From Symmetry Breaking to Bound State: $H \to \mu\mu$ and Toponium

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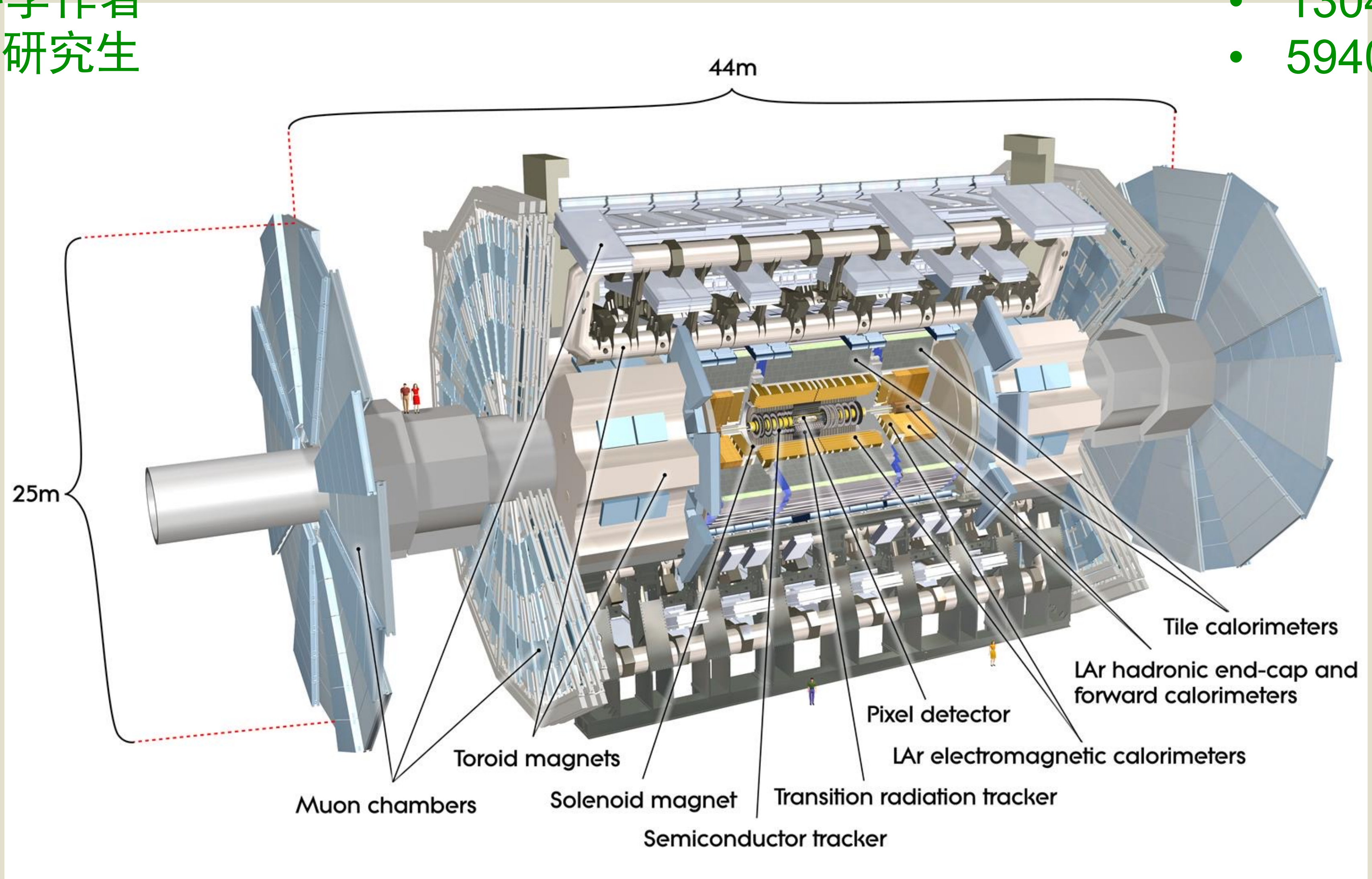
第八届全国重味物理与量子色动力学研讨会

重庆大学，2026年4月25日

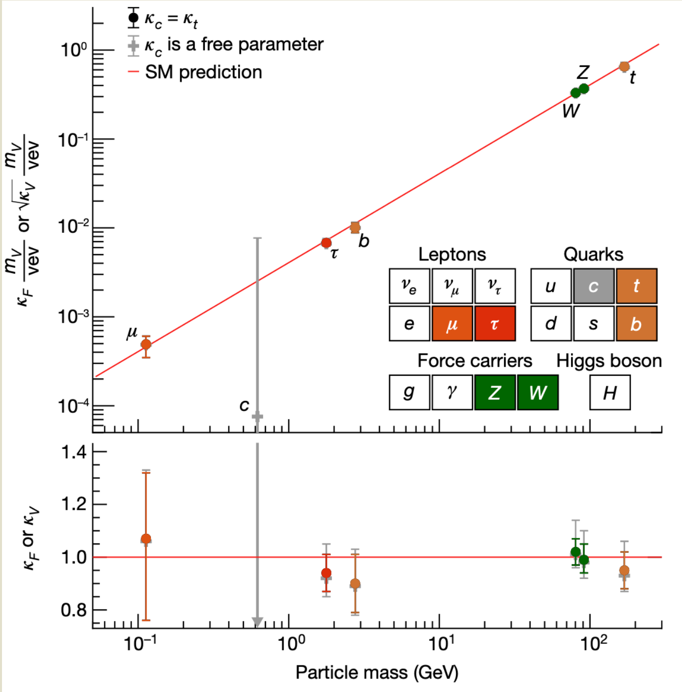
ATLAS (A Toroidal LHC ApparatuS)

- 约2900位科学作者
- 1190位博士研究生

- 1304位工程师
- 5940位活跃成员

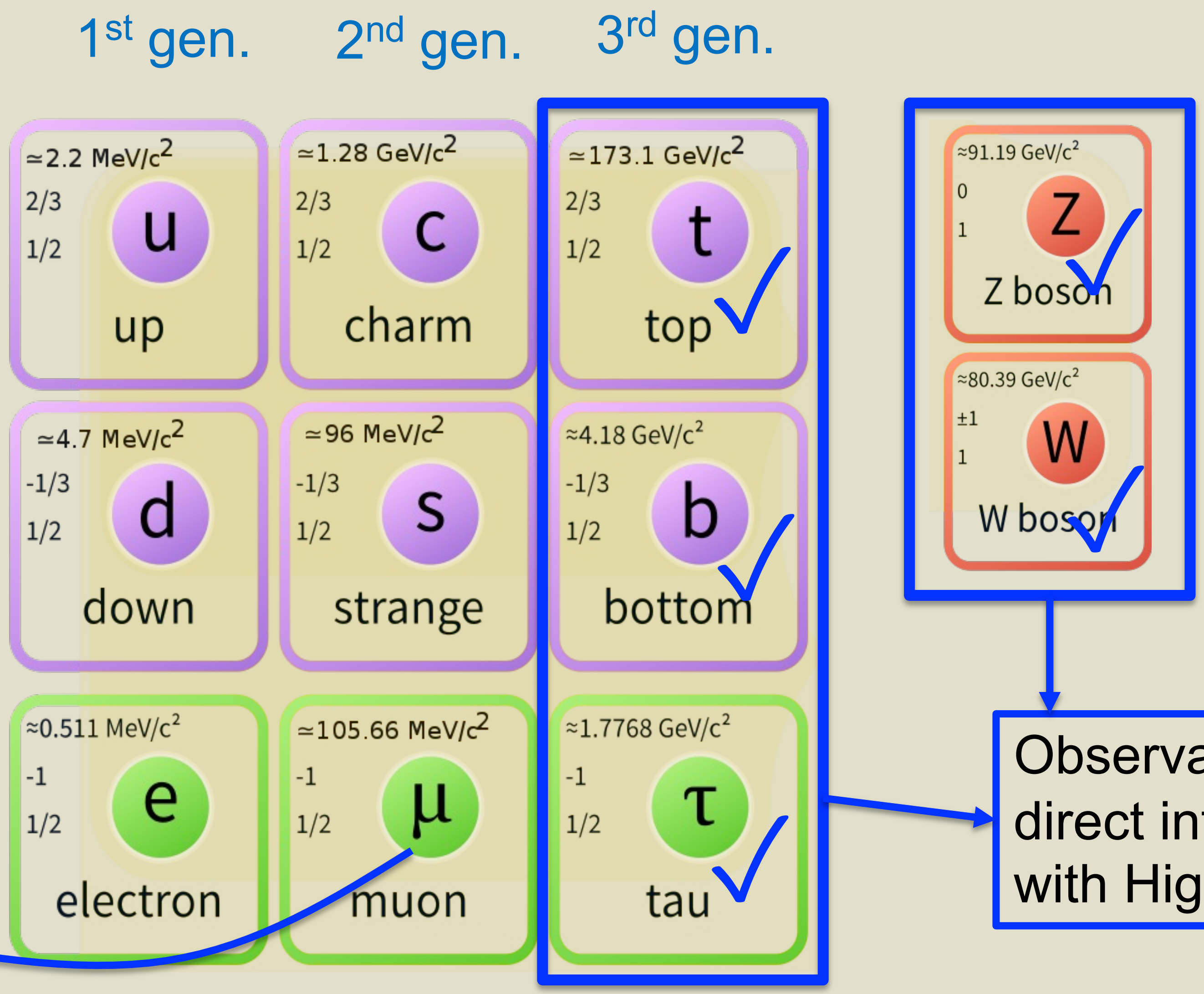


$H \to \mu\mu$



Nature 607, 52–59 (2022)

Current understanding of Higgs boson coupling



Observation of direct interaction with Higgs boson

To be established at the LHC

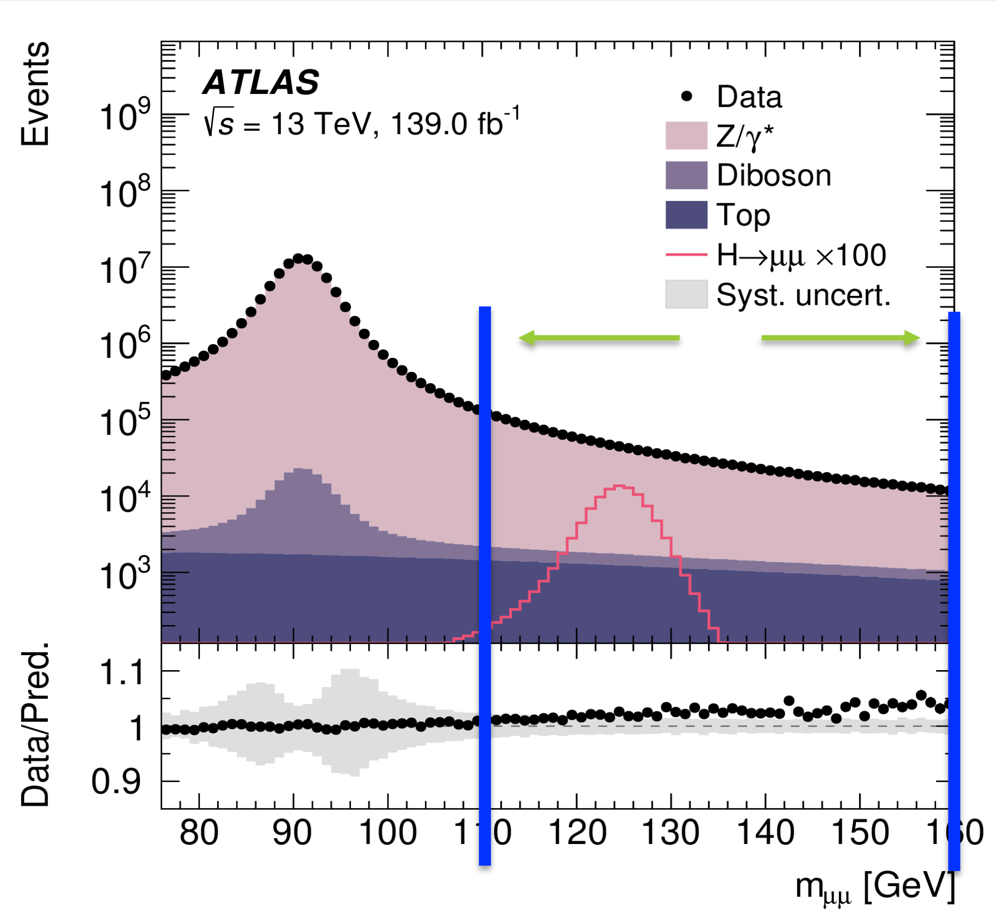
$H \to \mu\mu$

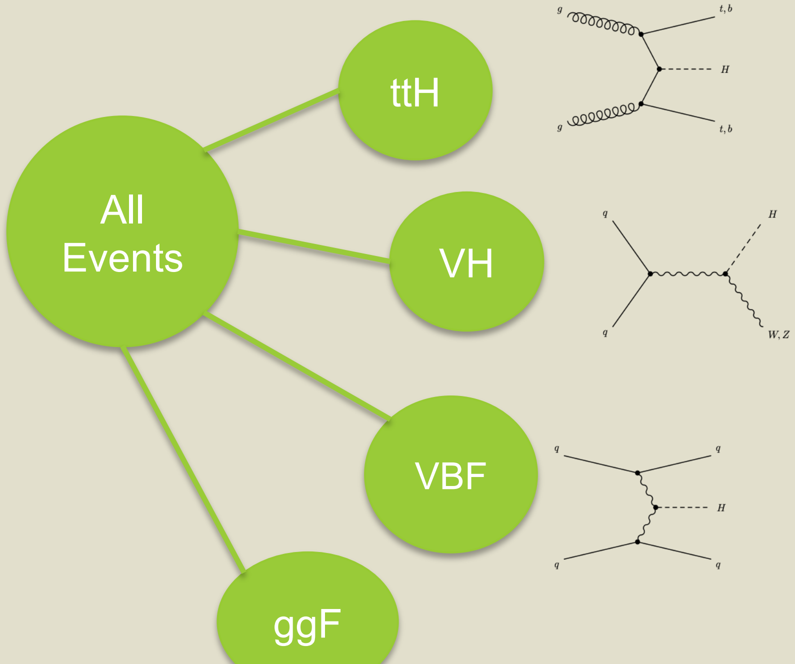
Dominant background: Drell—Yan process

BR(H→μμ)=0.02%

困难：海量的DY本底

方案：针对不同的Higgs产生mode来设计信号区间，以压低本底

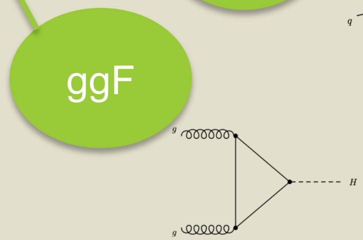




at least one bjet

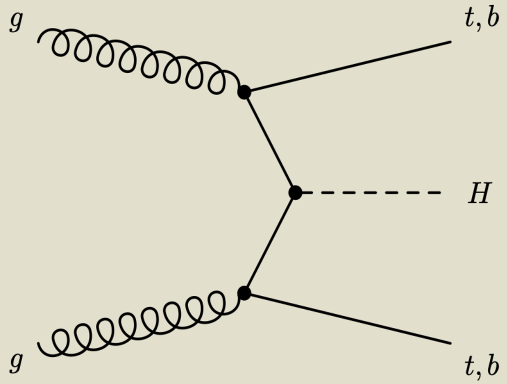
2/3/4 leptons, no bjet

2 leptons, no bjet

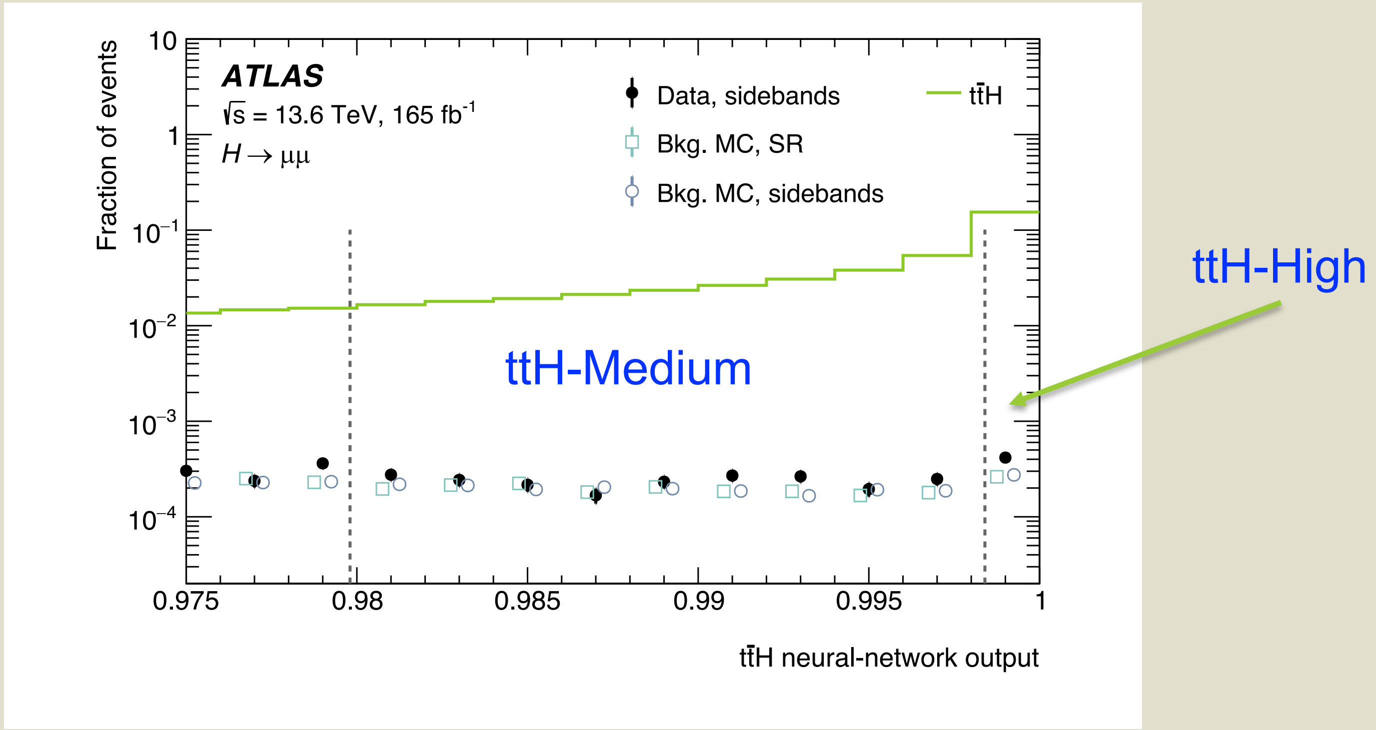


2 leptons, no bjet

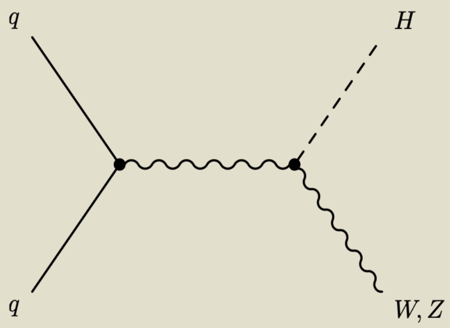
ttH (2 categories)



