Новые результаты Большого адронного коллайдера по материалам EHS-HEP конференции 2021

СЕМИНАР ОЭПВАЯ 9 СЕНТЯБРЯ 2021

ПРОФ. Л.Н.СМИРНОВА

Major 2021 summer conferences

6/6

52 talks (plenary and parallel) - 25 posters - **15 New Results**

26/7

53 talks (plenary and parallel) - 35 posters - **26 New Results**

23/8

25 talks (plenary and parallel) - **4 New Results**

Три важнейших конференции ФВЭ 2021

9th LHCP,
Париж,
6-12 июня 2021

ESP-HEP,
Гамбург + DESY,
26-30 июля 2021

SUSY, 23-28 авг.
Не рассматриваем!

Временной статус работы Большого адронного коллайдера (БАК)

Актуальны физические результаты, полученные с использованием полной интегральной светимости L_{int}, собранной во втором сеансе

- Анализ полных данных второго сеанса (Run 2)
- Близкое завершение периода длительной остановки БАК (LS2) – очередной этап модернизации коллайдера и детекторов
- Показаны запланированные далее этапы

ATLAS + CMS – детекторы общего назначения

A vast physics program

ATLAS EXPERIMENT

- Physics@LHC is most ambitious and farthest reaching HEP program ever
- **Huge dataset with well understood detector performance** allows
  - Precision measurements $\mathscr{L}_{\mathrm{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + \mathrm{hc} + |D_\mu\phi|^2 - V(\phi)$
    - Determine fundamental parameters, probe higher-order QCD and EW effects
  - Access to rare processes (e.g. production of WWW or $t\bar{t}t\bar{t}$)
    - Probe poorly or untested corners of SM
  - Broad search program at TeV scale and beyond (high energy frontier) & feeble interactions (low coupling frontier)
    - Directly address compelling issues: naturalness, dark matter, flavor puzzles, etc.
  - Study of new states of matter —> quark-gluon plasma

Stéphane Willocq (Univ. of Massachusetts, Amherst)

- Обширный фронт исследований, много результатов.
- Анализы сконцентрированы на прецизионой проверке СМ путем измерения редких процессов, отвечающих высоким порядкам расчетов КХД (QCD) и электослабой теории (EW)
- Получение новых состояний материи (КГП, адроны с новой структурой)

Исследования бозона Хиггса и редких процессов

- **Higgs**
  - Observation of all main production mechanisms → ggF, VH, VBF, ttH
  - Observation of Yukawa interactions w/ 3rd generation fermions → $\begin{pmatrix} t \\ b \end{pmatrix}, \begin{pmatrix} \nu \\ \tau \end{pmatrix}$
  - Constraints on Higgs self-interaction via HH cross section
- **Rare processes**
  - Observation of all weak boson scattering modes (incl. $W^{\pm}W^{\pm}$) as well as $\gamma\gamma \to \gamma\gamma$ and $\gamma\gamma \to WW$
  - Observation of $t\bar{t}W$, $t\bar{t}Z$ and tZq + evidence for $t\bar{t}t\bar{t}$ production and $H \to \ell\ell\gamma$

CMS: для бозона Хиггса измерена костанта связи с мюоном - след.слайд

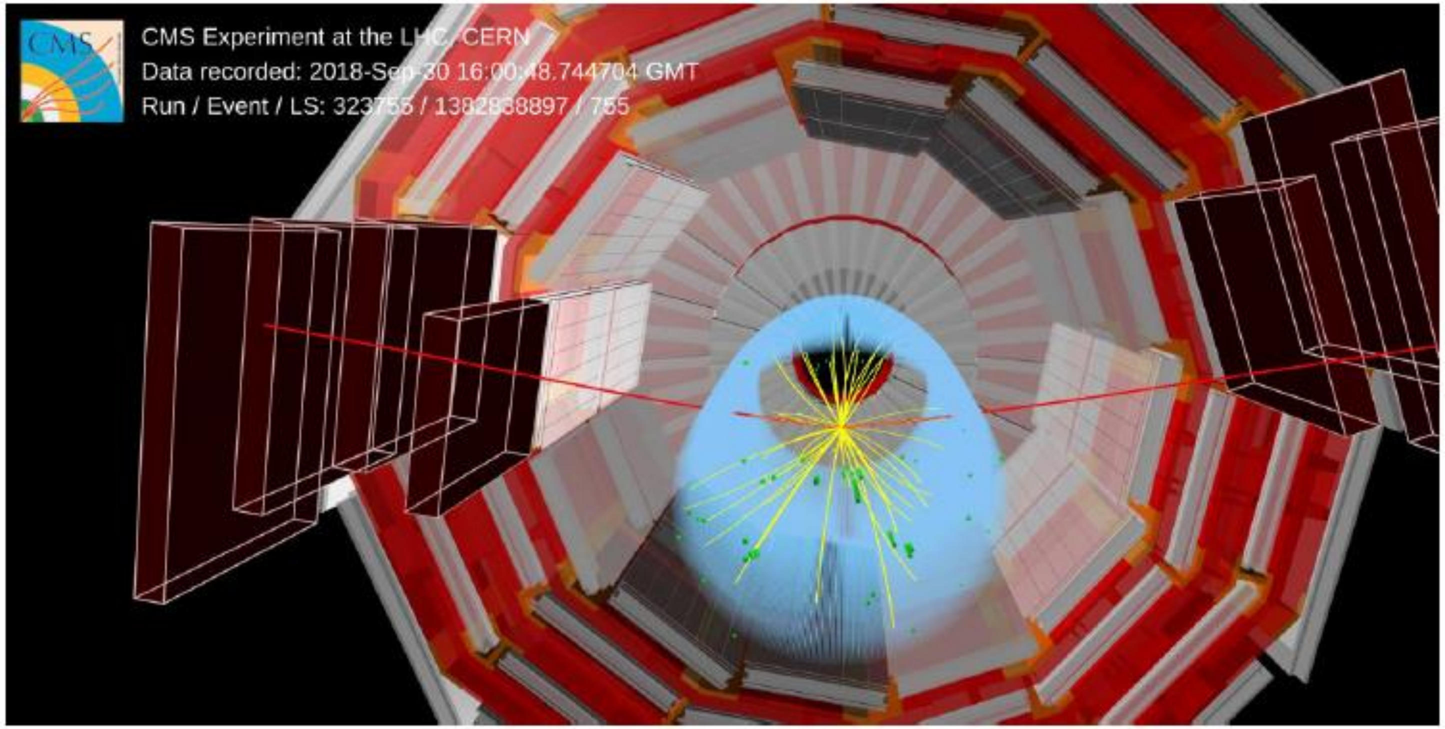
ATLAS+CMS: Измерения рождения двух бозонов Хиггса (HH)

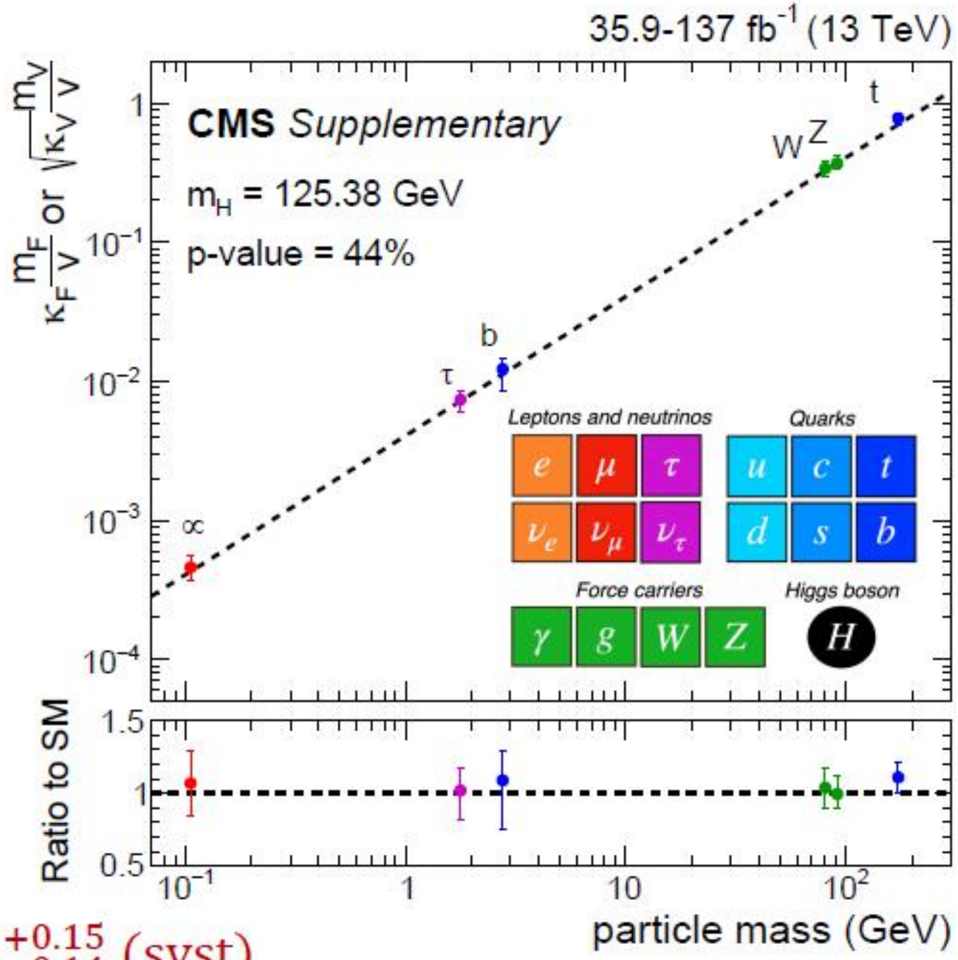
Evidence for H → $\mu\mu$

- First evidence of the coupling of the Higgs boson with fermions of the second generation

JHEP 01 (2021) 148

H → $\mu\mu$ candidate in gluon fusion channel
Mass = 125.46 ± 1.13 GeV





- Signal strength, relative to the SM prediction $\mu = 1.19^{+0.40}_{-0.39}\,(\text{stat})^{+0.15}_{-0.14}\,(\text{syst})$
- **Obs. (exp.) significance 3.0σ (2.5σ)**

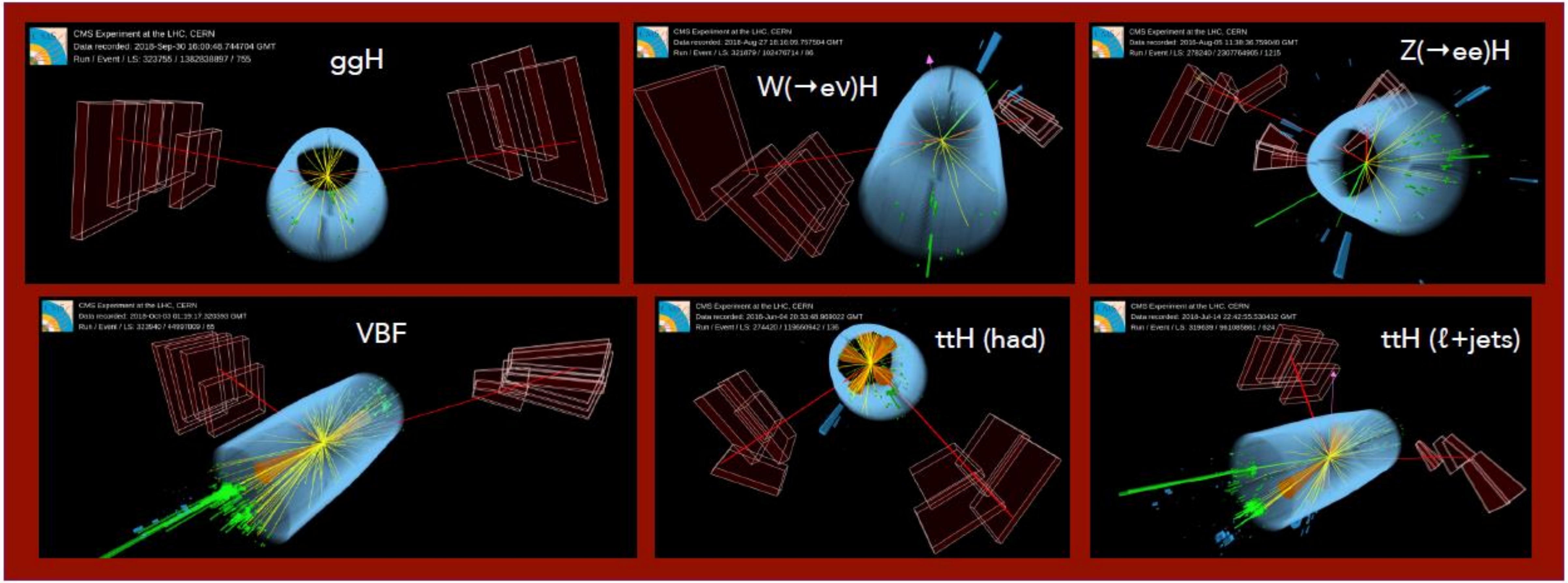
ATLAS представил результат на ICHEP 2020

Talks of Silvio Donato (Mon) and Kerstin Tackmann (Tu

First Evidence for H → μμ

для разных механизмов рождения бозона Хиггса
разные типы событий

Exclusive categories: ggH, VBF, VH and ttH



Higgs couplings to τ leptons

New

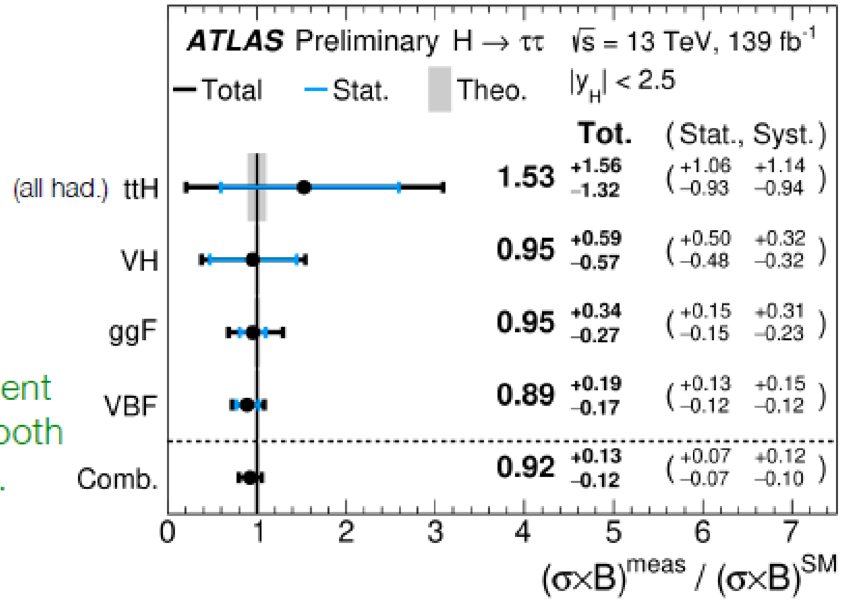
ATLAS-CONF-2021-044

ATLAS EXPERIMENT

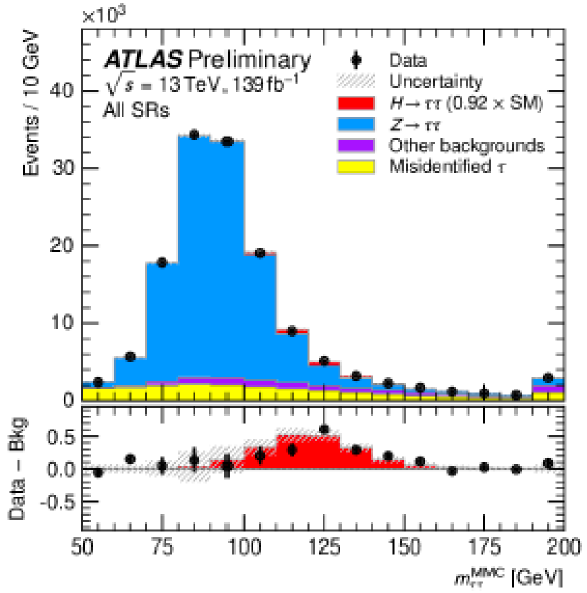
- Run 2: ~8 x 10⁶ Higgs bosons produced

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \boxed{\psi_i y_{ij}\psi_j\phi + hc + |D_\mu\phi|^2} - V(\phi)$$

- $\mathscr{B}(H \rightarrow \tau\tau) = 6.3\,\%$ —> test **Yukawa interactions with leptons**
- Expt. challenge: 2-4 neutrinos in final state, poor mass resolution
- Multiple BDTs used to suppress $Z \rightarrow \tau\tau$ and $t\bar{t}$ background, and categorize event purity for each production mechanism
- Dominant $Z \rightarrow \tau\tau$ background from MC, controlled with $Z \rightarrow \ell\ell$ data via kinematic embedding procedure

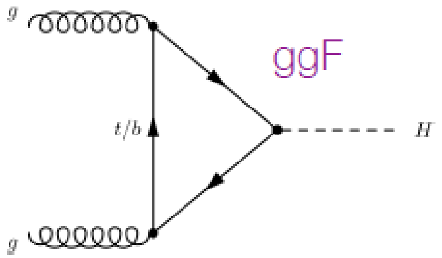


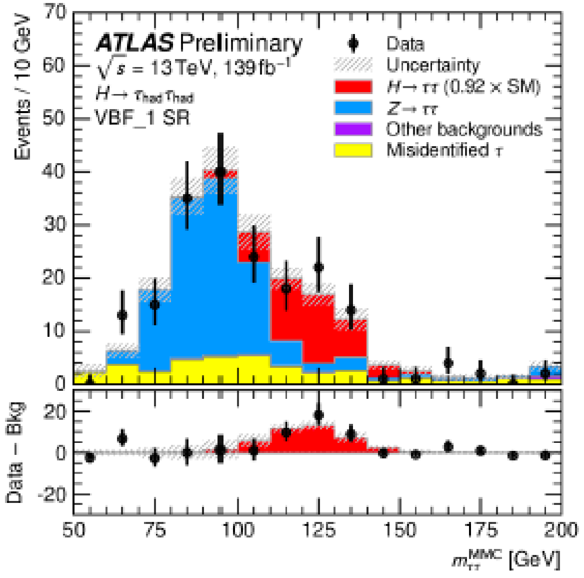
factor of 2.5 improvement over 36 fb⁻¹ analysis in both stat and syst uncert.



- ggF significance

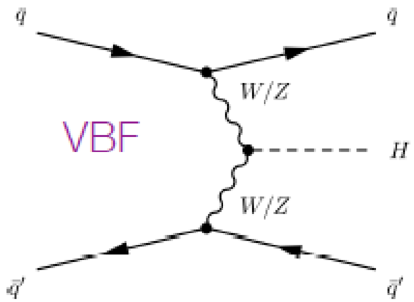
$3.9\,\sigma\,(4.6\,\sigma)$ obs (exp)





- VBF significance

$5.3\,\sigma\,(6.2\,\sigma)$ obs (exp)



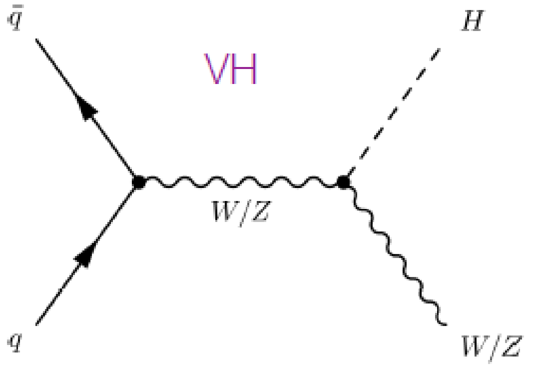
Higgs couplings to 2nd gen quarks

ATLAS-CONF-2021-021

ATLAS EXPERIMENT

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\,\overline{\psi}\not{D}\psi + \boxed{\psi_i\, y_{ij}\, \psi_j\, \phi + \mathrm{hc} + |D_\mu \phi|^2} - V(\phi)$$

- Test of **Yukawa interactions w/ 2nd generation fermions**: evidence for leptons only
- **Search for H—> cc** in associated $V(\ell\ell, \ell\nu, \nu\nu)\,H$ production
- Dedicated charm tagging
- Results:



$$VW(\to cq) \text{ with } 3.8\,\sigma\,(4.6\,\sigma) \text{ obs (exp)}$$

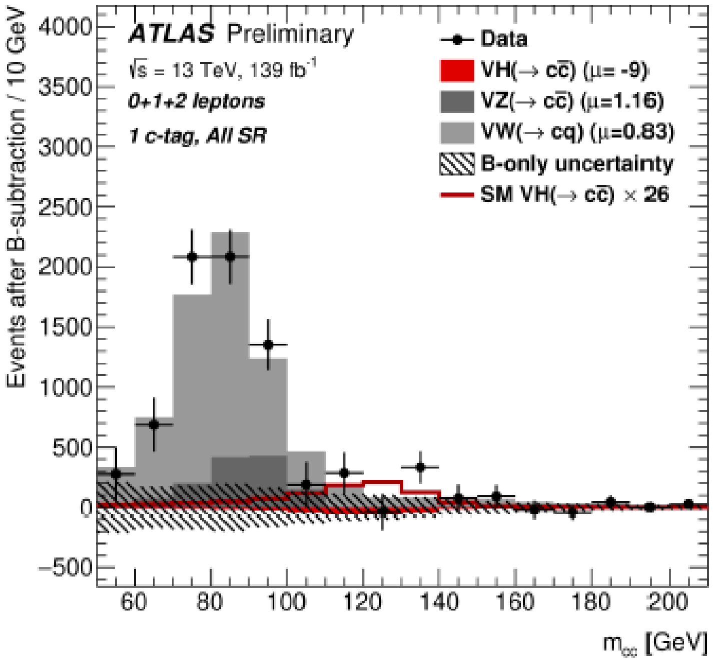
$$VZ(\to cc) \text{ with } 2.6\,\sigma\,(2.2\,\sigma) \text{ obs (exp)}$$

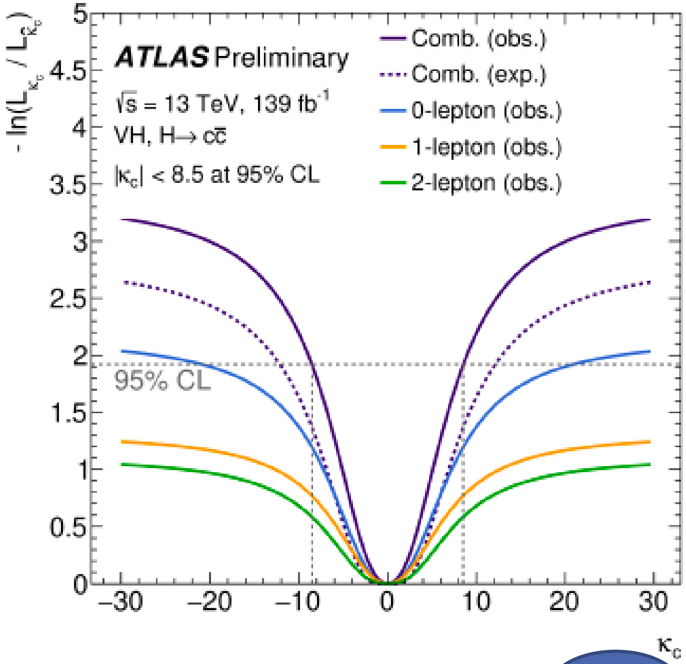
$$\boxed{VH(\to cc) < 26\,(31)\,\sigma_{SM} \text{ obs (exp)}}$$

- Charm Yukawa modifier

$$|\kappa_c| < 8.5\,(12.4) \text{ obs (exp)}$$

first direct constraint



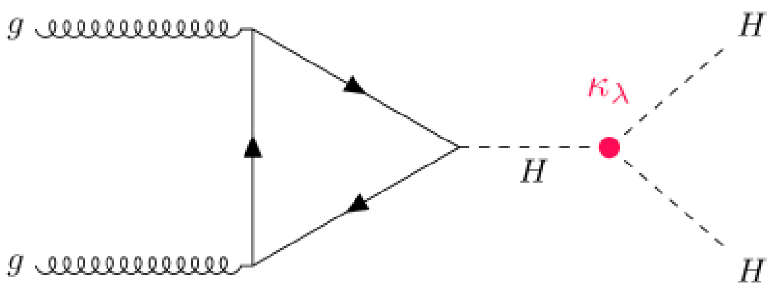


Di-Higgs production

New

ATLAS-CONF-2021-030

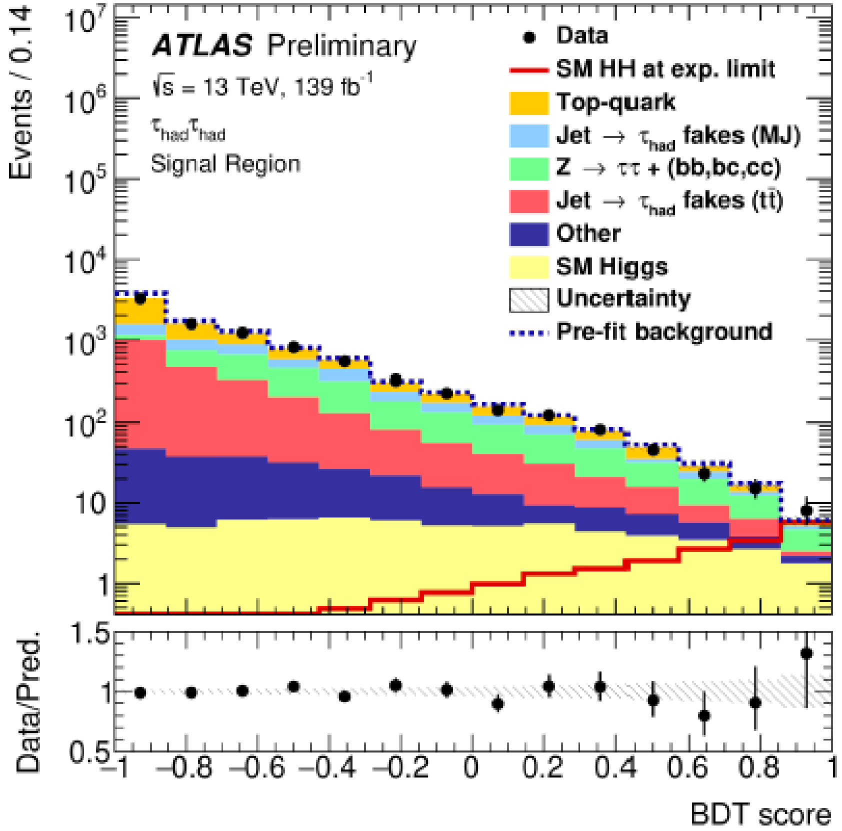
$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\,\overline{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + \text{hc} + |D_\mu\phi|^2 - \boxed{V(\phi)}$$



