos are massive

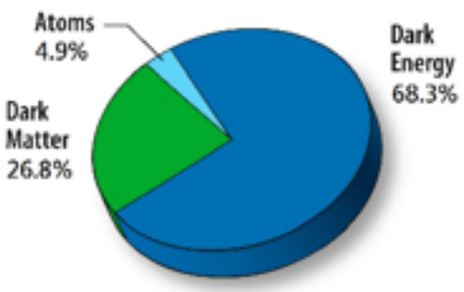
- It cannot address some basic curiosities and questions about *our* Universe

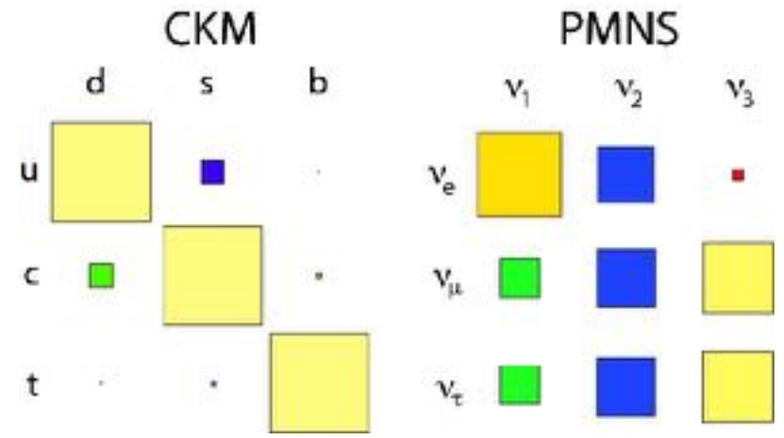
Questions and Curiosities

- 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

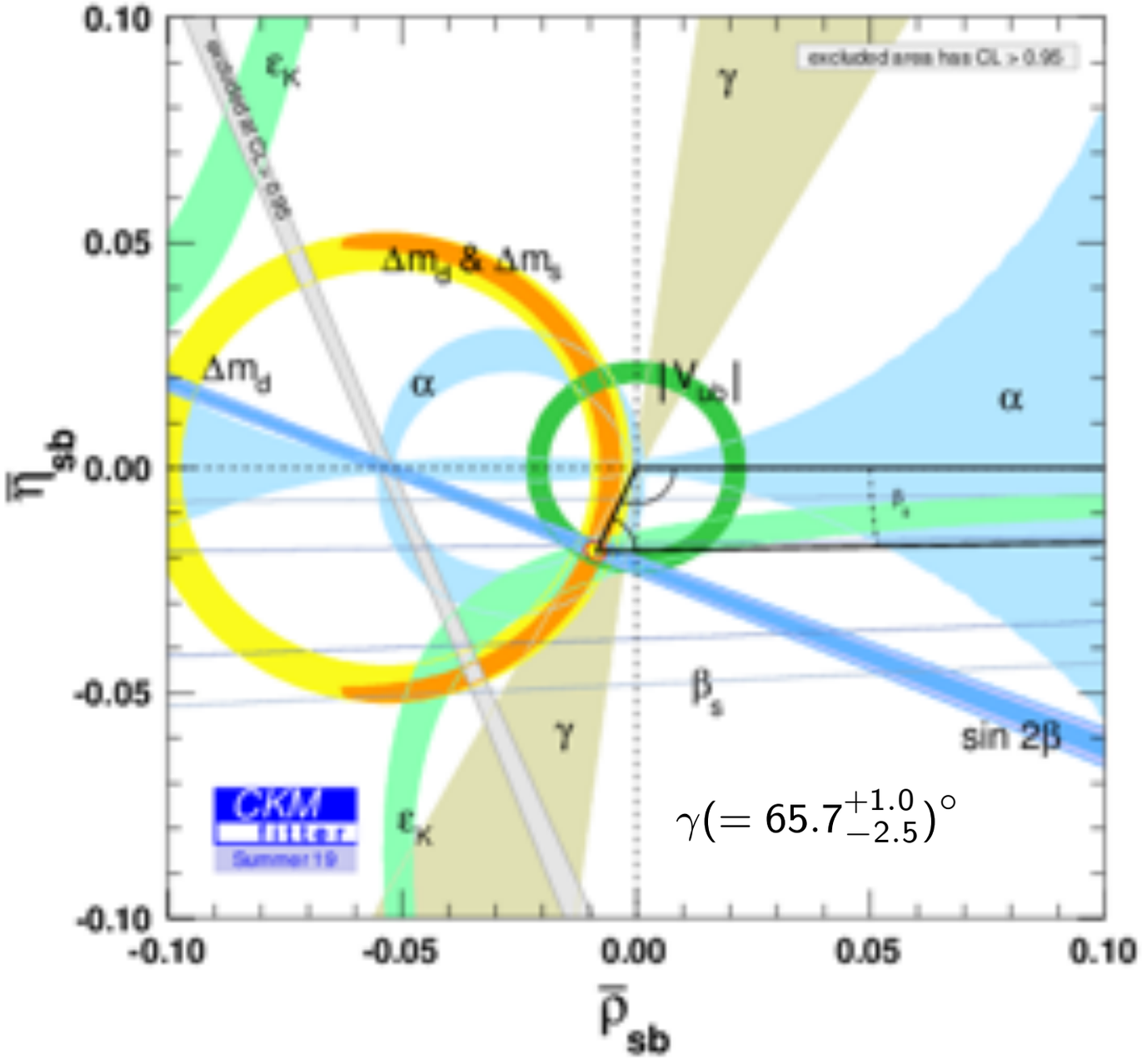
- Measurement of very small and precise predictions
  - variety of such observables across the spectrum
  - typically referred to as indirect search for New Physics
  - At LHC now merging with standard Physics thanks to amount of data

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

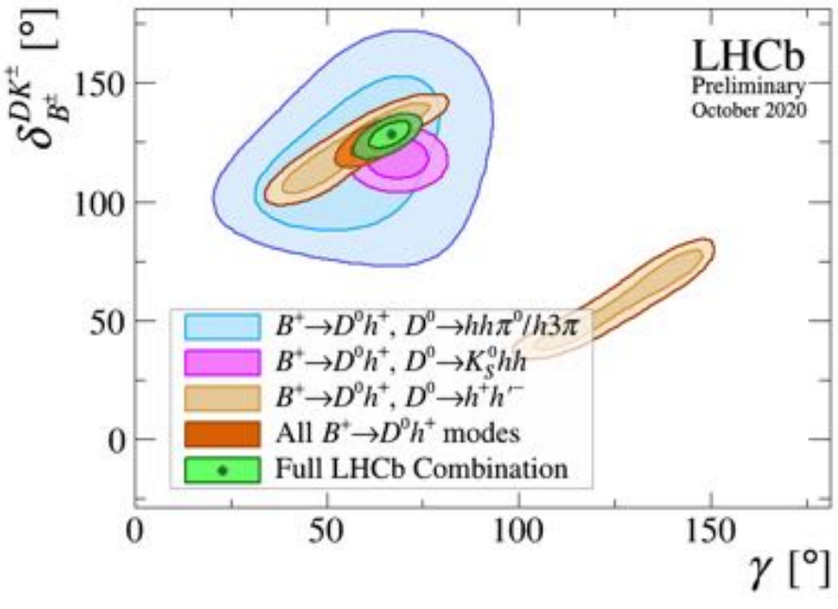
- New computational tools for more efficient data mining and increasing sensitivity
- New technologies to improve detection techniques and try new avenues



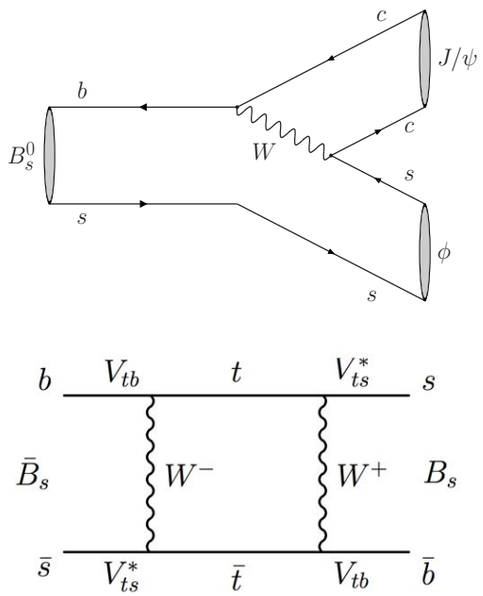
$$V_{\mathrm{CKM}} \sim \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & |V_{\mathrm{ub}}|, \gamma \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & |V_{\mathrm{cb}}| \\ \Delta m_d, \beta & \Delta m_s, \beta_s & |V_{\mathrm{tb}}| \end{pmatrix}$$

CP Violation

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



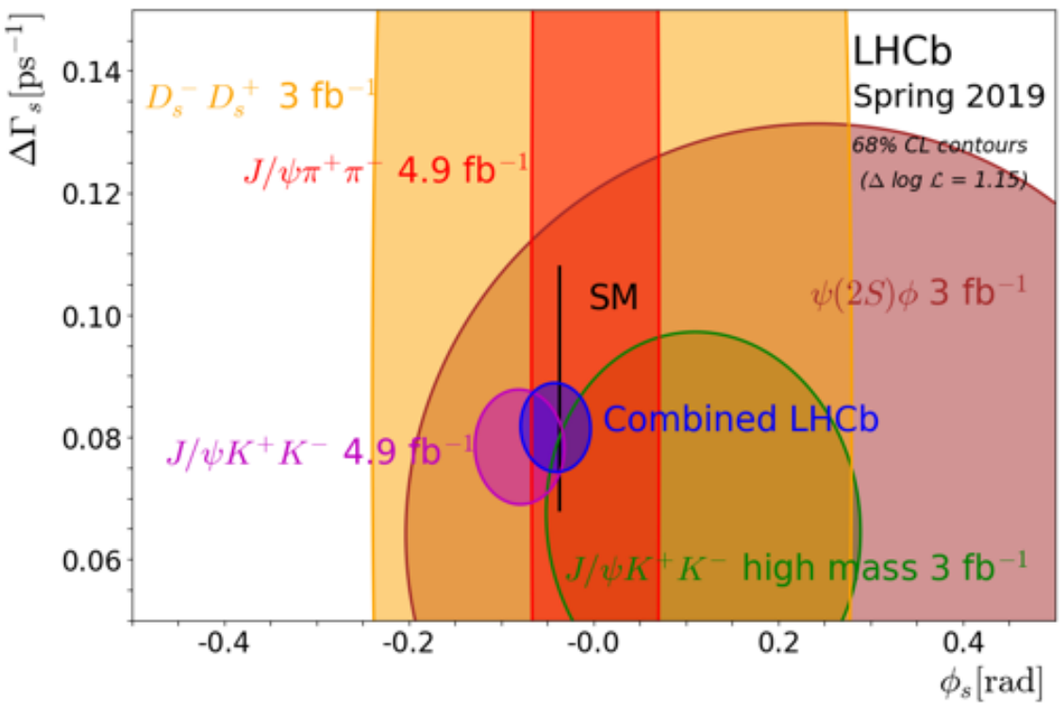
Φ_s and $B_s^0 \to J/\Psi\,\phi$



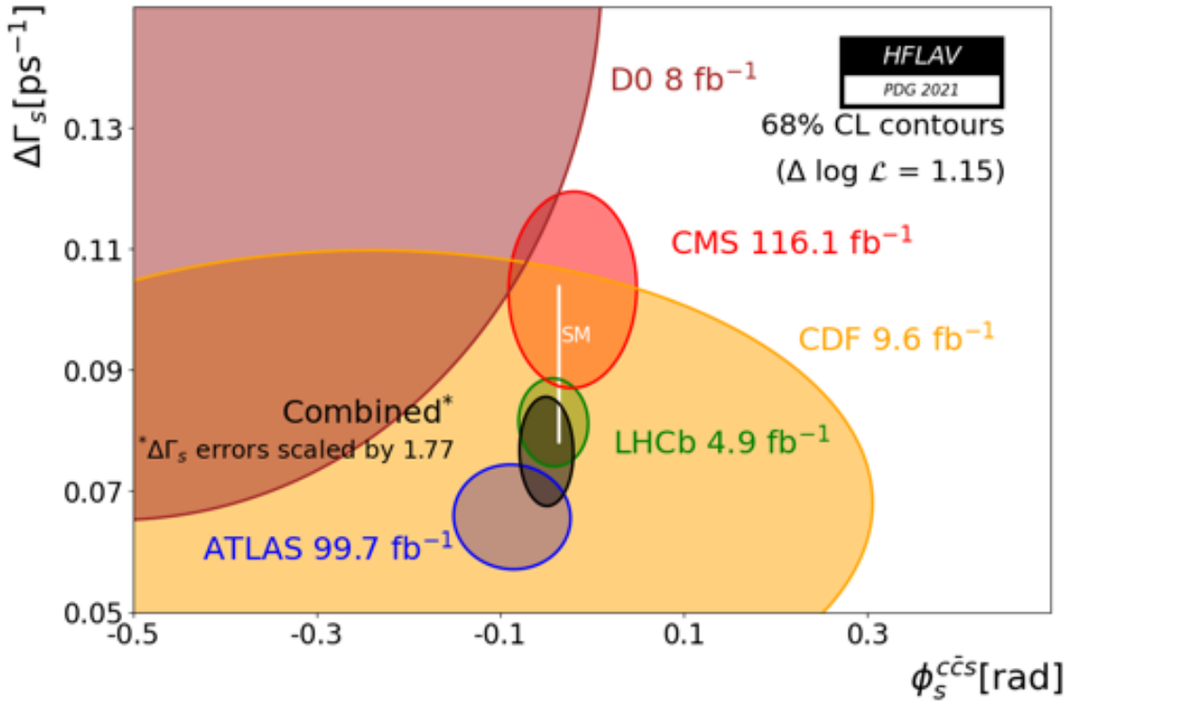
- Golden mode for Bs
  - clean experimental signature and theoretical prediction

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

- Different trigger strategies for ATLAS and CMS
  - uncertainties competitive with LHCb
- LHCb provides measurement with several channels



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

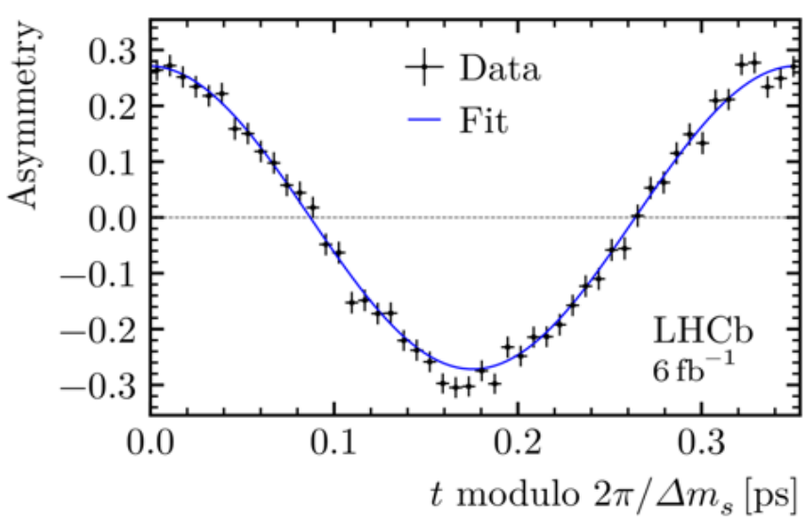


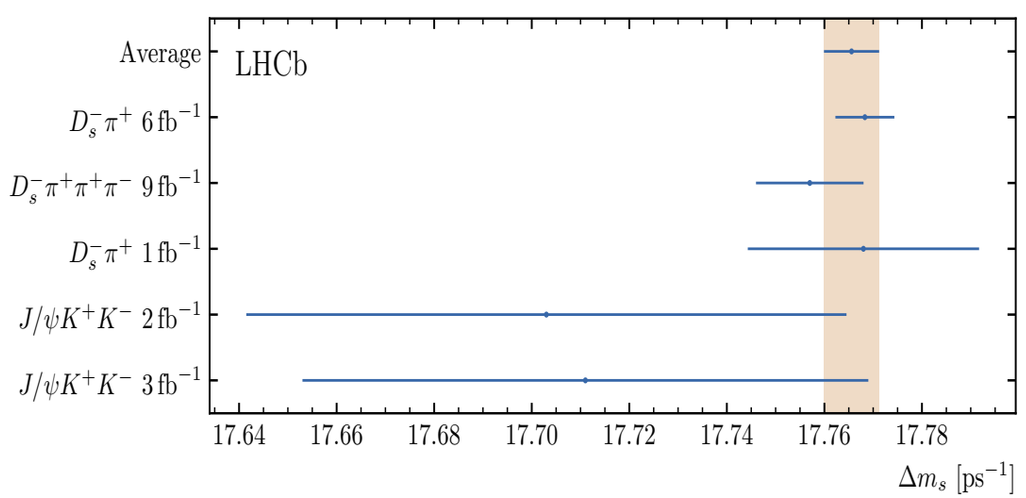
Basem Khanji

B_s^0 oscillation and time-dependent CPV

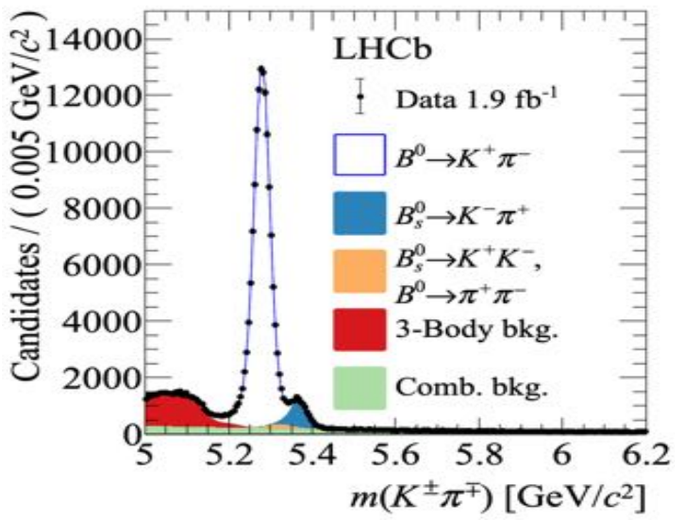
▻ Most precise measurement oscillation frequency in $\mathrm{B_s^0 \to D_s^- \pi^+}$

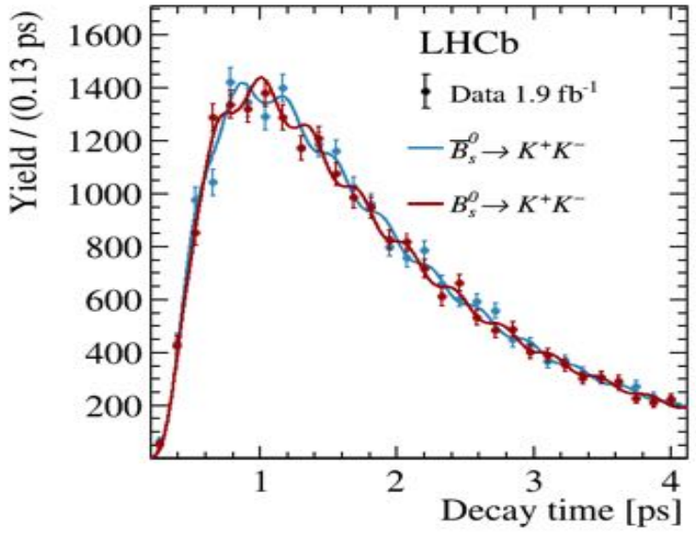
$$\Delta m_s = 17.7656 \pm 0.0057\,\mathrm{ps}^{-1}$$

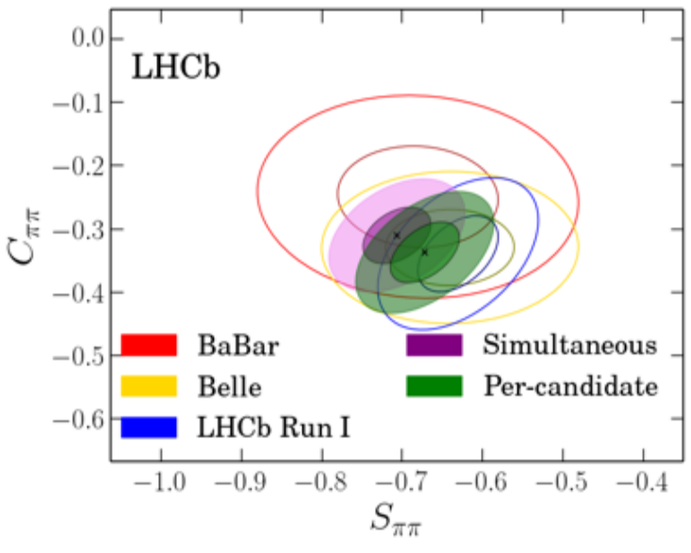




▻ First observation of time-dependent CP violation in $B^0_{s,d} \to h^+h^-$



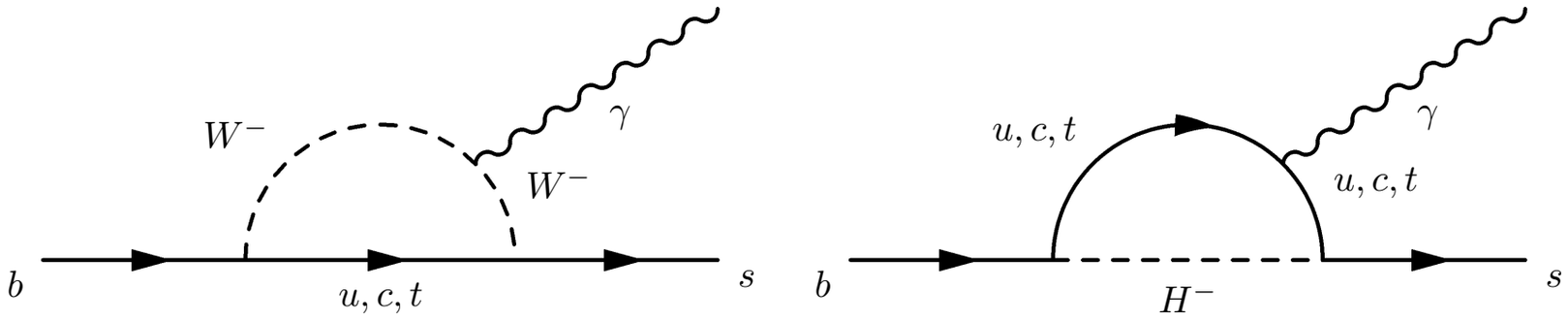




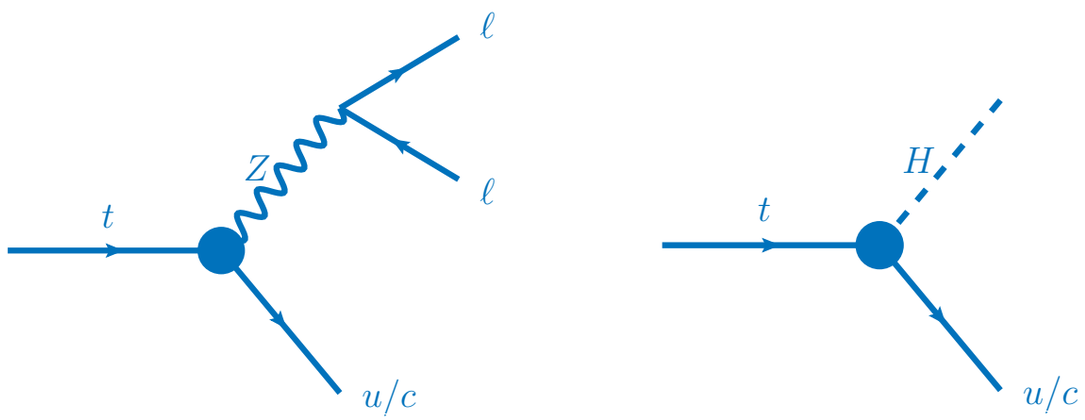
$S_{\pi\pi} = -0.706 \pm 0.042 \pm 0.013,\ S_{KK} = +0.123 \pm 0.034 \pm 0.015$