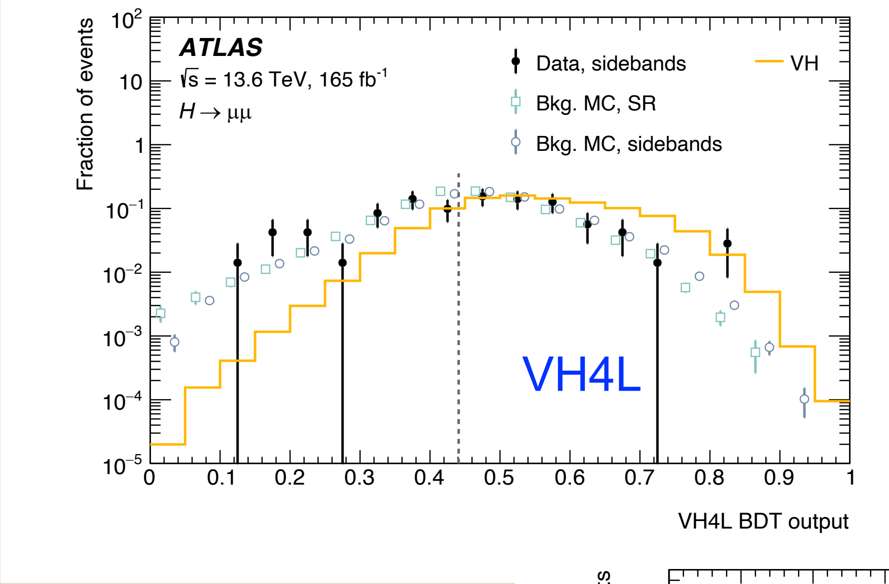
- Target: both hadronic and leptonic decays
- Neural Networks (NN) trained with 30 variables to separate signal from backgrounds
- 2 categories defined based on NN output



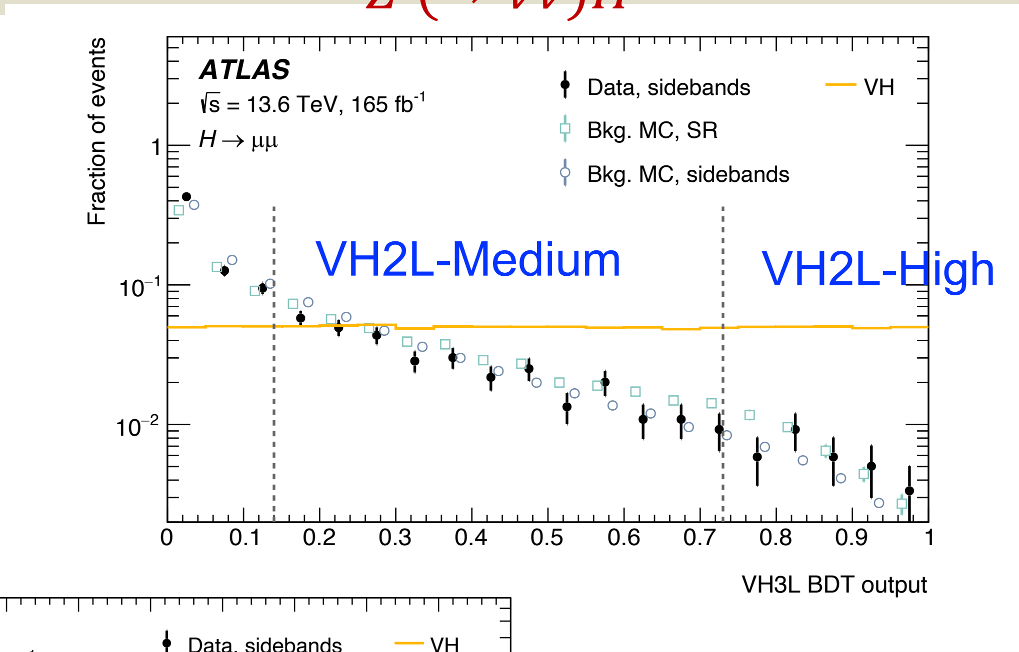
VH (8 categories)

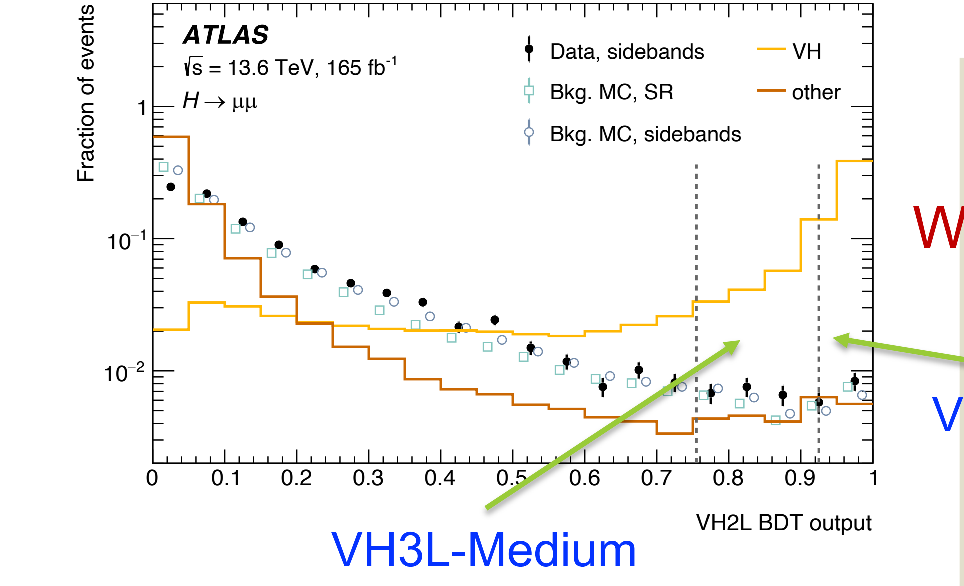


$Z\ (\to ee/\mu\mu)H$



$Z\ (\to \nu\nu)H$





$W\ (\to e\nu/\mu\nu)H$

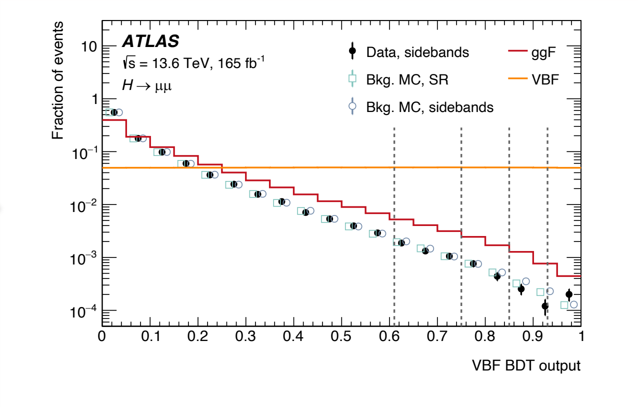
VH3L-High

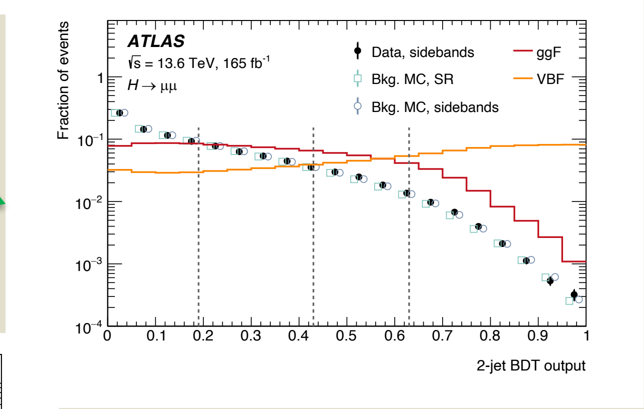
- BDTs trained with 15 variables (ZH 4-lep) and 9 variables (ZH 2-lep)
- BDT trained with 12 variables for WH

VBF/ggF (13 categories)

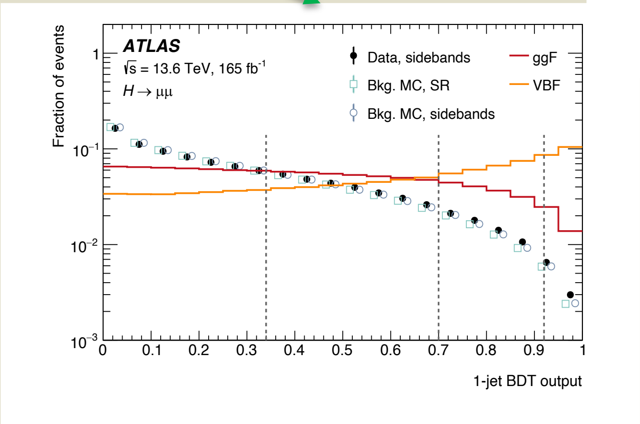
剩余的事例

2 jet

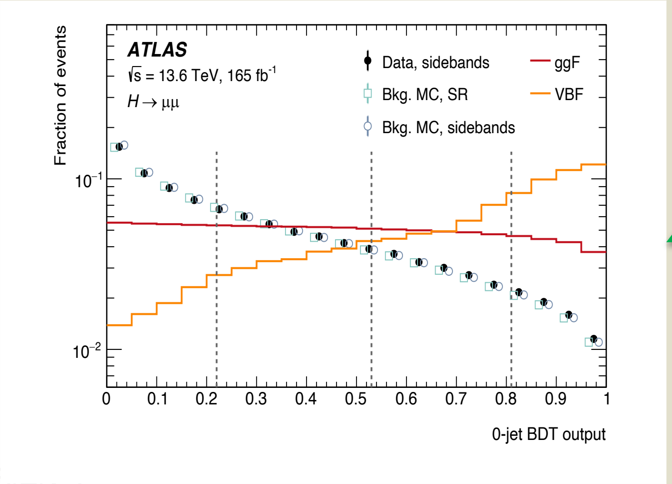




1-jet



0-jet

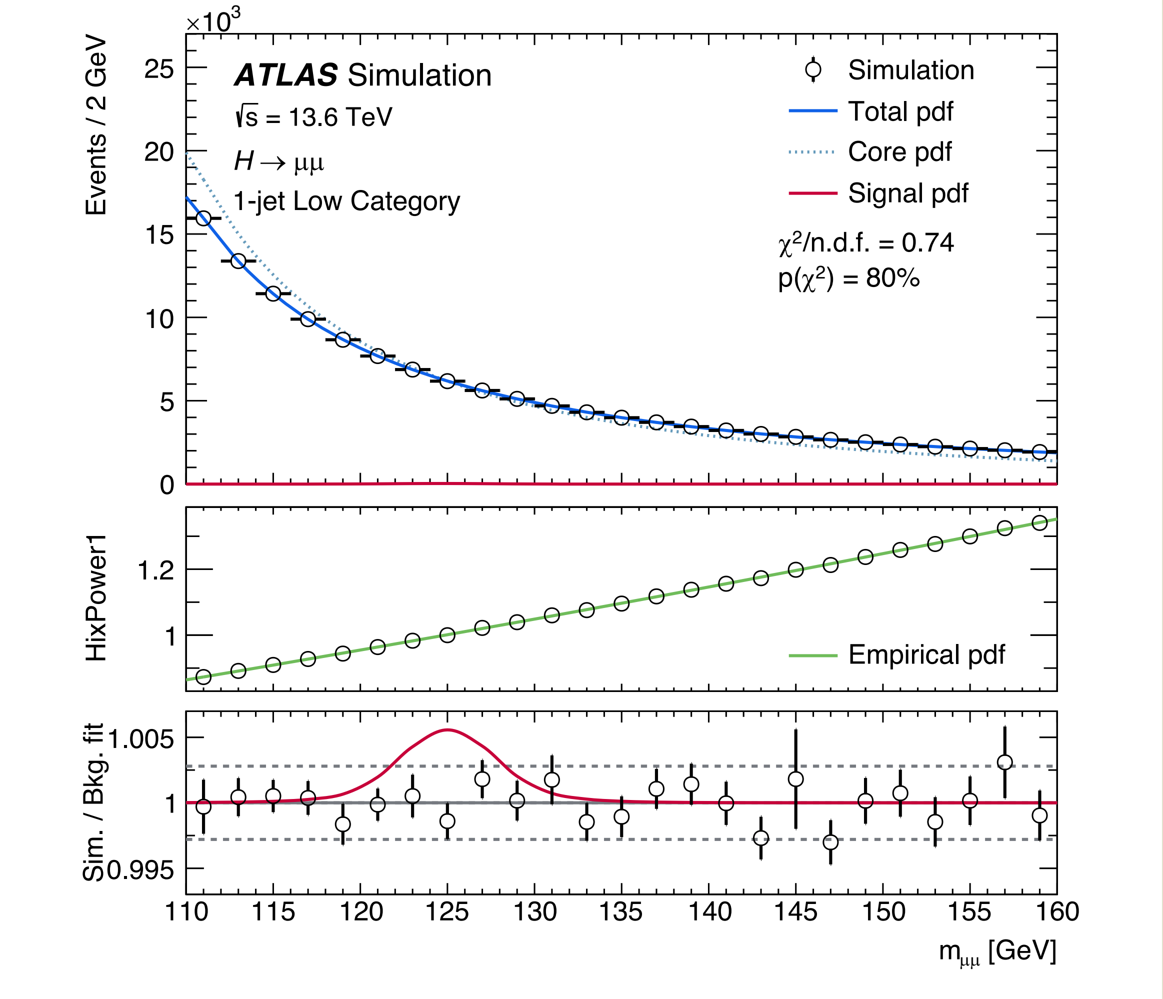


Background Modeling

Proposed model with two components:

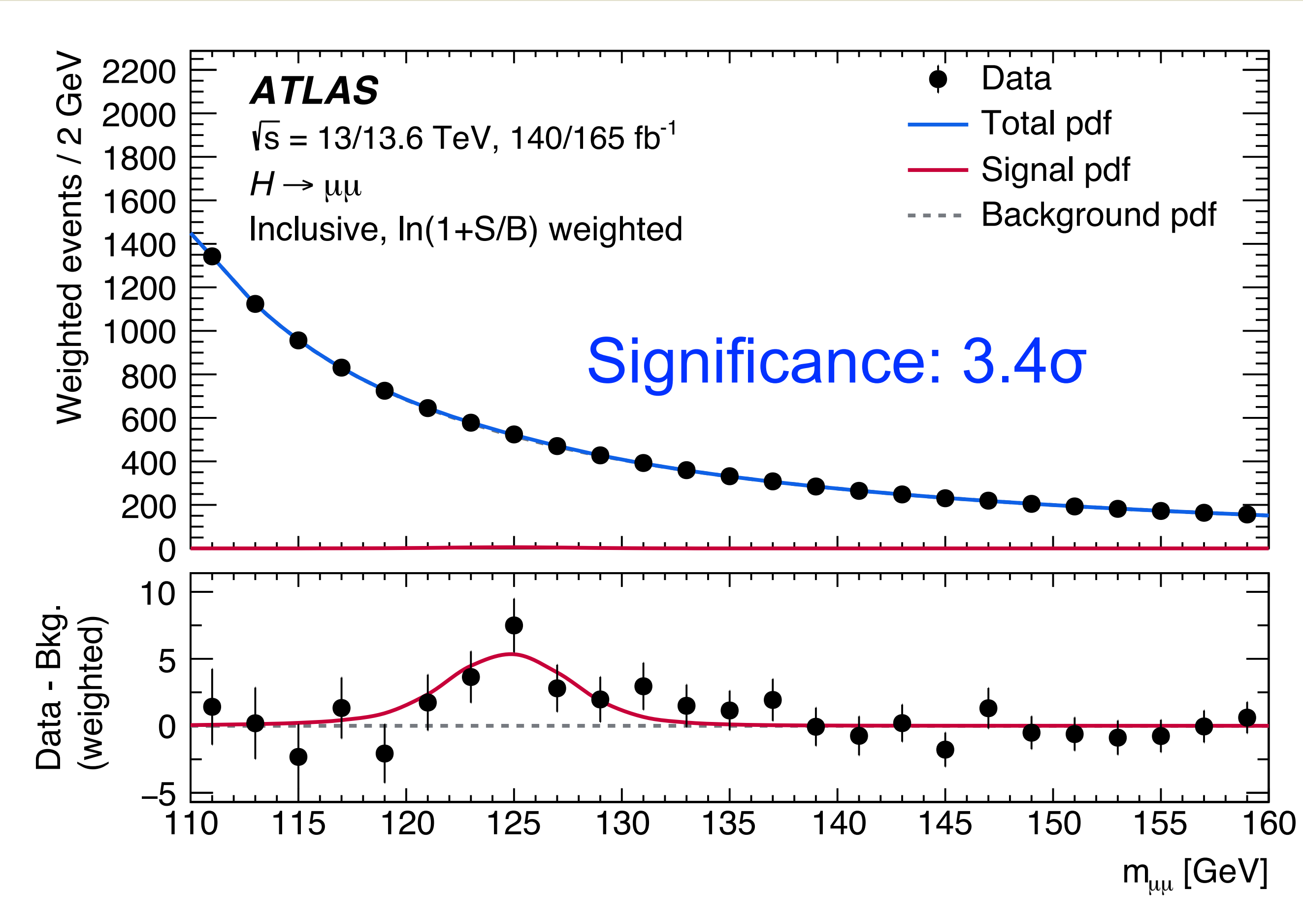
[fix] x [floating]

- Fixed part (physics motivated): LO 2→2 Drell-Yan analytic lineshape
  m(μμ) resolution effect included by smearing with Gaussian
- Floating part: empirical functions

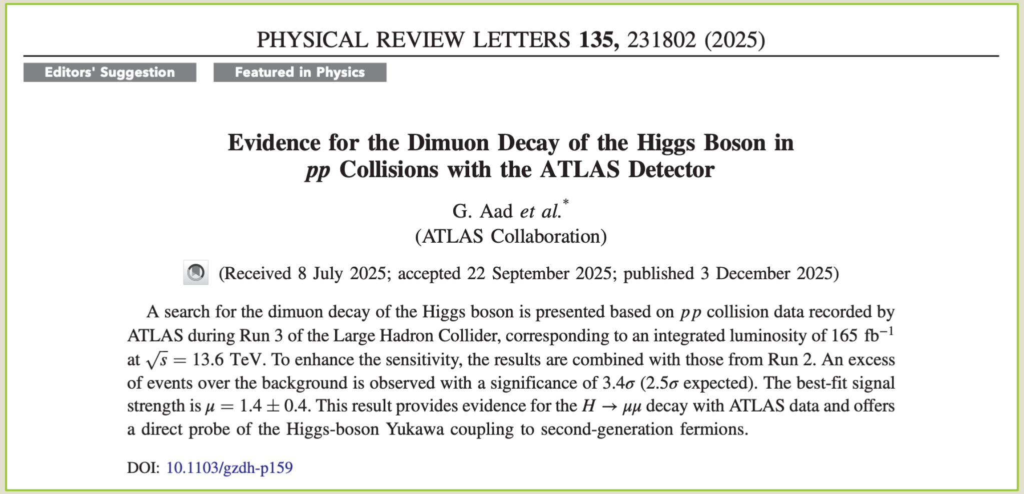


Simultaneous fit with 23 categories to extract signal strength

Evidence of Higgs to dimuon decay from ATLAS



arXiv:2507.03595 Phys. Rev. Lett. **135**, 231802 (2025)


PHYSICAL REVIEW LETTERS **135**, 231802 (2025)

Editors' Suggestion Featured in Physics

Evidence for the Dimuon Decay of the Higgs Boson in *pp* Collisions with the ATLAS Detector

G. Aad *et al.**
(ATLAS Collaboration)

(Received 8 July 2025; accepted 22 September 2025; published 3 December 2025)

A search for the dimuon decay of the Higgs boson is presented based on pp collision data recorded by ATLAS during Run 3 of the Large Hadron Collider, corresponding to an integrated luminosity of 165 fb^{-1} at $\sqrt{s} = 13.6$ TeV. To enhance the sensitivity, the results are combined with those from Run 2. An excess of events over the background is observed with a significance of 3.4σ (2.5σ expected). The best-fit signal strength is $\mu = 1.4 \pm 0.4$. This result provides evidence for the $H \to \mu\mu$ decay with ATLAS data and offers a direct probe of the Higgs-boson Yukawa coupling to second-generation fermions.

