Новости физики высоких энергий по материалам Европейской конференции по физике высоких энергий 2025
(7-11 июля, Марсель, Франция)

Семинар ОЭФВЭ 18.09.2025

Профессор Л.Н. Смирнова

Физический факультет

Юбилейная конференция по КХД

QCD 25: 40th anniversary
30 June-4 July 2025. Montpellier, France

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MONTPELLIER FRANCE
30 june – 04 july
2025
QCD
25
40th ANNIVERSARY

Европейская конференция по физике высоких энергий 2025, Марсель, Франция, 7 – 11 июля 2025

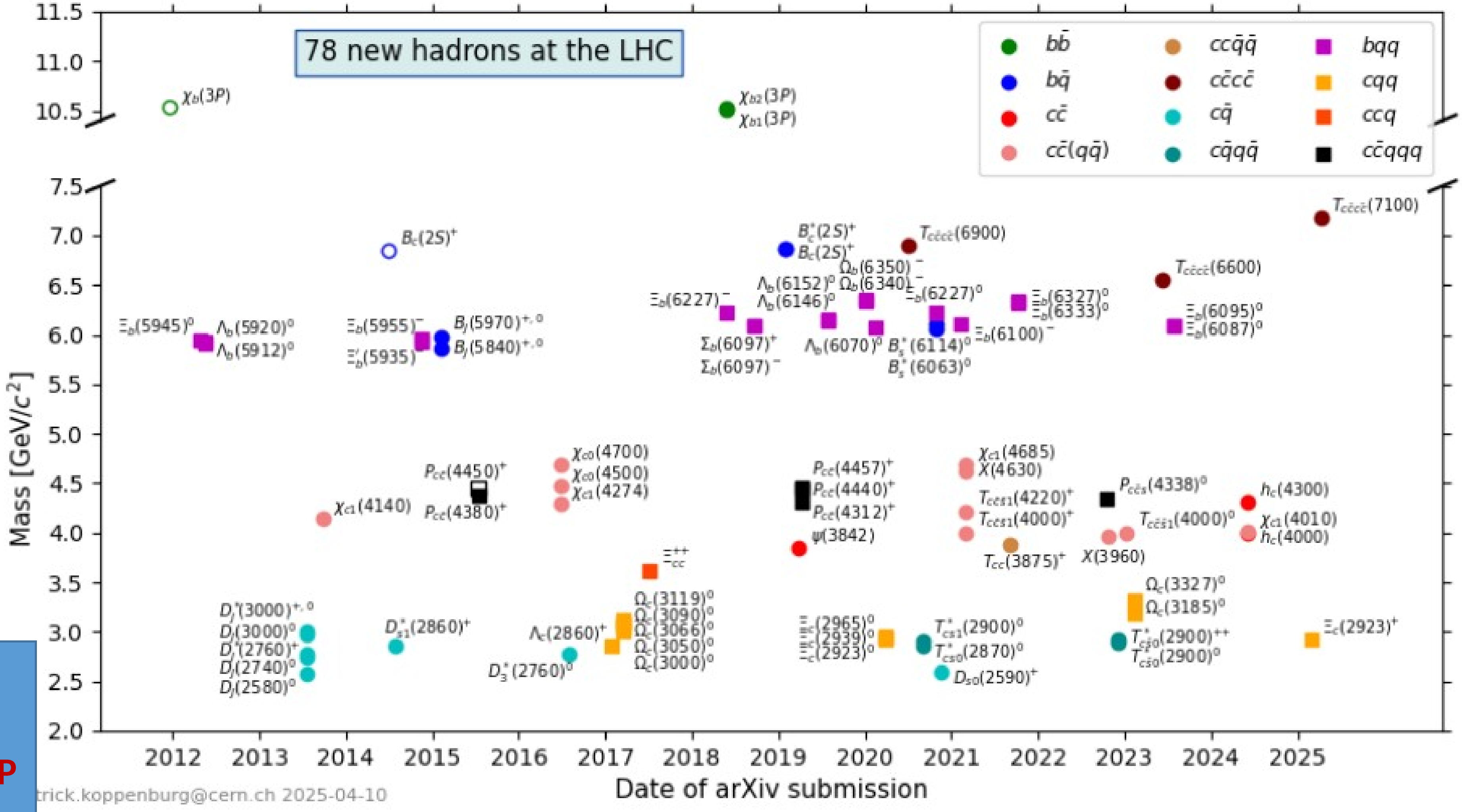
Previous conferences in this series were held in Hamburg (in 2023), Hamburg (online, in 2021), Ghent, Venice, Vienna, Stockholm, Grenoble, Krakow, Manchester, Lisbon, Aachen.

QFTHEP 270
(МГУ, Москва)

Open Symposium European Strategy oh Particle Physics
23-28 June 20205, CERN

59th Rencontres de Moriond: QCD & High Energy Interactions, La Thuile, April 2025

An exotic hadron factory



LHCb Highlights Vladimir V. Gligorov EPS-HEP 2025, Marseille, 09.07.2025

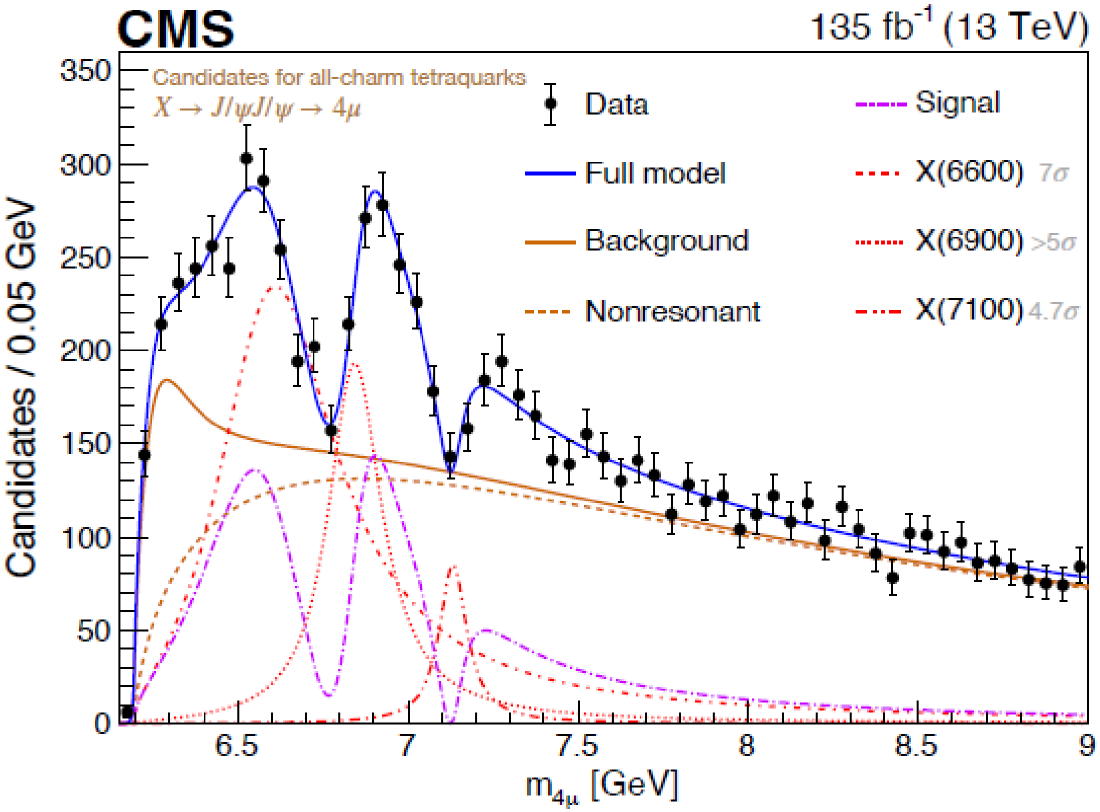
Credit to Patrick Koppenburg for the picture

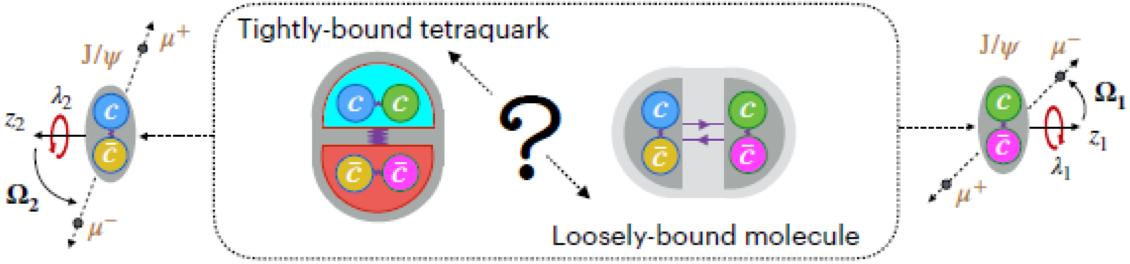
Determination of J^{CP} all-charm tetraquarks

arXiv:2506.07944
Submitted to Nature

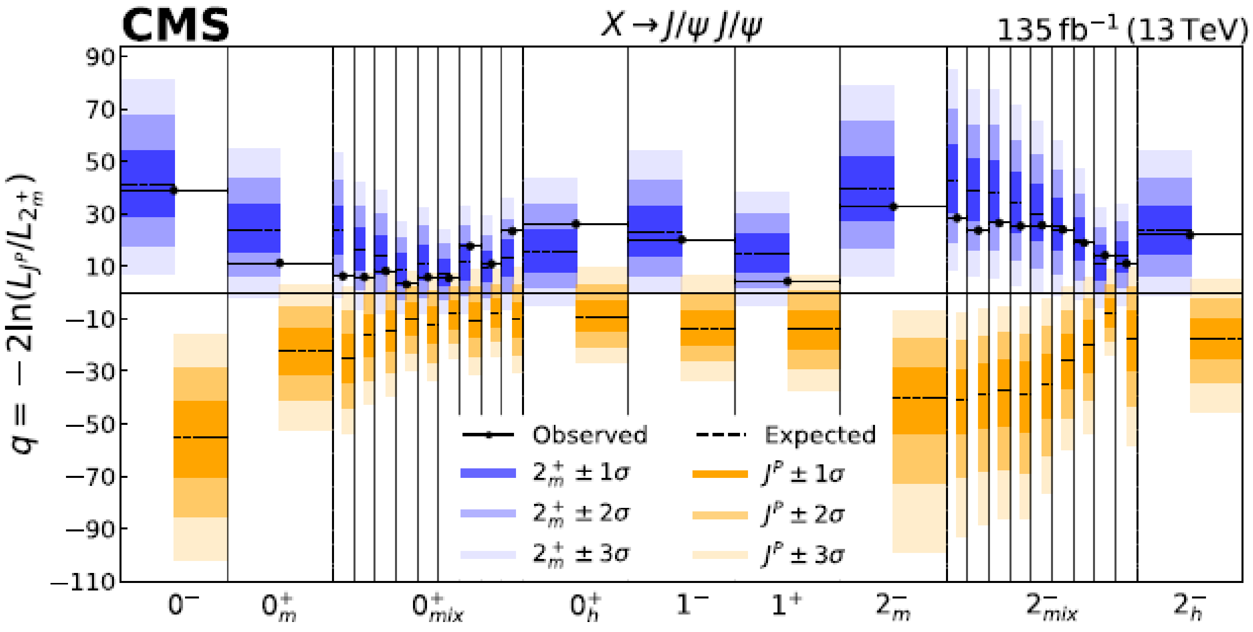
Observation of 3 X states in the $J/\psi J/\psi$ final state

Mass spacings following a radial Regge trajectory plus interference pattern
→ the 3 X particles form a family of cccc states with **same quantum numbers**





J^{CP} can be inferred from the polarizations of the mesons
→ angular distributions of the decay muons



CP = ++ established

Data consistent with 2+ (bound tetraquark) and inconsistent with others

Determination of J^{CP} all-charm tetraquarks

arXiv:2506.07944
Submitted to Nature

Observation of 3 X states in the $J/\psi J/\psi$ final state

Mass spacings following a radial Regge trajectory plus interference pattern

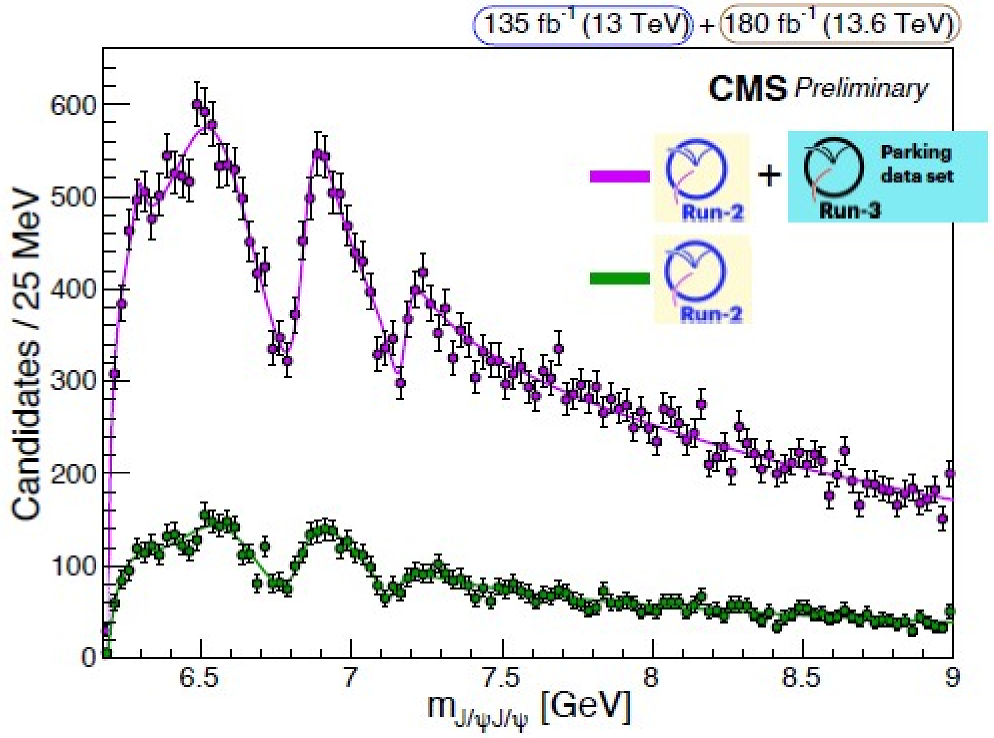
→ the 3 X p

BPH-24-003

Run-3 will bring significantly larger sample statistics thanks to parking data stream

3.6 times more $J/\psi J/\psi$ pairs

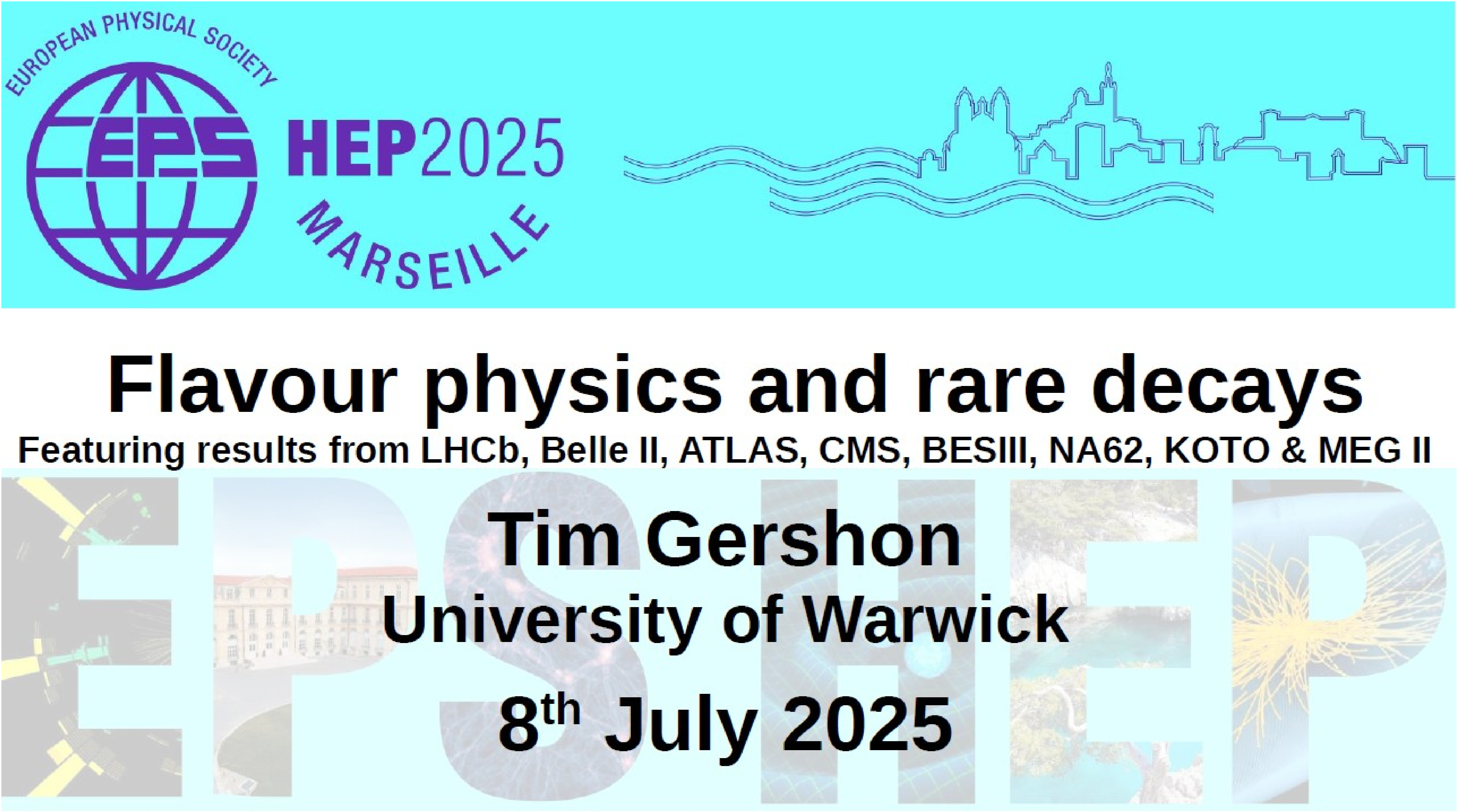
Expect more detailed studies of X family with enhanced dataset available



CP = ++ established

Data consistent with 2+ (bound tetraquark) and inconsistent with others

Физика распадов тяжелых адронов на существующих установках



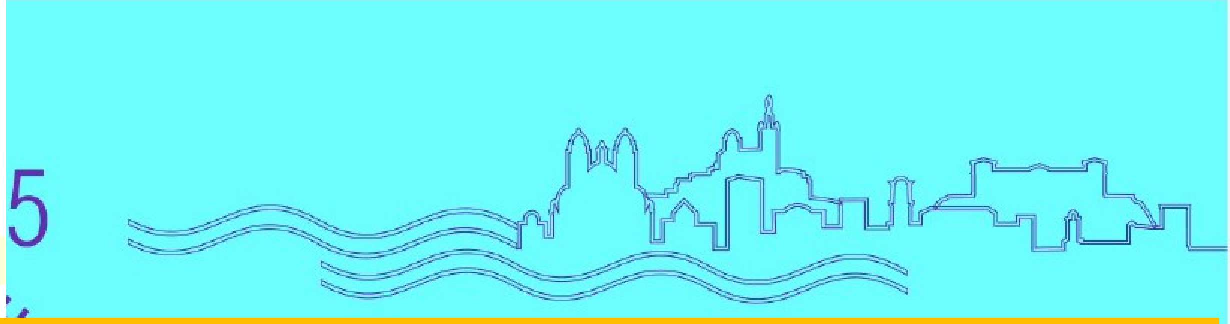
Основные разделы доклада Т. Гершона

From ...

- CP violation
- Quantum correlations
- Rare decays

- 1964: Discovery of $K_L \to \pi^+\pi^-$
  - Prior understanding: K_L is CP-odd
    - therefore cannot decay to $\pi^+\pi^-$, therefore long-lived
  - Later understood that K_L is not an equal admixture of K^0 and $\overline{K}^0$ states
    - CP-violation
- 1967: Sakharov conditions for evolution of matter-dominated universe
  1) baryon number violation
  2) C & CP violation
  3) thermal inequilibrium

Pisma Zh.Eksp.Teor.Fiz. 5 (1967) 32



- 1973: Kobayashi & Maskawa explanation of CP violation
  - Arises from single complex phase in 3x3 quark mixing matrix
  - Makes many distinctive and important predictions (see later)
- 2025: Observation of CP violation in baryon decays

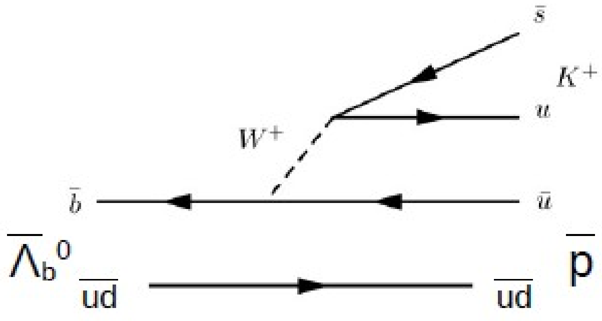
To get a baryon asymmetry, need either CP violation in baryon decays, or a mechanism to convert another asymmetry into baryons

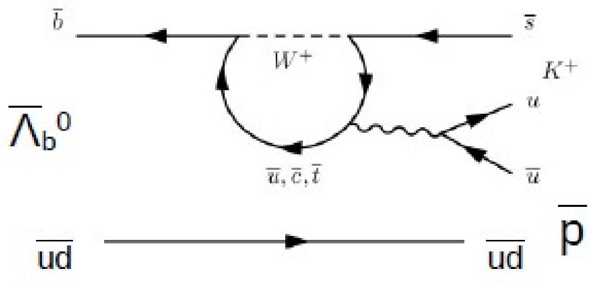
KM theory predicts CP violation in baryon decays but not seen until ...

- 2025: Observation of CP violation in baryon decays

CP violation in decay

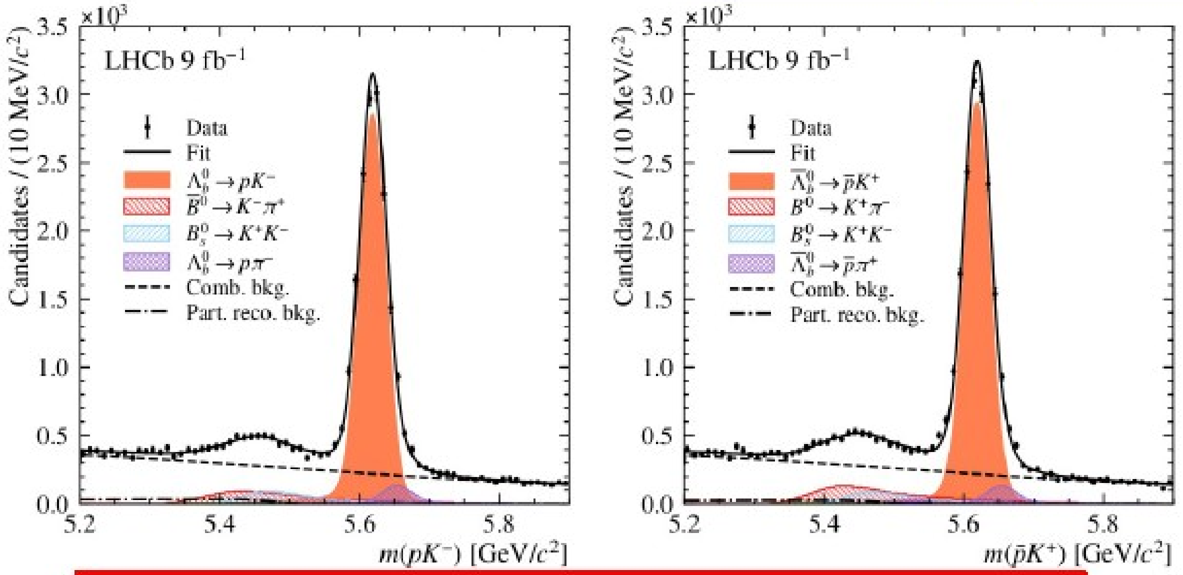
- Caused by interference between two amplitudes with different weak (CP violating) and strong (CP conserving) phases
- Often realised by “tree” and “penguin” diagrams
  - e.g. for $B^0 \to K^+\pi^-$
  - so why not for $\overline{\Lambda}_b^0 \to \overline{p}K^+$?





Relative weak phase ~ $\arg(-V_{ub}^* V_{us}/(V_{tb}^* V_{ts}))$ ~ γ

PR D111 (2025) 092004



$$\boxed{A_{CP}(\overline{\Lambda}_b^0 \to \overline{p}K^+) = (-1.1 \pm 0.7 \pm 0.4)\%}$$

Results account for small corrections due to production & detection asymmetries

Observation of CP violation in $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ decays

arXiv:2503.16954
to appear in Nature

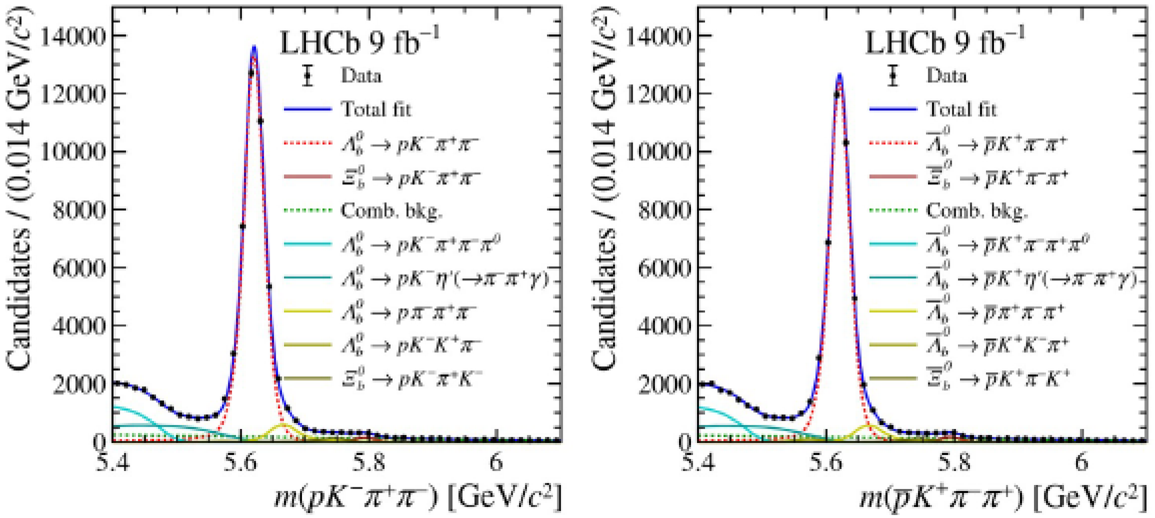
- Large samples of charmless 4-body Λ_b^0 decays available
- Use $\Lambda_b^0 \rightarrow \Lambda_c^+(pK^-\pi^+)\pi^-$ as reference channel

$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$ 5.2σ from zero

Enhanced CP violation effects appear in localised regions of phase space

- Largest for $m(p\pi^+\pi^-) < 2.7$ GeV/c^2

$$A_{CP} = (5.4 \pm 0.9 \pm 0.1)\%$$

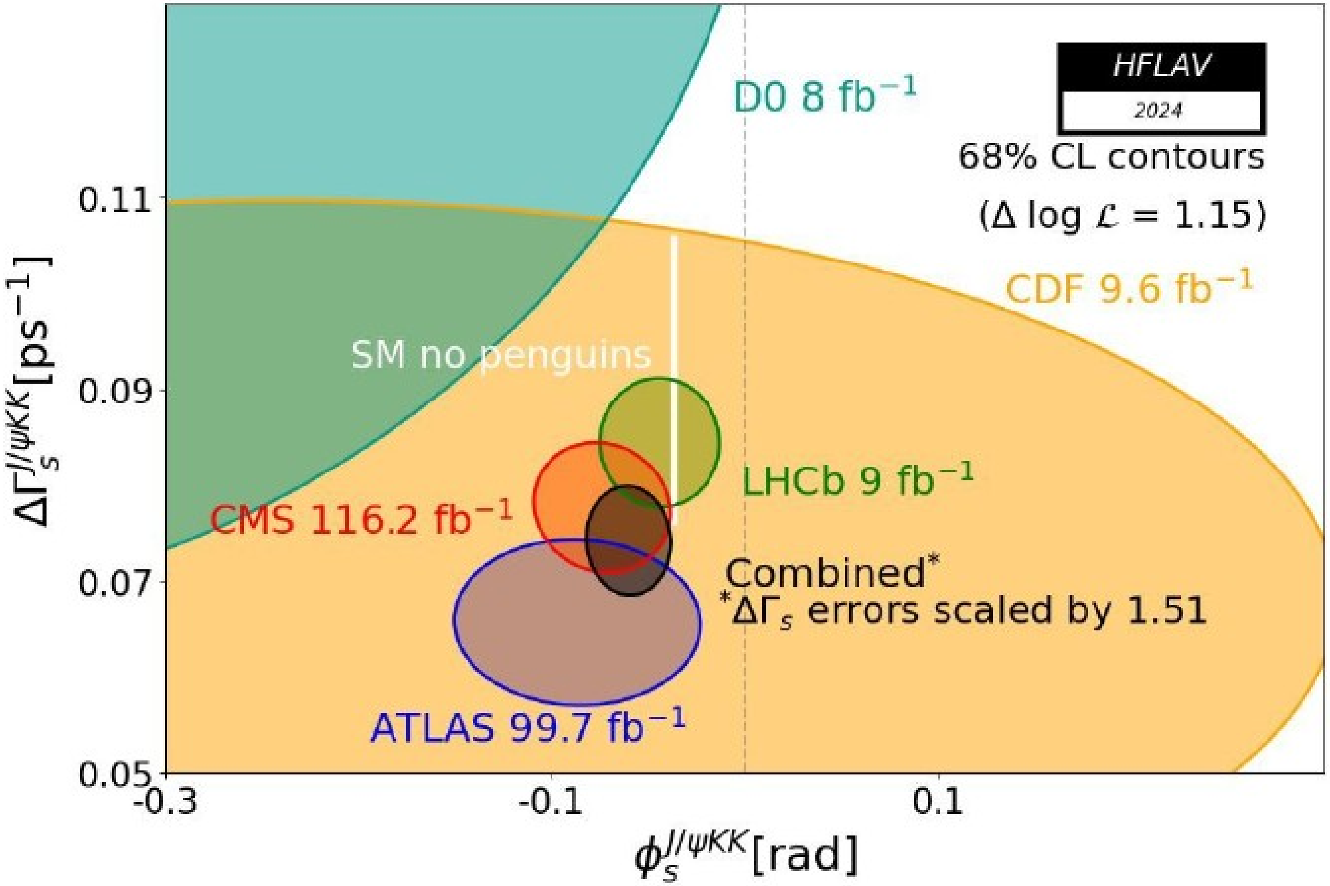


Significant milestone in CP violation history!