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

Flavor **C**hanging **N**eutral **C**urrents



- Forbidden in Standard Model at tree level
- Typically small predicated 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

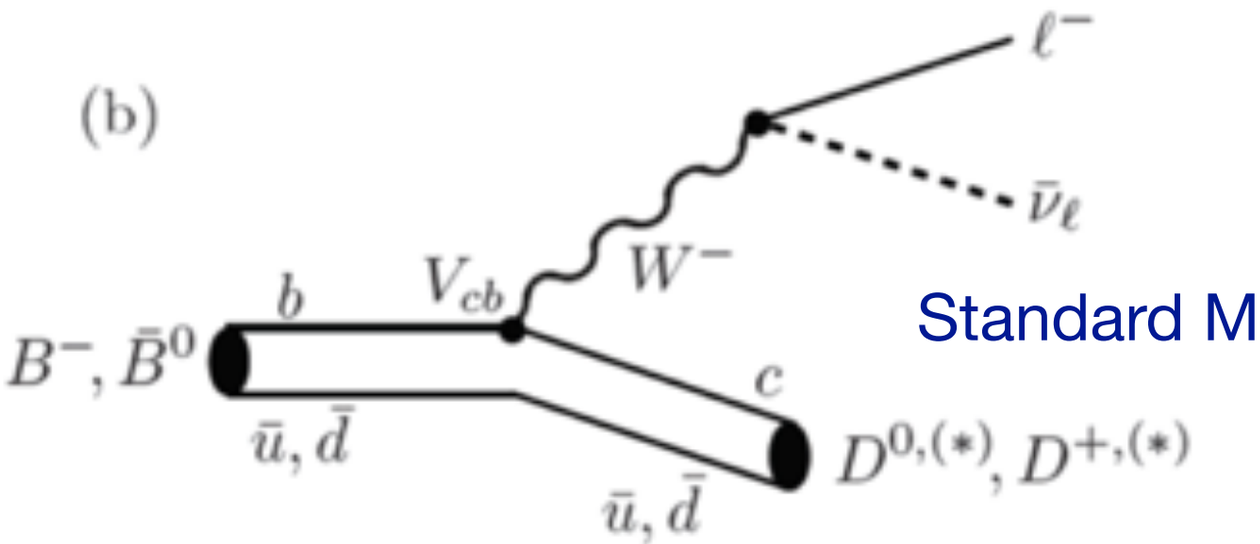
$\mathrm{BR}(t \to qH) \sim 10^{-15}$

$\mathrm{BR}(t \to qZ) \sim 10^{-14}$

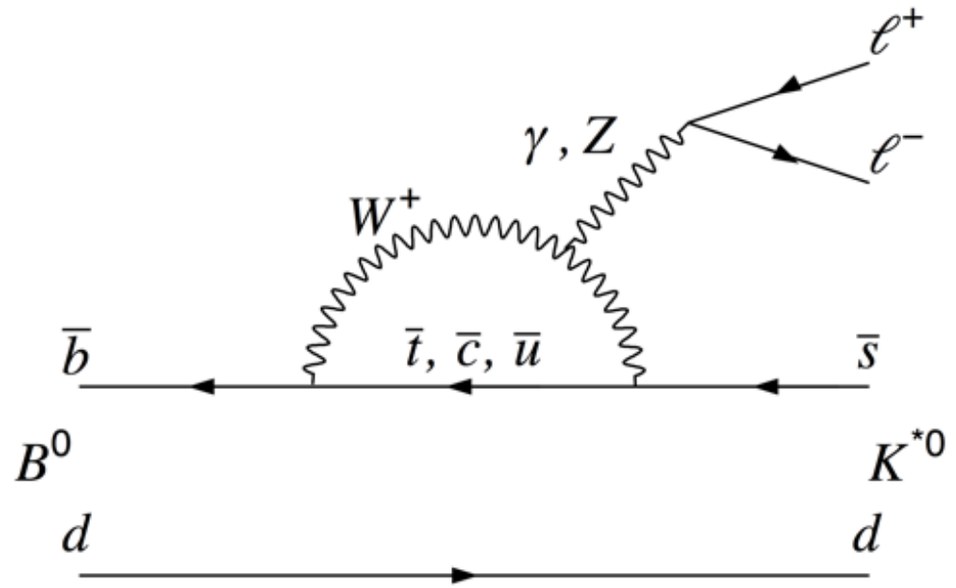
New CMS-PAS-TOP-20-007

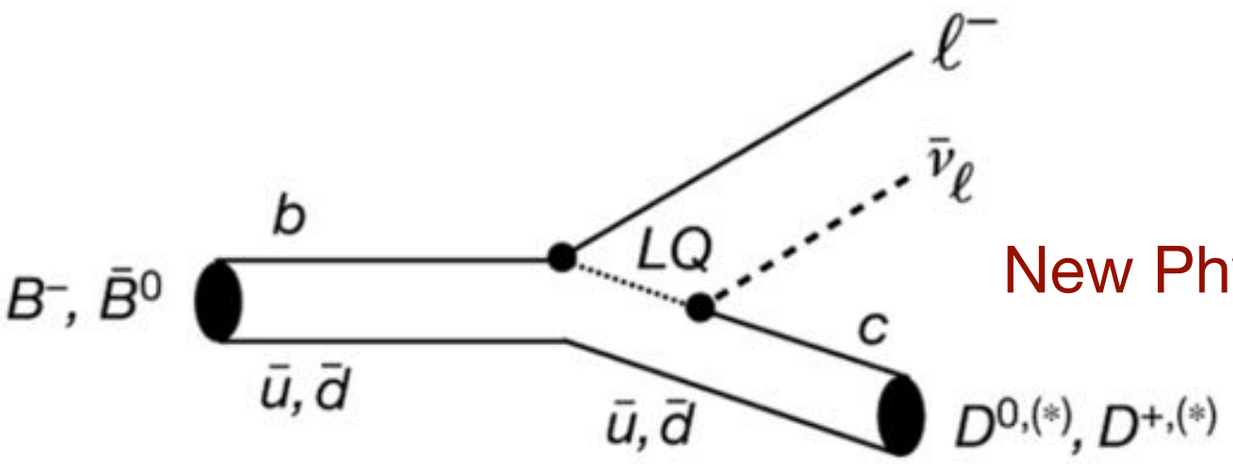
$\mathrm{B}(t \to Hu) < 1.9 \times 10^{-4}$

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

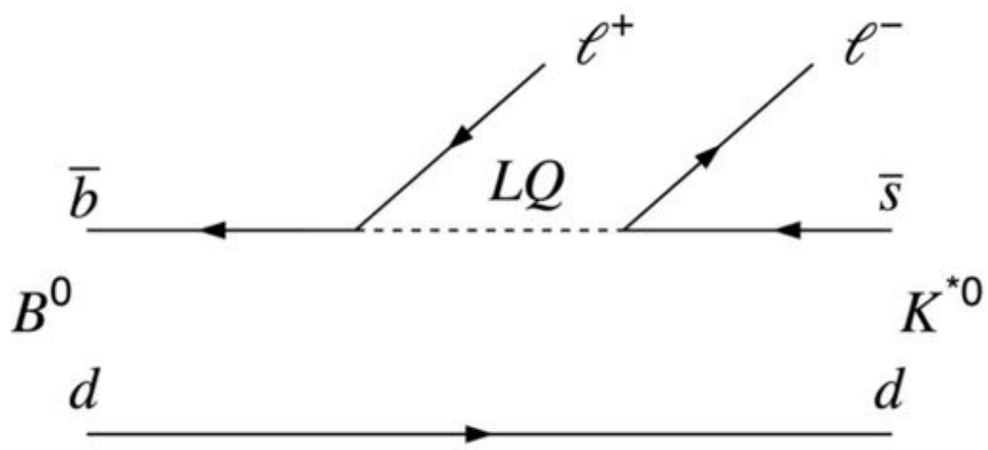


Standard Model



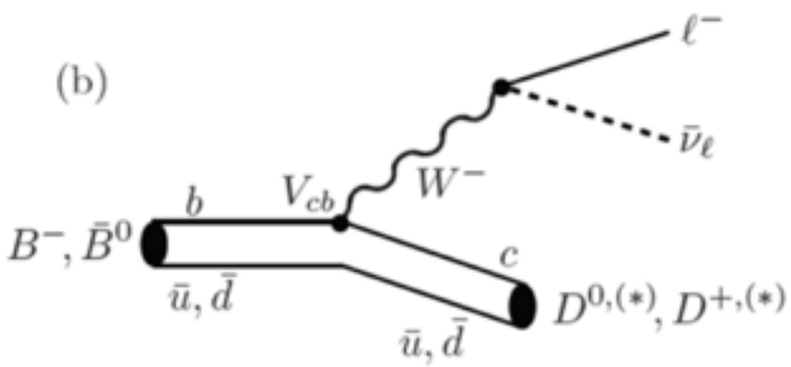


New Physics

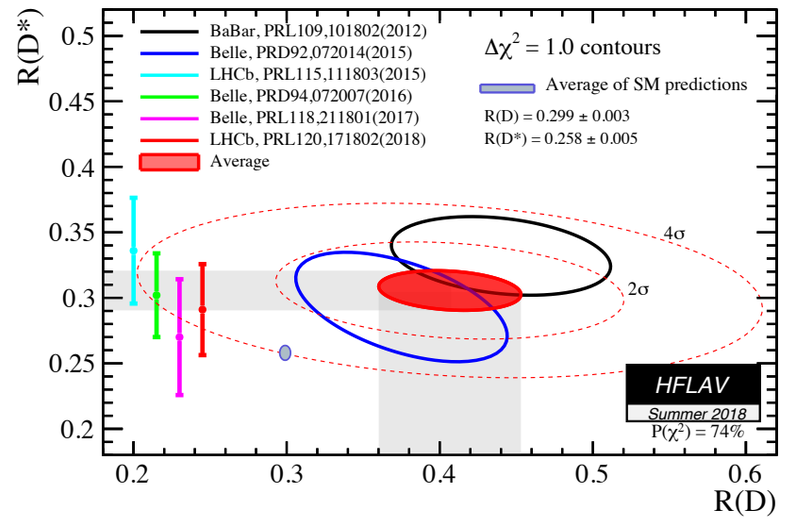


Lepton Flavor Universality

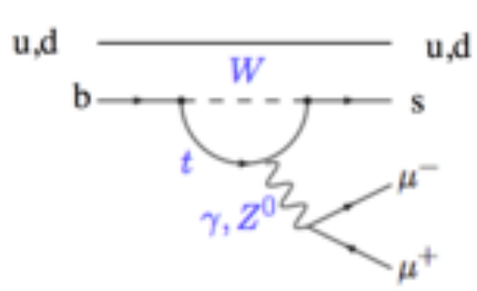
Long Standing Anomalies



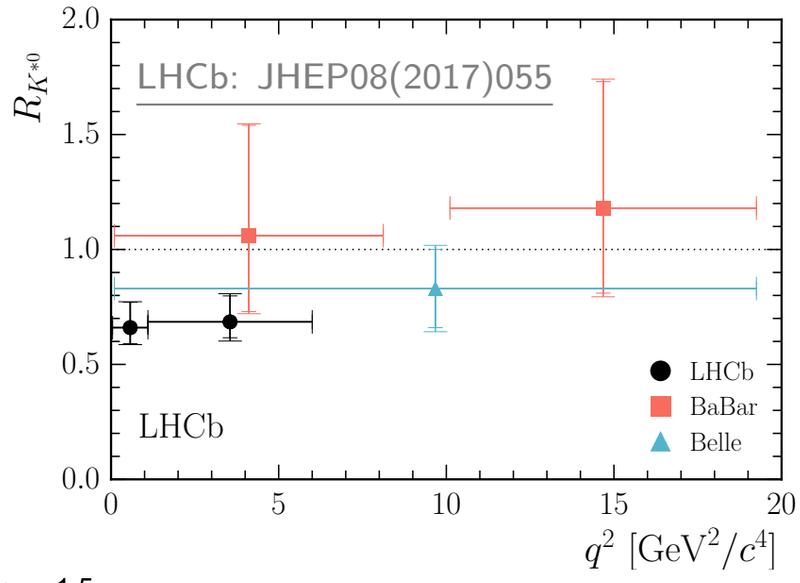
$$R(D^*) = \frac{BF(B \to D^* \tau \nu)}{BF(B \to D^* \mu \nu)}$$



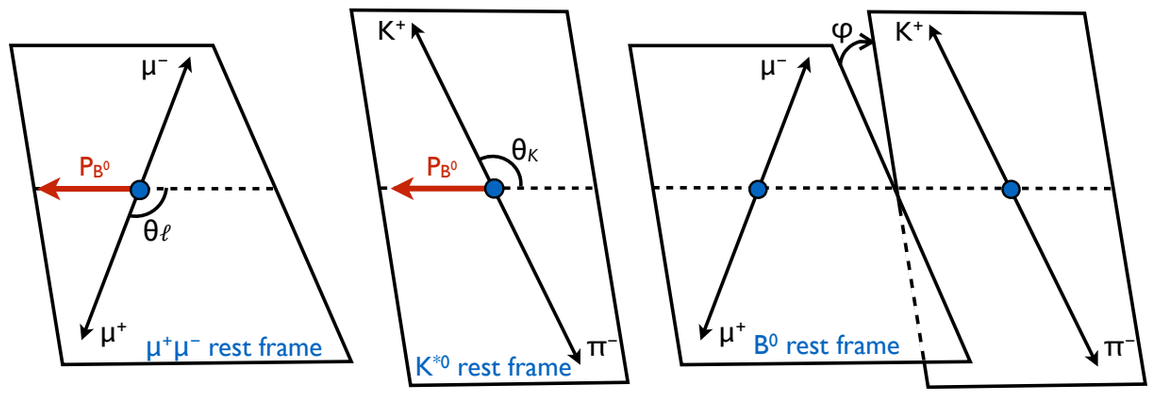
muons / electrons [b → s]

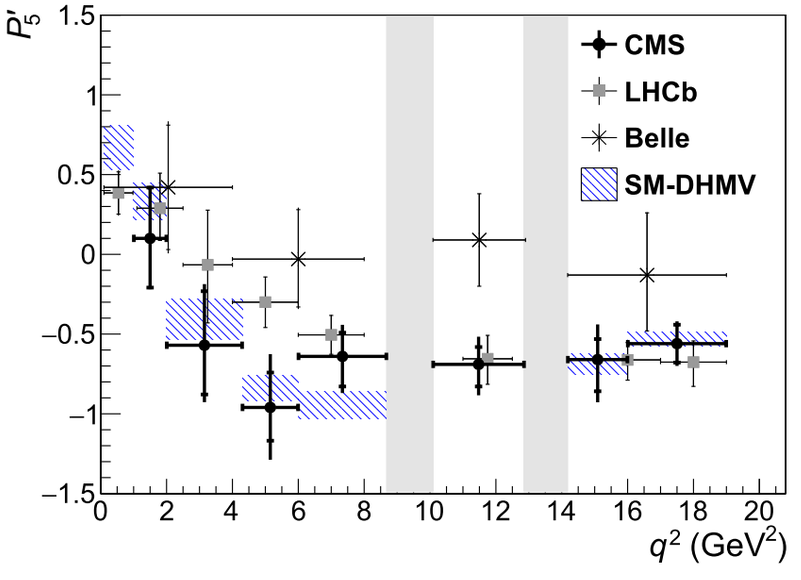


$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$



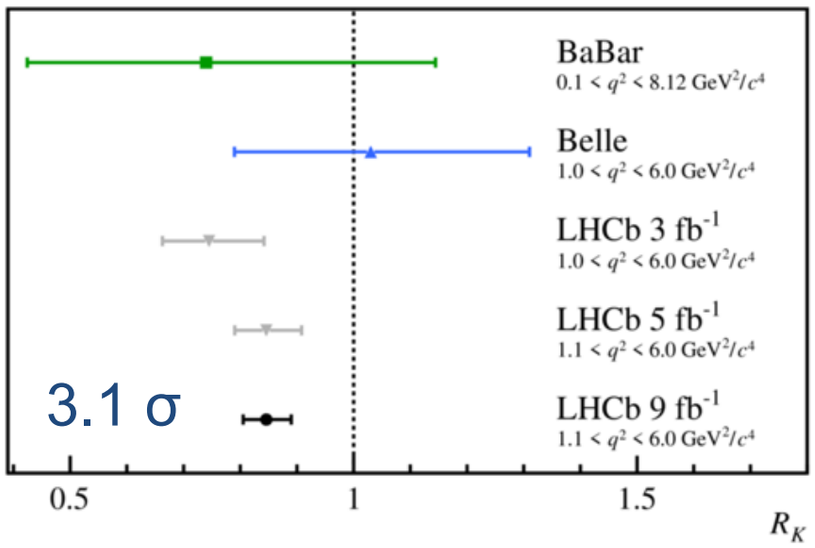
$$\tilde{B^0} \to K^{*0}(K^+\pi^-)\mu^+\mu^-$$





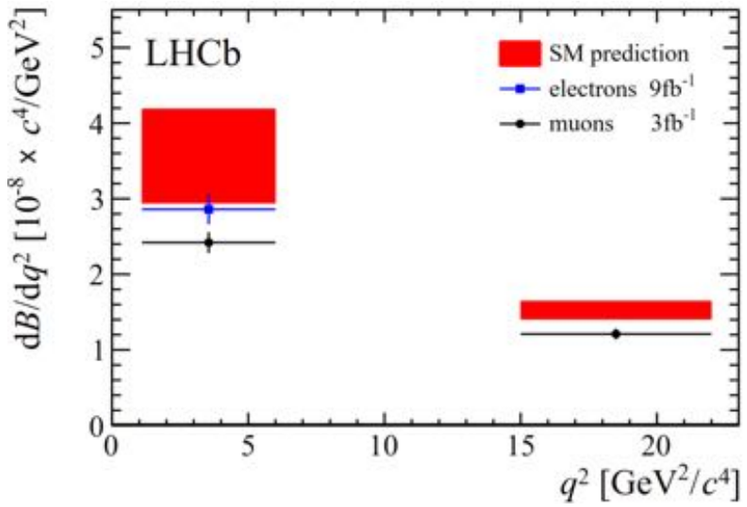
Anomaly stands still

Yanting Fan

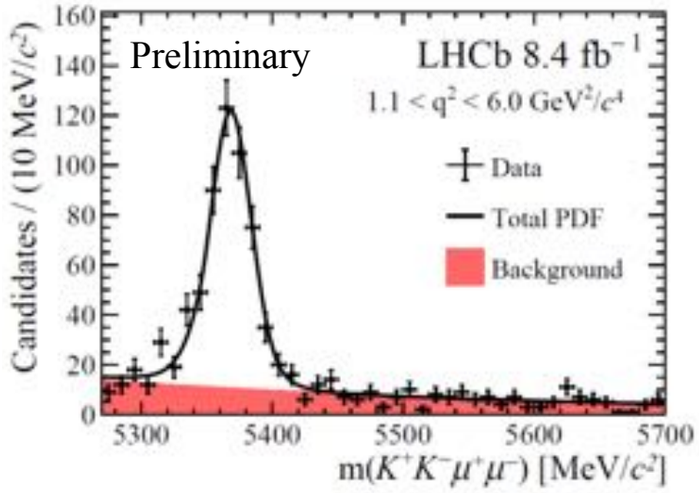


$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \Big/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))}$$
$$= \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))} \cdot \frac{N(K^+J/\psi(ee))}{N(K^+ee)} \cdot \frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$

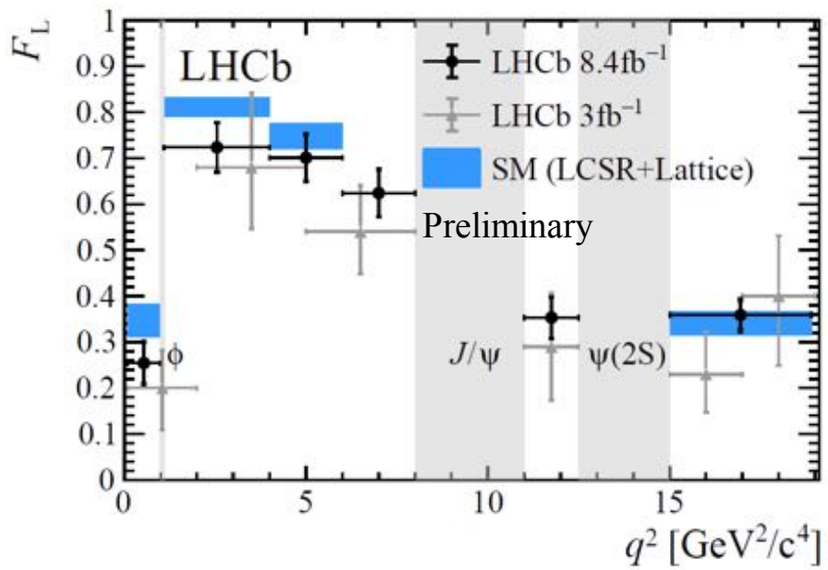
$$R_K = 0.846^{+0.044}_{-0.041}$$



- New angular analysis in $B_s^0 \to \phi\mu^+\mu^-$
  - Discrepancy wrt predictions similar to $K^{*0}\mu^+\mu^-$
  - CP Asymmetries and averages compatible with SM