- **Direct access to Higgs potential**
  - Last part of SM needing direct test
  - Small HH XS (ggF 31 fb @NNLO)
- HH —> bbbb (33%), bbττ (7.3%), bbγγ (0.3%)
- **HH —> bbττ channel**
  - Trigger: single lepton, lepton+τ_{had}, single τ_{had}, di-τ_{had}
  - MVAs (BDT and NN) used for signal vs. bkg
  - $Z(\ell\ell)$+heavy flavor CR
  - multiple fake-tau CRs
  - most sensitive channel to non-resonant HH

$$\boxed{\sigma_{HH}/\sigma_{HH}^{SM} < 4.7\ (3.9)\ \text{obs (exp)}}$$

factor of 4 improvement over 36 fb^{-1} analysis

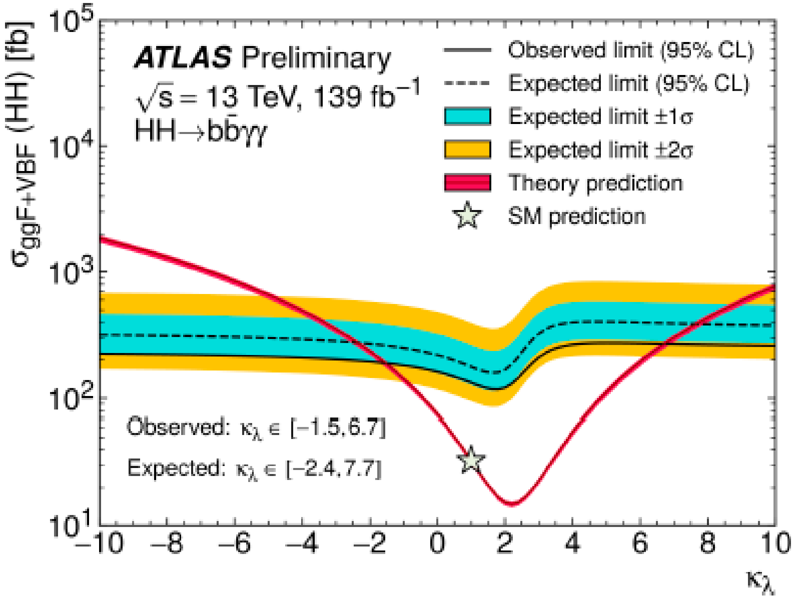


Di-Higgs production

ATLAS-CONF-2021-016 ATLAS-CONF-2021-035

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\,\overline{\psi}\,\not{D}\,\psi + \psi_i\, y_{ij}\, \psi_j\, \phi + \mathrm{hc} + |D_\mu \phi|^2 - \boxed{V(\phi)}$$

- **HH —> bbγγ**



$$\sigma_{HH}/\sigma_{HH}^{SM} < 4.1\ (5.5)\ \text{obs (exp)}$$

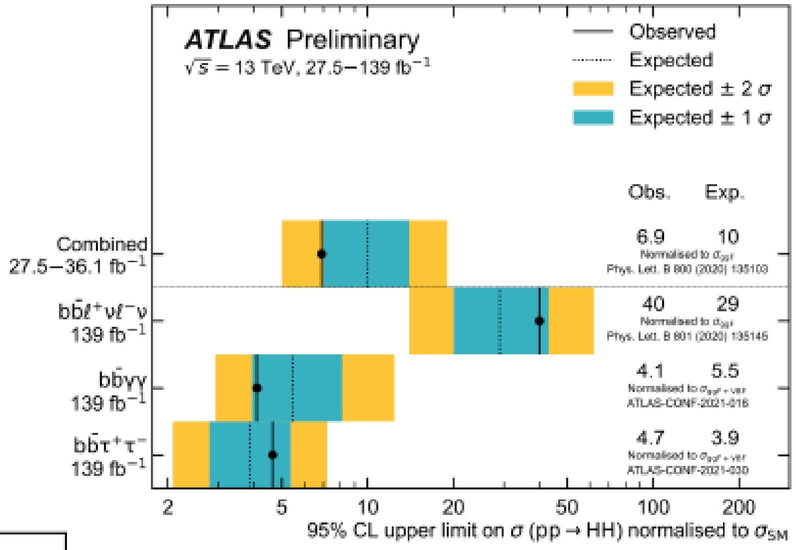
factor of 5 improvement over 36 fb^{-1} analysis

self-coupling modifier κ_λ

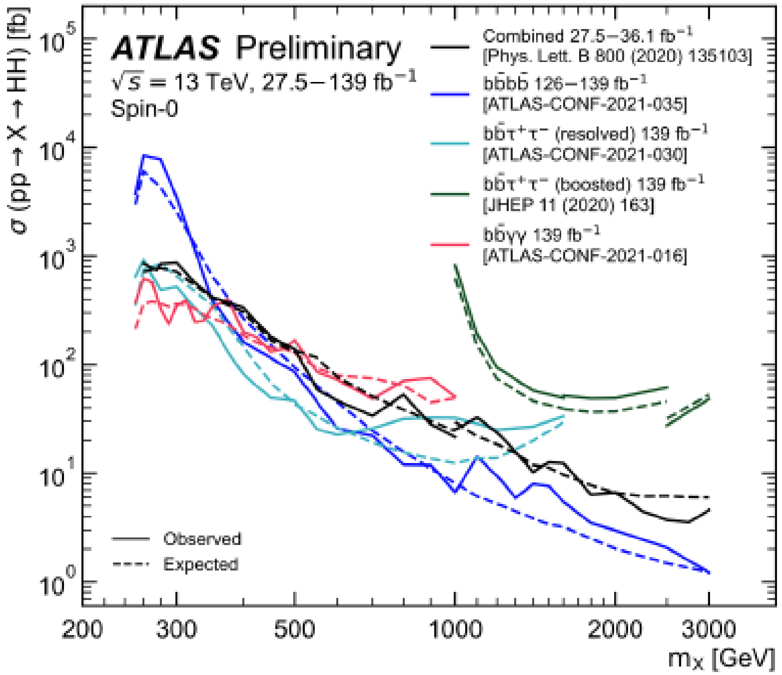
$$\lambda_{HH}/\lambda_{HH}^{SM} \in [-1.5, 6.7]$$

$$(\text{exp } [-2.4, 7.7])$$

strongest constraint



- **Search for HH resonances** New
  - HH —> bbbb, bbττ, bbγγ
  - HH —> bbbb with both resolved and merged topologies
    - Data-driven bkg
    - Dominates for m(X) > 700 GeV



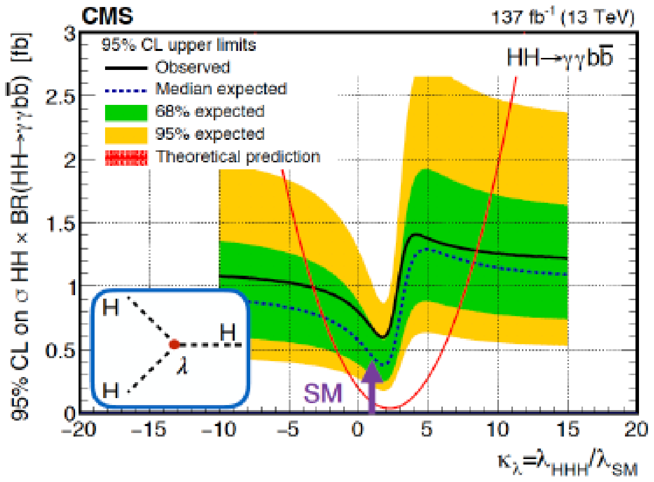
Поиск резонансов в системе двух хиггсовских бозонов

Результат измерения рождения пар бозона Хиггса (HH) в CMS

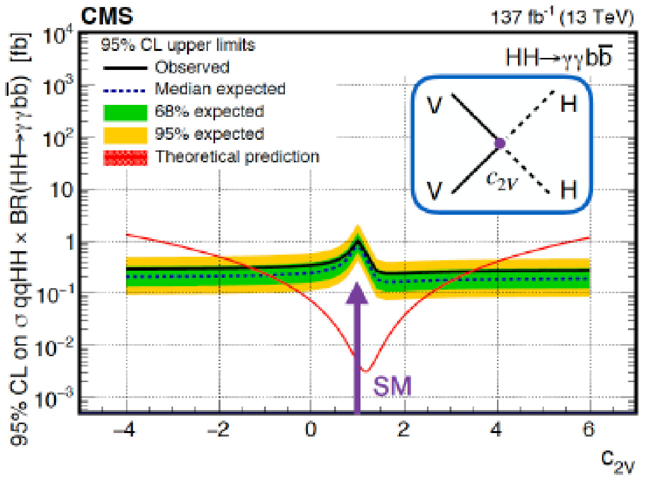
Full Run-2, 137 fb⁻¹

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

Phys. Briefing



Driven by ggF categories



Driven by VBF categories

Inclusive $\mathrm{HH} \rightarrow \gamma\gamma\mathrm{b}\bar{\mathrm{b}}$
$\sigma/\sigma_{SM} < 7.7$ (5.2) at 95% CL

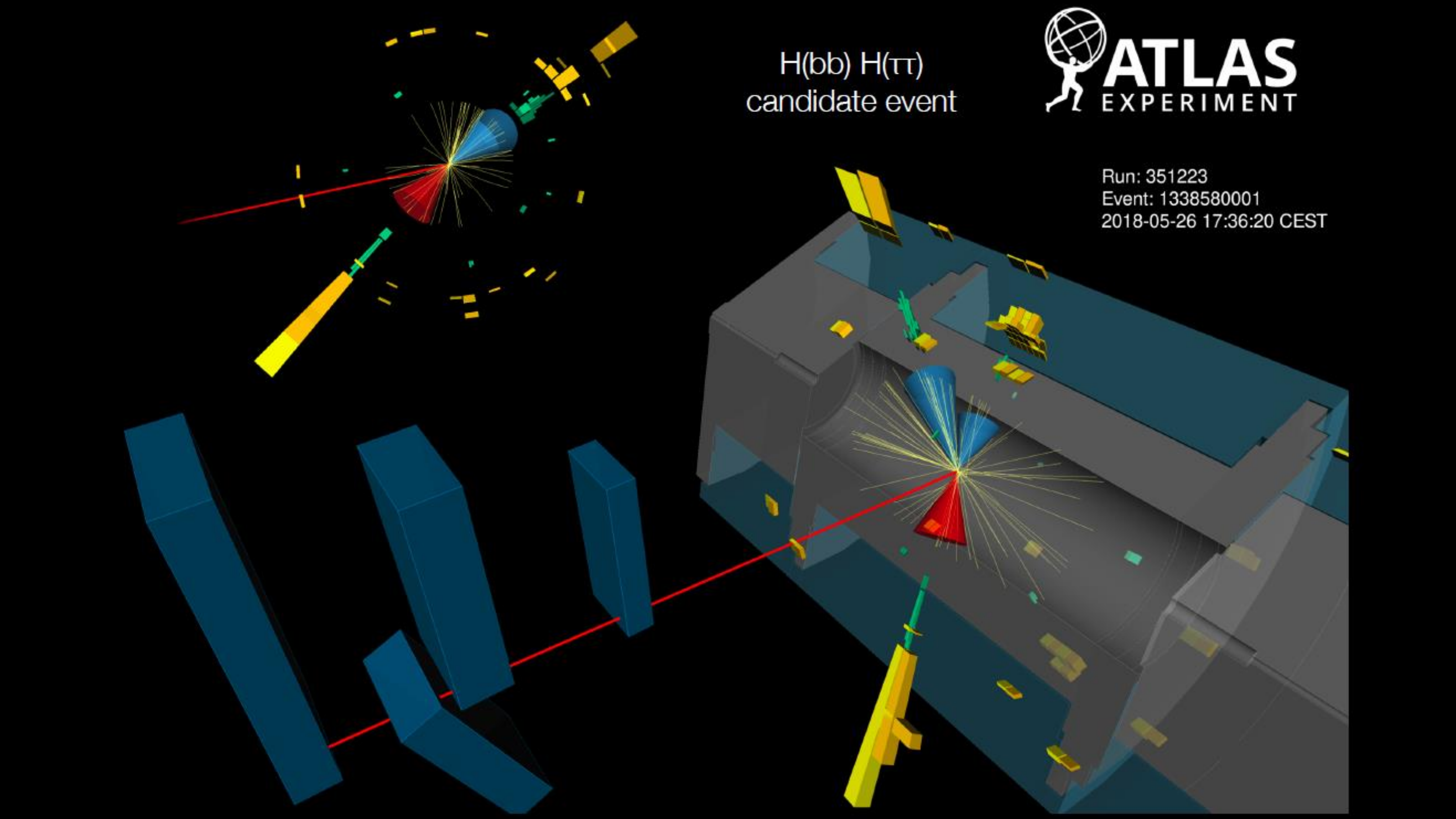
VBF $\mathrm{HH} \rightarrow \gamma\gamma\mathrm{b}\bar{\mathrm{b}}$
$\sigma/\sigma_{SM} < 225$ (208) at 95% CL

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

In SM: $\lambda_{\mathrm{HHH}} = \lambda = m_{\mathrm{H}}^2/2v^2$

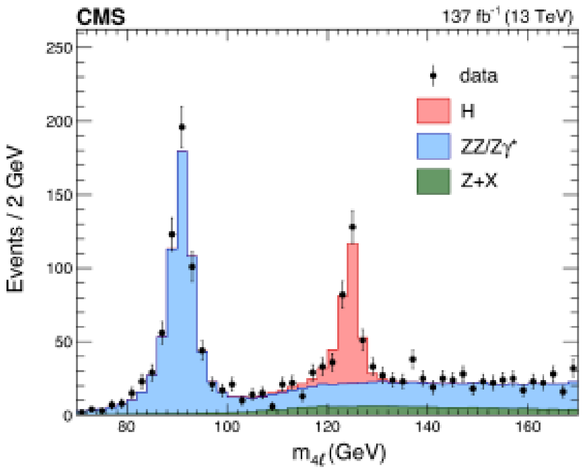
Разные механизмы рождения H бозона определяются разными диаграммами, соответственно разными константами вершин: трёхбозонные и четырёх-бозонные с двумя векторными бозонами и двумя H

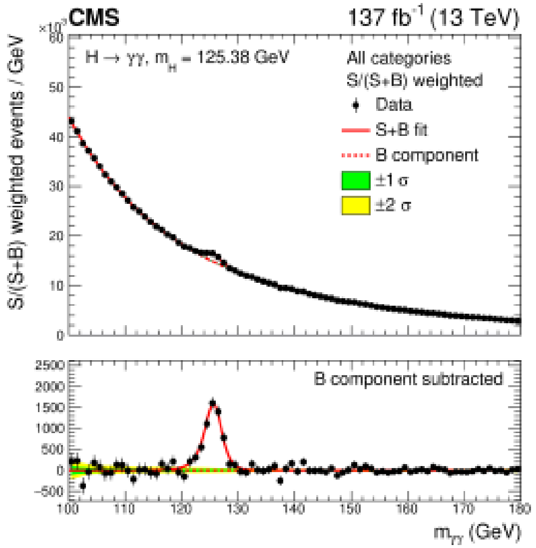
Близкие результаты экспериментов для измерения сечения рождения пар HH


H(bb) H(ττ)
candidate event
ATLAS
EXPERIMENT
Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST

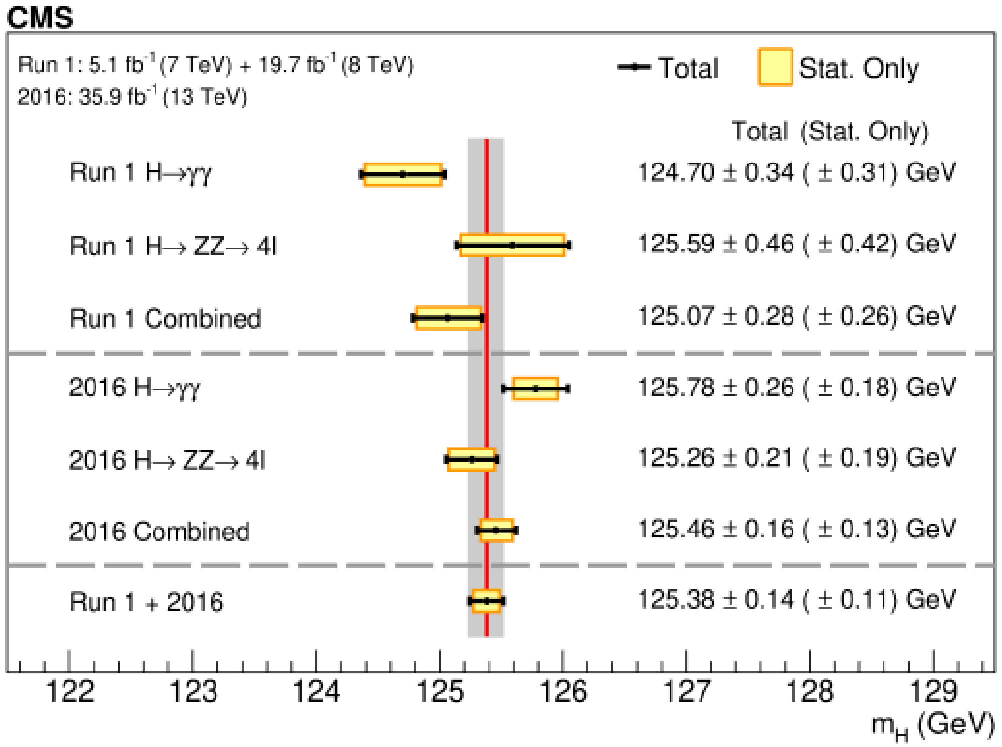
Higgs Mass Measurements

CMS





Run-2 2016, 35.9 fb^{-1}



H → ZZ → 4ℓ

$$m_{\rm H} = 125.26 \pm 0.21\,(\text{total})\ \text{GeV}$$

H → γγ

- using a refined calorimeter calibration

$$m_{\rm H} = 125.78 \pm 0.26\,(\text{total})\ \text{GeV}$$

CMS-HIG-16-041
JHEP 11 (2017) 047

Run-2/2016 combination

$$m_{\rm H} = 125.46 \pm 0.16\,(\text{total})\ \text{GeV}$$

CMS-HIG-19-004
PLB 805 (2020) 135425

The Higgs boson mass measurement uncertainty is still dominated by statistics

Combination with Run-1 result

$$m_{\rm H} = 125.38 \pm 0.14\,(\text{total})\ \text{GeV}$$

PDG (1/06/2021) 125.25 ± 0.17 GeV

- currently the most precise measurement (1.1‰)
- central value consistently used in CMS analyses

Z-boson + jets production

New

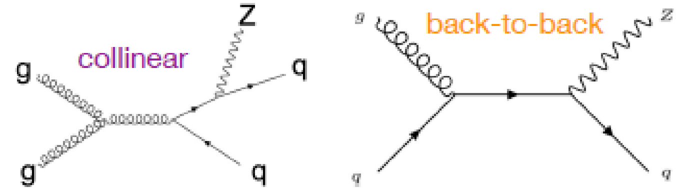
ATLAS-CONF-2021-033

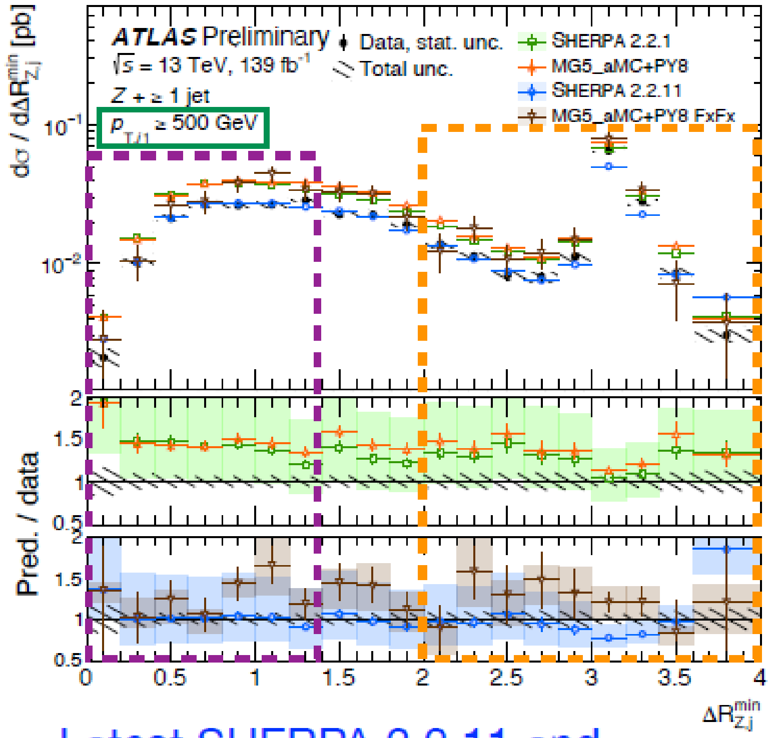
ATLAS EXPERIMENT

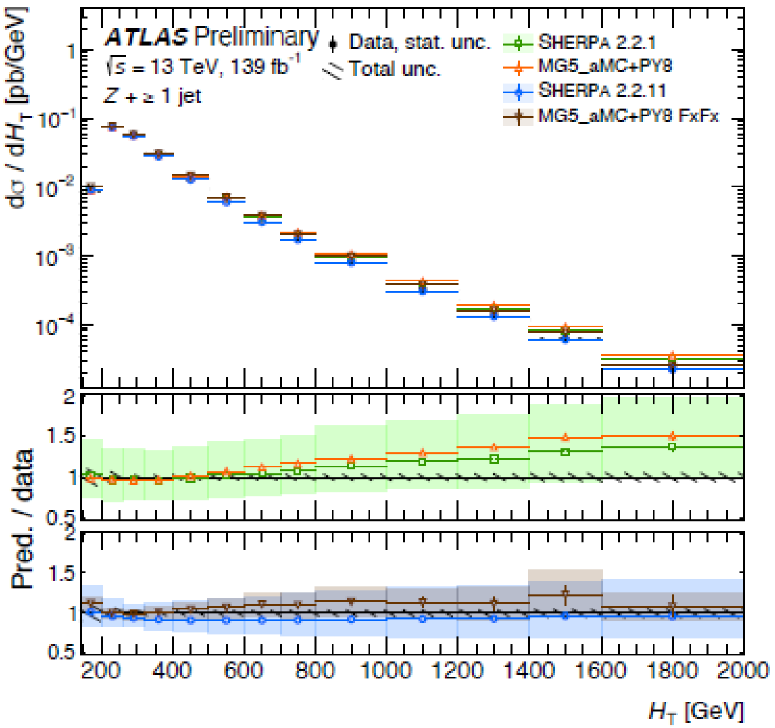
- Run 2: ~8 x 10⁹ Z bosons produced

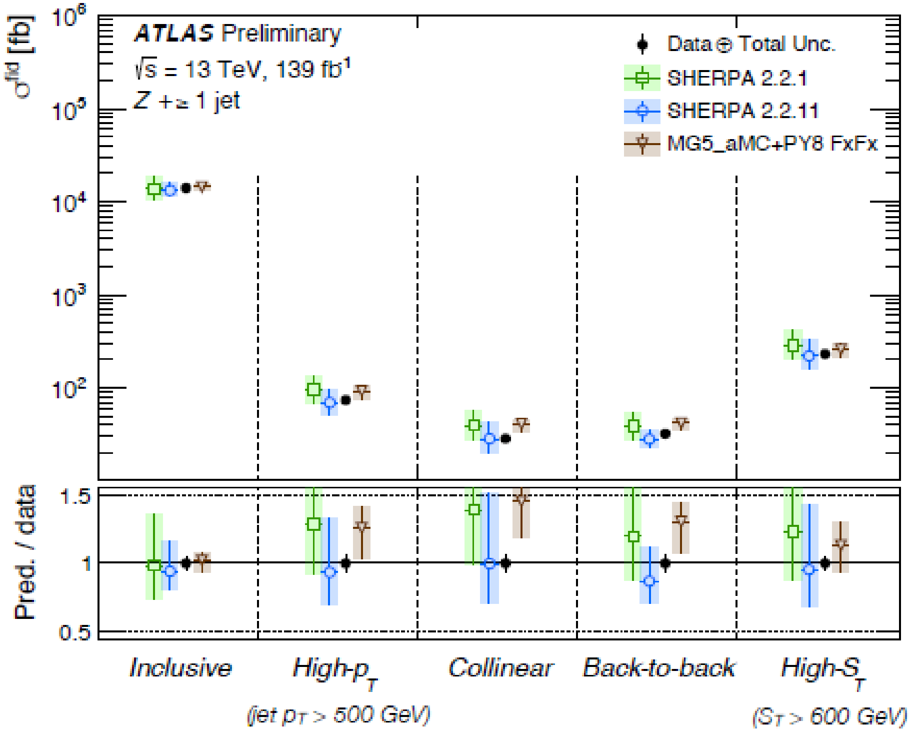
$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{i\,\overline{\psi}\,\not{D}\,\psi} + \psi_i\, y_{ij}\, \psi_j\, \phi + \text{hc} + |D_\mu \phi|^2 - V(\phi)$$