But, theoretical predictions for CP asymmetries, integrated over multiple resonances, are extremely challenging

Important next step: amplitude analysis to associate effects to resonances including interference effects

World average of $\beta_s(B_s \to J/\psi\varphi)$

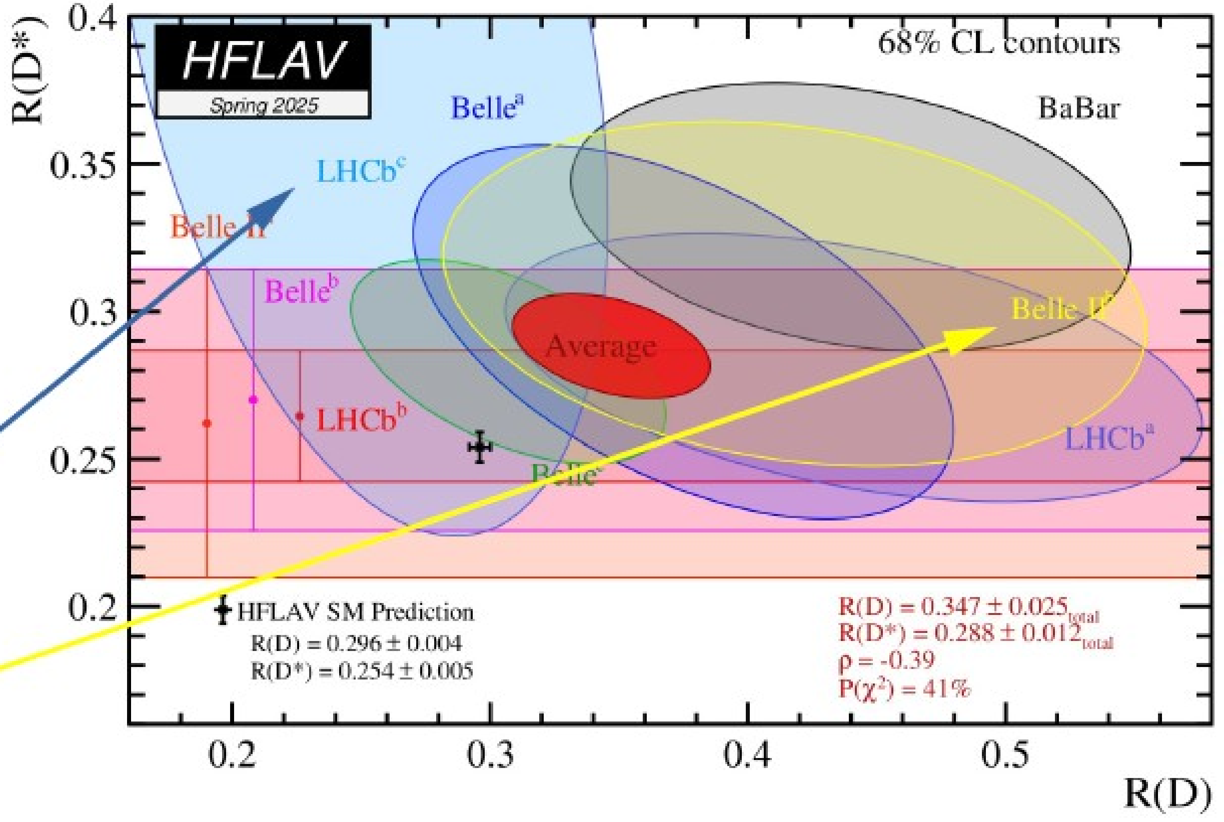


$$\varphi_s(B_s \to J/\psi\varphi) = -2\beta_s(B_s \to J/\psi\varphi) = -60 \pm 14 \text{ mrad}$$

c.f. precision on $2\beta(B^0 \to J/\psi K_S) \sim 16$ mrad

Interest in decays involving τ &/or ν

- Most significant anomaly today is in the branching fractions of $B \rightarrow D^{(*)}\tau\nu$ decays
  - R ratios to $\mathcal{B}(B \rightarrow D^{(*)}l\nu)$, $l = \tau$ c.f. e,μ
  - World averages for R(D)-R(D*) discrepant with SM predictions at 3.8σ
  - Theoretically clean; experimentally challenging
- Latest new results



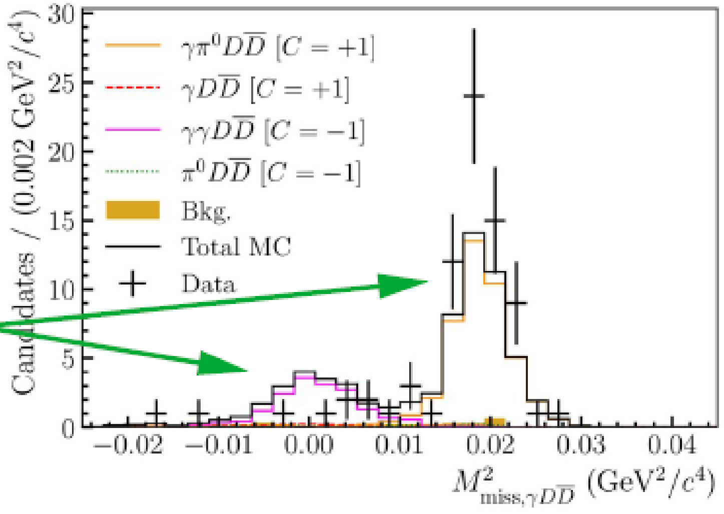
CP even $D^0\overline{D}^0$ pairs at BESIII

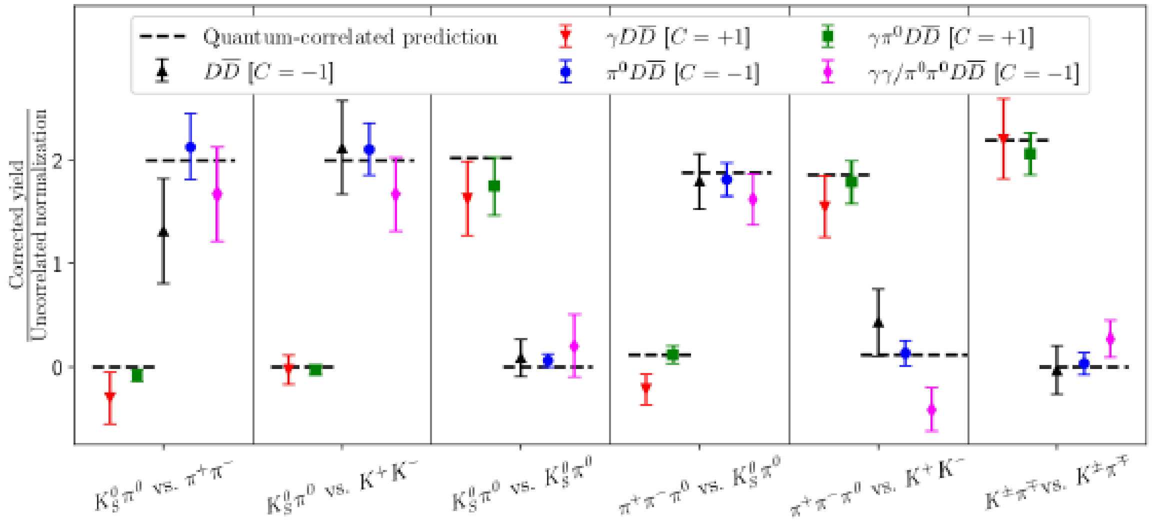
arXiv:2506.07906
arXiv:2506.07907

- CP even $D\overline{D}$ pairs produced in $e^+e^- \to D\overline{D} + \gamma$ (or any odd # γ)
- Data from e^+e^- collisions at $\sqrt{s}$ = 4.13−4.23 GeV, in five final states:
  - C = −1: $D\overline{D}$, $D^*\overline{D}$ / $D\overline{D}^* \to \pi^0 D\overline{D}$, $D^*\overline{D}^* \to \gamma\gamma/\pi^0\pi^0 D\overline{D}$
  - C = +1: $D^*\overline{D}$ / $D\overline{D}^* \to \gamma D\overline{D}$, $D^*\overline{D}^* \to \gamma\pi^0 D\overline{D}$

$D\overline{D}\gamma$ + missing energy reconstructed

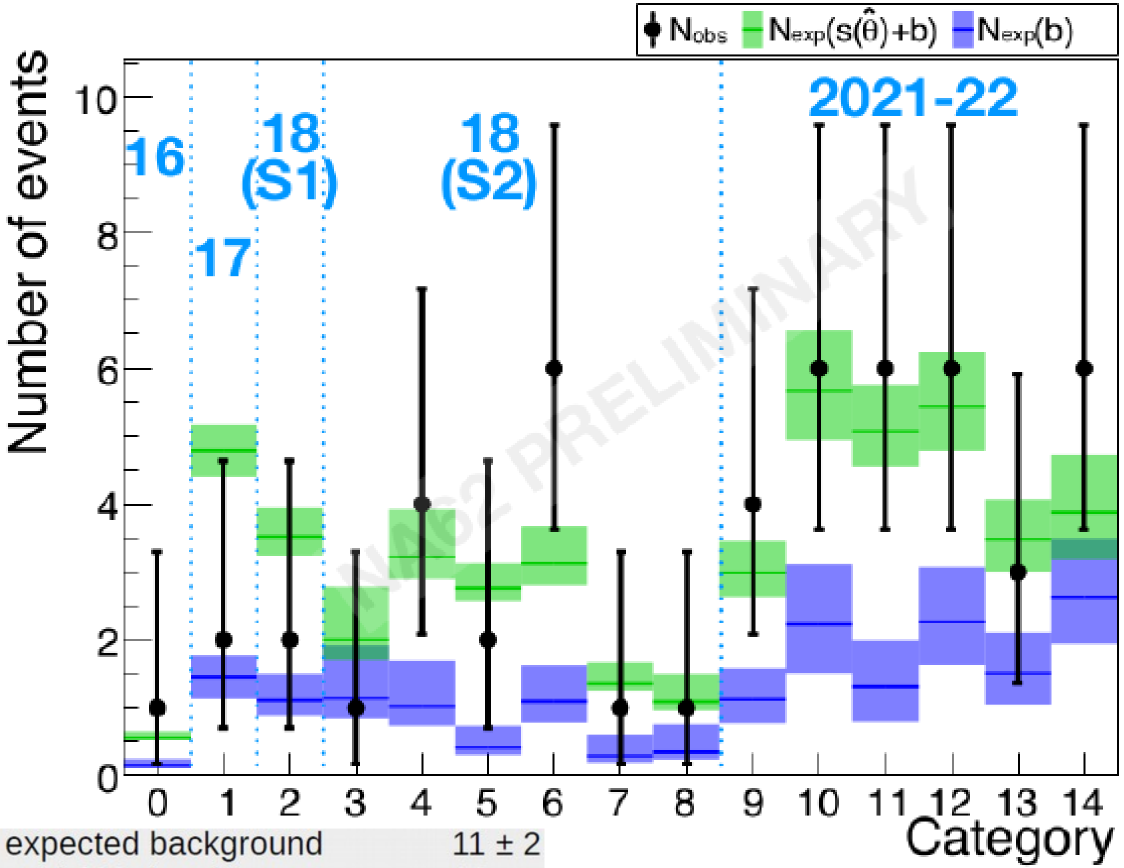
Simulation does not include quantum correlations – clear suppression/enhancements observed

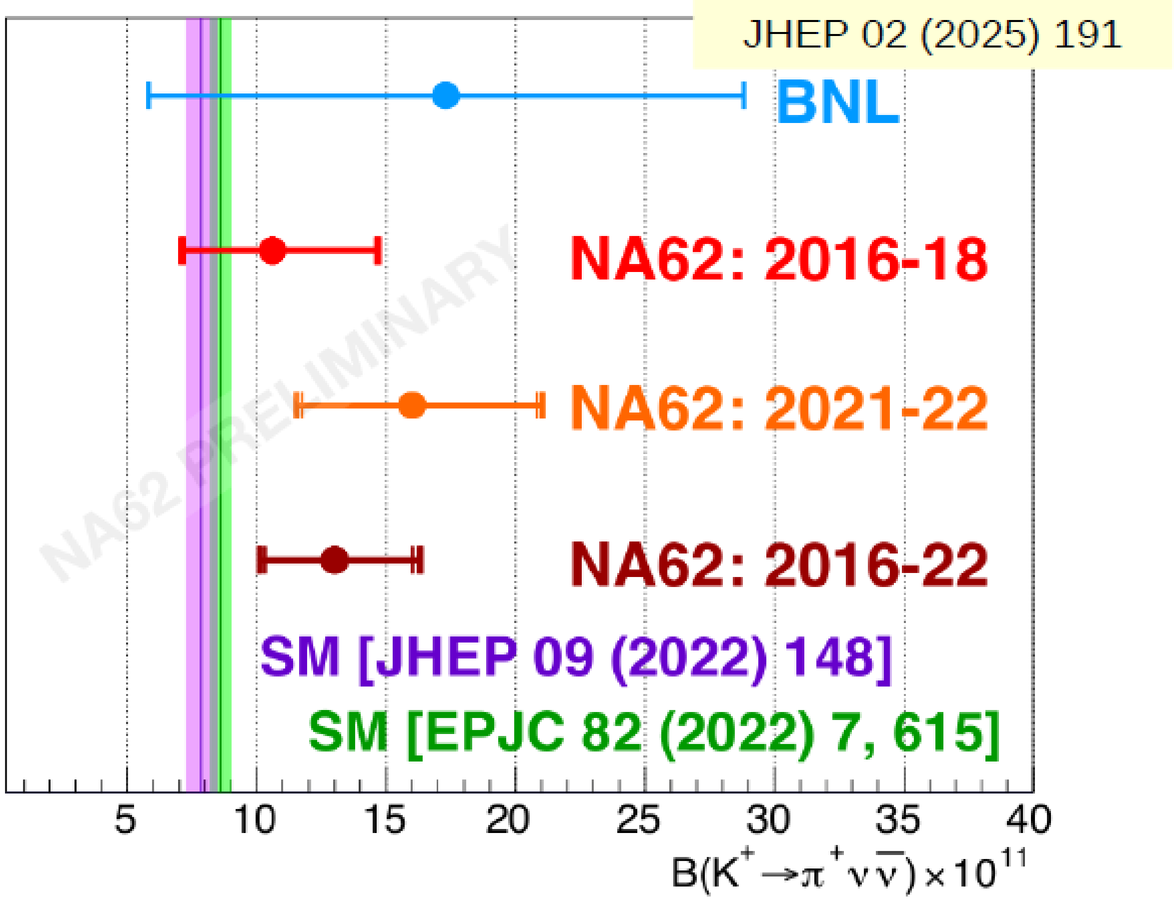




New opportunities for studies with larger data samples – very interesting prospects for STCF

NA62 result on $K^+ \to \pi^+ \nu \bar{\nu}$ (2016-22 data)





• Total expected background	11 ± 2
• Expected SM signal	10
• Observed decays in signal regions	31

>5σ from zero
Consistent with SM within 2σ
Further data-taking until end of Run 3

$$B(K^+ \to \pi^+ \nu \bar{\nu}) = \left(13.0\,^{+3.0}_{-2.7}\big|_{\rm stat}\,^{+1.3}_{-1.3}\big|_{\rm syst}\right) \times 10^{-11}$$

Rare decays

- In recent years, discussion of rare B decays has involved frequent use of the word “anomalies”
- Three sets of observables
  - theoretically pristine: lepton universality violating
    - latest FCNC results consistent with SM

    arXiv:2505.03483, PRL 134 (2025) 181803, PRL 134 (2025) 121803, PRL 131 (2023) 051803, PR D108 (2023) 032002
  - theoretically clean: purely leptonic final states
    - latest results ($\mathcal{B}(B \to \mu^+\mu^-)$) consistent with SM

    PL B842 (2023) 137955, PRL 128 (2022) 041801, PR D105 (2022) 012010, JHEP 04 (2019) 098
  - theoretically more challenging: branching fractions and angular observables
    - anomalies persist
- Most relevant question: how to overcome theoretical uncertainties?
  - several directions being pursued ...

SMU

Theoretical Overview and Motivation

- FCNCs in c-hadron decays mediated by $c \to u$ transitions, which have even smaller SM predictions, remain less explored
- Rare c-hadron decays differ from those of b- and s-hadrons due to their loop contributions being mediated by lighter quarks, resulting in significant long-distance effects that are hard to predict analytically. Consequently, SM predictions are less reliable, and new physics searches focus on contributions that significantly exceed SM expectations
- $\boldsymbol{D^0 \to \mu^+\mu^-}$ is such one interesting case[1]; the SM predicted $\mathcal{B}(D^0 \to \mu^+\mu^-)$ is of the order of $\mathbf{3 \times 10^{-13}}$ The **most sensitive result to date**, from LHCb[2] **set an upper limit at $\mathbf{3 \times 10^{-9}}$ at 95% CL, four orders of magnitude larger than the SM prediction, indicating a substantial unexplored territory**

1. Phys.Rev.D 66 (2002) 014009
2. Phys.Rev.Lett. 131 (2023) 4, 041804

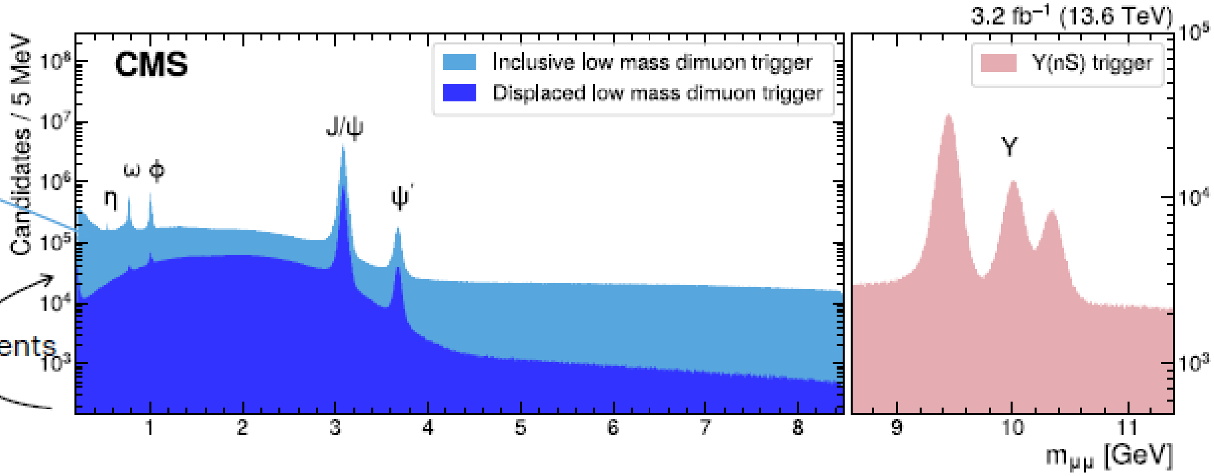
Search for rare D^0 decay

arXiv:2506.06152
Submitted to PRL

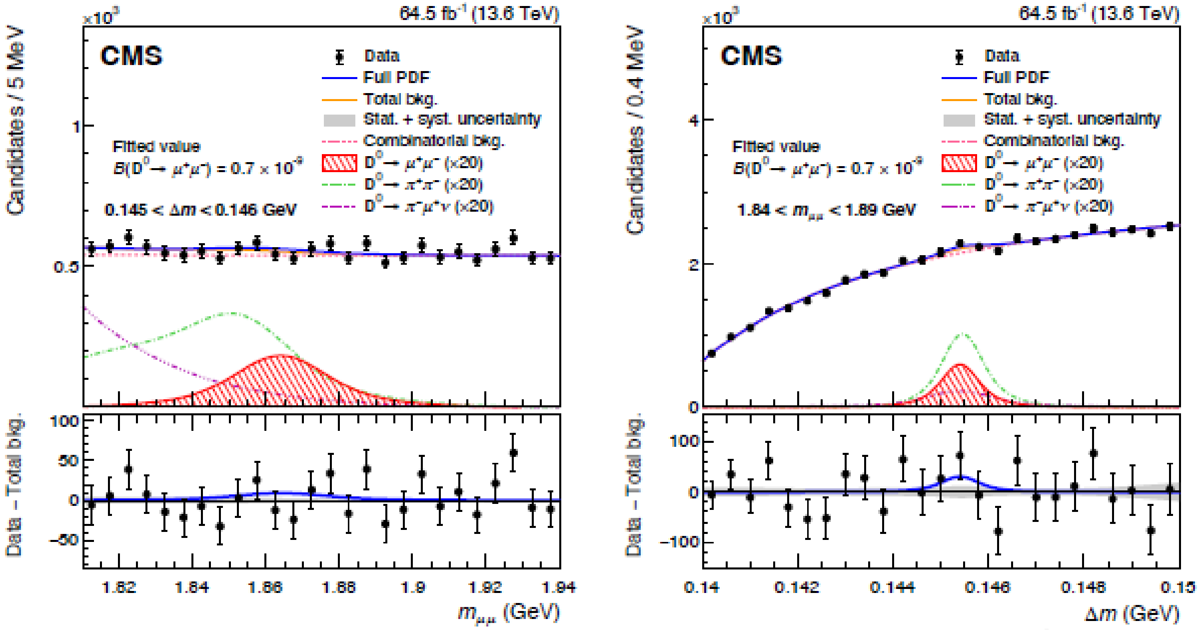
Parking data set
Run-3

In Run-3 using a new inclusive dimuon trigger, the low-mass coverage below 8.5 GeV is extended. Crucial for future low-mass flavor physics studies.