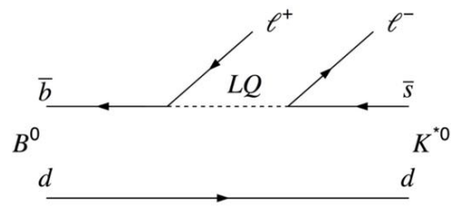


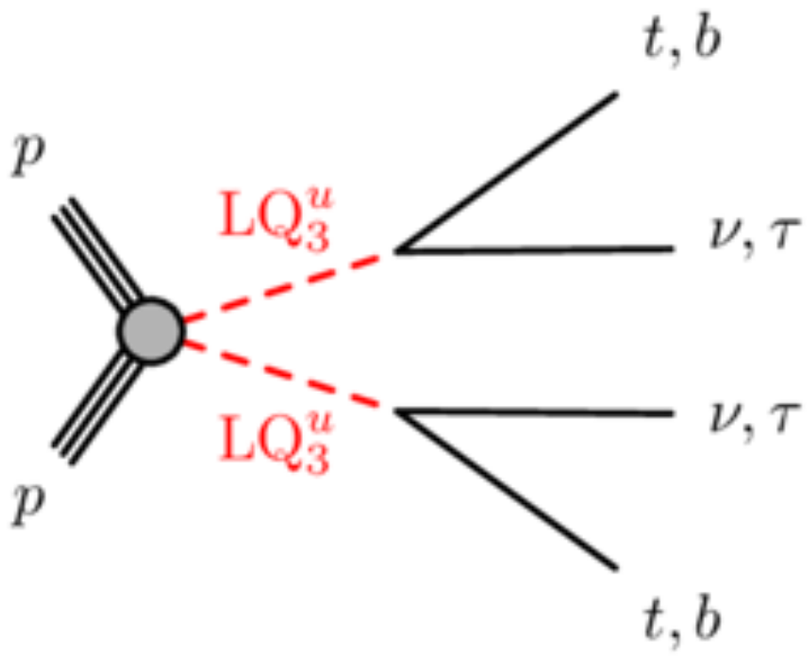
$$\frac{1}{\mathrm{d}(\Gamma+\overline{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^3(\Gamma+\overline{\Gamma})}{\mathrm{d}\cos\theta_l\, \mathrm{d}\cos\theta_K\, \mathrm{d}\phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K(1+\tfrac{1}{3}\cos 2\theta_l)$$
$$+ F_{\mathrm{L}}\cos^2\theta_K(1-\cos 2\theta_l)$$
$$+ S_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos\phi$$
$$+ A_5 \sin 2\theta_K \sin\theta_l \cos\phi + \tfrac{4}{3} A_{\mathrm{FB}}^{CP} \sin^2\theta_K \cos\theta_l$$
$$+ S_7 \sin 2\theta_K \sin\theta_l \sin\phi + A_8 \sin 2\theta_K \sin 2\theta_l \sin\phi$$
$$+ A_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big]$$

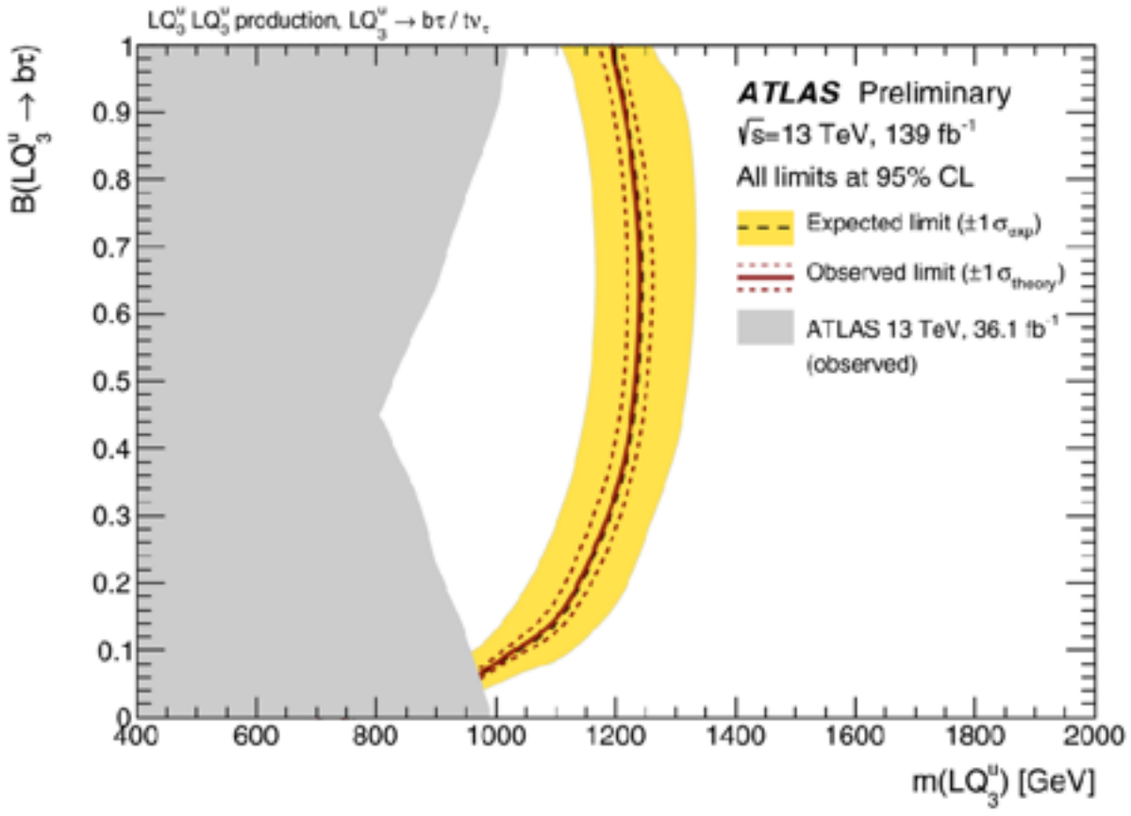


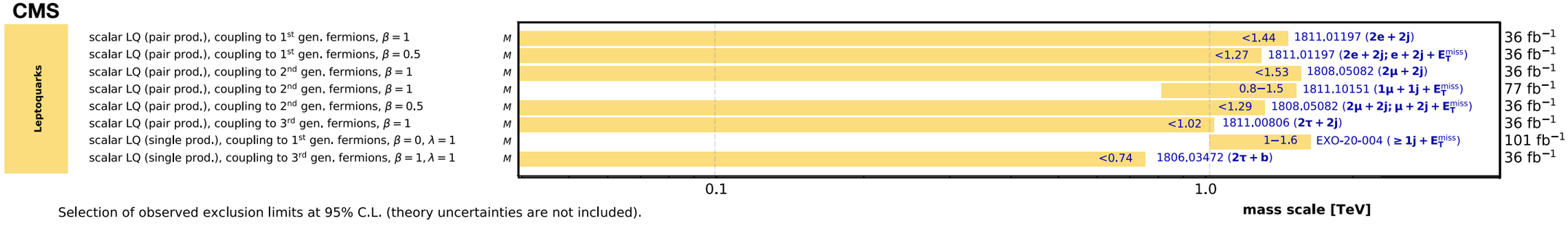
Tackling Anomalies at High Mass

- Tree-level explanation of B anomalies with preferred coupling to 2nd and 3rd generations
  - Pair- and single-production of leptoquarks







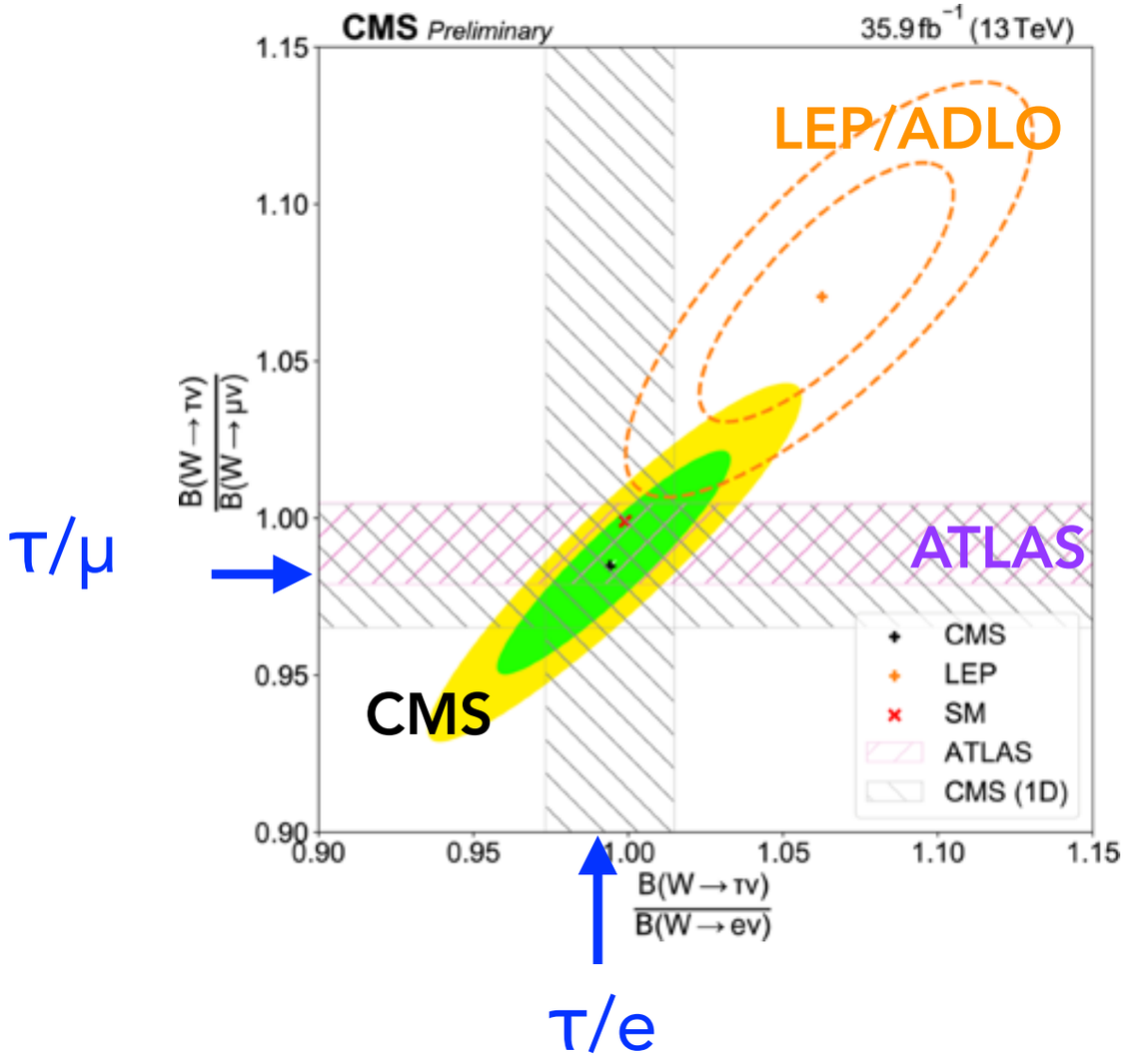


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

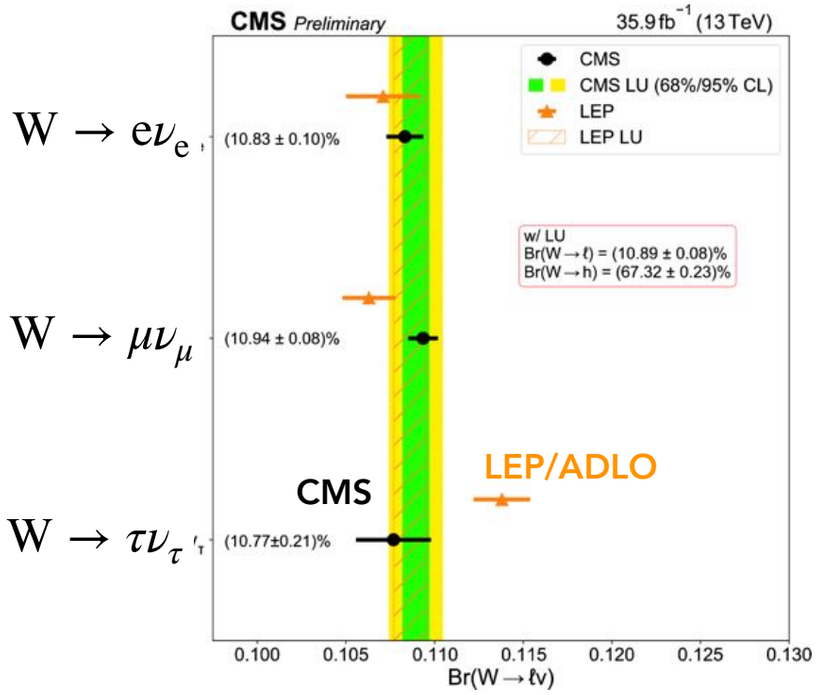
Hakil Saka

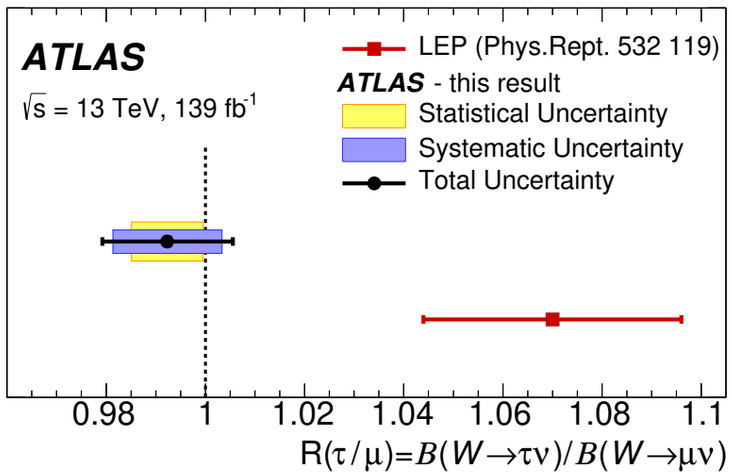
Lepton Universality in W decays

▻ Compare W branching fraction in e, μ, τ

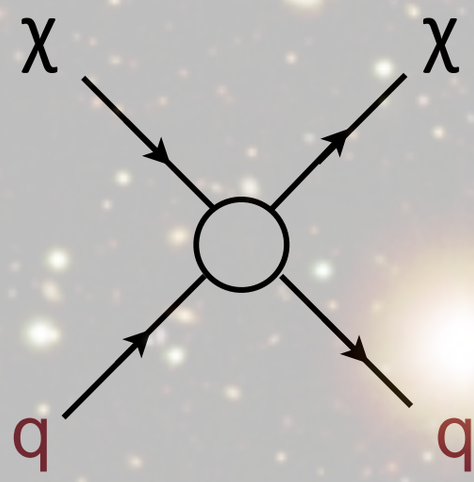


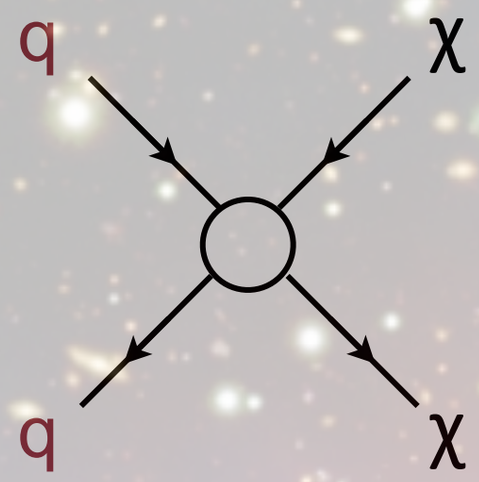
Branching fractions W → e, μ, τ



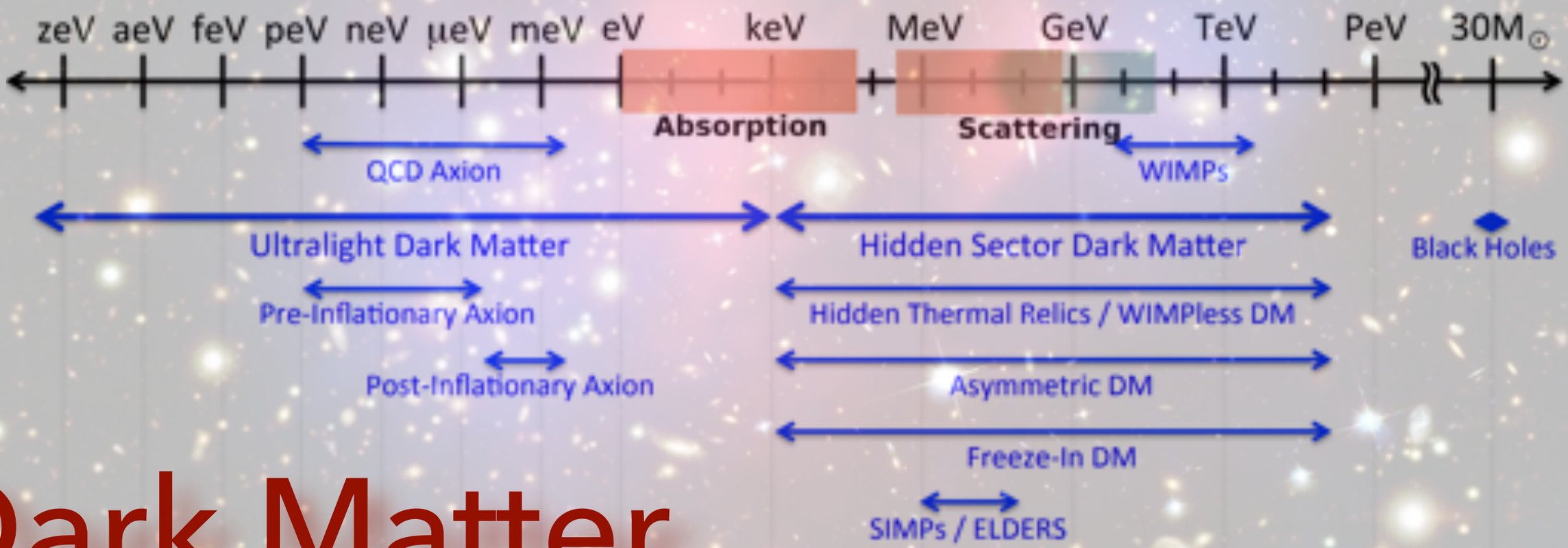


▻ Very good agreement between LHC and Standard Model





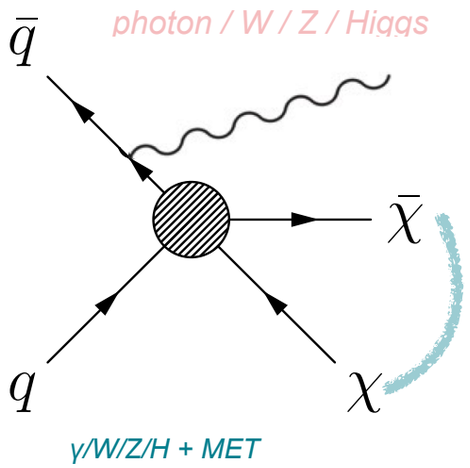
Direct Detection *Production at Colliders*

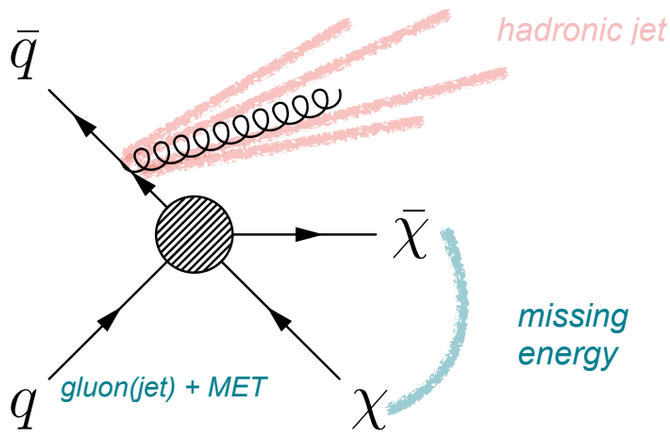


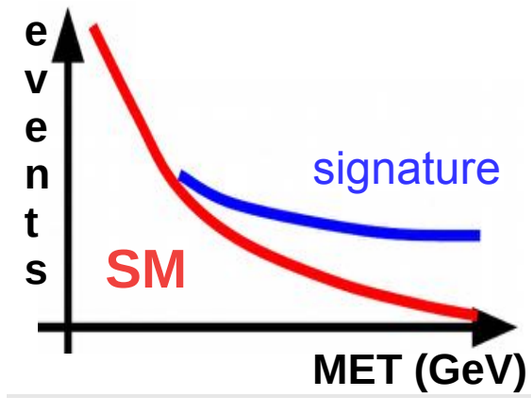
Dark Matter

The known unknown

Dark candidates at LHC

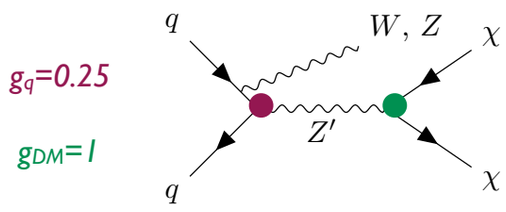




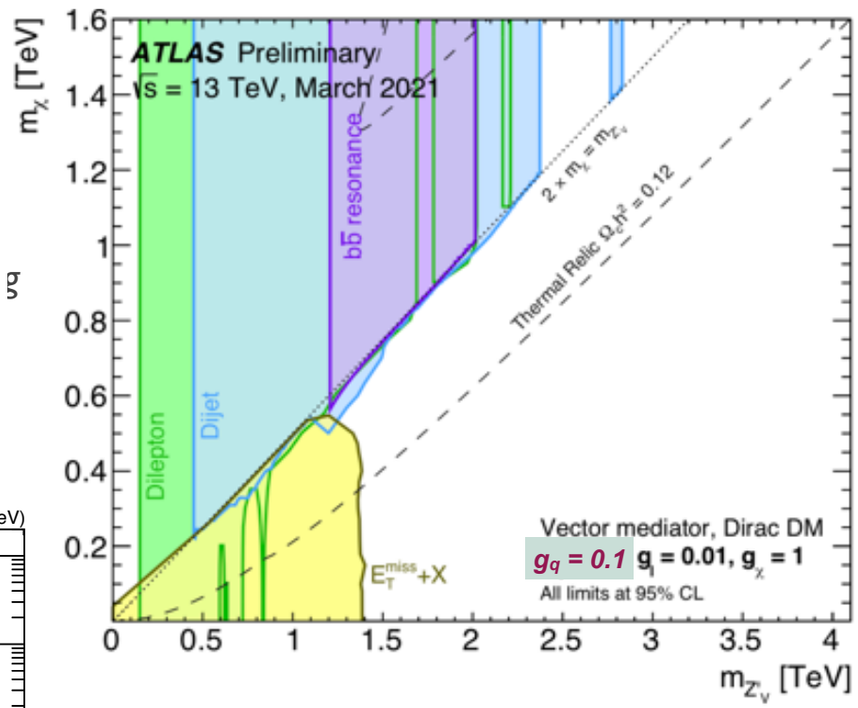


Deborah Pinna

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

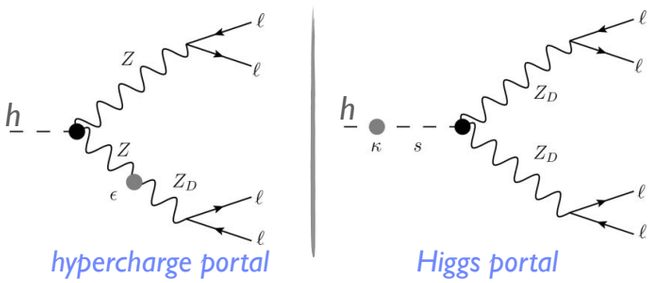


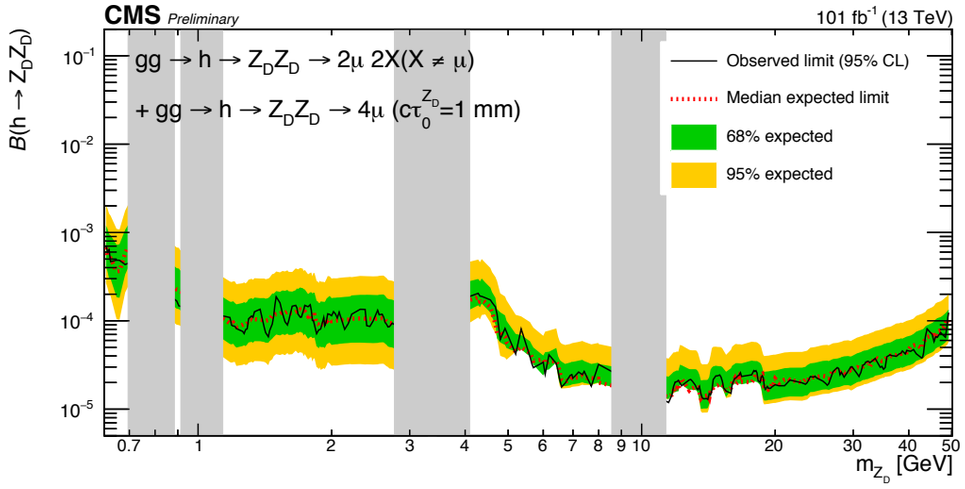
also visible decays



- Search for hidden sector also at very low mass

Hidden dark sector
dark/SM sectors interaction through dark photon Z_D, which can decay into SM particles