DOI: 10.1103/gzdh-p159

- Paper accepted by PRL as Editor’s Suggestion
- Inclusion in the American Physical Society‘s outreach to the press, link

13 Years of $H \to \mu\mu$

```
/*
 * @author Haifeng Li <Haifeng.Li@cern.ch>
 * @date   Sep 03, 2012
 * @usage  Fitting macro for H -> mu mu background.
 */

// ROOT
#include "TTree.h"
#include "TH1D.h"
#include "TRandom.h"
#include "TCanvas.h"
#include "TFile.h"
#include "TText.h"

// RooFit
#ifndef __CINT__
#include "RooGlobalFunc.h"
#endif
#include "RooRealVar.h"
#include "RooDataSet.h"
#include "RooDataHist.h"
#include "RooGaussian.h"
#include "RooPlot.h"
#include "RooGenericPdf.h"
#include "RooMinuit.h"
//Local
#include "util/plotFit.h"


using namespace RooFit ;
```

```
// model
RooWorkspace* w = new RooWorkspace("w","w");
w->import(mll);

// Working version for [105, 160]
//w->factory("EXPR::bkgPDF('exp( a2*pow((mll-97), 0.2) )', mll, a2[-1

//
//w->factory("EXPR::bkgPDF('(a1*mll + a2*(2*mll*mll -1 ) + a3*(4*mll*

//
//w->factory("EXPR::bkgPDF('exp( a1*pow((mll-100), 0.2) + (a2)*(2*pow


// H->gamma gamma
//w->factory("EXPR::bkgPDF('exp( a1*(mll-100)/100.+a2*(mll-100)*(mll-

// Good  : Chebychev Polynomials
//w->factory("EXPR::bkgPDF('exp( a1*(mll-100)/100.+a2*(2*pow((mll-100
0.02,-100.,-5E-5] , a4[-0.25,-50.,50.])" );



//
//w->factory("EXPR::bkgPDF('exp( a1*(mll-100)/100.+a2*(2*pow((mll-100


//w->factory("RooPolynomial::poly_bg(mll, {poly_c1[-7.44E-3, -1., 1],
//w->factory("Chebychev::poly_bg(mll, {poly_c1[-7.44E-3, -1., 1], pol
//w->factory("Chebychev::poly_bg(mll, {poly_c1[-7.44E-3, -2., 2], pol



//w->factory("RooPolynomial::poly_bg(mll, {poly_c1[1, 0., 10], poly_c
//w->factory("EXPR::exp_bg('exp( a2*pow((mll-97), a3) )', mll, a2[-1,
//w->factory("PROD::bkgPDF( exp_bg ,  poly_bg)");



//w->factory("Chebychev::poly_bg(mll, {poly_c1[-7.44E-3, -1., 1], pol
//w->factory("RooExponential::exp_bg( mll, a2_bg[-0.1,-0.5,-0.001])"
//w->factory("SUM::bkgPDF(  frac_bg[0.6, 0.01, 0.9]*exp_bg ,  poly_bg


// Working version
w->factory("Chebychev::poly_bg(mll, {poly_c1[-0.7969, -1., 1], poly_c
w->factory("RooExponential::exp_bg( mll, a2_bg[-0.1584,-0.5,-0.001])"
w->factory("SUM::bkgPDF(  frac_bg[0.382, 0.01, 0.9]*exp_bg ,  poly_bg
```

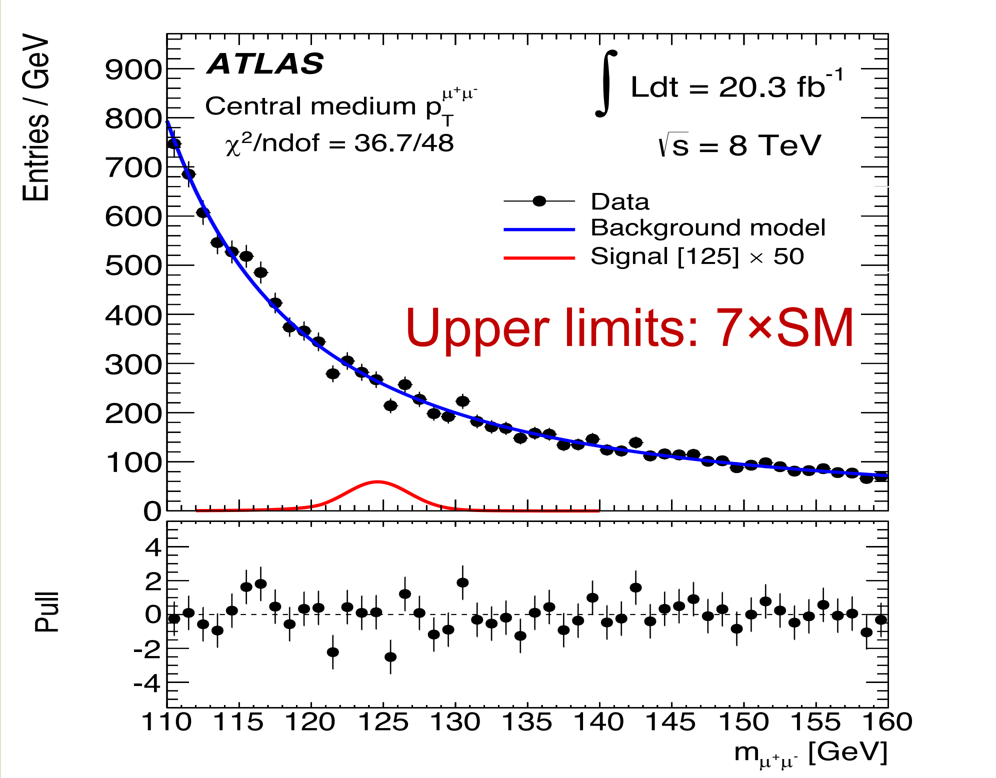
- 第一篇文章（2012年开始，2014年PLB）：李海峰，从零构建分析的所有部分，本底拟合函数，分析程序，统计程序等
- 第二篇文章（2017年PRL）：李海峰（分析负责人，文章编辑）
- 第三篇文章（2020年PLB）：李海峰（分析早期负责人）。分析团队变大
- 第四篇文章（2025年PRL）：VBF优化以及统计分析

A thirteen-year query for the Higgs coupling to second generation fermion

13 Years of $H \to \mu\mu$

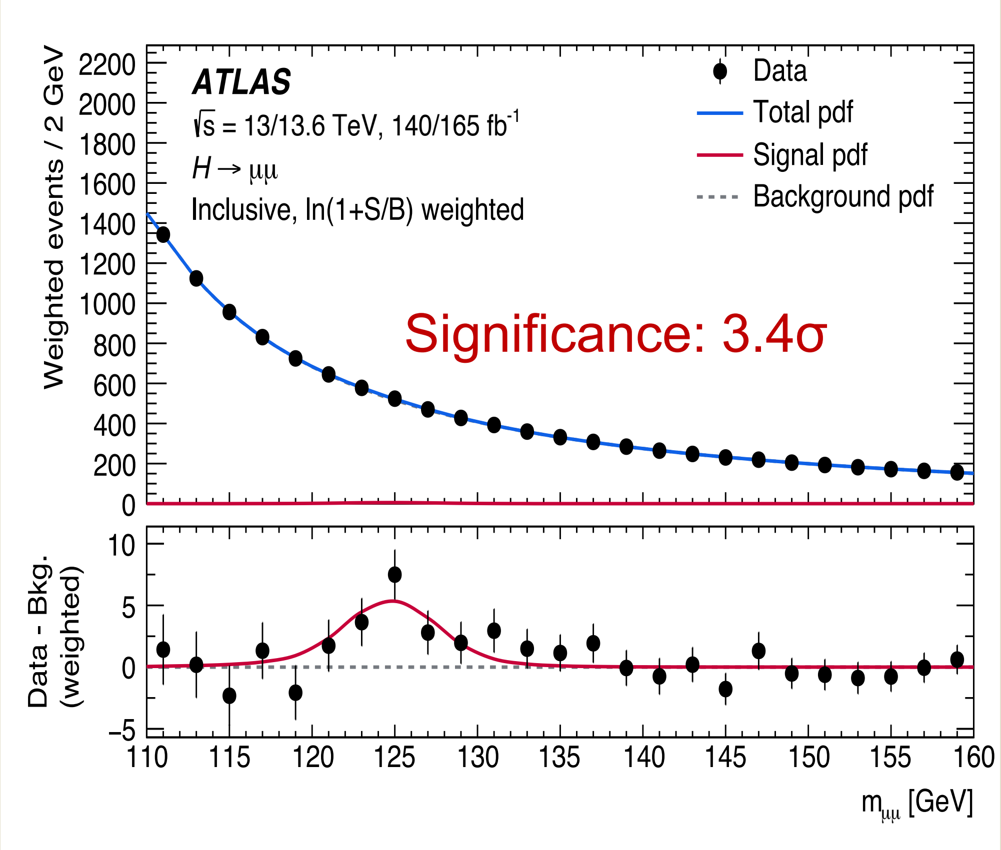
2014 ggF+VBF cutbased	→	2017 ggF+VBF (BDT)	→	2020 add VH and ttH	→	2025 more categories

First paper in 2014



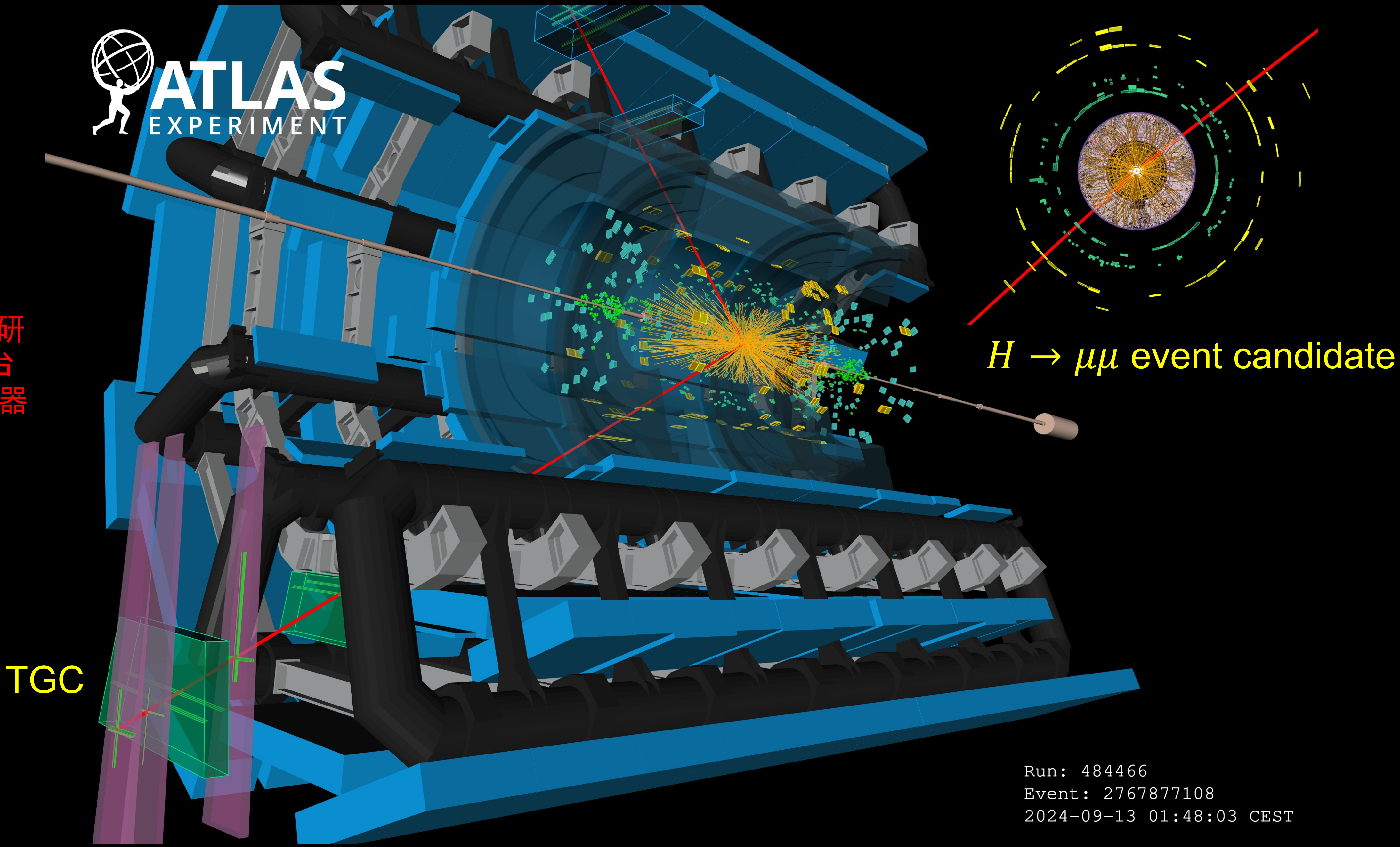
[Phys. Lett. B 738 (2014) 68-86]

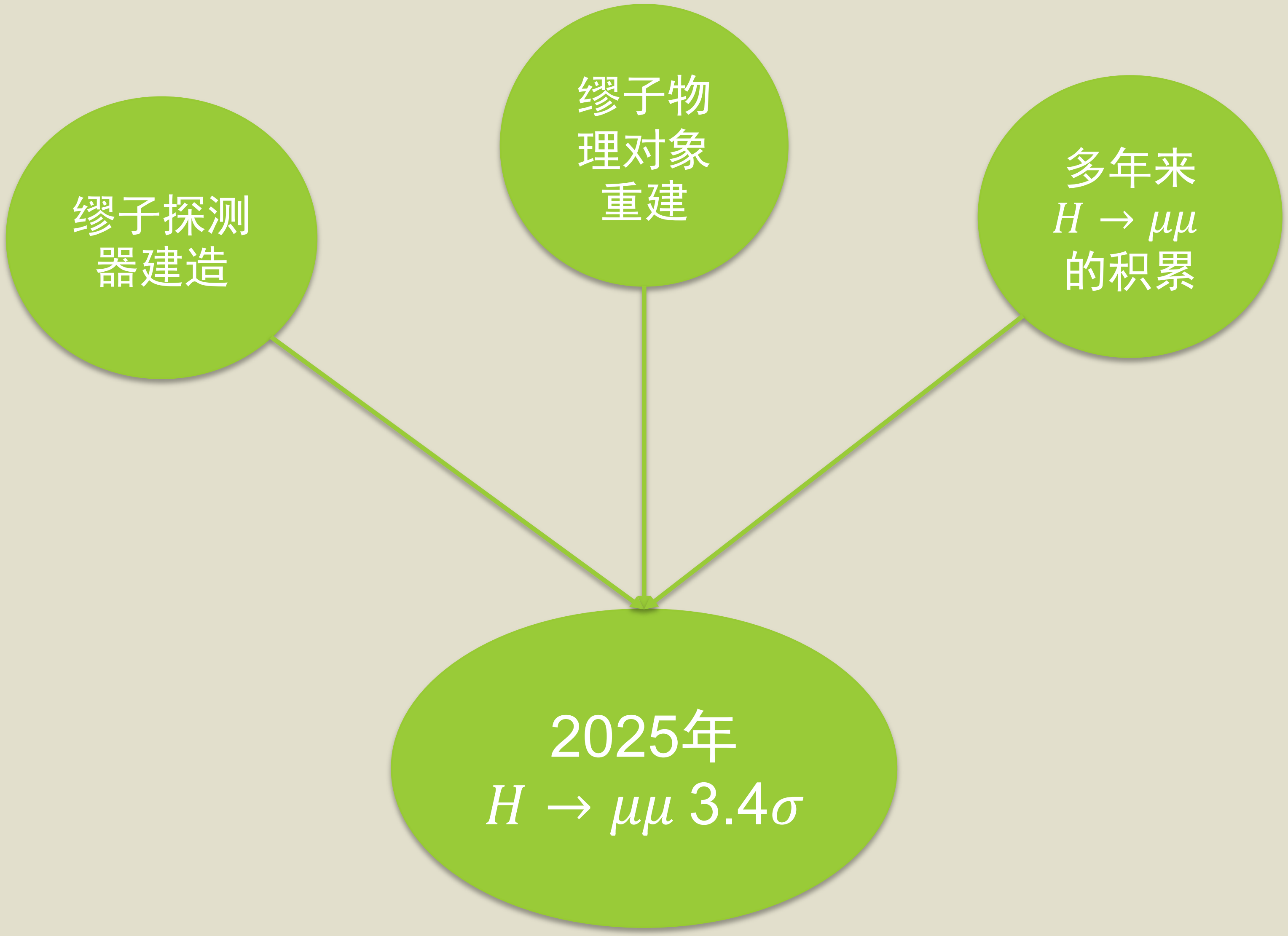
Fourth paper in 2025



[Phys. Rev. Lett. **135**, 231802 (2025)]

山大负责研
制了400台
TGC探测器




缪子探测
器建造
缪子物
理对象
重建
多年来
$H \to \mu\mu$
的积累
2025年
$H \to \mu\mu$ 3.4σ

学术评价

美国物理学会旗下《物理》杂志以“Deciphering the Origin of Quark and Lepton Mass”为题作为研究亮点专门报道。

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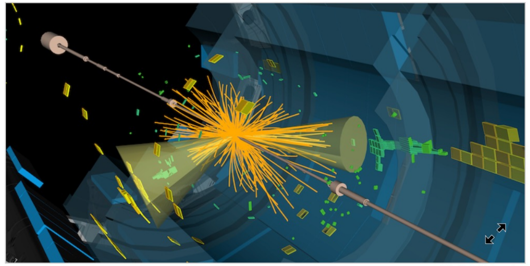
VIEWPOINT

Deciphering the Origin of Quark and Lepton Mass

Chris Quigg
Fermi National Accelerator Laboratory, Batavia, IL, US

December 3, 2025 • *Physics* 18, 190

Measurements of the decay of the Higgs boson into muon–antimuon pairs provide evidence for the mechanism by which quarks and leptons acquire their mass.