More events



2D unbinned maximum likelihood fit $m_{\mu\mu}$ and $\Delta m = m_{D^{0*}} - m_{D^0}$



Study of the rare D^0 decays mediated by flavor changing neutral currents

Rare decays of charmed hadrons via $c \to u$ process

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.1\,(2.4) \times 10^{-9} \text{ at } 90\,(95)\%\ \text{CL}$$

Setting the most stringent limit on flavor changing neutral currents in the charm sector

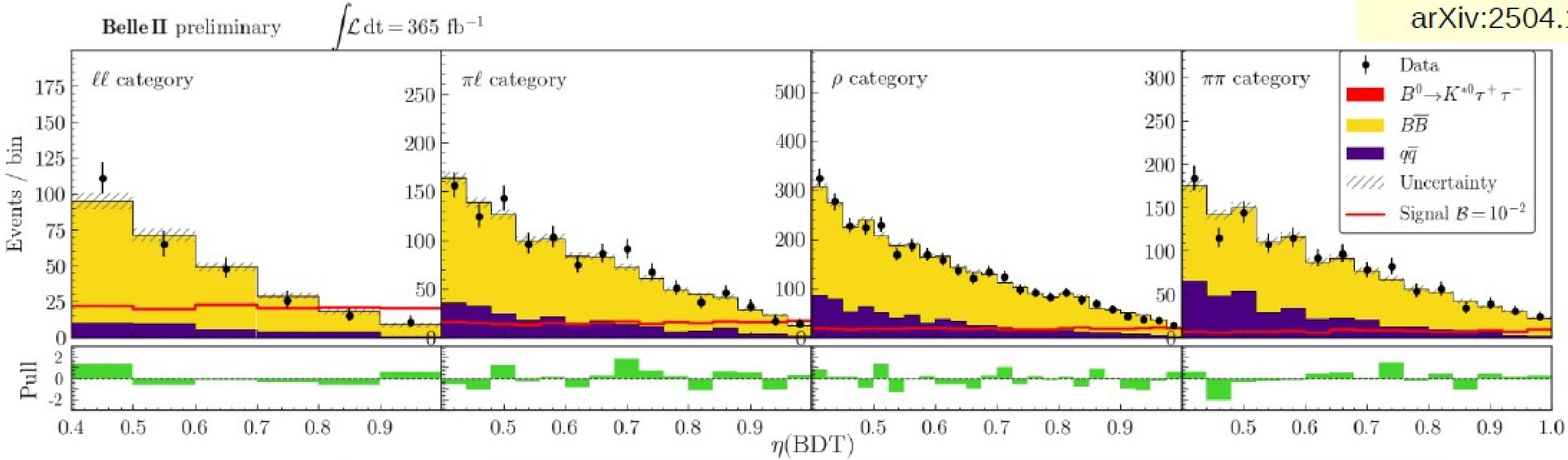
Recent Highlights

$B^0 \to K^{*0}\tau^+\tau^-$

[Not fundamentally cleaner theoretically, but BSM effects may be larger for heavier leptons]

- Experimentally highly challenging due to missing ν from τ decays & background from $D_{(s)}$ decays
- Exploit kinematic constraints in $e^+e^- \to B_{sig}B_{tag}$, with B_{tag} reconstructed in hadronic decay modes
- Signal-background separation through BDT, separately for different τ final states

arXiv:2504.10042



LHCb amplitude fit of $B^0 \to K^{*0}\mu^+\mu^-$ gives a limit
$B(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$ at 90% CL
JHEP 09 (2024) 026

$\boxed{B(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3} \text{ at 90\% CL}}$

SM prediction $O(10^{-7})$

Digression: Quantum correlations

- All measurements of decay-time-dependent CP violation in $\Upsilon(4S) \to B^0\overline{B}^0$ rely on the quantum entanglement of the final state
  - In this case the state is C odd, i.e. $|\psi\rangle = (|B_1\rangle|\overline{B}_2\rangle - |B_2\rangle|\overline{B}_1\rangle)/\sqrt{2}$
  - New ideas to exploit this still emerging, e.g. arXiv:2506.11196
- Quantum entanglement also used to study hadronic D decay properties in $\psi(3770) \to D^0\overline{D}^0$ decays (also a C odd configuration)
  - These measurements are crucial inputs for charm mixing & CP violation measurements, and for the determination of γ from $B^\pm \to DK^\pm$ and related processes
- Noted long-ago that C even quantum entangled pairs offer various interesting possibilities
  - $|\psi\rangle = (|B_1\rangle|\overline{B}_2\rangle + |B_2\rangle|\overline{B}_1\rangle)/\sqrt{2}$
  - e.g. Sensitivity to CP violation effects from interference between mixing and decay in decay-time-integrated analyses

The future

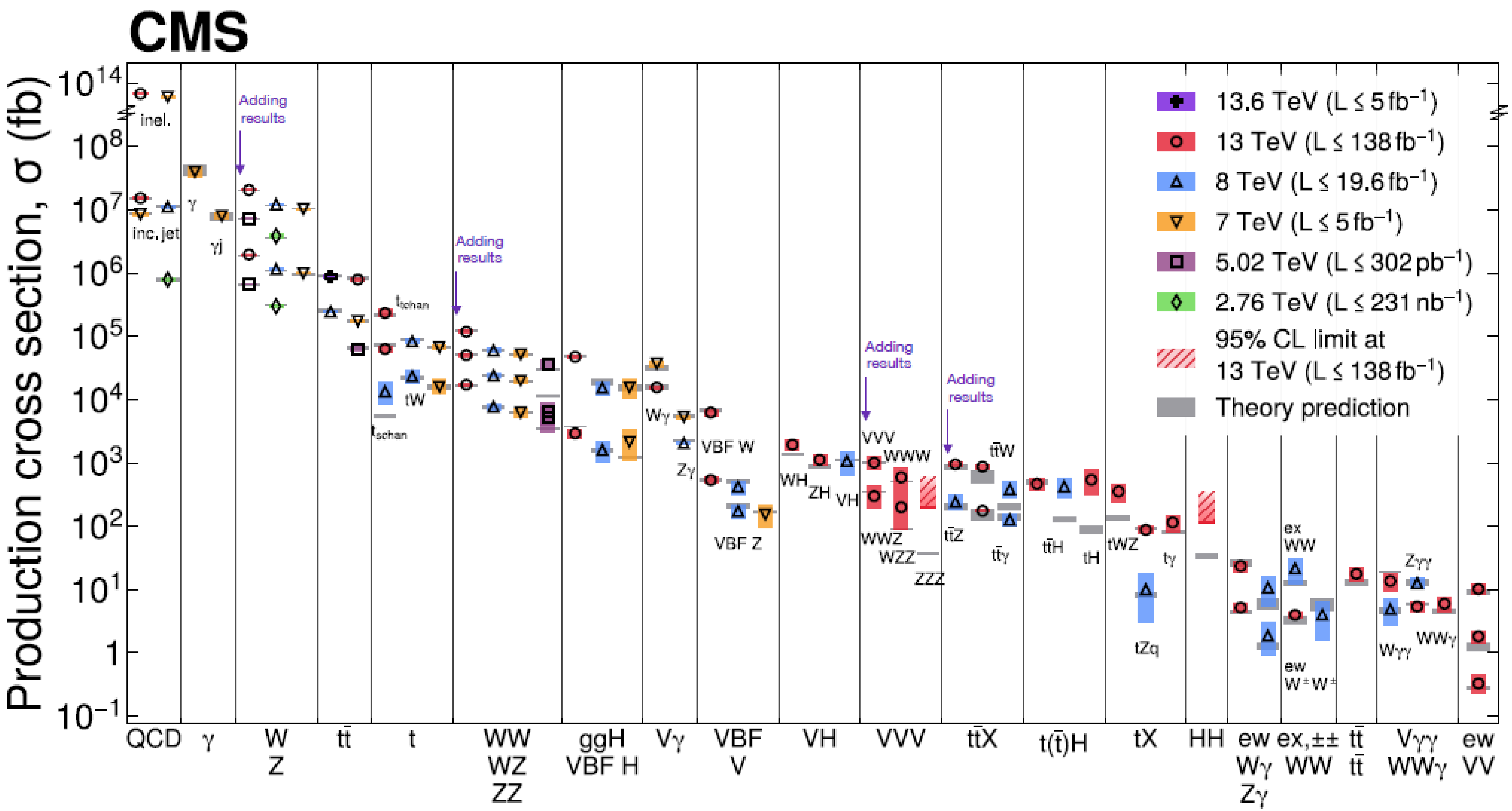
- Exciting prospects in medium term with HL-LHC, ATLAS and CMS upgrades (3/ab), LHCb Upgrade II (300/fb) and Belle II (50/ab), plus completion of BESIII &, potentially, STCF
  - Samples sizes for B, D & τ decays will increase typically by a factor of 100
    - Precision improved by factor 10 for most observables
- Further progress in kaon physics from NA62 & KOTO (plus LHCb)
  - KOTO2 proposal can push further on K_L rare decays
  - Currently no clear plan to push further on some interesting K observables
- Will flavour physics still be interesting by mid-2040s?
  - Certainly, because still scope for further improvement
    - In particular for experimentally challenging decays involving τ &/or ν

Summary

- Huge amount of progress in recent years
  - Precision in many areas now sufficient that subleading effects need to be accounted for
    - e.g. penguin pollution in $\beta_{(s)}$ measurements, long-distance effects in rare decays
  - Methods exist to do this and are being pursued
    - exciting new ideas still appearing
- Improvements in analysis techniques giving better than anticipated precision
  - e.g. machine learning techniques in selection and flavour tagging
- Far too much to cover, apologies if I missed your favourite topic
    - charm mixing, CP violation and rare decays, beauty and charm lifetimes, determinations of CKM angles γ and α, determinations of $|V_{cb}|$ and $|V_{ub}|$, polarisation in $B \to VV$ decays, hadron spectroscopy including discoveries of exotic hadrons, searches for lepton flavour violation and other SM null tests, …
- Data still to exploit and much more on the way – near and longer term prospects are bright
  - More in talks by Vava Gligorov, Karim Trabelsi and Sophie Renner

From millibarns to femtobarns

Physics Report 1115 (2025) 3



Cross-Section measurements of selected processes as of May 2024

We are continuing the exploration of these processes using Run-3

Top quark-antiquark excess

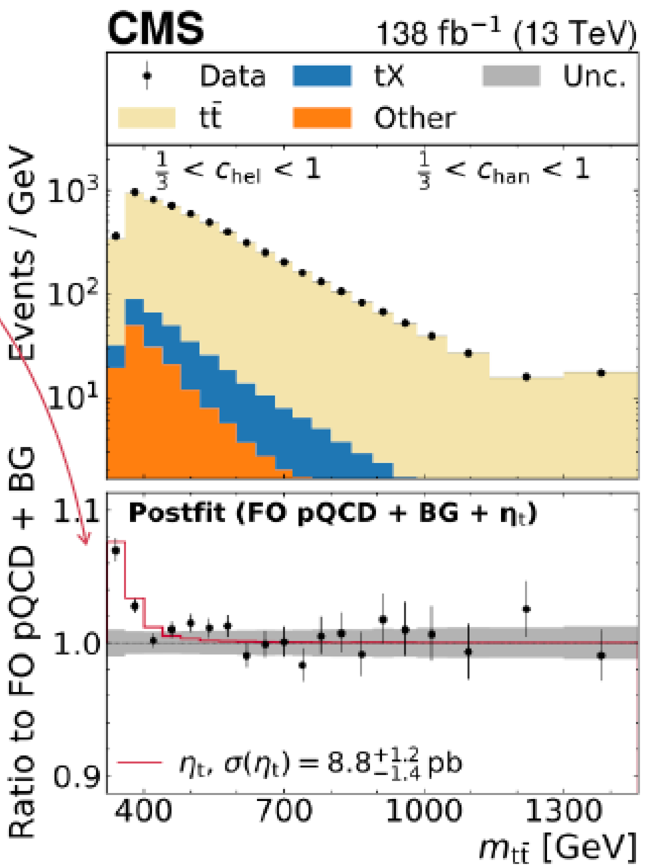
arXiv:2503.22382
Submitted to ROPP

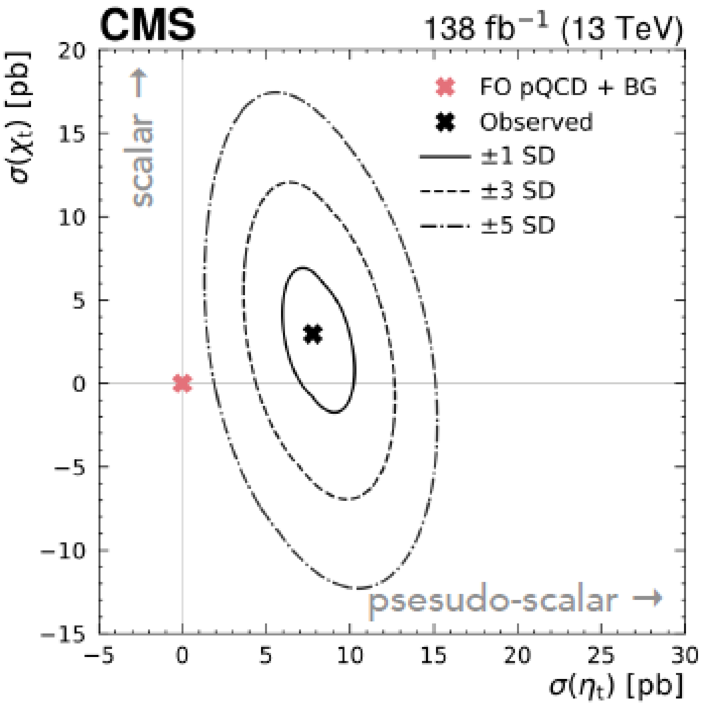
In the search for H/A resonances into $t\bar{t}$ observed an excess of data at threshold

Measured cross section of a quasi-bound

$$\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}\,\text{pb}$$

Compatible with NRQCD prediction $\sigma(\eta_t) = 6.4$ pb
arXiv:2102.11281 arXiv:2401.08751





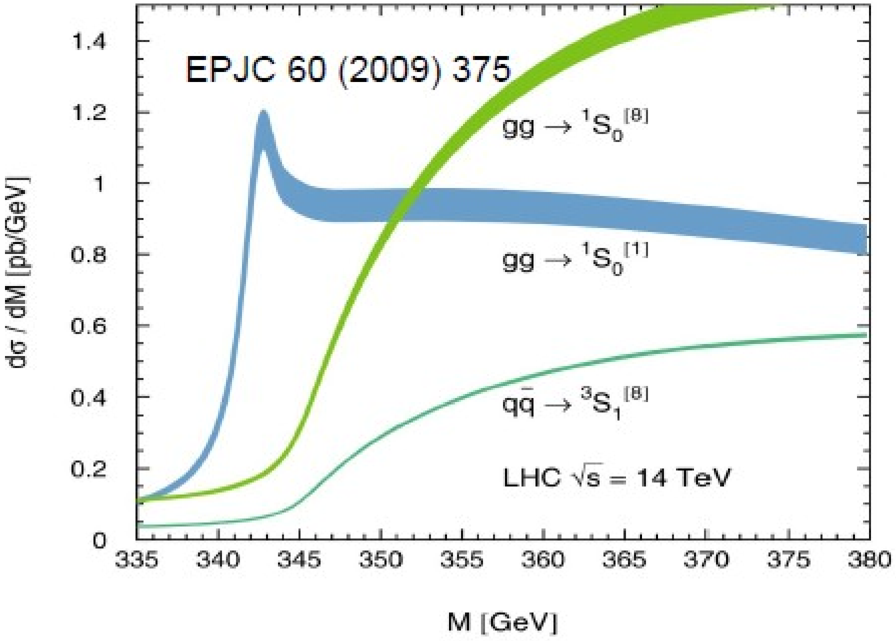
Excess compatible with pseudo-scalar hypothesis

Observation of a NRQCD effect is a great triumph.

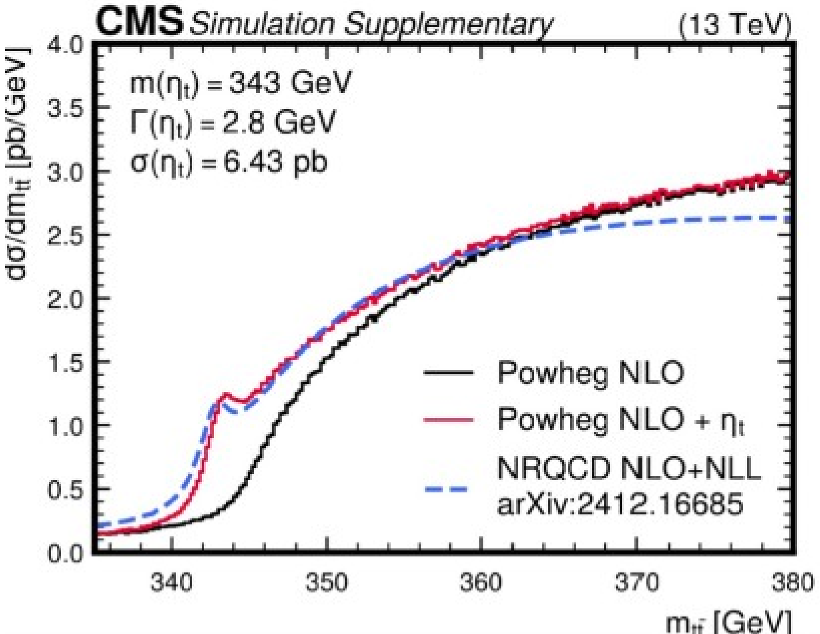
Modelling of the $t\bar{t}$ threshold region is challenging and requires further theoretical investigation

Recent Highlights

Top production at threshold



Experiment	Model	Cross Section (pb)
ATLAS	**NR-QCD**	**9.0 +- 1.2 (stat) +- 0.6 (syst)**
ATLAS	Pseudoscalar	13.4 +- 1.7 (stat) +- 1.0 (syst)
CMS	**Pseudoscalar**	**8.8 +- 0.5 (stat) +- 1.2 (syst)**



- NR-QCD quasi-bound state can also be approximated with a simplified model: pseudoscalar resonance with appropriate mass/width/coupling
- Nominal cross sections for additional state agree between ATLAS and CMS, but with different signal models
- Non-negligible theory modeling uncertainties in both cases (but different methods used for uncertainty breakdowns)
- More theoretical study needed for improved interpretations in the future

arXiv:2503.22382, ATLAS-CONF-2025-008

Bound to be discovered? ATLAS explores top-quark interactions near threshold

7 July 2025 | By

ATLAS Collaboration

The top quark is a bit of a loner. While other quarks can join together to form bound states called hadrons, the top quark's extremely short lifetime means it decays almost instantly – disappearing before it can form a long-lasting bond.

But not all relationships have to last forever. Under certain conditions, physicists predict that a top quark and an anti-top quark could exchange gluons for a short time before decaying independently. This fleeting interaction, called a *quasi-bound state*, can only form when both top quarks are produced almost at rest (i.e. non-relativistically) and the collision energy is close to twice the top quark's mass. This is the *production threshold*, and the mass of this quasi-bound state would be slightly below it.

Observation of ttbar cross-section enhancement at threshold

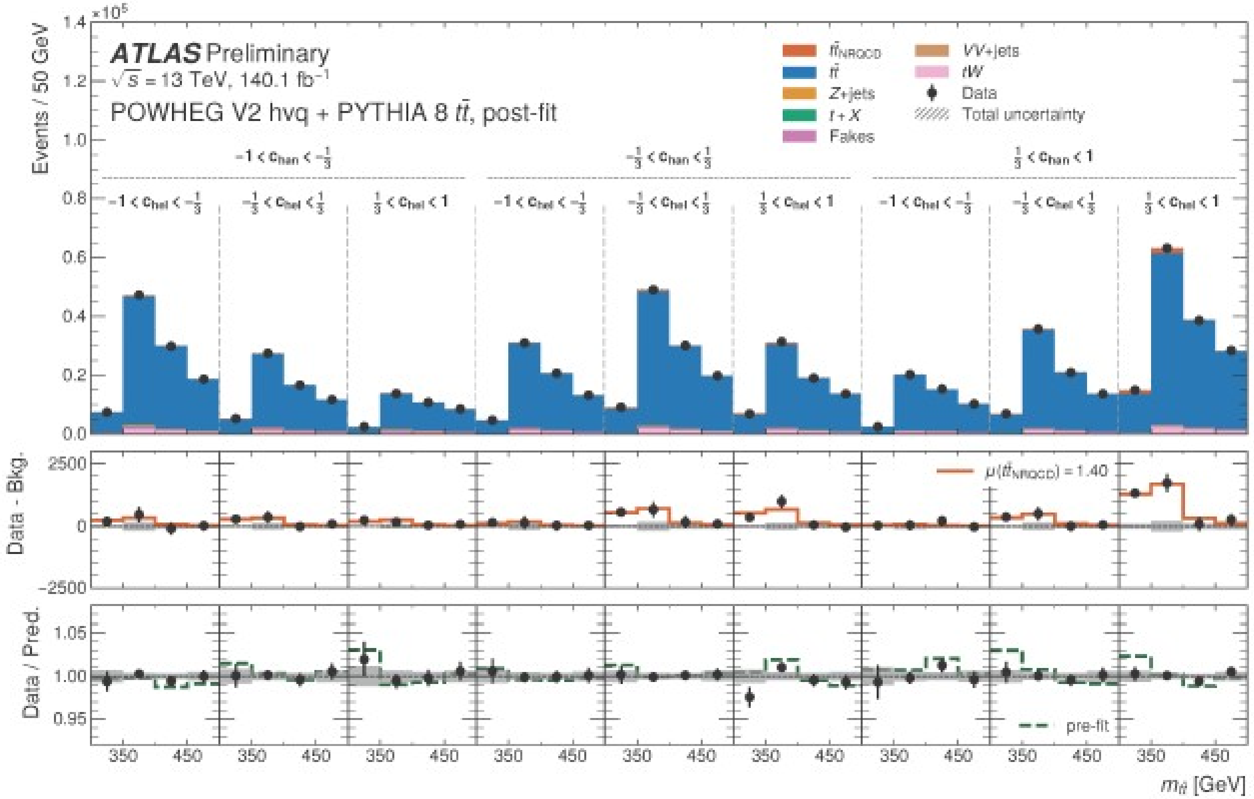
- Use tt→ℓνb ℓνb leptonic decay:
  - Reconstruction of m_{tt} → mass resolution **~20%** at threshold
  - Enhance sensitivity using lepton angular variables sensitive to tt spin correlation (c_{hel} and c_{han}) signal behaves as "*pseudo-scalar*"
- Fit to the data in 9 SR with m_{tt} bins (300-500 GeV)
  - Background Model: baseline pQCD
  - Signal Model: NRQCD (from Fuks et al.)
- Bkg.-only hypothesis rejected at **7.7σ**

$\sigma(tt_{NRQCD}) = 9.0 \pm 1.3$ pb (expected 6.4pb, 5.7σ)

ATLAS **observed** this *elusive* NRQCD phenomena

more work is needed on theory side (off-shell effects, matching pQCD and NRQCD, other NRQCD effects, ...) to better establish the properties of the observed signal

ATLAS-CONF-2025-008 Physics Briefing



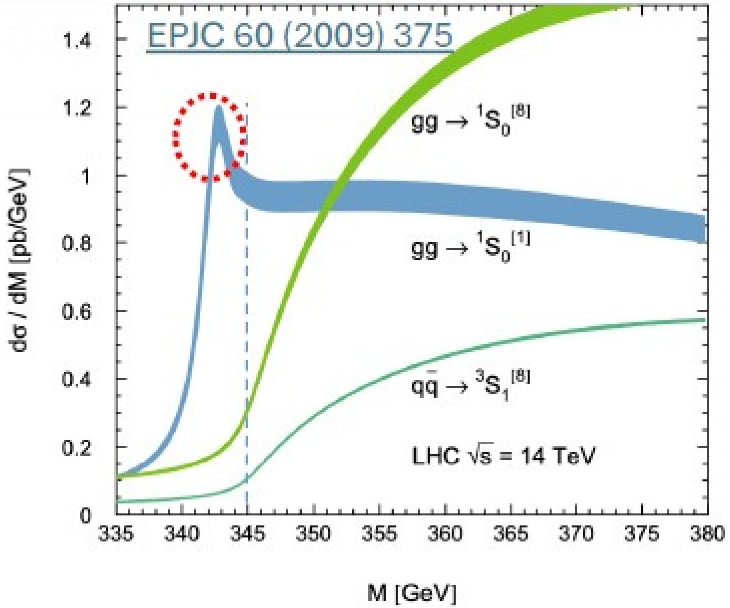
Parallel Session talk by Haifeng Li

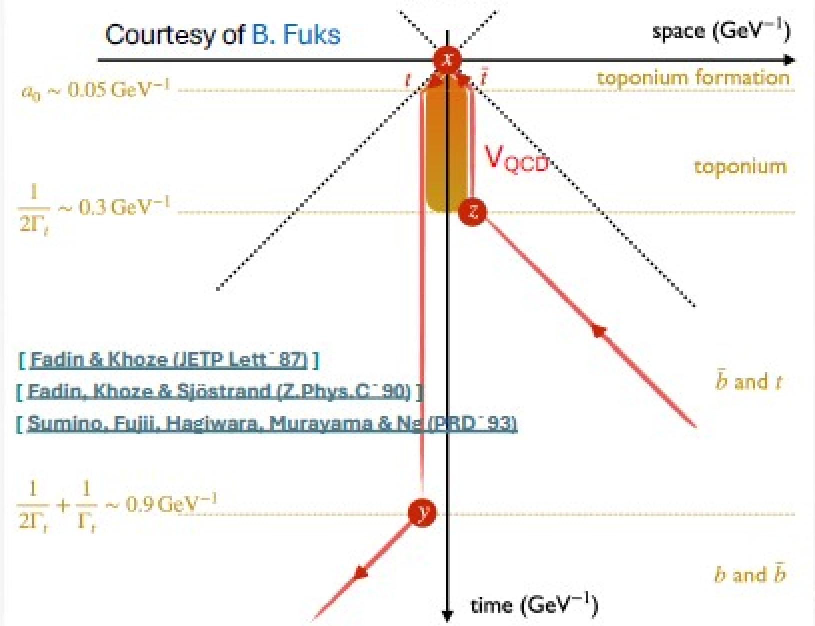
Observation of a ttbar cross-section enhancement at threshold

New

ATLAS EXPERIMENT

- Non-Relativistic QCD predicts the formation at threshold (m_{tt}~$2m_t$~345 GeV) of **quasi-bound-state** *(Toponium)*: spin-singlet - color-singlet $^1S_0^{[1]}$
- Our baseline tt modeling - PS-matched pQCD predictions reweighted to NNLO-QCD+NLO-EW – is missing these NRQCD states
- Experimentally extremely challenging: small effect (1% of total xs) in a m_{tt} region much smaller than experimental resolution
- **New modeling** of NRQCD effects via the re-weighting of the tt production MEs through the non-relativistic QCD Green's function and projection to color singlet (Fuks et al. EPJC 85 (2025) 157) used as "signal"
- CMS measurement based on simplified model (pseudo-scalar resonance η_t)
  - $\sigma(\eta_t)=8.8^{+1.2}_{-1.4}$ pb >5 σ observation arXiv:2503.22382





Charting the Higgs Sector

Ultimate Precision at 13 TeV

HIG-21-018

Combination of 16 CMS published analyses incorporating

7 decay channels *($\gamma\gamma$, ZZ, WW, bb, $\tau\tau$, $\mu\mu$, $Z\gamma$)*

6 production channels *(ggH, VBF, WH, ZH, ttH, tH)*

Searches for H to invisible

H off-shell production

A wide array of the interpretations is provided

Signal strengths
inclusive/production/decay/production×decay

Signal strengths with $\sigma \times \mathscr{B}$

Cross sections
STXS stage 0/STXS stage 1.2

Coupling modifiers
resolved/effective/off-shell/ratio

Higgs self-couplings

SMEFT

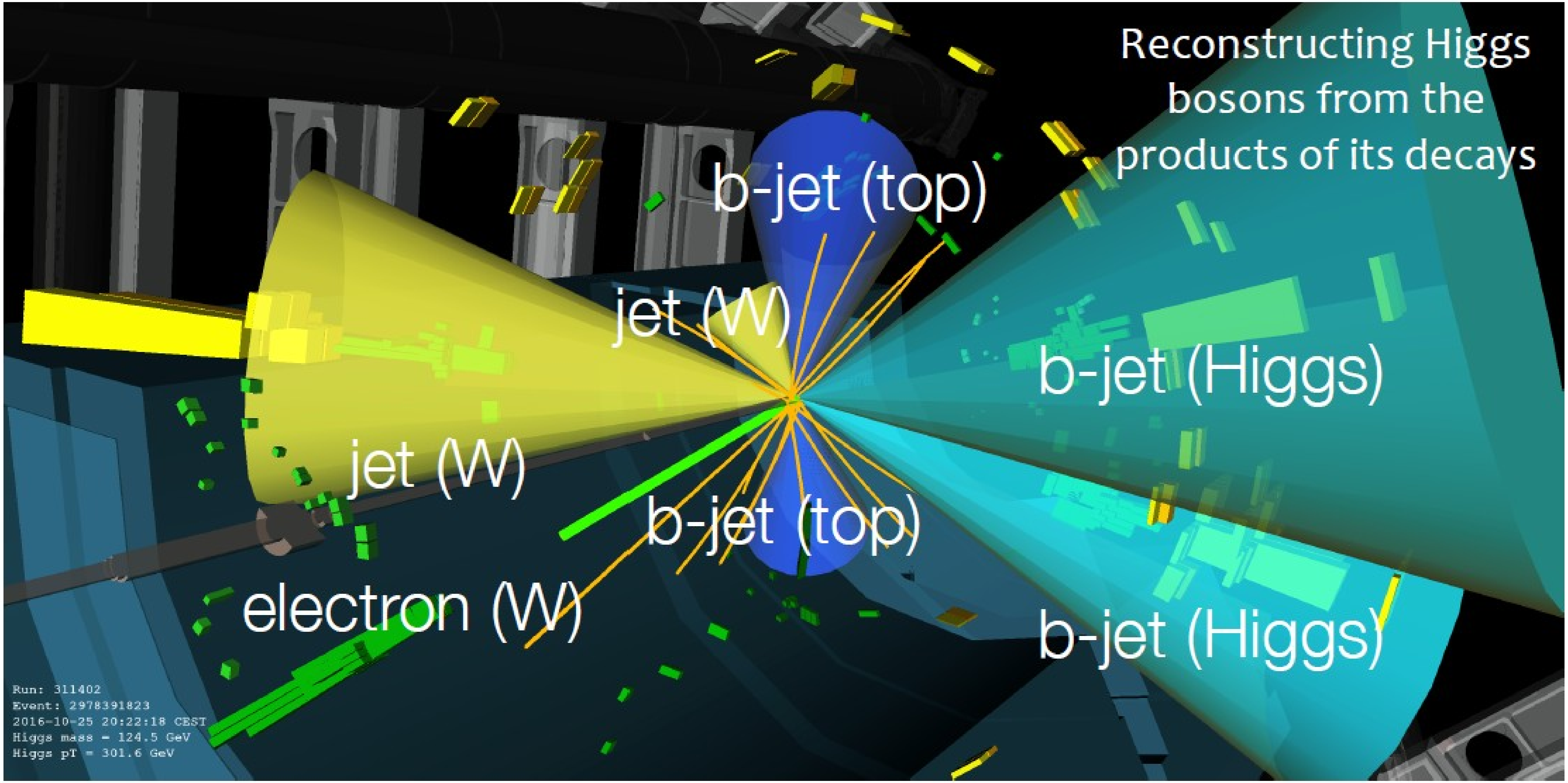
Signal strength inclusive

$$\sigma/\sigma_{\mathrm{SM}} = 1.014^{+0.055}_{-0.053}(\text{total}) = 1.014 \pm 0.028\,(\text{stat.})\,^{+0.025}_{-0.024}\,(\text{exp.})\,^{+0.040}_{-0.039}\,(\text{theo.})$$