LHC Physics Program

- Intense scrutiny of Higgs and Yukawa sector

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$

Precision Electroweak
QCD

$$+|D_\mu\phi|^2 - V(H)$$

Higgs properties
Higgs self interaction

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

Higgs coupling to bosons and fermions
CKM matrix and CP Violation

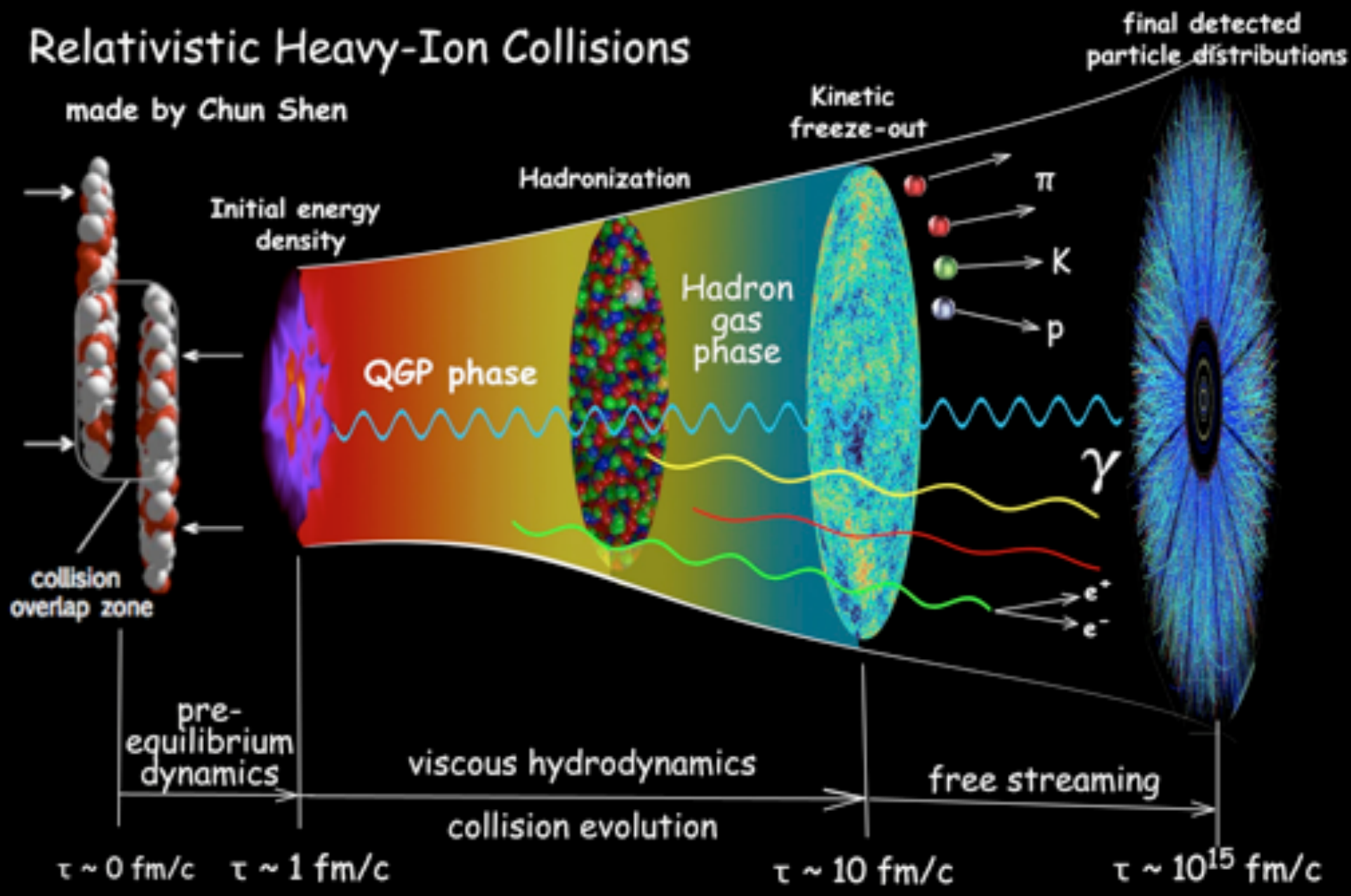
- While keeping a wide open eye on new phenomena

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

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

Quantum Chromo Dynamics

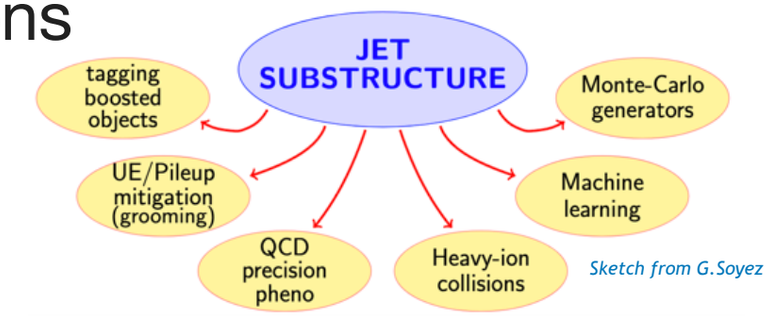
Quark-Gluon Plasma and Spectroscopy



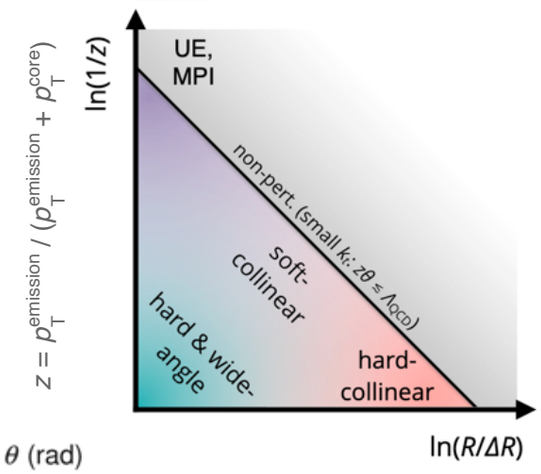
Jet substructure

Leticia Cunqueiro Mendez

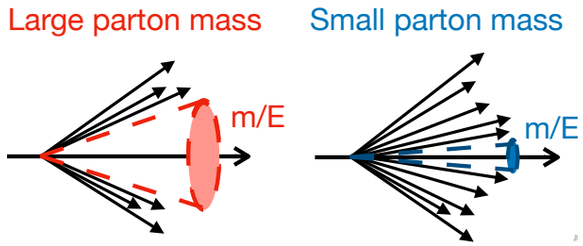
- Internal radiation pattern used in pp and ion-ion collisions
  - reliable predication
  - valuable probe in both high density matter and rare searches
    - distinguish QCD jets from W/Z/H



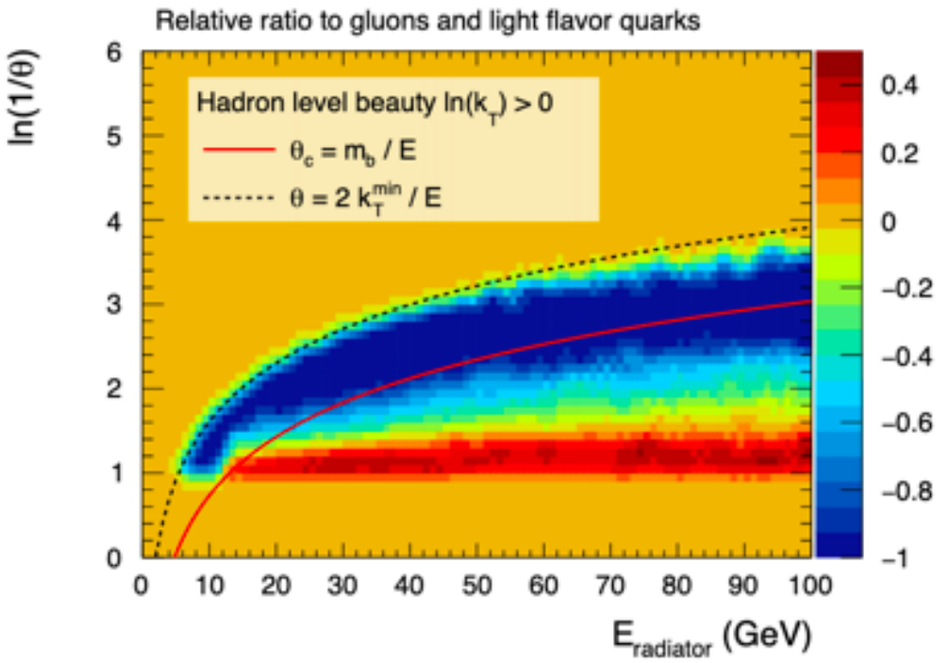
- Systematic study of radiation versus opening (Lund Plane)
  - complementary kinematic regions in ALICE and ATLAS+CMS



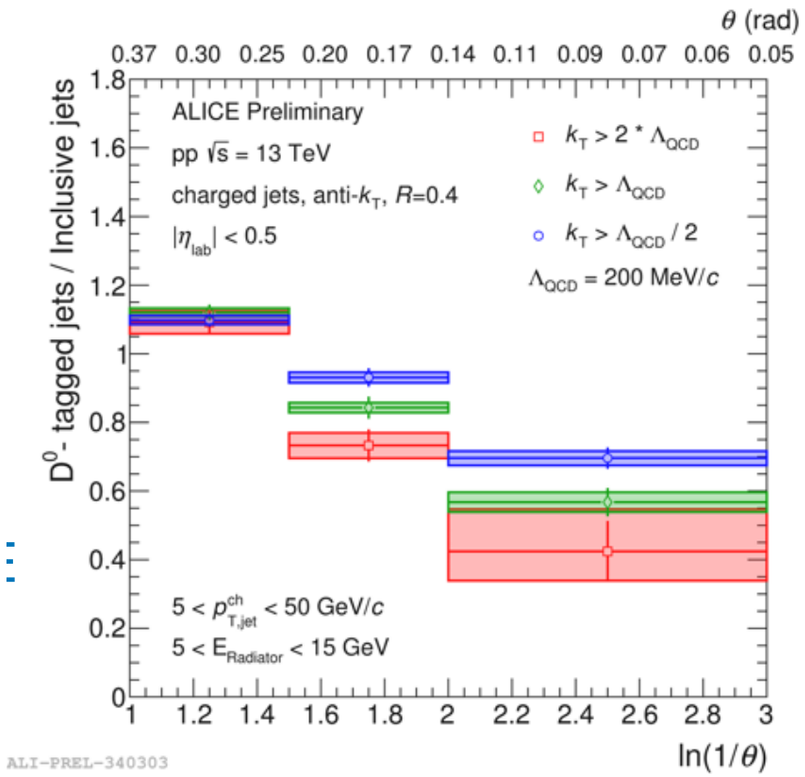
- Jets with heavy flavor to probe mass dependency



$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\mathrm{inclusive\ jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\ jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_T, E_{\mathrm{Radiator}}}$$



Radiator: quark lead prong



Large θ

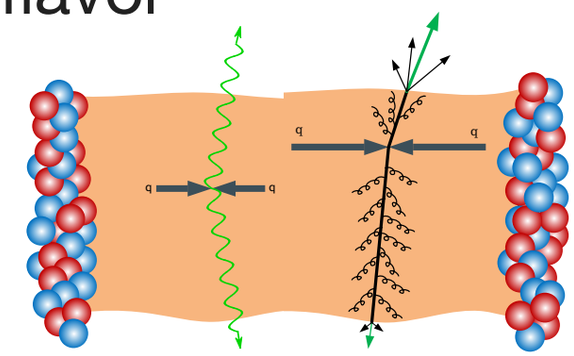
Small θ

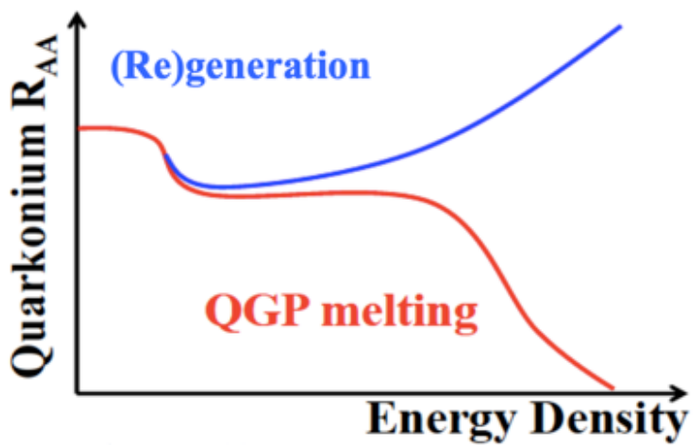
Interaction in QGP

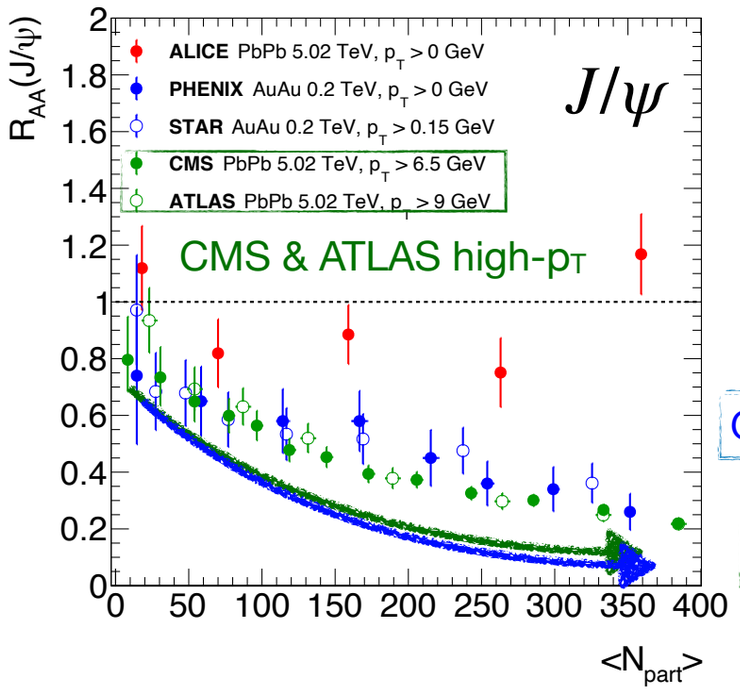
Laura Havener
Sebastian Tapia

- 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

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





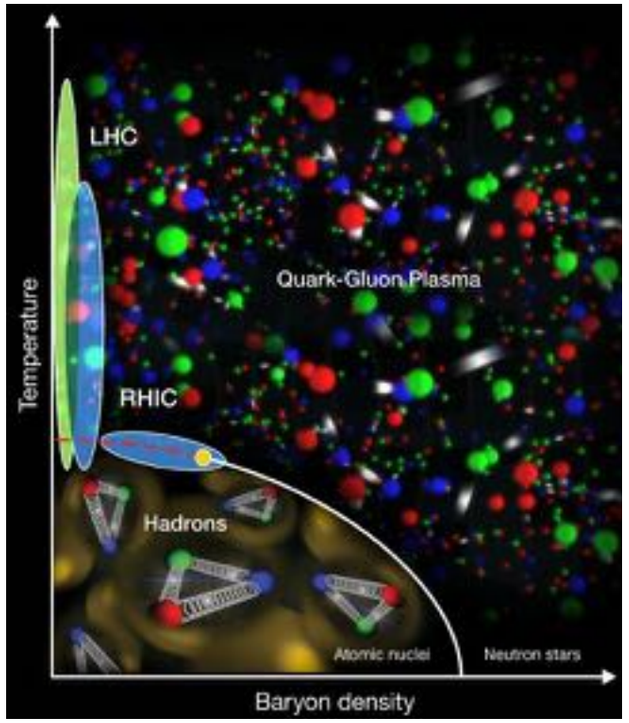


ATLAS arXiv:1805.04077

Smaller suppression at LHC

Gradual decrease vs N_{part} in RHIC

R_{AA}(RHIC) ~ R_{AA}(LHC) at high-p_T



Agreement between RHIC and high pT LHC despite different energy density

Observation of odderon

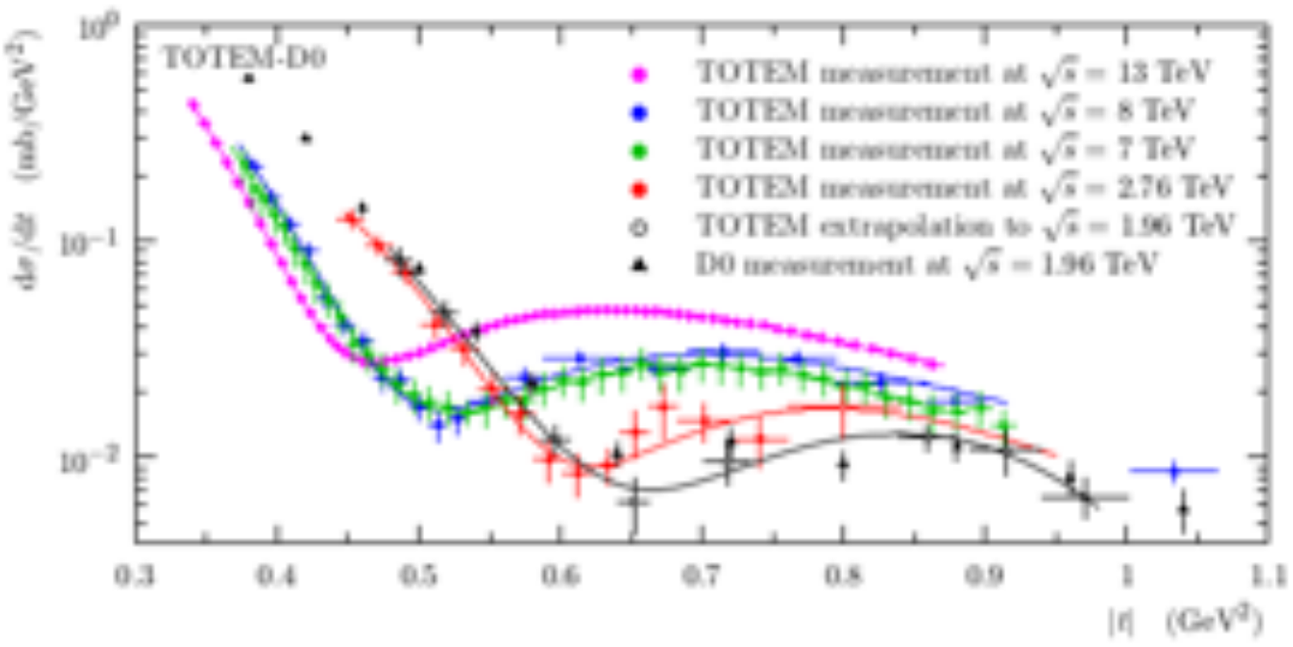
- Structure in differential cross section of elastic scattering

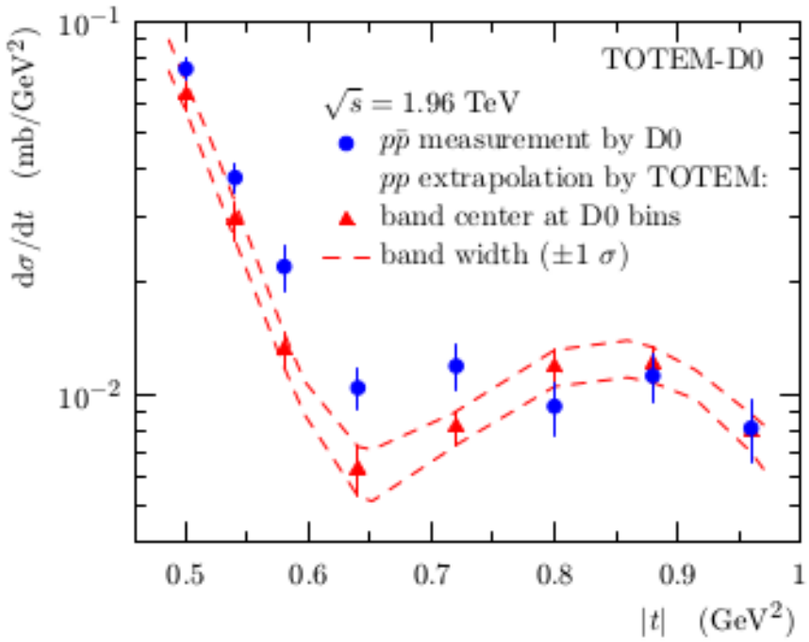
  D0 measured elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV.

