TeV 物理实验进展综述

Qiang Li (PKU)

2022/08/08

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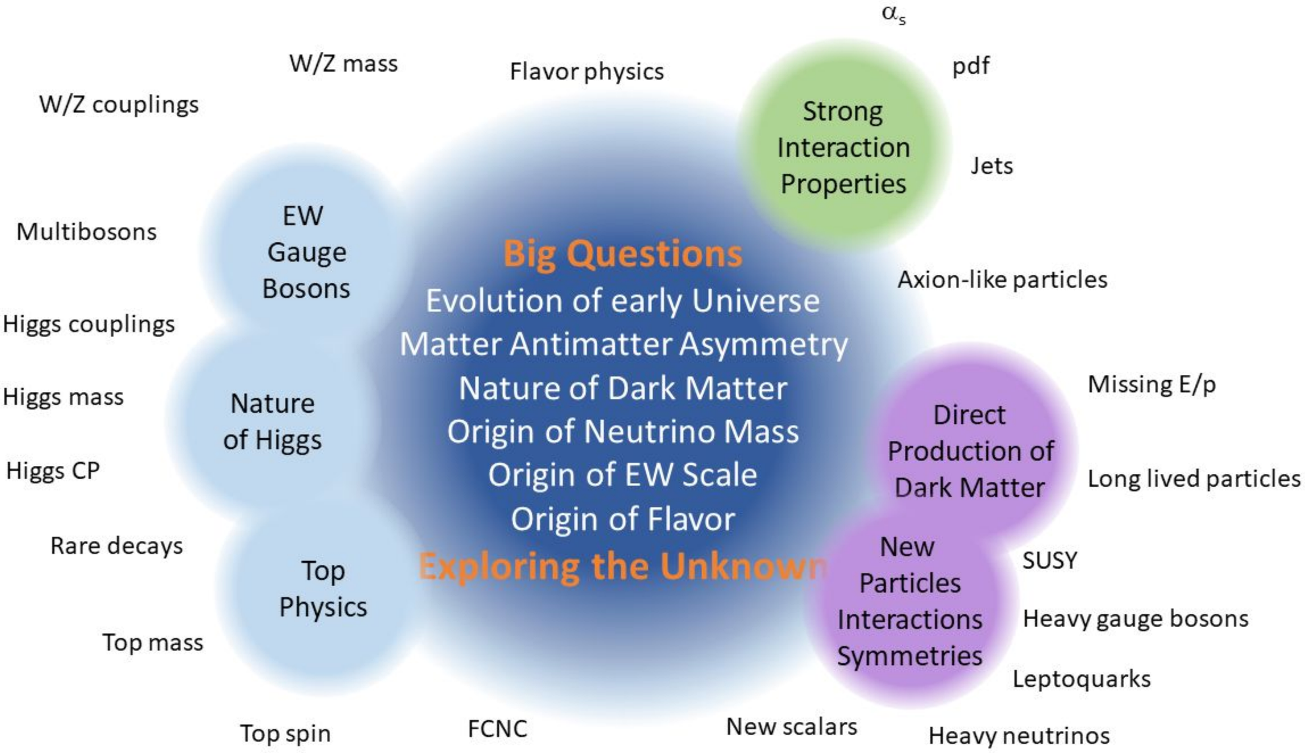
TSUNG-DAO LEE INSTITUTE

中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会

Energy Frontier: explore the TeV energy scale and beyond

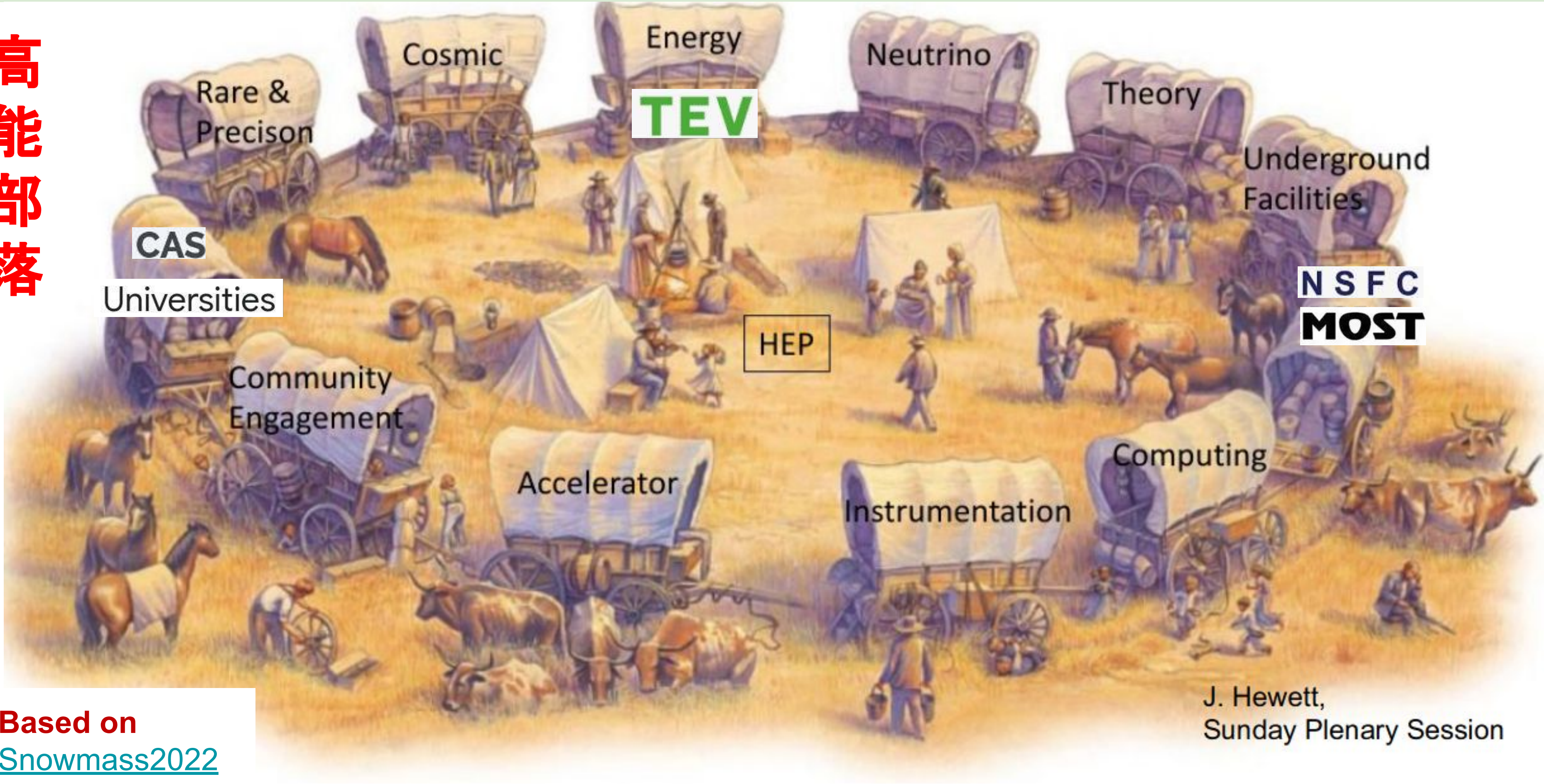
Aims at investigating open fundamental questions and exploring the unknown…through the breadth and multitude of collider physics signatures

美国Snowmass2022
高能量前沿总结



Together For a Shared Future

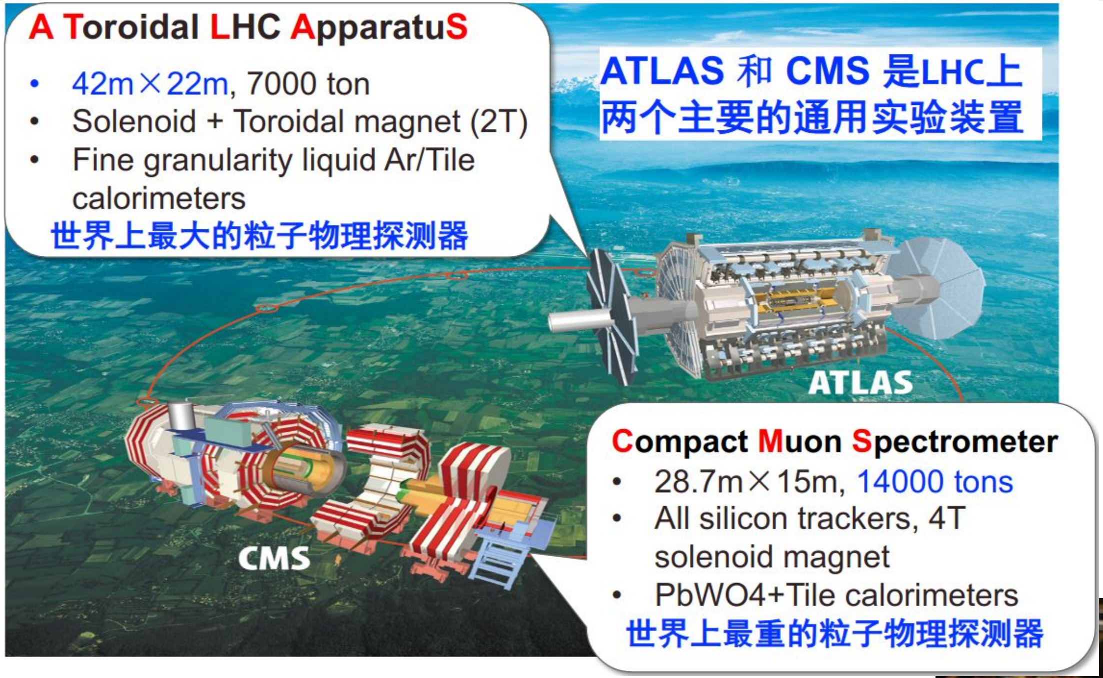
高能部落



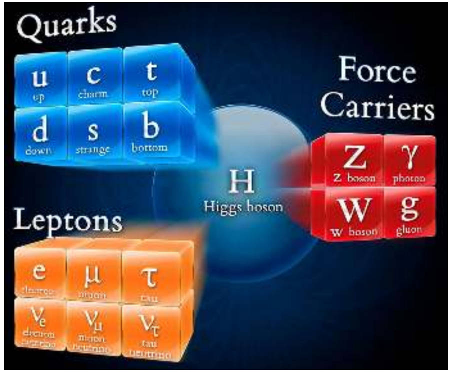
J. Hewett,
Sunday Plenary Session

Based on
Snowmass2022

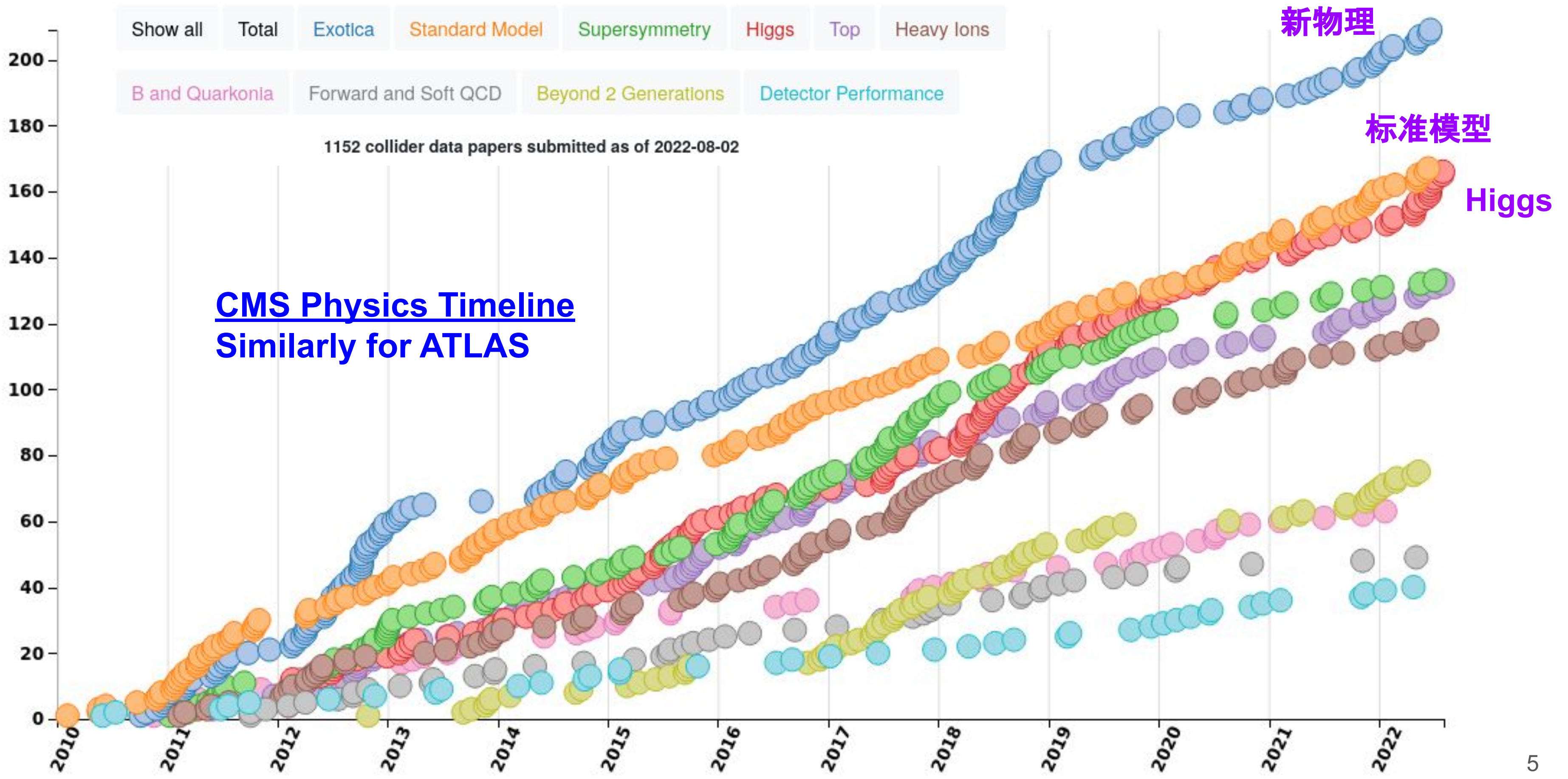
Fruitful LHC & TeV Physics



- **Fundamental Physics at small length scale.**
- **Vast and rich physics program at the high energy frontier.**

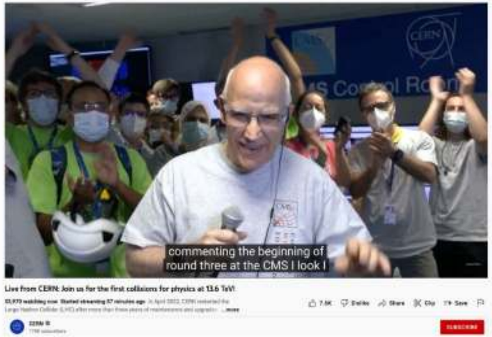


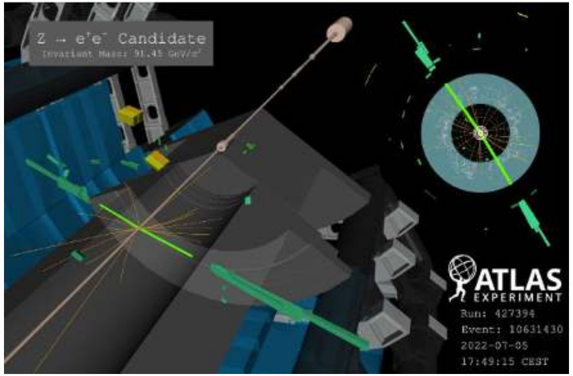
Fruitful LHC & TeV Physics

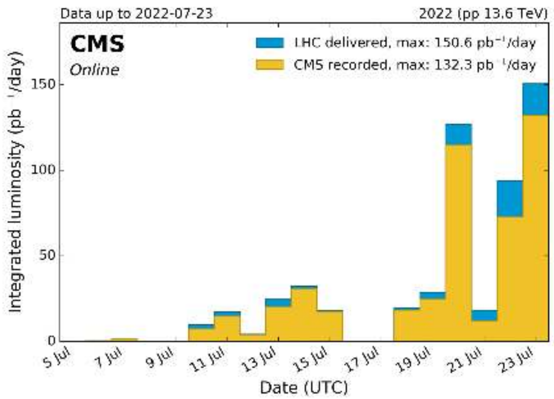


LHC Status

First Stable Beams at 13.6 TeV – 5th July



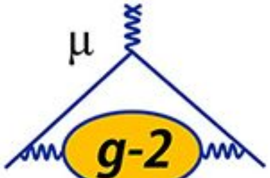


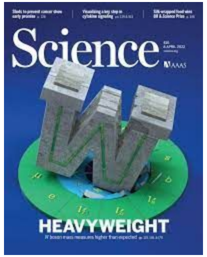


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Detector
https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