- Test SM in events w/ $Z(\rightarrow ee, \mu\mu)$ and ≥ 1 jet with $p_T > 100$ GeV
  - SM predictions w/ event generators up to NLO QCD + NLO EW
  - Measure cross section in more extreme phase space: collinear vs. back-to-back jet emission, high jet p_T or high sum p_T









- Latest SHERPA 2.2.11 and MG5_aMC + Py8 (FxFx) provide improved modeling esp. in collinear region and at high p_T

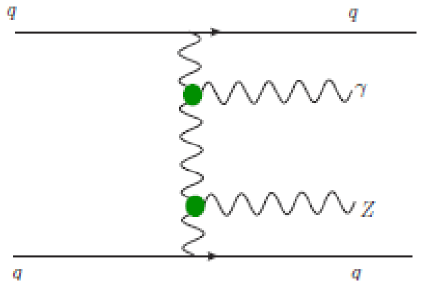
Vector-boson scattering

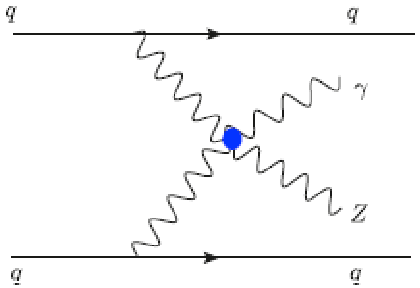
New

CERN-EP-2021-137 ATLAS-CONF-2021-038

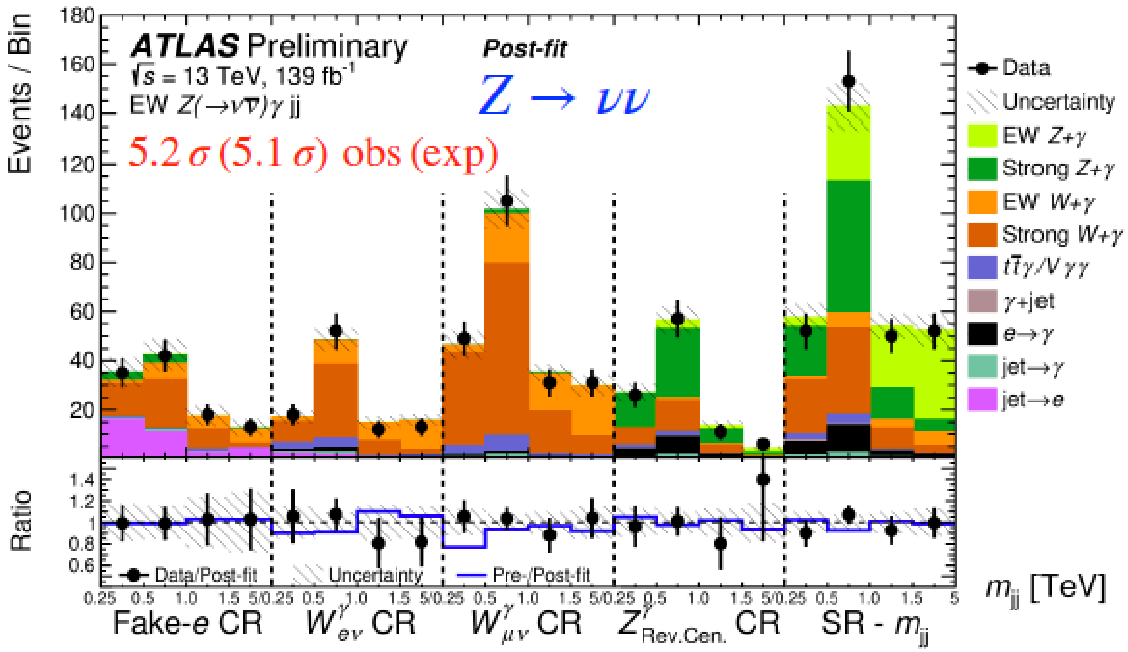
$$\mathscr{L}_{\rm SM} = \boxed{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} + i\,\overline{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + \text{hc} + |D_\mu\phi|^2 - V(\phi)$$

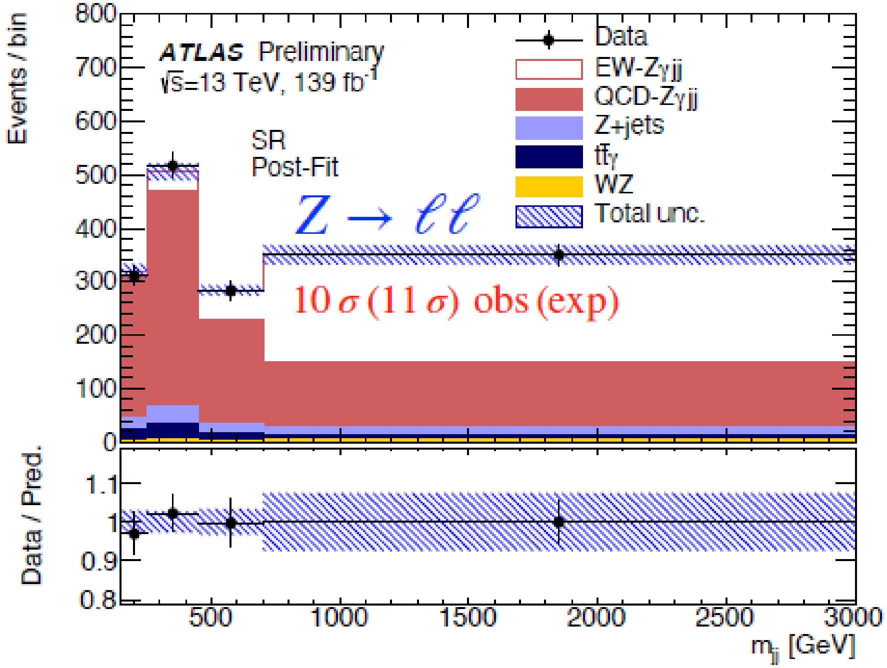
- Key test of EW symmetry
  - —> **vector boson self-interactions**
  - —> cubic and quartic couplings; previously observed all $VVjj$, except $Z\gamma jj$
- Events characterized by jets with large mass and rapidity gap
- Signal strength for $Z\gamma jj$ EW production (rel. to LO prediction)
  - $Z \rightarrow \nu\nu$: $\mu_{\rm EW} = 1.03 \pm 0.16\,({\rm stat}) \pm 0.19\,({\rm syst})$
  - $Z \rightarrow \ell\ell$: $\mu_{\rm EW} = 0.95 \pm 0.08\,({\rm stat}) \pm 0.11\,({\rm syst})$





most precise with 13% cross-section uncert.





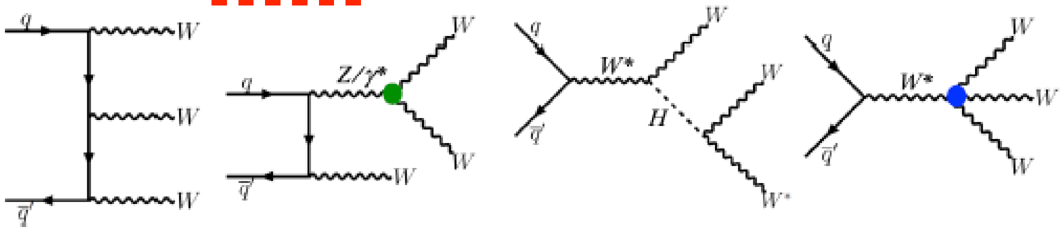
WWW production

New

ATLAS-CONF-2021-039

ATLAS EXPERIMENT

$$\mathscr{L}_{\mathrm{SM}} = \boxed{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} + i\,\overline{\psi}\,\not{D}\,\psi + \psi_i\, y_{ij}\, \psi_j\, \phi + \mathrm{hc} + |D_\mu \phi|^2 - V(\phi)$$



- Rare process providing access to **W/Z self-interactions**
  —> cubic and quartic couplings

- Channels: $W^\pm W^\pm W^\mp \to \ell^\pm\nu\,\ell^\pm\nu\,qq'$ with $\ell = e, \mu$
  $\to \ell^\pm\nu\,\ell^\pm\nu\,\ell^\mp\nu$

- Main bkg: $WZ \to \ell\nu\,\ell\ell$ estimated w/ control regions

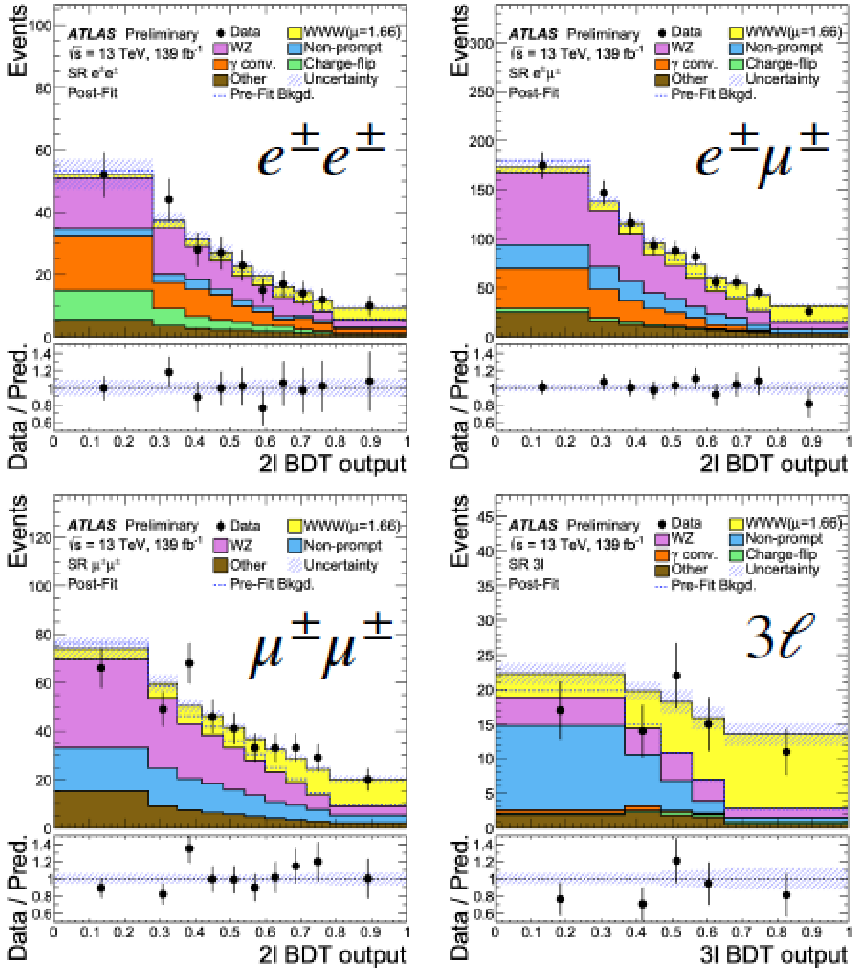
- Signal extracted w/ BDTs for 2ℓ and 3ℓ channels

- **First WWW observation** with significance of $8.2\,\sigma\,(5.4\,\sigma)$ obs (exp)

$$\boxed{\sigma(pp \to W^\pm W^\pm W^\mp) = 850 \pm 100\,(\mathrm{stat}) \pm 80\,(\mathrm{syst})\ \mathrm{fb}}$$

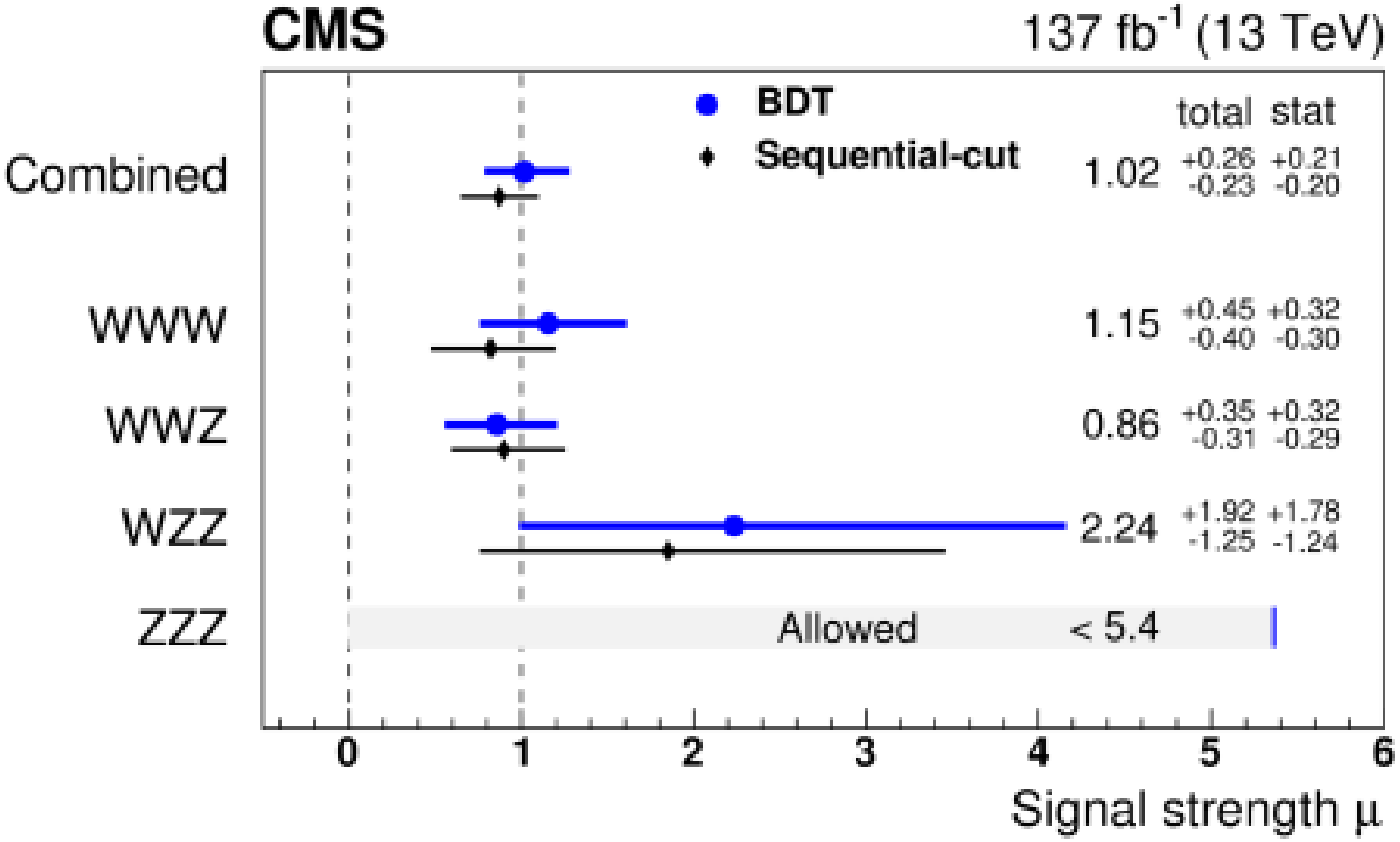
signal strength : 1.66 ± 0.28

SM for WWW + WH : 511 ± 42 fb at NLO QCD



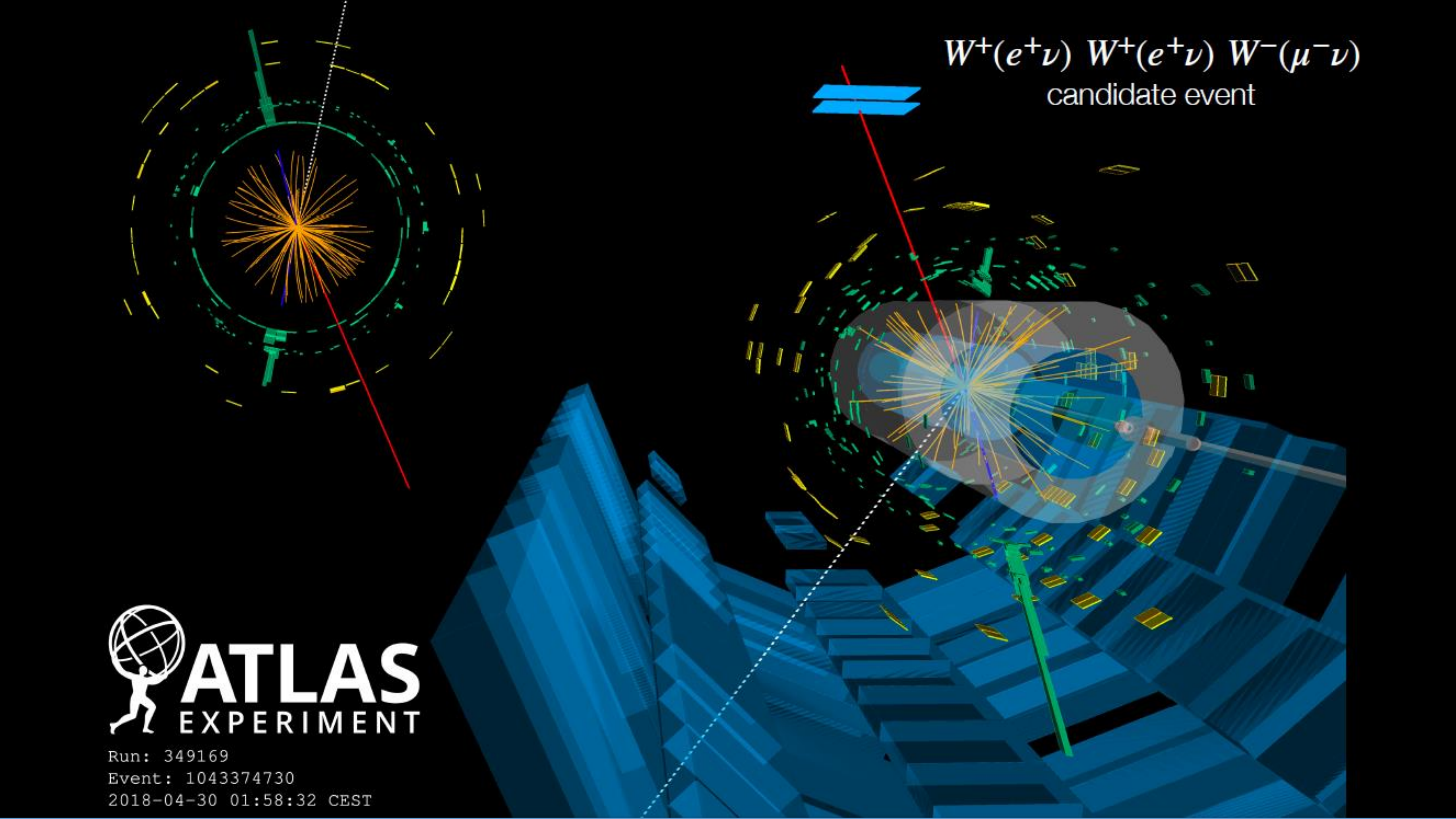
CMS Рождение трех векторных бозонов VVV

Observation of VVV production (5.7σ), **evidence for WWW and WWZ** (3.3σ)



CMS-SMP-19-014
PRL125 (2020) 151802

Phys. Briefing


$W^+(e^+\nu)\ W^+(e^+\nu)\ W^-(\mu^-\nu)$
candidate event
ATLAS
EXPERIMENT
Run: 349169
Event: 1043374730
2018-04-30 01:58:32 CEST

Top-quark production

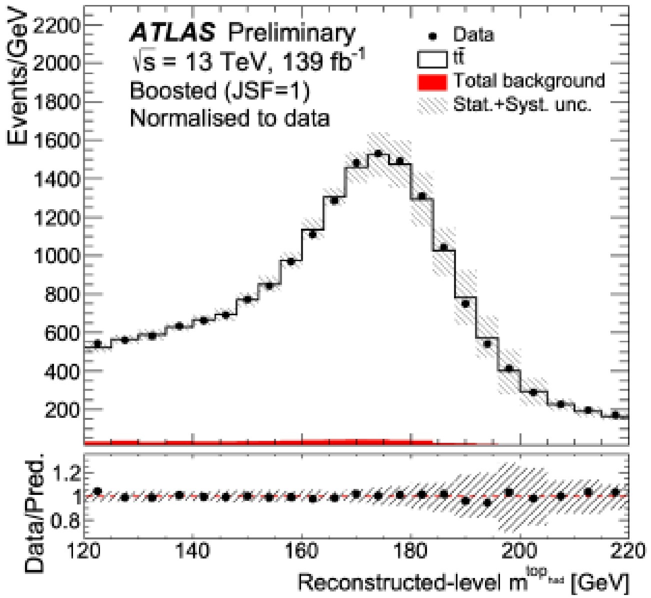
New

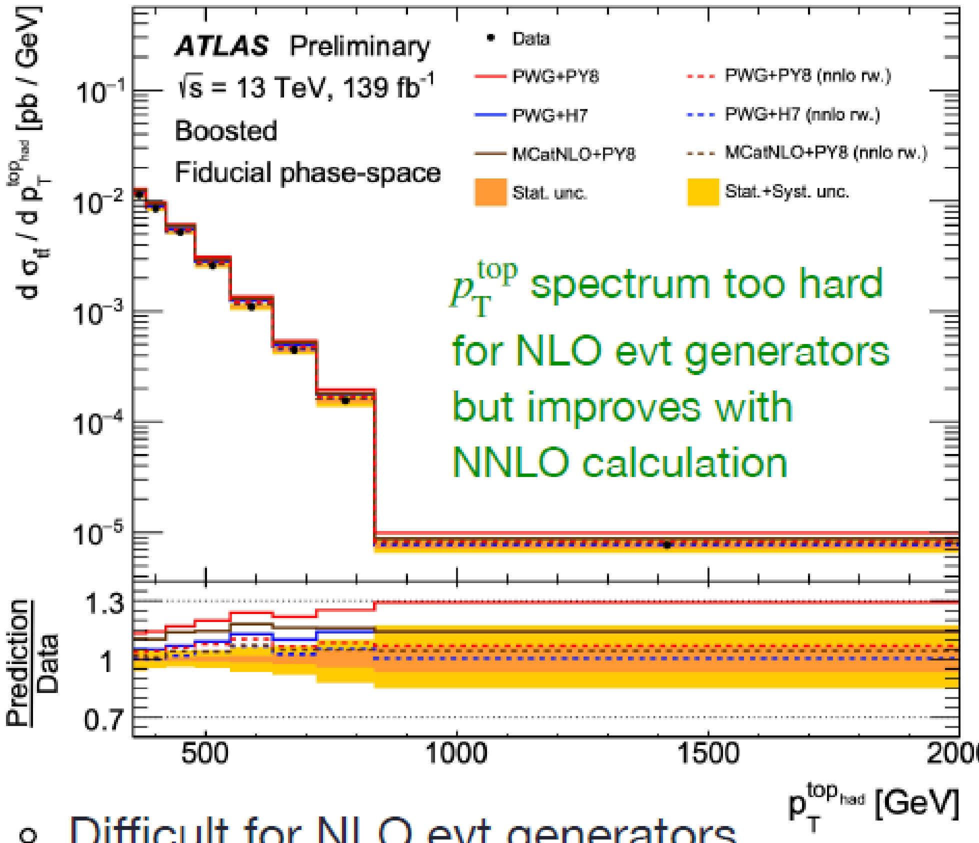
ATLAS-CONF-2021-031

ATLAS EXPERIMENT

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{i\bar{\psi}\not{D}\psi} + \psi_i y_{ij}\psi_j\phi + \text{hc} + |D_\mu\phi|^2 - V(\phi)$$

- Run 2: ~1.2 x 10^8 $t\bar{t}$ produced
- Test SM at high p_T^{top}, where deviations expected from BSM, measure both $t\bar{t}$ system and radiation
  - SM predictions at NNLO QCD + NLO EW
- l+jets channel: $t\bar{t} \to Wb\,Wb \to \ell\nu b\, qq'b$
  - Reconstruct hadronic top as reclustered R=1.0 anti-kt jet w/ p_T > 355 GeV, |η|<2.0, and mass ∈ 120-220 GeV
  - Reduce jet energy scale uncertainties by using mass of reconstructed hadronic top
    —> jet energy scale factor
    —> ~30% reduction in σ_{syst}^{tot}
  - Differential cross sections provided for 16 variables
    (8 for the first time for boosted top quarks)



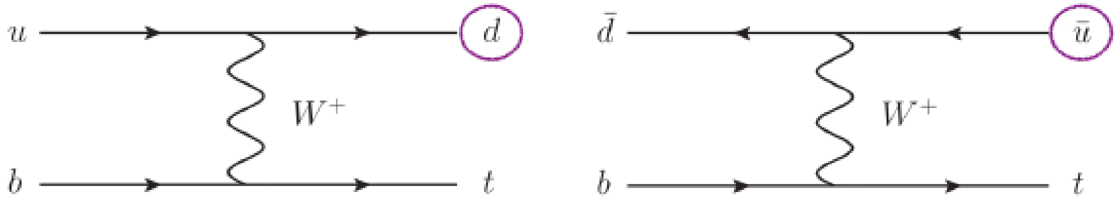


- Difficult for NLO evt generators to model additional radiation
- Constraints placed on EFT operators $\mathcal{O}_{tG}$ and $\mathcal{O}_{tq}^{(8)}$