  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

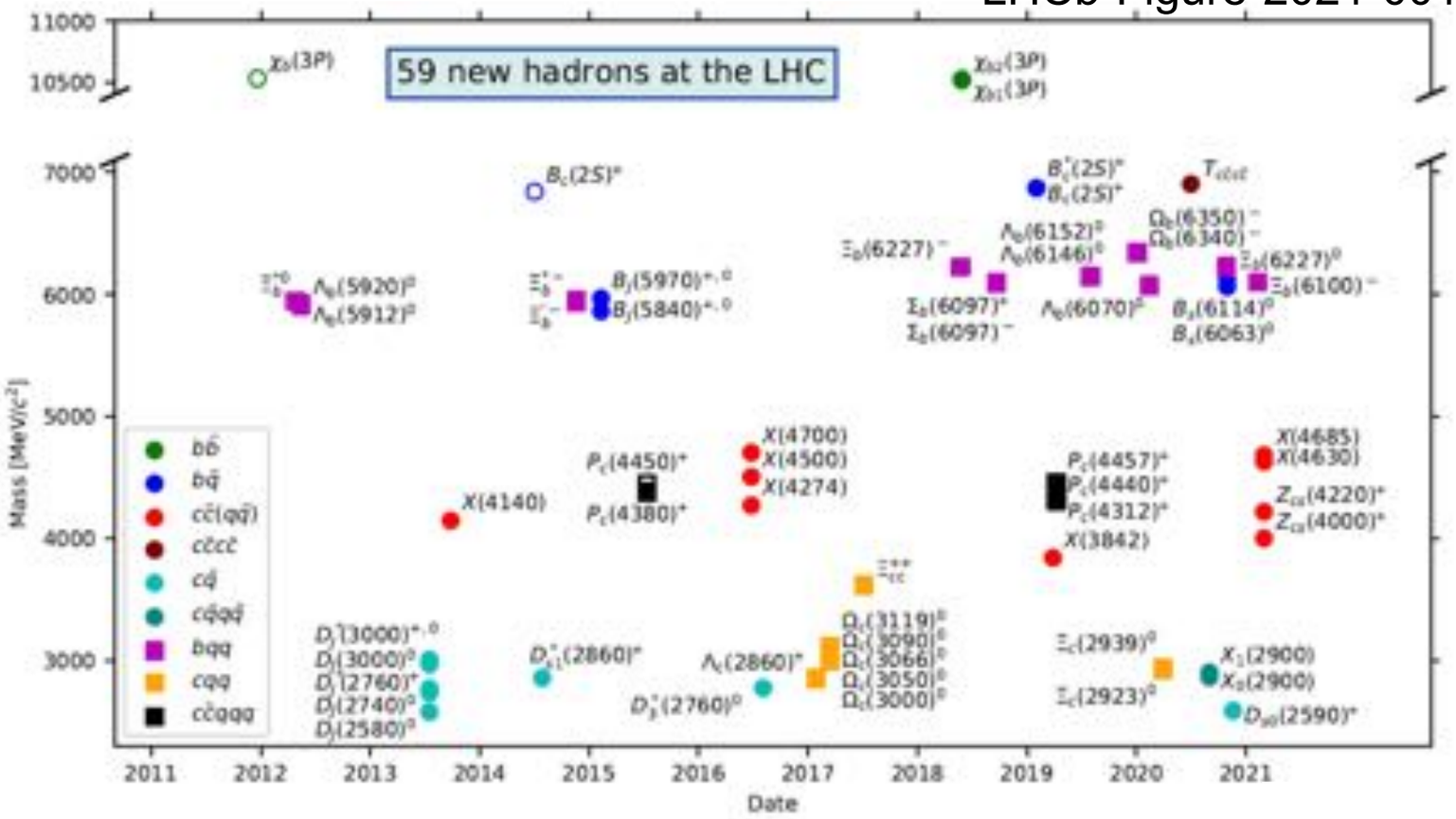




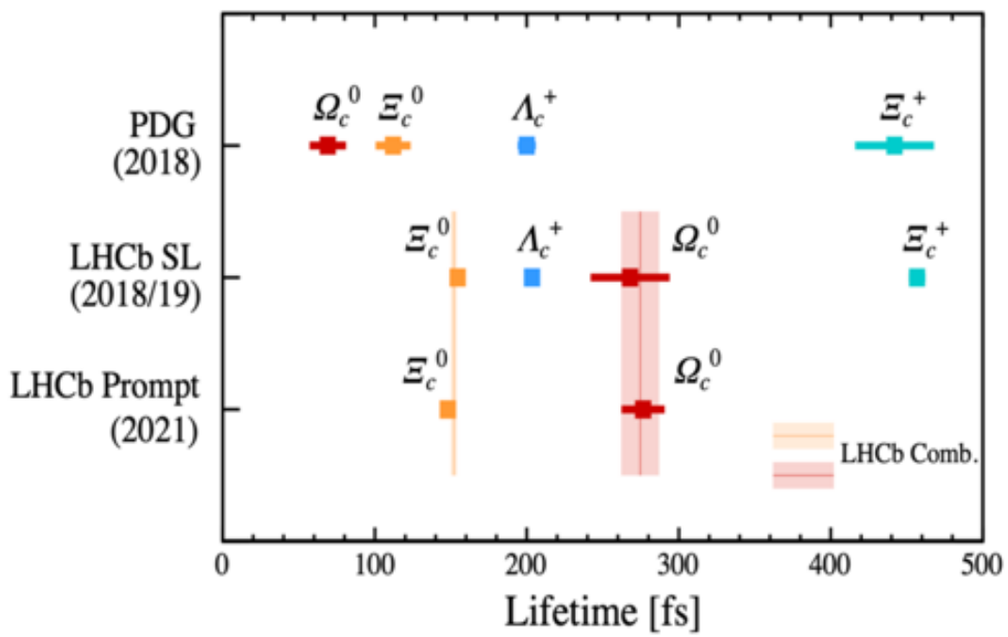
Spectroscopy

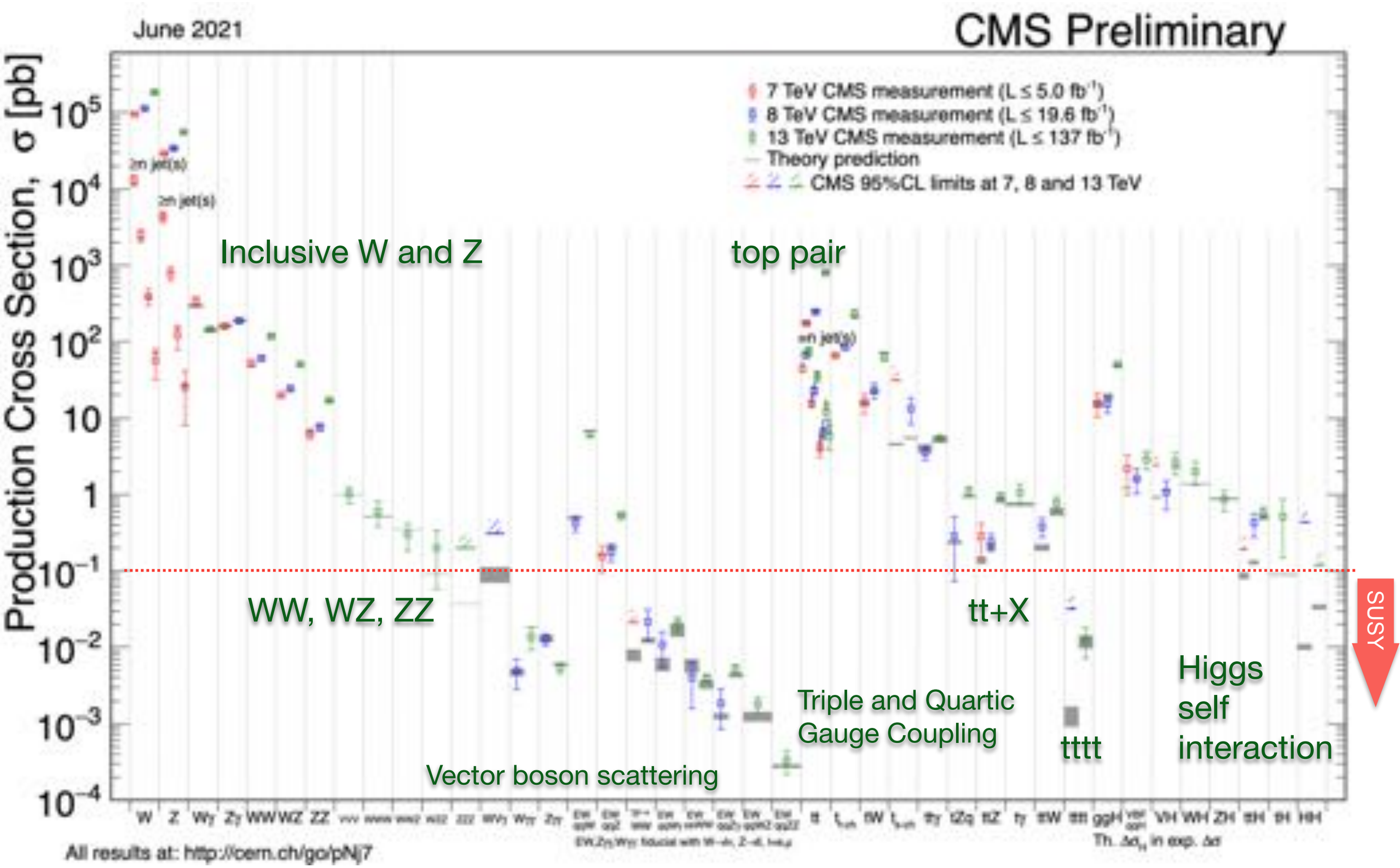
- New Age of spectroscopy and fruitful collaboration with theory
  - systematic study of tetra- and penta-quarks

LHCb-Figure-2021-001



- Interesting discrepancy in baryon lifetimes confirmed
  - interesting to see theory prediction and previous measurement





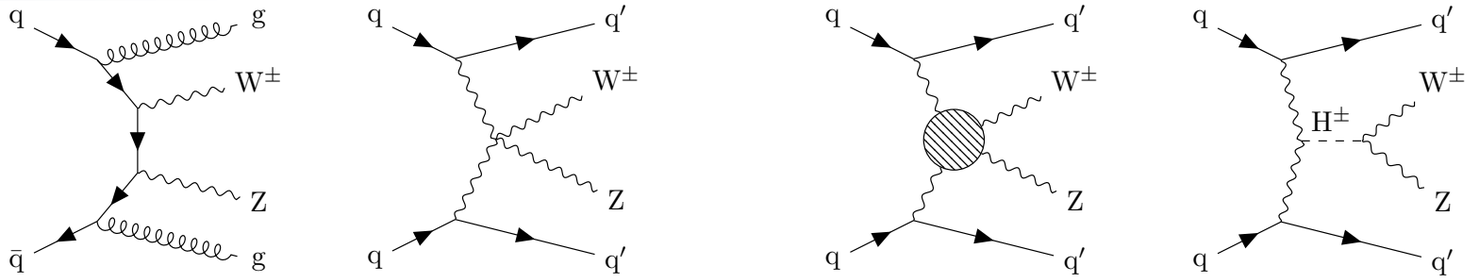
Electroweak Sector

New Physics through Precision

Vector Boson Scattering

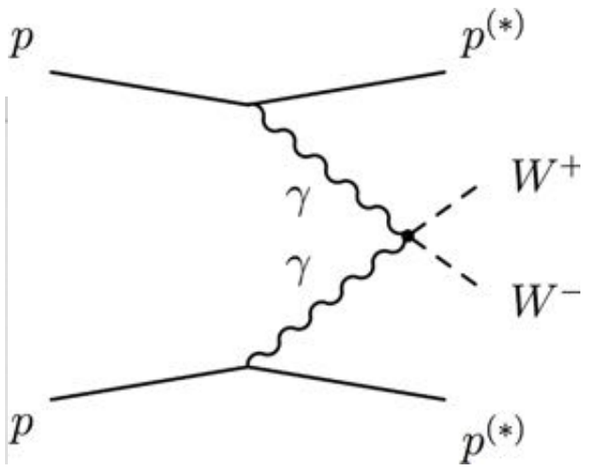
Roberto Covarelli

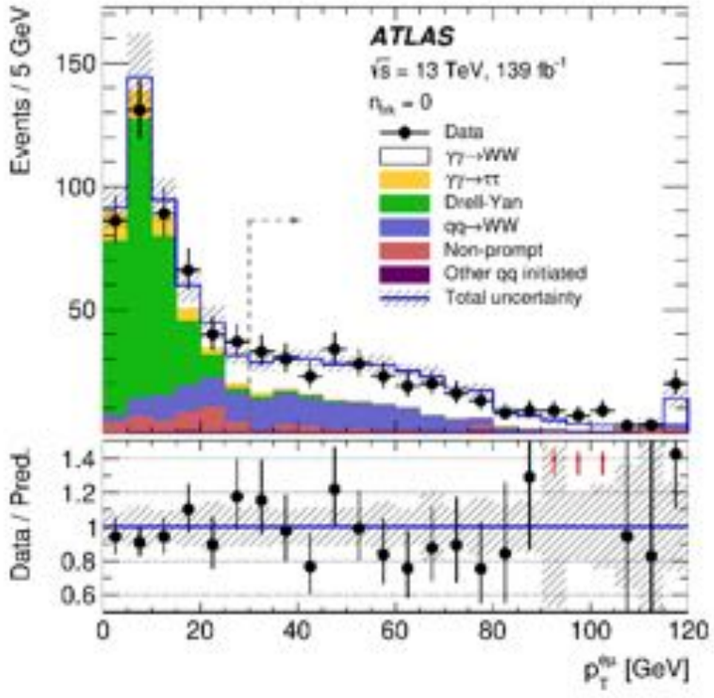
- Quartic gauge couplings known exactly in SM and sensitive to new physics contributions
  - Disentangle QCD and EW contribution through jet kinematics
  - suppress QCD background with novel ML techniques

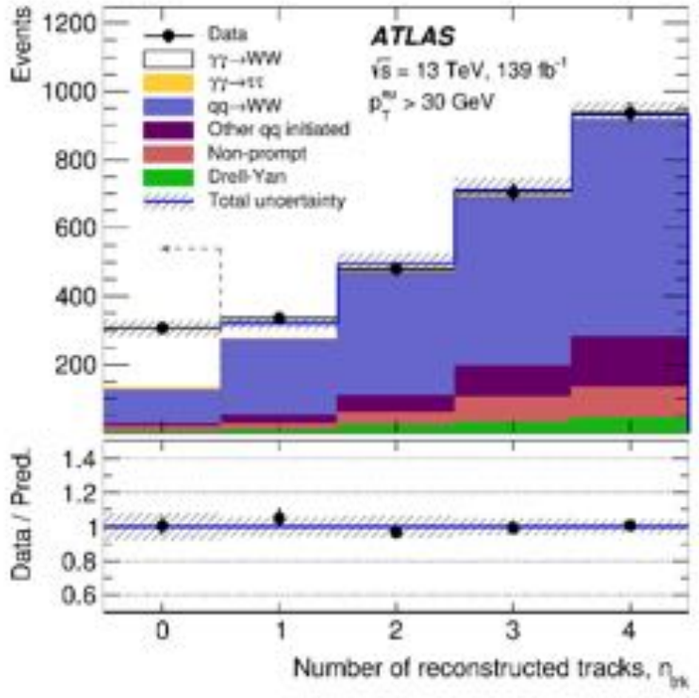


- Important milestone for longterm LHC program towards study of WW scattering
  - Observation of Same-sign WW in 2017!

- First observation of $\gamma\gamma \to W^+W^-$



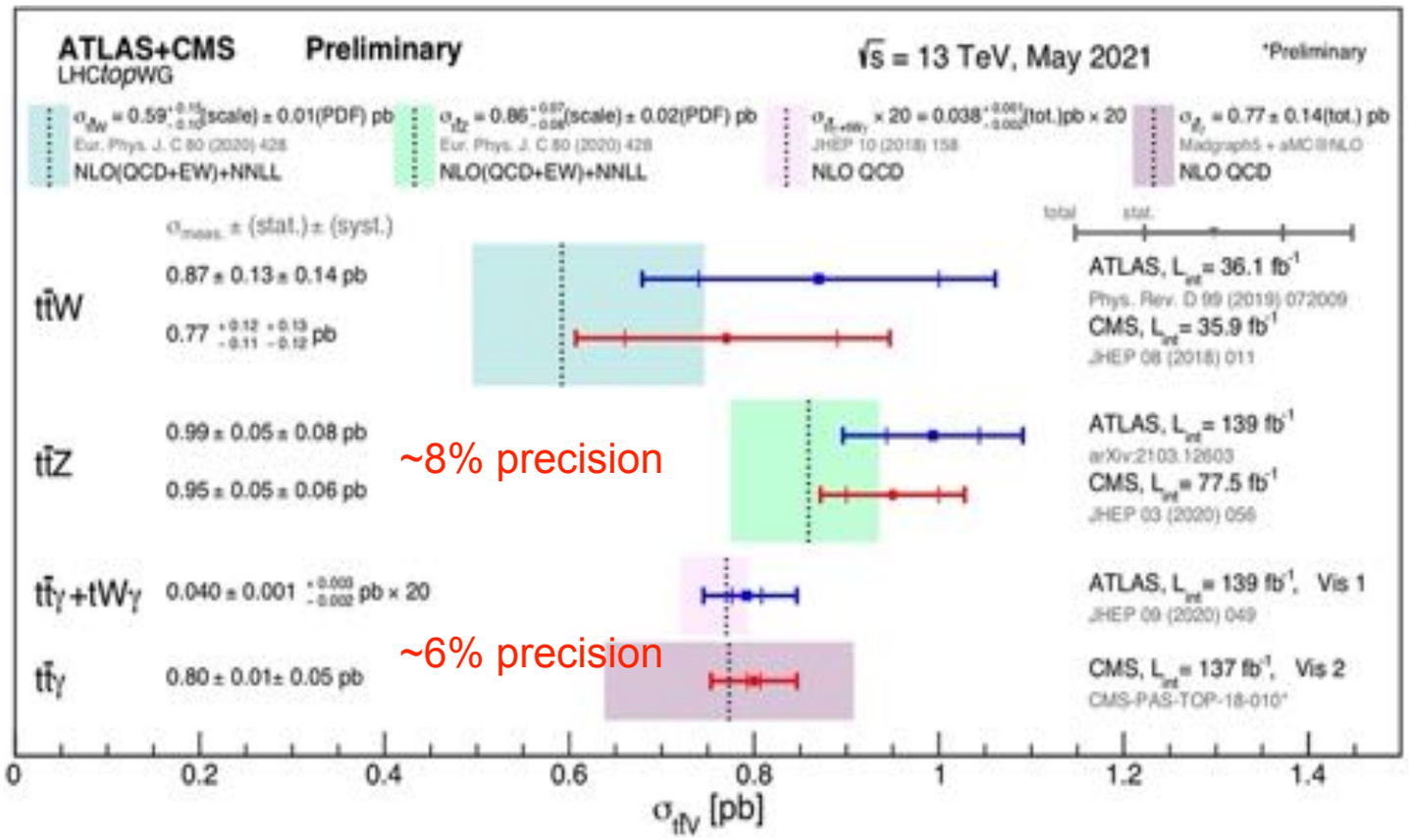




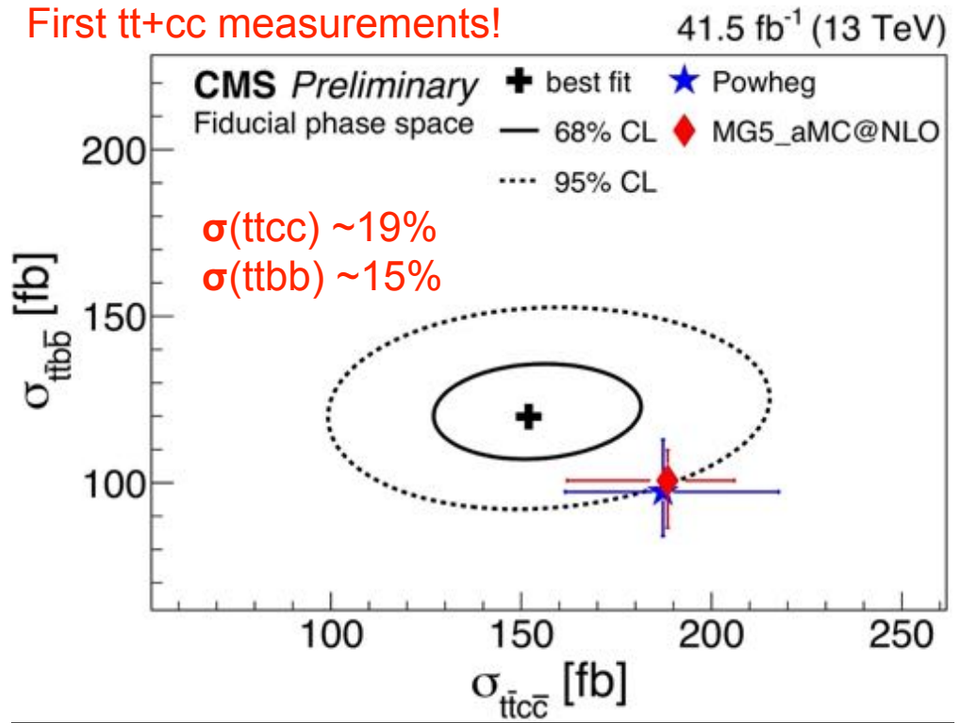
- Comprehensive input with various VV modes to constrain EFT operators

Top agreement with theory

Joshuha Thomas-Wilsker



First tt+cc measurements!