Great Potential and Rich Physics

Mode	ATLAS/CMS	LHCb	ALICE
proton-proton	250 - 270 fb^{-1}	25 – 30 fb^{-1}	200 pb^{-1}
lead-lead	7 nb^{-1}	1 nb^{-1}	7 nb^{-1}
proton-lead	0.5 pb^{-1}	0.1 pb^{-1}	0.25 pb^{-1}
oxygen-oxygen	0.5 nb^{-1}	0.5 nb^{-1}	0.5 nb^{-1}
proton-oxygen	LHCf 1.5 nb^{-1}	2.0 nb^{-1}	

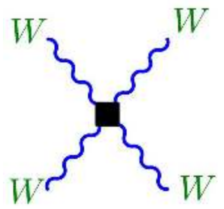


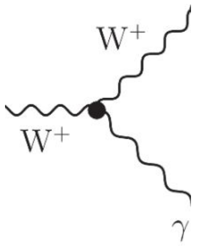


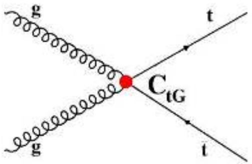
Going Beyond:

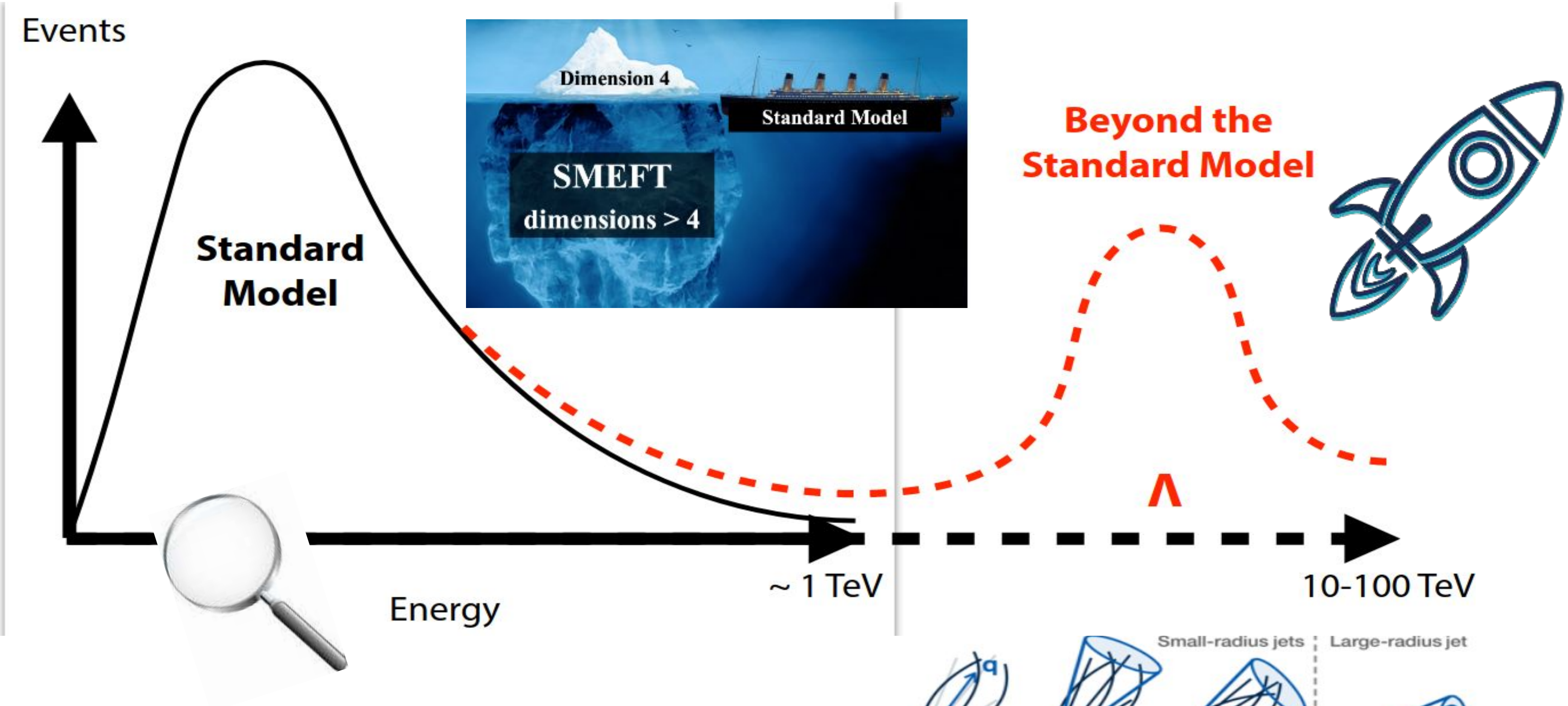
- Dark Matter,
- CP violation,
- Flavor symmetry,
- Fine Tuning,
- **Neutrino Mass**
- *Lepton Flavor Universality Violation*
- *Muon g-2*
- ***W-mass!***

Indirect and Direct Searches

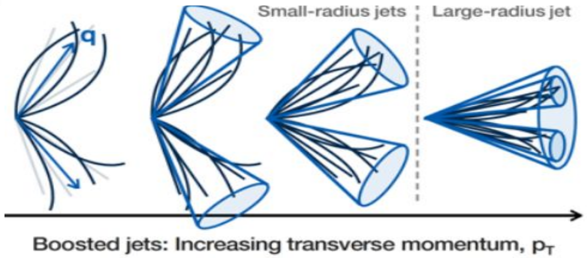








$$L_{\text{EFT}} = L_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$



HEPSummerDays2022 July 15th

14个国内ATLAS及CMS组的交流汇报；100人左右在线参与。

Friday, July 15, 2022

08:50 - 08:59 Photos 9'
Material: Slides

08:59 - 10:10 Session Morning-1
Convener: Prof. Yajun Mao (Peking University)

09:00 - 09:20 Openings 20'
Speakers: Prof. Yuanning Gao (Peking University), Prof. Zhengguo Zhao

09:20 - 09:45 IHEP ATLAS 25'
Speakers: Yanping Huang (高能所), Dr. yanping huang (ihep)
Material: Slides

09:45 - 10:10 IHEP CMS 25'
Speakers: Jin Wang (高能所), Jin Wang (IHEP)
Material: Slides

10:10 - 10:30 Morning Coffee

10:29 - 12:10 Session Morning-2
Convener: Haijun Yang (Shanghai Jiao Tong University)

10:30 - 10:55 Tsinghua ATLAS 25'
Speakers: Prof. Xin Chen (University of Wisconsin-Madison), mingming xi
Material: Slides

10:55 - 11:20 Tsinghua CMS 25'
Speaker: Prof. Zhen Hu (Tsinghua University)
Material: Slides

11:20 - 11:45 Beihang CMS 25'
Speaker: Prof. Li Yuan (Beihang University)
Material: Slides

11:45 - 12:10 SYSU CMS 25'
Speaker: Dr. Meng Lu (SYSU)
Material: Slides

13:29 - 15:10 Session Afternoon-1
Convener: Prof. Yaquan FANG Yaquan (高能所)

13:30 - 13:55 Nanjing ATLAS 25'
Speaker: Dr. 力钢 夏 (Nanjing University)
Material: Slides

13:55 - 14:20 Zhejiang CMS 25'
Speaker: Prof. Meng Xiao (Zhejiang University)
Material: Slides

14:20 - 14:45 SJTU/Lee ATLAS 25'
Speaker: Prof. Kun LIU (Tsung-Dao Lee Institute, Shanghai Jiao Tong University)
Material: Slides

14:45 - 15:10 Fudan CMS 25'
Speaker: Dr. Xuyang Gao (Fudan University)
Material: Slides

15:10 - 15:25 Afternoon Tea

15:24 - 17:00 Session Afternoon-2
Convener: Prof. Mingshui CHEN (IHEP)

15:25 - 15:50 USTC CMS 25'
Speaker: Prof. Nan (楠) Lu (鲁) (University of Science and Technology of China)
Material: Slides

15:50 - 16:15 Shandong ATLAS 25'
Speaker: Prof. Haifeng Li (Shandong University)
Material: Slides

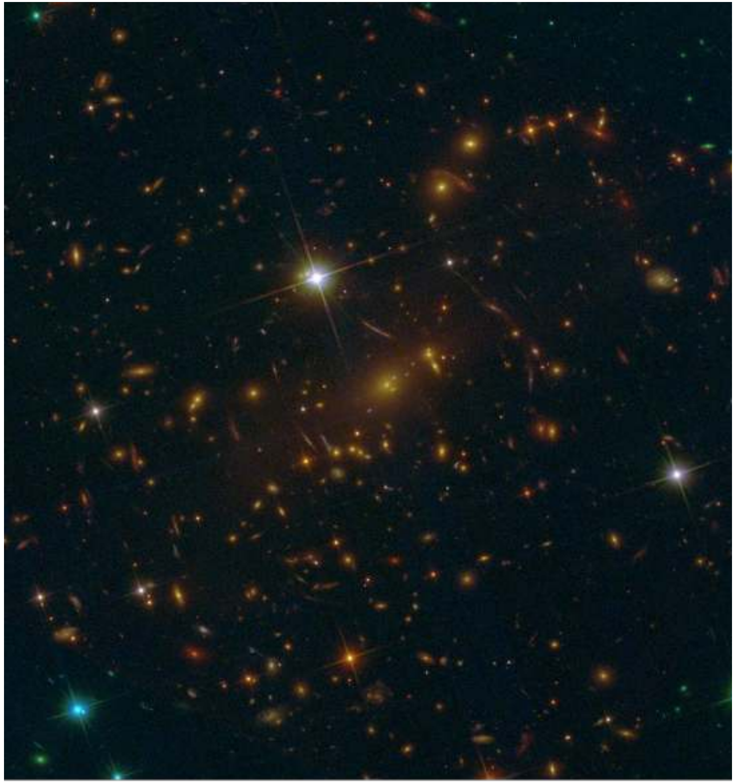
16:15 - 16:40 USTC ATLAS 25'
Speaker: Prof. Yusheng Wu (University of Science and Technology of China)

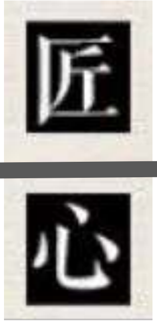
16:40 - 17:00 PKU CMS 20'
Speaker: Prof. Chen Zhou (PKU)
Material: Slides

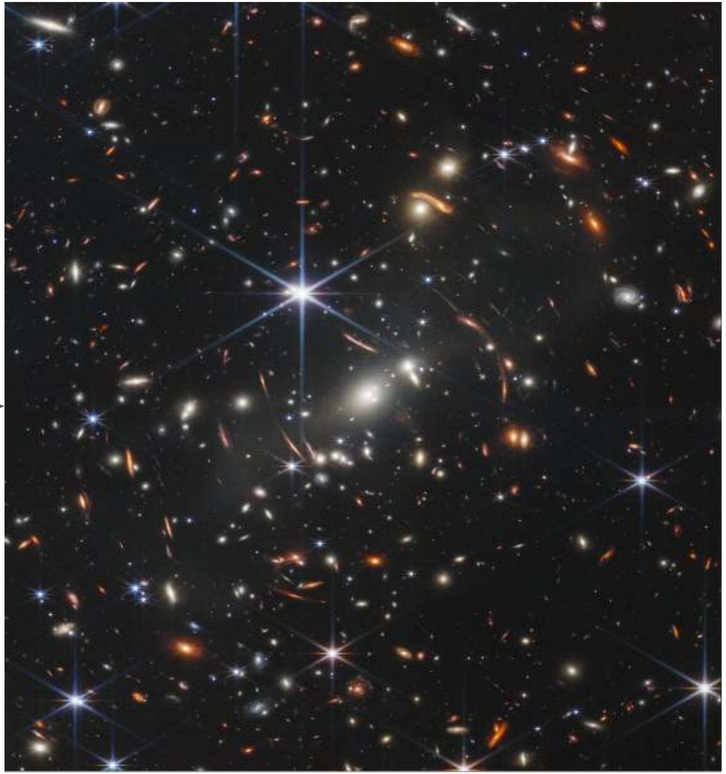
本次报告侧重国内团队过去一年有重要贡献的亮点工作！

Sorry for any bias and ignorance.