5.4% 2.7% 2.5% 3.9%

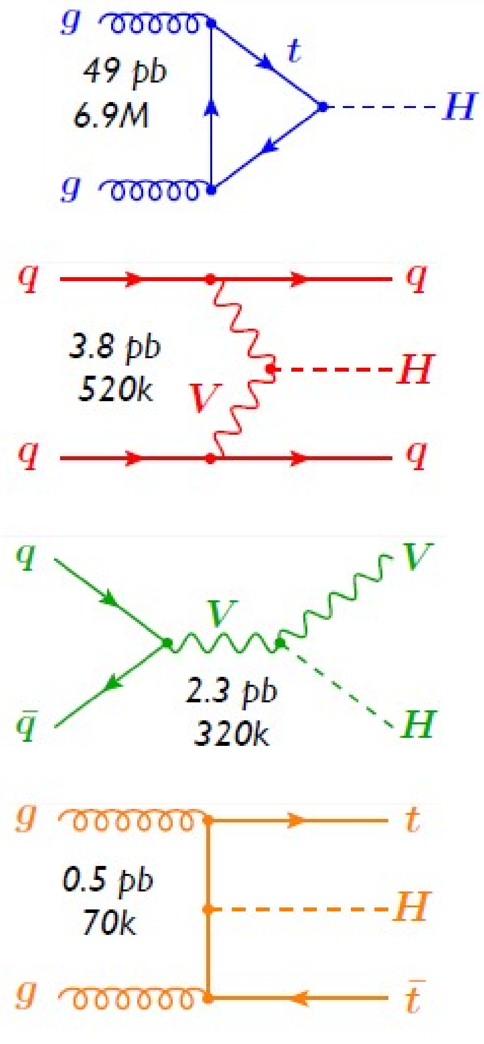
Recent Highlights

Zoom inside a Higgs event in ATLAS



Higgs production at the LHC

Decreasing cross-section



σ [pb]
#Higgs produced during Run-2

gluon fusion
ggH: 86%

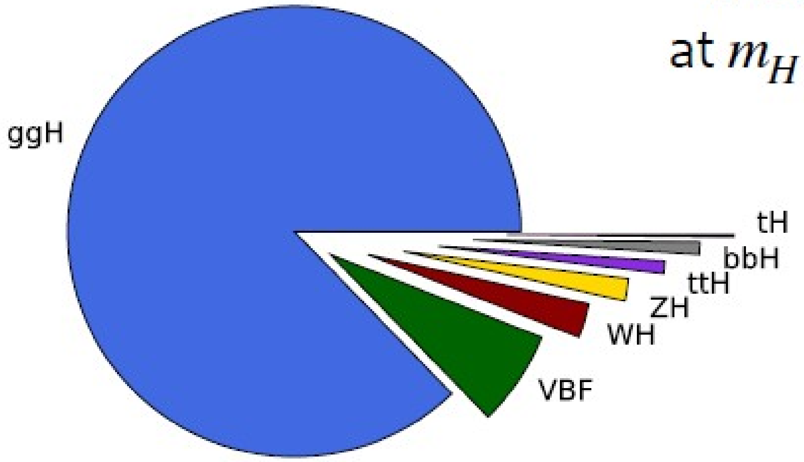
vector boson fusion (**VBF**): **6.5%**

W,Z associated production
WH/ZH: 4%

$t\bar{t}H$ associated production: 1%

- **LHC is a Higgs factory**
- About **8 million Higgs bosons** produced by LHC during Run-2 **per experiment**
- Since $m_H \sim 125$ GeV, a wide range of production and decay modes accessible

Higgs production cross sections at $m_H \sim 125$ GeV

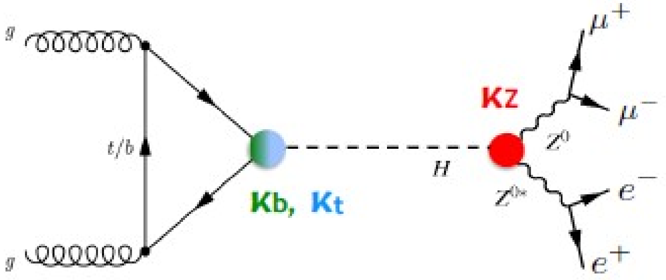


Interpreting the rates as Higgs couplings

The likelihood can be explicitly written in terms of "coupling modifiers": ***κ-framework***

$$\mu_i = \frac{\sigma^i}{\sigma^i_{SM}} \quad \text{and} \quad \mu_f = \frac{BR^f}{BR^f_{SM}} \qquad \mu \rightarrow \mu(\kappa): \mu^{if}(\kappa) = \sigma^i(\kappa) BR^f(\kappa) = \frac{\sigma^i(\kappa)\Gamma^f(\kappa)}{\Gamma_H(\kappa)}$$

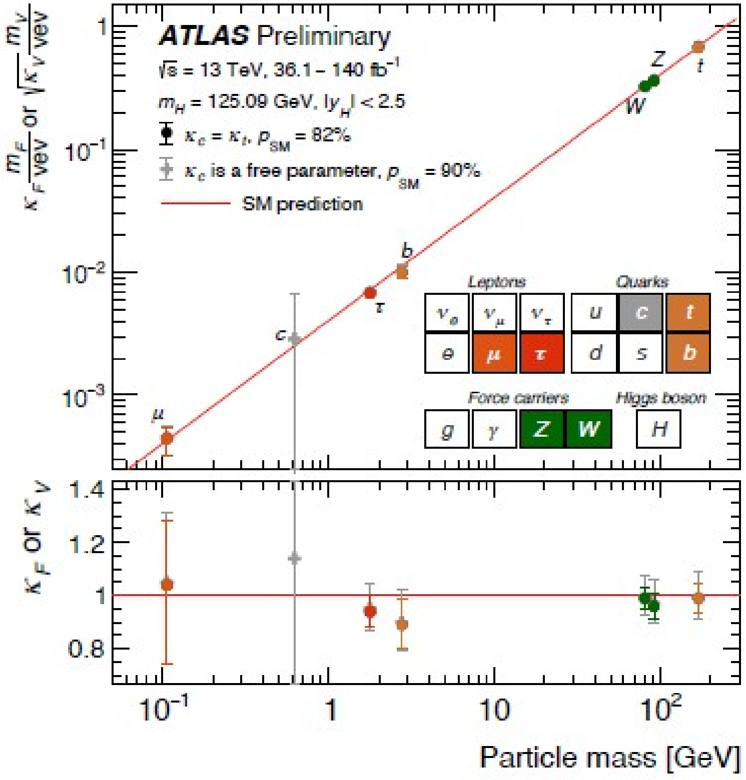
NEW



Example diagram:
ggH production,
$H \rightarrow ZZ$ decay

$$\mu_{ggH} \cdot \mu^{ZZ} \propto \frac{(1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b) \cdot \kappa_Z^2}{\kappa_H^2}$$

In the SM, Higgs couplings
proportional to particle masses => test the SM
- Couplings to **W/Z at 5-10%**
- Couplings to 3[rd] **generation to 10-20%**

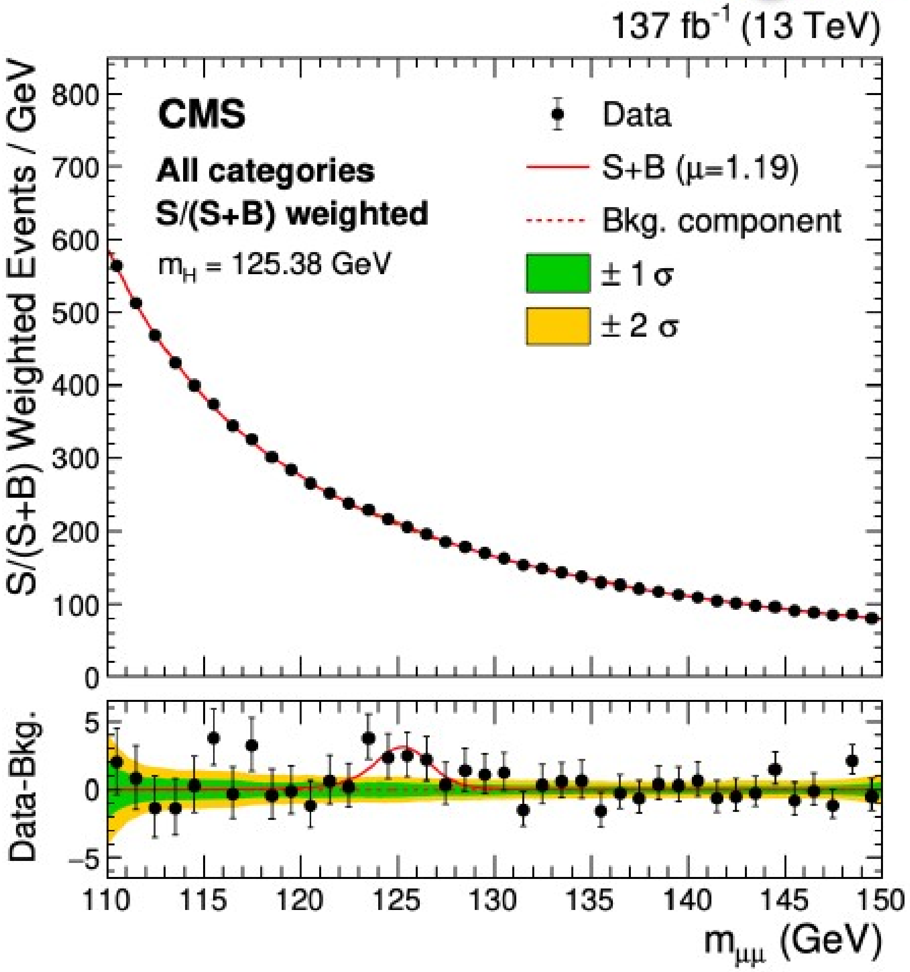


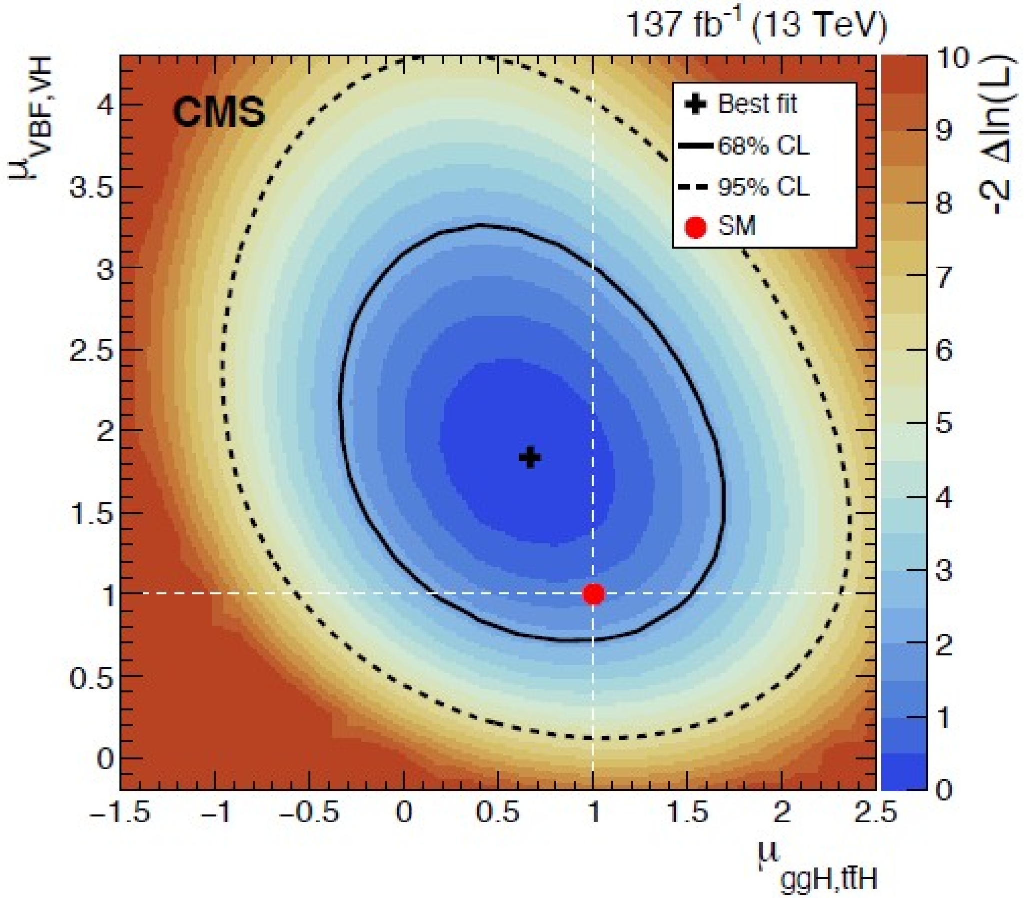
ATLAS-CONF-2025-006

$$\mu = 1.2 \pm 0.4$$

CMS: JHEP 01 (2021) 148

significance: 3.0σ (2.5σ exp.)



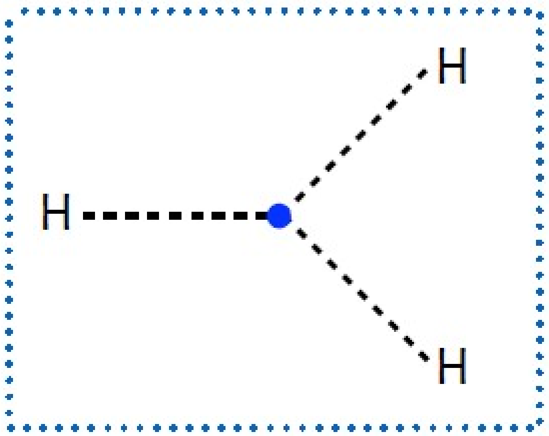


gluon-fusion and VBF with similar sensitivity

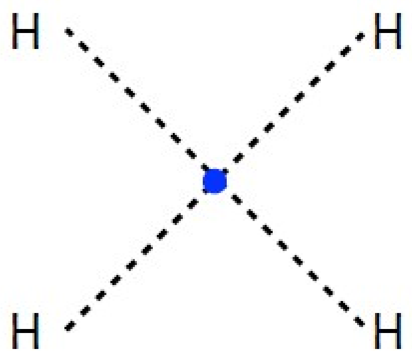
31

Higgs boson self coupling

H^3 ("λ_3" or simply "λ")



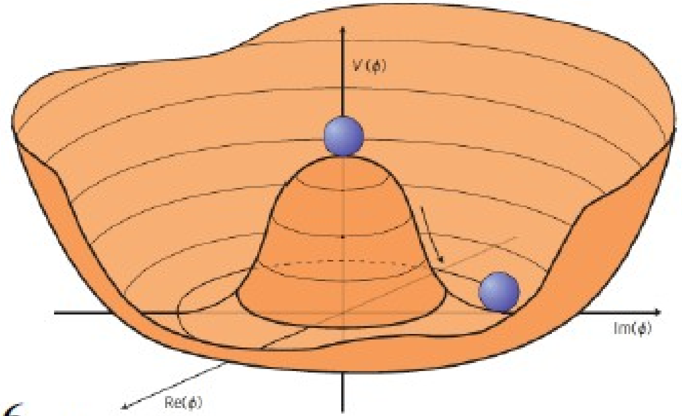
H^4 ("λ_4")



Need to measure the Higgs potential

$$V^{SM}(H) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$$

BSM potential at low E



$$V^{BSM}(H) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4 + \frac{\lambda_5}{v} H^5 + \frac{\lambda_6}{v^2} H^6 + \cdots$$

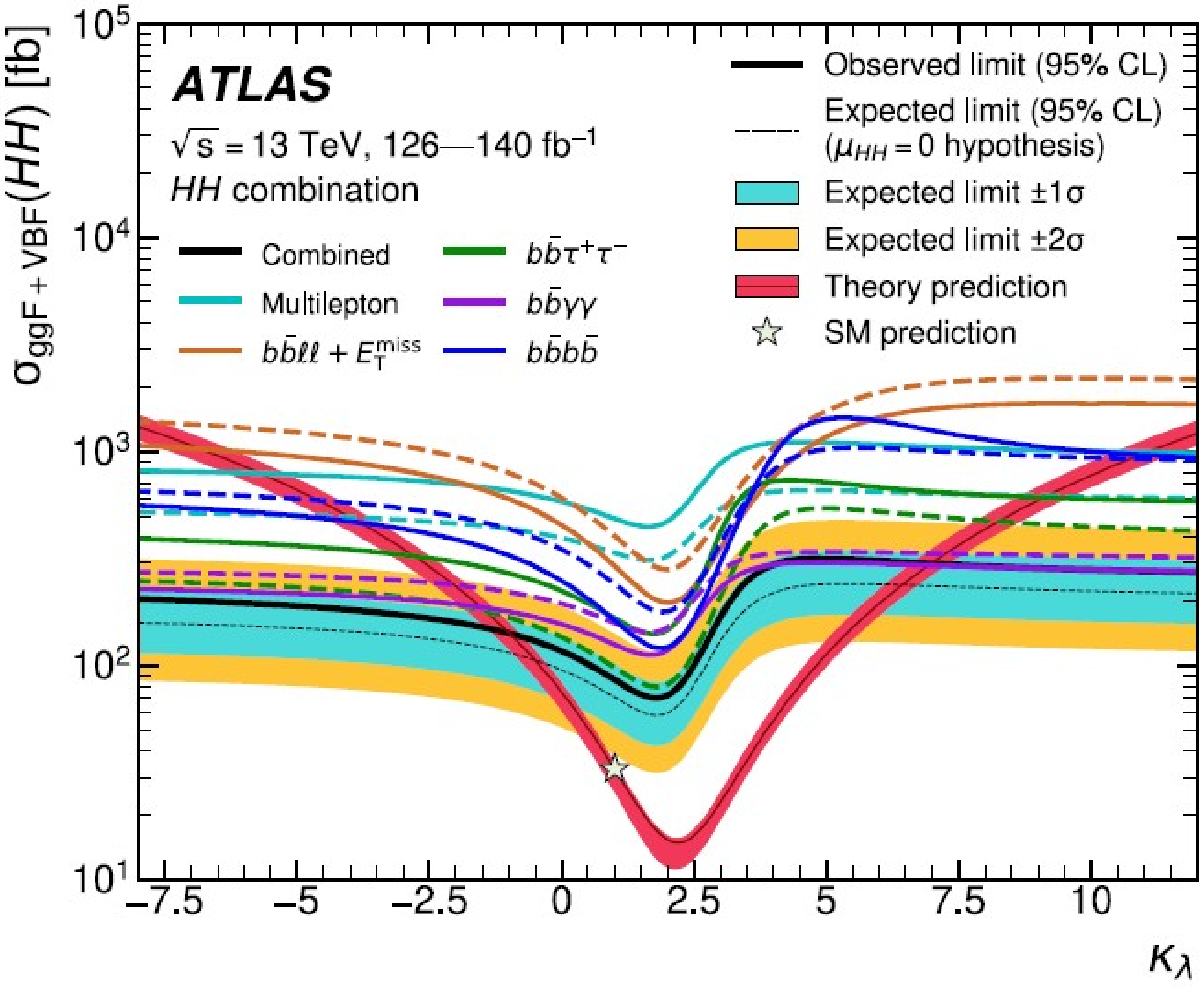
In EFTs, adding dimension-6 (BSM at scale E>Λ), the λ_i are not independent:

$$\lambda_3 = \lambda \left(1 + c_6 \frac{2v^4}{m_H^2 \Lambda^2} \right) \equiv \lambda (1 + \bar{c}_6)$$

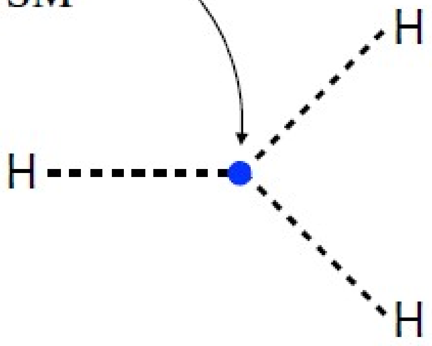
A measure of $\bar{c}_6 \neq 0$ (e.g. **via HH rate**) **hint of 1st phase transition (Sakharov condition for $n_B \gg n_{\bar{B}}$)**

But: **HH is an <u>extremely rare</u>** process at LHC: $\sigma_{ggHH} < \frac{\sigma_{ggH}}{1000}$ (34 fb @ $\sqrt{s} = 13.6\,\mathrm{TeV}$)

Higgs self-coupling (Run2 legacy)



$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$



most stringent 95% CLs on Higgs boson self-coupling from HH:

$$-1.2 < \kappa_\lambda < 7.2 \text{ (ATLAS)}$$
$$-1.39 < \kappa_\lambda < 7.02 \text{ (CMS)}$$

CMS-PAS-HIG-20-011

ATLAS: PRL 133 (2024) 101801

Pushing further: triple-Higgs

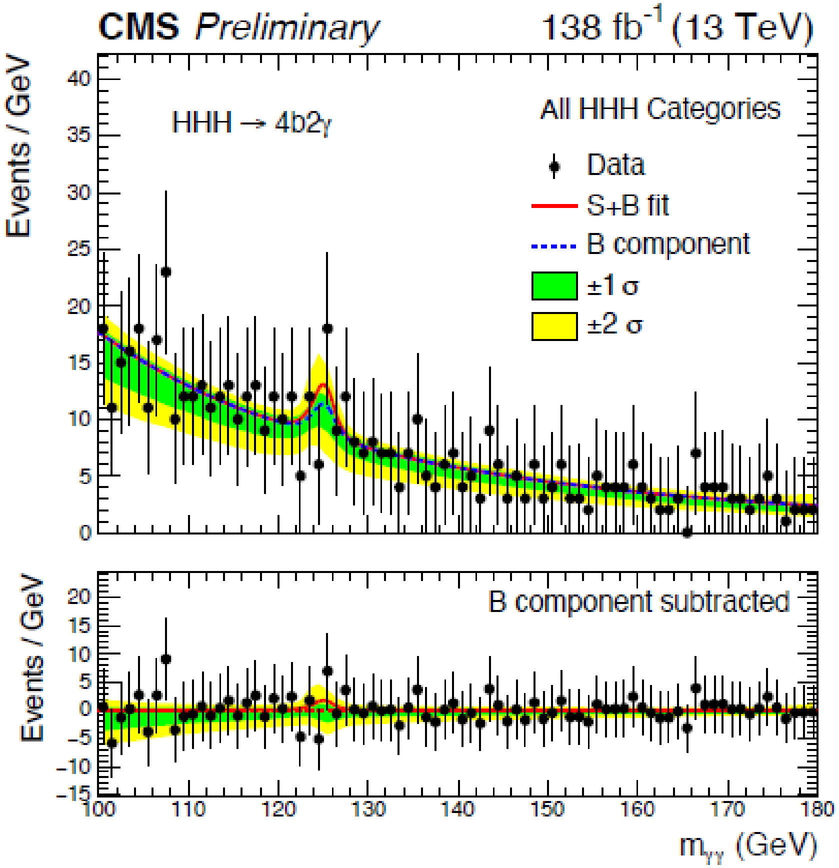
Tri-Higgs (HHH) production sensitive to both λ_3 and λ_4

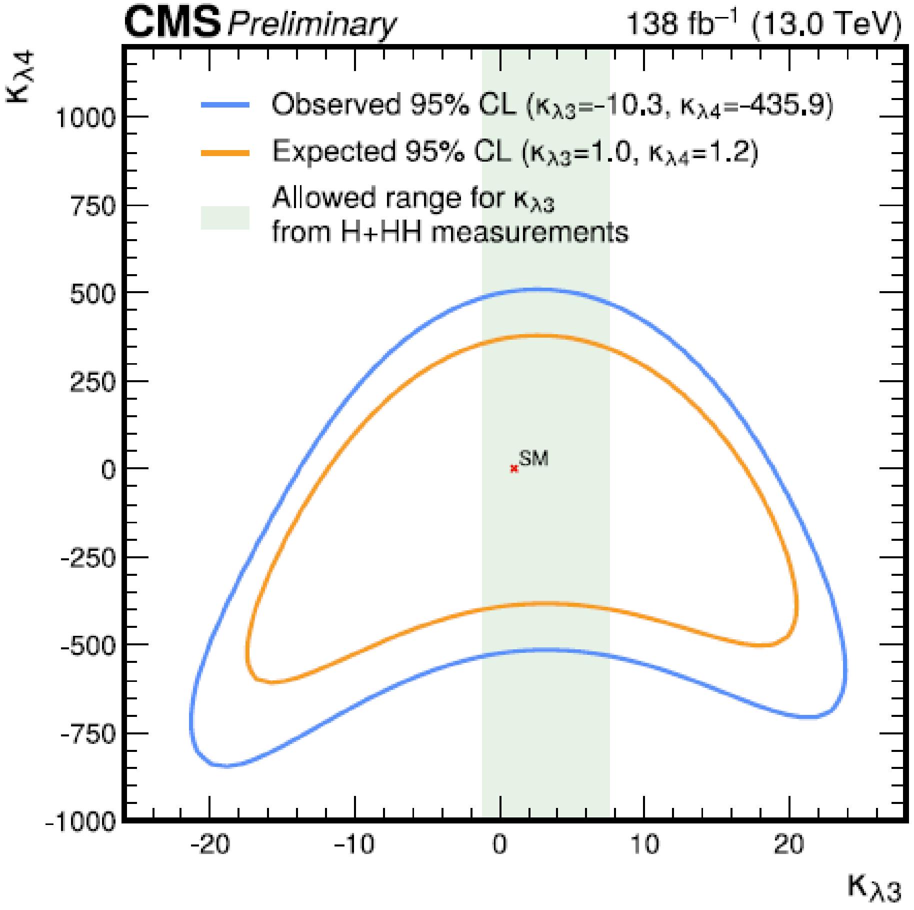
Recent ATLAS measurements: HHH → 6b (PhysRevD.111.032006)

CMS new Run-2 analysis of $HHH \to 4b2\gamma$ **ultra-rare: $\sigma \times \mathscr{B} \sim 0.2$ ab**

CMS-PAS-HIG-24-015

NEW





$\mu_{HHH} < 3400$ (2086 exp.)