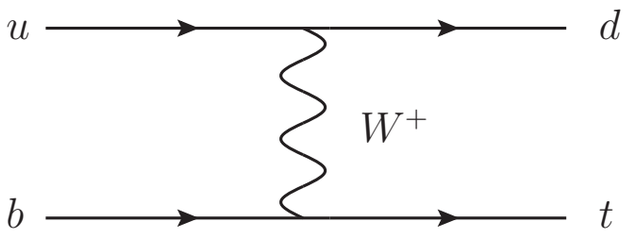


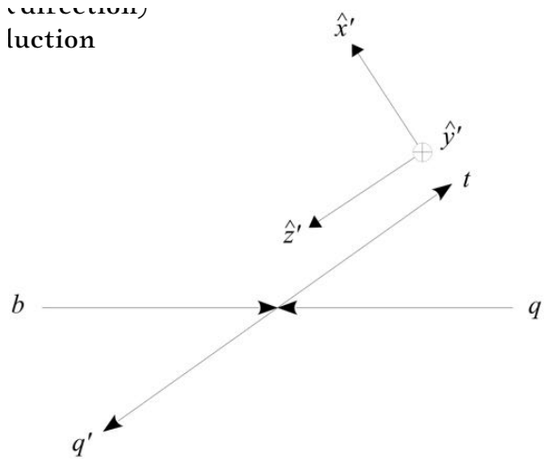
- Competing precision between theory and experiment in ttZ
- tt+bb production now exceeding theoretical knowledge!
  - Important background in study of top-Higgs Yukawa coupling
- Now also tt+cc with 19% precision
  - key role of c-tagging
- Precision theory input needed to reduce uncertainties
  - important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

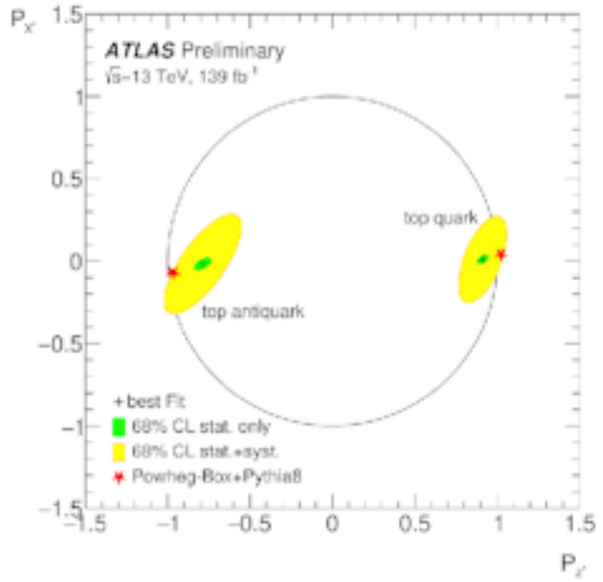
top and W properties

Sven Menke
I. Gorbunov

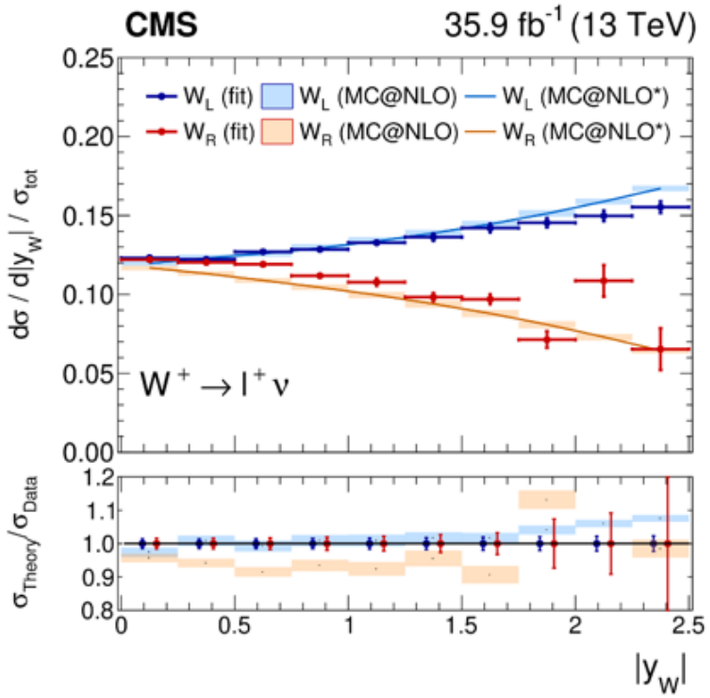
- Infer spin of weakly-produced single-top from angular analysis in $t \to bl\nu$
  - polarisation consistent with SM prediction and sensitive to new physics contributions

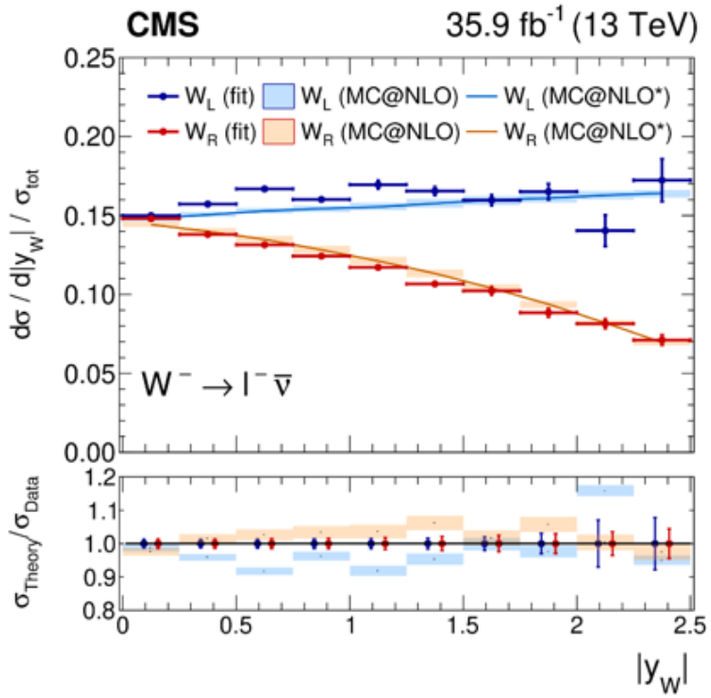






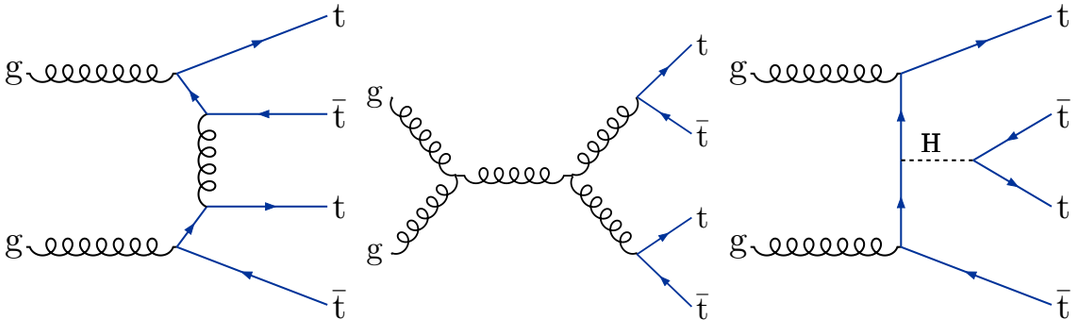
- Measurement of W helicity to approach W mass
  - differential cross section for W^+ and W^-
  - Aim at reduced uncertainty in W mass by constraining also PDFs
    - correct and abundant simulation a key ingredient

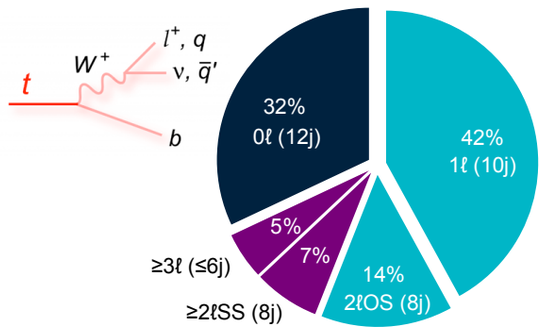




4-top production

Carlo Gottardo

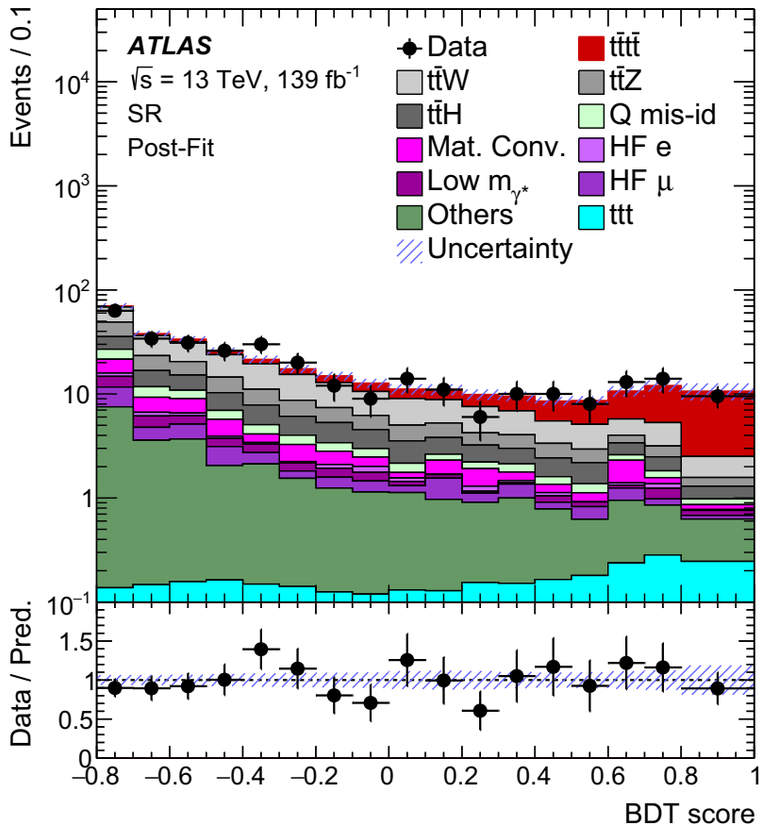


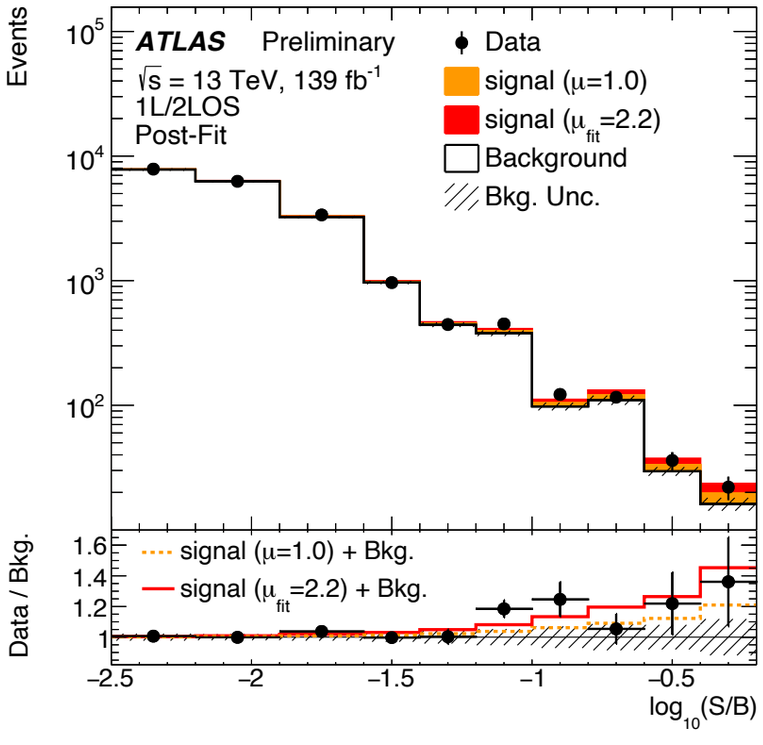


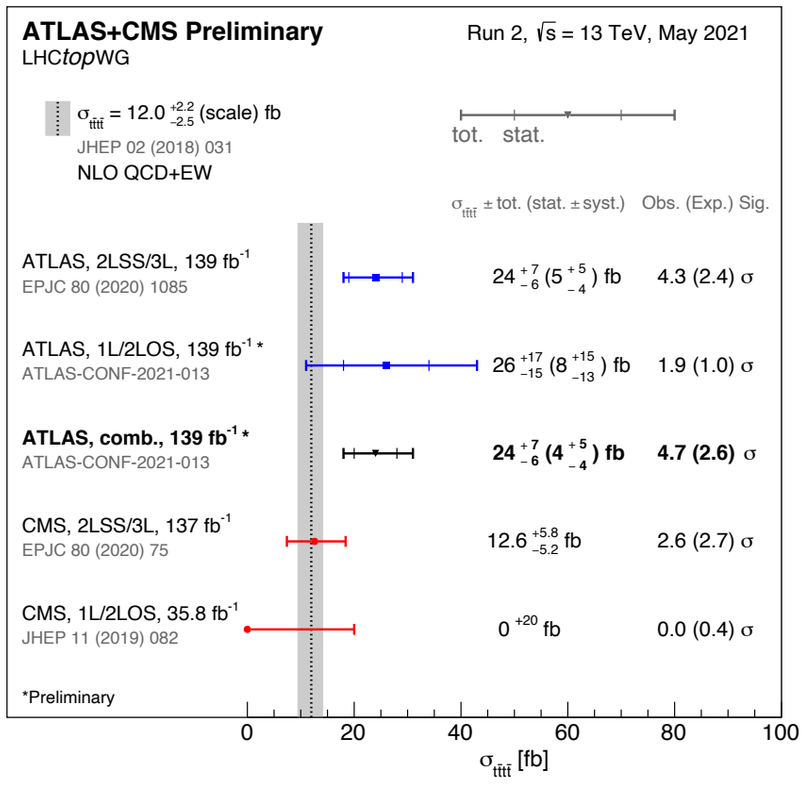
- SM cross section: 12 fb @ 13 TeV
- Several final states combined
  - key role of BDT discriminants in this search

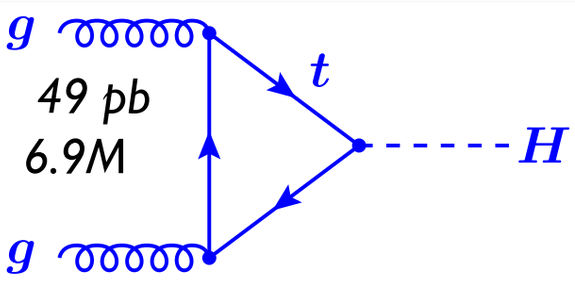
Dominant uncertainties:

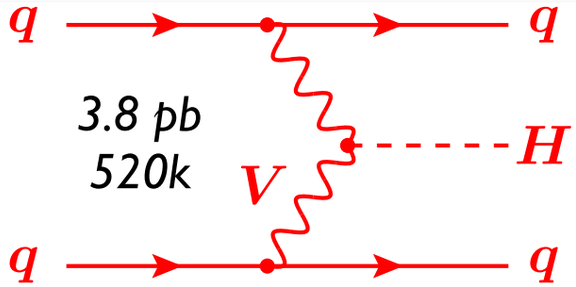
$t\bar{t}$+≥1b modelling,(±8 fb), $t\bar{t}$+≥1c cross-section (±5 fb)

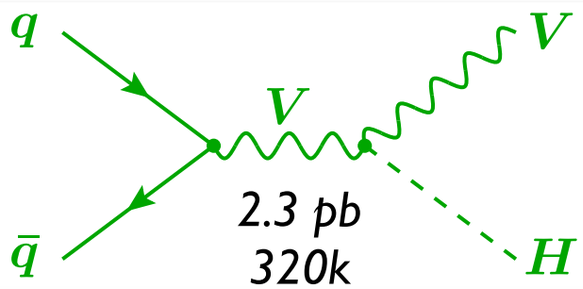


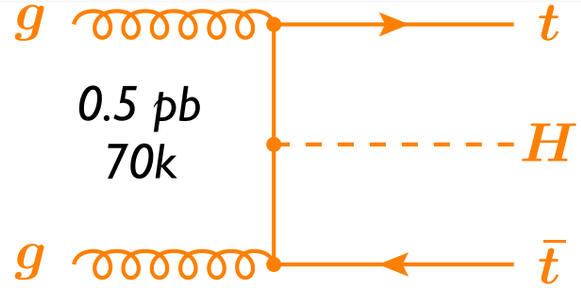




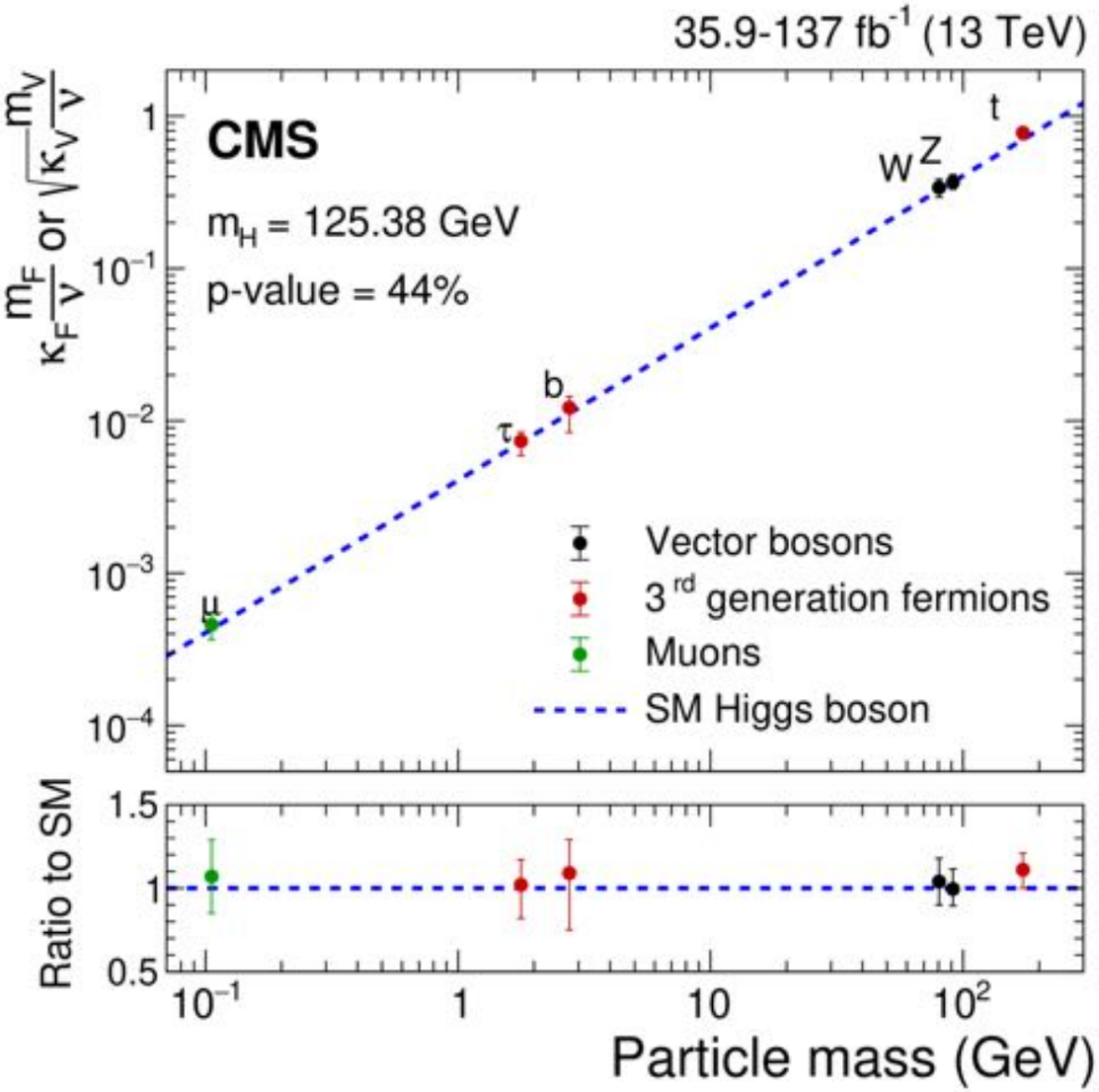








σ *[pb]*
#Higgs produced during Run-2



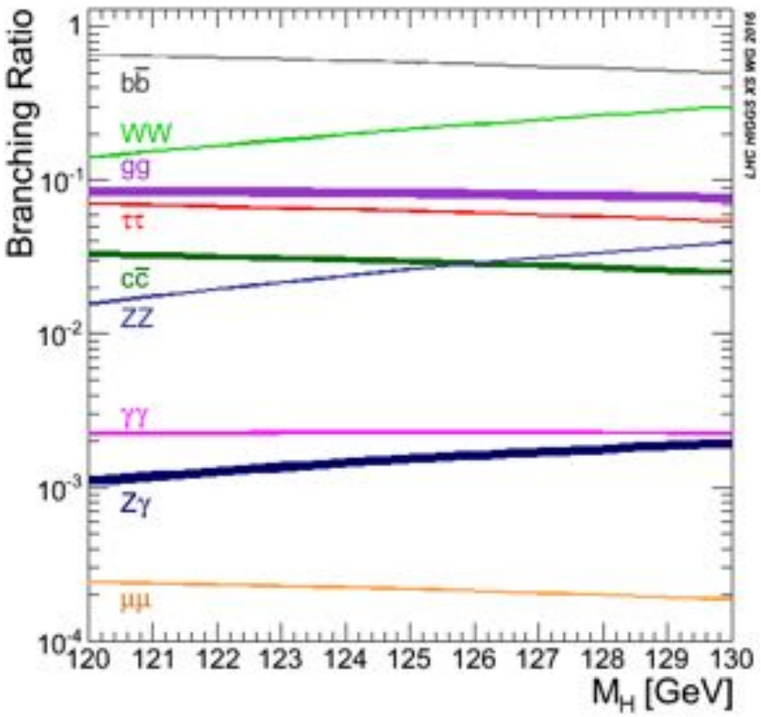
Higgs

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



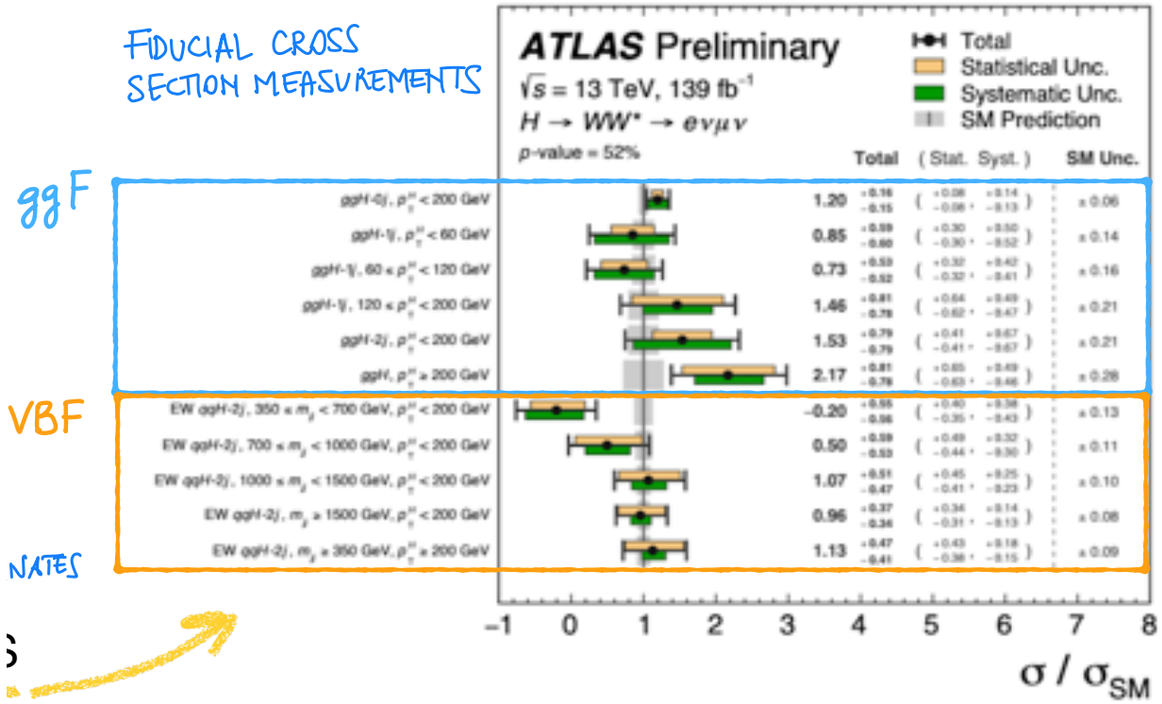
- So far it walks and talks like the Standard Model Higgs