Huge efforts on performance improvement

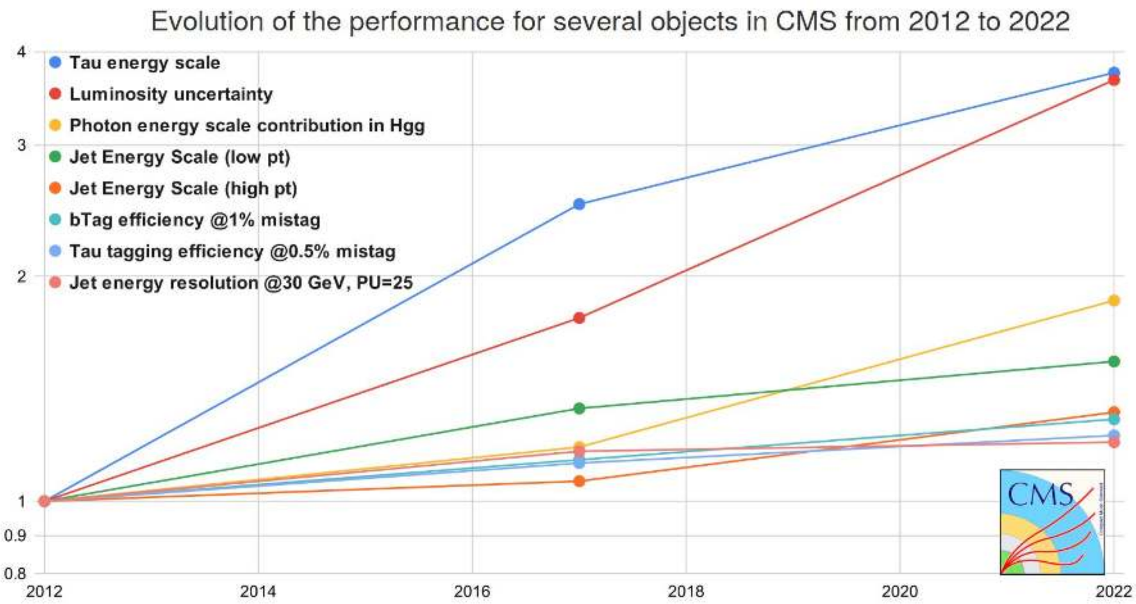


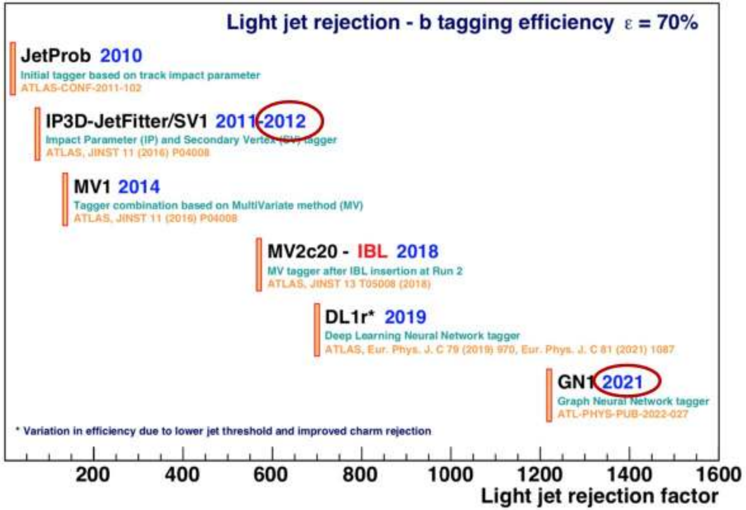




Hubble https://bithole.dev/misc/jwst-comparison/ **JWST**

Huge efforts on performance improvement

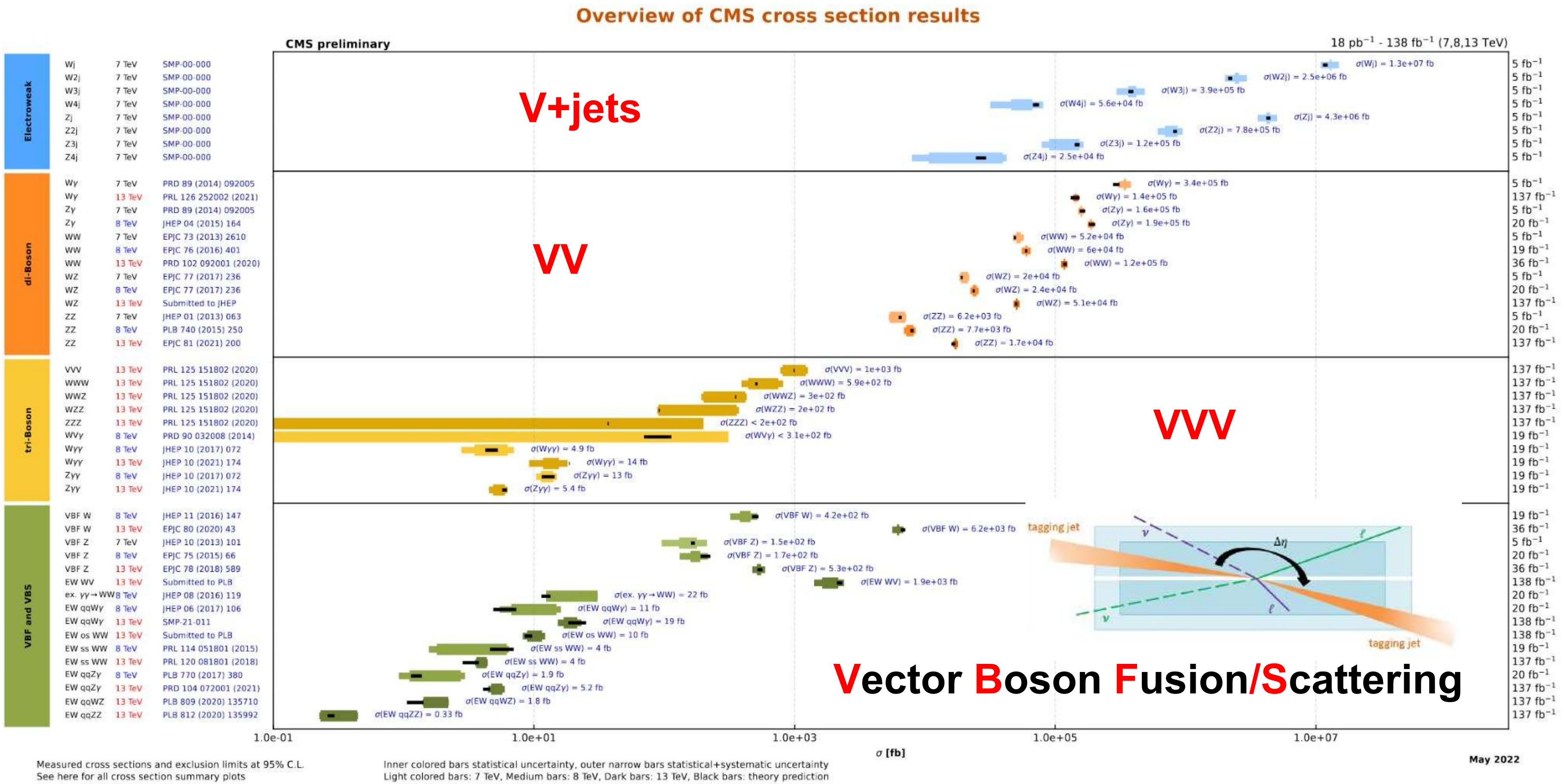




Fabiola Gianotti Higgs@10

中国组在电子、缪子、光子、tau、喷注标记等等方面做出了大量重要贡献，承担了多个协调人、召集人职位！

Stair to X 通往X的阶梯 CMS ATLAS SM Summary Plots



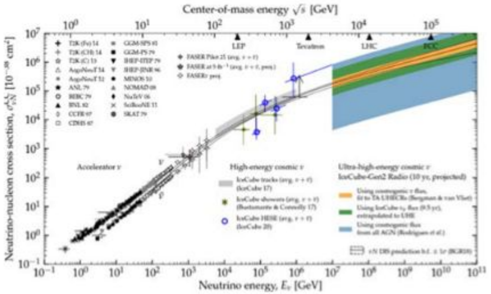
US Snowmass Summary July 2022

Changed Landscape in science

The landscape has changed,
but the fundamental physics drivers have not

Concentrate on measurements, not limits

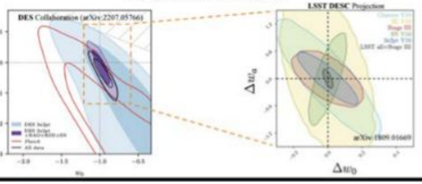
标准模型测量本身即为重要的成果！



Our knowledge of the cosmos and its connection to particle physics has increased tremendously.

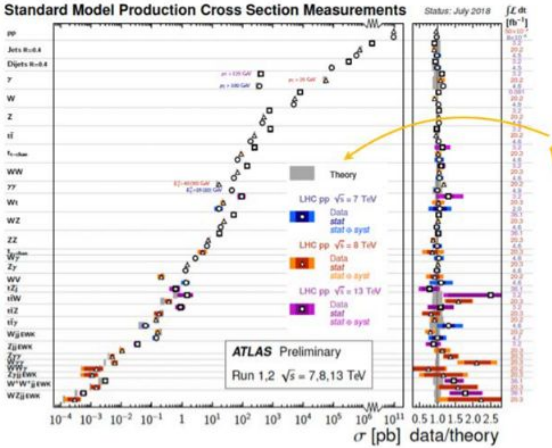
Precision cosmology

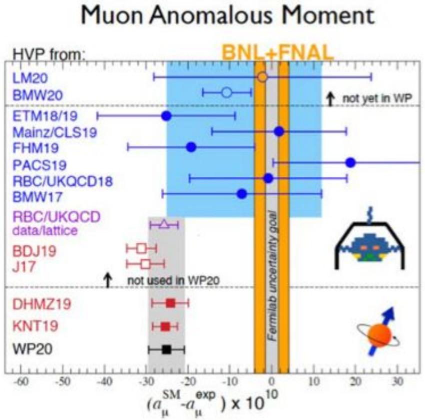
The discovery of **dark energy** led to a **precision measurement program** to understand its physics.



We continued to improve our knowledge of the Standard Model
We've measured couplings, particle masses and the structure of interactions
New quark and gluon combinations, magnetic and electric dipole moments

Glory in our successes – and shamelessly promote them

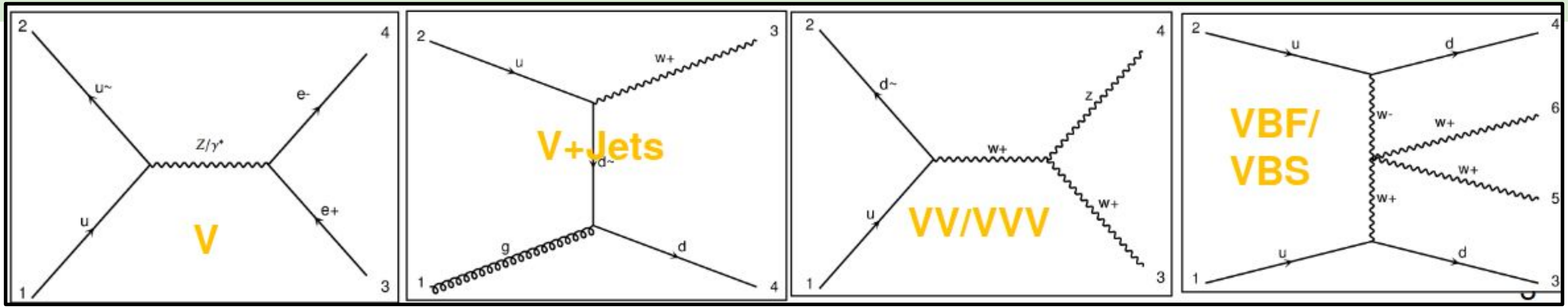


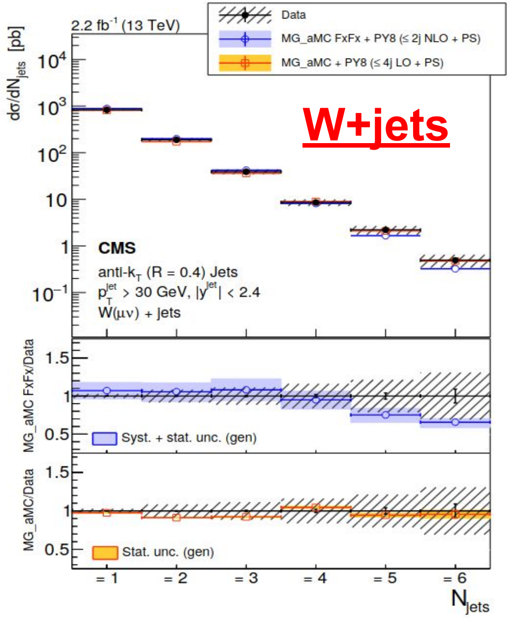


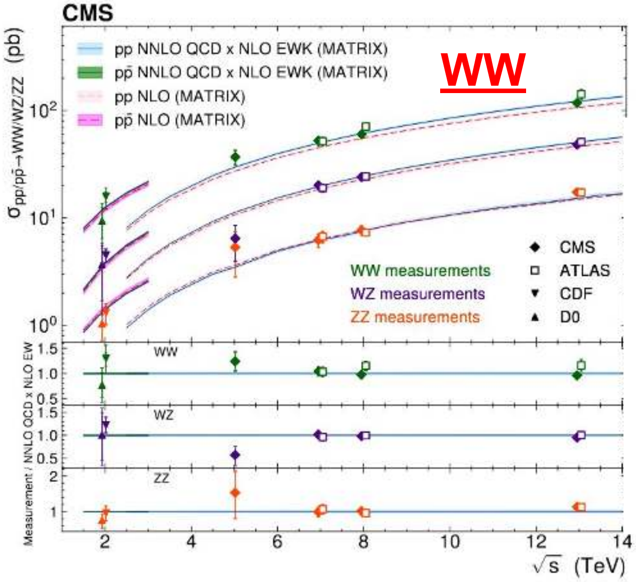
LHC Run 1 & 2: **Experimental** and **Theoretical** triumph (see J. Thaler talk)


START
460 × 260

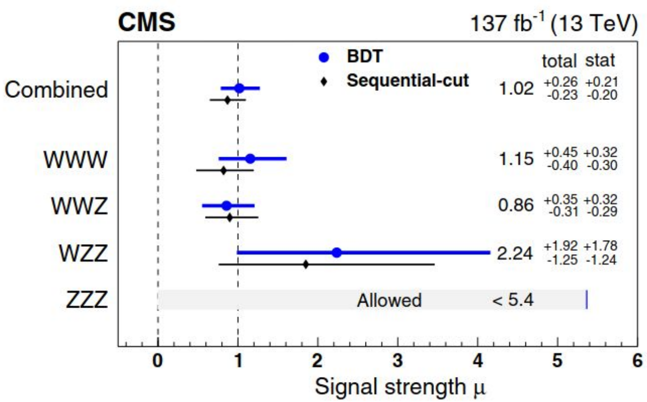
W-boson related topics



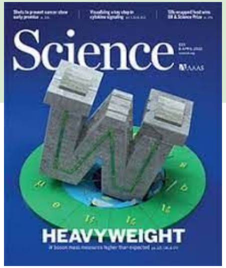




WWW discovery



W Mass



D0 (4.3+1.1 fb^{-1}) *[Phys. Rev.* ***D89*** *(2014) 012005]*

m_W = 80375 ± 11 (stat.) ± 20 (sys.) MeV

CDF (8.8 fb^{-1}) *[Science* ***376*** *(2022) 170]*

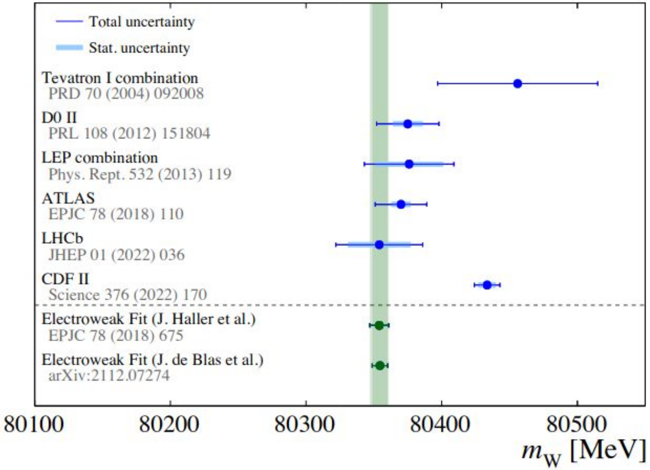
m_W = 80433.5 ± 6.4 (stat.) ± 6.9 (sys.) MeV

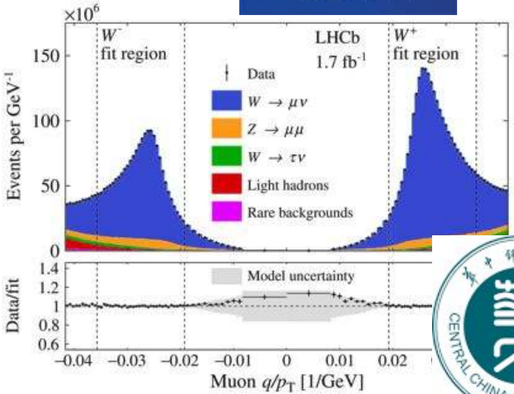
ATLAS (4.6 fb^{-1}) *[Eur. Phys. J.* ***C78*** *(2018) 110]*

m_W = 80370 ± 7 (stat.) ± 18 (sys.) MeV

LHCb (1.7 fb^{-1}) *[JHEP* ***01*** *(2022) 036]*

m_W = 80354 ± 23 (stat.) ± 22 (sys.) MeV





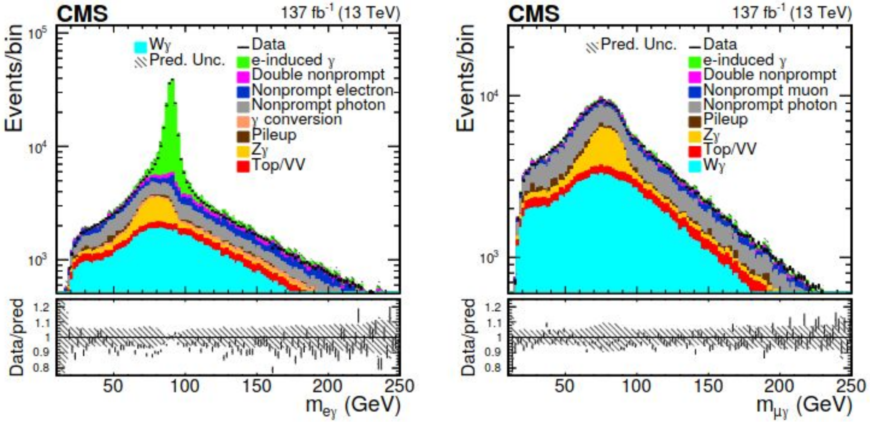
- **studies ongoing towards a combination between Tevatron and LHC measurements**
- **CMS Intermediate results**
  - Phys. Rev. D 102 (2020) 092012:
    - Measurements of the W boson rapidity, helicity, double-differential cross sections, and charge asymmetry
  - CERN-THESIS-2021-271 thesis of Elisabetta Manca
    - "...of the order of 10 MeV, using the data… in 2016"