ATLAS Collaboration

Figure 1: Display of a proton–proton collision event recorded at the ATLAS detector in 2022. ATLAS has now characterized the decay of Higgs bosons into muon–antimuon pairs, confirming previous measurements by the CMS Collaboration.

《物理评论快报》主编Robert Garisto： “温伯格是正确的”

Robert Garisto · 2nd
Chief Editor for PRL at American Physical Society
18h ·

Connect

The ATLAS experiment at CERN has found evidence (3.4σ) of Higgs bosons decaying into pairs of muons. This agrees with the Standard Model mechanism for mass generation for leptons (such as muons) laid out in 1967 in a famous PRL by Steven Weinberg, "A model of leptons", which used the symmetry breaking mechanism laid out by Higgs and by Englert and Brout in PRL in 1964. The figure shows that the observed signal strength 1.4±0.4 is above the null value of 0, and consistent with the SM value of 1.

A glib way of putting it is, "Weinberg was right."

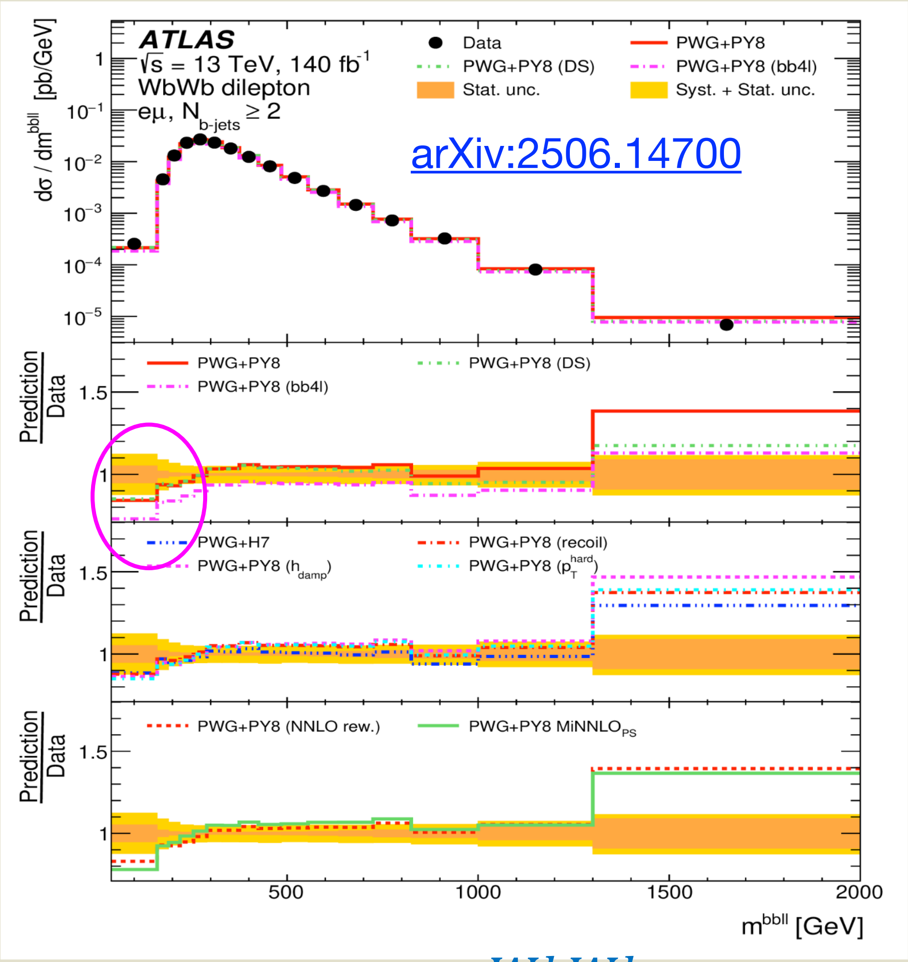
Gavin Salam（英国牛津大学教授）

- H→μμ将首次证明第二代费米子的质量来自于汤川耦合
- 它值得与世界媒体一起举办一场盛大的活动来宣布它

Toponium

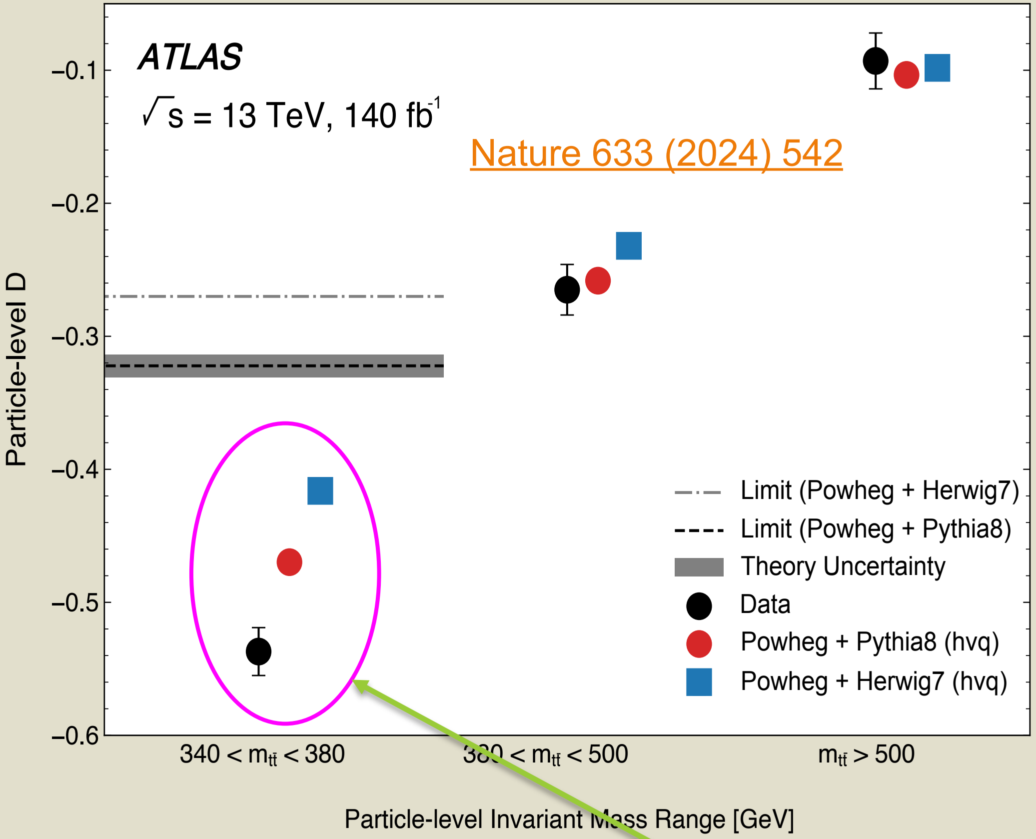
Threshold Region Measurement is Challenging

Previous hints



$pp \rightarrow WbWb$

Quantum Entanglement (QE) measurement using $t\bar{t}$



Stronger QE in data than MC.
Missing toponium contributions?

教科书上说不可能

1.10 Intermediate Vector Bosons (1983) | 47

carries no *net* charm, for if the c is assigned a charm of $+1$, then $\bar{c}$ will have a charm of -1; the charm of the ψ is, if you will, 'hidden'. To confirm the charm hypothesis, it was important to produce a particle with 'naked' (or 'bare') charm [39]. The first evidence for charmed baryons ($\Lambda_c^+ = udc$ and $\Sigma_c^{++} = uuc$) appeared already in 1975 (Figure 1.13) [40], followed later by $\Xi_c = usc$ and $\Omega_c = ssc$. (In 2002 there were hints of the first *doubly* charmed baryon at Fermilab.) The first charmed mesons ($D^0 = c\bar{u}$ and $D^+ = c\bar{d}$) were discovered in 1976 [41], followed by the charmed strange meson ($D_s^+ = c\bar{s}$) in 1977 [42]. With these discoveries, the interpretation of the ψ as $c\bar{c}$ was established beyond reasonable doubt. More important, the quark model itself was put back on its feet.

However, the story does not end there, for in 1975 a new *lepton* was discovered [43], spoiling Glashow's symmetry. This new particle (the tau) has its own neutrino, so we are up to six leptons, and only four quarks. But don't despair, because 2 years later a new heavy meson (the *upsilon*) was discovered [44], and quickly recognized as the carrier of a fifth quark, b (for *beauty*, or *bottom*, depending on your taste): $\Upsilon = b\bar{b}$. Immediately the search began for hadrons exhibiting 'naked beauty', or 'bare bottom.' (I'm sorry. *I* didn't invent this terminology. In a way, its silliness is a reminder of how wary people were of taking the quark model seriously, in the early days.) The first bottom baryon, $\Lambda_b^0 = udb$, was observed in the 1980's, and the second ($\Sigma_b^+ = uub$) in 2006; in 2007 the first baryon with a quark from all three generations was discovered ($\Xi_b^- = dsb$). The first bottom mesons ($\bar{B}^0 = b\bar{d}$ and $B^- = b\bar{u}$) were found in 1983 [45]. The $B^0/\bar{B}^0$ system has proven to be especially rich, and so-called 'B factories' are now operating at SLAC ('BaBar') and KEK ('Belle'). The *Particle Physics Booklet* also lists $B_s^0 = s\bar{b}$ and $B_c^+ = c\bar{b}$.

At this point, it didn't take a genius to predict that a sixth quark (t, for *truth*, of course, or *top*) would soon be found, restoring Glashow's symmetry with six quarks and six leptons. But the top quark turned out to be extraordinarily heavy and frustratingly elusive (at 174 GeV/c^2, it is over 40 times the weight of the bottom quark). Early searches for 'toponium' (a $t\bar{t}$ meson analogous to the ψ and Υ) were unsuccessful, both because the electron–positron colliders did not reach high enough energy and because, as we now realize, the top quark is simply too short-lived to form bound states – apparently there *are* no top baryons and mesons. The top quark's existence was not definitively established until 1995, when the Tevatron finally accumulated enough data to sustain strong indications from the previous year [46]. (The basic reaction is $u + \bar{u}$ (or $d + \bar{d}$) $\to t + \bar{t}$; the top and anti-top immediately decay, and it is by analyzing the decay products that one is able to infer their fleeting appearance.) Until the LHC begins operation, Fermilab will be the only accelerator in the world capable of producing top quarks.

"as we now realize, the top quark is simply too short-lived to form bound states - apparently there are no top baryons and mesons." -- Section 1.9, David Griffiths, Introduction to Elementary Particle Physics, Second Edition

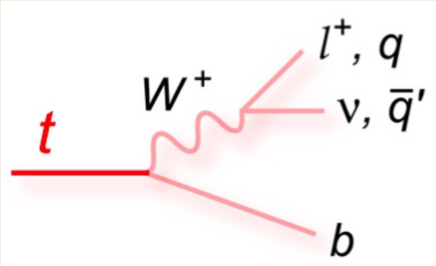
"The top quark is too short-lived to form observable hadron states and its mass is again inferred indirectly, from observations on the decay products of $t\bar{t}$ pairs, as we shall see." -- Section 3.1, B.R. Martin and G. Shaw, Particle Physics, Fourth Edition

做实验不能完全按照大多数人的看法来进行

LHC is a top quark factory

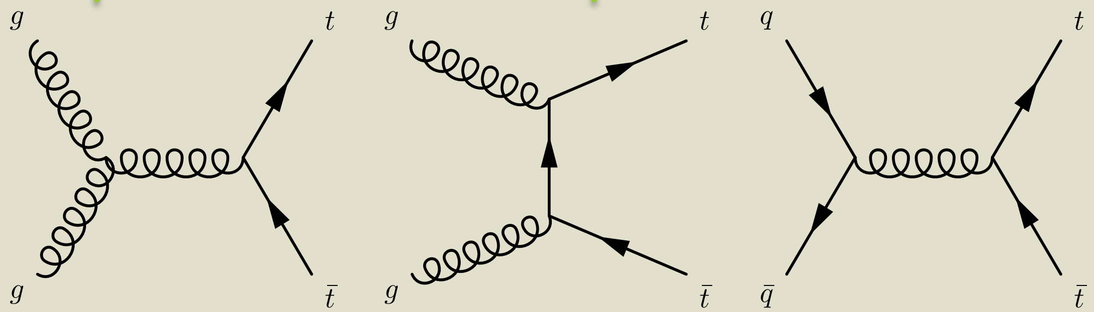
$$m_t \approx 172.5\ \mathrm{GeV}$$
$$\Gamma_t = 1.326\ \mathrm{GeV}$$
$$\tau_t = 1/\Gamma_t = 5.17 \times 10^{-25}\mathrm{s}$$

- LHC is a $t\bar{t}$ factory
  - $\sigma_{t\bar{t}} = 834$ pb at LHC Run 2
  - 0.83M $t\bar{t}$ events per fb^{-1}
  - LHC大约每天获取1fb^{-1}的数据
- Decay (EW) almost 100% with



Dominant

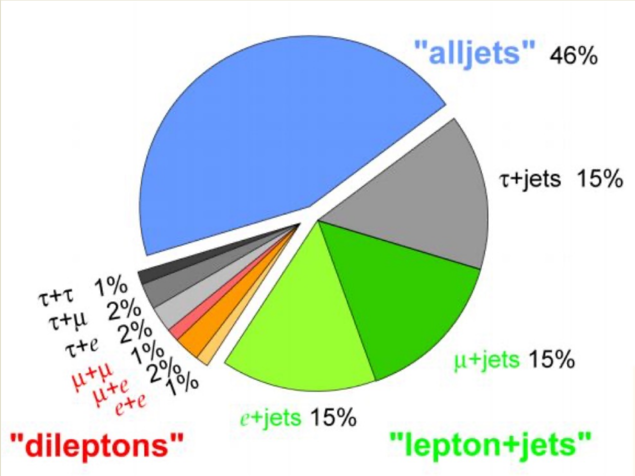
$t\bar{t}$ production (QCD)



~90%

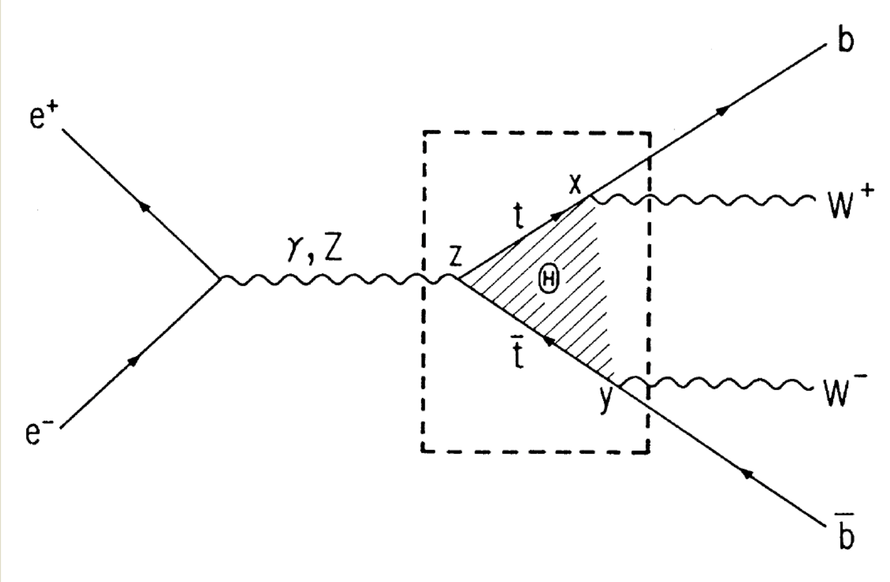
~10%

$t\bar{t}$ decay



Top quark and $t\bar{t}$ Threshold Region

- Toponium: QCD predicts a quasi-bound state close to the threshold for low momentum top quarks
- The prediction was made even before the top quark discovery



Phys. Rev. D 47 (1993) 56

部分理论文章：

- V.S. Fadin and V.A. Khoze, JETP Lett. 46 (1987) 525
- Y. Sumino *et al.*, Phys. Rev. D 47 (1993) 56
- W.-L. Ju *et al.*, JHEP 06 (2020) 158 （浙大杨李林等）

近期文章：

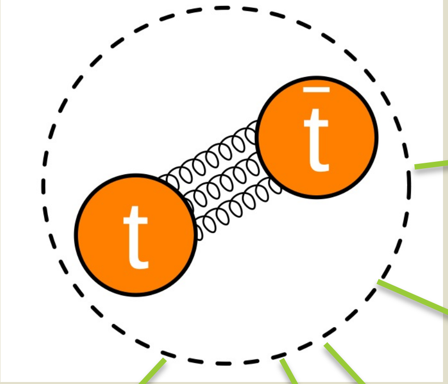
- Fu, Li, Yang, Li, Zhang, Shen, arXiv:2412.11254, Phys. Rev. D 111, 114020 (2025) （北航张玉洁、复旦沈成平等）
- Luo, Huang, Liu, arXiv:2508.17646 （兰大刘翔等）

Toponium from NRQCD

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)\psi = E\psi$$

$$V(r) = -C_F\frac{\alpha_S}{r} + F_0 r$$

C_F: Color factor;
r: Bohr radius;
F_0: Constant



For small distances: $V(r) \approx -C_F\frac{\alpha_S}{r}$,
$C_F = \frac{4}{3}$ for color singlet; $\alpha_S = \alpha_S(1/r)$

Binding energy of toponium:
$$E_0 = -\frac{1}{2}\frac{m_t}{2}(C_F\alpha_S)^2 \approx -2\ \text{GeV}$$

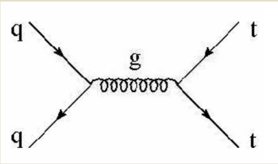
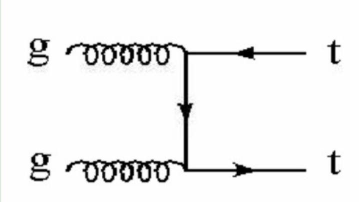
Width of topinium: $2\Gamma_t = 2.56$ GeV.
Lifetime of toponium: $\tau \approx 2.59\times 10^{-25}$s

Mass of toponium:
$$m_{\eta_t} = 2m_t - E_0 \approx 345 - 2\ \text{GeV} = 343\ \text{GeV}$$