- *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

ATLAS-CONF-2021-014



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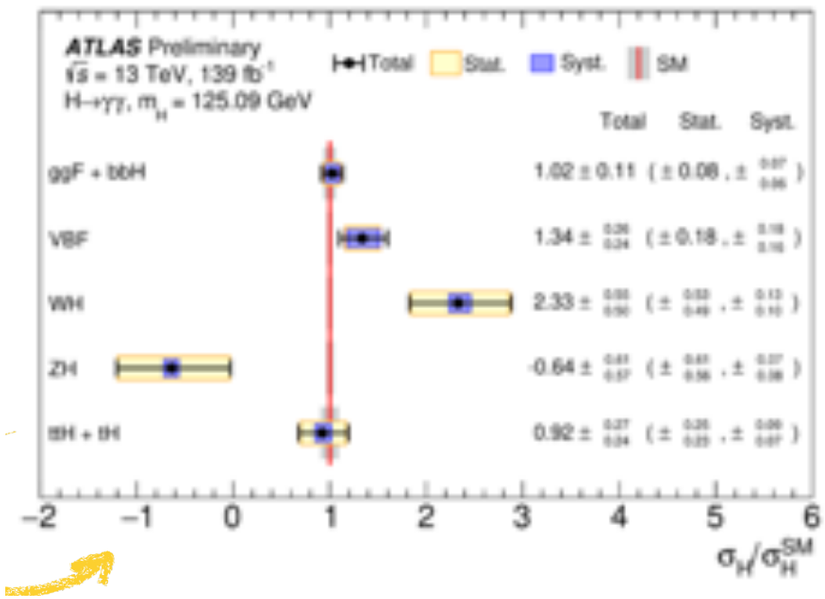
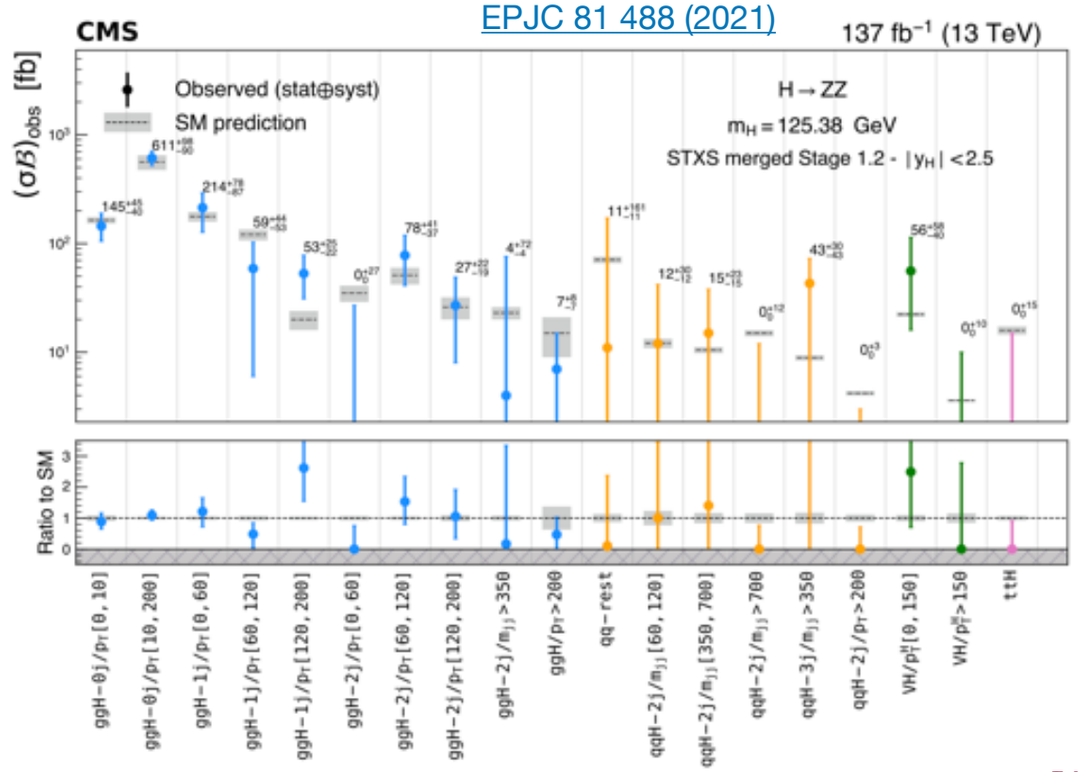


- Study of spin and CP also in agreement so far with Standard Model precisions
- Theory and experimental uncertainties now comparable
  - fruitful collaboration with theory

EPJC 81 488 (2021)

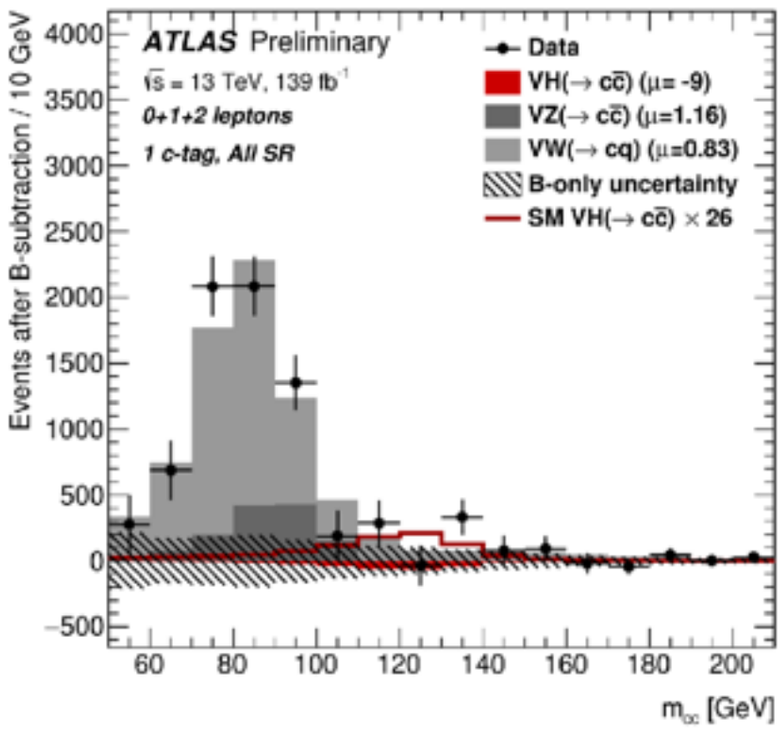


$H \to c\bar{c}$

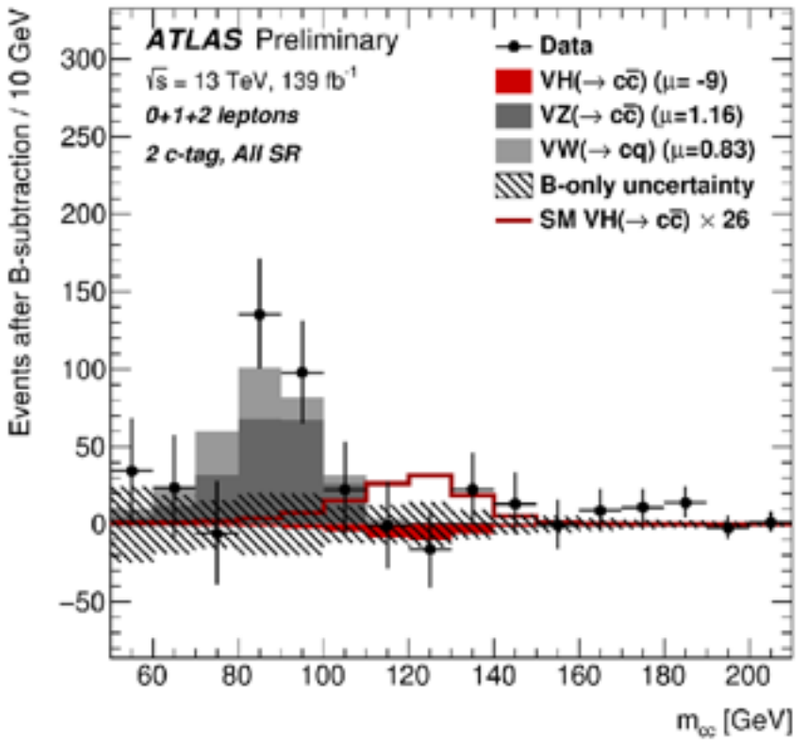
- Higgs produced together with vector bosons

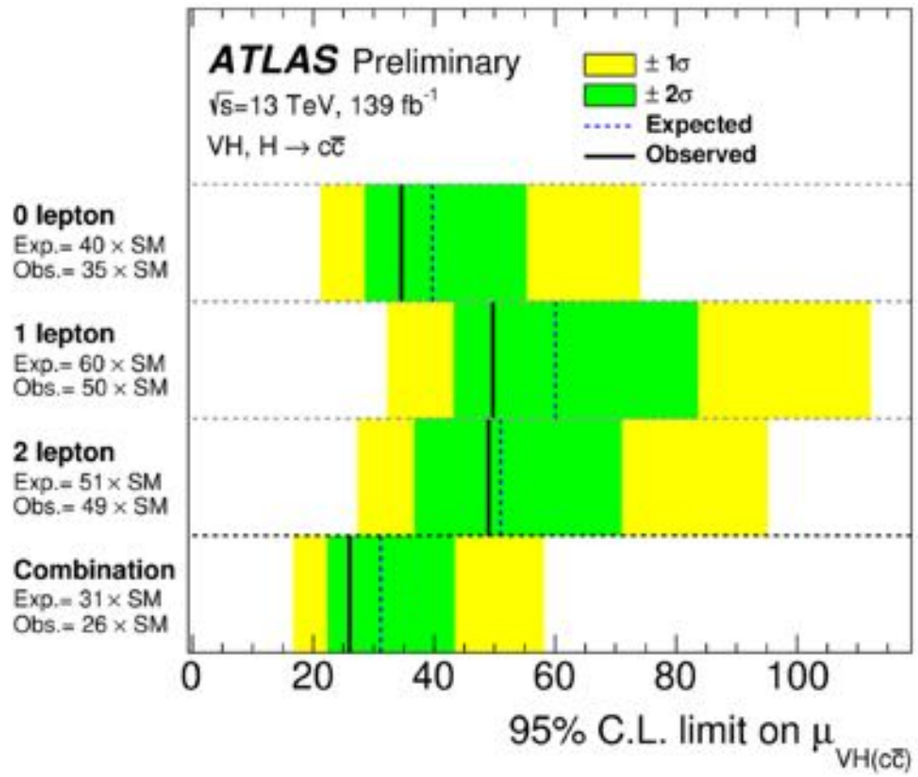
Manuella Victer

1 c-tag



2 c-tags





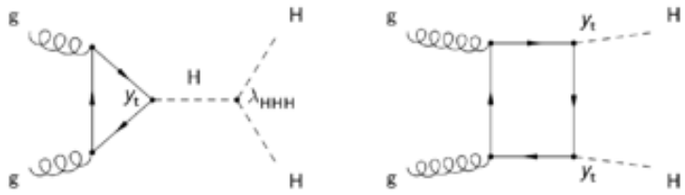
- Remarkable achievement thanks to novel tagging techniques
  - Higgs Branching fraction 3% !
- Within reach with future improvements and copious data at HL-LHC

Higgs Self-Interaction

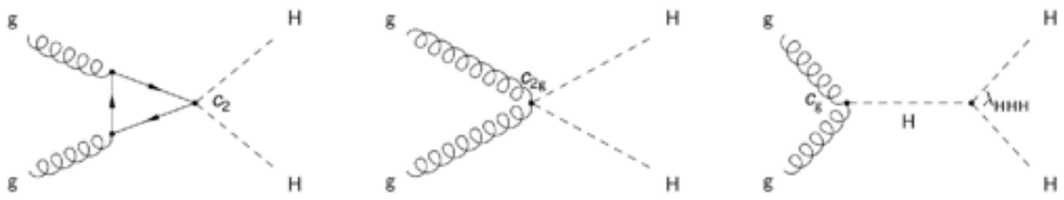
Pierluigi Bortignon

- Understanding Higgs sector requires measurement of its self-interaction

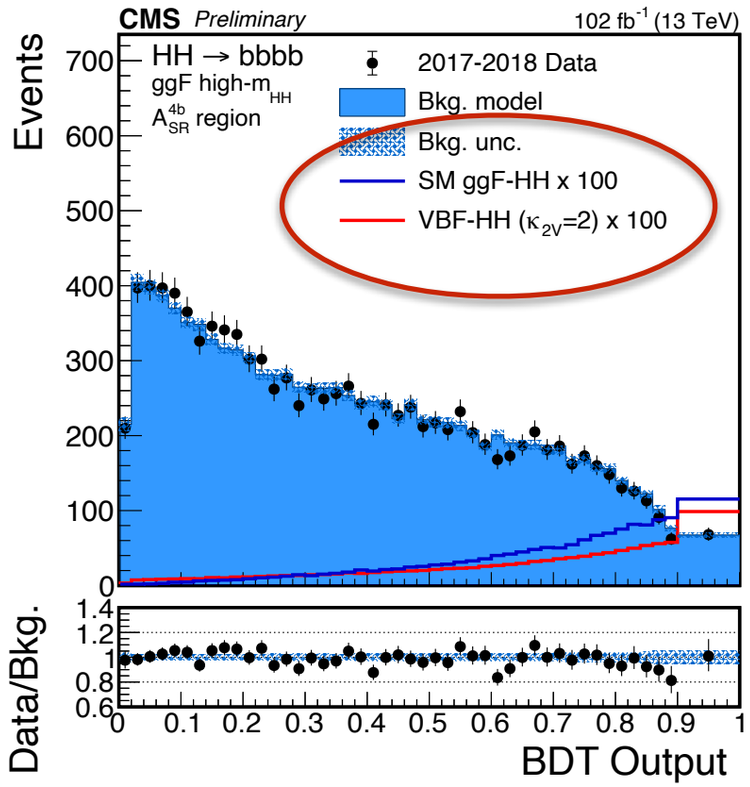
Standard Model



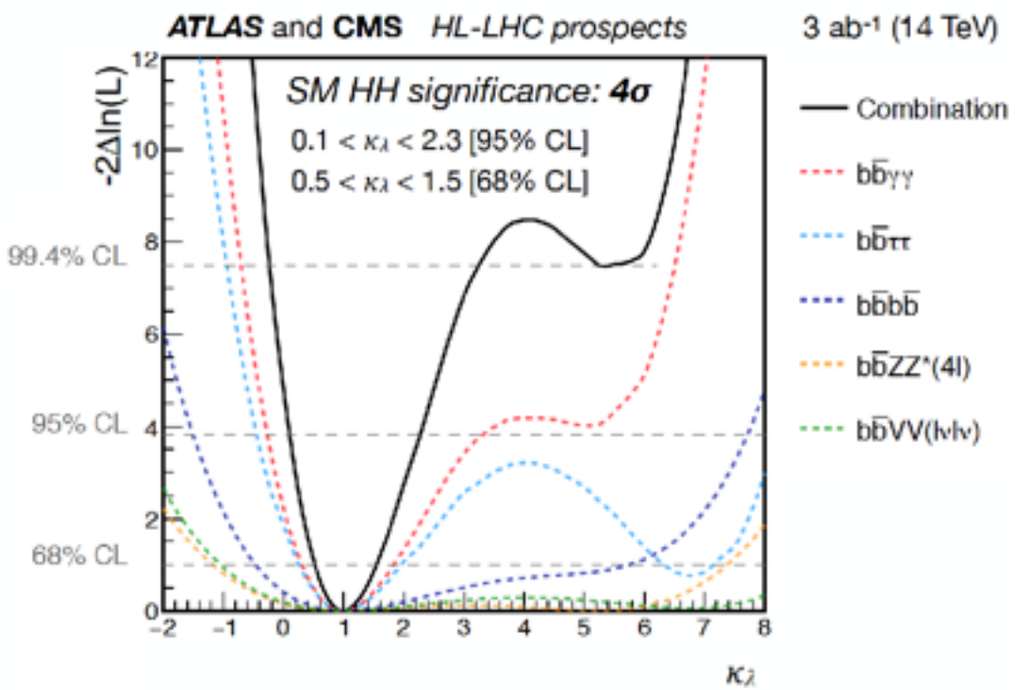
New Physics

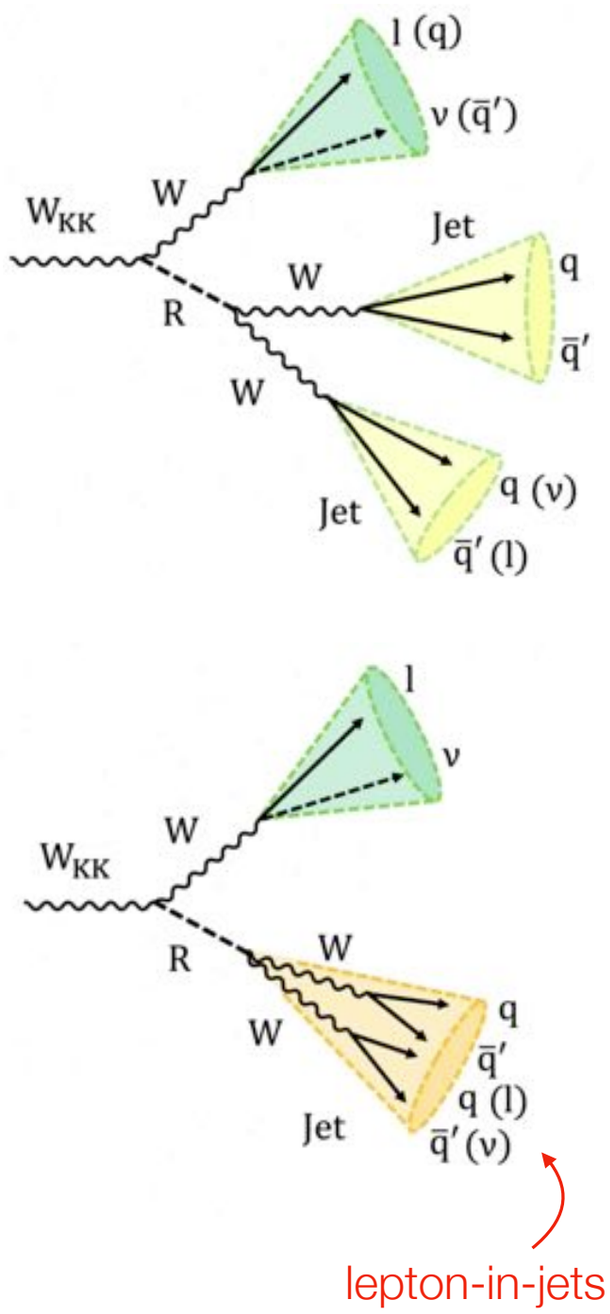


- Updated search in bbbb
  now excluding x4 SM (expected x7 SM)

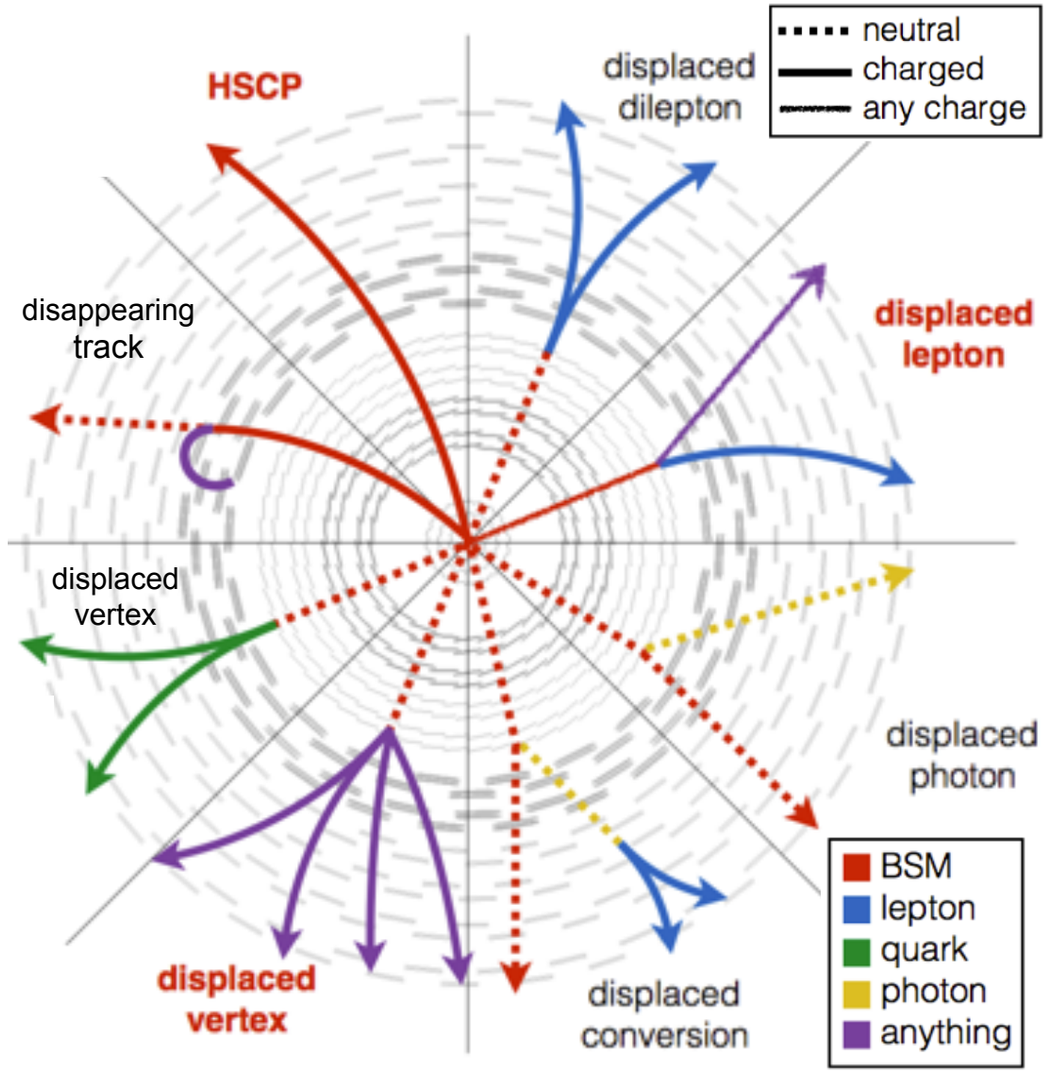


- Cornerstone of Run3 and HI-LHC
  - currently limited by statistics
  - room for even more sophisticated analysis techniques





lepton-in-jets



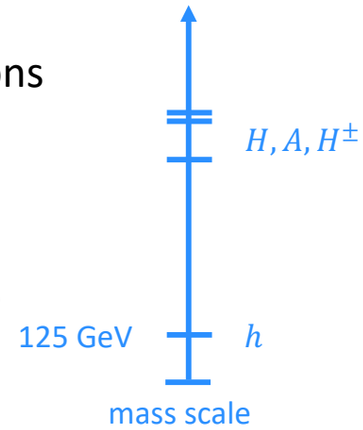
Credits: J. Antonelli

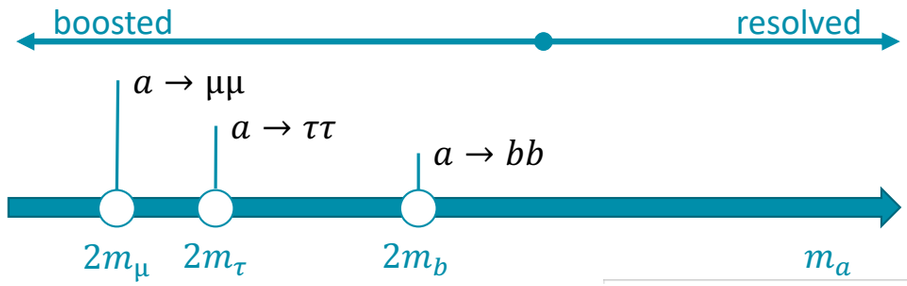
Exotic Phenomena

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

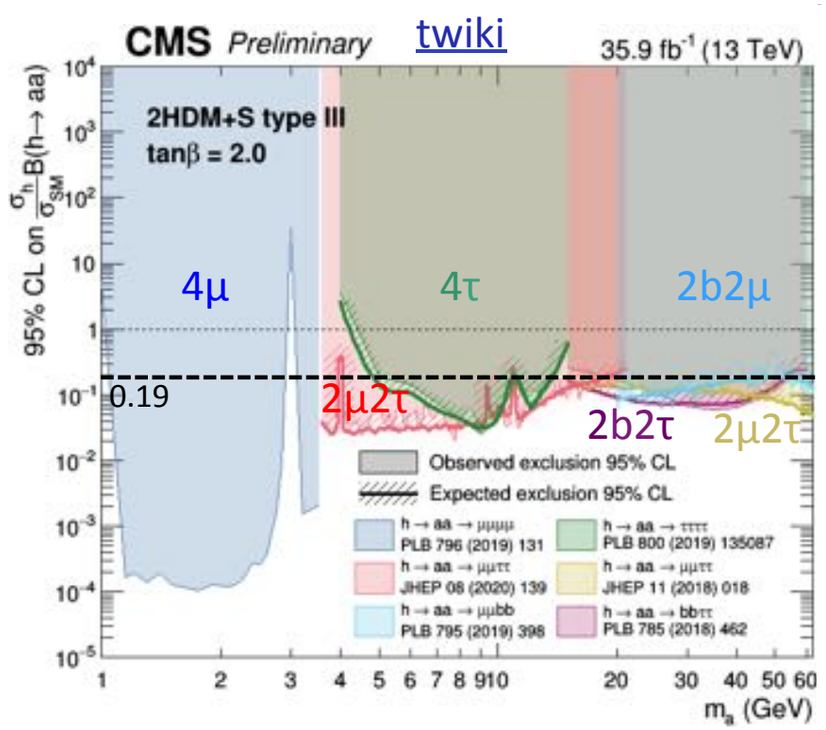
2HDM has 5 Higgs bosons
- h: "SM" Higgs
- H: heavy Higgs
- A: pseudoscalar
- $H^{\pm}$: charged Higgs