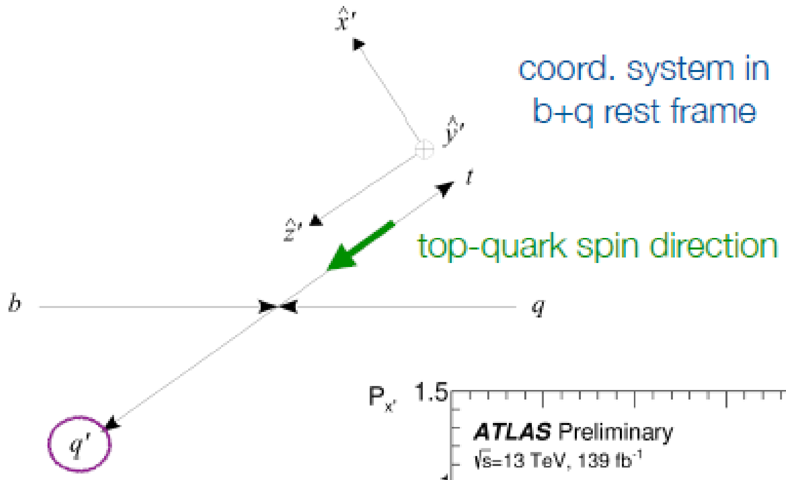
Single-top quark polarization

ATLAS-CONF-2021-027

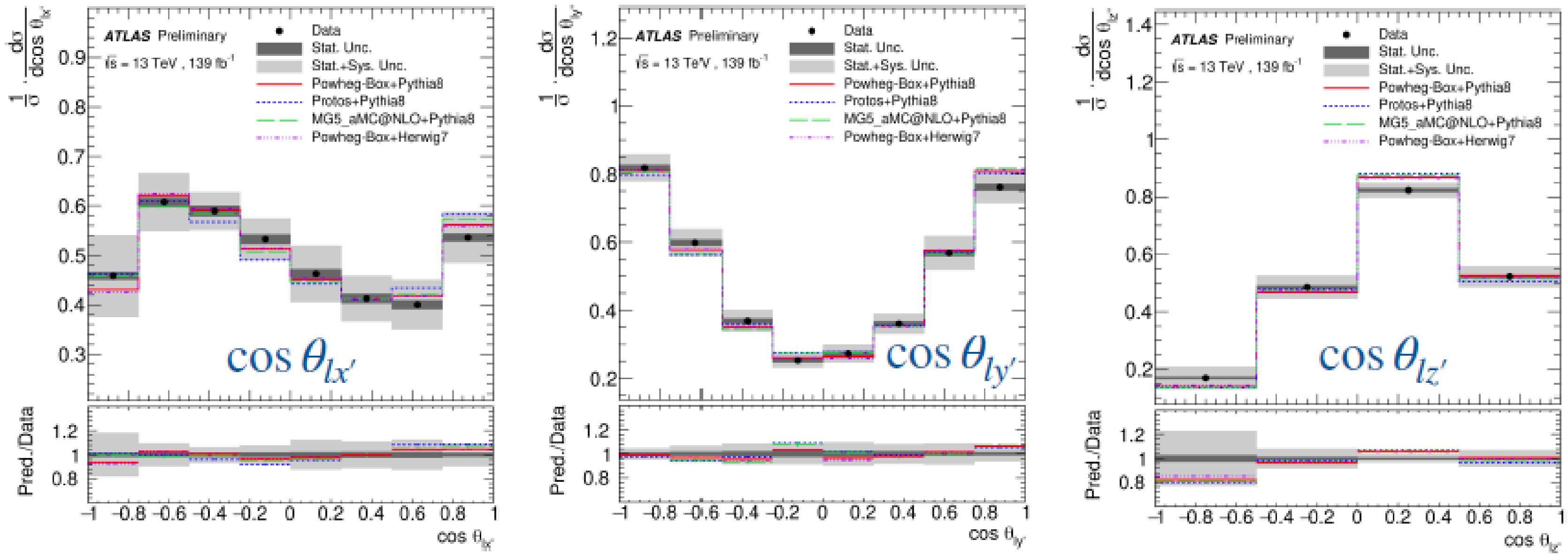
- t-channel dominates single top-quark production

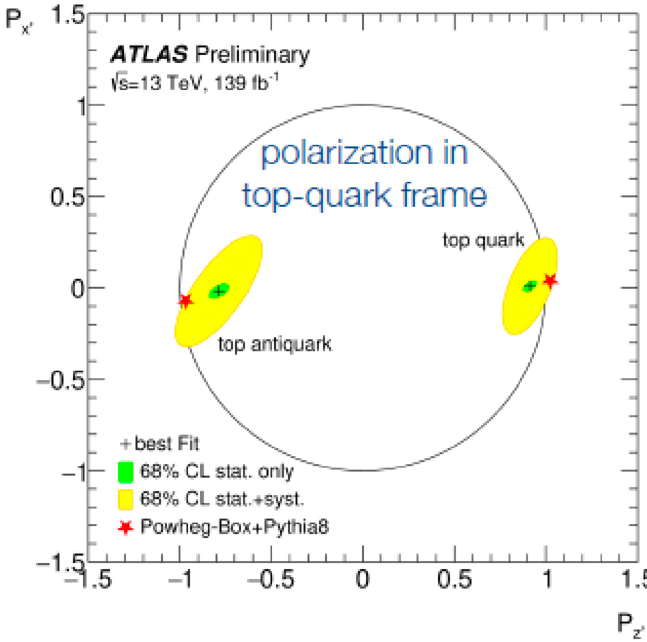


$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{i\,\overline{\psi}\not{D}\,\psi} + \psi_i\, y_{ij}\, \psi_j\, \phi + \mathrm{hc} + |D_\mu \phi|^2 - V(\phi)$$



- High polarization expected from V-A structure of CC weak interaction + test BSM impact on tWb vertex
- First measurement of polarization vector in 3-D via angular distributions of lepton (e or μ) from $t \to b\ell\nu$ decay





- Constraints placed on Re and Im parts of EFT operator $\mathcal{O}_{tW}$

Top-Quark Mass Measurements

CMS

In the SM, the value of the *Instability Scale* Λ ($> 10^9$ GeV) depends on $\alpha_S(m_Z)$ and the **top-quark mass** $m(\mathrm{t})$

Run-2 2016, 35.9 fb^{-1}

CMS-PAS-TOP-19-009

From $\mathrm{t\bar{t}}$ events

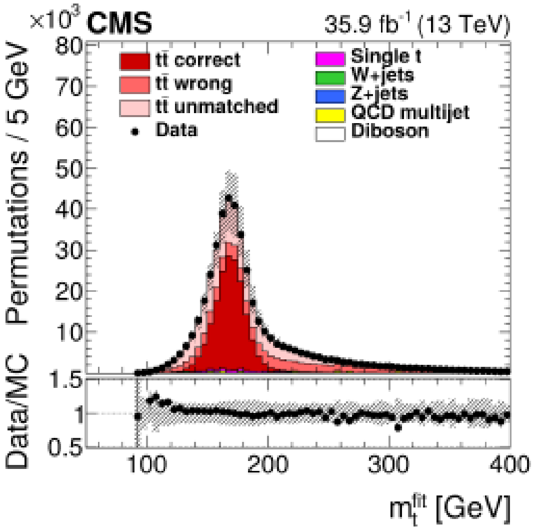
- **Run-1 legacy**

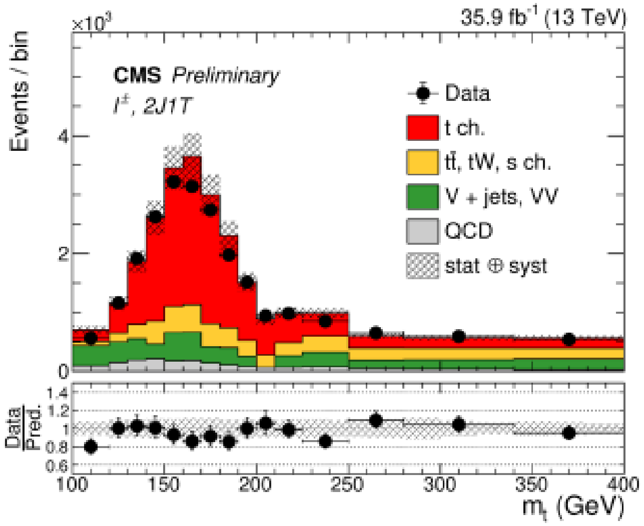
  $m(\mathrm{t}) = 172.44 \pm 0.13 \pm 0.47$ GeV

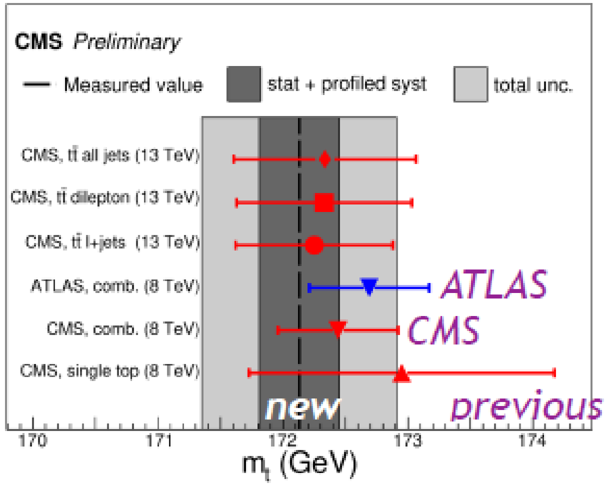
- **Run-2 lepton+jets**

  $m(\mathrm{t}) = 172.25 \pm 0.08 \pm 0.62$ GeV

CMS-TOP-17-017
EPJC 78 (2018) 891







From single top events

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

- $m(\mathrm{t}) = 172.44 \pm 0.77$ GeV
- $m(\bar{\mathrm{t}})/m(\mathrm{t}) = 0.995 \pm 0.006$
- $m(\bar{\mathrm{t}}) - m(\mathrm{t}) = 0.83^{+0.77}_{-1.01}$ GeV

Alternative methods

- M_{T2}, Dilepton $M_{\ell\mathrm{b}}$, kinematic endpoints, b-hadron lifetime, ℓ+SecVtx, ℓ+J/ψ, etc.
- less precise but different systematic uncertainties
- in agreement with main measurement

Running of the Top-Quark Mass

CMS

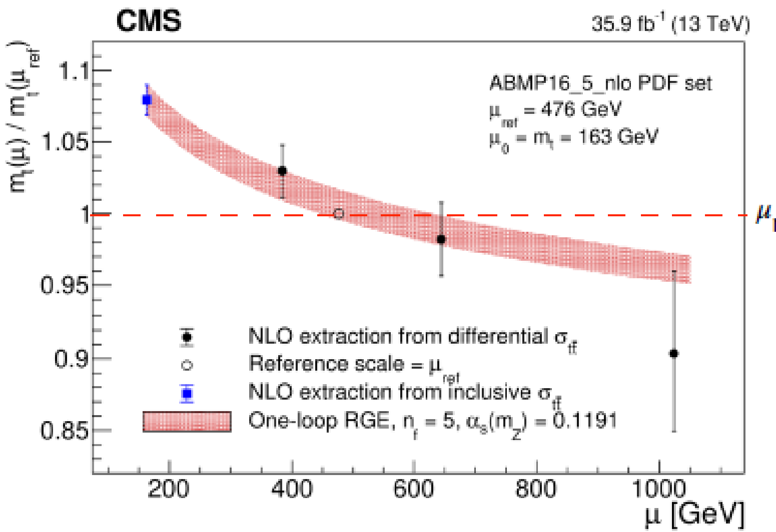
"Pole" mass from multi-differential cross section measurements

- in $e^{\pm}\mu^{\mp}$ final state
- as functions of mass and rapidity of the $t\bar{t}$ system, and jet multiplicity
- unfolded at parton level
- compared with NLO predictions in $\overline{\text{MS}}$ scheme

$$m(t) = 170.83 \pm 0.72\ \text{GeV}$$

CMS-TOP-18-004
EPJC 80 (2020) 658

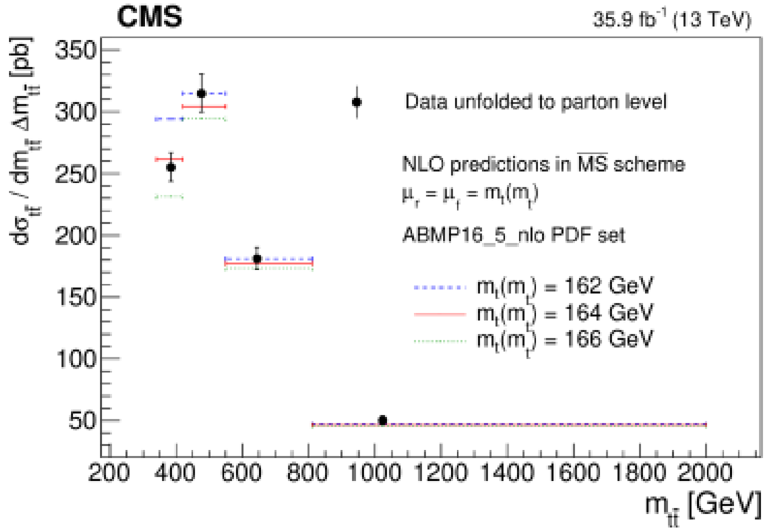
Run-2 2016, 35.9 fb^{-1}



uncertainty evolved from inclusive measurement at scale $\mu_0 = 163$ GeV

Evolution of the top quark mass from the differential cross section as a function of $m_{t\bar{t}}$

$d\sigma_{t\bar{t}}/dm_{t\bar{t}}$



CMS-TOP-19-007
PLB 803 (2020) 135263

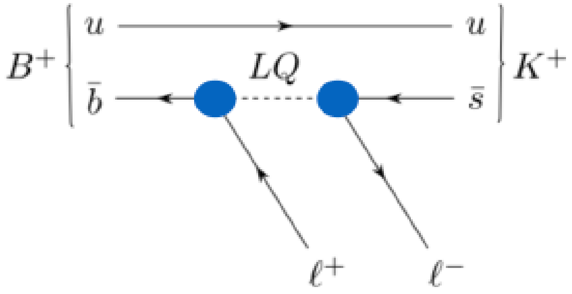
Top-quark running mass probed up a scale of order 1 TeV

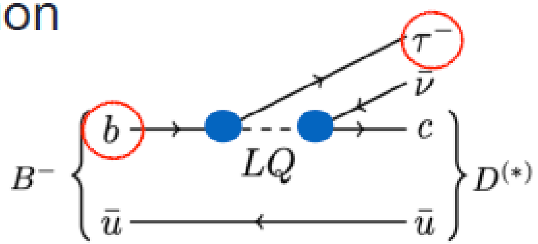
- compared to RGE prediction at one-loop precision ($n_f = 5$)
- scale dependance found consistent with predictions at the 1.1σ level
- no-running hypothesis excluded at the 95% CL

Flavor anomalies

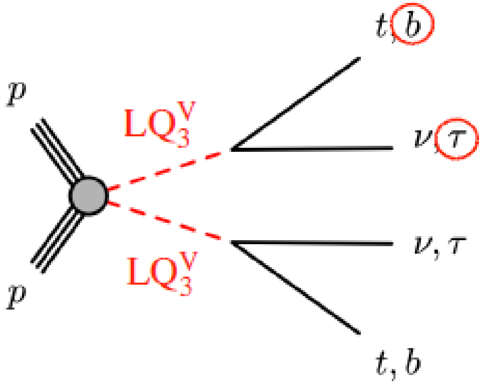
- Recent results from B decays indicate deviations from lepton-flavor universality
  - $R(K^{(*)}) = \dfrac{\mathscr{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathscr{B}(B \to K^{(*)}e^+e^-)}$ and $R(D^{(*)}) = \dfrac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}\ell\nu)}$ (with $\ell = e, \mu$) both disagree w/ SM at ~3σ
  - Vector leptoquarks a potential explanation

(diagrams by LHCb and D.Zanzi)

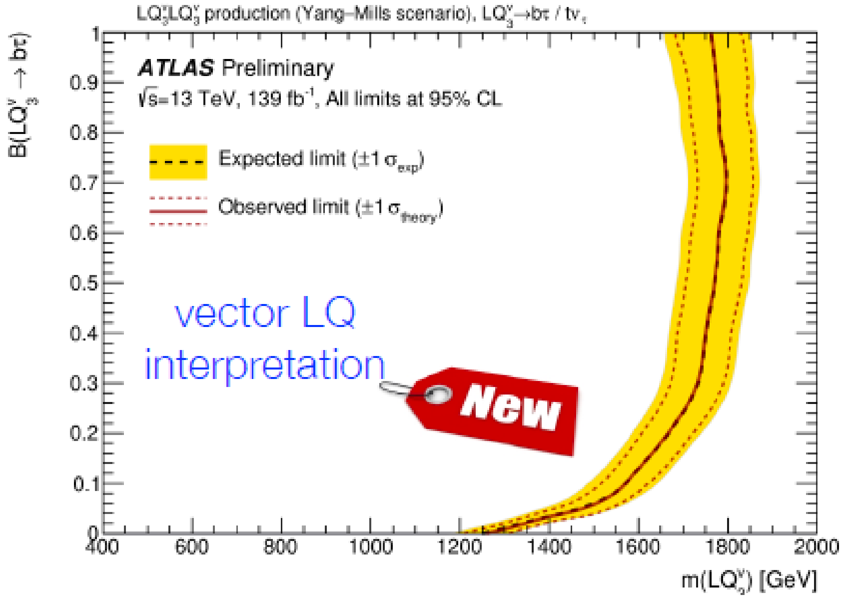




- **Search for LQ pair production*** (other relevant searches not covered here)
  - Trigger on $E_{\mathrm{T}}^{\mathrm{miss}}$ + require offline $E_{\mathrm{T}}^{\mathrm{miss}} > 280$ GeV, 1 τ_{had}, ≥ 2 b-tagged jets
  - Main bkg: $t\bar{t}$ and single top from CRs
  - $m(\mathrm{LQ}_3^{\mathrm{V}}) > 1.8$ TeV for $\mathscr{B}(\mathrm{LQ}_3^{\mathrm{V}} \to b\tau) \sim 0.5$
  - Addresses $R(D^{(*)})$ anomaly at ~expected scale



ATLAS-CONF-2021-008



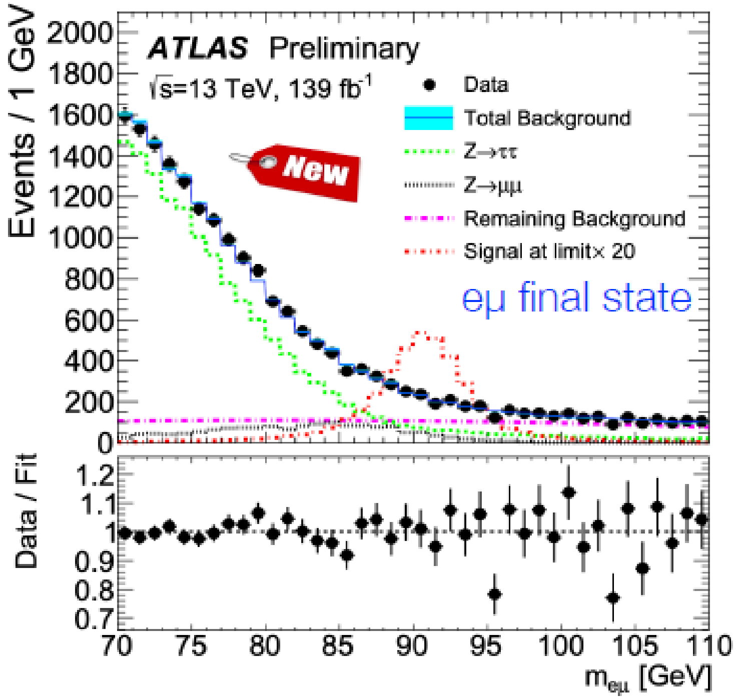
* search also targeting SUSY stop to stau production

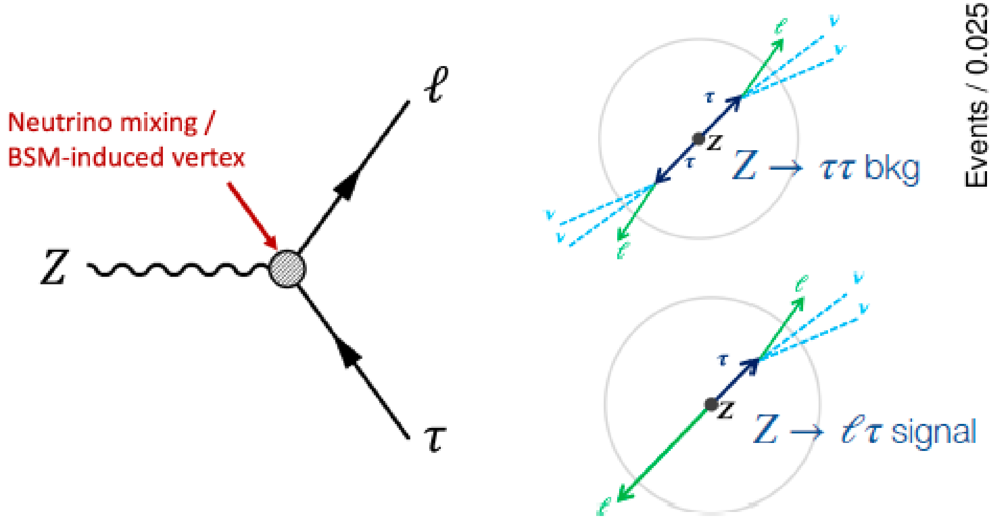
Lepton flavor violation

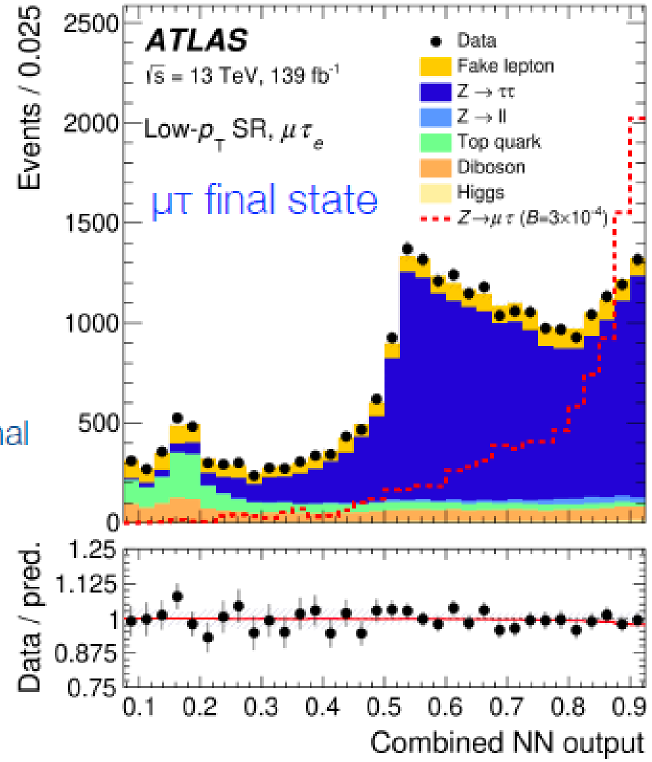
ATLAS-CONF-2021-042 arXiv:2105.12491

$\mathscr{L} = \mathscr{L}_{SM} + \boxed{\mathscr{L}_{BSM}}$

- Run 2: ~8 x 10⁹ Z bosons produced
- Lepton flavor violation only observed in neutrino oscillations, ~negligible for $\ell^{\pm}$ in SM
- Z —> e μ search based on $m_{\ell\ell'}$ w/ reduced uncert. normalizing to Z—>ee, μμ
- Z —> e τ, μ τ search w/ NNs to suppress $Z \to \tau\tau$, $t\bar{t}$, VV & $W \to \ell\nu$ + jets bkg







- LEP limits surpassed by factors of 5 ($Z \to e\mu$) and 2 ($Z \to e\tau, \mu\tau$)

Upper limits at 95% CL	ATLAS	LEP
B(Z —> e μ)	0.34 × 10⁻⁶	1.7 × 10⁻⁶ (OPAL)
B(Z —> e τ)	5.0 × 10⁻⁶	9.8 × 10⁻⁶ (OPAL)
B(Z —> μ τ)	6.5 × 10⁻⁶	12 × 10⁻⁶ (DELPHI)

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

CMS

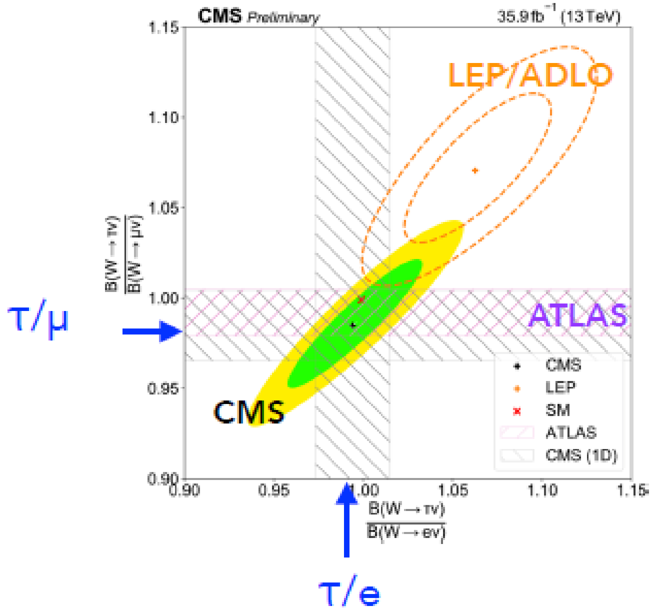
Using $t\bar{t}$ events in the dilepton channel, select relatively unbiased samples **of on-shell W bosons**