Bohr radius of toponium: $r = \frac{2}{C_F\alpha_S m_t} \approx 0.01$fm

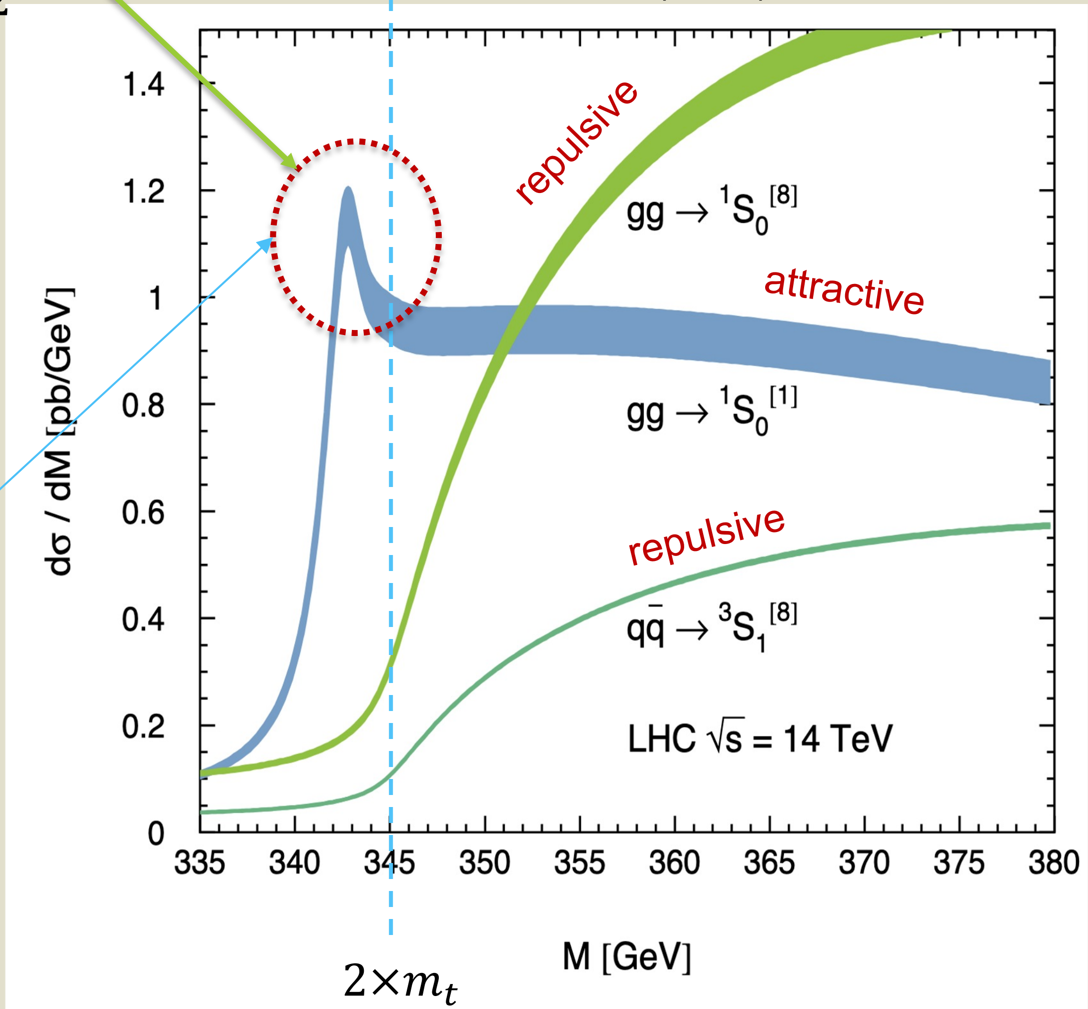
The Bohr radii of the ground states of charmonium and bottomonium are about 0.3 fm and 0.2 fm

NRQCD Predictions

	$^{3}S_{1}^{[8]}$	100% OCTET
	$^{1}S_{0}^{[1]}$	10% SINGLET
	$^{1}S_{0}^{[8]}$	90% OCTET

$$\frac{(\uparrow\downarrow - \downarrow\uparrow)}{\sqrt{2}}$$

EPJC 60 (2009) 375-386

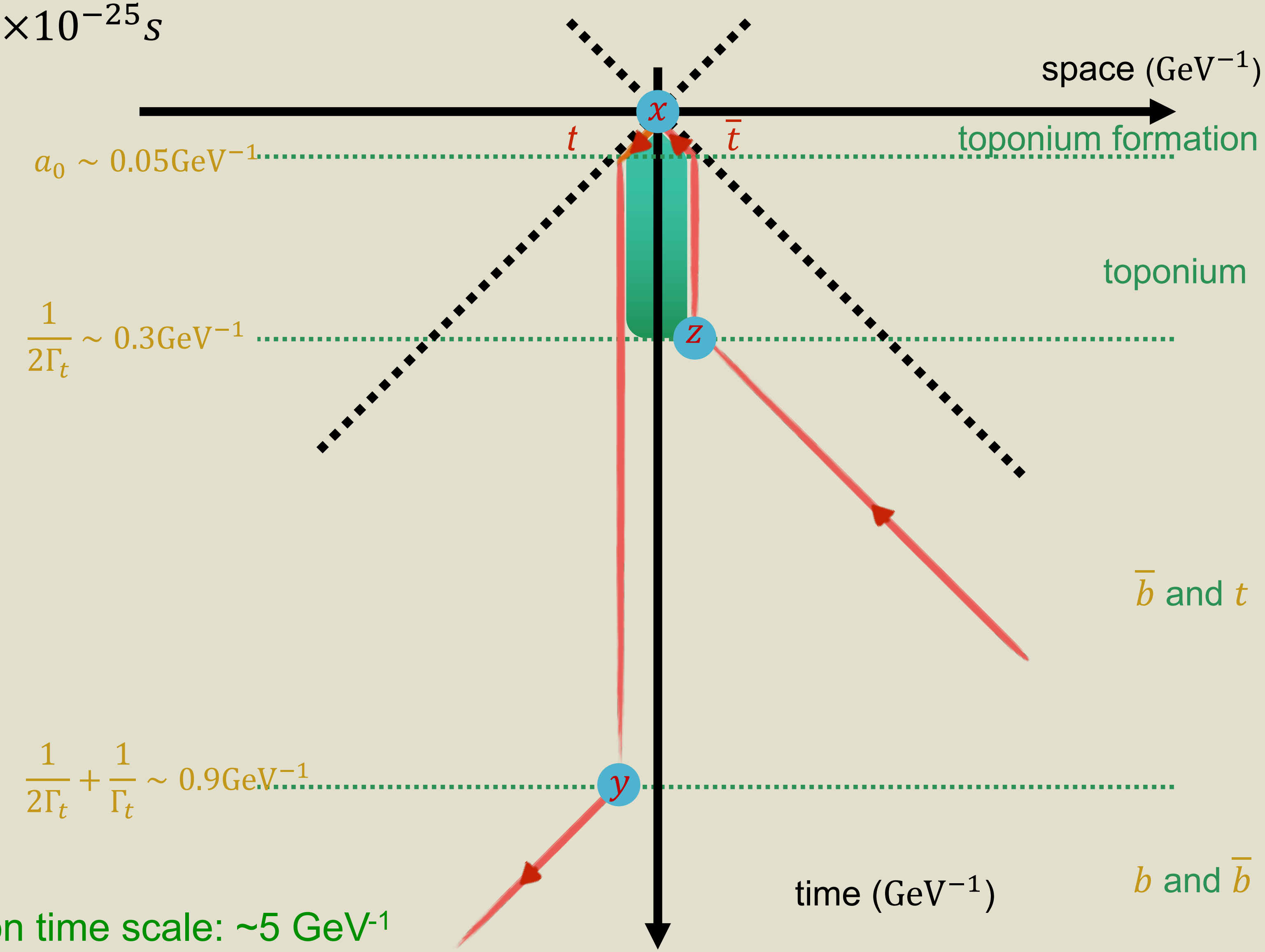


Color-singlet - attractive
CP-odd / pseudoscalar spin state!

Toponium Decays

$1\ \text{GeV}^{-1} = 6.852\times10^{-25}s$

From B. Fuks



Hadronization time scale: ~5 GeV^{-1}

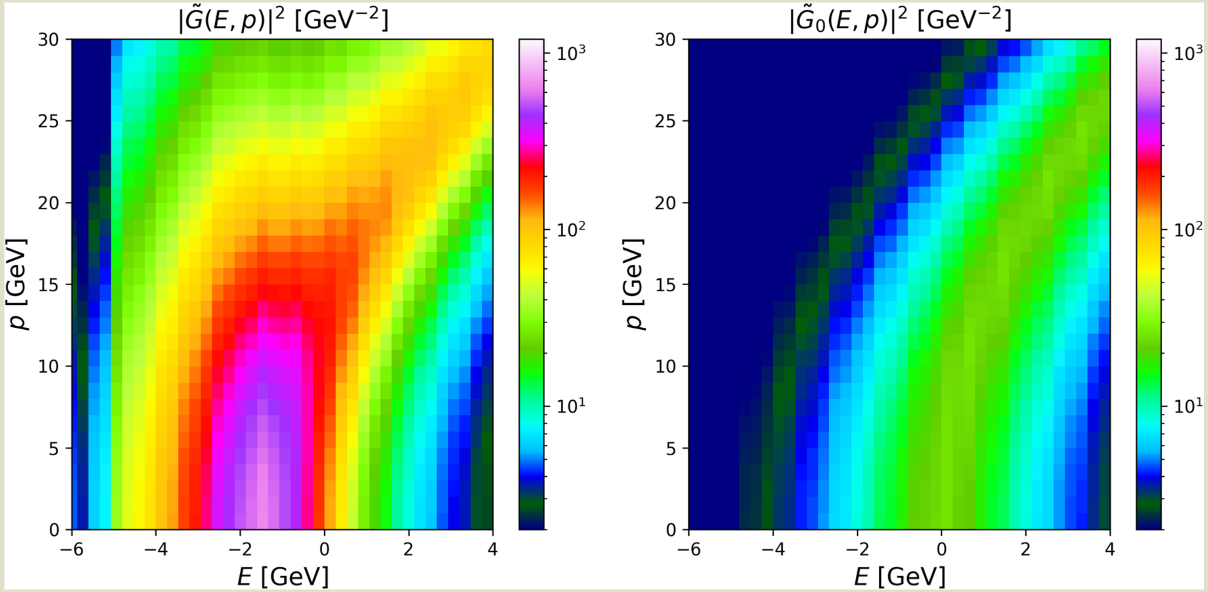
Quasi-bound State from NRQCD

- *S*-wave, color-singlet state with Green's function of non-relativistic (NR) QCD by Eur. Phys. J. C 85 (2025) 157（B. Fuks, K. Hagiwara, 马凯, 郑亚娟）
- Generate $gg \to tt \to b\ell\nu b\ell\nu$ with MG5_aMC. Spin correlations included
- Reweight matrix element with QCD Green's functions (solutions to the Lippmann-Schwinger equation)

$$|\mathcal{M}|^2 \quad \to \quad |\mathcal{M}|^2 \left| \frac{\widetilde{G}(E;\, p^*)}{\widetilde{G}_0(E;\, p^*)} \right|^2$$

$\tilde{G}$: Green's function considering QCD potential

$\tilde{G}_0$: Free Green's function



This model includes NRQCD calculations

Background Modelling

Extremely challenging measurement: need precise modelling of the $t\bar{t}$ threshold region

- $t\bar{t}$: main background. Powheg v2 hvq + Pythia8, using narrow-width approximation (NWA), with approximate spin correlation
  - 2D reweighting in (cosθ*, M($t\bar{t}$)) to NNLO QCD (from MATRIX) and NLO EW (HATHOR)
  - θ*: angle between the momentum of the top quark in the $t\bar{t}$ center-of-mass frame and the momentum of the $t\bar{t}$ system in the lab. frame
- $t\bar{t}$: alternative MC sample (for syst.), Powheg v2 bb4l + Pythia8
  - Simulate $pp \to b\ell\nu b\ell\nu$ including off-shell, non-resonant contributions, and exact spin correlations at NLO

Advanced MC generators and state-of-art high-order QCD/EW calculations play crucial rules in this search

Event Categorization

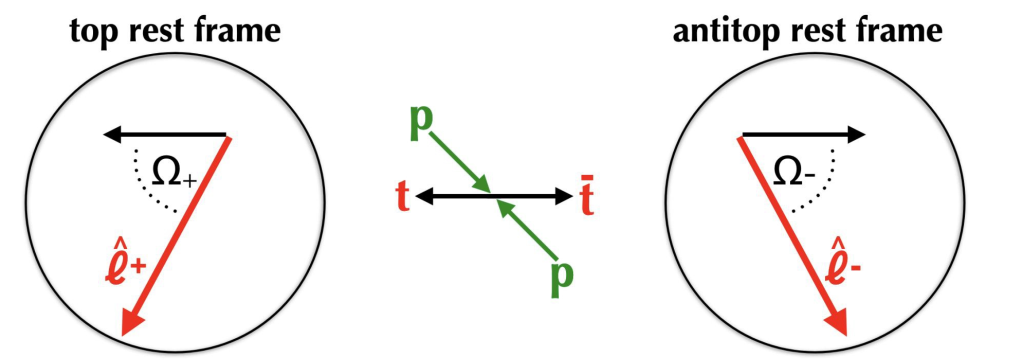
W. Bernreuther, D. Heisler, Z.-G. Si, JHEP 12, 026 (2015)

SR events are categorized into 9 regions based on two observables: c_{hel} and c_{han}

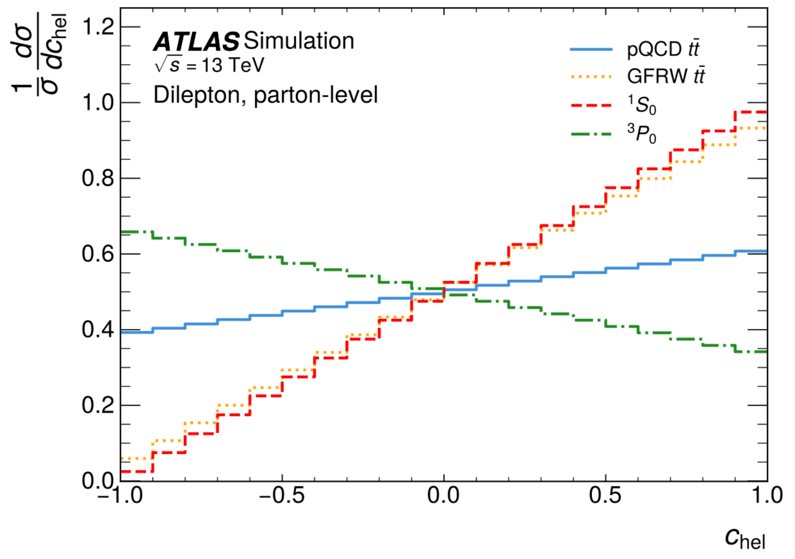
$$c_{hel} = \vec{\ell}_{+} \cdot \vec{\ell}_{-} ,$$

where the $\vec{\ell}_{\pm}$ are the lepton directions in $t\bar{t}$ center-of-mass frame, and then in turn boosted into t and $\bar{t}$ frames. This distribution has a maximum slope for a spin-singlet state

c_{han}: flip the $\vec{\ell}$ in t direction. This distribution has a maximum slope for a spin-triplet state



$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}^+ \cdot \hat{\ell}^+ + \mathbf{B}^- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot \mathbb{C} \cdot \hat{\ell}^-\right)$$



Event Categorization and Fitting

	$-1 < c_{hel} < -\frac{1}{3}$	$-\frac{1}{3} < c_{hel} < \frac{1}{3}$	$\frac{1}{3} < c_{hel} < 1$
$-1 < c_{han} < -\frac{1}{3}$	SR1	SR2	SR3
$-\frac{1}{3} < c_{han} < \frac{1}{3}$	SR4	SR5	SR6
$\frac{1}{3} < c_{han} < 1$	SR7	SR8	SR9

CR-Fakes ee	CR-Fakes $e\mu$	CR-Fakes $\mu\mu$	CR-Z

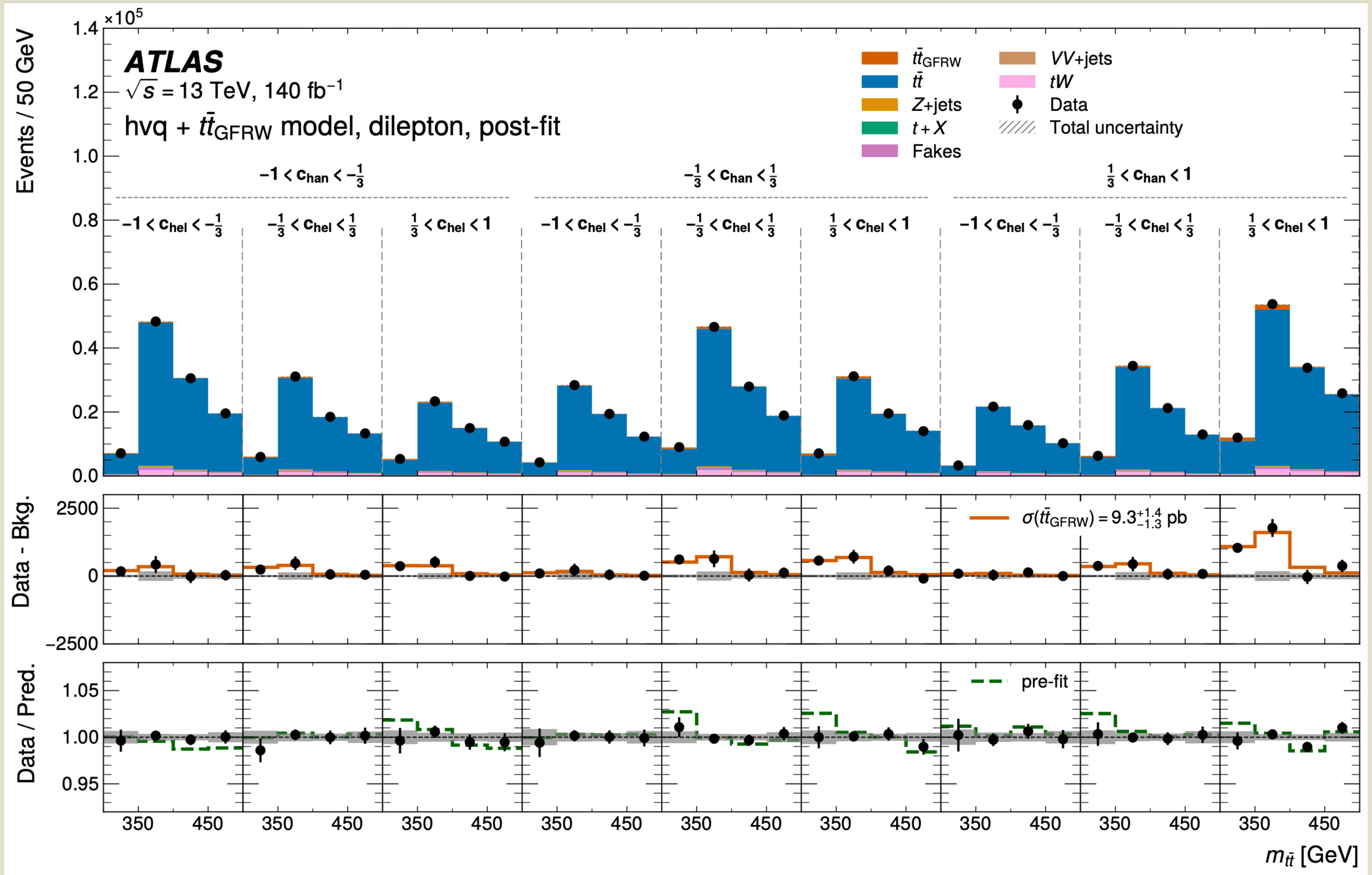
Simultaneous fitting to $m_{t\bar{t}}$ with 13 categories with profile likelihood method