W/Z+γ

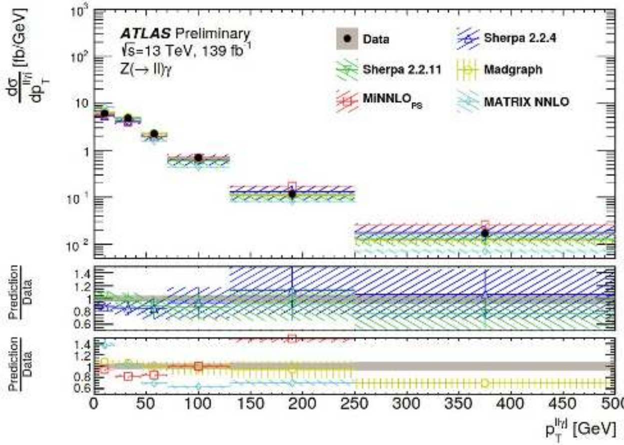
PRL126, 252002 (2021) PRD105 (2022) 052003 ATL-CONF-2022-047

双玻色子

- **Wγ fiducial cross section**
  - based on fit to mlγ distribution:
  - σ = 15.44 ±0.05 (stat) ±0.84 (exp) ±0.12 (theory) pb
  - Theoretical cross sections at NLO:
    - MadGraph5_aMC@NLO 0+1 jets: 15.44 ±1.24 pb
    - POWHEG “NLO competition” scheme: 22.45 ±3.21 pb
  - Limits on dimension 6 EFT operators



- **Zγ+jets differential cross section measurements**
General good agreement is observed between data and state-of-the art theoretical NNLO predictions MATRIX/MiNNLO PS and with MADGRAPH5_aMC@NLO and SHERPA multiage NLO generators.



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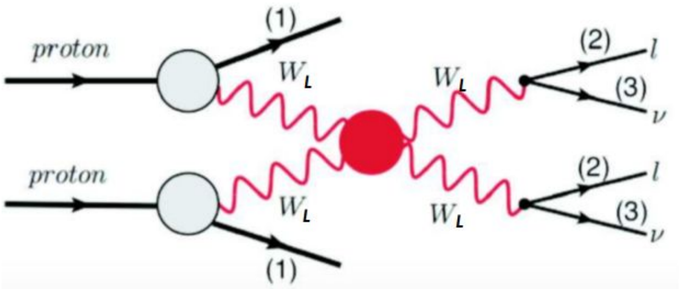
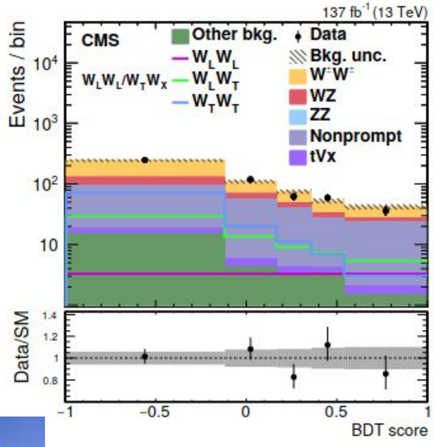
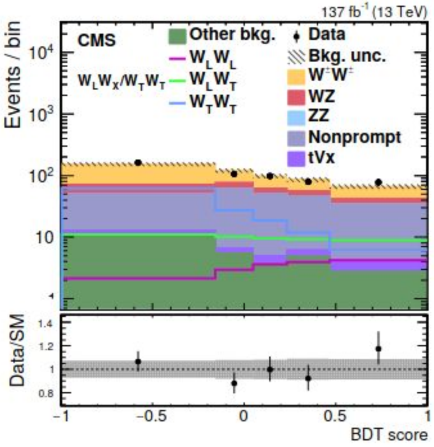
Polarized Vector Boson Scattering

极化散射

PLB 812 (2021) 136018





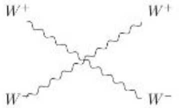


Boson scattering and Interaction

- **Yang-Mills Non-Abelian interactions**
- **Electroweak symmetry breaking**

Observed (expected) significance
LL and LT+LL: **0.88 (1.17); 2.3 (3.1)σ**

- We did know something about the Higgs mass
- Either M_H < 800 GeV or perturbative unitarity violated around 3 TeV



Cross sections grow with energy without Higgs

Unitarity, 1977

- Led to the powerful idea of a "no-lose" theorem

Ref

- "The LHC had to find a Higgs or something else at an accessible scale"

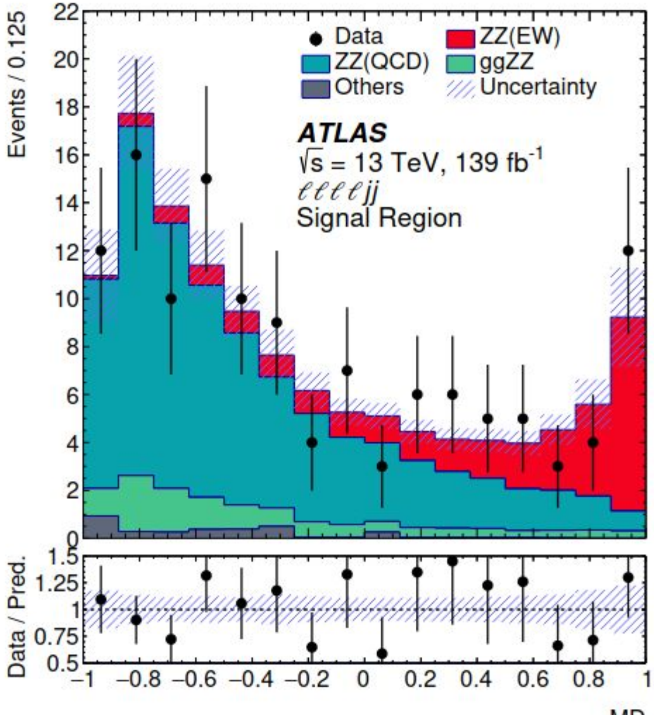
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

ZZ/WV scattering

arXiv:2004.10612 arXiv:2112.05259

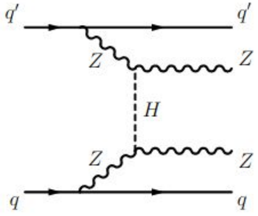
observation of EW production of ZZjj

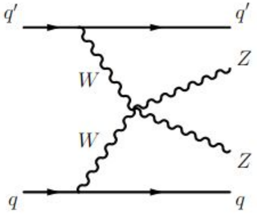
Milestone-electroweak-symmetry-breaking
(ATLAS Physics Briefing)

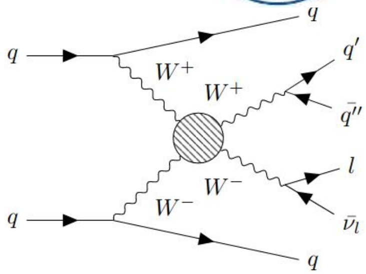


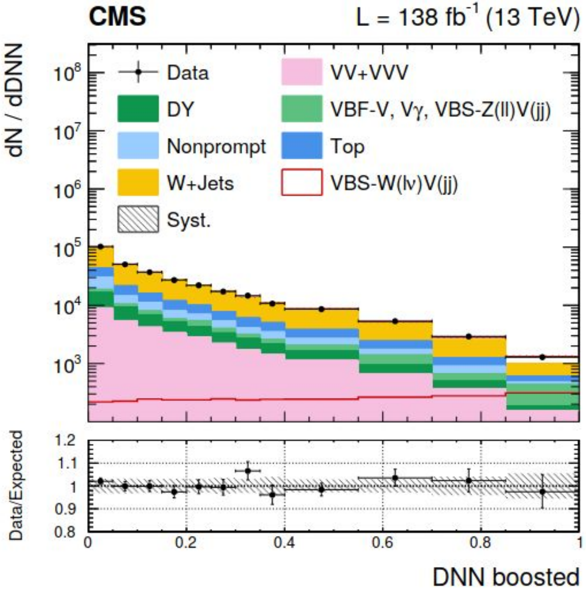
Evidence of EW production of WVjj

4.4 (5.1) σ Observed(expected)





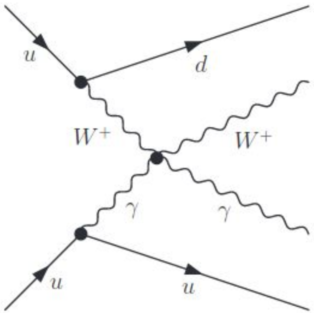


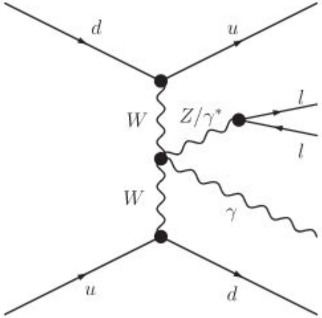


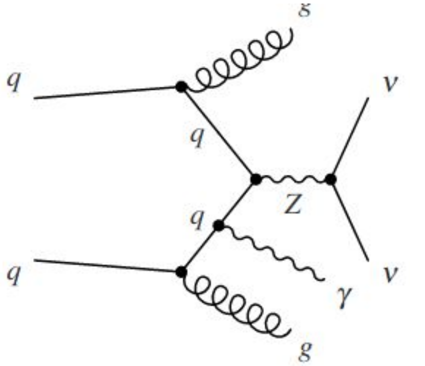
W/Z+γ scattering

CMS-PAS-SMP-21-011 PRD 104, 072001 (2021) EPJC 82 (2022) 2, 105

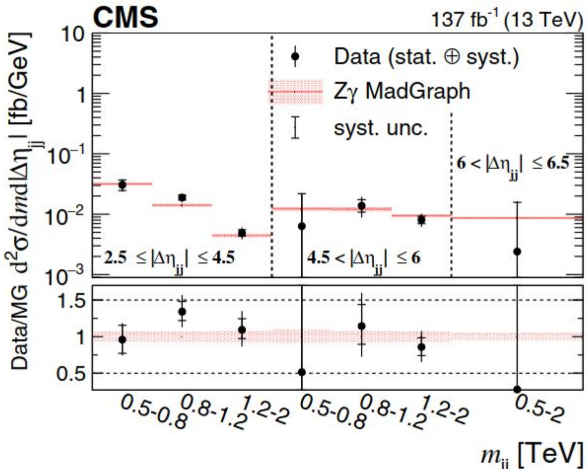
- 含光子的散射过程被发现
  - Differential Distributions，stringent limits on anomalous Quartic Gauge Couplings

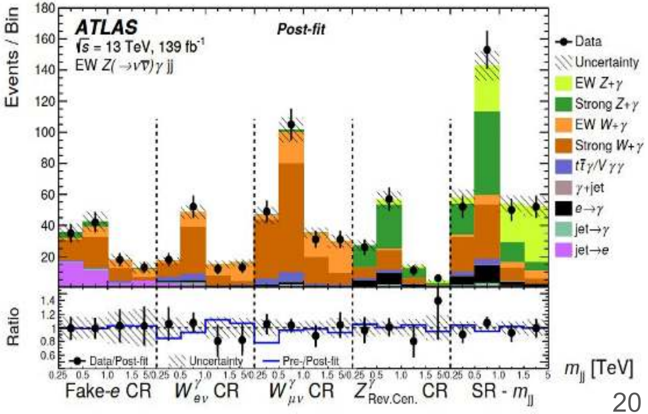






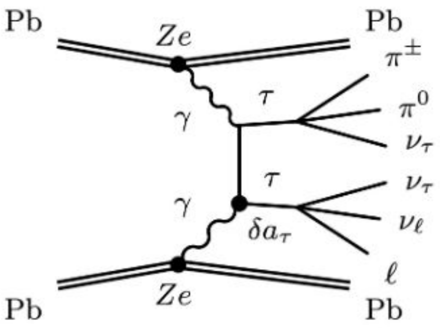
Expected. limit	Observed. limit	u_{bound}
$-5.1 < f_{M0}/\Lambda^4 < 5.1$	$-5.6 < f_{M0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M1}/\Lambda^4 < 7.4$	$-7.8 < f_{M1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M2}/\Lambda^4 < 1.8$	$-1.9 < f_{M2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M3}/\Lambda^4 < 2.5$	$-2.7 < f_{M3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M4}/\Lambda^4 < 3.3$	$-3.7 < f_{M4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M5}/\Lambda^4 < 3.6$	$-3.9 < f_{M5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T0}/\Lambda^4 < 0.51$	$-0.47 < f_{T0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T1}/\Lambda^4 < 0.31$	$-0.31 < f_{T1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T2}/\Lambda^4 < 0.92$	$-0.85 < f_{T2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T5}/\Lambda^4 < 0.31$	$-0.31 < f_{T5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T6}/\Lambda^4 < 0.25$	$-0.25 < f_{T6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T7}/\Lambda^4 < 0.68$	$-0.67 < f_{T7}/\Lambda^4 < 0.73$	3.1

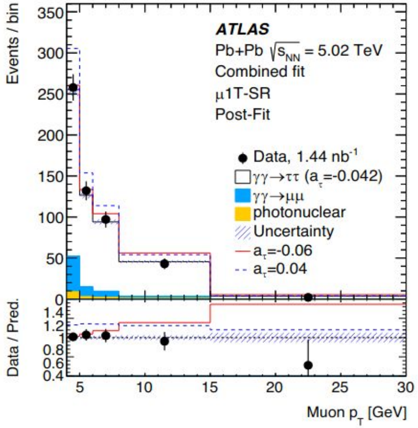




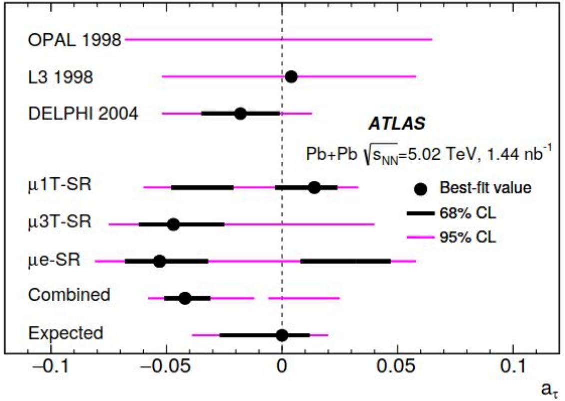
γγ→ττ arXiv:2204.13478 arXiv:2206.05192

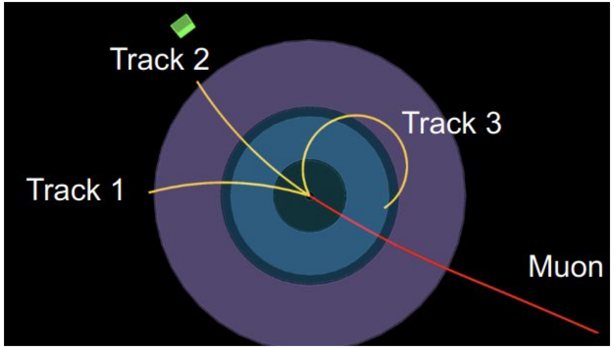
observation of τ-lepton pair production in ultraperipheral lead-lead collisions and constraints on the τ anomalous magnetic moment