- Stronger dependence of HHH cross section from λ_3 than λ_4
- Green area: constraints from H+HH

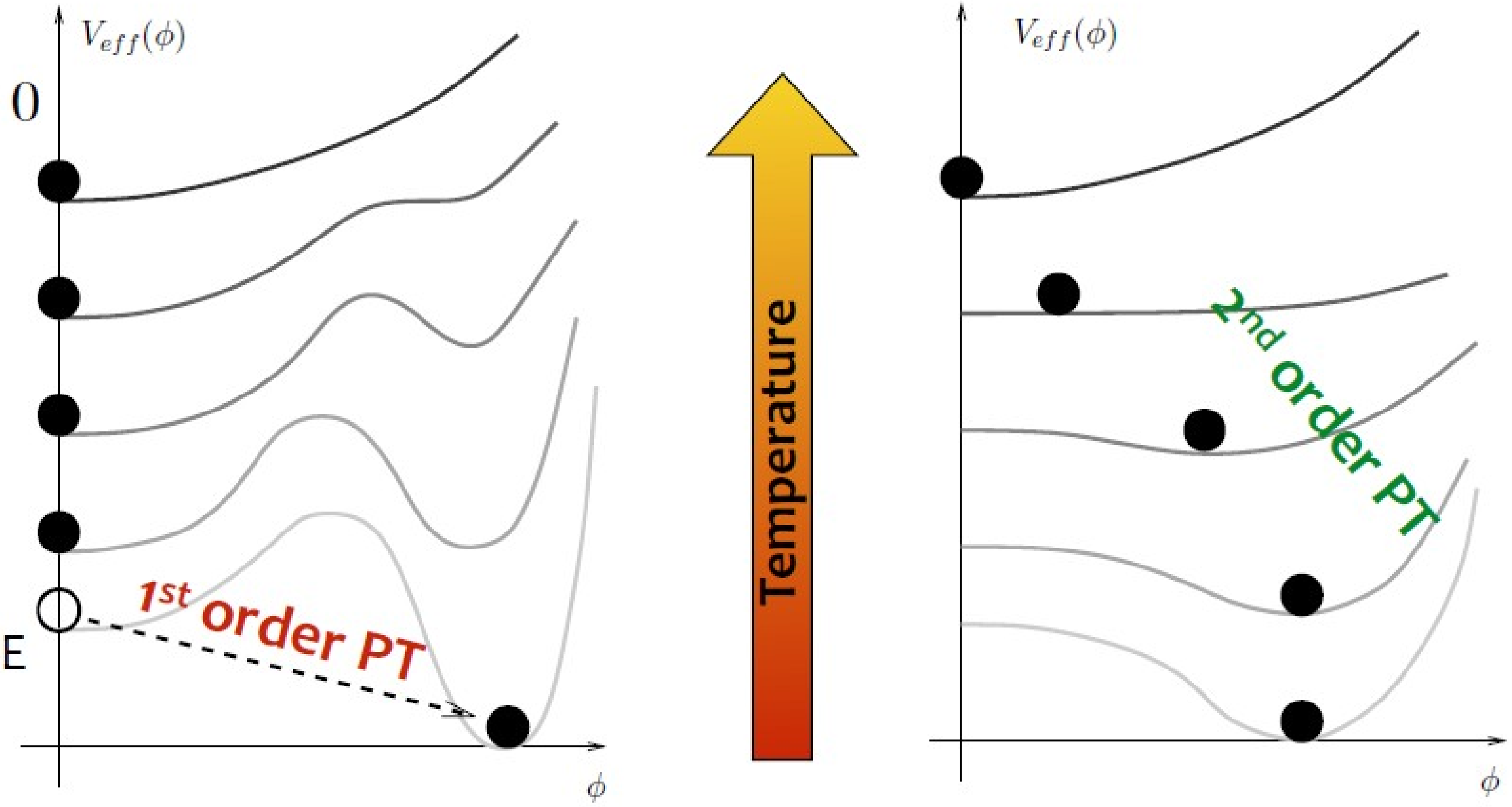
Higgs potential vs baryogenesis

Why matter >> anti-matter in the universe?

CP-violation (CKM matrix) is too weak to explain why $n_B \gg n_{\bar{B}}$

1 minimum at $\phi = 0$ (stable) at E>100 GeV

2 minima: $\phi = 0$ and $\phi \neq 0$ at low E



1 minimum at $\phi = 0$ (stable) at E>100 GeV

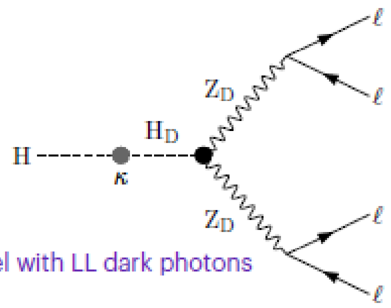
1 minimum at $\phi \neq 0$ at low E

Sakharov condition for $n_B \gg n_{\bar{B}}$: **1st order phase transition** (PT)

Low mass searches

Scouting data set
Run-3

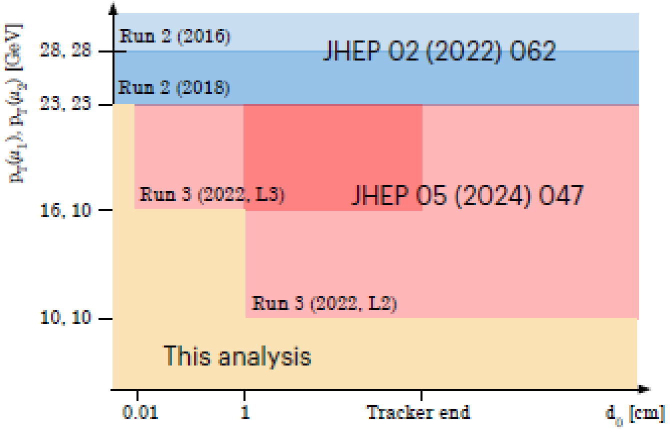
Going beyond the designed trigger constraints with the scouting data set. Record reduced information at high rates, opening up otherwise inaccessible low-mass phase space



HADH model with LL dark photons

H decays to long lived dark particles with muons in the final state

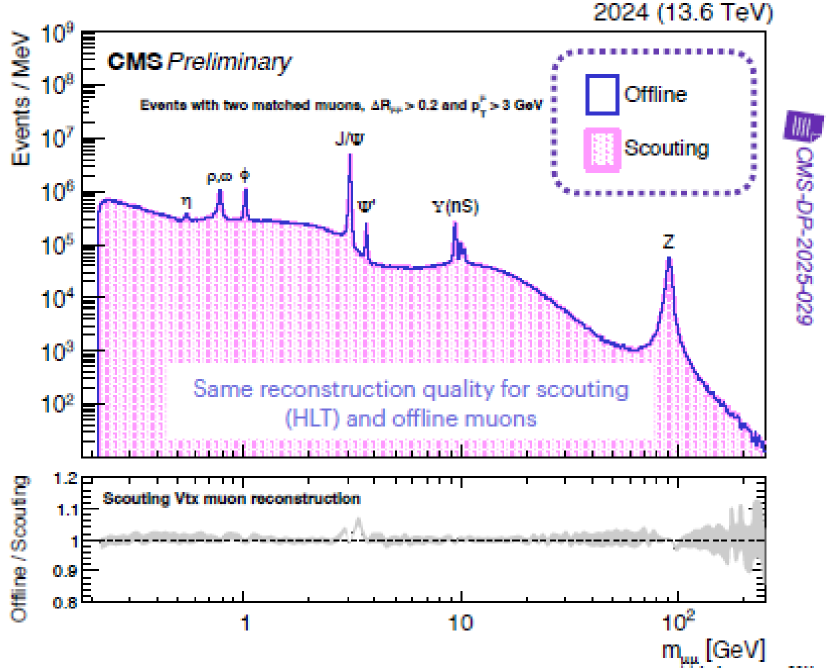
Extending the reach wrt previous analysis



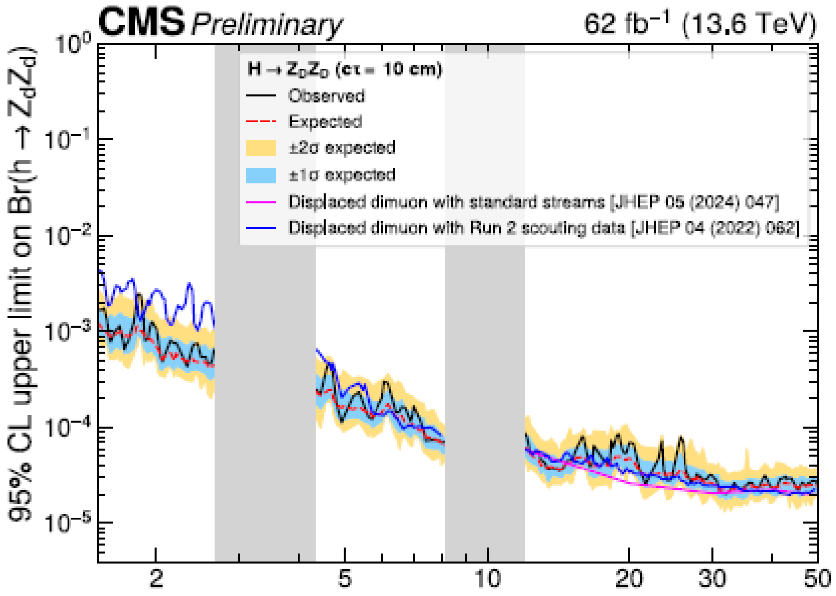
Lower lepton p_T lower masses can be probed

EXO-24-016

$\mu\mu$ resonances



CMS-DP-2025-029



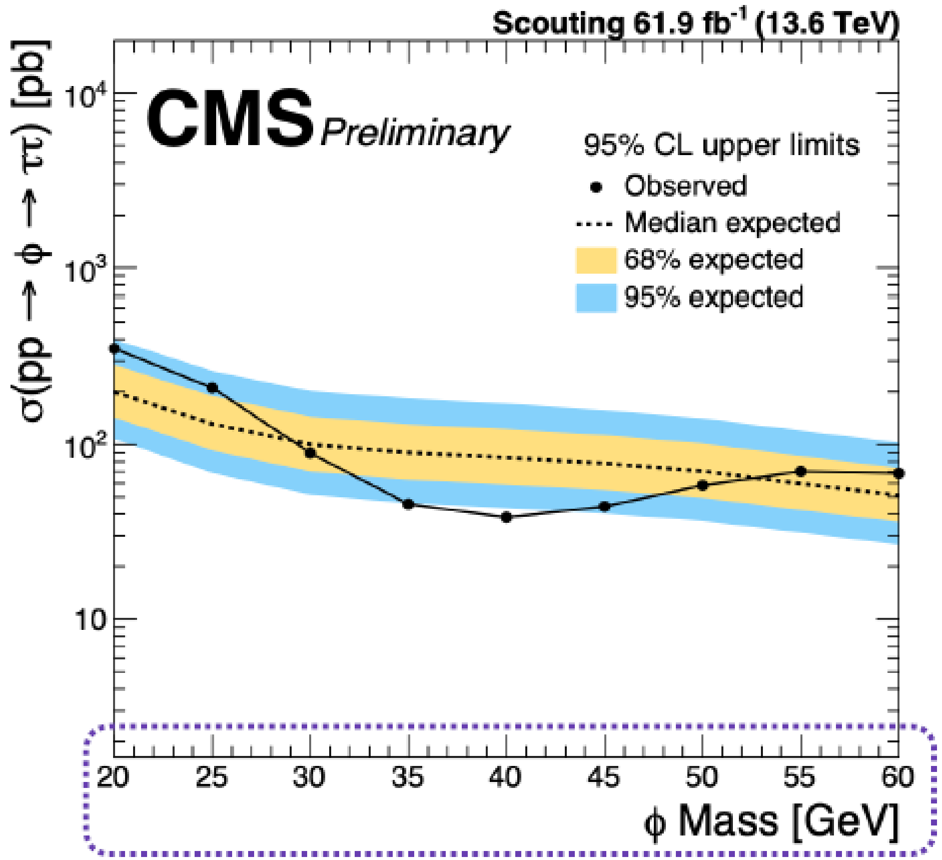
Recent Highlights

Low mass searches

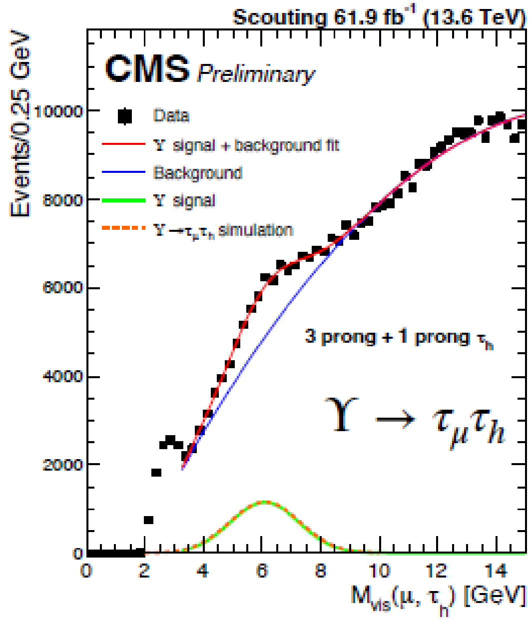
$\tau\tau$ resonances

Scouting data set Run-3

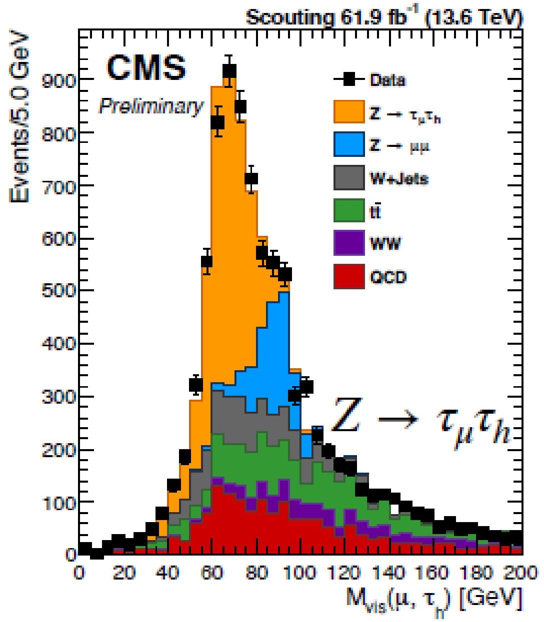
Going beyond the designed trigger constraints with the scouting data set. Record reduced information at high rates, opening up otherwise inaccessible low-mass phase space



SM candles



Structure at the Υ mass

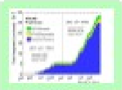


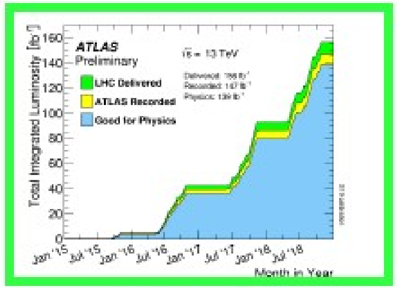
Reached offline-like resolution

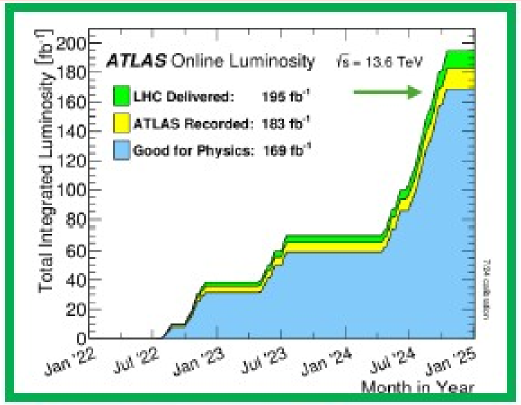
First time masses <60 GeV explored at hadron colliders

ATLAS Highlights

This talk ...







~90% of LHC delivered luminosity used in physics analyses

ATLAS reached **1400** publications: AtlasPublicResults

Run 1:
25 fb^{-1} @ 7+8 TeV

Run 2:
140 fb^{-1} @ 13 TeV

Run 3: 2022-2024
168 fb^{-1} @ 13.6 TeV

HL-LHC:
3 ab^{-1} @ 13.6 TeV

- This talk will highlight a few results focusing on what is **new** (shown for the **first time** at this conference New)
  and of **highest impact on particle physics** → Some results using Run 2 + Run 3 data up to 2024 → **308 fb^{-1}** in total

21 NEW results released for this conference

More details of the ATLAS results in other plenary talks by Emanuele Di Marco, Timothy Gershon, Josh Bendavid, Francesco Prino and Tamara Vazquez + the 56 ATLAS talks in parallel sessions + 18 ATLAS posters

Higgs Boson Physics

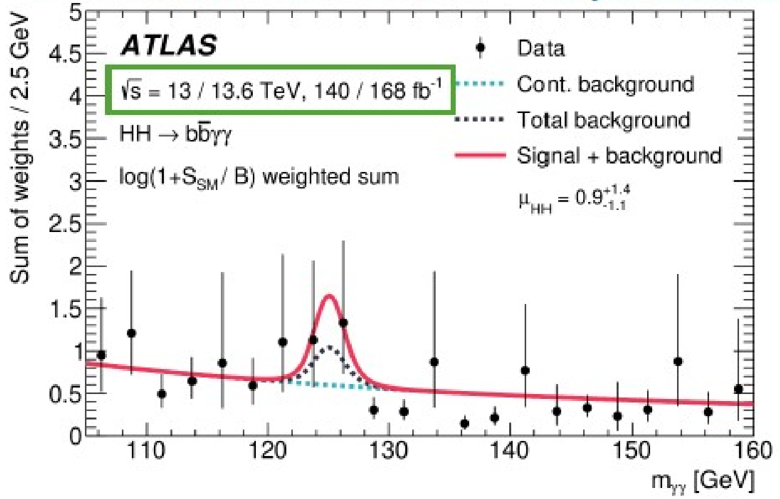
ATLAS

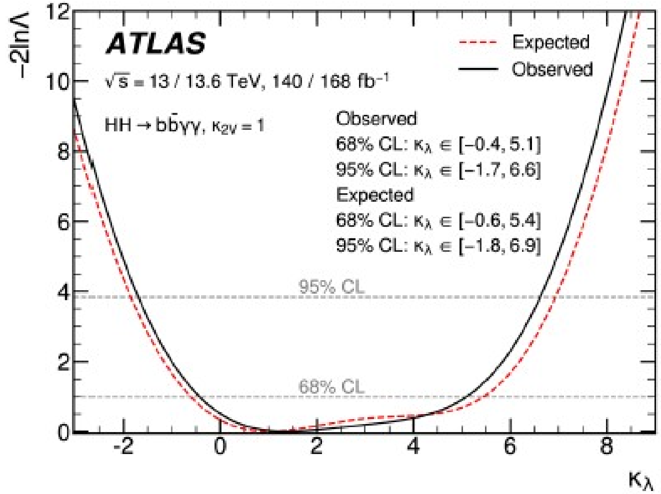
Search for HH→ bbγγ

CERN-EP-2025-140 sub. PLB

Physics Briefing

- New measurement using reprocessed Run 2 + Run 3 (2022-2024!) → Total **308 fb^{-1}**
- **Timely calibration of physics objects** for Run 3 (up to 2024!)
- Improvements on HH sensitivity relative to Run 2 legacy analysis:
  - Additional data: **50%**
  - New flavor tag algorithm **GN2**: **20%**
  - Analysis preoptimization: **10%**
  - m_{bb} kinematic fit : **5%**
- Signal extracted by a fit to $m_{\gamma\gamma}$ in 7 BDT categories
  - Observed $\mu(\sigma/\sigma_{SM})_{HH} = 0.9^{+1.4}_{-1.1}$
  - 0.8 σ significance (1.0 expected)
  - Similar sensitivity of Legacy Run 2 combination (5 chan.)
- Higgs boson self-coupling modifier (coupling normalized to its SM prediction) $\kappa_\lambda \in [-1.7,6.6]$ @95% CL





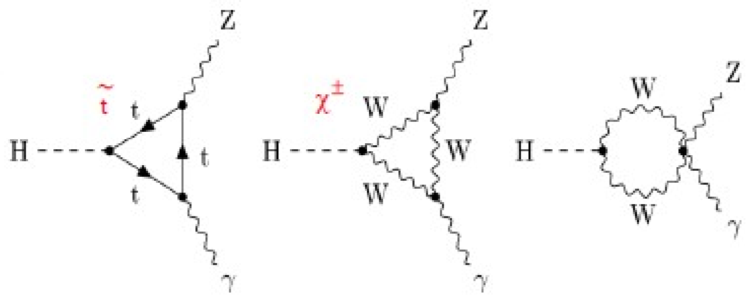
$H \rightarrow Z\gamma$

New

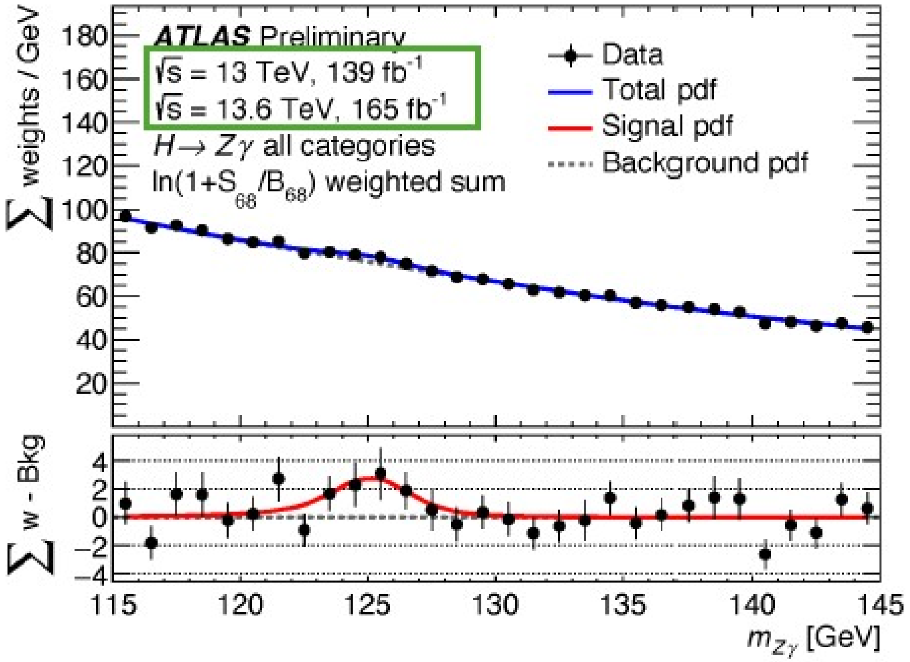
ATLAS EXPERIMENT

- Rare decay loop-suppressed in the SM with BR=1.5×10^{-3} → Sensitive to BSM effects
- Intriguing ATLAS+CMS in Run 2: $\mu(\sigma/\sigma_{SM})=2.2\pm0.7$ (Obs./Exp. Significance 3.4/1.6σ - about 2σ above SM prediction) Phys. Rev. Lett. 132 (2024) 021803
- Use Run 3 up to 2024!
- Fit to $m_{Z\gamma}$ 2 leptons $Z\rightarrow\ell\ell$ (e,μ) + isolated photon in 13 Categories
- **Run 3**: $\mu(\sigma/\sigma_{SM})=\mathbf{0.9^{+0.7}_{-0.6}}$ significance **1.4σ** (exp. SM **1.5σ**)
- **Combined Run2+Run3**: $\mu=\mathbf{1.3^{+0.6}_{-0.5}}$ significance **2.5σ** (exp. SM **1.9σ**)

Sensitivity improved by **60%** relative to Run 2 and by **20%** relative to ATLAS+CMS combination



ATLAS-CONF-2025-007 Physics Briefing



Parallel Session talk by Tamar Zakereishvili

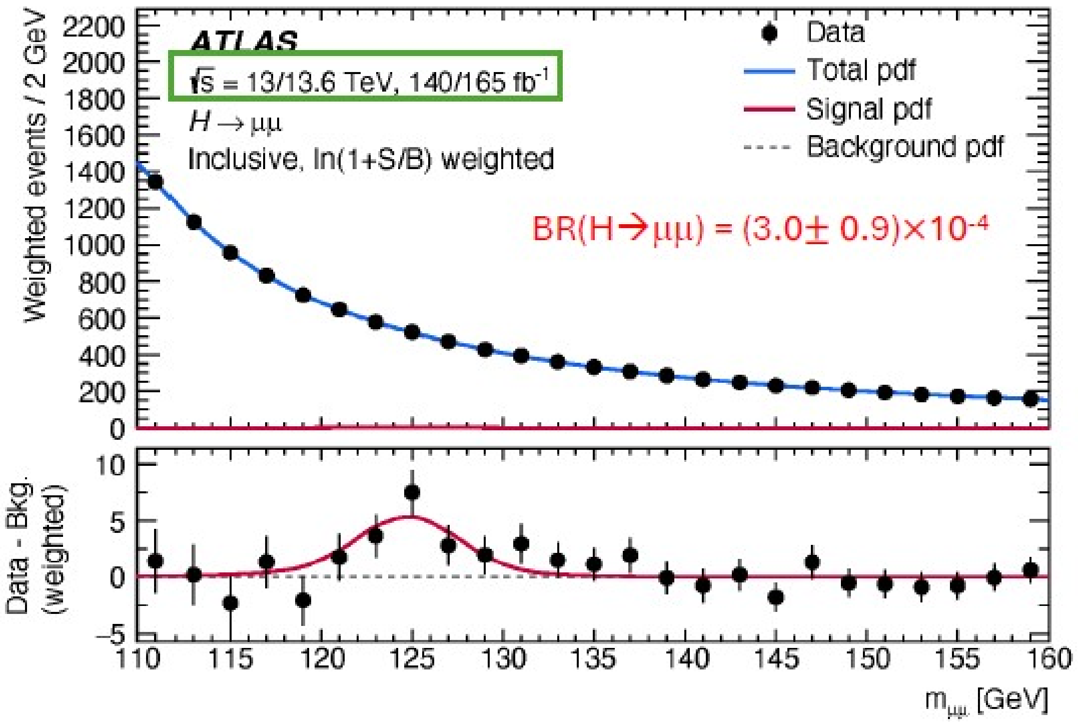
$H \rightarrow \mu\mu$

New

- Test **SM Yukawa sector** on **2^{nd} Fermion generation**
- Rare decay **BR~2×10^{-4}** with huge DY background: S/B inclusive ~0.2%

CERN-EP-2025-149 sub. PRL   Physics Briefing

- 23 Categories based on Higgs production mode and kinematic (BDT/NN) to enhance S/B
- Use Run 3 up to 2024!
- **Run 3:** $\mu(\sigma/\sigma_{SM})$**=1.6 ± 0.6** → **2.8 σ** (Exp. 1.8 σ)
- **Combined Run 2+Run 3:** $\mu(\sigma/\sigma_{SM})$**=1.4 ± 0.4** → **3.4 σ** (2.5 σ)



STRONG **evidence for $H \rightarrow \mu\mu$** decay in agreement with SM

Sensitivity improved by ~50% relative to Run 2 analysis

Run 2 Higgs coupling combination

New

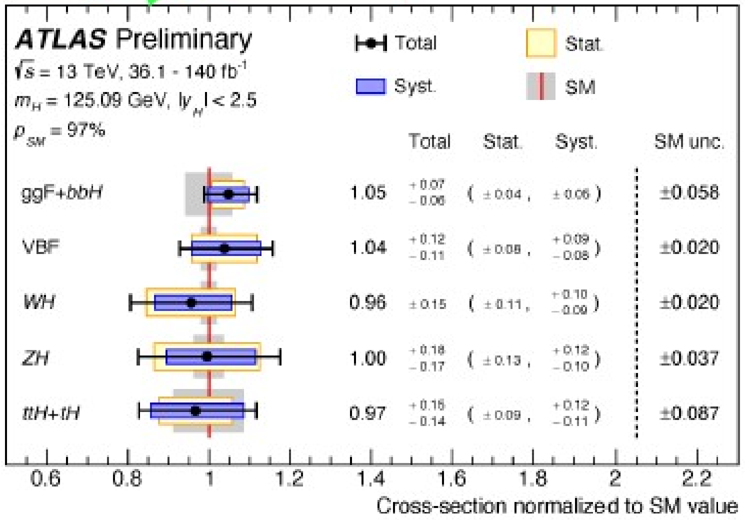
ATLAS EXPERIMENT

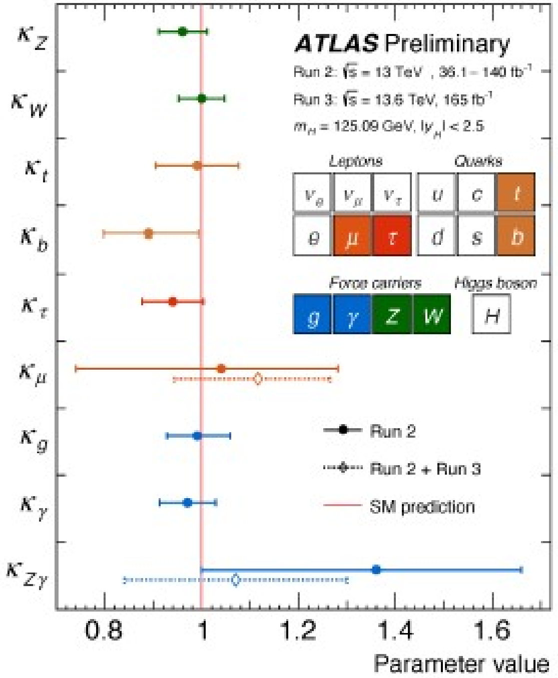
ATLAS-CONF-2025-006

- Added new Run 2 measurements relative to Nature 607 (2022) 52
  ttH→bb, VH→bb,cc, H→ττ, H→WW*
- $\mu(\sigma_{obs}/\sigma_{SM}) = 1.023^{+0.056}_{-0.053}$ (0.028(stat)±0.026(exp)±0.039(th))
- Main improvements on σ (BR fixed to SM)
  - WH/ZH reduced by **30/20%** new V(H→bb)
  - ttH+tH reduced by **25%** new tt(H→bb)
- Test SM with coupling modifiers κ (coupling normalized to its SM prediction)

$$\sigma_i \times B(H \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{SM} \times B^{SM}(H \to f)$$