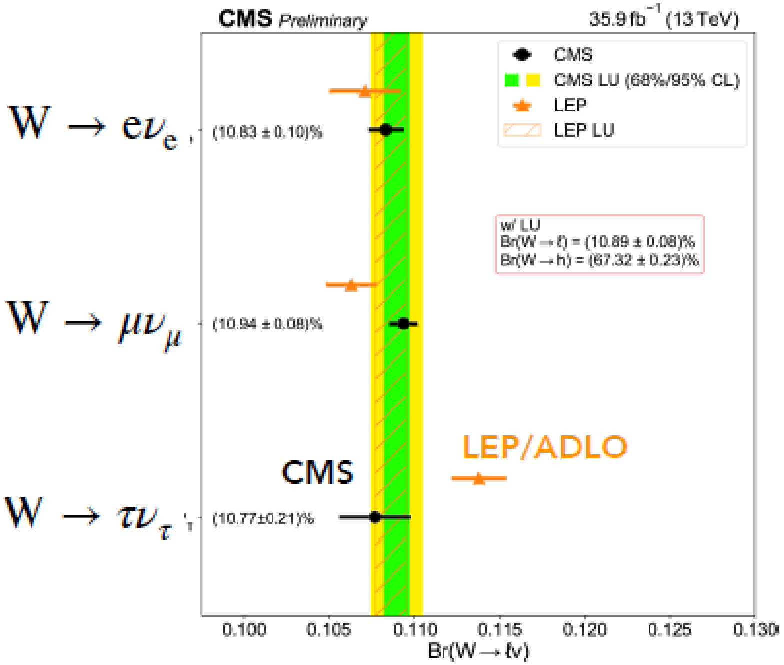
Run-2 2016, 35.9 fb^{-1}

CMS-PAS-SMP-18-011

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

Branching fractions W → e, μ, τ





result consistent with SM and with recent ATLAS (most-precise) τ/μ result

CMS LU result is consistent with and improves on LEP/ADLO result

A long-standing LEP "tension" (>2.5σ) is **gone**

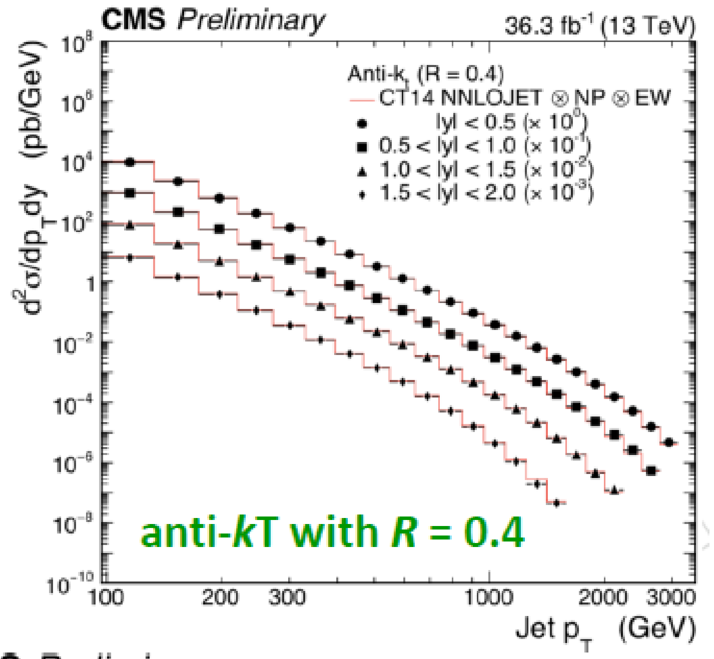
CMS Jet differential distributions

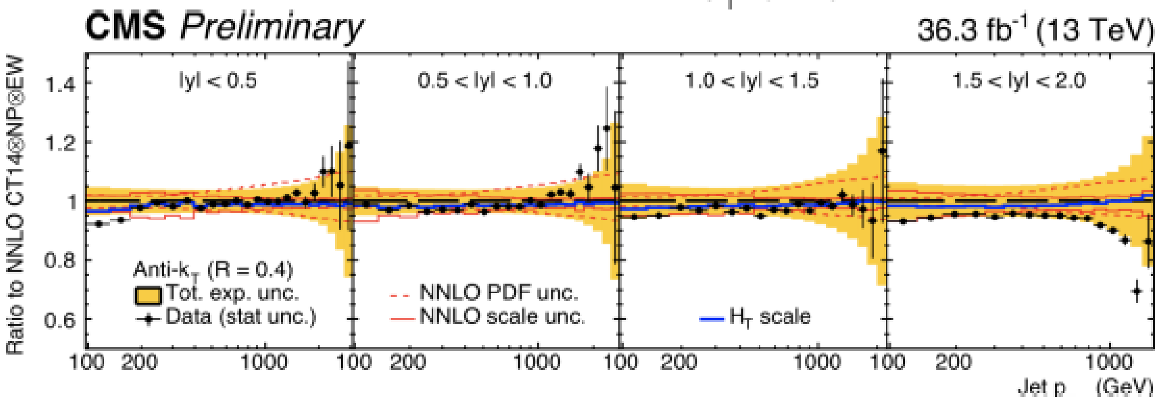
- Several analyses measure multi-differential distributions of inclusive and multi–jet QCD events
- Distributions are unfolded to particle level

CMS-PAS-SMP-20-011

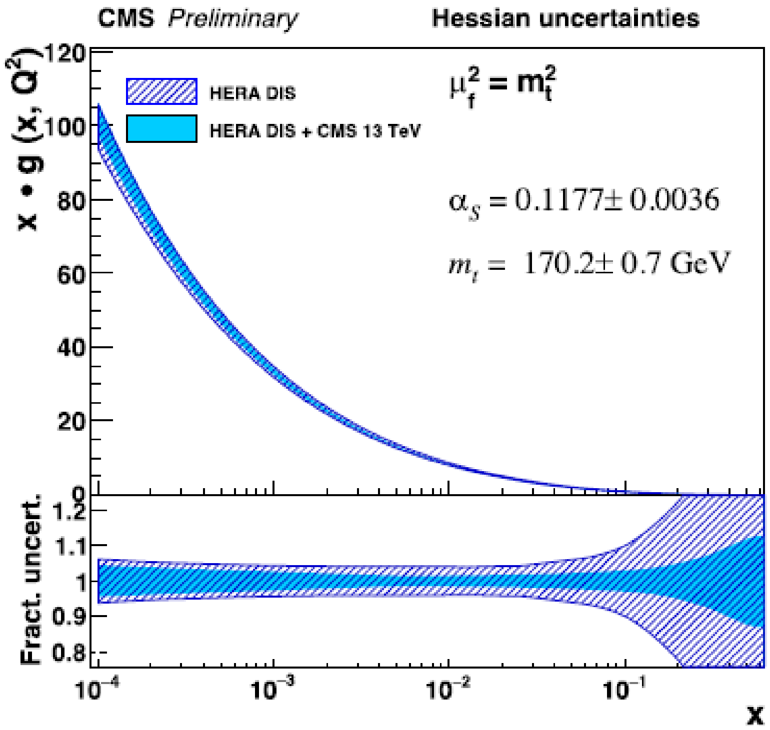
NEW

Inclusive jet cross sections double differential in jet transverse momentum p_T and rapidity y





Improvement in the gluon PDF determination with CMS measurements: jet and tt differential distributions



$\alpha_S(m_Z)$ and m_t are also obtained from the fit

Constraints are also derived on SMEFT Wilson coefficients by fitting them together with PDFs, $\alpha_S(m_Z)$ and m_t

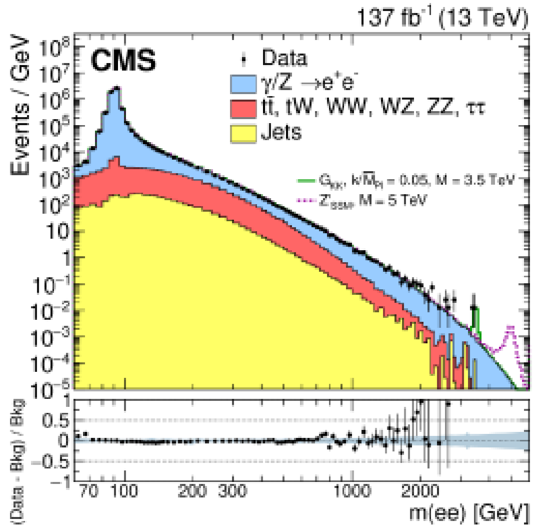
Talks of Patrick Connor (Mon) and Paolo Azzurri (Wed)

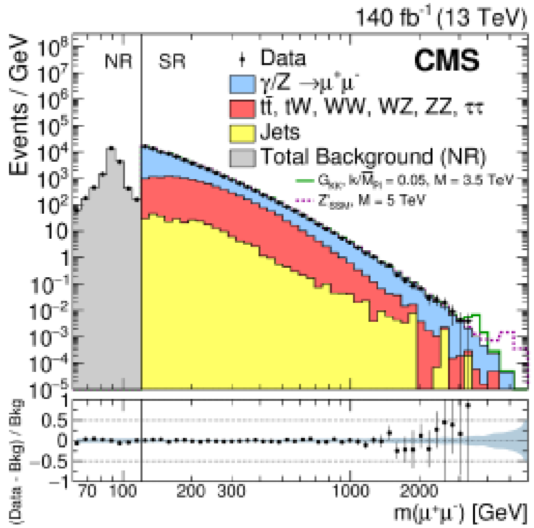
Search for Heavy Resonances

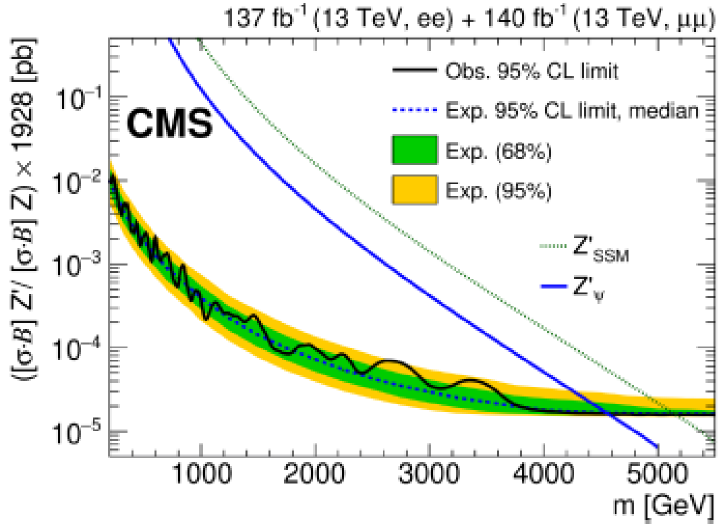
CMS

Dilepton resonances

Full Run-2, ≥137 fb⁻¹





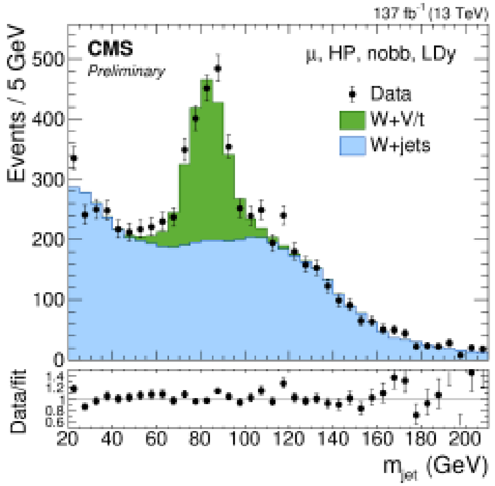


CMS-EXO-19-019
Submitted to JHEP

Phys. Briefing

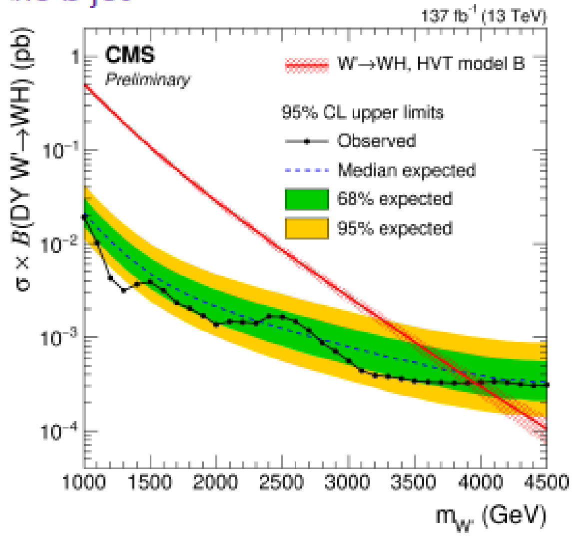
Diboson resonances

CMS-PAS-B2G-19-002



WW, WZ, WH in lepton + merged jet final state

muon channel
|Δy|<1
no b jet

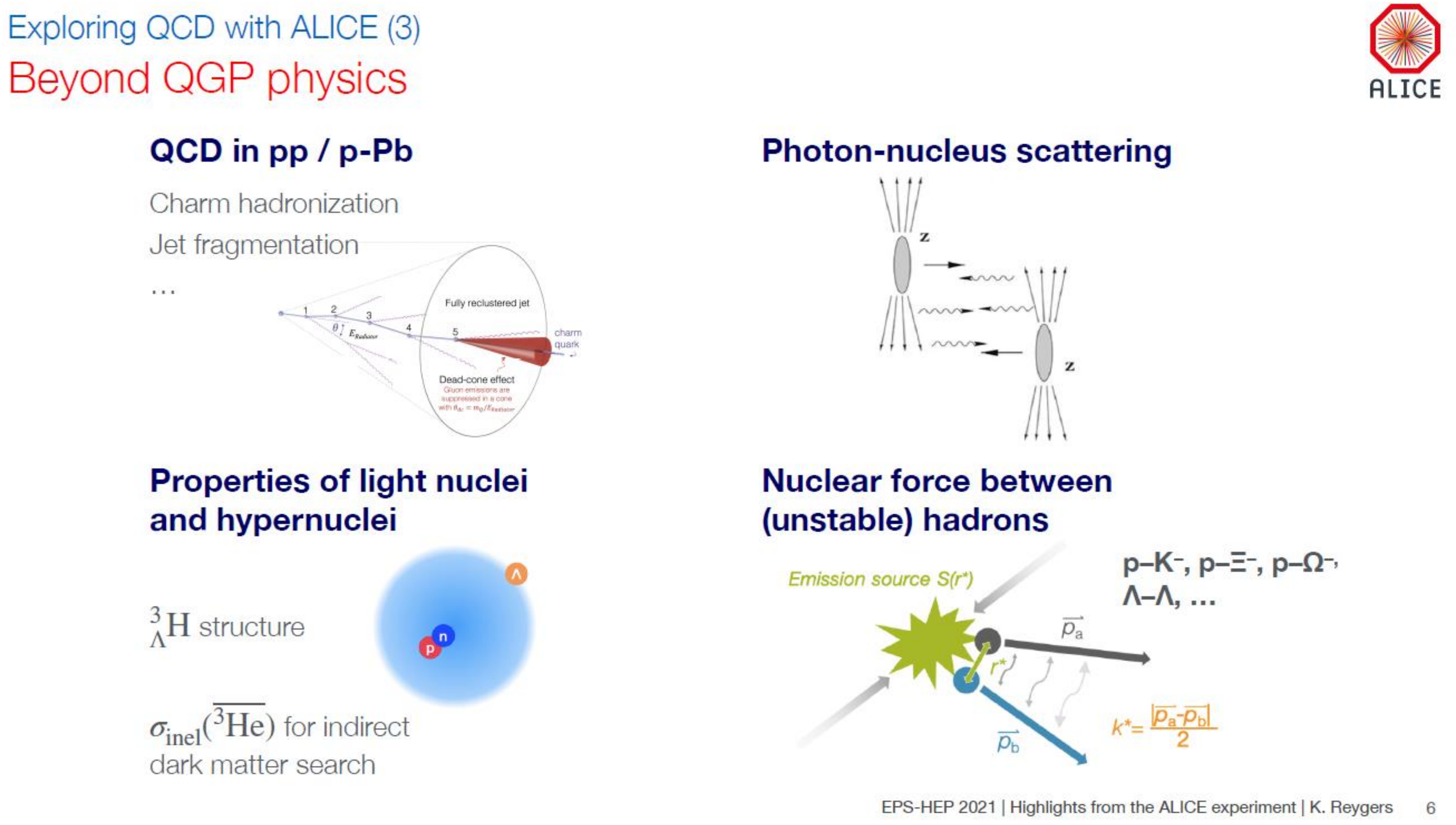


Limits on cross section × BF translate into limits on resonance masses

depending on models new W' or Z' resonances with masses up to > 4 TeV are excluded

Focus of Run-3: searches for long-lived particles (LLP)

ALICE – изучает КГП (кварк-глюонную плазму) и другие явления КХД

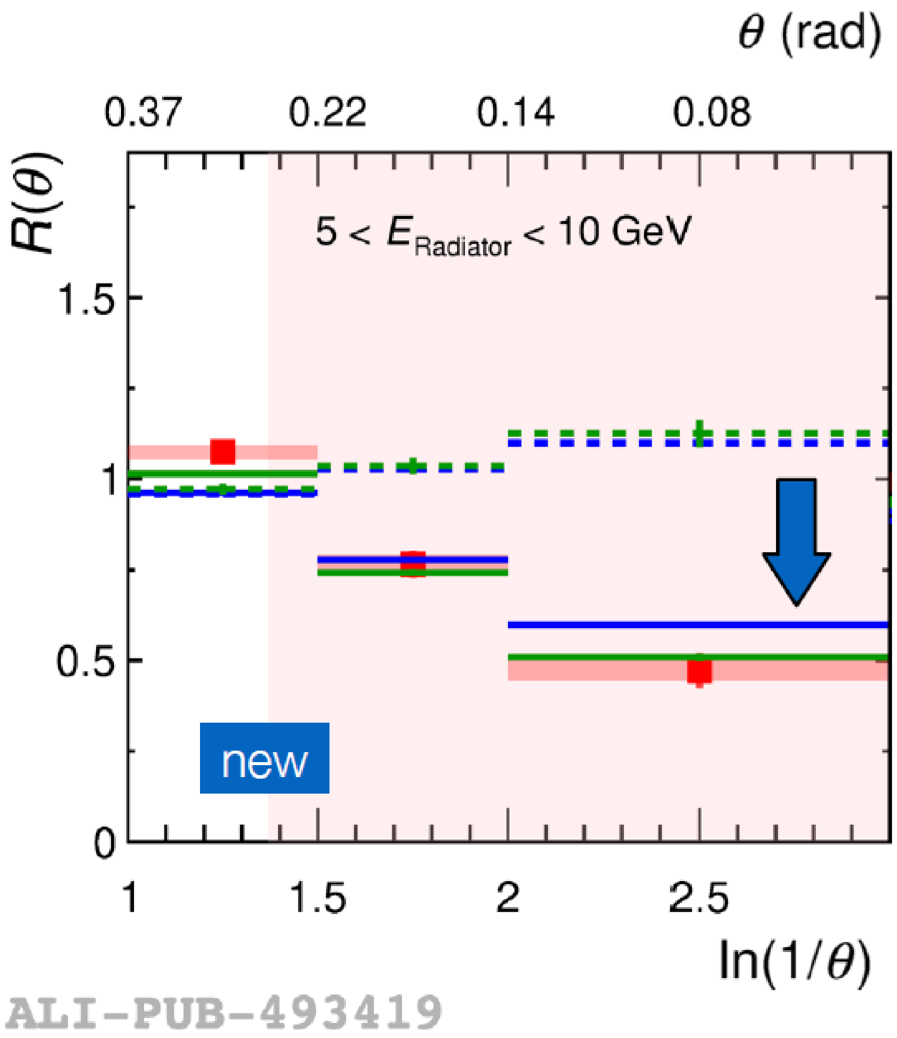


- КХД в pp и p-Pb взаимодействиях
- Рассеяние виртуальных фотонов на ядрах свинца
- Свойства легких ядер и гиперядер
- Ядерные силы между нестабильными адронами

ALICE – первое прямое наблюдение эффекта темного конуса для тяжелых кварков

Direct observation of the dead-cone effect in QCD (2)

Significant suppression of small-angle splittings for small E_{charm}



Y. L. Dokshitzer, V. A. Khoze, and S. I. Troian, “On specific QCD properties of heavy quark fragmentation (’dead cone’)”, J. Phys. G17 (1991) 1602–1604

$$R(\theta) = \frac{dn/d\ln 1/\theta|_{\mathrm{D0\,jets}}}{dn/d\ln 1/\theta|_{\mathrm{incl.,jets}}} \qquad k_{\mathrm{T}} > \Lambda_{\mathrm{qcd}} = 200\,\mathrm{MeV}/c$$

- ALICE Data
- PYTHIA 8
- SHERPA
- PYTHIA 8 LQ / inclusive no dead-cone limit
- SHERPA LQ / inclusive no dead-cone limit

Dead-cone effect results in

$\Delta E_{\mathrm{b}} < \Delta E_{\mathrm{c}} < \Delta E_{\mathrm{u,d,s}}$ in the QGP

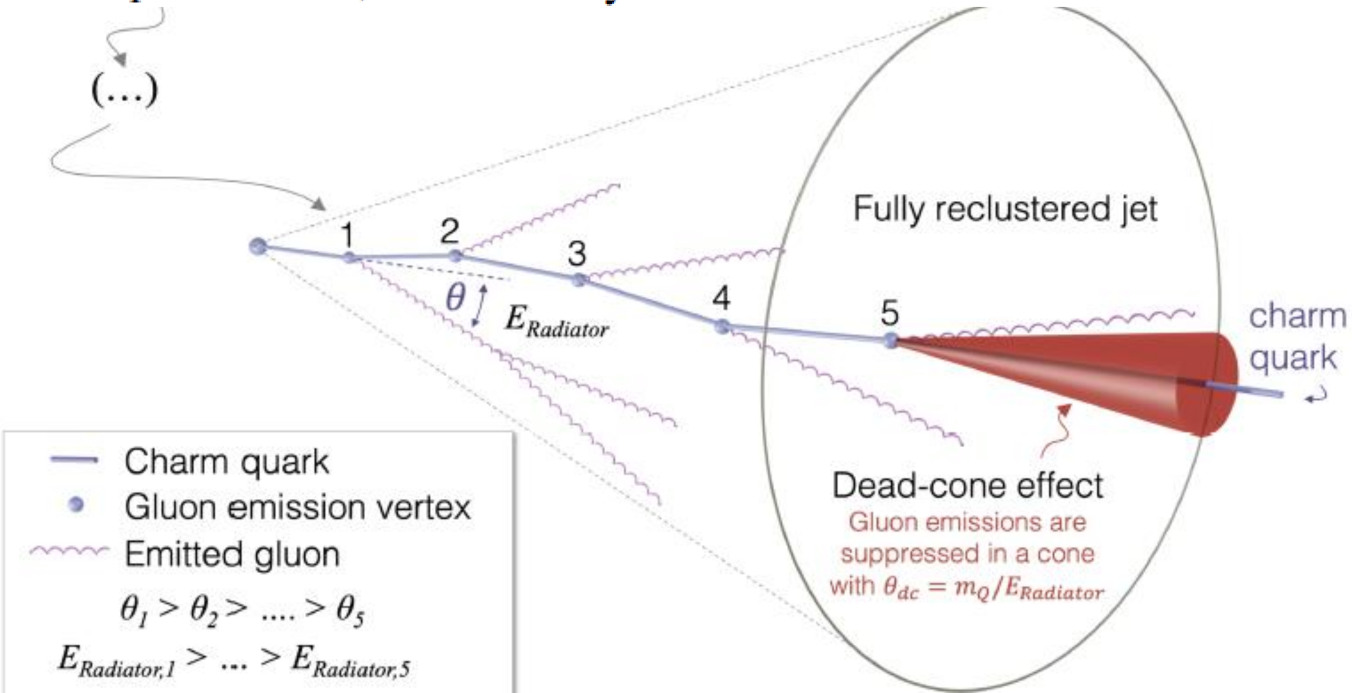
arXiv:2106.05713 talk Vít Kučera

arXiv:2106.05713
Эффект представлен для струй с D^0

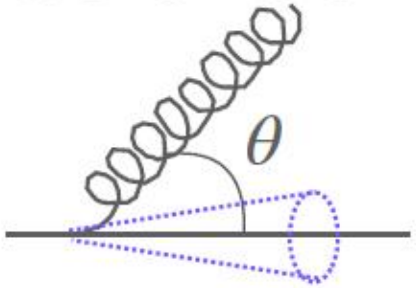
The observable used to reveal the dead-cone is built by constructing the ratio of the splitting angle (θ) distributions for D^0-meson tagged jets and inclusive jets, in bins of E_{Radiator}. This is given by,

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

where the θ distributions were normalised to the number of jets which contribute with n splittings (where $n > 1$) for the given E_{Radiator} and k_{T} selection, denoted by $N^{\mathrm{D^0\,jets}}$ and $N^{\mathrm{inclusive\ jets}}$ for the D^0-meson tagged and inclusive jet s … he angle is natural given that … to $\ln(1/\theta)\ln(k_{\mathrm{T}})$.