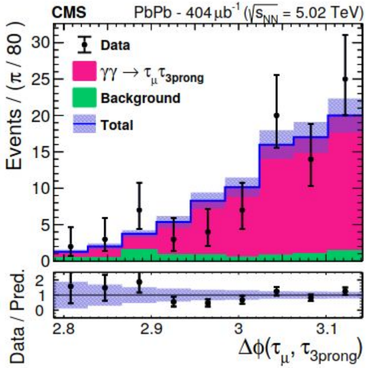


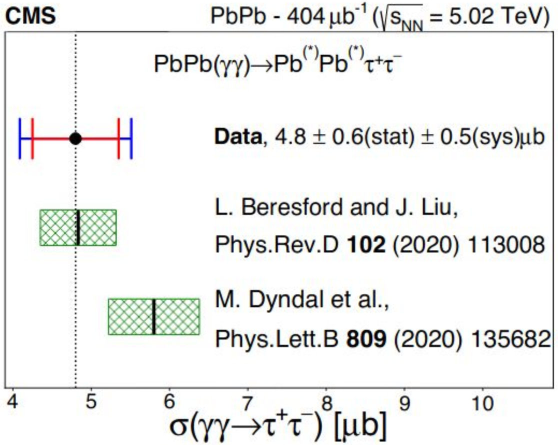


光子
对撞



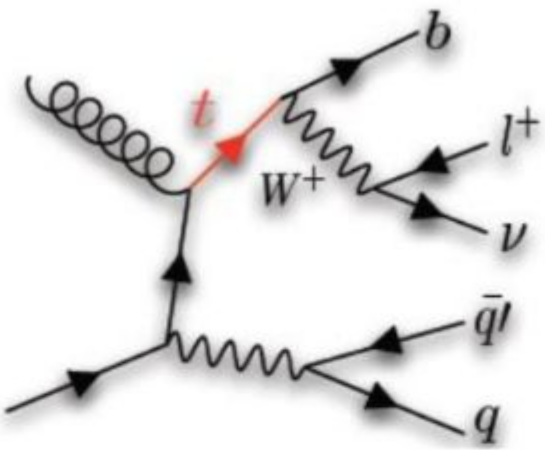






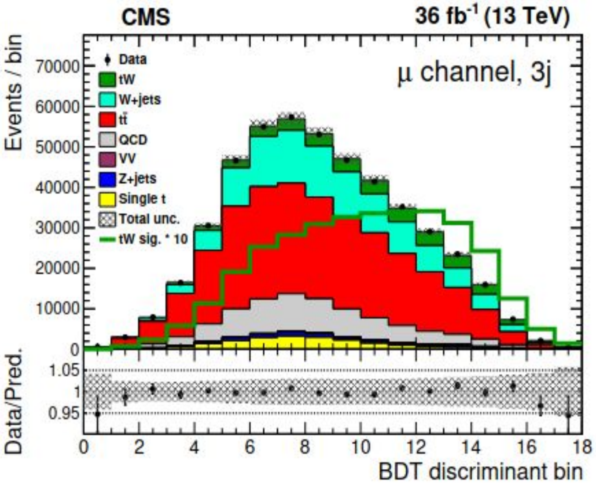
Top+W

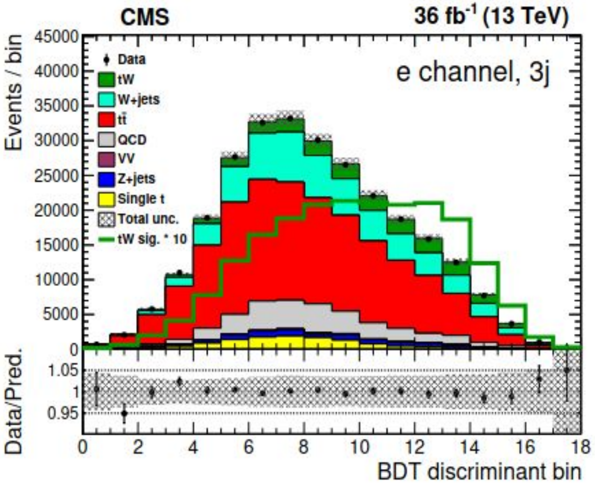
JHEP 11 (2021) 111



7.4 (6.8) σ

- **First observation** on this process through **semi-leptonic** decay channel.
- Offers full reconstruction of the top quark system, allowing top property measurements.
- interferes with tt at NLO, Diagram Removal as default, Diagram Subtraction for systematic.





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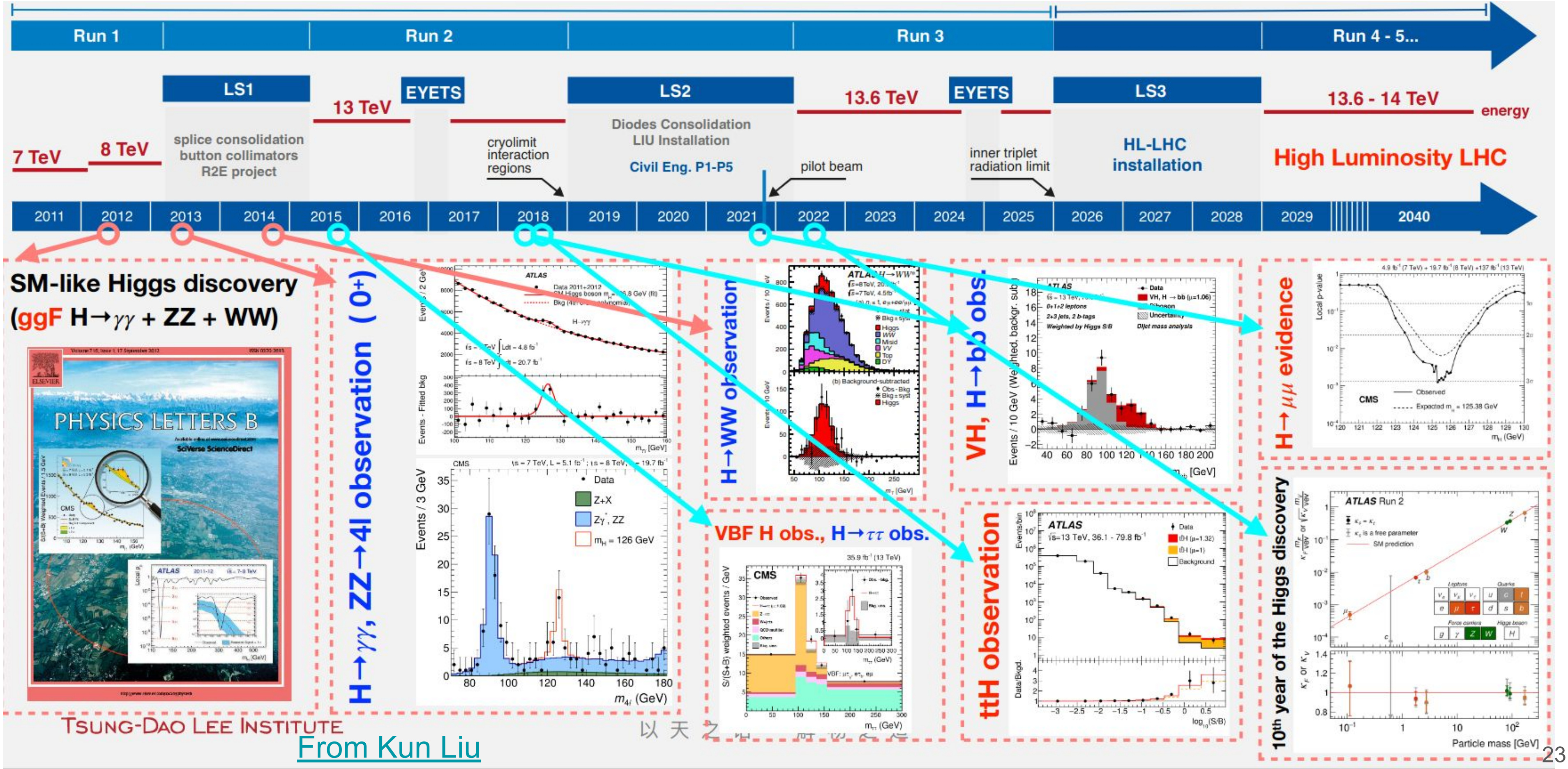
Institute of High Energy Physics
Chinese Academy of Sciences

Higgs@10



From Kun Liu

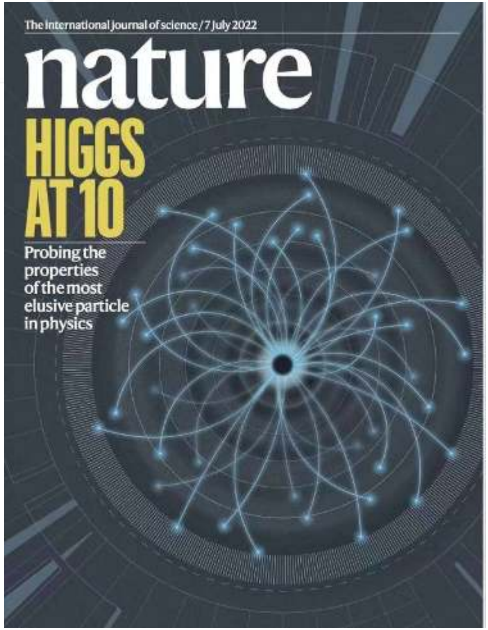
Higgs@10

- 2012 - I am born!
- 2013 - First steps
- 2014 - Who am I?
- 2015 - Why am I alone?
- 2016 - Not afraid of dark!
- 2017 - Trip to the tau-land
- 2018 - From top to bottom
- 2019 - I am getting precise
- 2020 - Meet 2nd generation
- 2021 - How broad am I?
- 2022 - I am charming!

From G. Landsberg

CERN 10 years HIGGS boson discovery

Scientific Symposium at CERN, July 4th, 2022



Higgs@10 in a coconut shell

https://indico.cern.ch/event/1135177/contributions/4763041/attachments/2474415/4246171/Higgs%4010_Fabiola.pdf

TODAY (numbers below are per experiment):

- All main Higgs boson production modes (ggF, VBF, VH, ttH+tH) established at > 5σ
- Couplings to gauge bosons (established in Run 1) measured to 6-8%
  Couplings to 3rd generation fermions (established in Run 2) measured to 7-11%
  Couplings to 2nd generation fermions: 3σ evidence for H→ μμ; first constraints on H→ cc
- Rare decays (e.g. H→ Zγ; H→ llγ at ~ 3σ level)
  Limits on invisible and exotic decays
- HH production: sensitivity x 3 SM cross-section
- Mass measured to ~ 0.1%
- Width measurement from off-shell/on-shell production demonstrated (3.6σ evidence for H off-shell production)
- $J^{CP}=0^{++}$ (large number of alternative hypotheses excluded > 99.9% C.L.)
- Inclusive studies complemented by increasing variety of differential/exclusive measurements (useful to constrain theory; provide additional constraints on couplings; sensitive to new physics in quantum loops affecting kinematic distributions)
- Searches for additional Higgs bosons (no sign yet …)
- Etc. etc.

Note: some of the above measurements were not expected to be possible in Run 2

Excellent summary from Fabiola in July 2022

Higgs@10

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1958 University of Science and Technology of China

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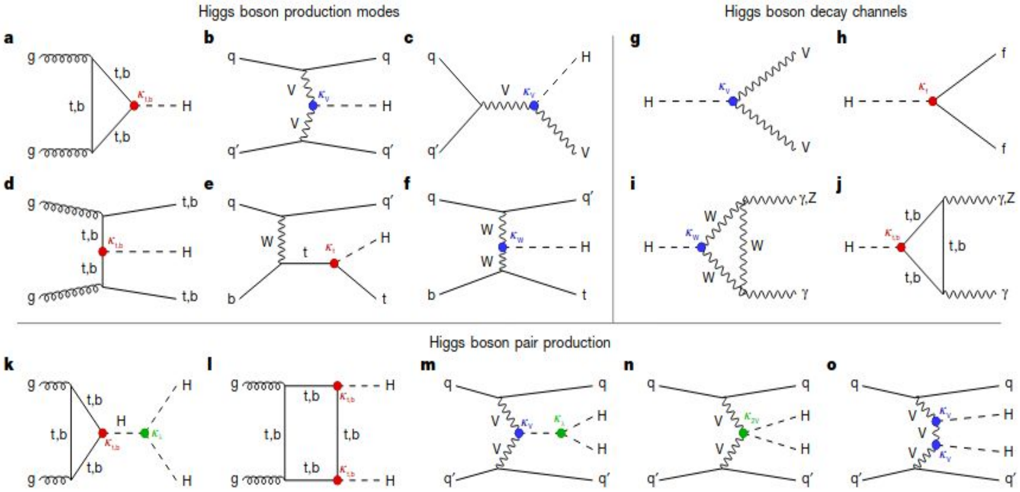
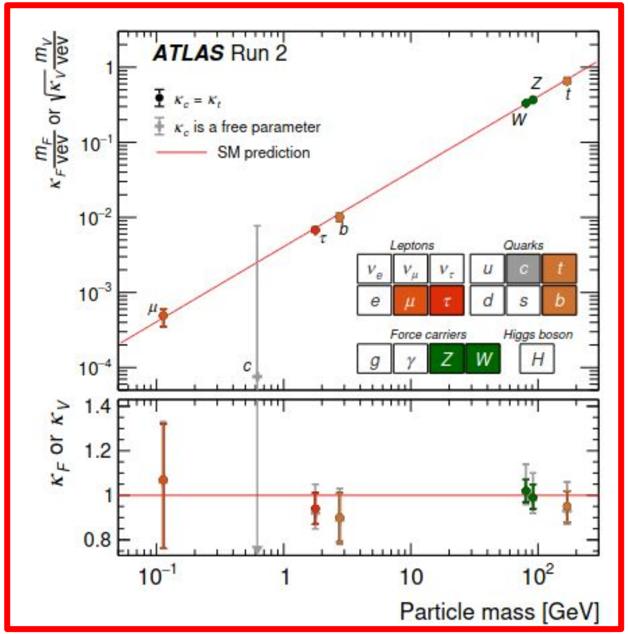
SHANGHAI JIAO TONG UNIVERSITY

SHANDONG UNIVERSITY 1901

Nature 607, 52–59; 60-68 (2022)





- Improvement in relative precision: 14% (Run 1) ➔ 6% (Run 2)
  - Theory uncertainty: 7% (Run 1) ➔ 4% (Run 2)

ATLAS

$\mu = 1.05 \pm 0.04\,(\text{th}) \pm 0.03\,(\text{exp}) \pm 0.03\,(\text{stat})$

CMS

$\mu = 1.002 \pm 0.036\,(\text{th}) \pm 0.033\,(\text{exp}) \pm 0.029\,(\text{stat})$

Fitting data from all production modes and decay channels with **a common signal strength parameter**

th – exp – stat uncertainties are of the same size

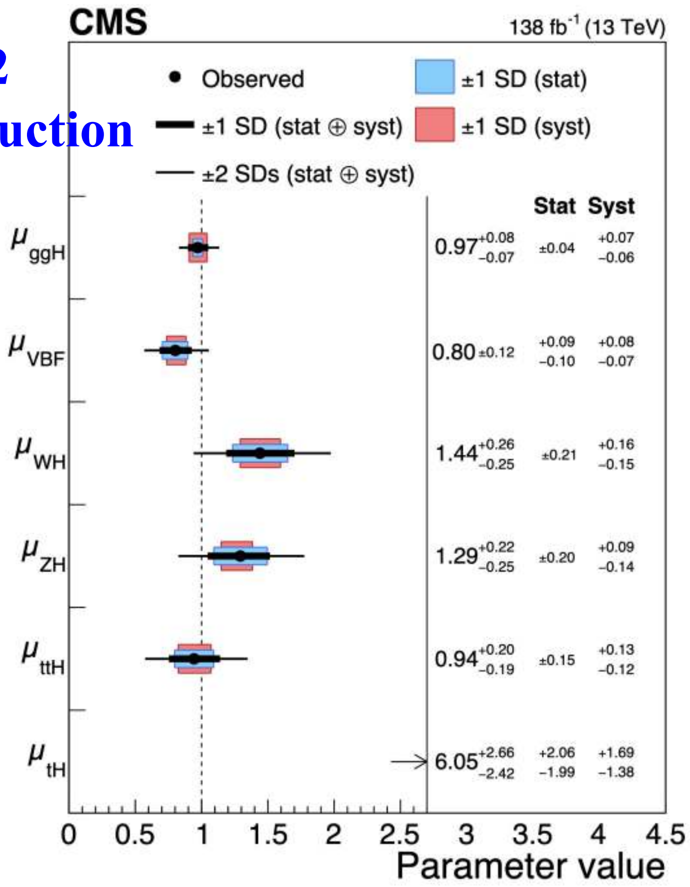
$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