Achieved precision* ranging from **5-10%** *(p_{SM} 89%)*



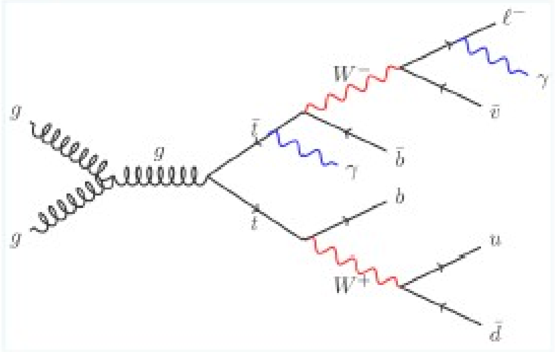


*No BSM contributions to Higgs boson width

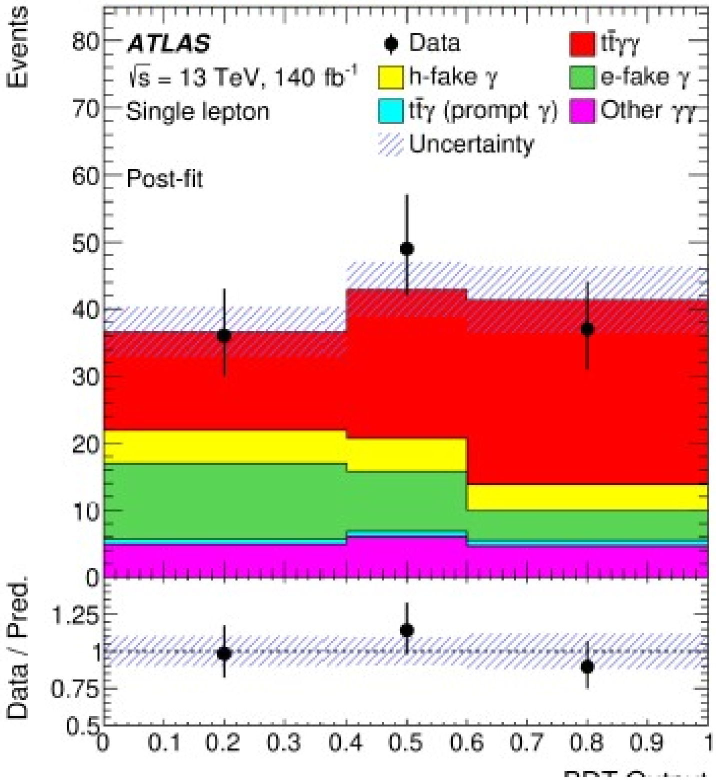
Observation of tt$\gamma\gamma$ process

New

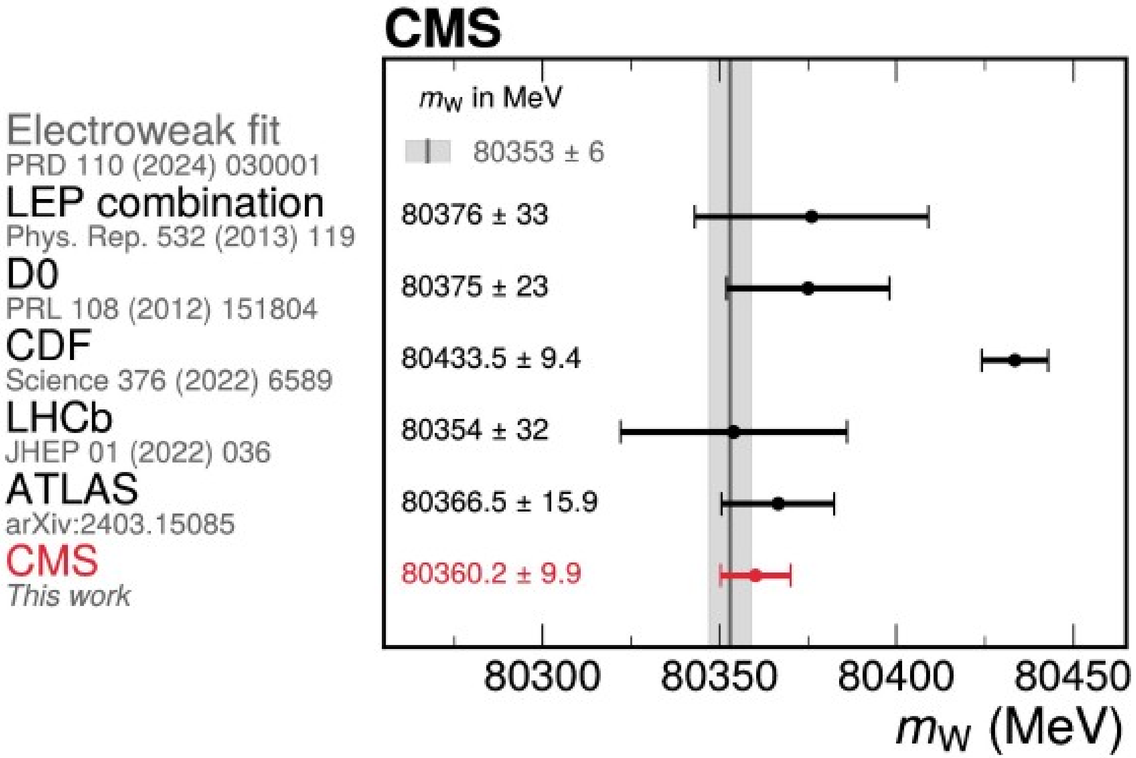
- Study production of top anti-top in association with tow prompt γ
- Very rare process: expected cross-section ~ few fb
- Select events with 1 leptons, 2 isolated photons and at least 4 jets of which at least one b-tagged
- Use BDT based on photon and other event variables (19 in total) to enhance backgrounds rejection (mainly fake photons in tt events)
- Measured fiducial cross-section $\sigma(tt\gamma\gamma) = (2.42^{+0.58}_{-0.53})$ fb
- Prediction from LO MC $1.5^{+0.4}_{-0.5}$ fb x estimated k-factor ~1.7
- Observed significance 5.2σ



arXiv:2506.05018 sub. to PLB



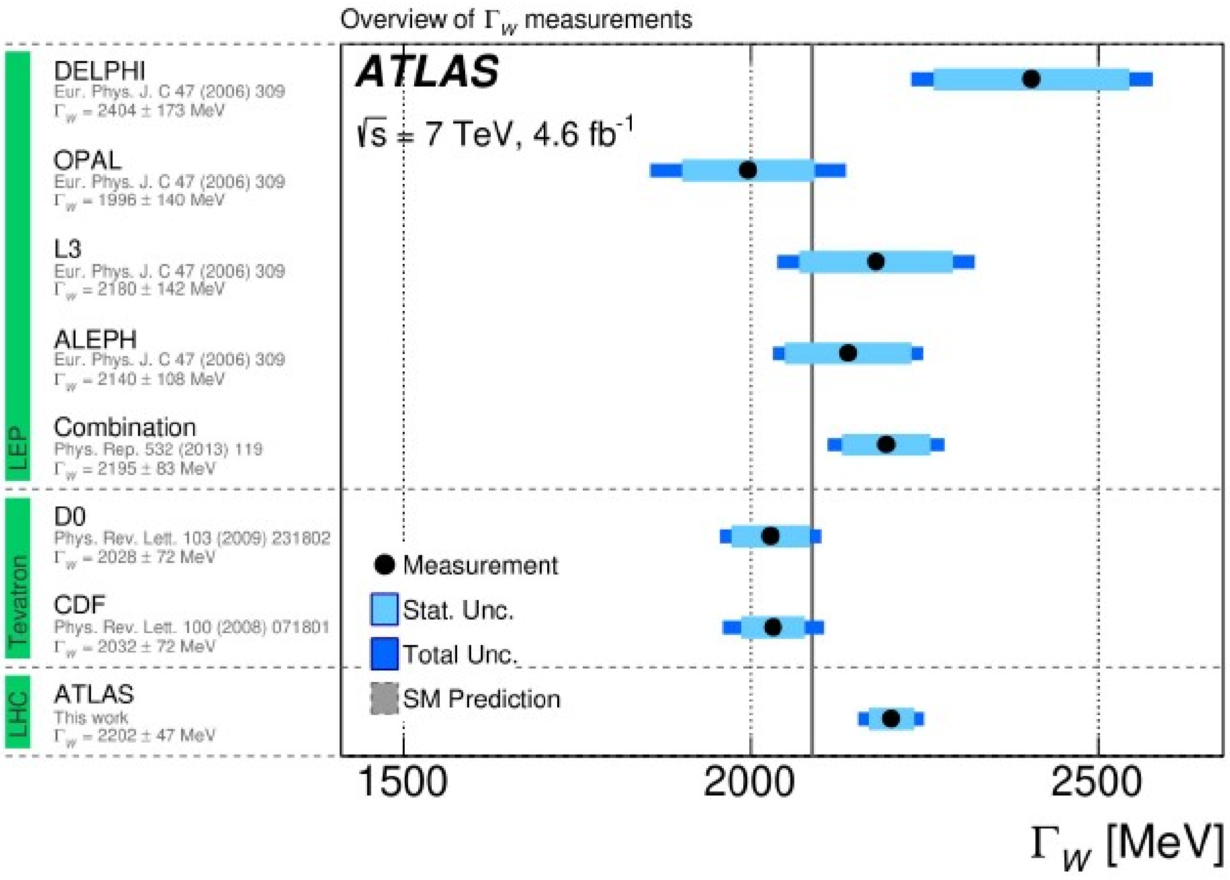
W mass

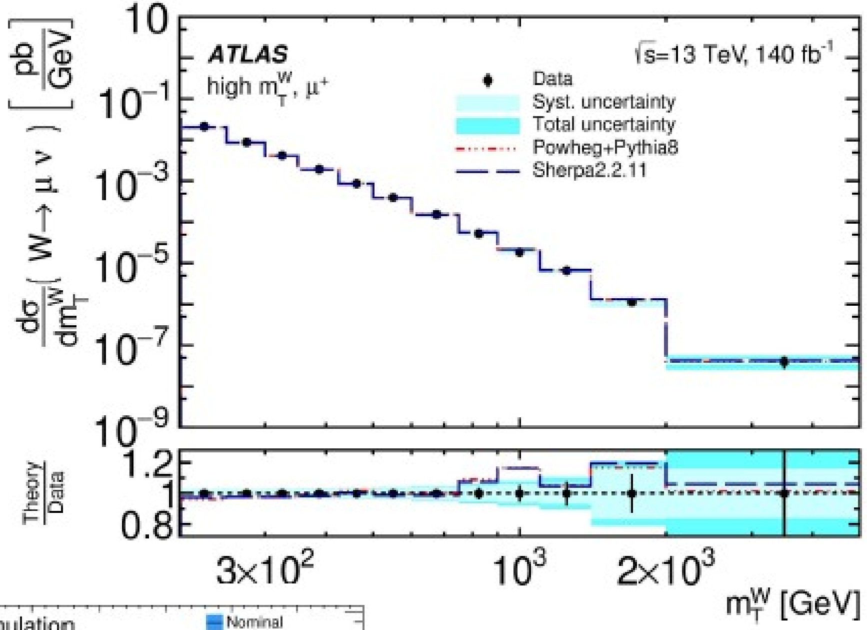


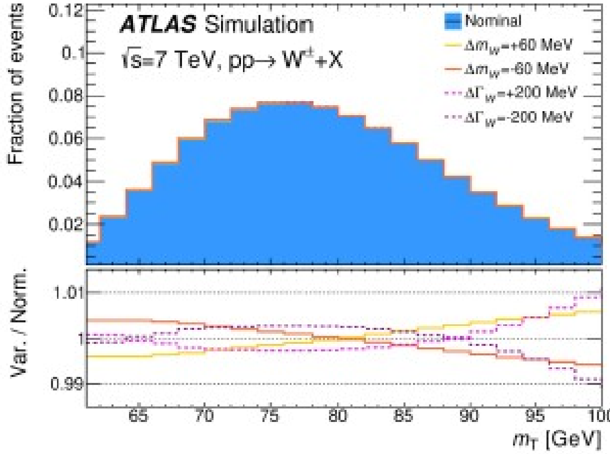
Source of uncertainty	Impact (MeV) Nominal	Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample size	2.4	6.0
Total uncertainty	9.9	9.9

- Recent CMS measurement is the most precise at the LHC, approaching quoted CDF precision, compatible with SM prediction and other measurements
- Exploits strong in-situ constraints to reduce PDF/QCD uncertainties
- Clear tension with CDF measurement

W width and off-shell production





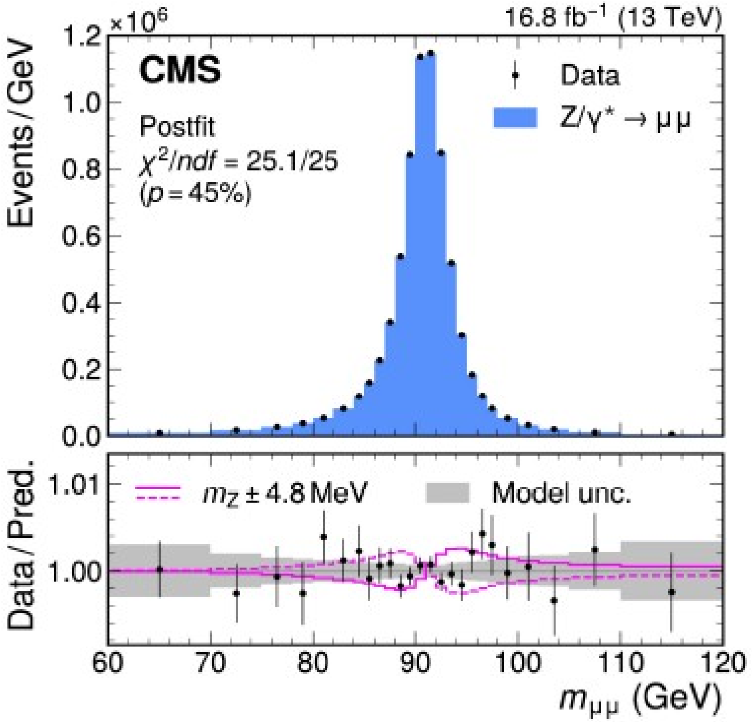


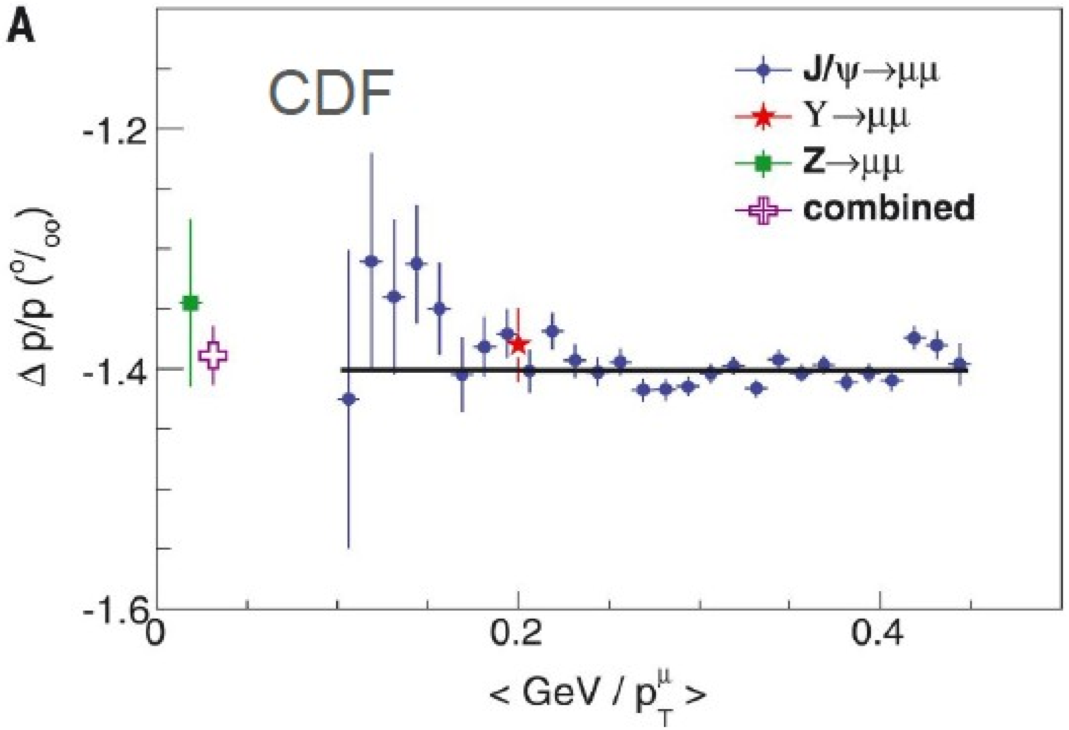
- W width is also predicted by the SM given mW and other parameters
- Updated ATLAS mW measurement includes most precise determination of the W width
- Sensitivity driven by the transverse mass distribution
- Recent cross section measurement also at high transverse mass

Eur. Phys. J. C 84 (2024) 1309, arXiv:2502.21088

Z mass

arXiv:2412.13872, *Science* 376 (2022) 6589, 170-176



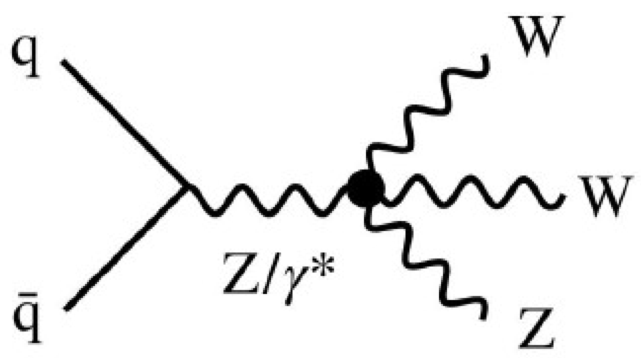


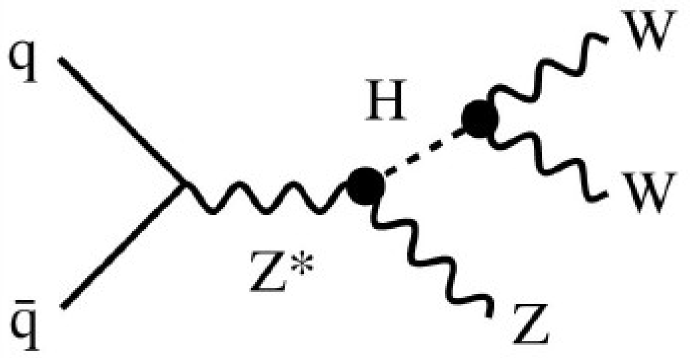
$$\mathbf{m_Z - m_Z^{PDG} = -2.2 \pm 4.8\ MeV}$$

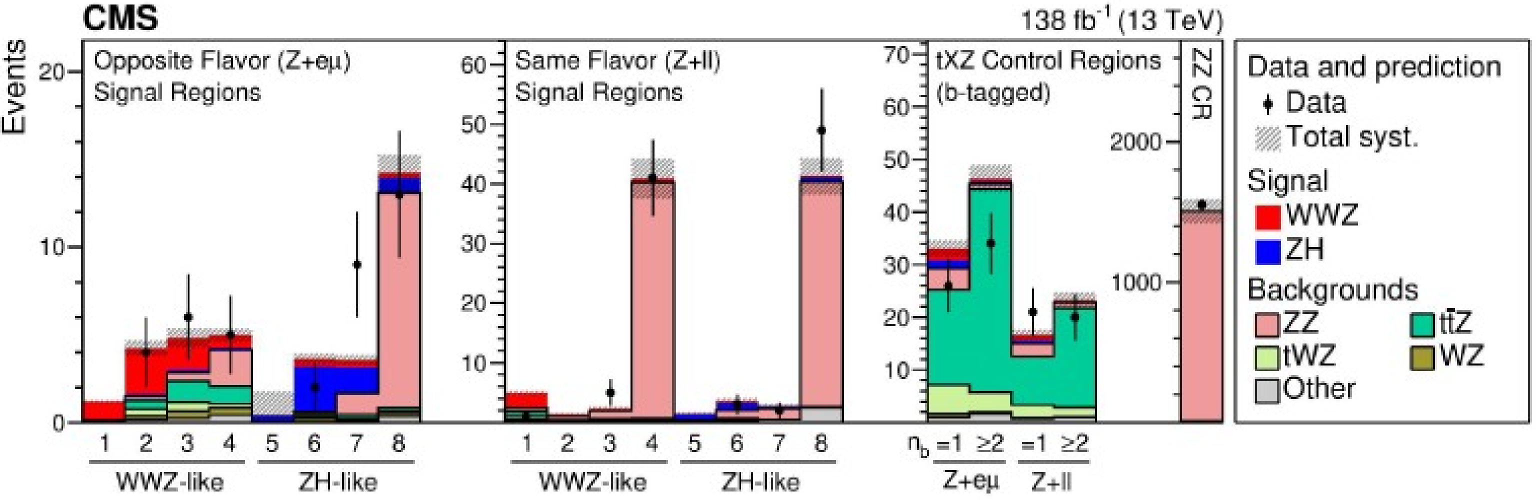
$$M_Z = 91,192.0 \pm 6.4_{\rm stat} \pm 4.0_{\rm syst}\ \mathrm{MeV}$$

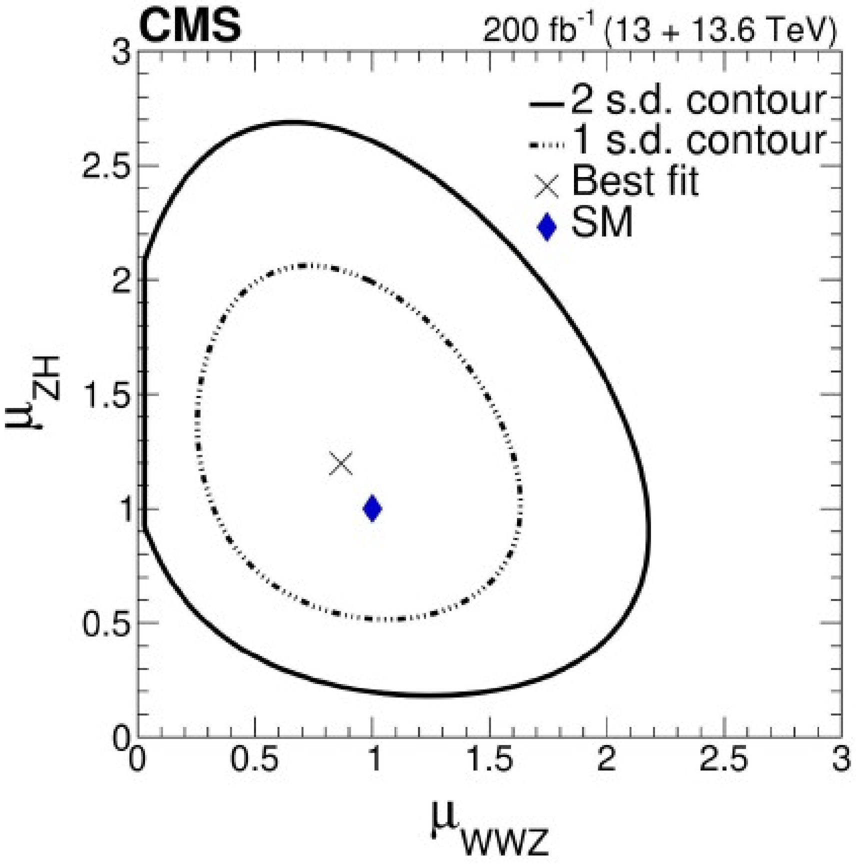
- mW measurement at hadron colliders requires very precise calibration of lepton energy/momentum scale
- Calibration with quarkonium can be used for an independent measurement of the Z mass
- CMS Z mass validation not quite an independent measurement since consistency with the LEP Z mass was used to define the final systematic uncertainties (and not fully blind during validation of the J/psi calibration)
- CDF Z mass measurement from J/psi + Upsilon 1S calibration is included in the PDG value (though with small weight compared to 2.1 MeV uncertainty from LEP)