Results: baseline $t\bar{t}$ + quasi-bound state (NRQCD)

Accepted by ROPP arXiv:2601.11780

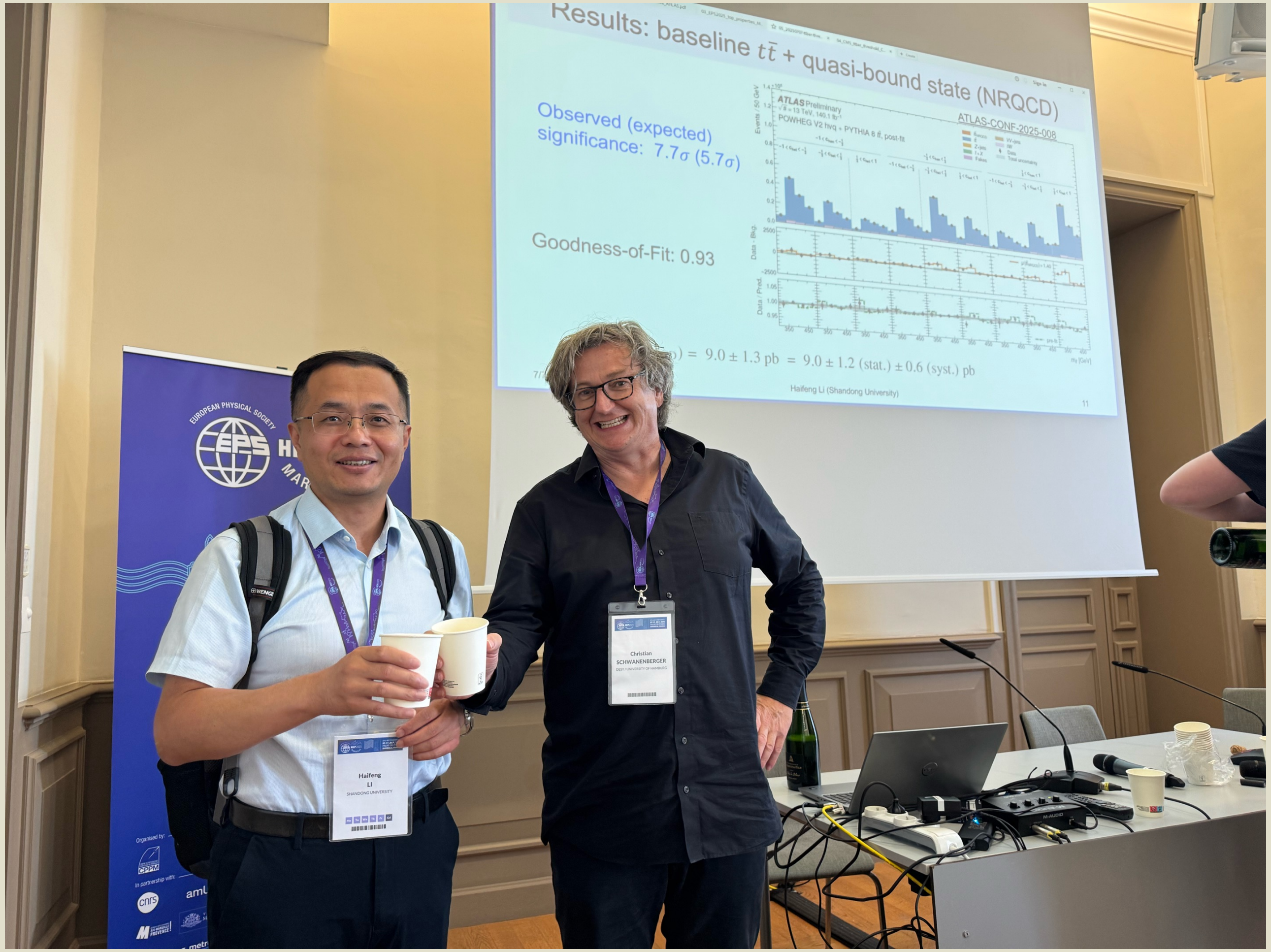
Observed (expected) significance: 8σ (6σ)

Link to my EPS-HEP 2025 talk
Link to my CLHCP2025 plenary talk



$$\sigma(t\bar{t}_{\mathrm{GFRW}}) = 9.3^{+1.4}_{-1.3}\ \mathrm{pb} = 9.3^{+1.1}_{-1.0}\ (\mathrm{stat.}) \pm 0.8\ (\mathrm{syst.})\ \mathrm{pb}$$

- First report about ATLAS results in EPS-HEP2025 in Marseille, France
- Celebration after toponium talks from ATLAS and CMS
- All the ATLAS&CMS management who attended EPS-HEP2025 listened the two talks
- Was one of the highlights for EPS-HEP2025



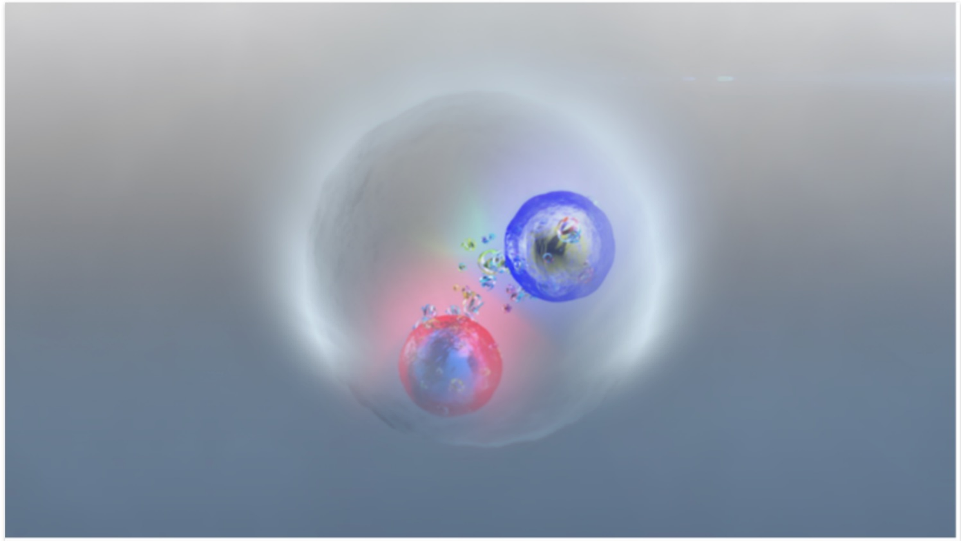
July 7th, 2025, Marseille, France

CERN Press Release after the ATLAS talk in EPS-HEP2025

Elusive romance of top-quark pairs observed at the LHC

The CMS and ATLAS experiments at CERN's Large Hadron Collider have observed an unforeseen feature in the behaviour of top quarks that suggests that these heaviest of all elementary particles form a fleeting union

8 JULY, 2025



Artist's impression of the short-lived union of a top quark and a top antiquark formed by the exchange of gluons. (Image: D. Dominguez/CERN)

An unforeseen feature in proton-proton collisions previously observed by the CMS experiment at CERN's Large Hadron Collider (LHC) has now been confirmed by its sister experiment ATLAS. The result, reported yesterday at the European Physical Society's High-Energy Physics conference in Marseille, suggests that top quarks – the heaviest and shortest-lived of all the elementary particles – can momentarily pair up with their antimatter counterparts to produce a "quasi-bound-state" called toponium. Further input based on complex theoretical calculations of the strong nuclear force -- called quantum chromodynamics (QCD) -- will enable physicists to understand the true nature of this elusive dance.

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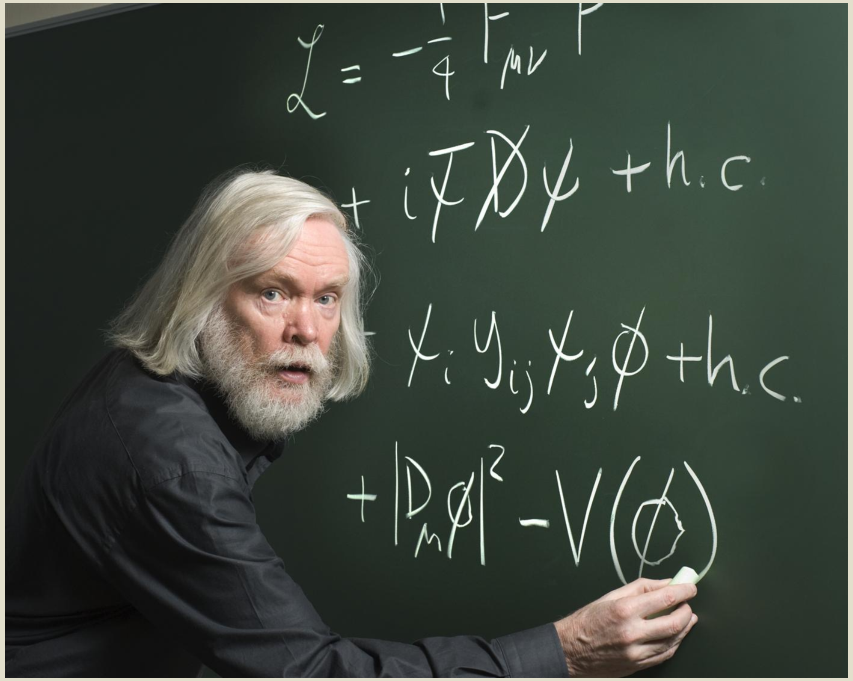
John Ellis



"Discovering toponium 50 years after the November Revolution would be an unanticipated and welcome golden anniversary present for its charmonium cousin that was discovered in 1974"

发现顶夸克偶素是对其姊妹粒子J/ψ发现50周年的意想不到的完美献礼

山大在顶夸克物理的长期耕耘

山大司宗国教授（world leading expert in $t\bar{t}$ spin correlation）

山大祝成光教授（ATLAS $t\bar{t}$ spin correlation measurements in 2014）

李海峰：Observation of toponium in ATLAS experiment in 2025

Conclusions

Higgs to dimuon from ATLAS

- Evidence to Higgs to dimuon decay. Observed (expected) significance is 3.4σ (2.5σ). Phys. Rev. Lett. **135**, 231802 (2025) PRL编辑推荐
- Important for probing Higgs boson coupling to the second-generation fermions

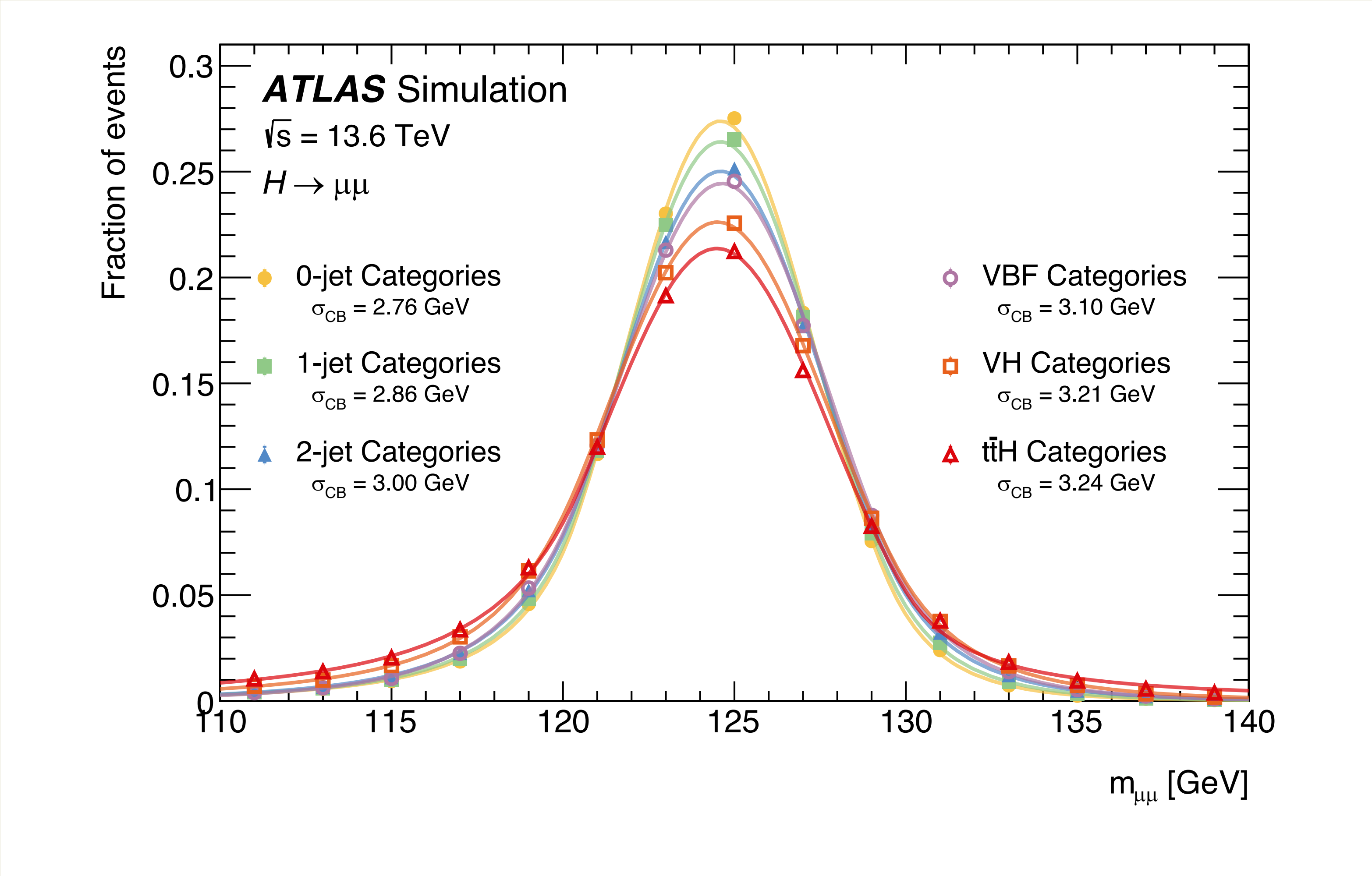
Toponium from ATLAS

- An excess of events is observed over the NNLO perturbative QCD prediction, with 8σ observed (6σ expected) near the $t\bar{t}$ production threshold by ATLAS with LHC Run 2 data. [arXiv:2601.11780, Accepted by Reports on Progress in Physics (IF 20.9)], [ATLAS Physics Briefing], [CERN Press Release]
- This excess is consistent with **color-singlet, S-wave, quasi-bound $t\bar{t}$ states** predicted by NRQCD with cross-section of 9.3 ± 1.3 pb
- CMS 2L results (Rep. Prog. Phys. 88 (2025) 087801) and also 1L CMS PAS TOP-25-002
- Observation of toponium opens a new field to study NRQCD with top quarks

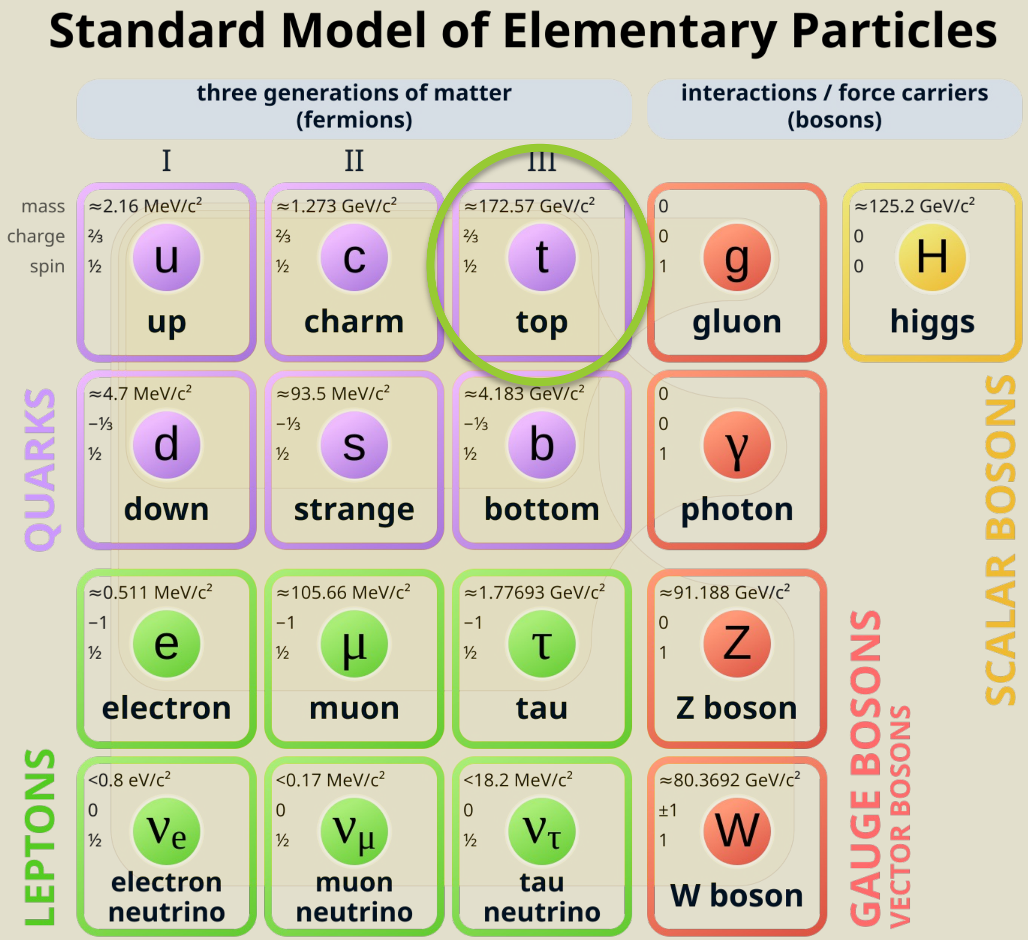
Backup

Signal Modeling

- Double-sided Crystal-Ball function



Top Quark



$$m_t \approx 172.5 \text{ GeV}$$

$$\Gamma_t = 1.326 \text{ GeV}$$

$$\tau_t = \frac{1}{\Gamma_t} = 5.17 \times 10^{-25} \text{s}$$

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{Production} \\ 10^{-27}\text{ s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{Decay} \\ 10^{-25}\text{ s}}} < \underbrace{\frac{1}{\Lambda_{\text{QCD}}}}_{\substack{\text{Hadronization} \\ 10^{-24}\text{ s}}} < \underbrace{\frac{m_t}{\Lambda_{\text{QCD}}}}_{\substack{\text{Spin flip} \\ 10^{-21}\text{ s}}}.$$