2HDM+S

twiki



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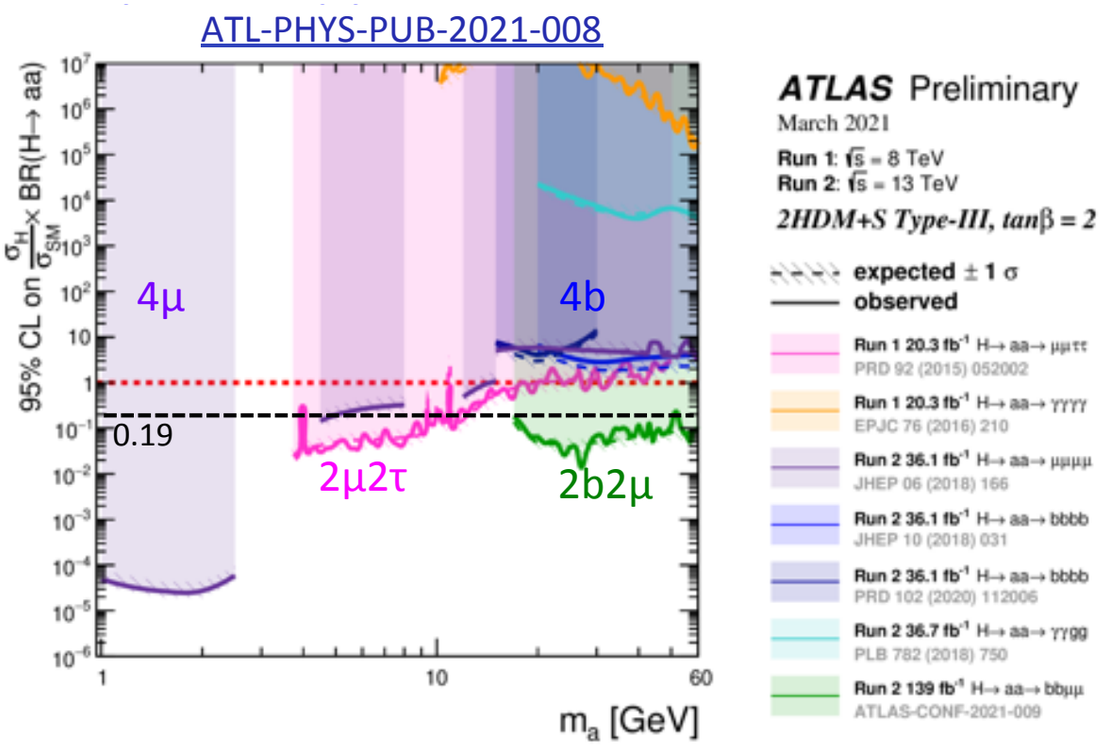
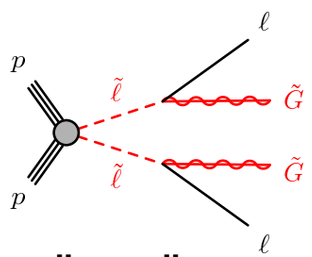


- So far no excess or evidence and only exclusion in theory parameter space
- High-Luminosity LHC two provide x20 increase in statistics

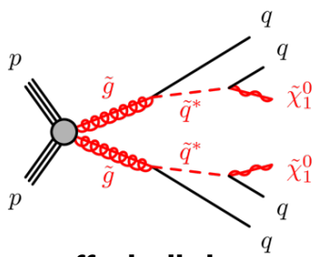
Imma Riu

Long-Lived Particles

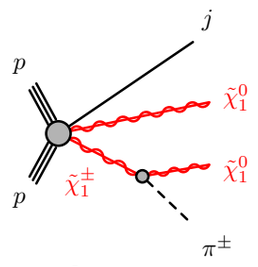
Elodie Resseguie
Lawrence Lee



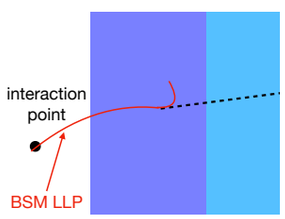
small coupling
e.g. coupling to gravitino



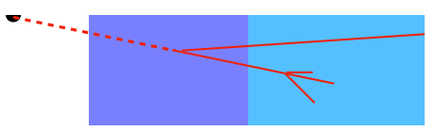
off-shell decays
e.g. squark mass > 10 TeV



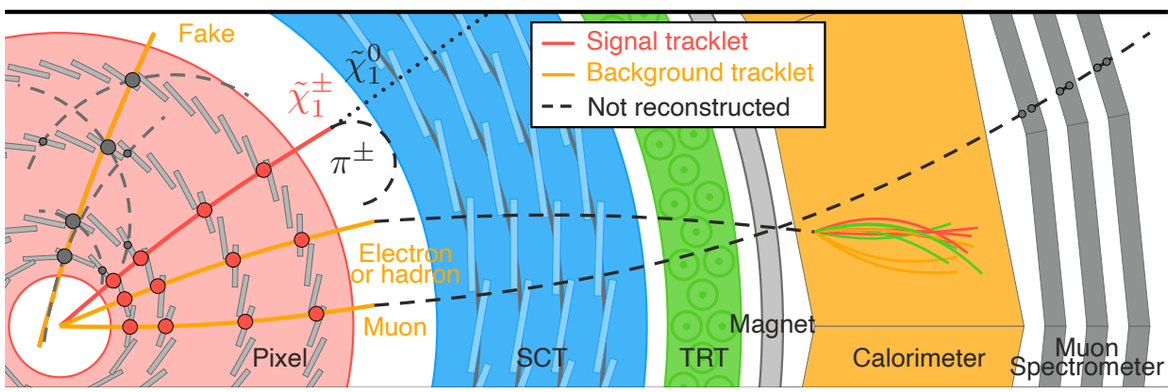
phase space
e.g. small mass splitting



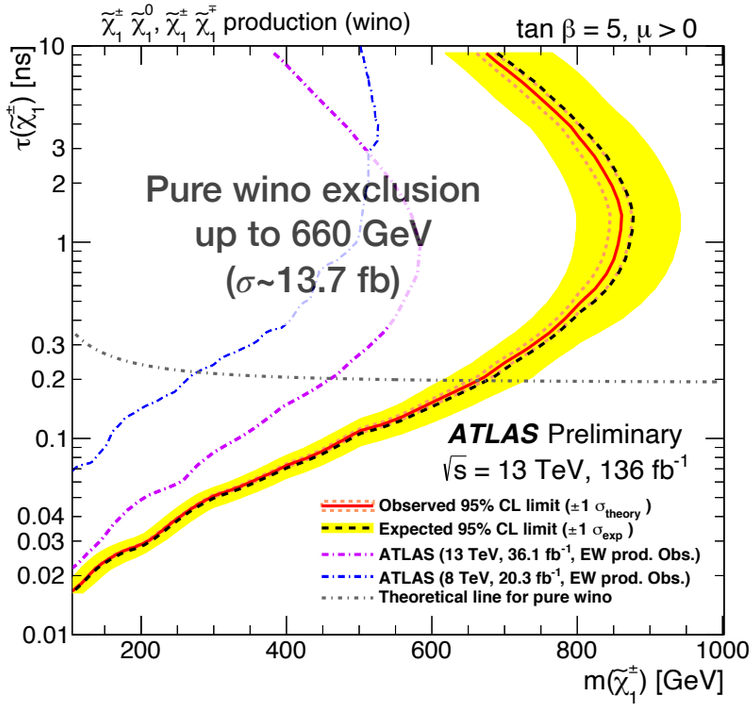
direct LLP detection
observable track

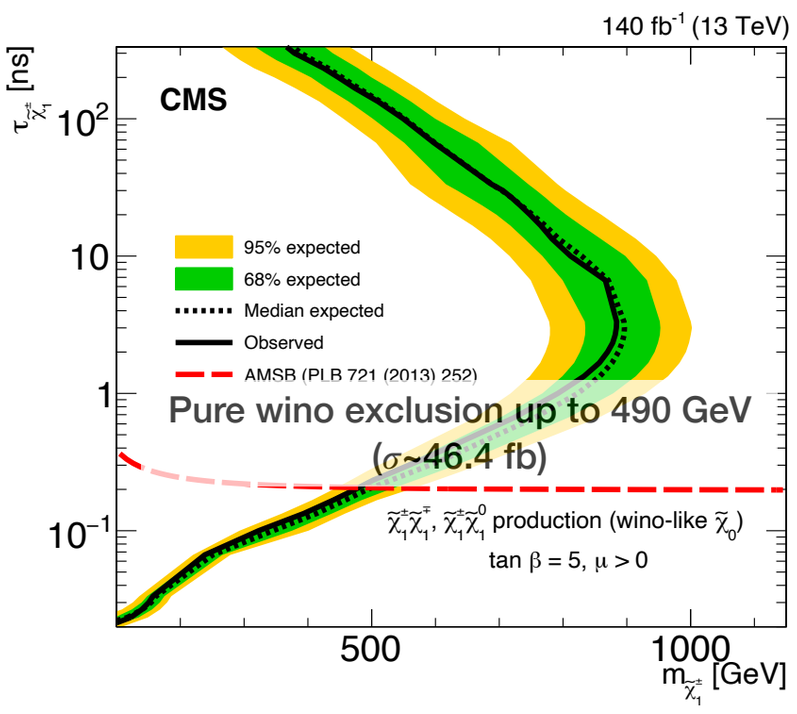


indirect LLP detection
observe decay products



- Tracks only in inner tracker and possible calorimetric veto

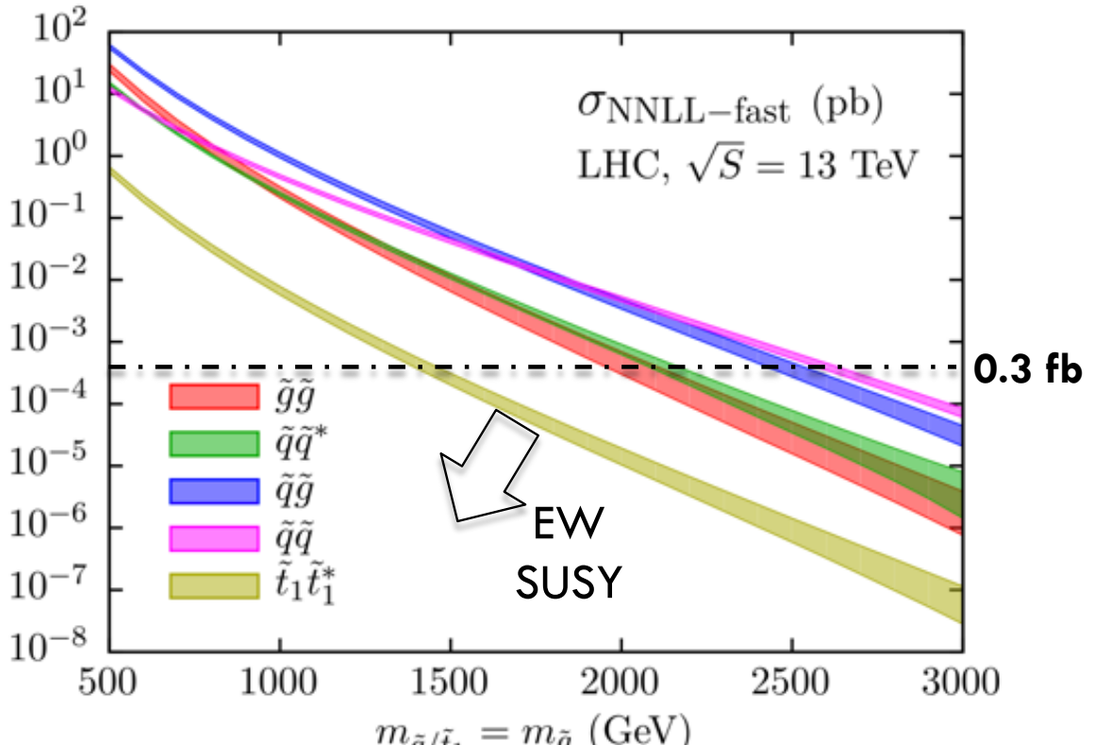


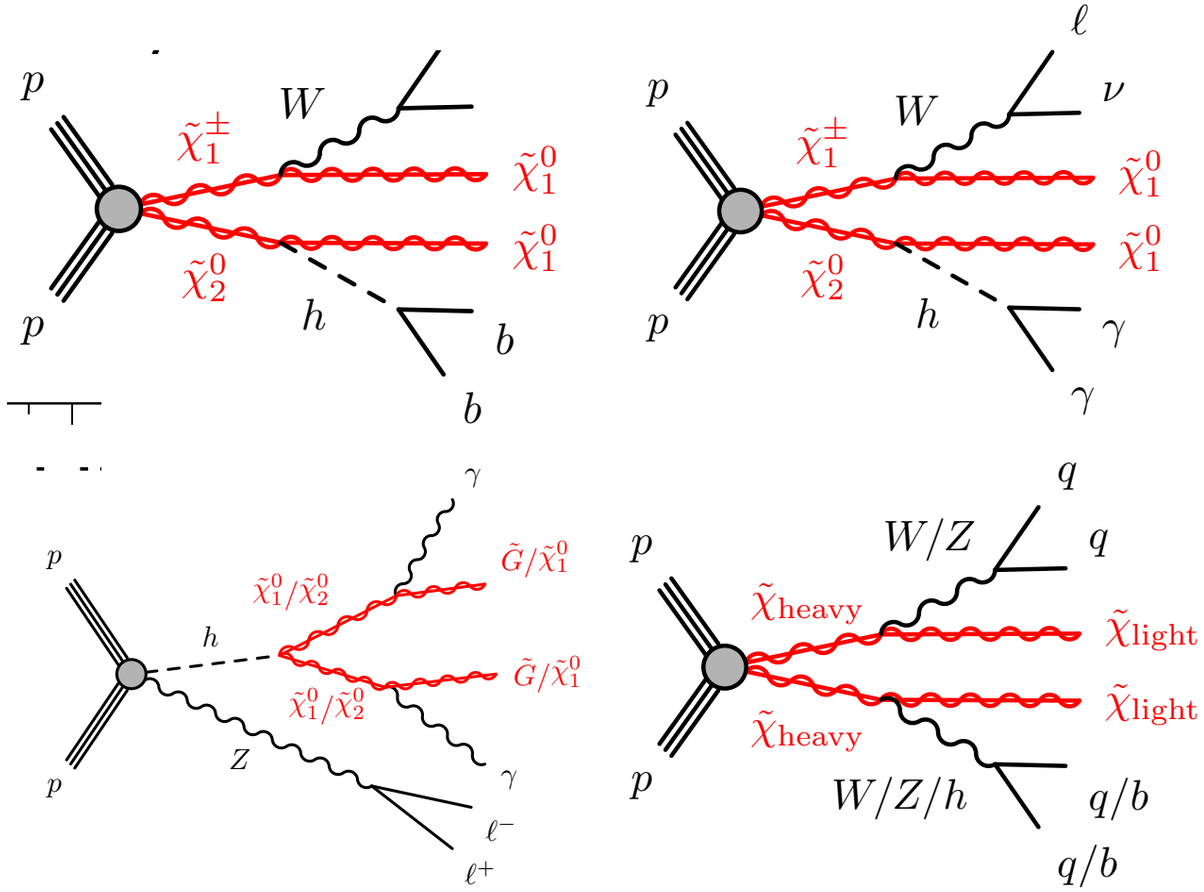


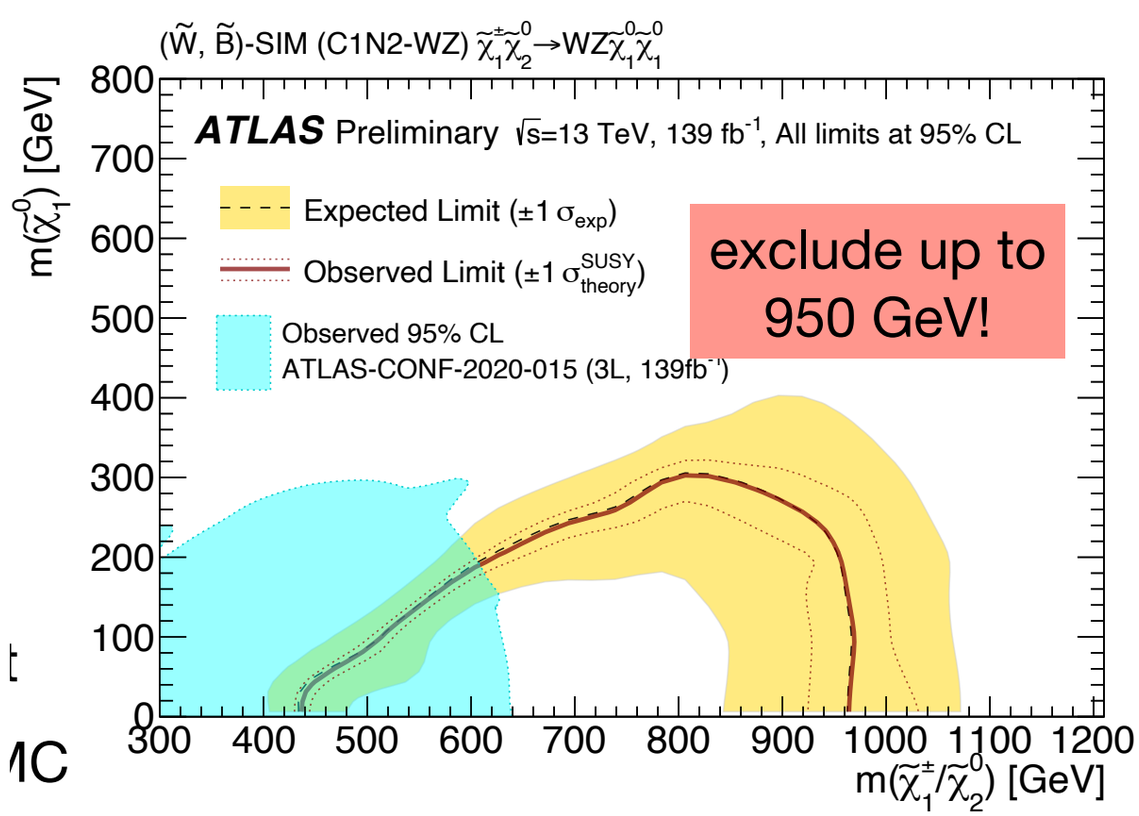
Supersymmetry

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→γγ and exotic Higgs decays in electroweak production



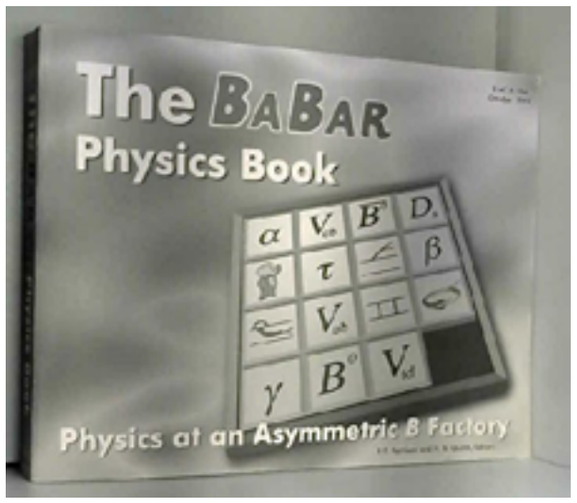


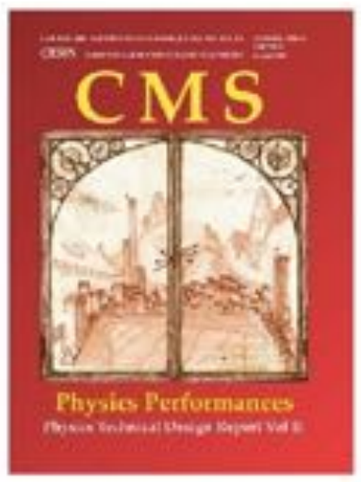


Advanced b-tagging and jet sub-structure

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 $1/\sqrt{\mathscr{L}}$ 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 additional to powerful ML techniques
- Human ingenuity assisted by Artificial Intelligence is putting us *further* ahead of statistics-only pace

Nice overview by Sergo Jindariani

x2 Run2

x10 Run3

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