Dead cone effect with heavy-quark Lund Plane



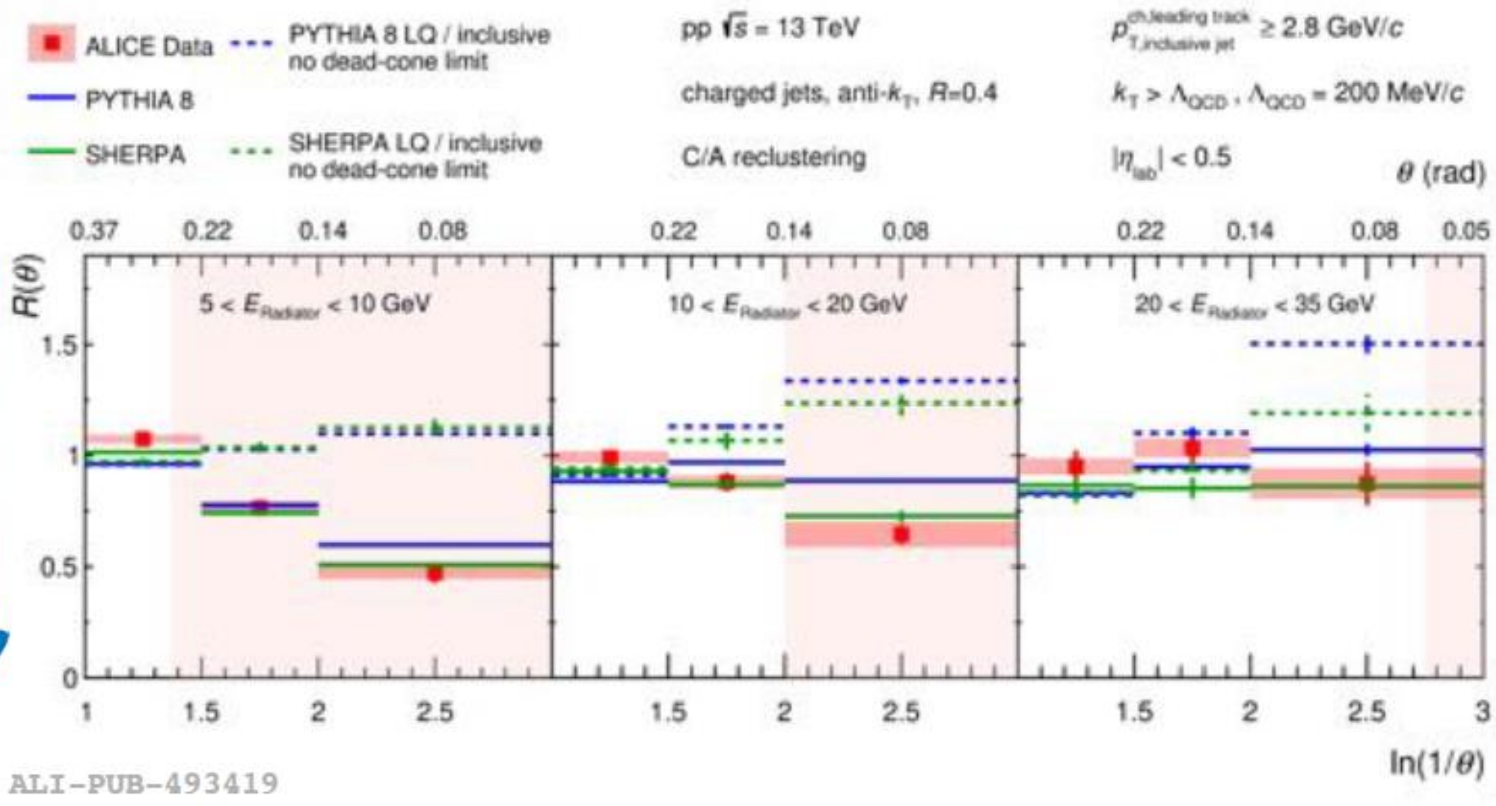
Dead cone angle: $\theta_0 = m/E$

→ Projections of the Lund plane of heavy-quarks make the first direct measurement of the dead cone possible!

→ Pattern of the parton shower is expected to depend on the mass of the initiating parton.

→ Gluon spectrum emitted from a heavy quark suppressed in within a cone of m/E from the emitter → ***dead cone effect***!

→ Suppression of splittings at low angles for D^0 jets compared to inclusive jets!



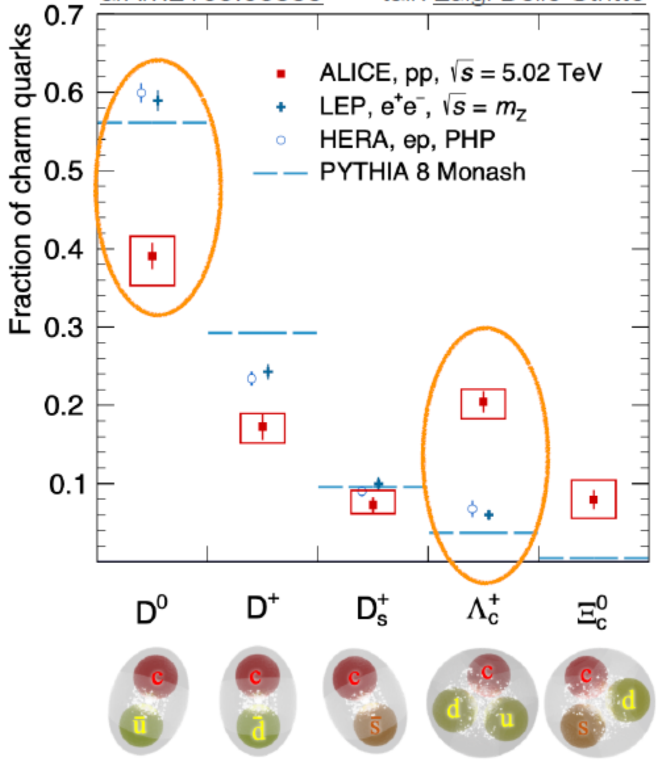
ALICE, arXiv: 2106.05713

ALICE показывает избыток рождения барионов с c кварками в pp взаимодействиях по сравнению с e^+e^- и e^-p взаимодействиями

Charm hadronization in pp (1):

More charm quarks in baryons in pp than in e^+e^- and ep collisions

arXiv:2105.06335 talk Luigi Dello Stritto



Charm quarks hadronize into baryons 40% of the time

~ 4 times more than in e^+e^-

H_c	$f(c \to H_c)[\%]$
D^0	$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.7}(\text{syst})$
D^+	$17.3 \pm 1.8(\text{stat})^{+1.7}_{-2.1}(\text{syst})$
D_s^+	$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$
Λ_c^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$
Ξ_c^0	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$

= 92,1

Новые явления КХД при адронизации c кварка в pp соударениях

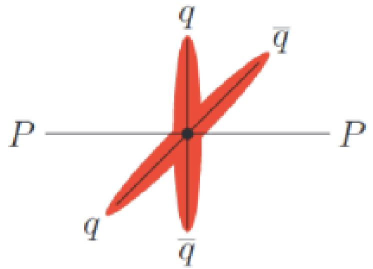
Competing theoretical ideas

Рассматриваются три теоретических подхода

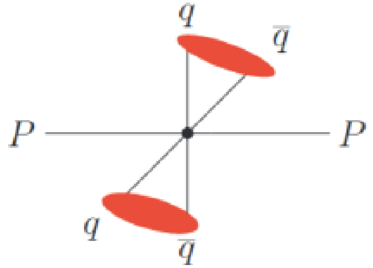
Color reconnections

String configuration that minimizes potential energy

Before colour reconnection



After colour reconnection?

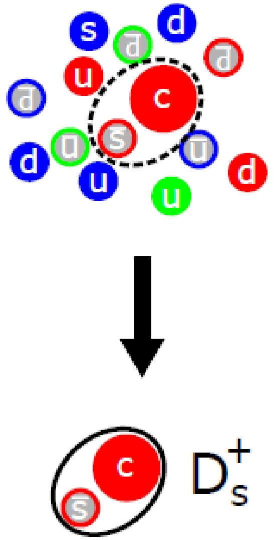


Christiansen, Skands, JHEP 1508 (2015) 003

Quark coalescence in phase space

Convolve quark distributions and hadron wave function

Assumes a high-density partonic system



Plumari et al., Eur.Phys.J.C 78 (2018) 348

SH model + RQM

Independent statistical hadronization + extra charm-baryon states predicted by rel. quark model (RQM)

$I(J^P)$	Qd state	$Q=c$ M	$Q=c$ M^{exp} [1]	$Q=b$ M	$Q=b$ M^{exp} [1]
$\frac{1}{2}(\frac{1}{2}^+)$	$1S$	2476	$2470.88(^{34}_{80})$	5803	5790.5(2.7)
$\frac{1}{2}(\frac{1}{2}^+)$	$2S$	2959		6266	
$\frac{1}{2}(\frac{1}{2}^+)$	$3S$	3323		6601	
$\frac{1}{2}(\frac{1}{2}^+)$	$4S$	3632		6913	
$\frac{1}{2}(\frac{1}{2}^+)$	$5S$	3909		7165	
$\frac{1}{2}(\frac{1}{2}^+)$	$6S$	4166		7415	
$\frac{1}{2}(\frac{1}{2}^-)$	$1P$	2792	2791.8(3.3)	6120	
$\frac{1}{2}(\frac{1}{2}^-)$	$2P$	3179		6496	

⋮

(many states …)

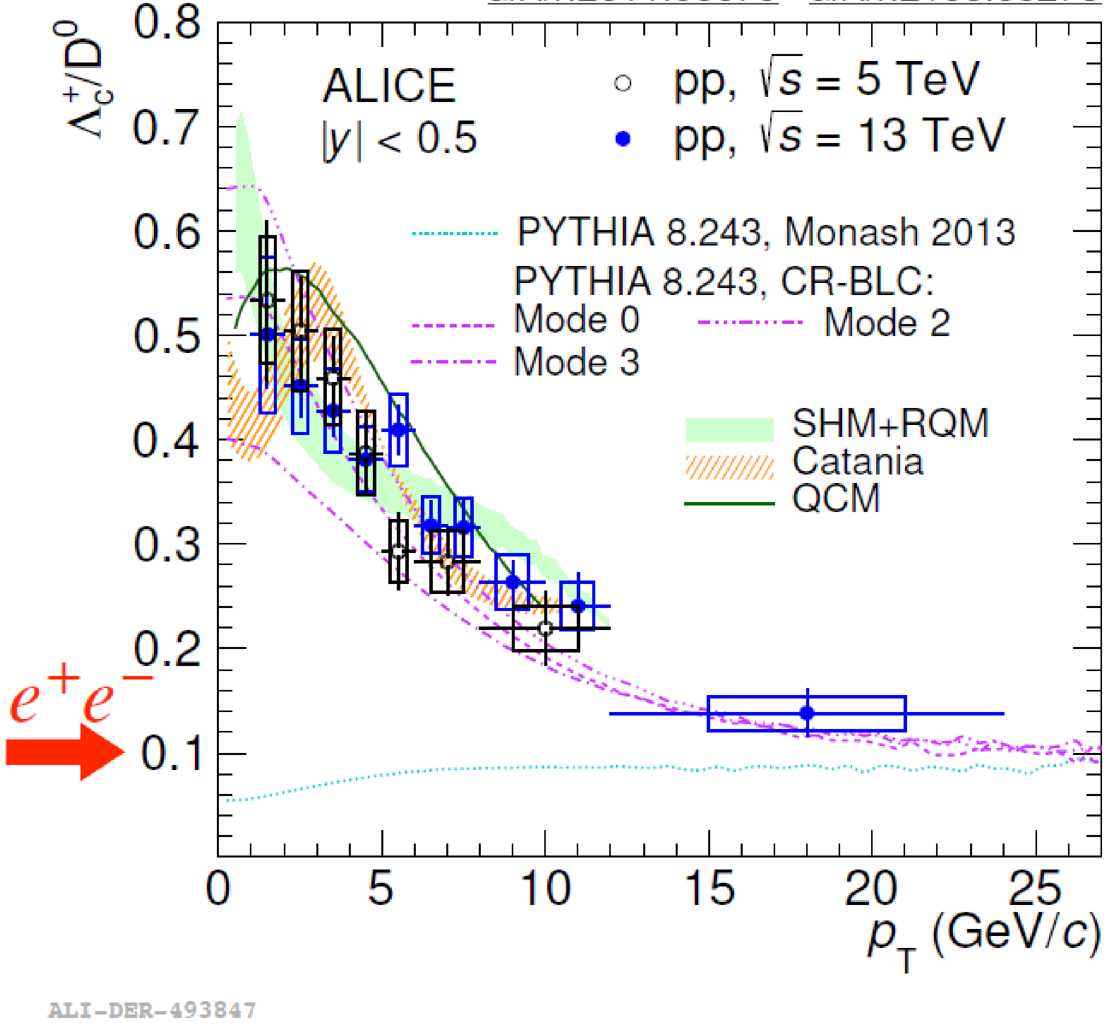
He, Rapp, PLB 795 (2019) 117

Зависимость эффекта от p_T адронов

Charm hadronization in pp (3)

Λ_c^+/D^0 ratio in pp significantly different than in e^+e^-

arXiv:2011.06079 arXiv:2106.08278



$$\Lambda_c^+ (udc) \to pK^-\pi^+$$
$$\to pK_s^0$$

Measurement of charmed hadrons down to unprecedentedly low p_T at midrapidity

Charm quark fragmentation not universal!

Standard PYTHIA 8 below data

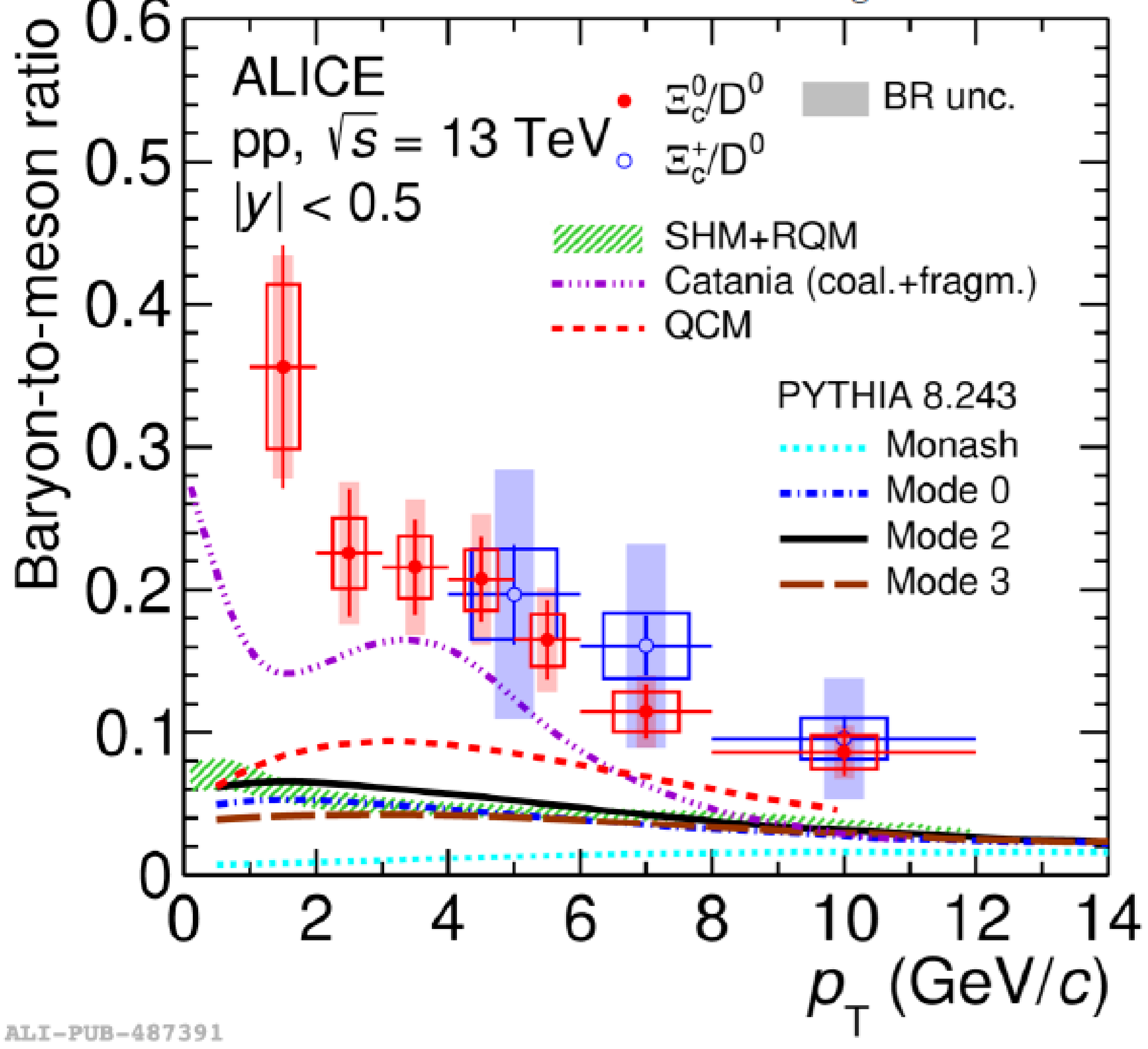
Fair description by

- PYTHIA 8 with CR
- Coalescence + fragmentation (Catania)
- SH mode + RQM
  (T = 170 MeV, additional states crucial)

Charm hadronization in pp (4):

Ξ_c^0/D^0 not described by models that get Λ_c^+/D^0 right!

arXiv:2105.05187 talk Luigi Dello Stritto



$$\Xi_c^0\,(dsc) \to \Xi^- e^+ \nu_e$$
$$\to \Xi^- \pi^+$$

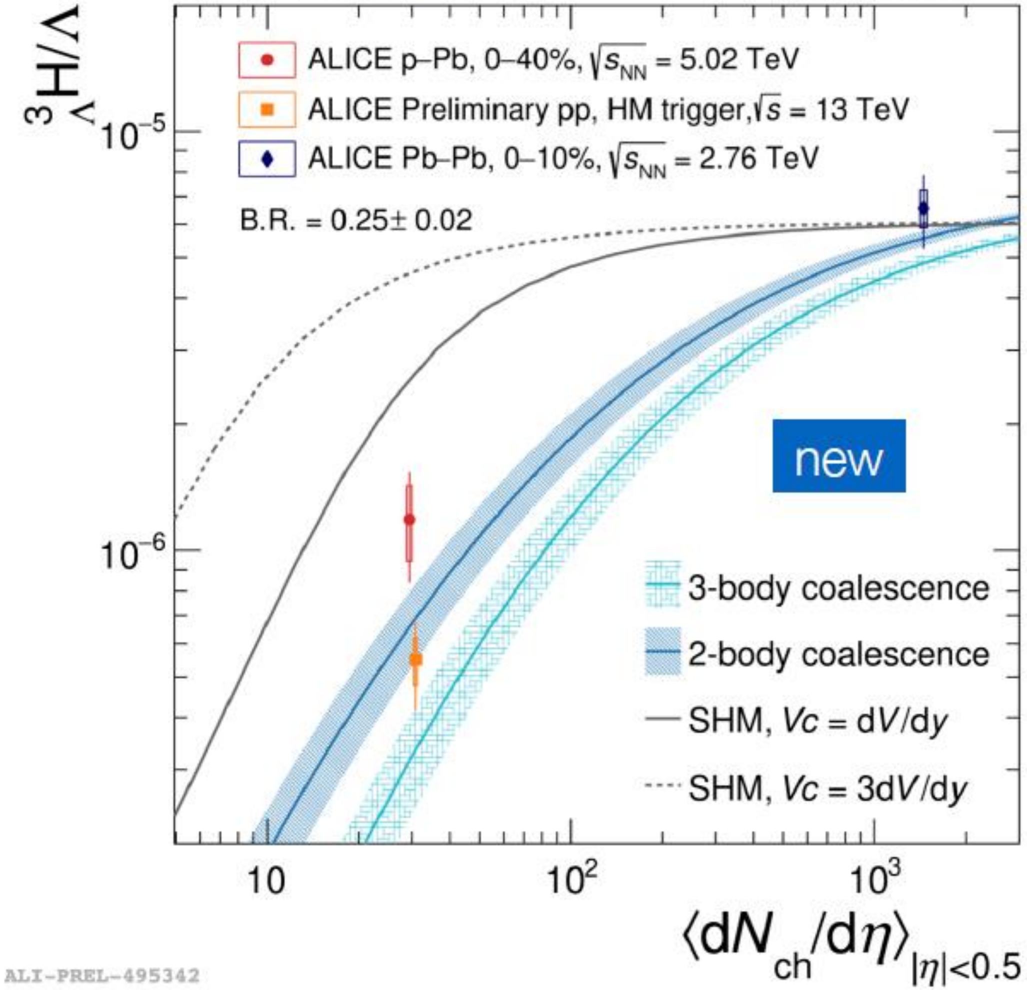
PYTHIA 8 with CR (mode 2) below data, even though this model describes Λ_c^+/D^0

Coalescence model comes closest to data

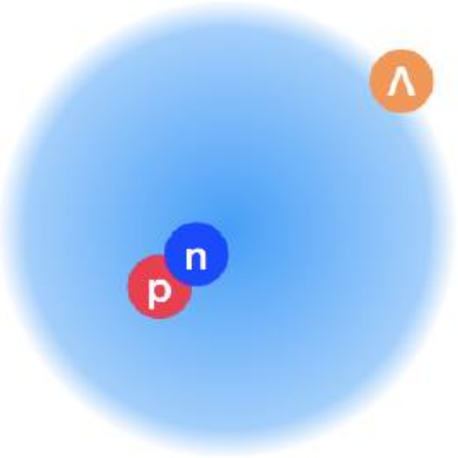
Hypertriton in pp and p-Pb

${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ yield ratio consistent with formation through coalescence

arXiv:2107.10627   talk Janik Ditzel

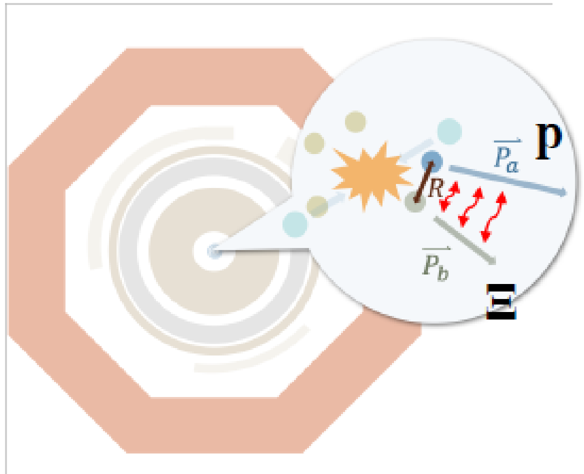


Образование гипертрития ${}^{3}_{\Lambda}H$

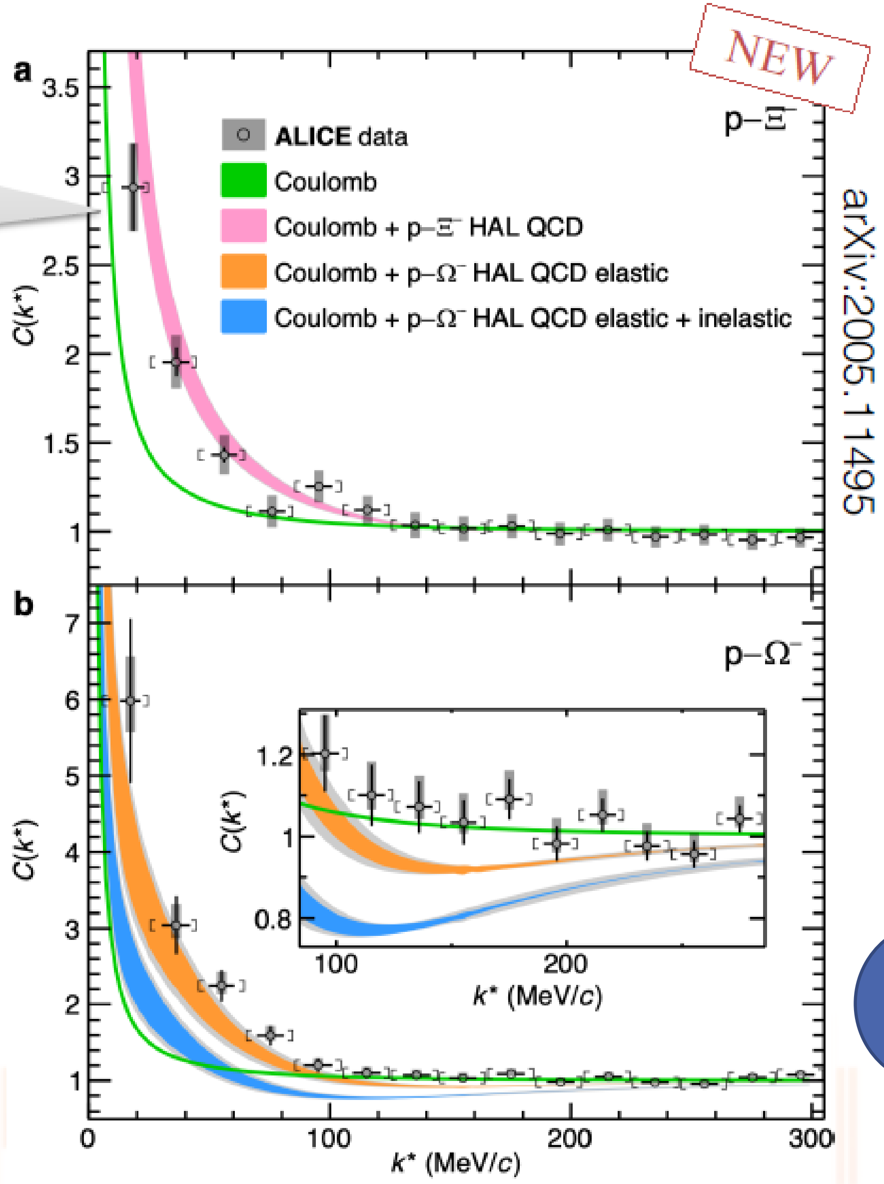


Formation mechanism provides insight into hypertriton structure
(in addition to lifetime and Λ separation energy)