Higgs@10

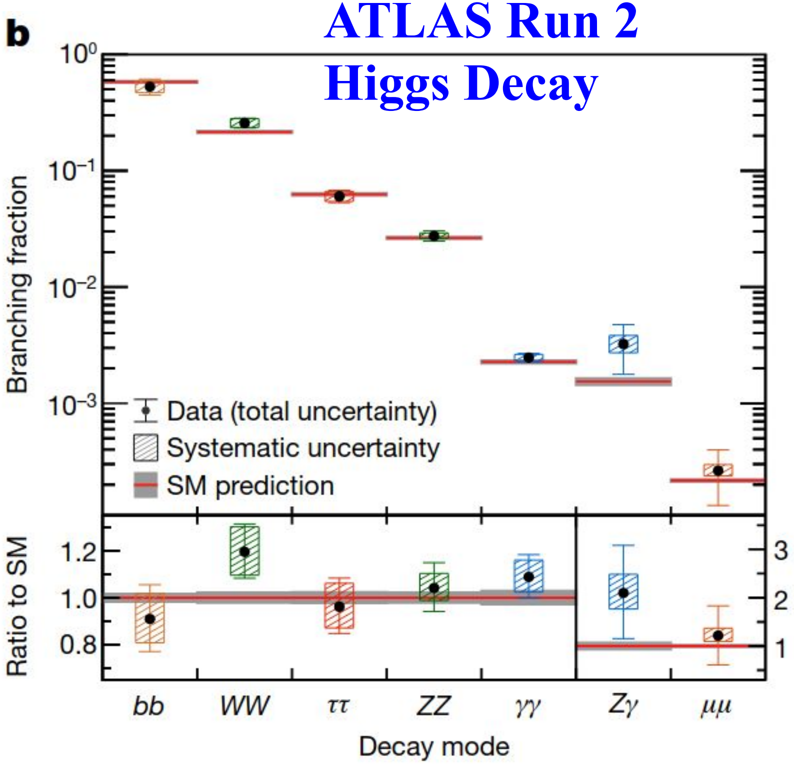
Nature 607, [52–59 (2022)]; [60-68 (2022)]

CMS Run 2
Higgs Production

> 5 SD



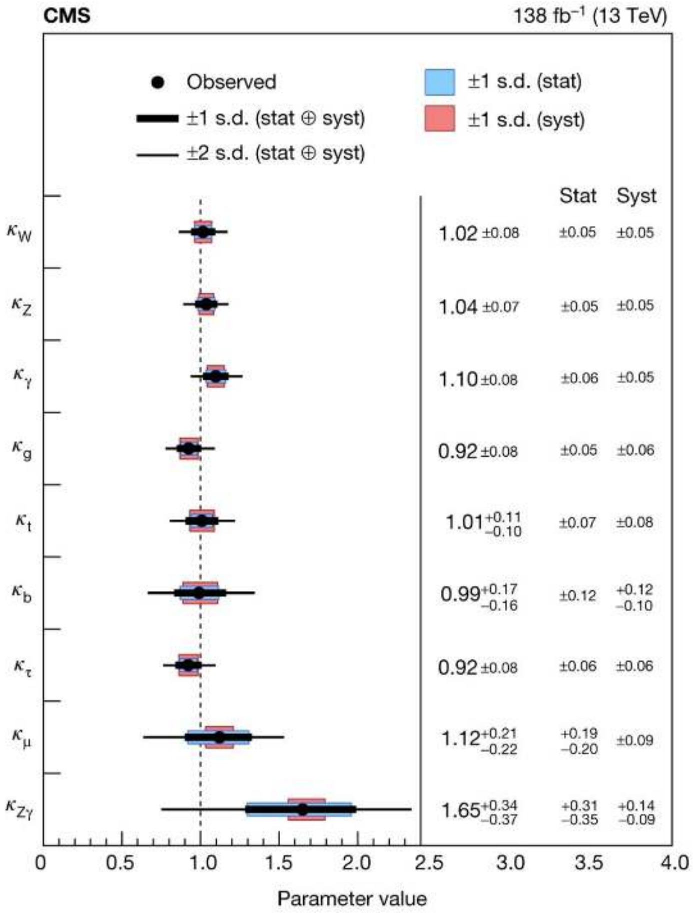
ATLAS Run 2
Higgs Decay

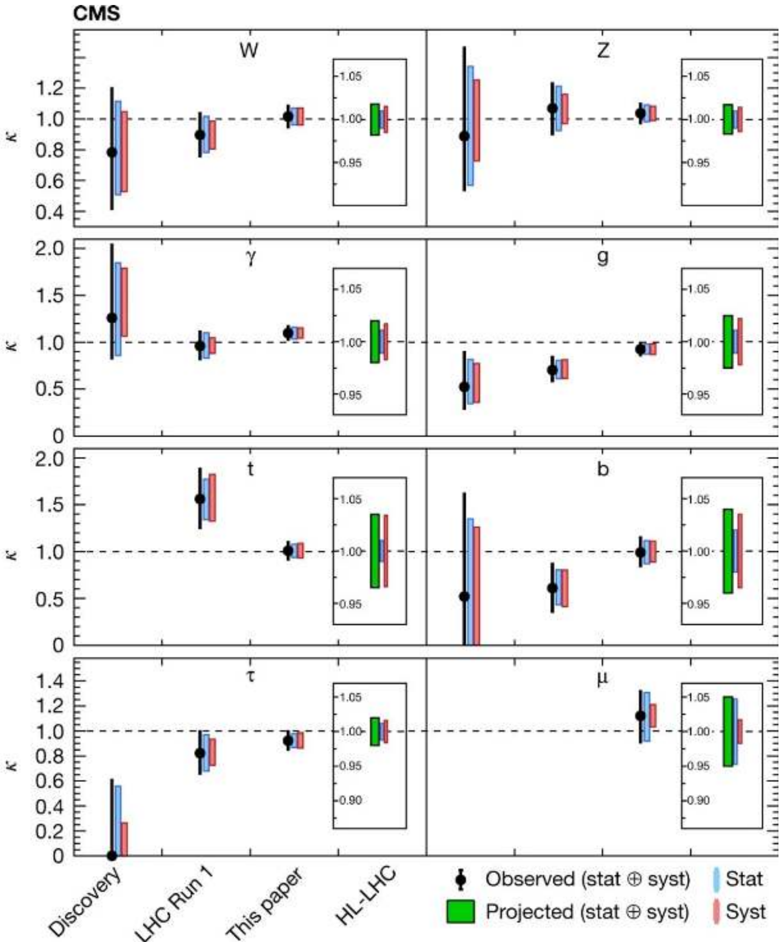


> 5 SD

Higgs@10

Nature 607, 52–59 (2022); 60-68 (2022)

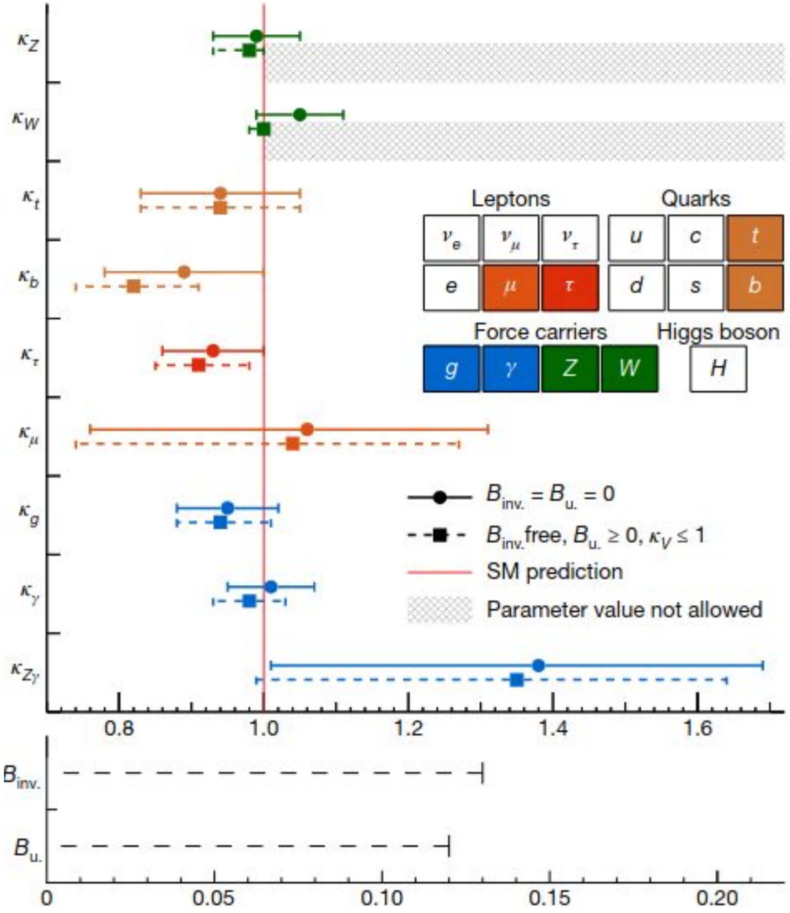




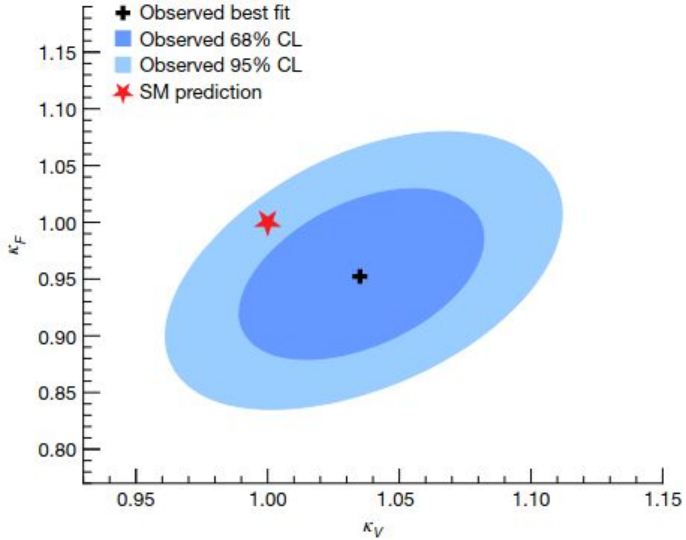
CMS: Coupling modifier measurements and their evolution in time.

Higgs@10

Nature 607, 52–59 (2022); 60-68 (2022)



ATLAS:
Reduced coupling strength modifiers and their uncertainties per particle type



Higgs Pair

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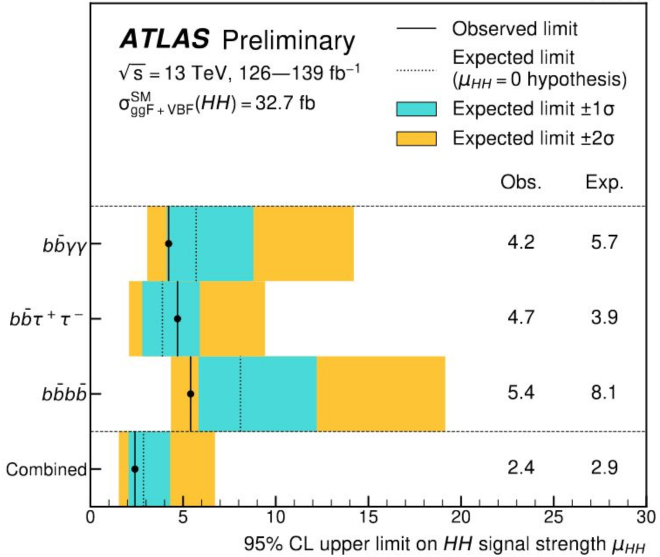
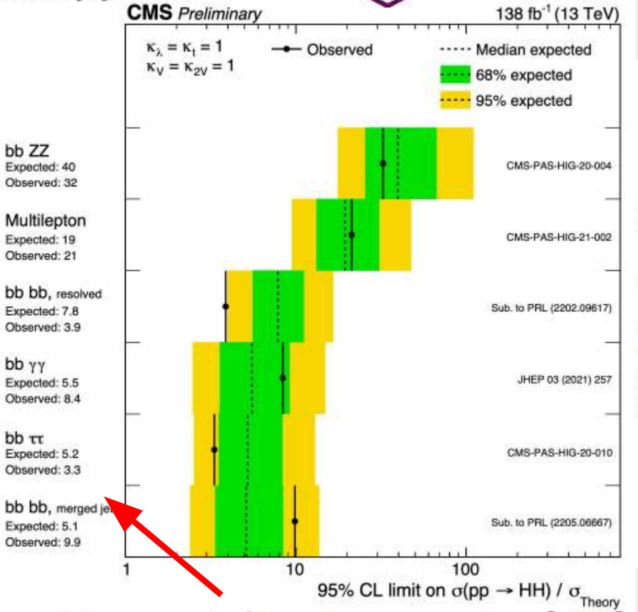
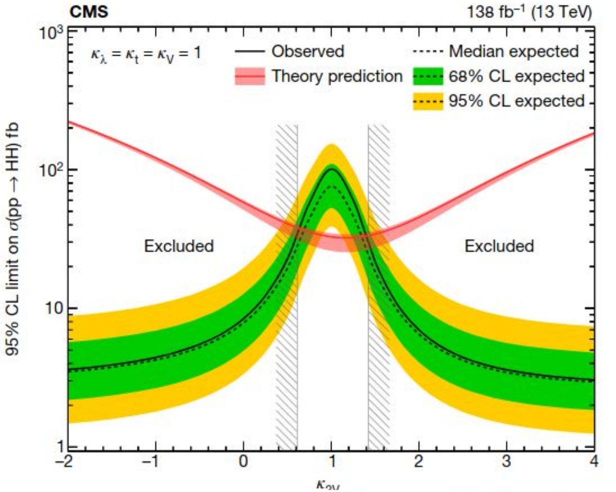
李政道研究所 TSUNG-DAO LEE INSTITUTE

Nature 607, 52–59; 60-68 (2022)
ATLAS-CONF-2022-050





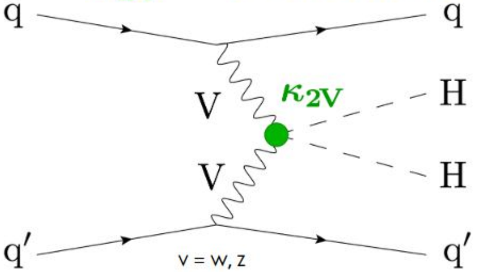


Limits on the Higgs boson self-interaction: sensitivity better than **2.4×SM!** On the way to challenge SM prediction!