Triboson Production



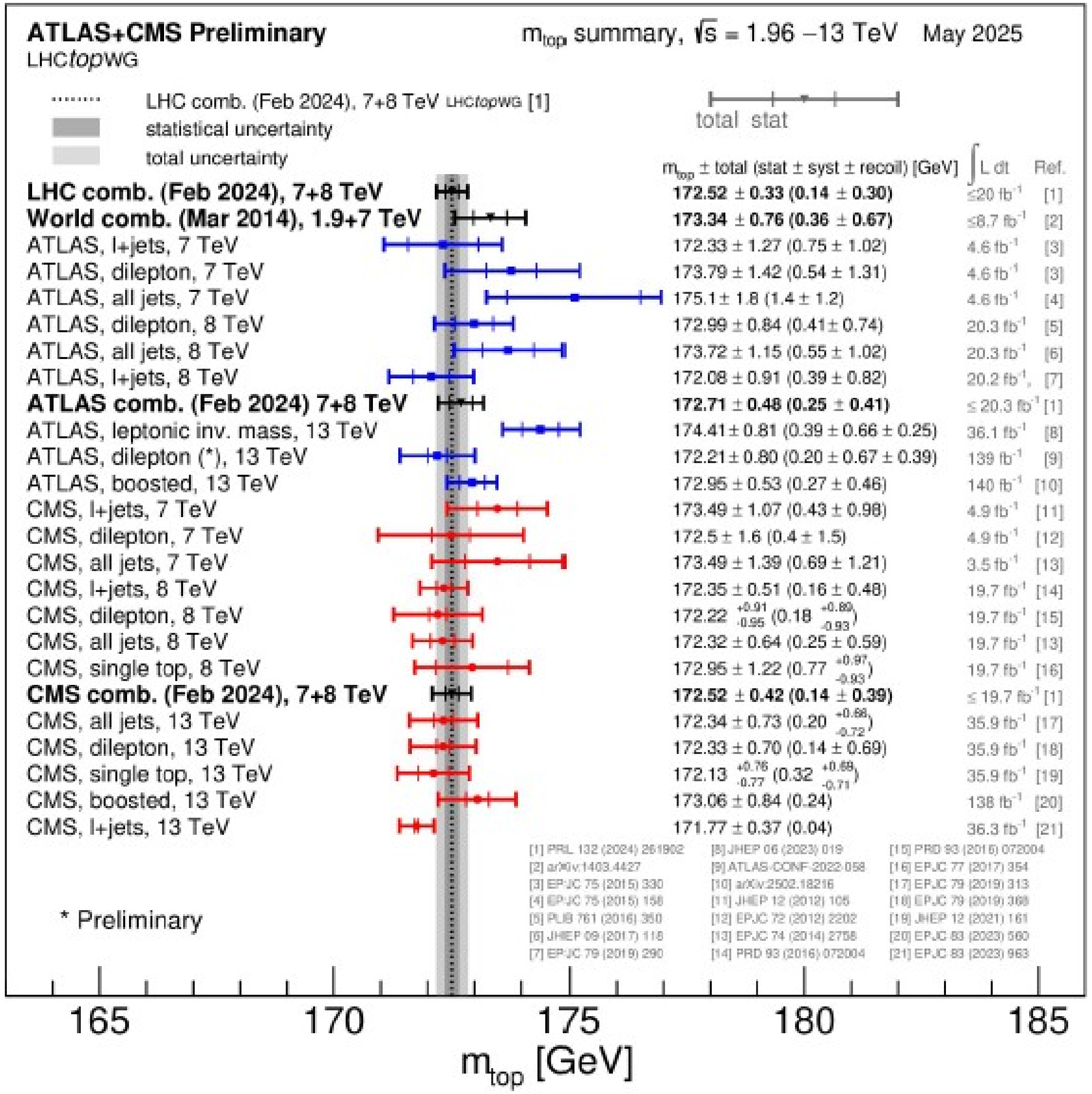


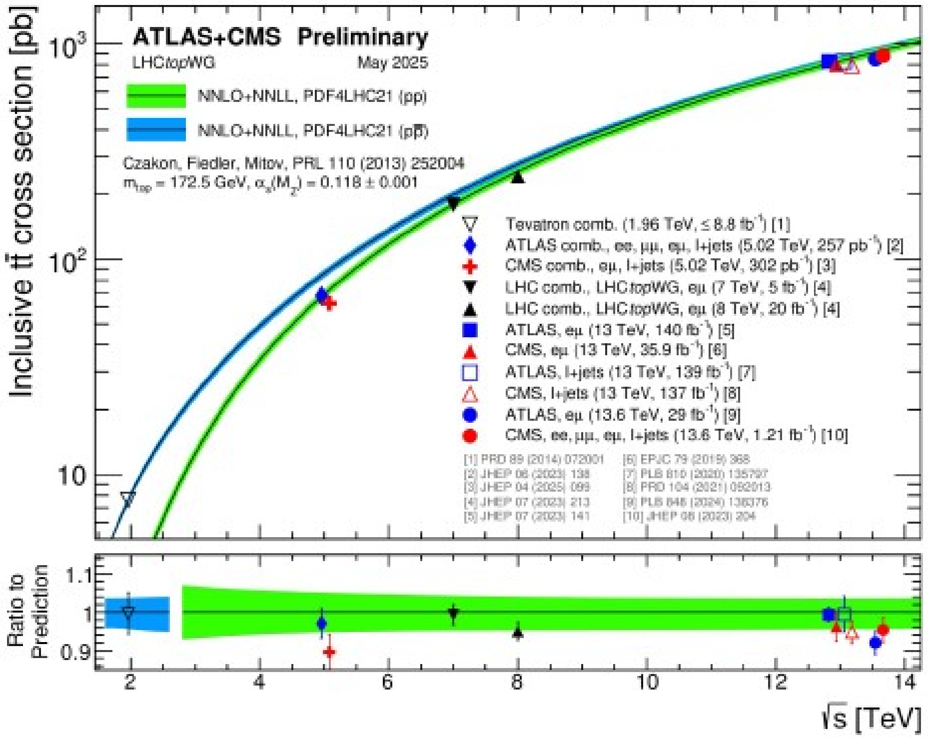




- WWZ production measured in events with 4 leptons (+ missing energy)
- Continuum contribution separated from ZH
- Results consistent with SM using Run 2+3 data

Top Mass

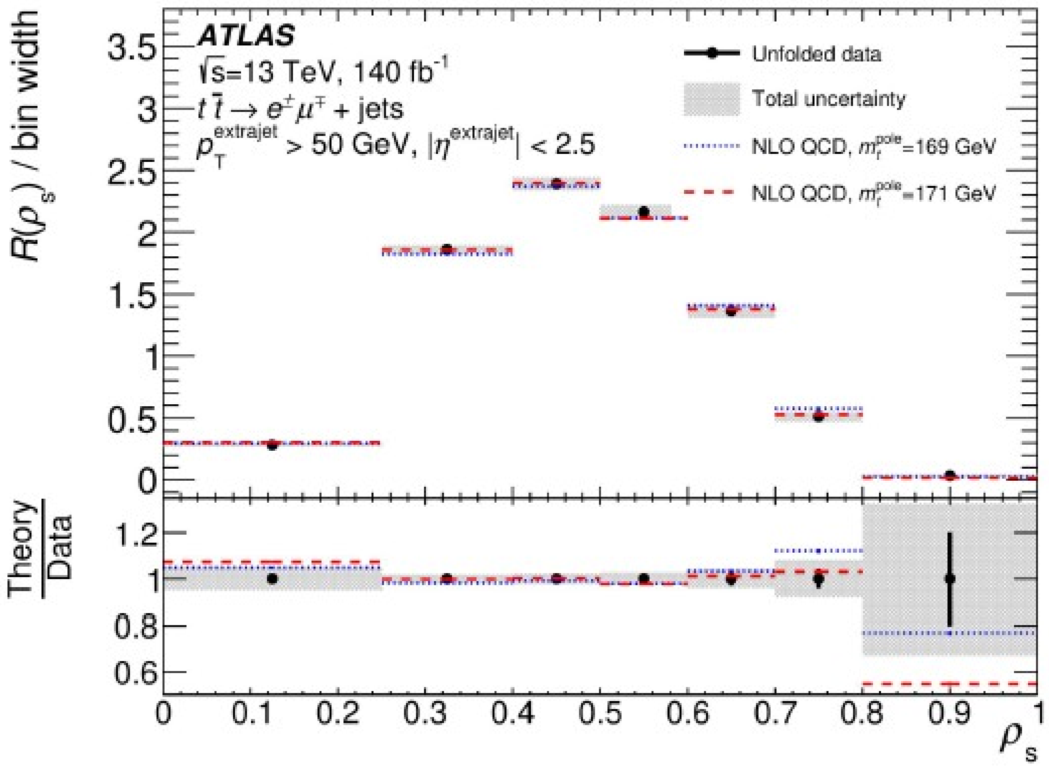


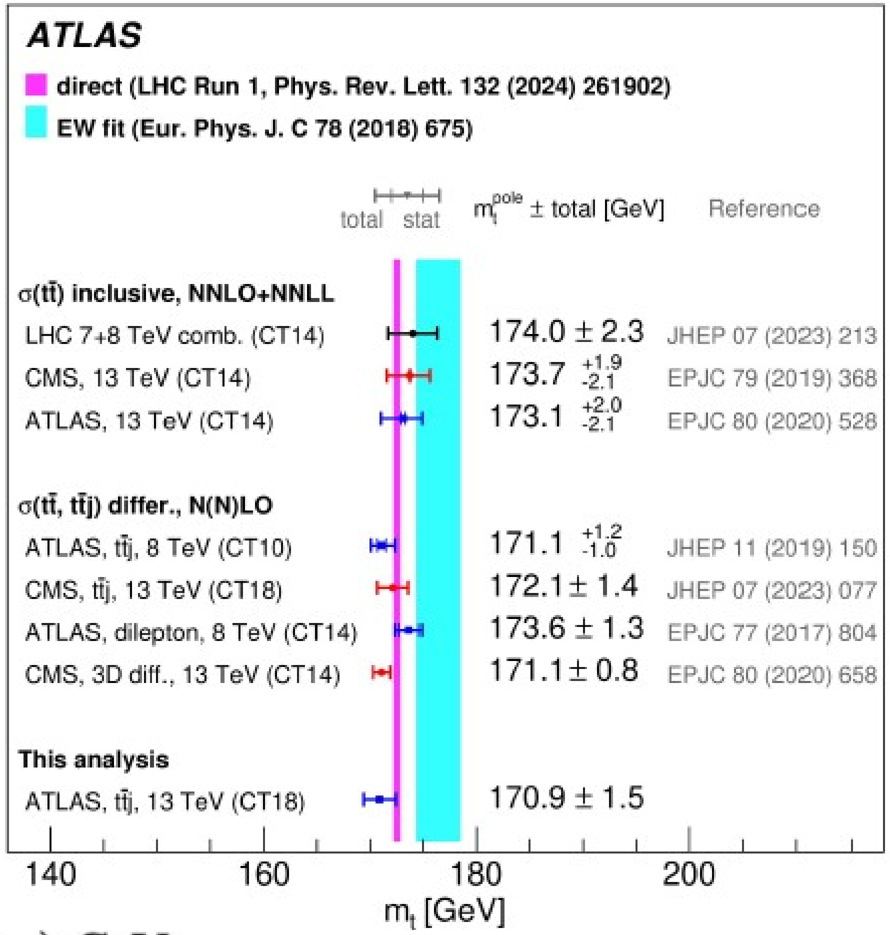


- Top mass at LHC measured most precisely from direct reconstruction of decay products, but with some theoretical ambiguity
- Pole-mass can be measured from production cross sections
- Important to test/establish consistency across many methods

Top pole mass

arXiv:2507.02632



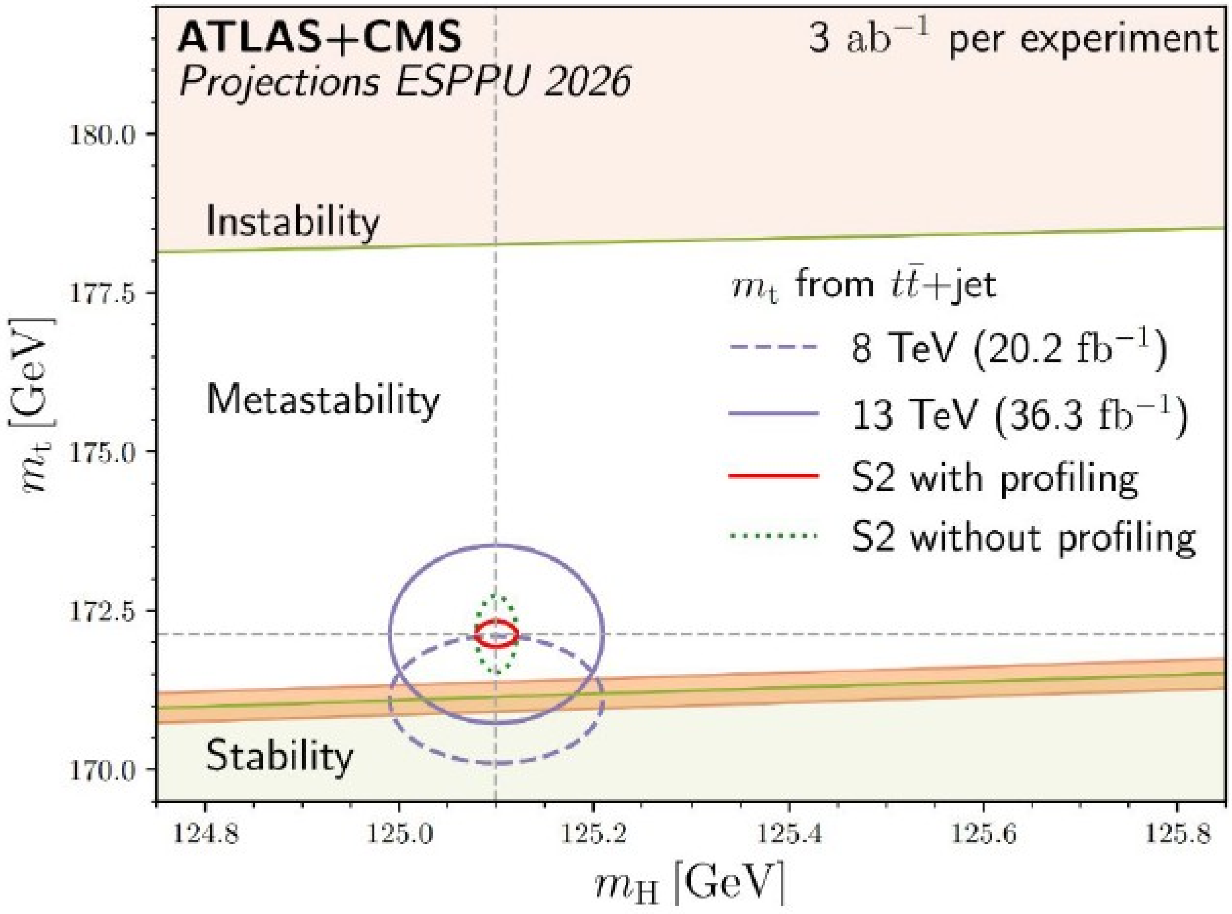


$$m_t^{\mathrm{pole}} = 170.73 \pm 0.33\ (\mathrm{stat.}) \pm 1.36\ (\mathrm{syst.})\ ^{+0.28}_{-0.34}\ (\mathrm{scale})\ ^{+0.24}_{-0.24}\ (\mathrm{PDF} + \alpha_s)\ \mathrm{GeV}$$

- Use of differential cross sections reduces theory uncertainties
- Presence of an additional jet enhances sensitivity to top mass and avoids theoretically difficult threshold production
- Largest uncertainties are related to parton shower modeling

Future: Top Mass

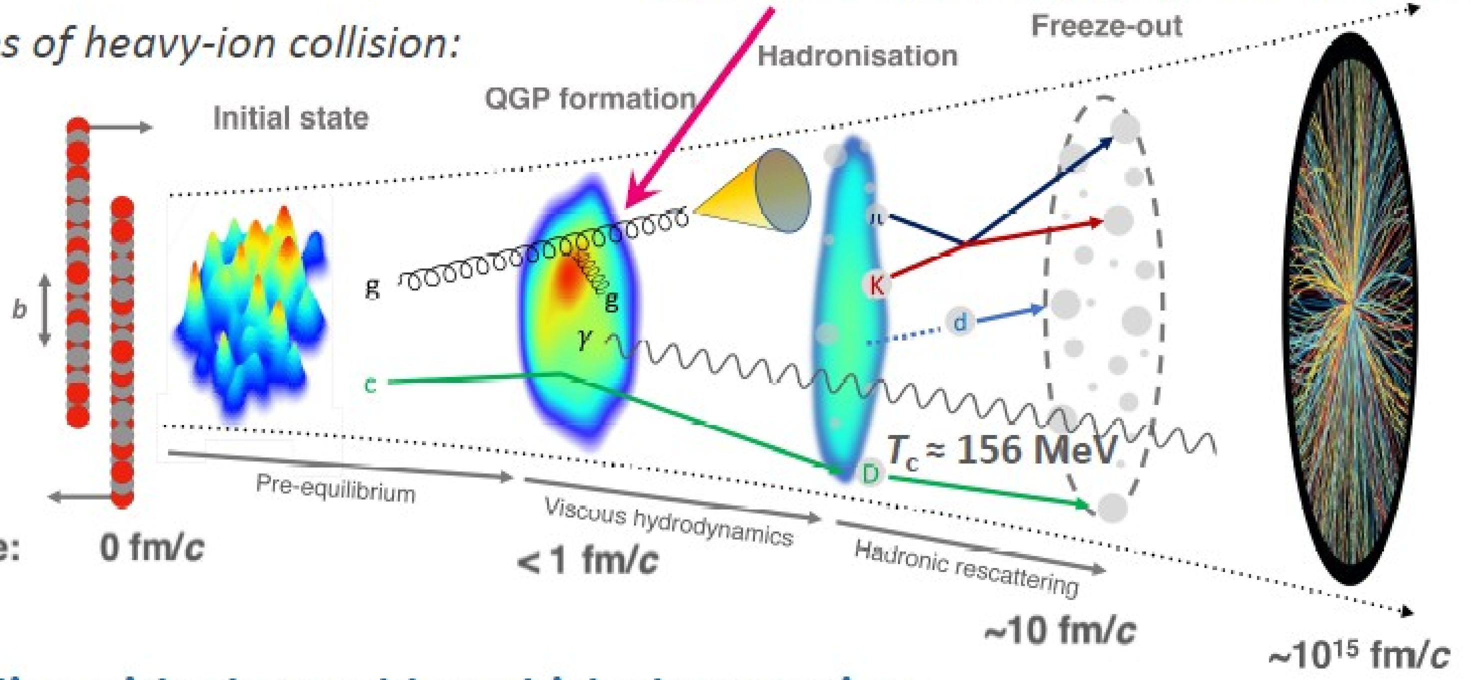
- HL-LHC projections for top mass precision range from 200-600 MeV depending on theoretical interpretation, and degree of control over systematic uncertainties



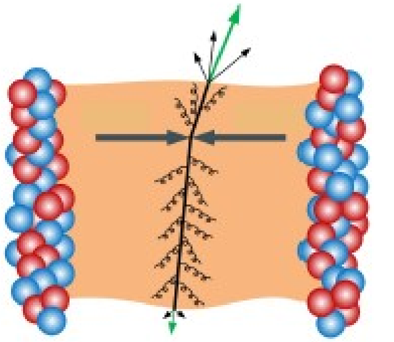
Physics with ALICE

Quark-gluon plasma (QGP) = deconfined strongly-interacting QCD matter with color degrees of freedom

stages of heavy-ion collision:



ALICE experiment: a journey through QCD
[EPJC 84 (2024) 8, 813]



parton energy loss

Studies with observables which characterize:

- **bulk properties** of the produced medium
- medium **interaction with hard probes, hadronisation**
- **collective effects**

Measurements at high multiplicities down to low p_T with precise PID are required (ALICE)

Heavy Ions: Theory
Urs Wiedemann, Fri 14:15

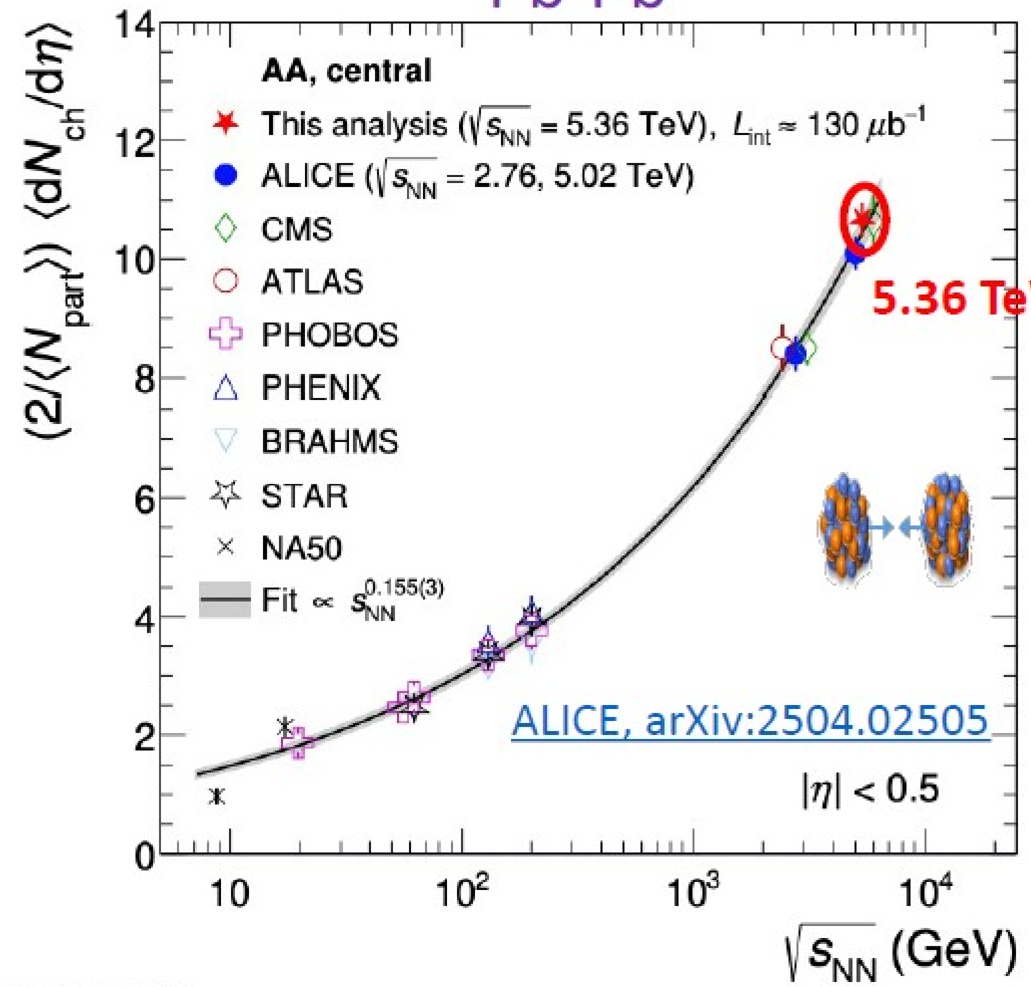
Heavy Ions: Experiment
Francesco Prino, Fri 14:45

Charge particle density ($dN_{ch}/d\eta$)

Abhi Modak
T04, Mon 14:40

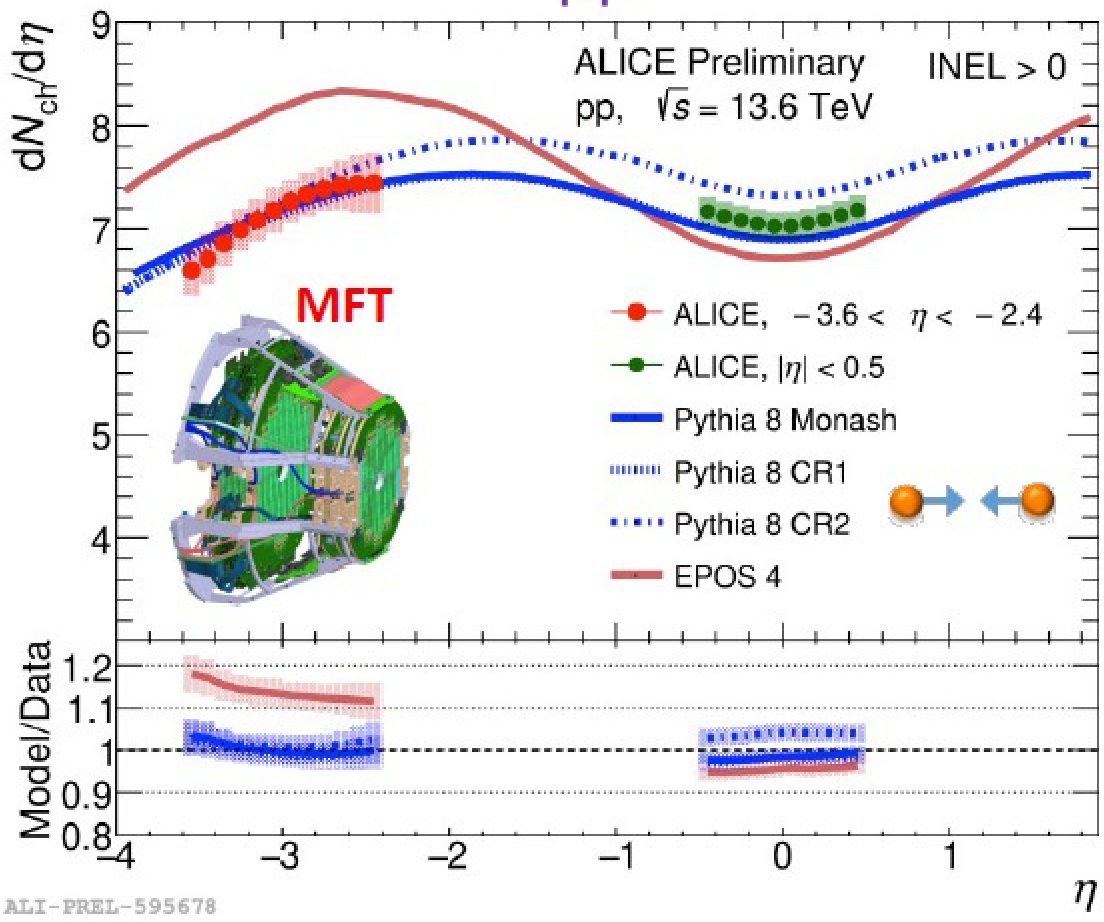
ALICE

Pb-Pb



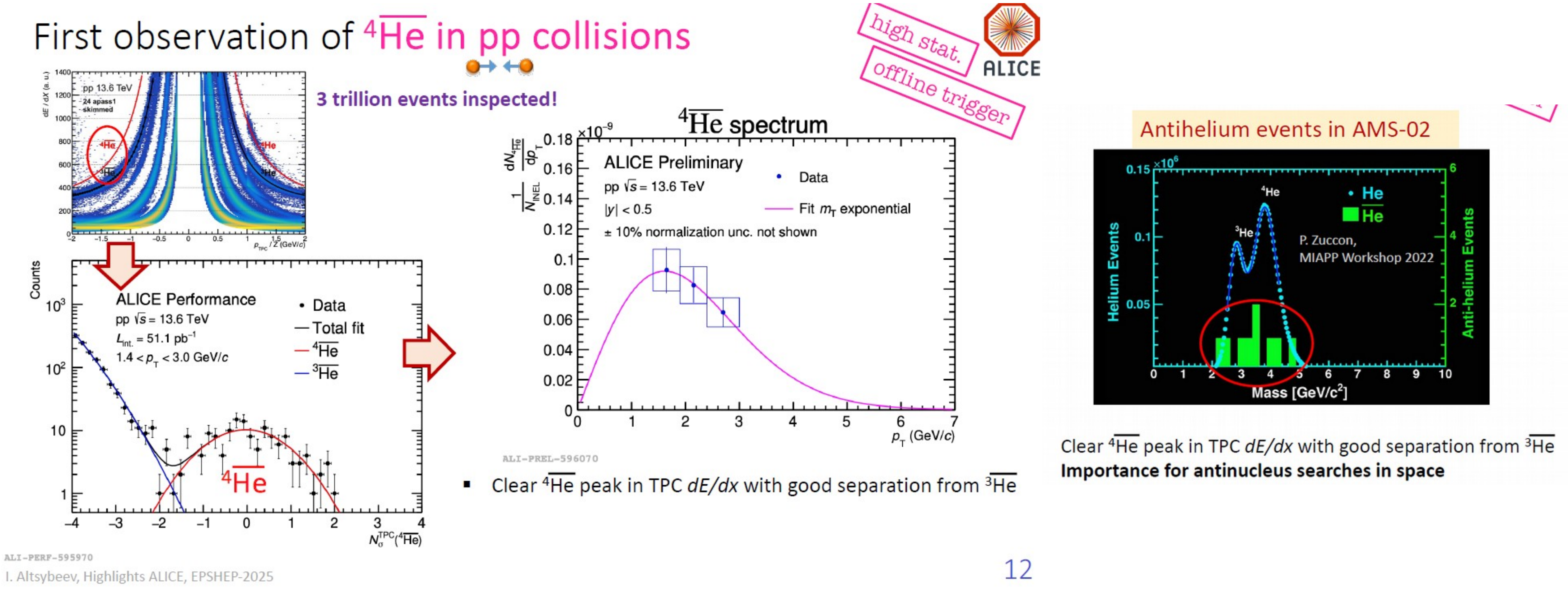
- First paper with Run 3 results

pp



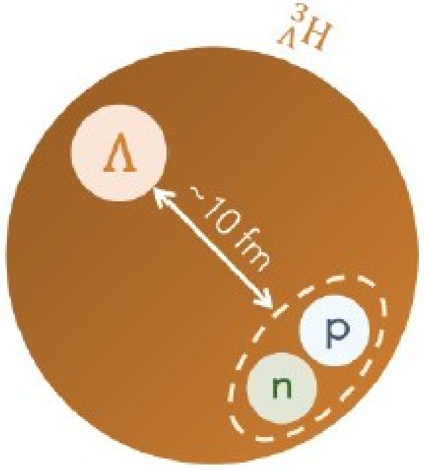
- First measurement using new MFT detector
- The trend at forward rapidities is compatible with PYTHIA 8