Unprecedented precision in proton-hyperon interactions



Correlation peak at small momentum differences: signature of interaction

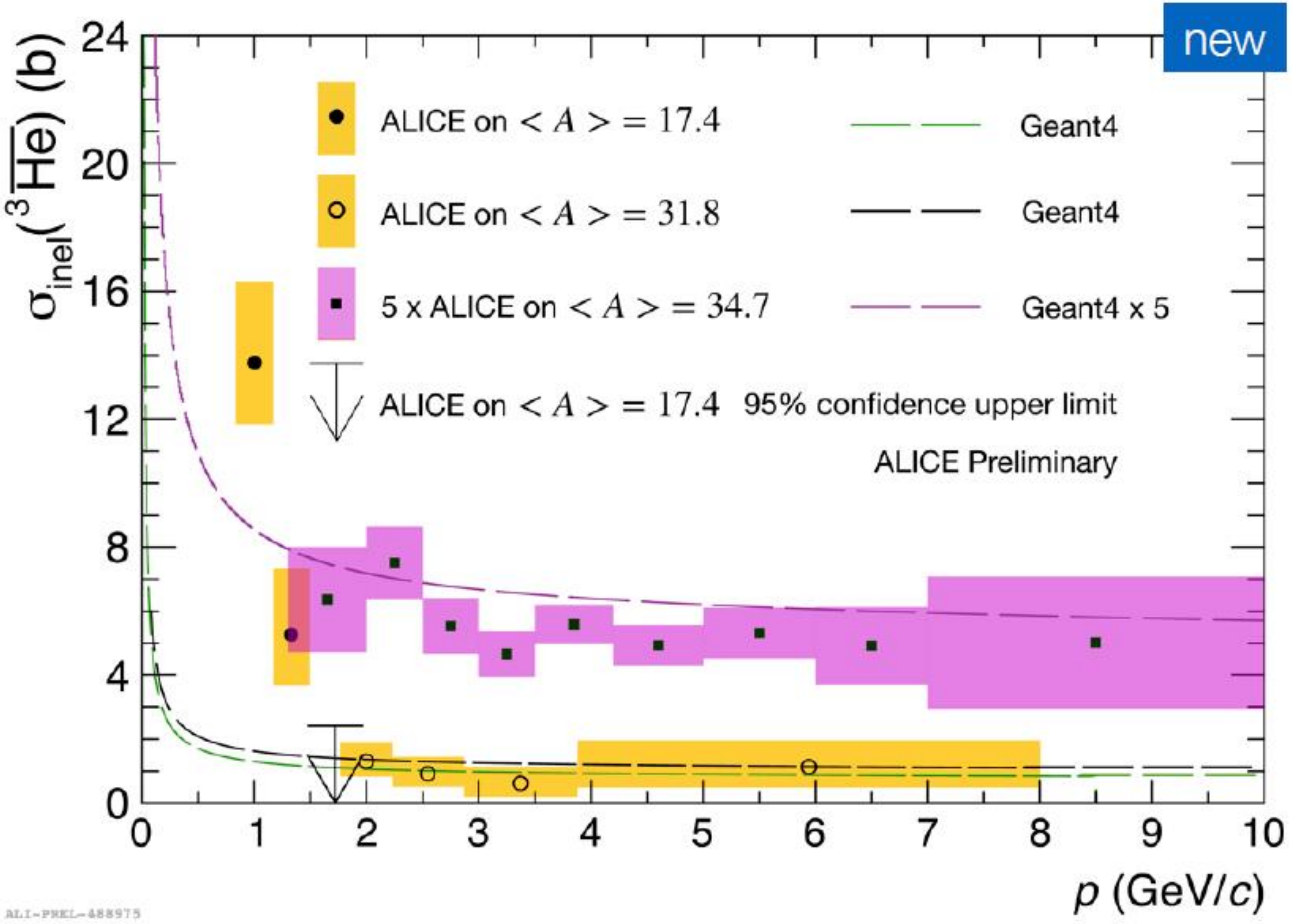


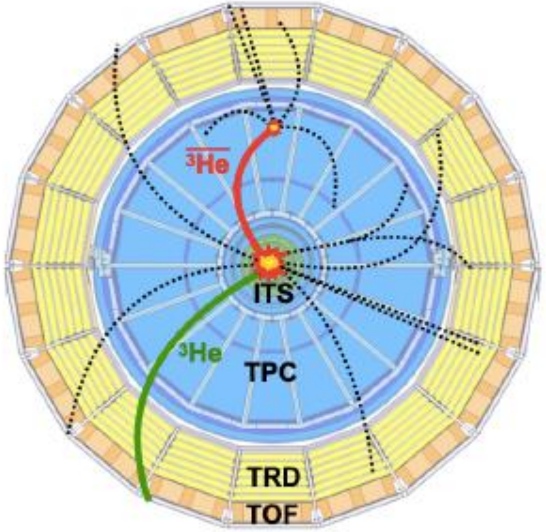
- Proton-hyperon strong interaction poorly known
- Measured in ALICE: momentum correlation of proton-hyperon pairs from a source of known size [1]
- Latest result [2]: precise measurement of attractive strong interaction for p-Ξ, p-Ω
  - Direct comparison to lattice QCD
  - p-Ξ important for neutron star EoS
- More to come in Run 3: d-Λ, p-Σ, Ω-Ω

[1] Characterizing the particle-emitting source using femtoscopy in pp collisions / A. Mathis
[2] ALICE measurements of Ξ- and Ω-nucleon int. and constraints on lattice QCD potentials / O. V. Doce

Inelastic cross section of $\bar{\mathrm{d}}$ and $^{3}\overline{\mathrm{He}}$ (3)

First-ever measurement of the interaction of antihelium with matter





Adjust inelastic cross section in GEANT 4 until reconstructed $^{3}\overline{\mathrm{He}}/^{3}\mathrm{He}$ ratio is reproduced

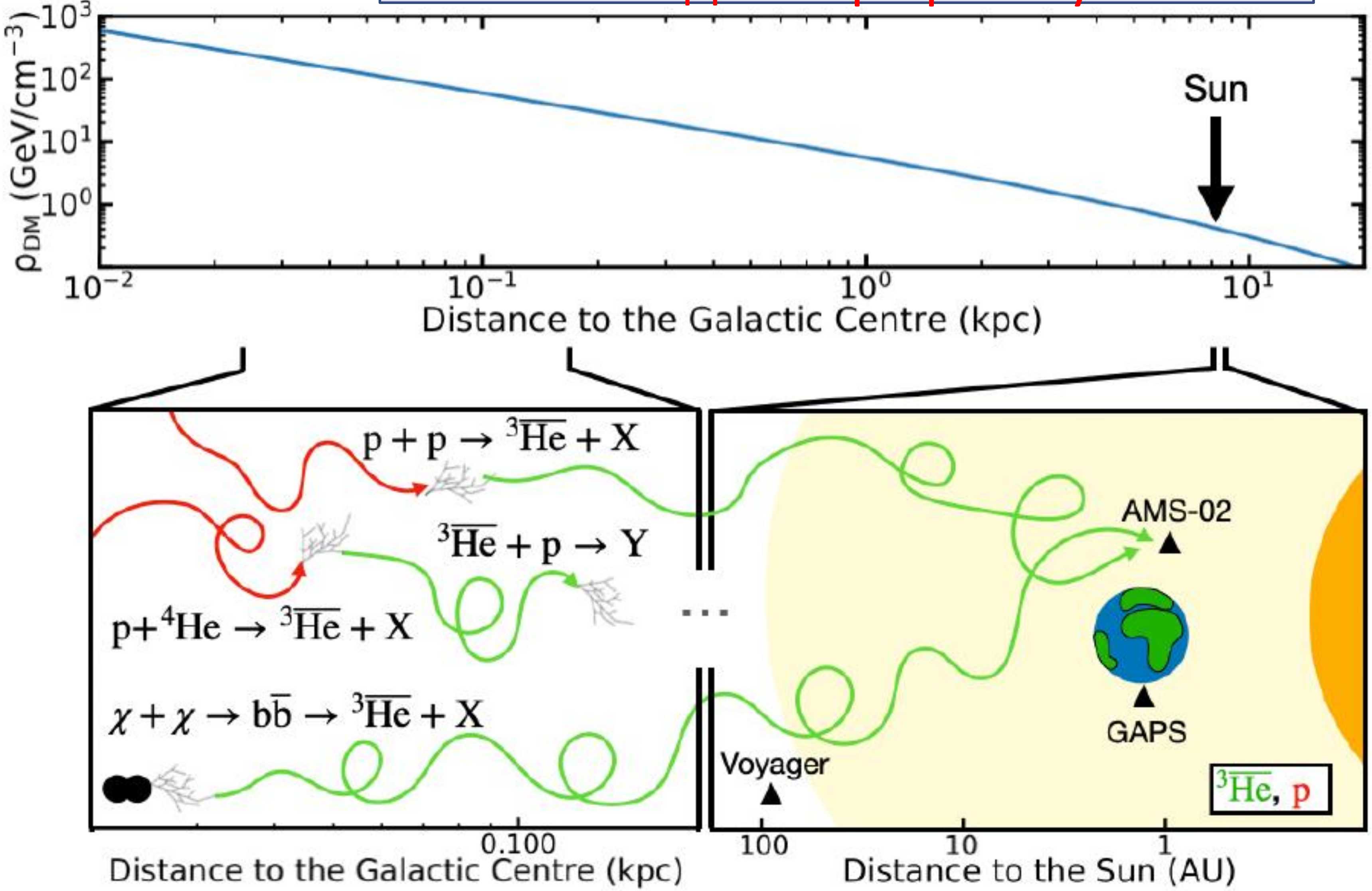
Indications of deviations from GEANT 4 at low p

Inelastic cross section of $\bar{d}$ and $^3\overline{\mathrm{He}}$ (1)

Input for dark matter searches in space

Physics highlights: the LHC as a versatile particle source

Вклад в астрофизику !



Indirect dark matter search:

$$\chi + \chi \rightarrow b\bar{b} \rightarrow \bar{d} + X$$
$$\chi + \chi \rightarrow W^+W^- \rightarrow \bar{d} + X$$
$$\chi + \chi \rightarrow b\bar{b} \rightarrow {}^3\overline{\mathrm{He}} + X$$
$$\chi + \chi \rightarrow W^+W^- \rightarrow {}^3\overline{\mathrm{He}} + X$$

Small astrophysical background

Critical input: inelastic cross section

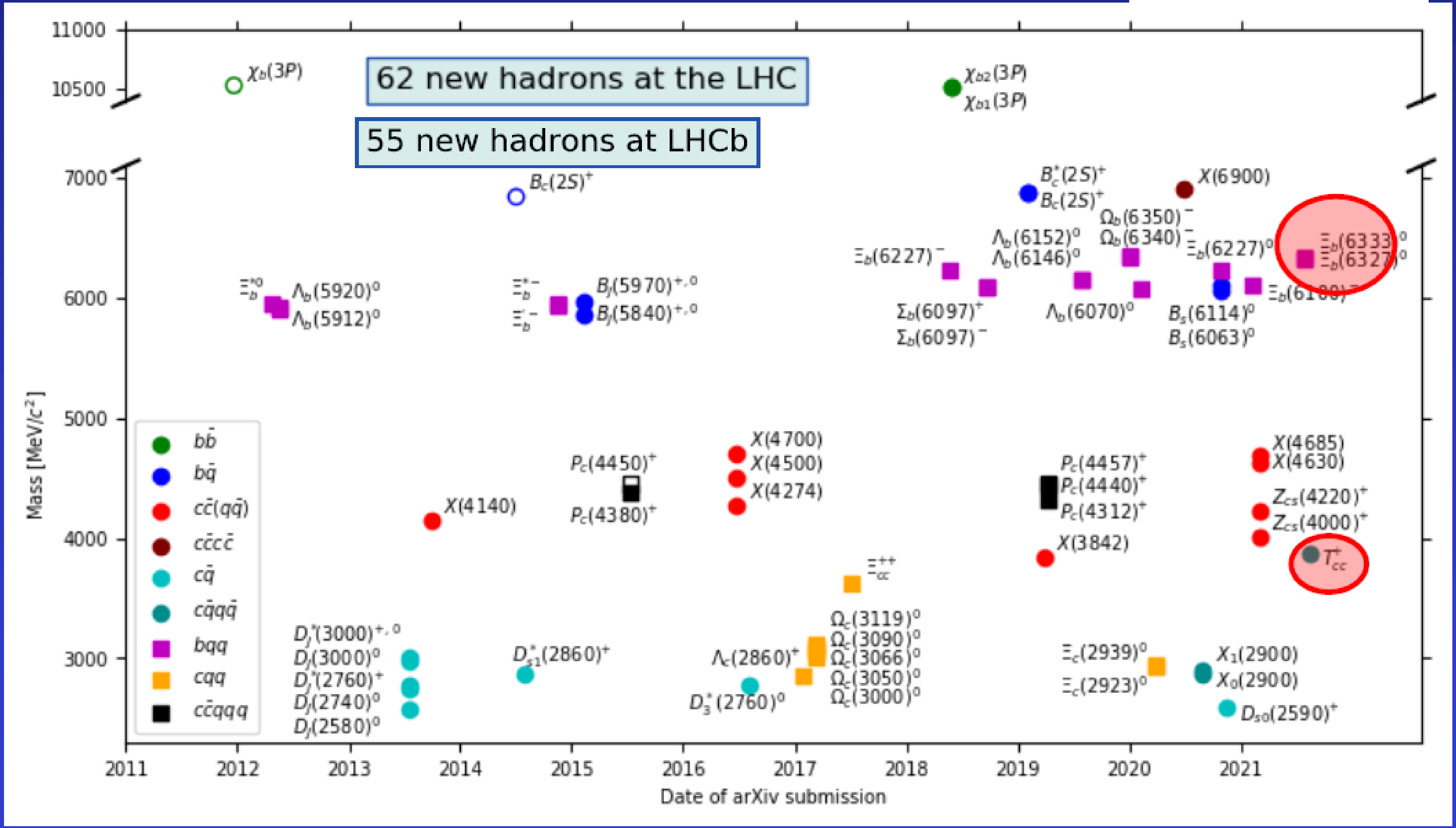
$\bar{d}$ + A inelastic cross section: PRL 125 (2020) 16, 162001

LHCb new results

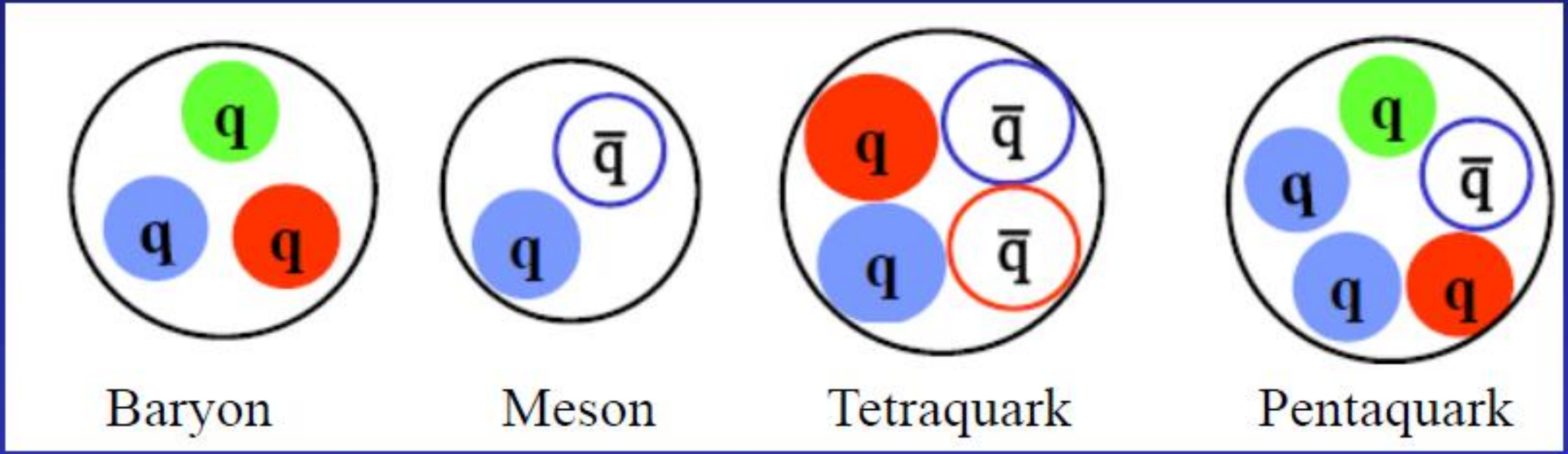
Новые экзотические адроны
Наблюдение осцилляций для B0s и D0
Измерение редких распадов

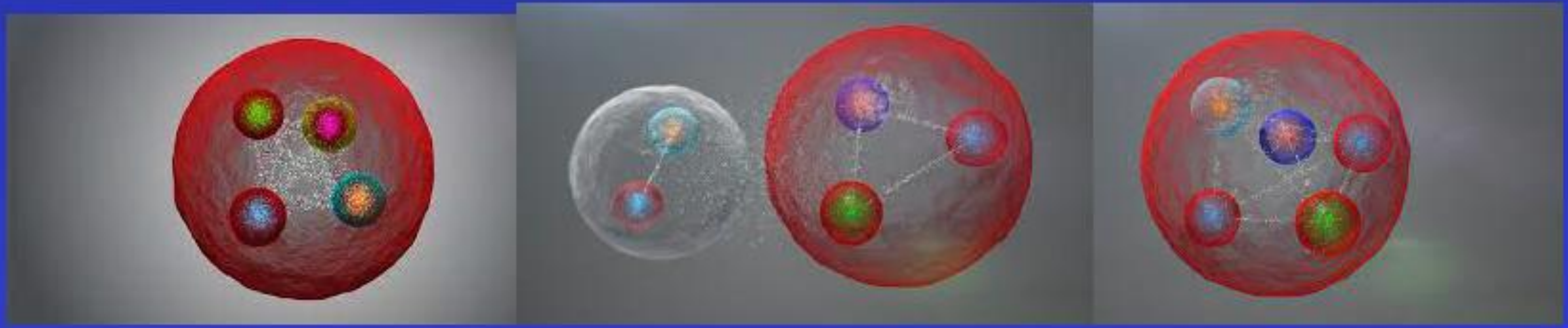
- **Status 28 July 2021**

from
[Patrick Koppenburg]



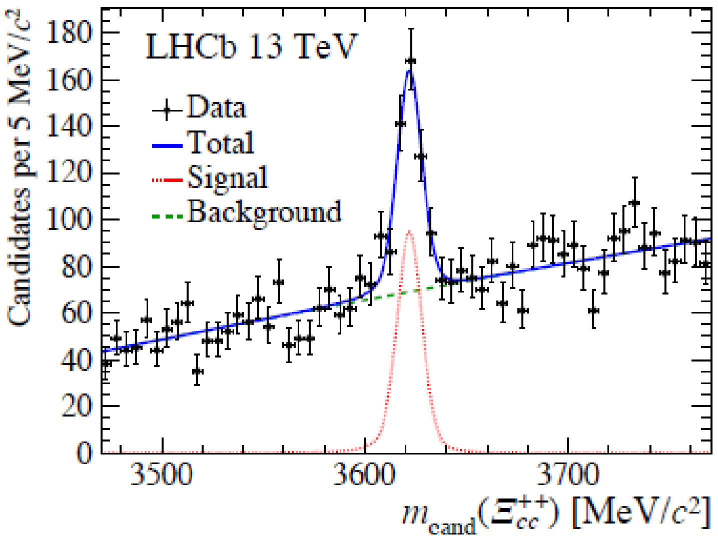
Exotic Spectroscopy





- States with two charm quarks (rather than a $c\bar{c}$ pair):

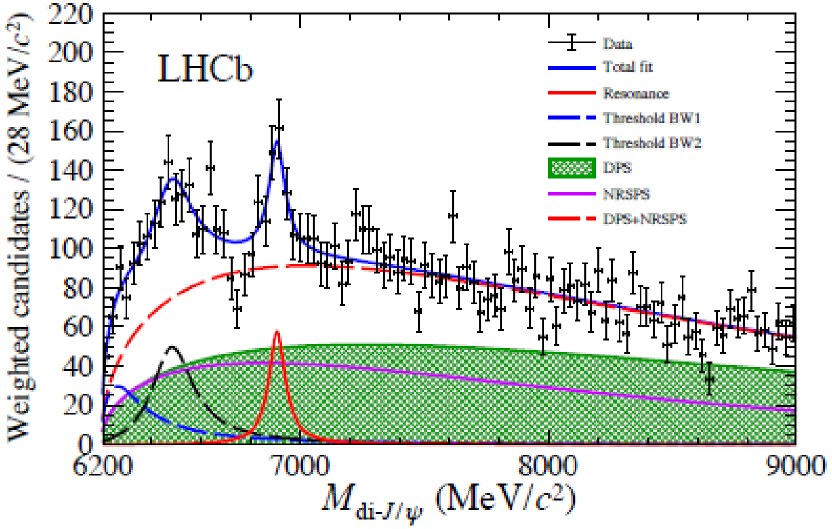
2017



Ξ_{cc}^{++} (ccu)

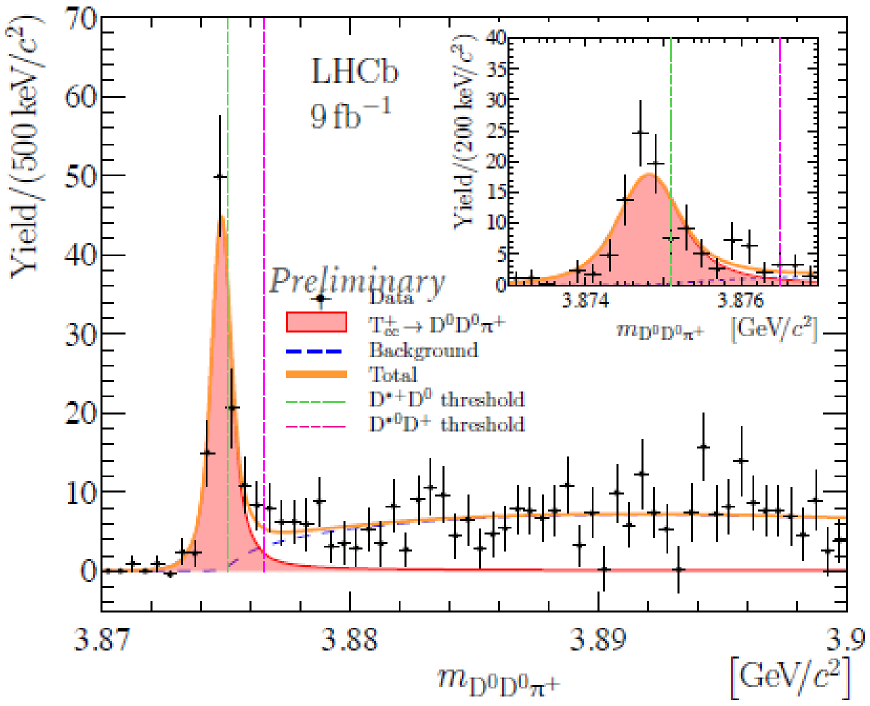
also: searches for Ξ_{cc}^{+} (ccd)

2020



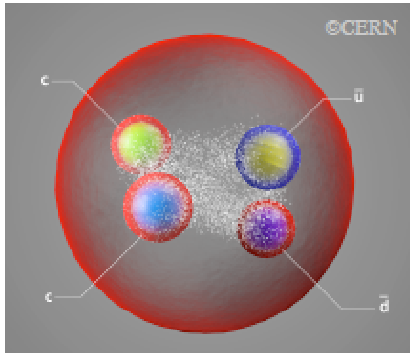
structure in $m(J/\psi J/\psi)$: $(cc\bar{c}\bar{c})$

2021: NEW



T_{cc}^+ $(cc\bar{u}\bar{d})$

- Now: Observation of a narrow peak in $m(D^0D^0\pi^+)$ at the threshold
  - manifestly exotic state: $cc\bar{u}\bar{d}$; expected isospin 0 and $J^P = 1^+$



- Mass measurement: relativistic Breit-Wigner lineshape gives
  $\delta m \equiv m_{T_{cc}^{+}} - (m_{D^{*+}} + m_{D^0}) = -273 \pm 61(\text{stat}) \pm 5(\text{syst})^{+11}_{-14}(J^P)\ \text{keV}/c^2$;
  mass ~3874.8 MeV/c²
  - consistent with some of theoretical predictions
- **width** $\Gamma_{\text{BW}} = 410 \pm 165(\text{stat}) \pm 43(\text{syst})^{+18}_{-38}(J^P)\ \text{keV}$ the smallest BW width of any known exotic state
- A more physical lineshape model explored as well, in upcoming [PAPER-2021-032]
  - A plethora of other studies: pole position, multiplicity dependence, characteristic size, etc: stay tuned for our papers!
- This result likely implies existence of a **weakly**-decaying $bb\bar{u}\bar{d}$ state (a tetraquark flying some mm before decay?)