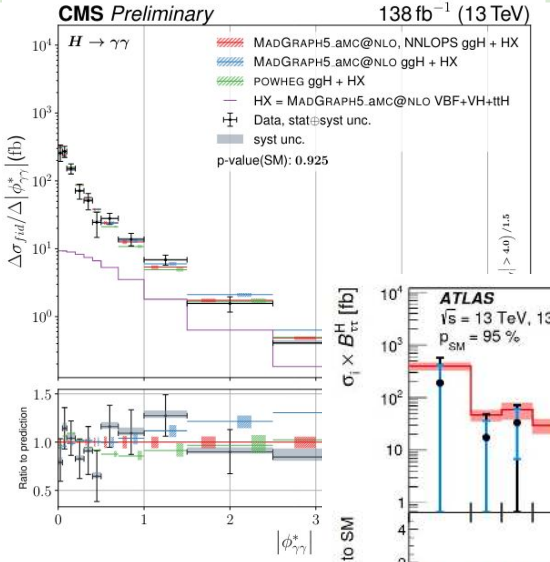
$$-0.4 < \kappa_\lambda < 6.3$$

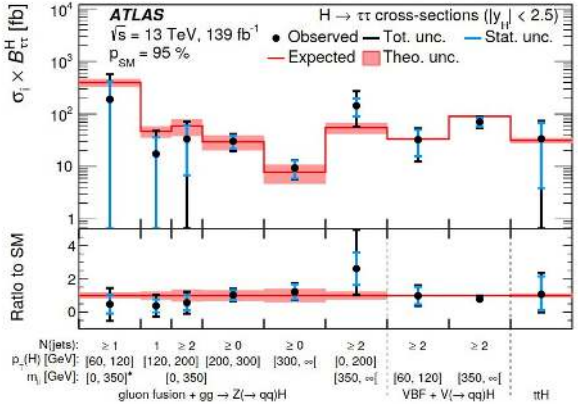
Merged 4b channel in CMS so far presents best expected sensitivity to SM ggF HH production, competitive sensitivity to Higgs self-coupling

$\kappa_{2V} = 0$ excluded

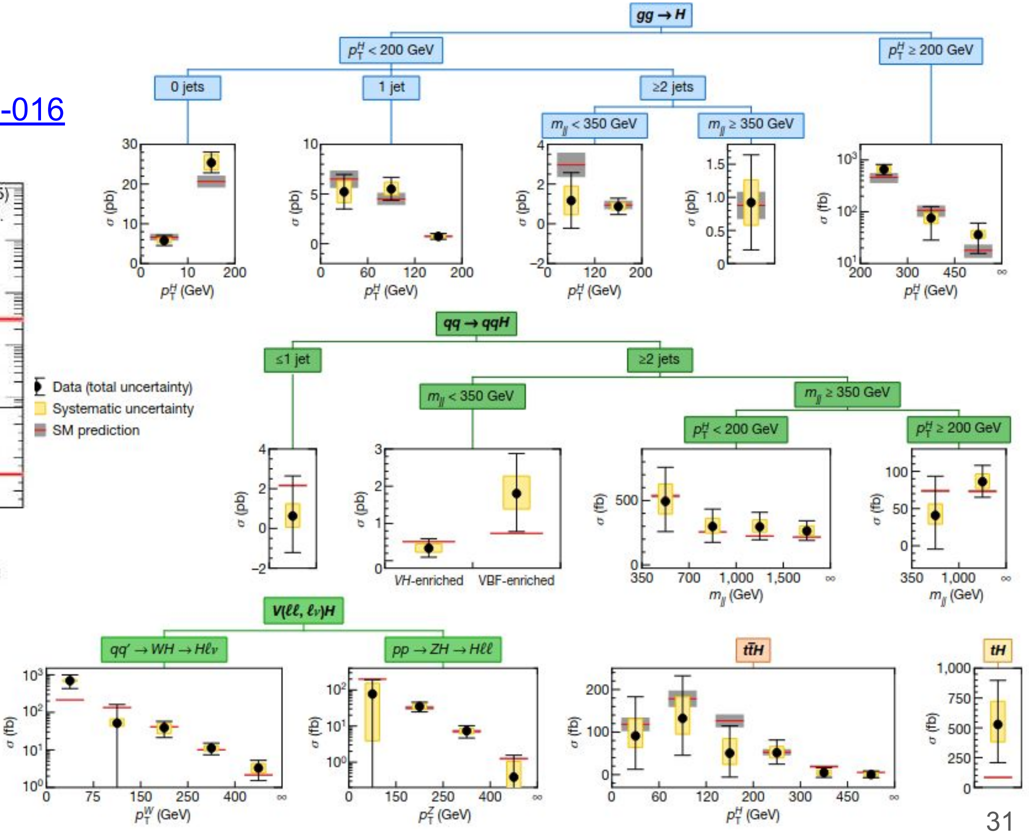


STXS, Differential





arXiv:2201.08269
arXiv:2202.00487
arXiv:2207.08615
arXiv:2207.00338
[CMS-PAS-HIG-19-016](CMS-PAS-HIG-19-016)



Study kinematics in **all production processes in several kinematic regimes** to maximize sensitivity to beyond SM physics while limiting model dependence

Higgs CP

Review of Particle Physics, Particle Data Group (2022)

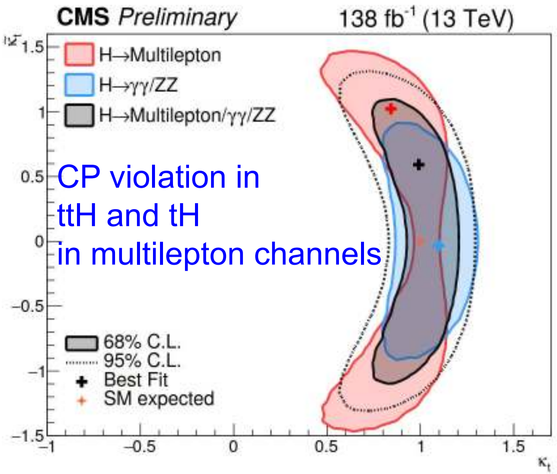
Citation: R.L. Workman *et al.* (Particle Data Group), to be published (2022)

H^0 $J = 0$

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

H^0 Signal Strengths in Different Channels

Combined Final States = 1.13 ± 0.06
$WW^* = 1.19 \pm 0.12$
$ZZ^* = 1.01 \pm 0.07$
$\gamma\gamma = 1.10 \pm 0.07$
$c\bar{c}$ Final State = 37 ± 20
$b\bar{b} = 0.98 \pm 0.12$
$\mu^+\mu^- = 1.19 \pm 0.34$
$\tau^+\tau^- = 1.15^{+0.16}_{-0.15}$
$Z\gamma <$ 3.6, CL = 95%
$\gamma^*\gamma$ Final State = 1.5 ± 0.5
$t\bar{t}H^0$ Production = 1.10 ± 0.18
tH^0 production = 6 ± 4
H^0 Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV = 56 ± 4 pb



CP violation in ttH and tH in multilepton channels

ATLAS-CONF-2022-032 JHEP06(2022)012 arXiv:2208.02686 arXiv:2205.05120

PARITY
IN DI-TAU DECAYS

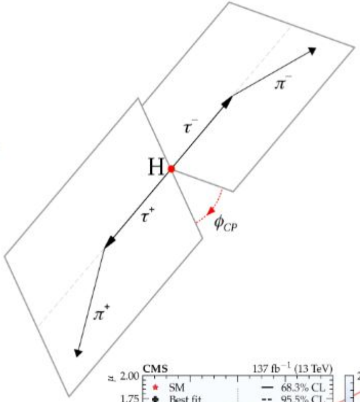
Tau leptons and bosons may interact differently with $H^0(125)$.

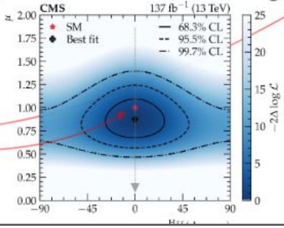
- SM predicts same parity for both.

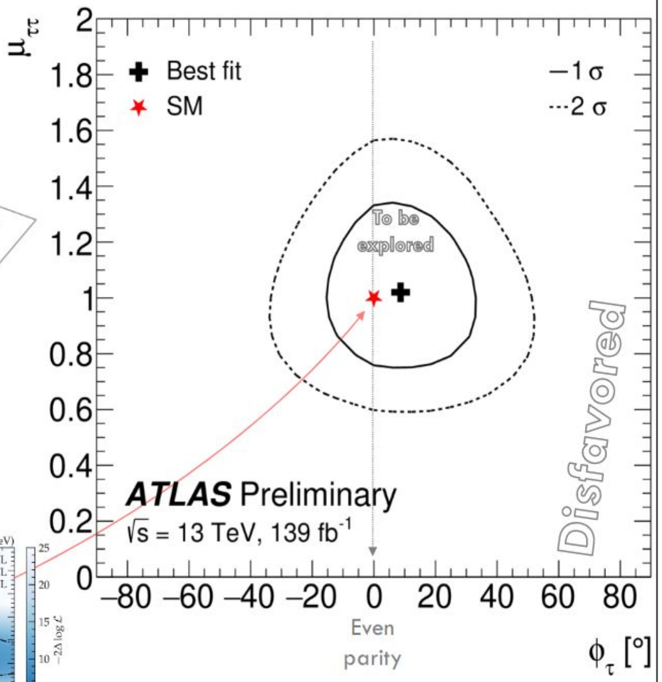
Probed via angular correlations in $H^0(125)\rightarrow\tau\tau$ decays.

Data compatible with even parity and **SM** prediction.

A decade turning the possible into the known





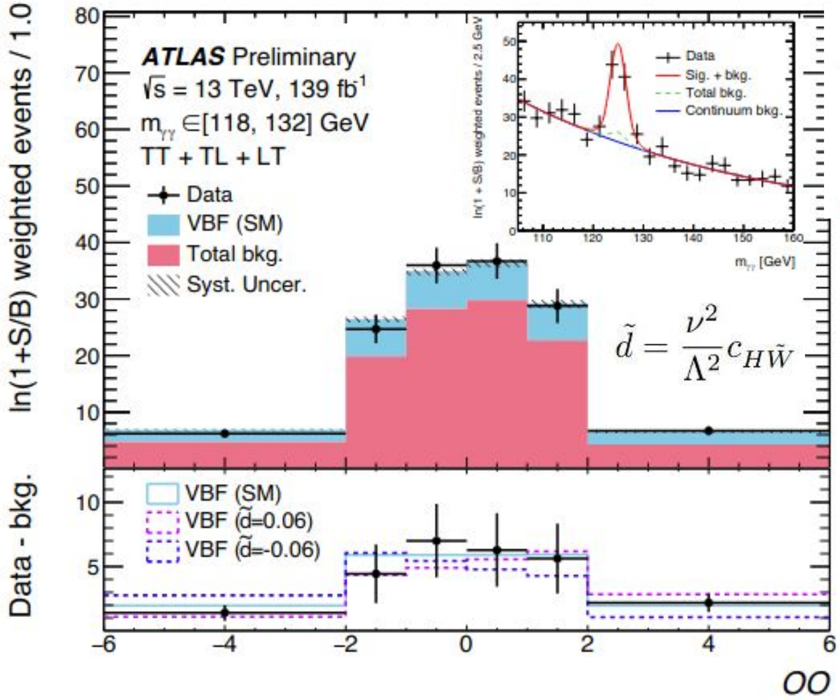


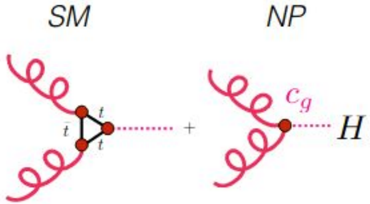
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

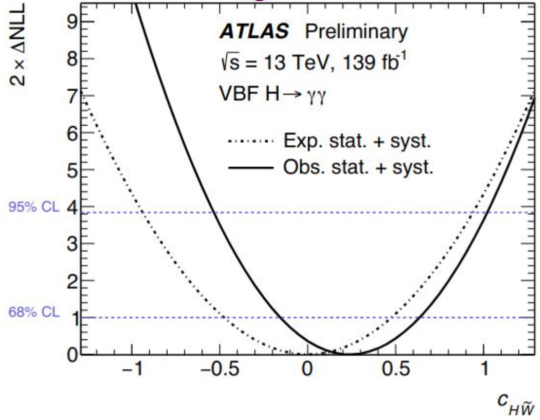
CP, EFT Delmastro 2208.02338 2207.00348

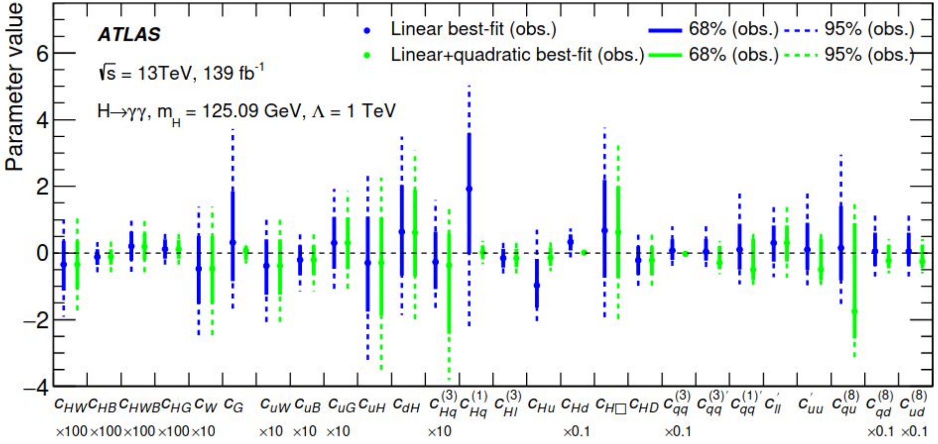
$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

VBF H→γγ/ττ, generic H→γγ









Higgs to Charm

arXiv:2207.08615 arXiv:2201.11428 (EPJC) arXiv:2205.05550 (PRL)

- Indirect and Direct Measurements
- CMS exploits **both merged and resolved** Hcc.
  - exploit advanced GNN-based charm & di-charm jet taggers **深度图神经网络**
  - **huge performance gains in charm tagging with the new ML techniques**
- HL-LHC expected sensitivity reach ~O(0.1-1) level with the use of novel tagger and strategy

Combining $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ p_T measurement and $H \to b\bar{b}$ and $H \to c\bar{c}$ (see

$\kappa_c \subset [-2.5, 2.5]$ at 95% CL

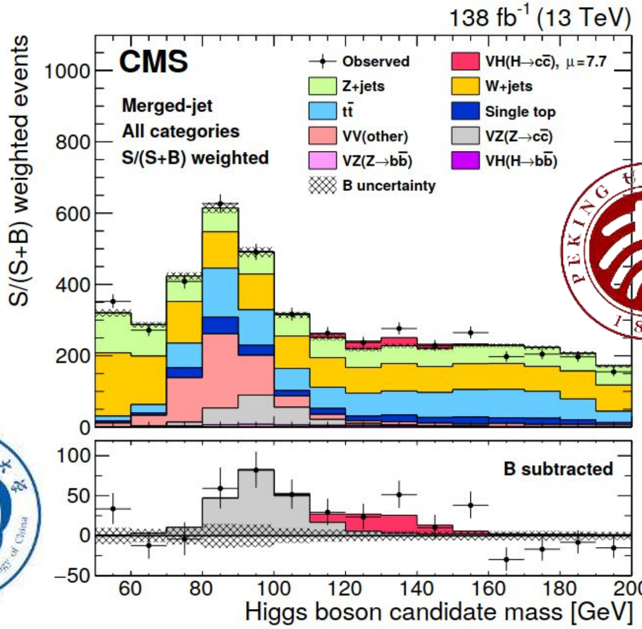
(assuming $\kappa_V = \kappa_t = 1$ and no non-SM decays)

ATLAS

Scenario	Observed 68% confidence interval	Observed 95% confidence interval
$B_{BSM} = 0$	$[-1.61, 1.70]$	$[-2.47, 2.53]$
No assumption on B_{BSM}	$[-2.63, 3.01]$	$[-4.46, 4.81]$

- $\mu_{VH(H\to cc)} < 14$ (7.6) observed (expected) $\mu_{VH(H\to c\bar{c})} = \frac{\kappa_c^2}{1 + \mathcal{B}_{SM}(H\to c\bar{c})(\kappa_c^2 - 1)}$
- setting stronger limit w.r.t. ATLAS full Run 2 result $\mu_{VH(H\to cc)} < 26$ (31) obs. (exp.)