Наблюдение антигелия в pp соударениях



First p_T-differential measurement of hypertriton in pp

- Lightest known hypernucleus
- Loosely bound object

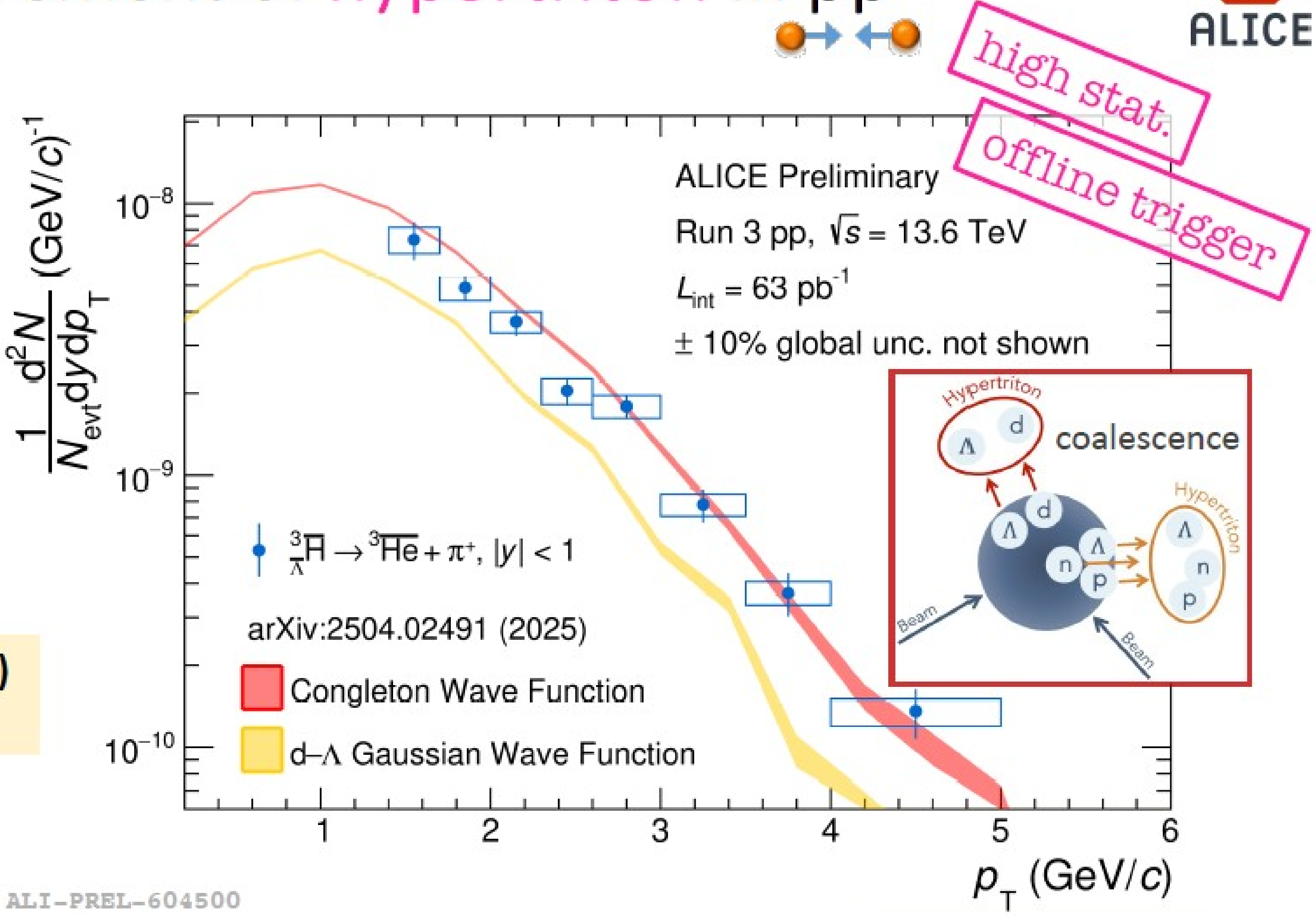


$m \sim 2.991\ \mathrm{GeV}/c^2$
$c\tau \sim 7.1\mathrm{cm}$
$B_\Lambda \sim 100\,\mathrm{keV}$

→ Interplay between **large $^3_\Lambda$H wave function (r_A)** and **small source size in pp collisions (R_S)**

$$B_3 \sim \left(\frac{2\pi}{R_S^2+(r_A/2)^2}\right)^3$$

B_A – coalescence parameter (A=3)

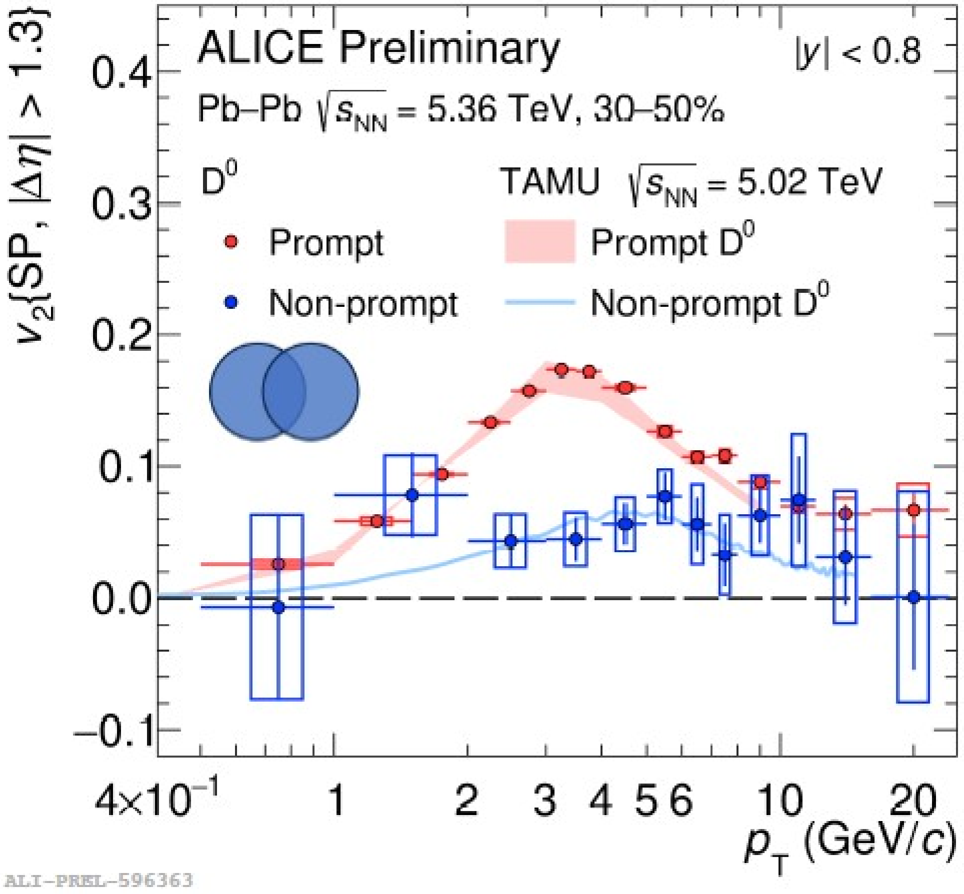


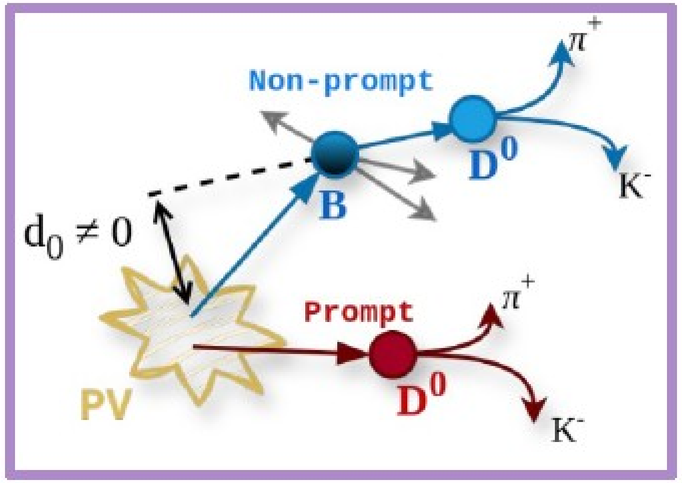
Carolina Anna Reetz
T04, Mon 14:20

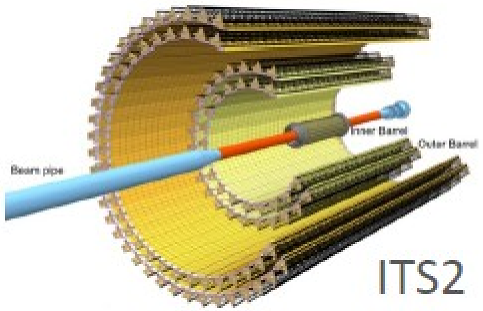
→ **$^3_\Lambda$H as ideal probe to study nucleosynthesis mechanism**

- Relevant for the equation of state of neutron stars

Anisotropic flow of charm and beauty



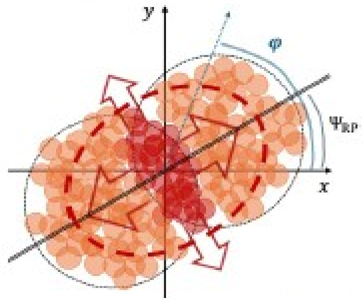




pointing res.

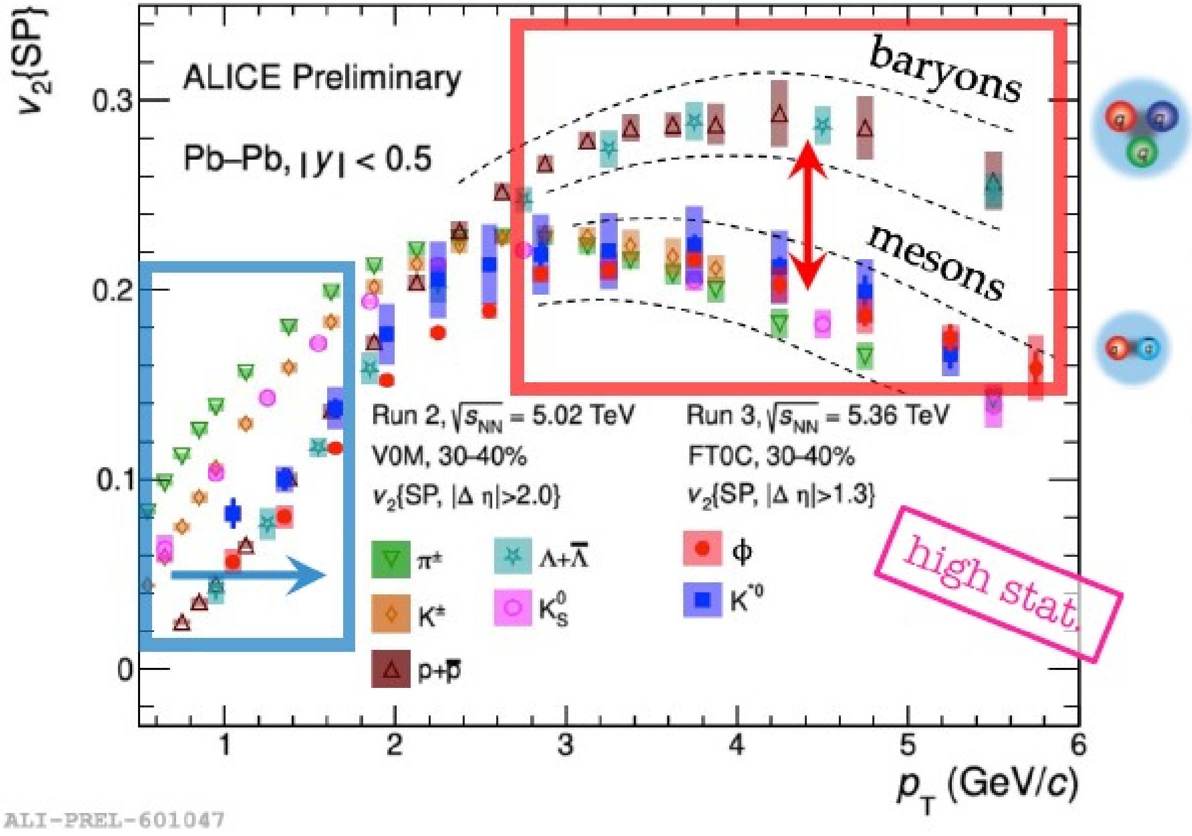
high stat.

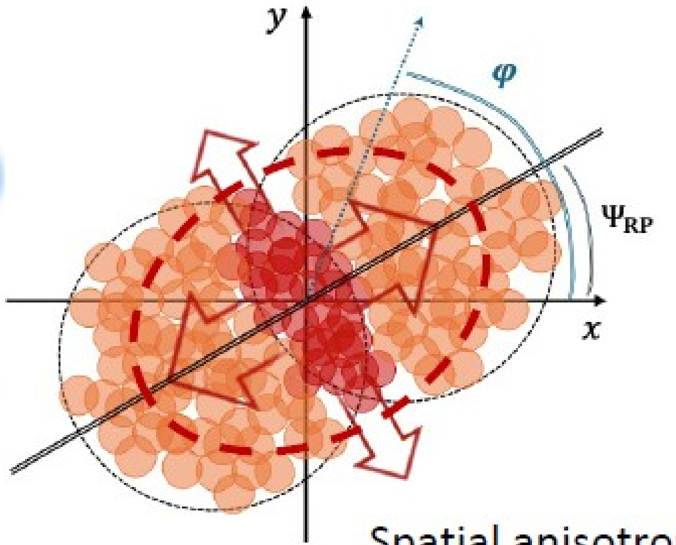
Marcello Di Costanzo
T04, Wed 17:00



- **Non-prompt D^0** flow (~beauty) smaller than **charm flow**

Anisotropic flow of particles in **Pb-Pb** collisions





Spatial anisotropy → **momentum anisotropy**

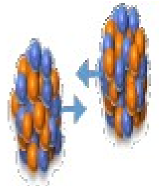
- quantified via Fourier decomposition:

$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{\infty} \boldsymbol{v_n}(cos[n(\varphi - \Psi_{RP})])\right)$$

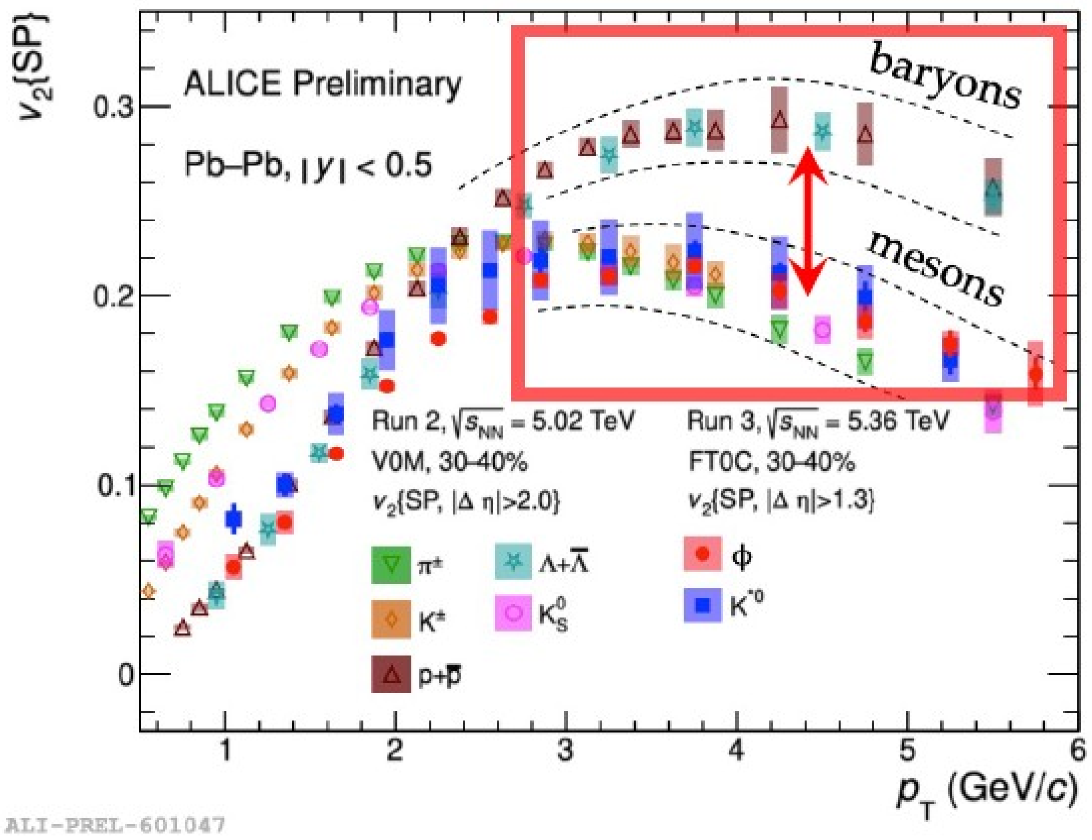
leading term: v_2 – "elliptic flow"

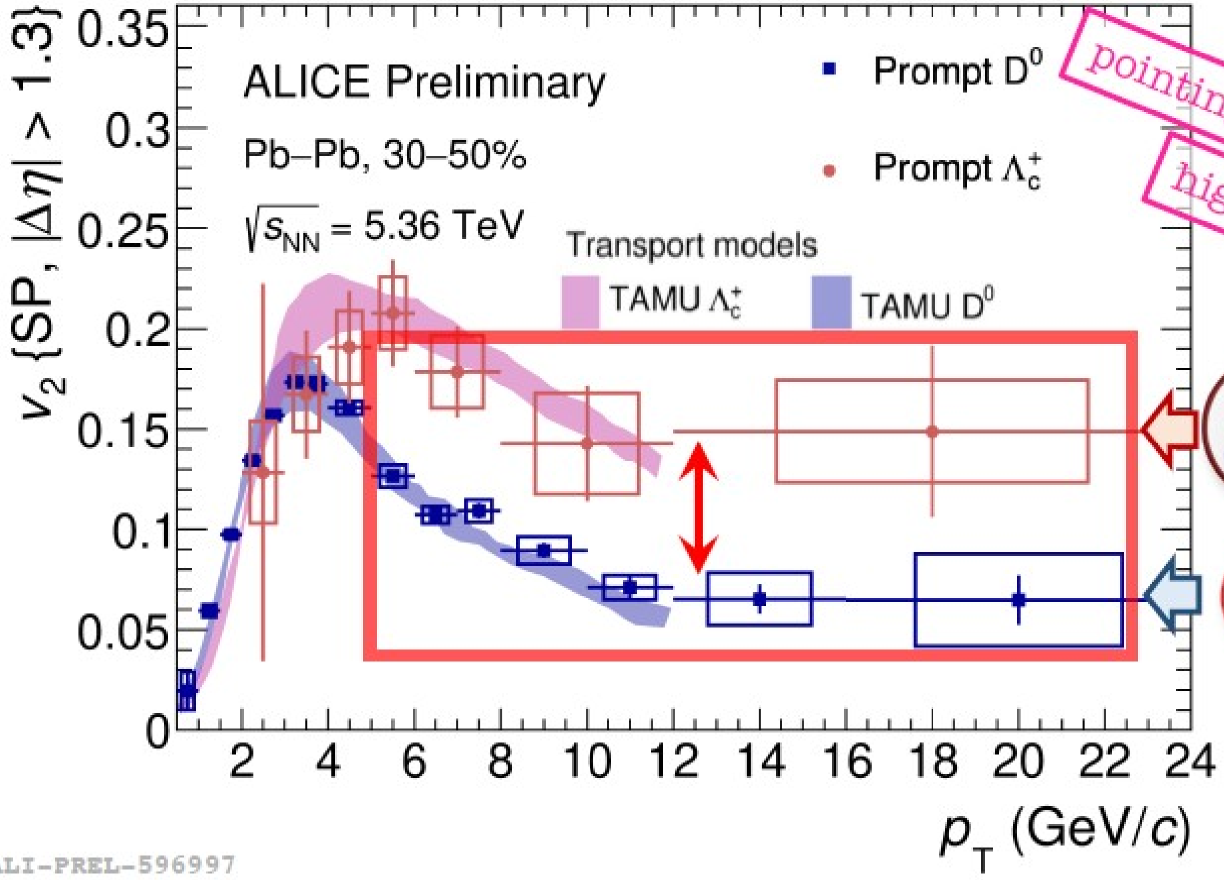
- Low p_T: **"ordering" by particle mass** → common velocity field
- High p_T: **baryon/meson grouping** → quarks recombine (coalescence)

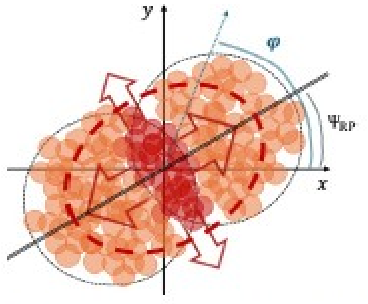
World-first measurement of Λ_c^+ baryon flow in Pb–Pb



ALICE

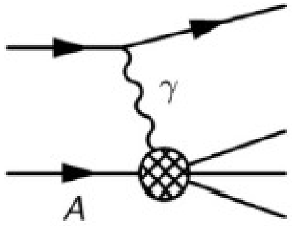






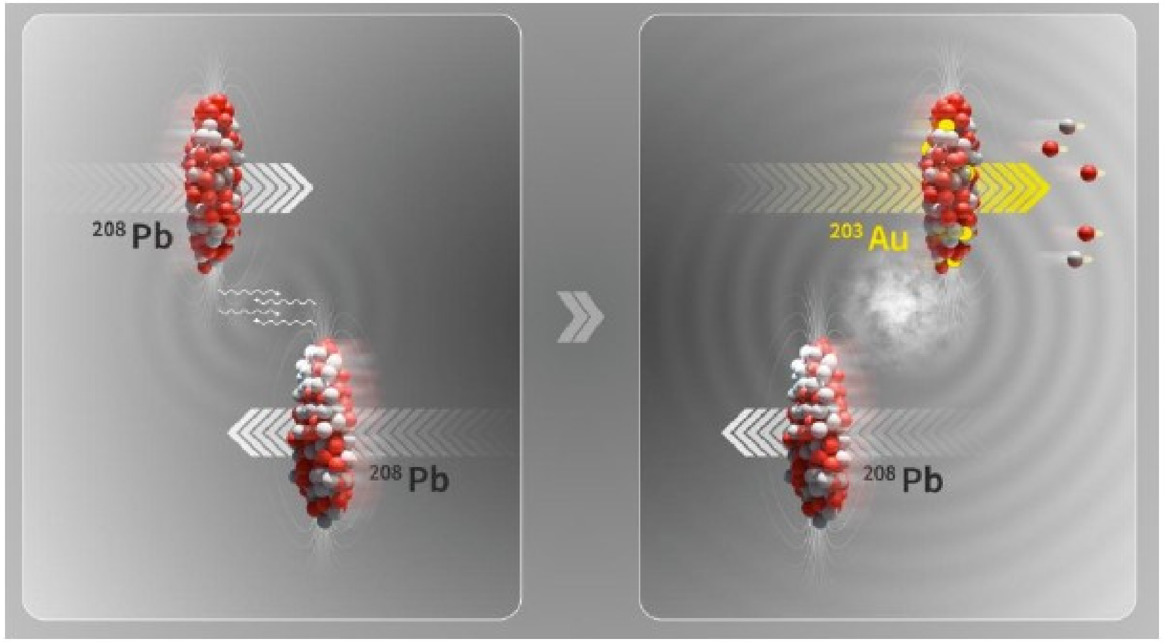
- First prompt charm-baryon v_2 measurement in heavy-ion collisions
- First evidence of **charm baryon/meson splitting** at intermediate/high p_T
  - **TAMU**: includes quark coalescence → captures the trend

Marcello Di Costanzo
T04, Wed 17:00

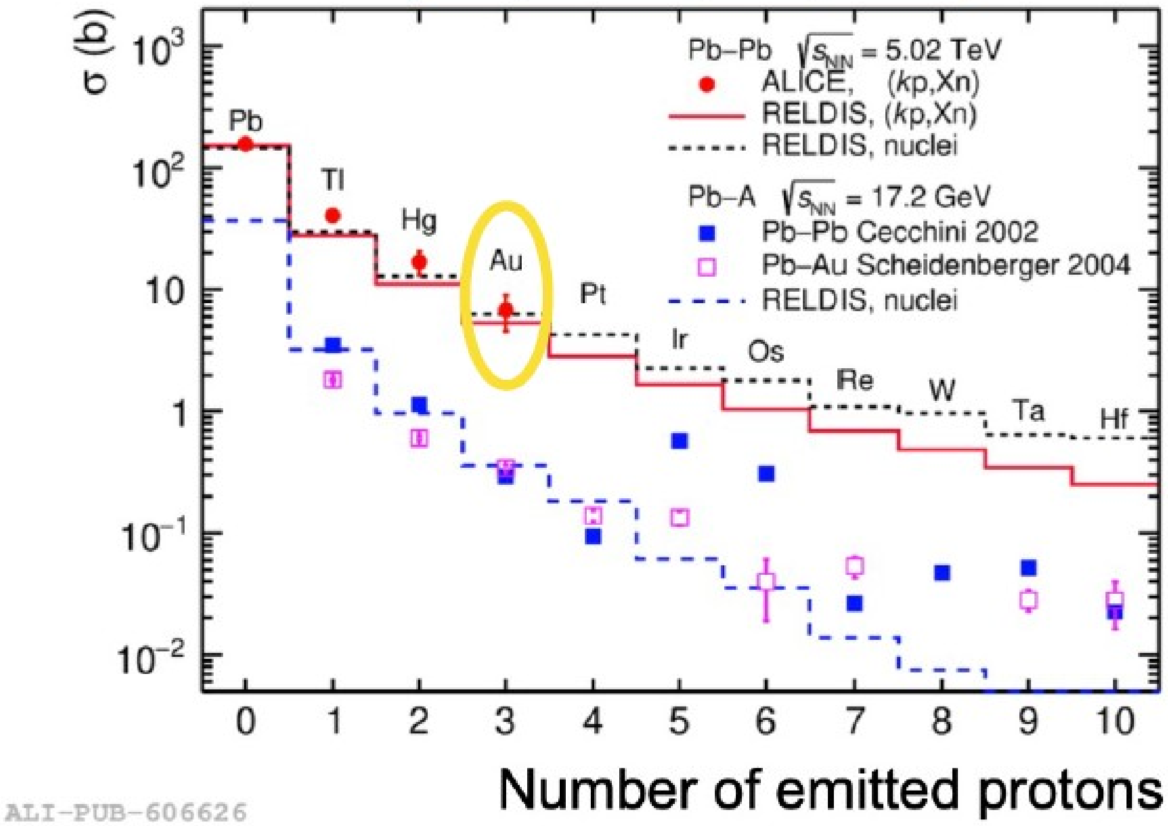


γ-Pb Ultra-Peripheral Collisions: Alchemy at the LHC

- Electromagnetic dissociation of Pb nucleus in ultraperipheral collisions
  - emission of 3 protons corresponds to **transmutation of Lead into Gold by light** (≈2.9 x 10^{-11} g of Au produced in Run 2)



ALICE, PRC111 (2025) 054906



Заключение

- Много новых результатов, особенно относящихся к определению квантовых чисел новых наблюдаемых состояний. Но в основном это пока лишь указания на предпочтения. Впереди долгий прецизионный анализ на большей статистике.
- Новые пары бозонов Хиггса с разными модами распада наблюдены, а также редкие виды распадов
- Новые данные по рождению антиядер в pp соударениях, аналогичных данным AA соударений, и ожидание новых пучков более легких ядер
- Усовершенствование установок и программного обеспечения