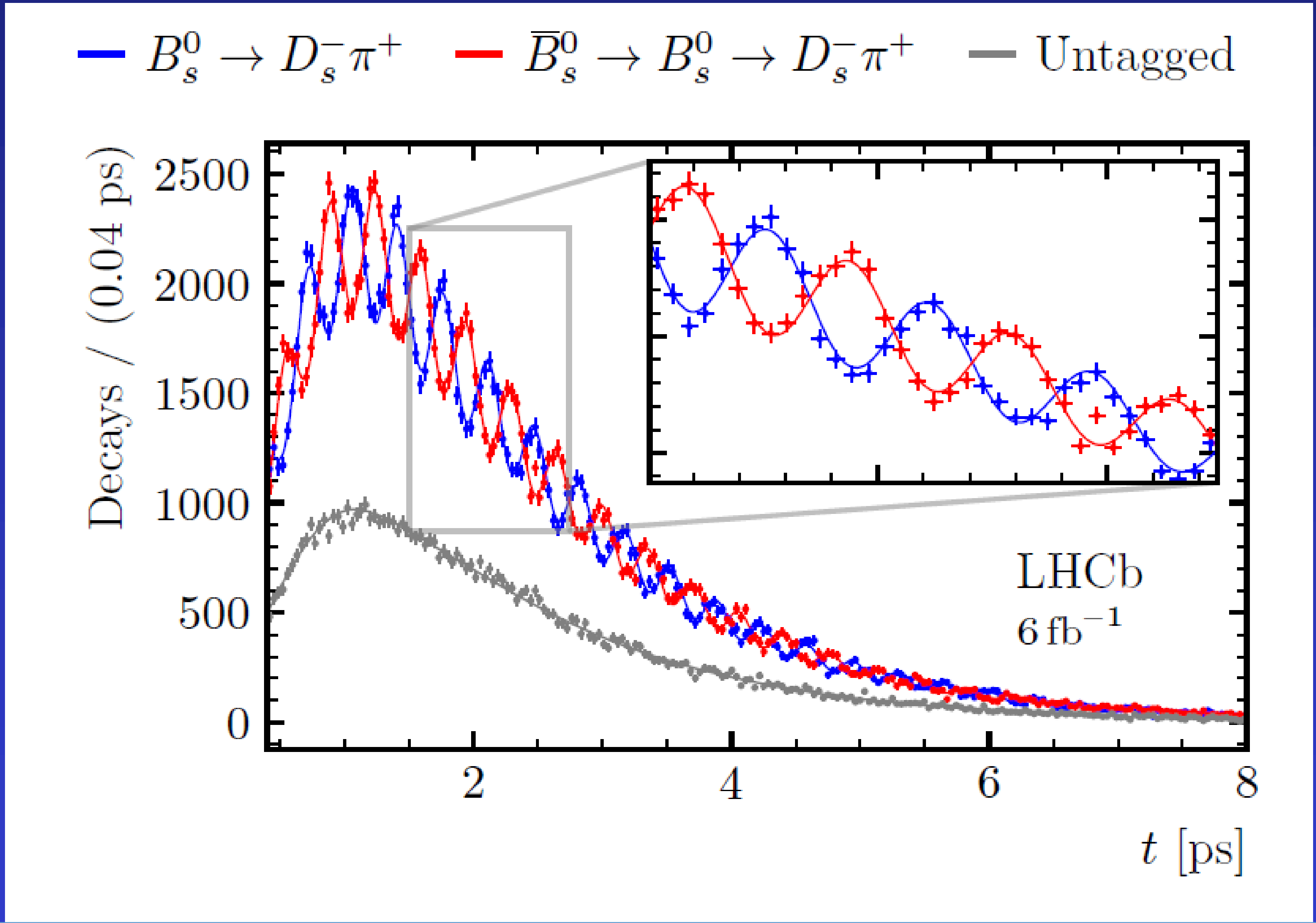
More details in our CERN-LHC seminar on 14th September.

Ученые открыли новую форму материи с помощью Большого адронного коллайдера (БАК). Экзотическая элементарная частица относится к так называемым тетракваркам — структурам, состоящим из четырех кварков, передает телеканал «Известия». Новинку назвали Tcc+, что указывает на наличие в составе двух очарованных кварков, при этом антикварков у частицы нет, что и делает её единственной в своём роде известной науке. Раньше считалось, что сложные кварки состоят из антиподов. Находка живет в 500 раз дольше, чем частицы с той же массой. Ученые называют Tcc+ рыхлой, у неё малая масса и большой радиус. Уникальные свойства новой частицы только предстоит изучить. Примечательно, что в открытии активно участвовали россияне. В частности, в состав научной коллаборации, которая работала над поиском частиц, входят ученые из Национального исследовательского центра «Курчатовский институт», а также сотрудники Института ядерной физики Сибирского отделения РАН.

При участии российских физиков в ЦЕРН обнаружили новую частицу — экзотический тетракварк Tcc+, представляющий собой новую форму материи. В коллаборацию LHCb, которая сделала открытие, входят Институт ядерной физики имени Г.И. Будкера Сибирского отделения РАН, Новосибирский государственный университет, Институт теоретической и экспериментальной физики имени А.И. Алиханова и другие организации. «Лента.ру» рассказывает о научном достижении и о том, что оно значит для физики частиц в целом.

Тетракварки являются экзотическими мезонами, то есть частицами, в которых число кварков равно числу антикварков. Экзотическими их называют потому, что изначально предполагалось существование частиц, состоящих либо из трех кварков, как протоны и нейтроны, либо из кварка и антикварка. В своих фундаментальных работах 1964 года физики Мюррей Гелл-Манн и Джордж Цвейг, в которых они предложили кварковую модель, упомянули возможность добавления кварк-антикварковой пары к минимальной мезонной или барионной кварковой конфигурации для образования адронов с четырьмя (тетракварк) или пятью (пентакварк) кварковыми составляющими. При этом считалось, что состав тетракварков всегда соответствует формуле qq'QQ', где q — это легкий кварк (верхний, нижний или странный), а Q — тяжелый кварк (очарованный или прелестный); апострофы обозначают соответствующие антикварки (легкие или тяжелые).
Физикам потребовалось 50 лет, чтобы получить однозначные экспериментальные доказательства существования экзотических адронов. В апреле 2014 года коллаборация LHCb опубликовала измерения, которые продемонстрировали, что частица Z (4430), впервые обнаруженная коллаборацией Belle, состоит из четырех кварков (ccud). Затем в июле 2015 года на Большом адронном коллайдере произошел поворотный момент в спектроскопии экзотических барионов, когда коллаборация LHCb сообщила о признаках существования пентакварков.
Считается, что первым экспериментально обнаруженным тетракварком стал Zc(3900), открытый в 2013 году сразу двумя независимыми научными коллективами на китайском электрон-позитронном коллайдере в BEPC II и в японской лаборатории Организации по изучению высокоэнергетических ускорителей. В 2015 году анализ распада лямбда-барионов, содержащих в своем составе один прелестный кварк (прелестные лямбда-барионы), раскрыл существование пентакварков — экзотических частиц, состоящих из пяти кварков. С тех пор экспериментально доказано существование 20 тетракварков и четырех пентакварков.

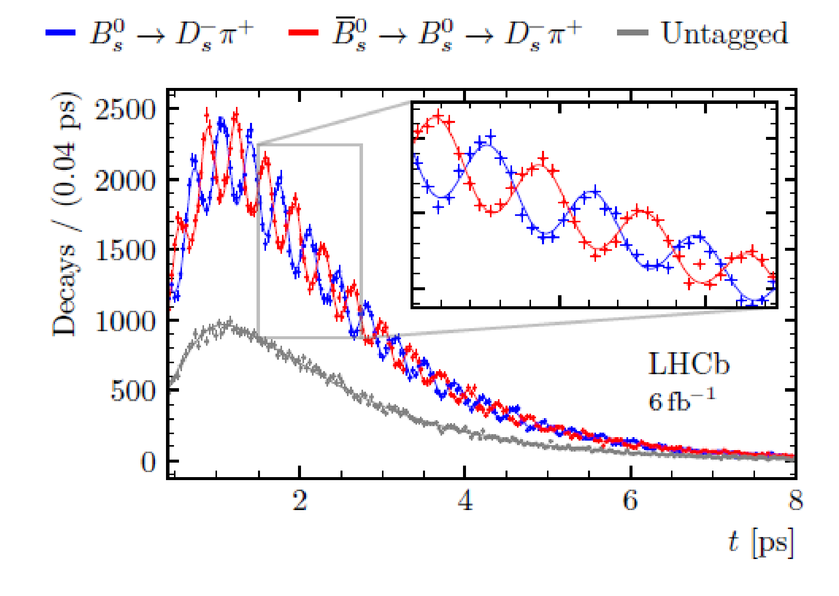
Oscillations, ~~CP~~ and charm

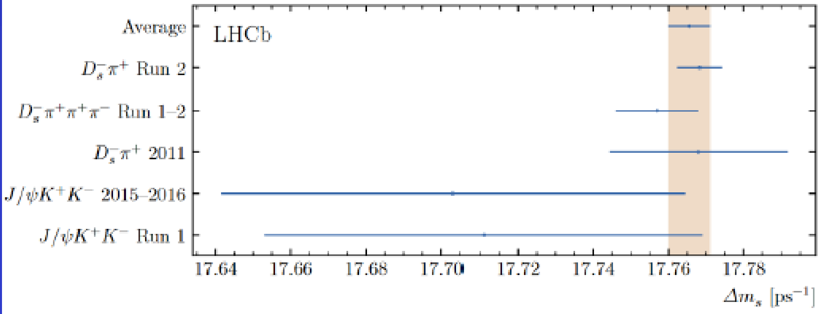


B_s Oscillations

LHCb-PAPER-2021-005, arXiv:2104.04421
LHCb-PAPER-2020-030, JHEP 03 (2021) 137

- **B_s^0 mass difference Δm_s**
  - Measured by oscillation frequency with $B_s^0 \to D_s^{\mp}\pi^{\pm}$ decays
  - Flavour tagging identifies B_s^0 / anti-B_s^0 at production
- **Legacy measurement**
  - $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ ps^{-1}$
  - Precision 3×10^{-4}
  - Including $B_s^0 \to D_s^{\mp}h^{\pm}\pi^{\pm}\pi^{\mp}$ et al.
  - $\Delta m_s = 17.7656 \pm 0.0057\ ps^{-1}$





Измерение величины разности масс Δm_s = 17.7656 ± 0.0057 пс$^{-1}$

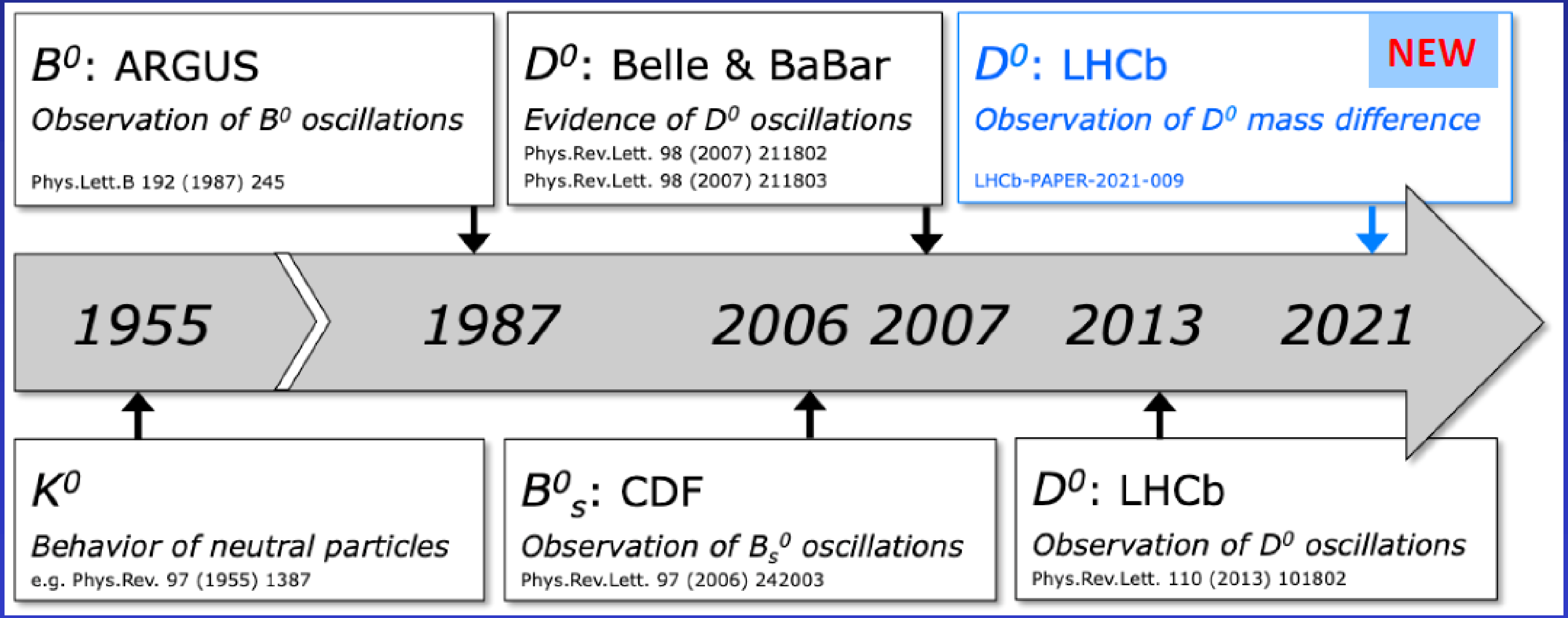
Измерения Δm_s в разных каналах распада и среднее значение величины

Neutral particle oscillations

- **Timeline**

NEW

LHCb-PAPER-2021-009
arXiv:2106.03744

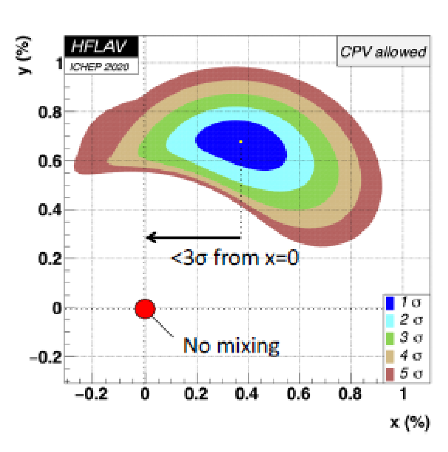


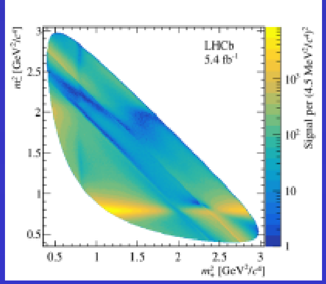
Charm mixing

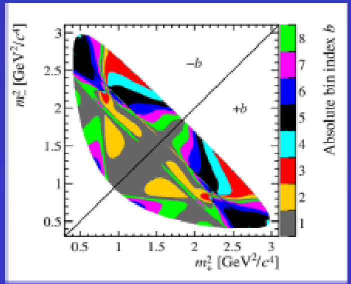
NEW

LHCb-PAPER-2021-009
arXiv:2106.03744

- **Charm D^0 Mixing**
  - Unique: up-type quarks
  - Small mixing, sensitive to $\cancel{CP}$
  - $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$ $\quad x \equiv (m_1 - m_2)c^2/\Gamma$ $\quad y \equiv (\Gamma_1 - \Gamma_2)/(2\Gamma)$
  - No measurement of $x \neq 0$ until this summer
- **Charm at LHCb**
  - Large cross section - σ_{cc} ~ 5 mb, charm rate ~2 MHz
  - Run 2 - dedicated Turbo trigger - 15 kHz to tape
- **$D^0 \rightarrow K_S^0 \pi^+\pi^-$**
  - 30.6M decays & very small background
- **Bin-flip method**
  - Measure asymmetry between D^0 and anti-D^0 in binned Dalitz plot $m^2(K_S^0\pi^-)$ vs $m^2(K_S^0\pi^+)$
  - In each bin approx. constant strong-phase difference between D^0 and anti-D^0 amplitude







Mixing and time-dependent CPV in charm decays at LHCb Federico Betti

Observation of mass difference

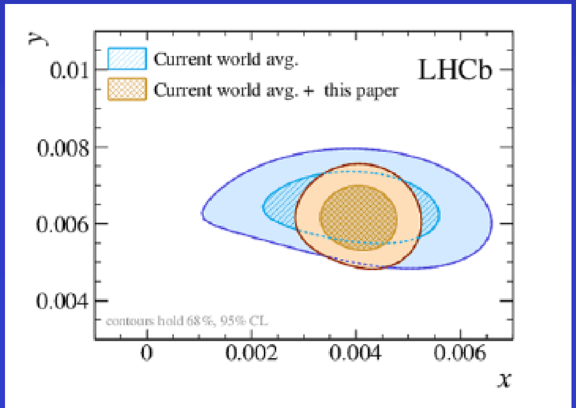
NEW

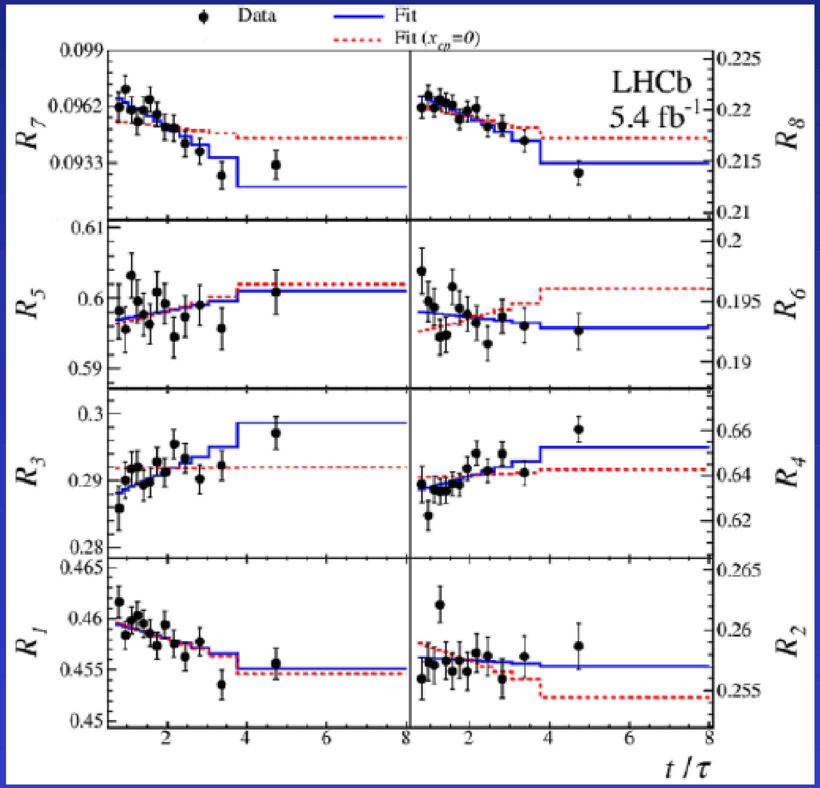
LHCb-PAPER-2021-009
arXiv:2106.03744

- **Observation**
  - of small mass difference
    in neutral charm meson eigenstates

$$
\begin{aligned}
x &= (3.98^{+0.56}_{-0.54}) \times 10^{-3},\\
y &= (\ 4.6^{+1.5}_{-1.4}\ ) \times 10^{-3},\\
|q/p| &= 0.996 \pm 0.052,\\
\phi &= 0.056^{+0.047}_{-0.051}.
\end{aligned}
$$

  - $m_1 - m_2 = 6.4 \times 10^{-6}$ eV = 1×10^{-38} g
  - Significance > 7 σ
  -





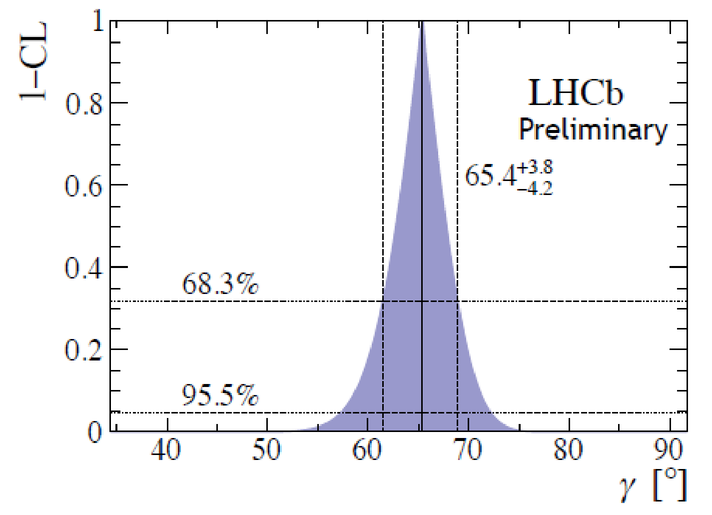
No evidence for ~~CP~~ at 2×10^{-4}

Mixing and time-dependent CPV in charm decays at LHCb Federico Betti

CKM angle γ and charm mixing

LHCb-CONF-2021-001

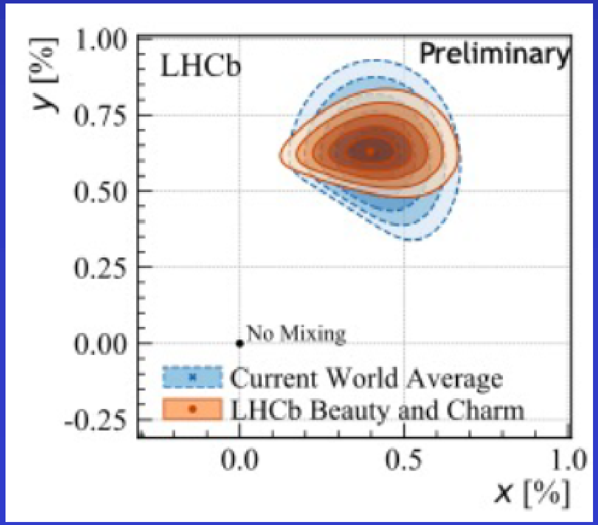
- **New method**
  - First simultaneous determination of CKM angle γ and charm mixing parameters
  - 151 observables, 52 parameters
- **CKM angle γ**
  - $\gamma = (65.4^{+3.8}_{-4.2})^\circ$
  - Most precise measurement



- **Comparison**

  NEW
  - Excellent agreement with indirect global CKM fits

    $\gamma = (65.8 \pm 2.2)^\circ$ UTfit
- **Charm mixing**
  - $y = (0.630^{+0.033}_{-0.030})\%$,
  - $x = (0.400^{+0.052}_{-0.053})\%$
  - Precision on y improved by factor 2

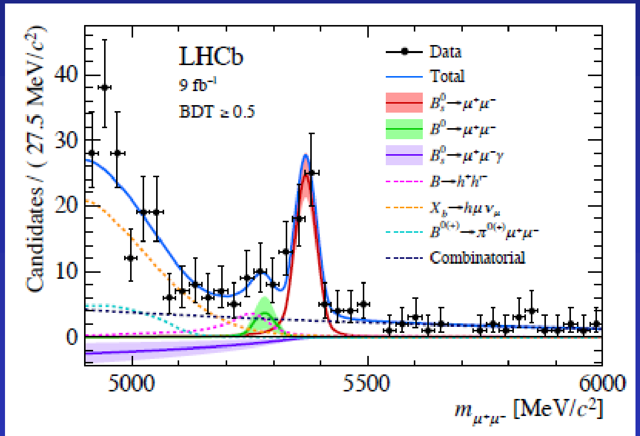


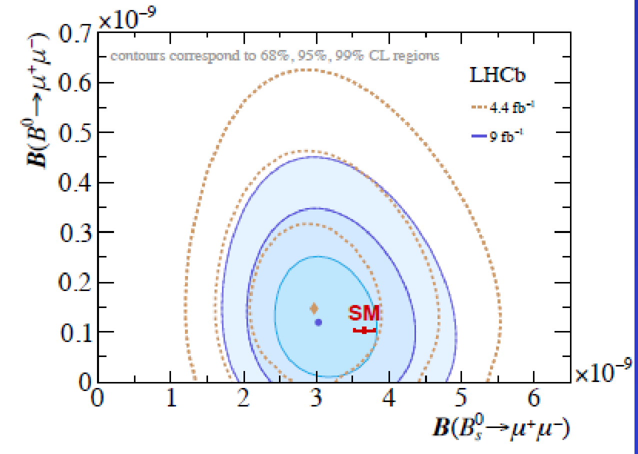
Measurement of the CKM angle gamma at LHCb
Mark Whitehead

$B_{(s)}^0 \to \mu^+\mu^-(\gamma)$

LHCb-PAPER-2021-007
LHCb-PAPER-2021-008

- **Very rare leptonic decay**
  - Helicity and CKM suppressed
  - Sensitive to New Physics
- **$B_s^0 \to \mu^+\mu^-$**
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.09^{+0.46}_{-0.43}\ ^{+0.15}_{-0.11} \times 10^{-9}$
  - Significance > 10 σ
  - in agreement with SM
- **$B^0 \to \mu^+\mu^-$**
  - $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ at 95% CL
- **First search for $B_s^0 \to \mu^+\mu^-\gamma$**
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2.0 \times 10^{-9}$ at 95% CL for $m_{\mu\mu} > 4.9$ GeV/c^2





Very rare decays at LHCb
Miguel Ramos Pernas

Новые измерения относительных вероятностей (Br) редких распадов B^0 и B^0_s на два мюона – наблюдается согласие с предсказаниями СМ

Заключение

Продемонстрирован широчайший спектр исследований в физике высоких энергий в диапазоне масс от 4 ТэВ до 10^{-6} эВ.

Границы применимости СМ по энергии пока не достигнуты, хотя есть косвенные эффекты её присутствия.

Наблюдается много новых явлений КХД, от темного конуса как свидетельства собственной массы кварка до новых структур экзотических адронов.

Адронные коллайдеры в этом году отмечают 50-летний юбилей!

Спасибо!