The toponium Green's function

From B. Fuks

$$K_{abcd}(x,y,z) = \left\langle 0 \middle| T\{t_c(y)\bar{t}_d(z) : \bar{t}_a(x)t_b(x) :\} \middle| 0 \right\rangle$$

$$= \frac{(1+\gamma^0)_{ca}}{2}\frac{(1-\gamma^0)_{bd}}{2}\int d^3r\left[K_1\big(y;(z^0,\vec{r})\big)\,K_2(z^0,\vec{r},\vec{z};x^0,\vec{x},\vec{x}) + K_1\big(z;(y^0,\vec{r})\big)\,K_2(y^0,\vec{y},\vec{r};x^0,\vec{x},\vec{x})\right]$$

Antitop-decay first

Top-decay first

Non-relativistic spin projection operators

1-particle-state and 2-particle-state propagators

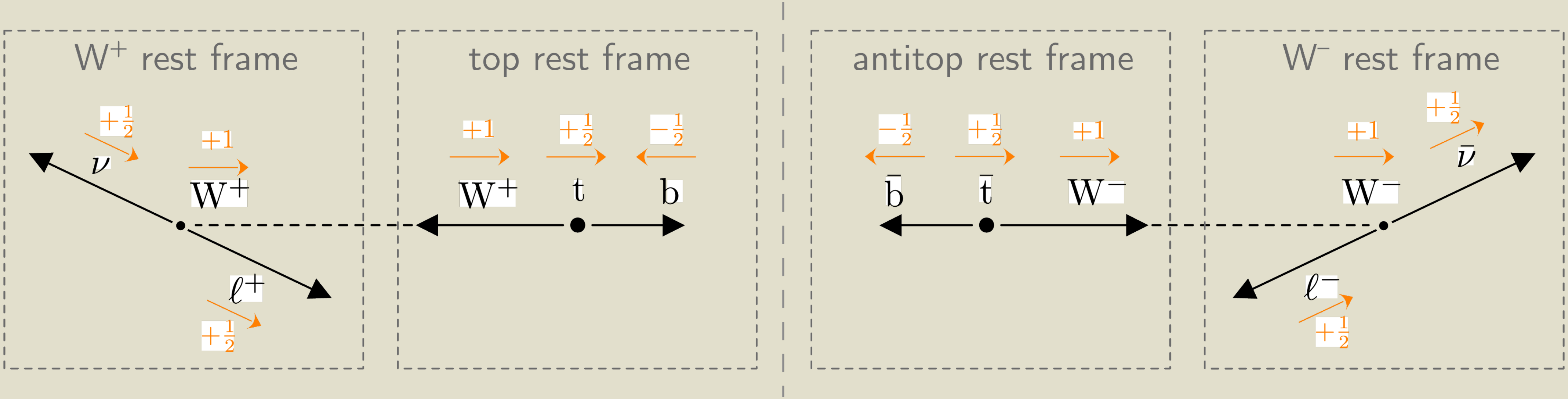
The toponium Green's function

- Solution to the Lippmann-Schwinger equation
  - Fourier transform of the QCD potential
  - S-wave contributions
- To be solved numerically

$$\widetilde{G}(E;p) = \widetilde{G}_0(E;p) + \int \frac{d^3q}{(2\pi)^3}\,\widetilde{V}_{\rm QCD}(\vec{p}-\vec{q})\,\widetilde{G}(E;q)$$

Free Green's function

$t\bar{t}$ Spin Correlation

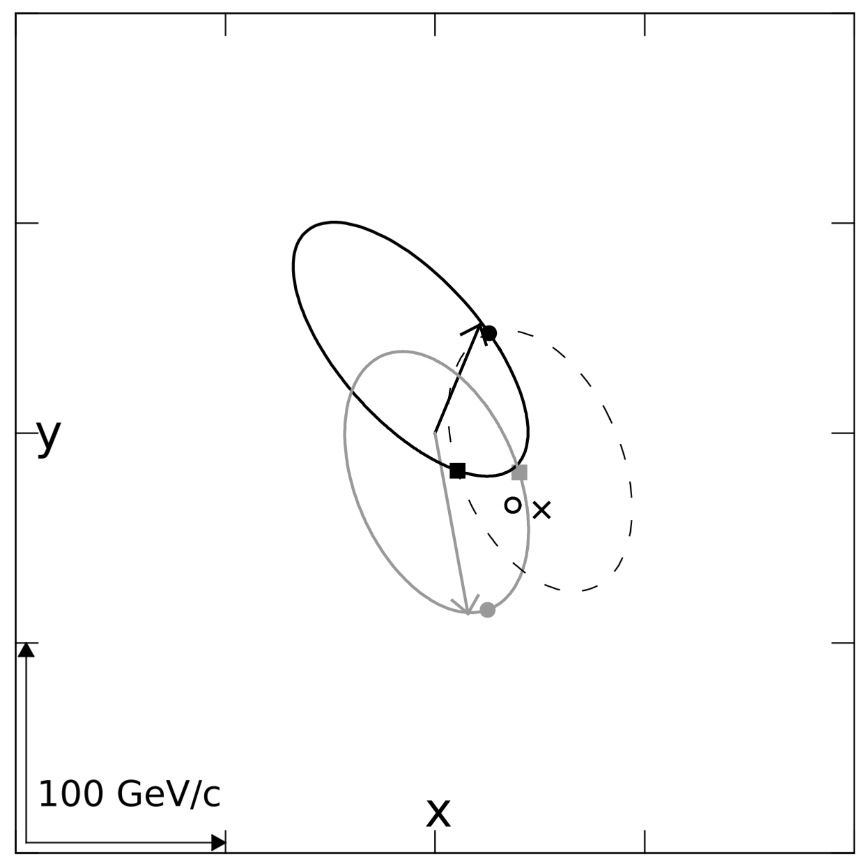


- Transfer of spin information to leptons due to parity violation of weak interaction + conservation of angular momentum
- Antilepton emitted preferably parallel to parent top quark spin
- Lepton emitted preferably antiparallel to parent antitop quark spin

Top quark pair reconstruction

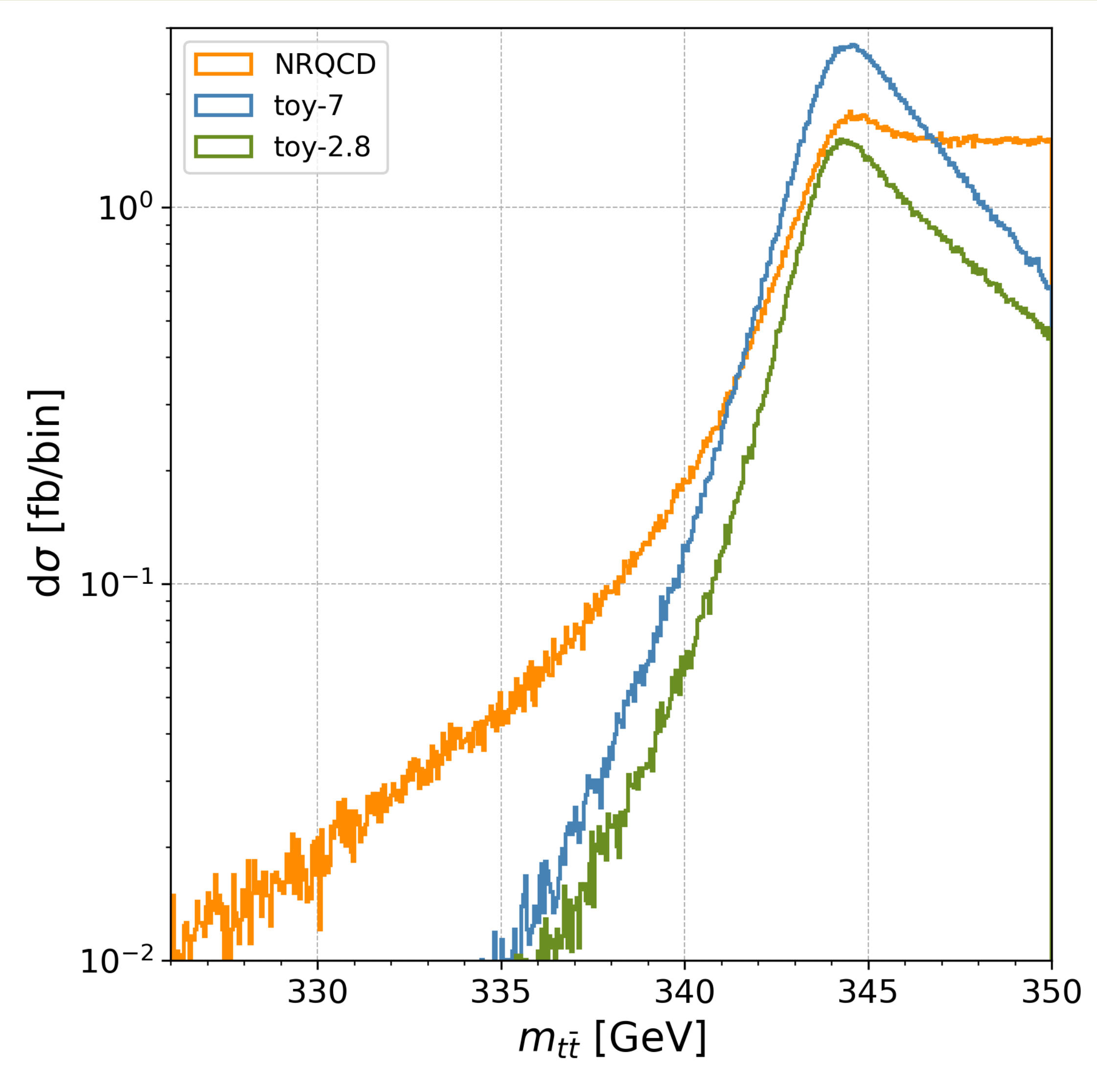
- $t\bar{t}$ system reconstructed from the 2 leading b-jets, charged leptons, and $\vec{\mathrm{p}}_{\mathrm{T}}^{\mathrm{miss}}$ using:
  1. Invariant mass of $\ell^{+}\nu_{\ell}\mathrm{b}$ and $\ell^{-}\bar{\nu}_{\ell}\bar{\mathrm{b}} = m_t = 172.5\ \mathrm{GeV}$
  2. Invariant mass of $\ell^{+}\nu_{\ell}$ and $\ell^{-}\bar{\nu}_{\ell} = m_{\mathrm{W}} = 80.4\ \mathrm{GeV}$
  3. $\vec{\mathrm{p}}_{\mathrm{T}}^{\mathrm{miss}}$ only from the two neutrinos: ν_{ℓ} and $\bar{\nu}_{\ell}$
- Ellipse method used to geometrically solve constraint equations for neutrino momenta
- m_t and m_{W} smeared if no solution found
- Solution found for 95% of events in SR – remaining discarded
- Resolution $\frac{|\mathrm{m}_{t\bar{t}}^{\mathrm{reco}} - \mathrm{m}_{t\bar{t}}^{\mathrm{true}}|}{\mathrm{m}_{t\bar{t}}^{\mathrm{reco}}} \sim 22\%$ at threshold
- Alternative methods tested did not improve sensitivity

NIM A 736 (2014) 169-178



Toponium：比较ATLAS和CMS的signal model

LHC Top WG meeting 4-6 June 2025, CERN

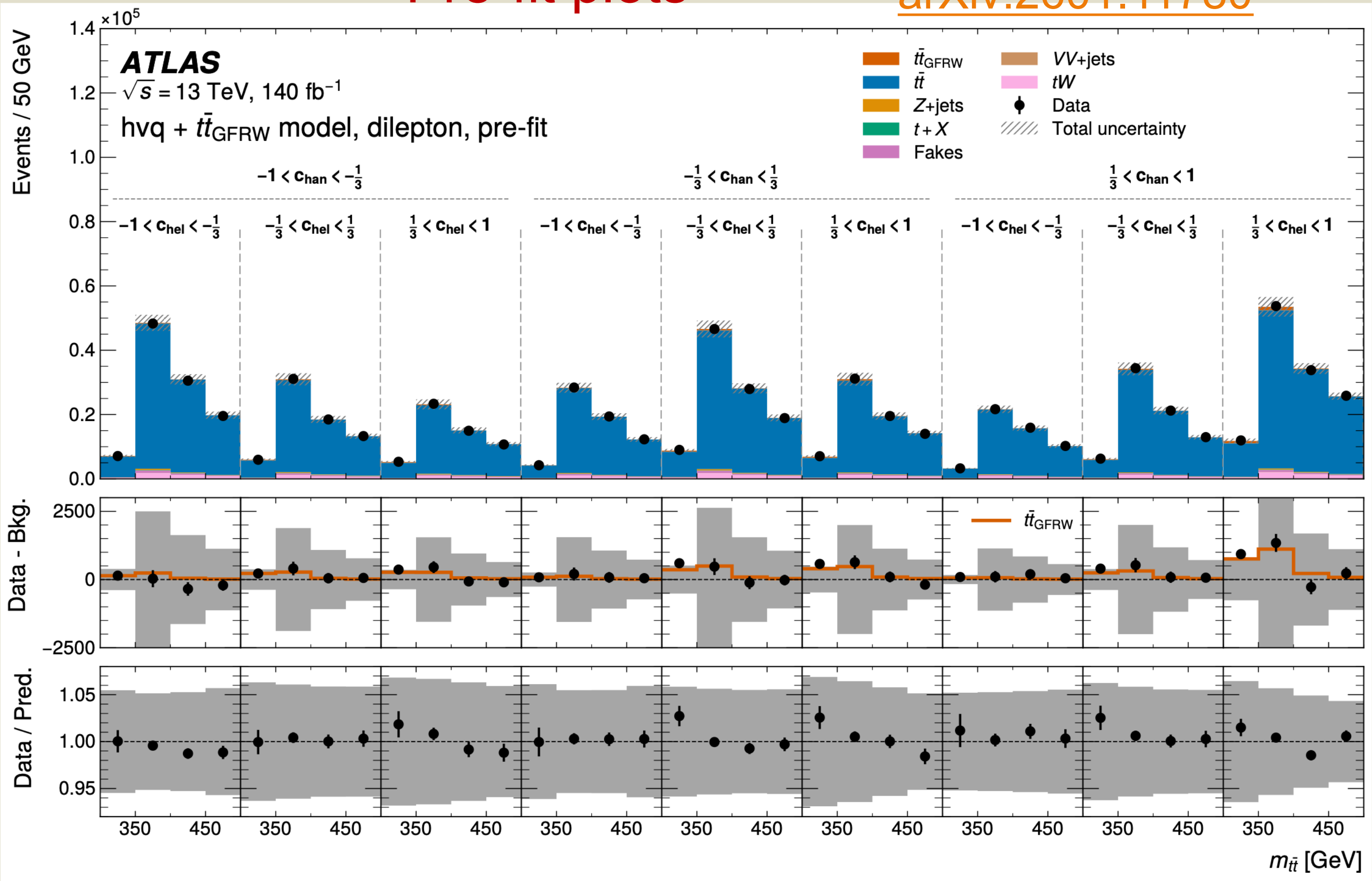


Background Estimations

- $t\bar{t}$: with a free-floating scale factor (SF); tW: estimation from MC
- Z+jets: get some contributions from Z→$\tau\tau$. Use the CR-Z to normalize the Z+b process

Pre-fit plots

arXiv:2601.11780

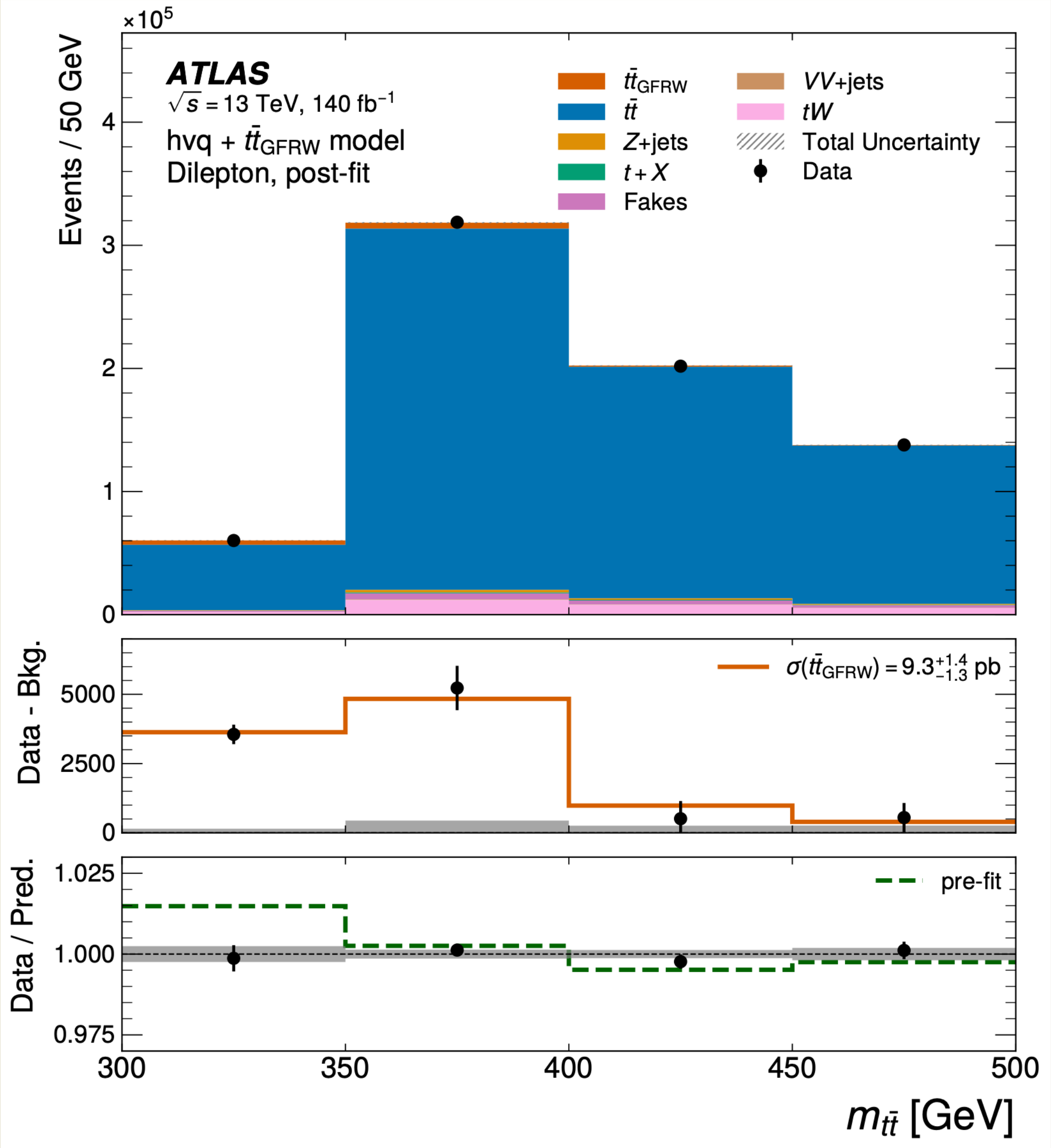


- fake / non-prompt leptons: Fakes represent 1.5% of SR yields. Data-driven estimation with 3 CR-Fakes

GFRW:
Green's Function Reweighted

All SRs

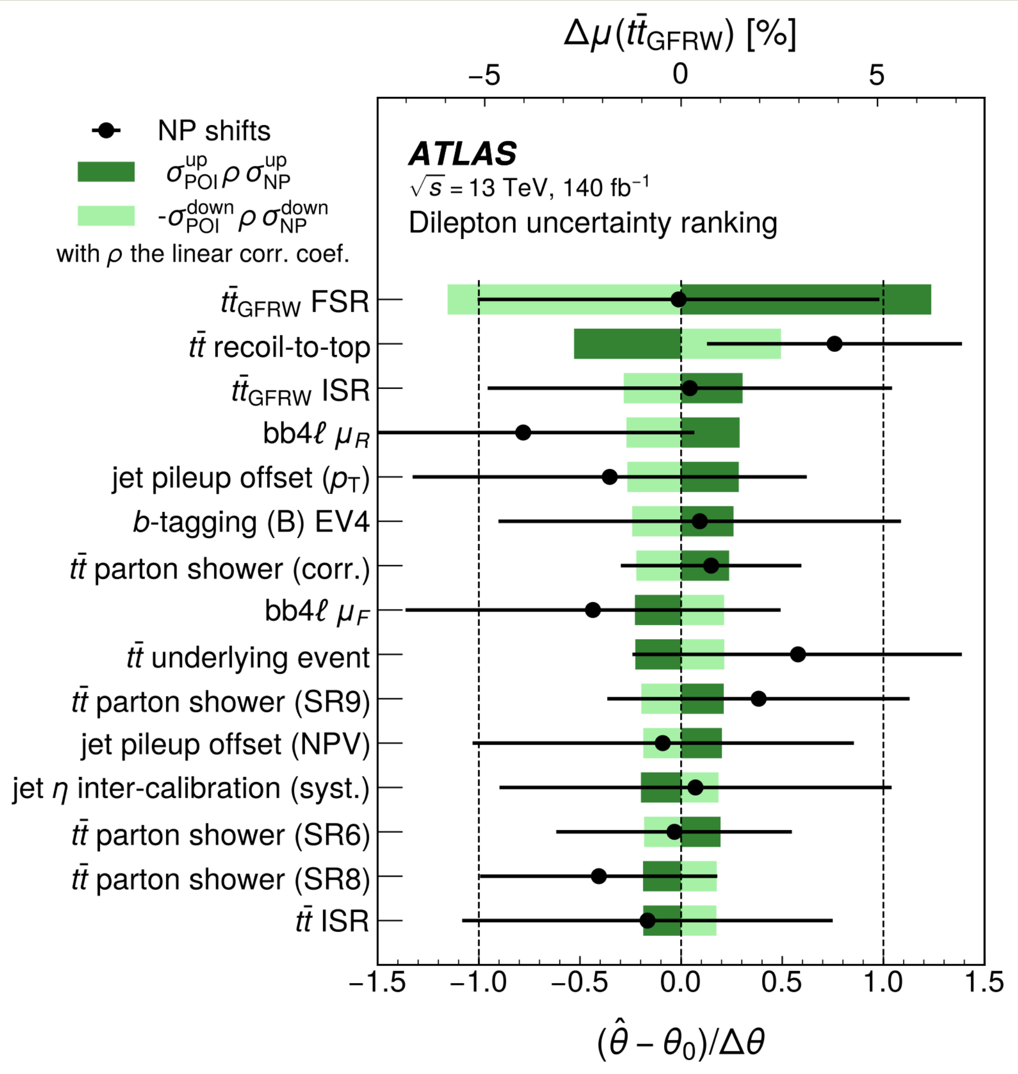
Post-fit



Impacts of Systematics

arXiv:2601.11780

- Quasi-bound state modelling: Parton shower [Herwig7]
- $t\bar{t}$ decay and off-shell [comparison to bb4l]
- NNLO QCD rew.: NNLO QCD scale variations



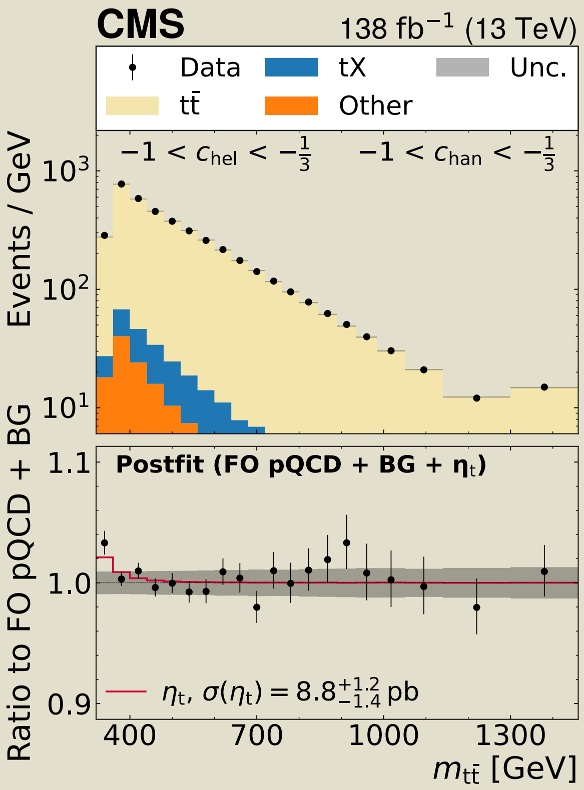
- No strong pulls or constraints
- Largest effects from toponium modelling and off-shell effect modelling

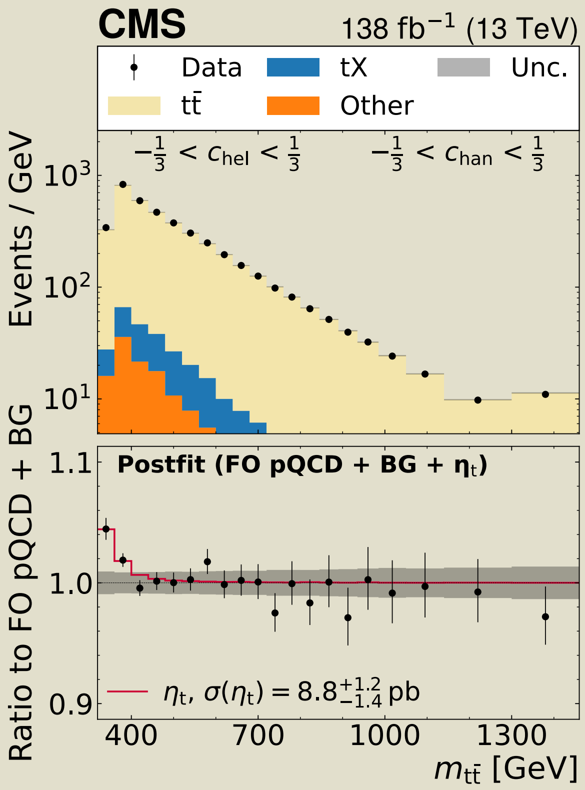
CMS Results: 2L

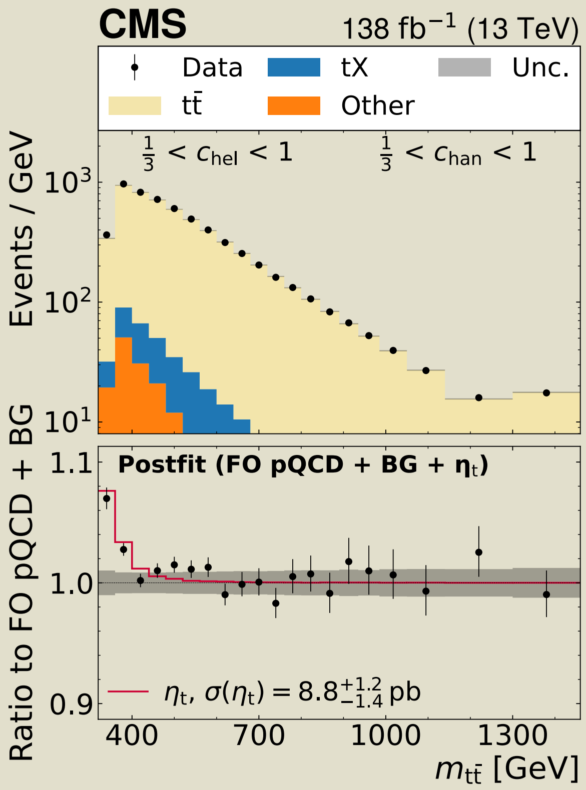
- arXiv:2503.22382, Rep. Prog. Phys. 88 (2025) 087801
- Use very similar analysis method compared with ATLAS

显著度大于5σ

Measured cross-section: $8.8^{+1.2}_{-1.4}$ pb

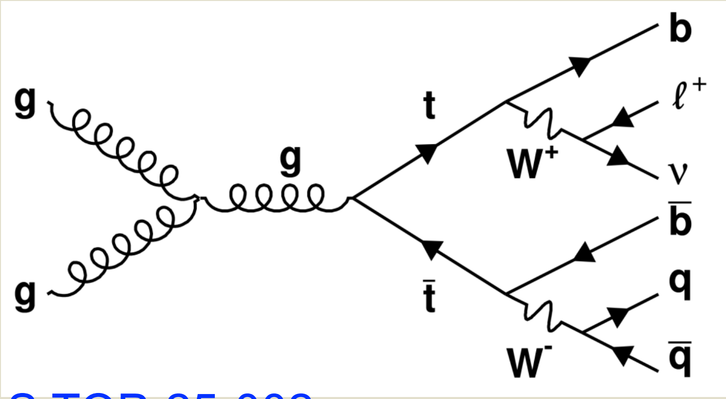






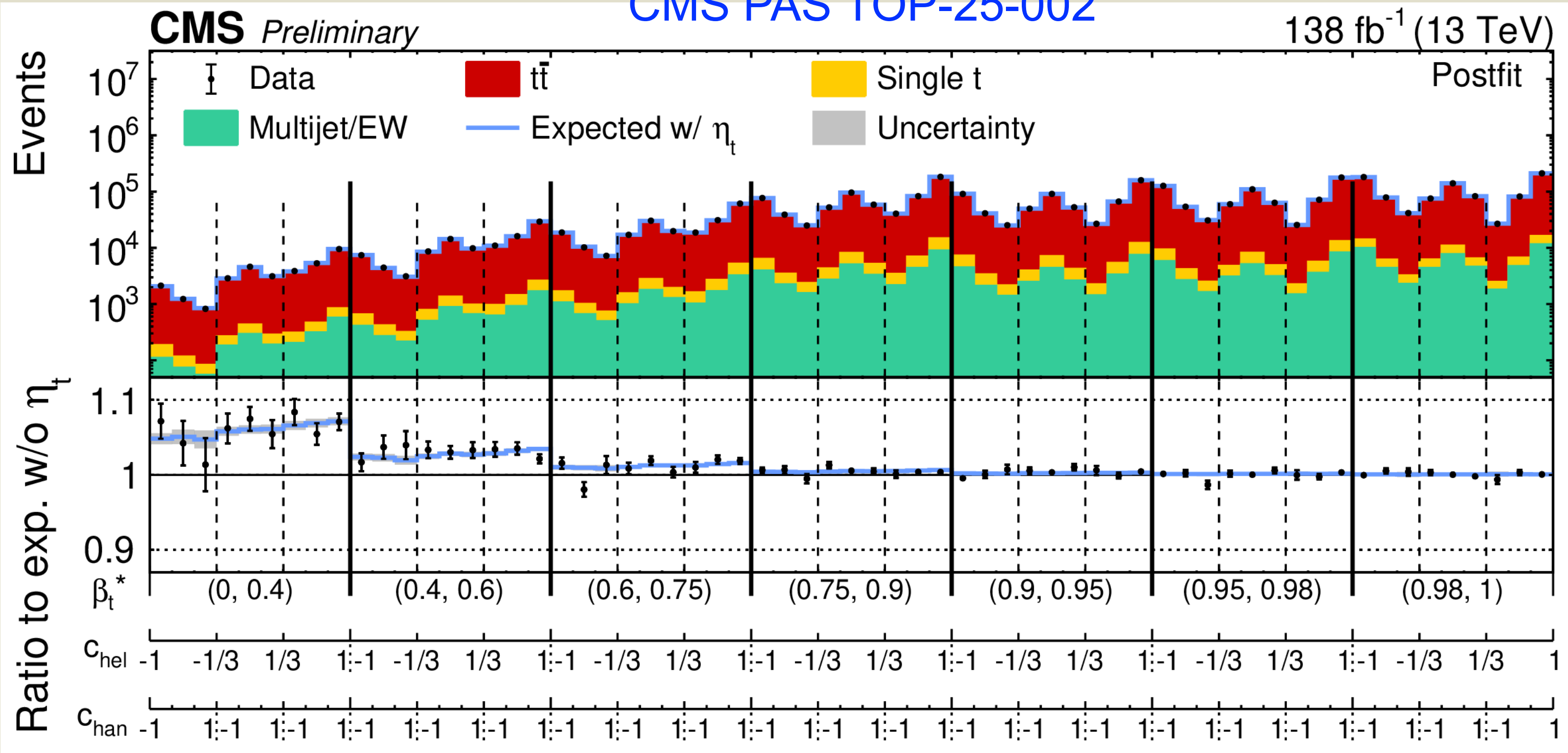
CMS Results: 1L

- 138 fb^{-1} of pp collisions at 13 TeV
- Lepton + jets final state. e/μ and >=4 jets

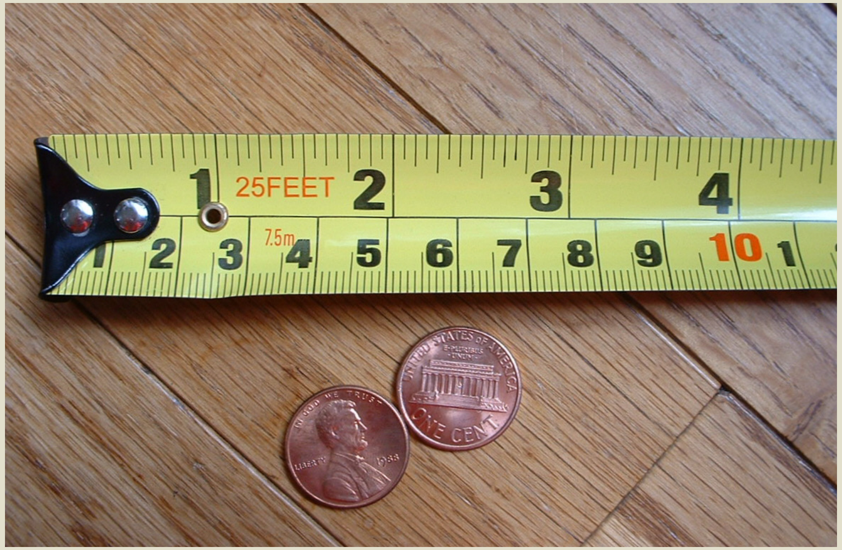


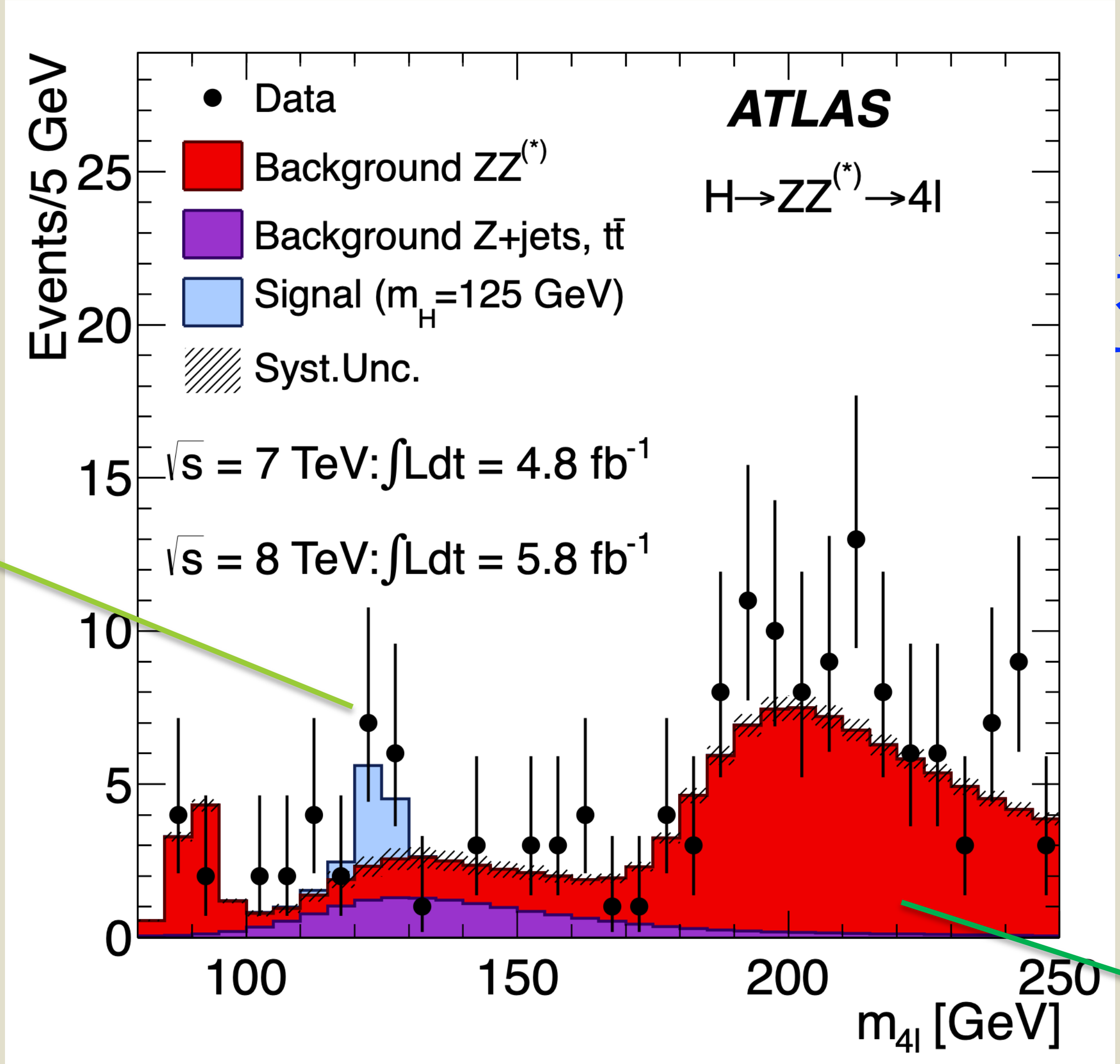
Total η_t cross section: 5.1 ± 0.9 pb
Observed significance: 6.1 σ

CMS PAS TOP-25-002



测量的原理





硬币

尺子

这是一个假设检验过程