CMS



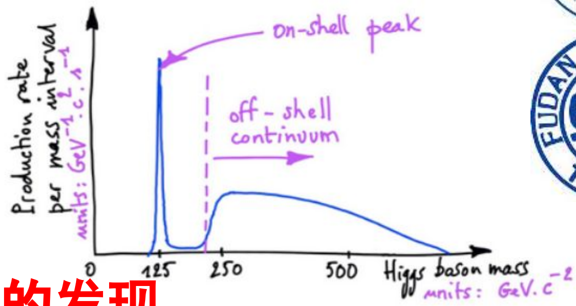
Higgs Width

arXiv:2202.06923 ~accepted by Nature Physics

H→ZZ→4l, 2l2v

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\,\text{MeV}$$

The first evidence for off-shell H boson production
Measurment on Higgs width with precision ~50%



- 2010: Theorists: "It can't be done at the LHC"
- 2012-2013: Theorists: "Maybe it can be done at the LHC" through off-shell interference effects

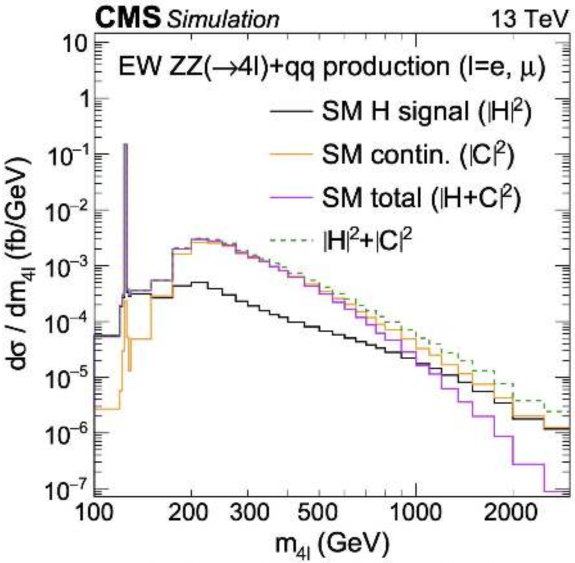
Sally Dawson

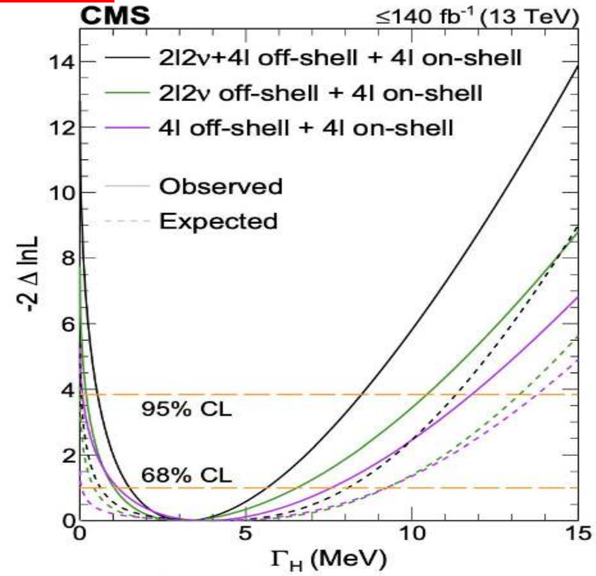
理论家倡导的发现

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}$$

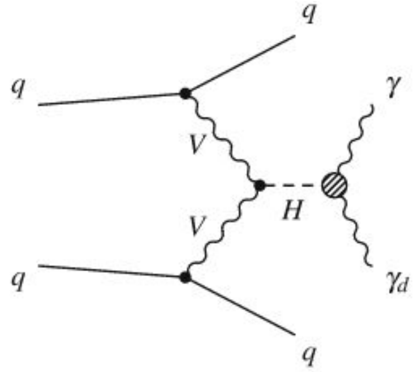
This method assumes that the couplings at the pole and off-shell are the same.

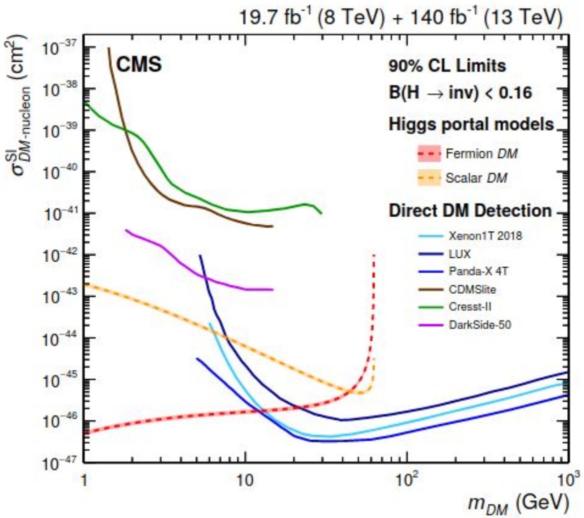




Dark, Invisible, Light Higgs

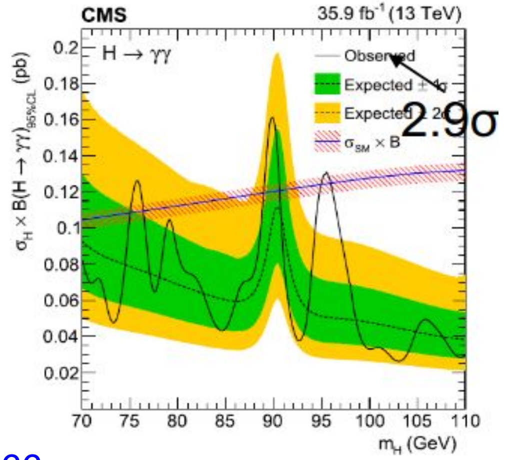
Dark Photon
[EPJC 82 (2022) 2, 105]





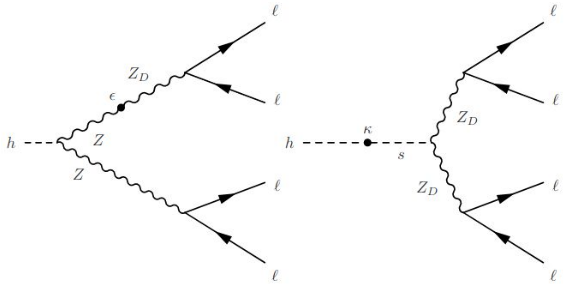
[PRD105 (2022) 092007] (CMS)

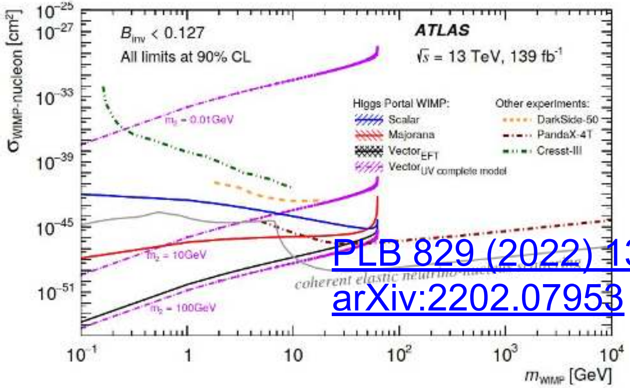
- Higgs Invisible Decay **0.18 (0.10) at the 95% C.L.**
- Spin-independent DM-nucleon scattering cross section in Higgs-portal models



Low mass Higgs⟶di-photon
[PLB 793 (2019) 320]

Higgs Related Dark Sector
[EPJC 82 (2022) 290]



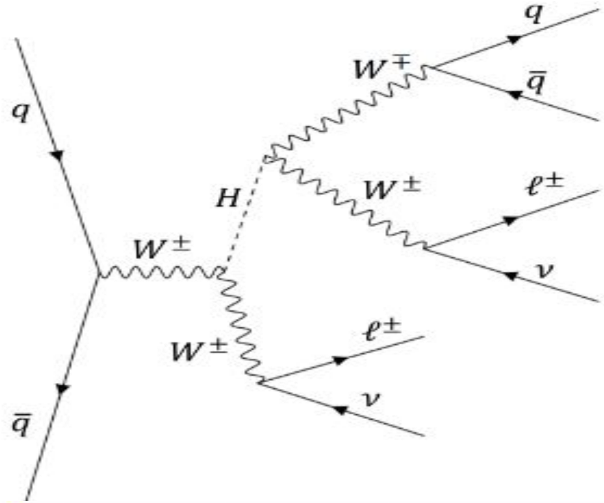


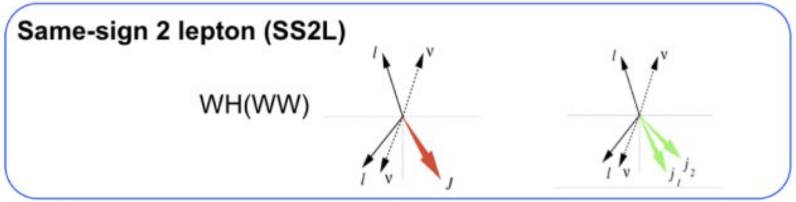
[PLB 829 (2022) 137066]
[arXiv:2202.07953]

Heavy Higgs

ATLAS-CONF-2022-033 ATLAS-CONF-2022-043

Model-independent search for a Generic Heavy Higgs boson (H) having both dim-4 and dim-6 interactions with SM particles

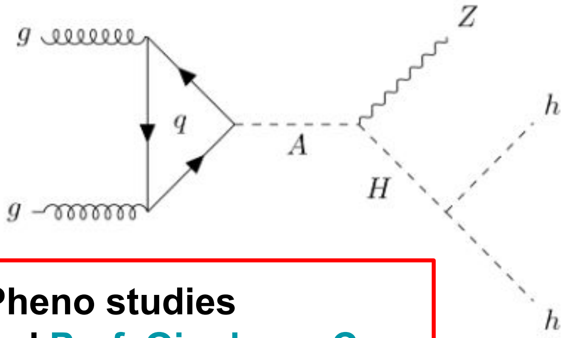




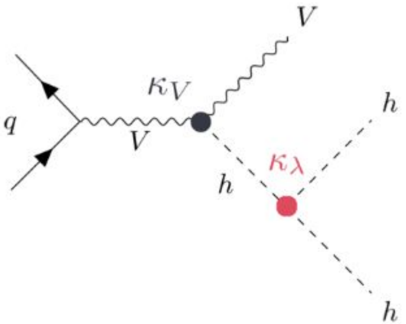
Vhh final states:

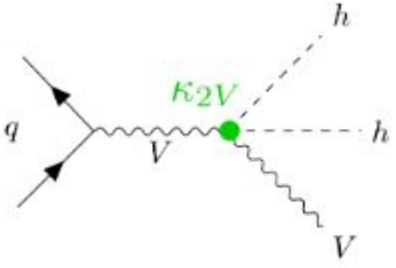
HHH and HHVV couplings

Heavy Higgs→hh



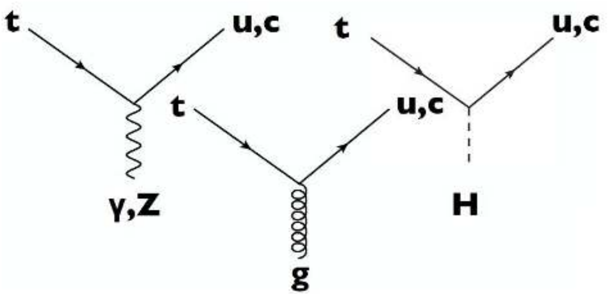
Inspired by Chinese Pheno studies
Prof. Yuping Kuang and Prof. Qinghong Cao





FCNC arXiv:2205.02537 ATLAS-CONF-2022-014 ATLAS-CONF-2021-049

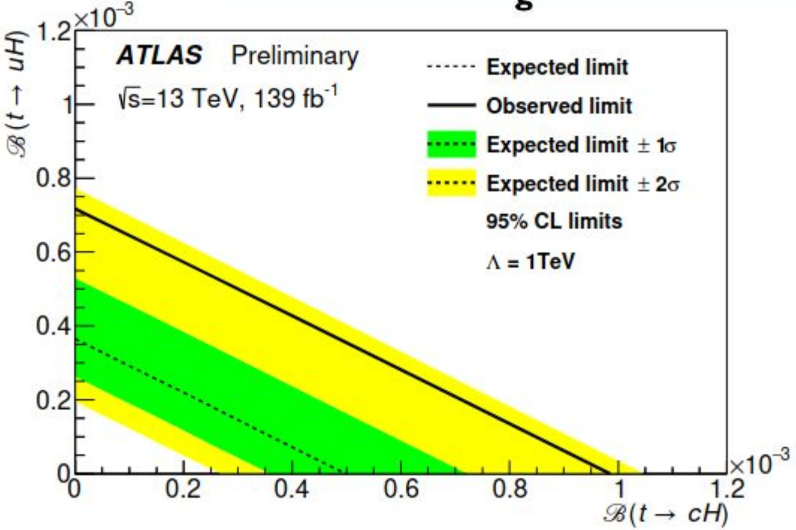
- **A factor of ~5 (2.5) improvement for expected (observed) upper limit**
  The statistical uncertainty is the dominant contribution
- **t → qZ, t → qγ, t → qg also updated by ATLAS**



Flavor-changing neutral currents (FCNC) decays

- are forbidden at tree level
- occur at one-loop level but are strongly suppressed by the **GIM mechanism**
- significantly enhanced in BSM extensions (maximum up to ~10^{-3})
- Any observation of top FCNC = BSM physics

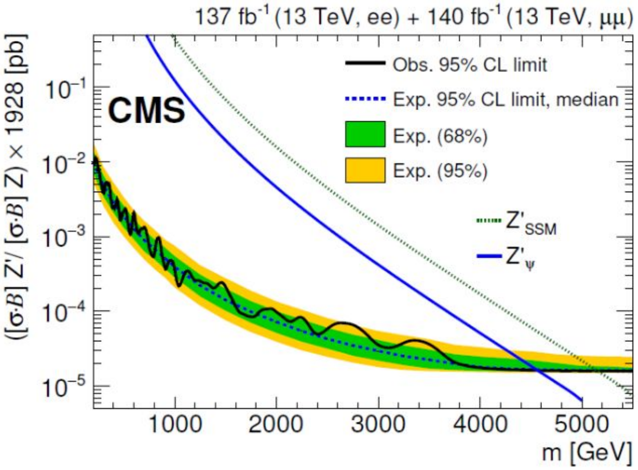
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$



X→ll, ll’

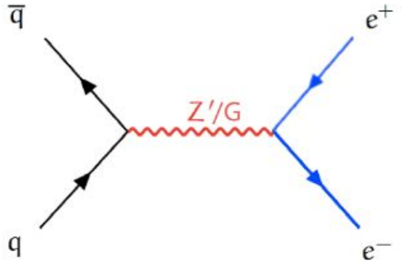
arXiv:2205.06709 JHEP 07, 208 2021 JHEP 06, 082 (2022)

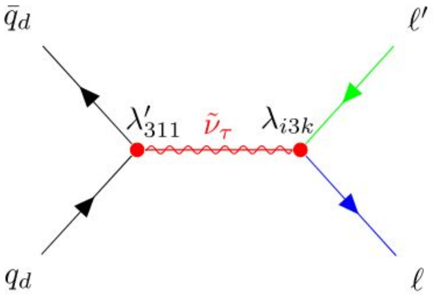
Flagship analysis on new physics searches at the LHC
Stringent limit set on SM-like Z’ above 5 TeV

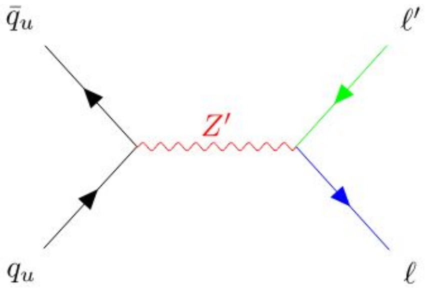


Channel	Z'_{SSM} Obs. [TeV]	Z'_{SSM} Exp. [TeV]	Z'_{ψ} Obs. [TeV]	Z'_{ψ} Exp. [TeV]
ee	4.72	4.72	4.11	4.13
μμ	4.89	4.90	4.29	4.30
ee + μμ	5.15	5.14	4.56	4.55

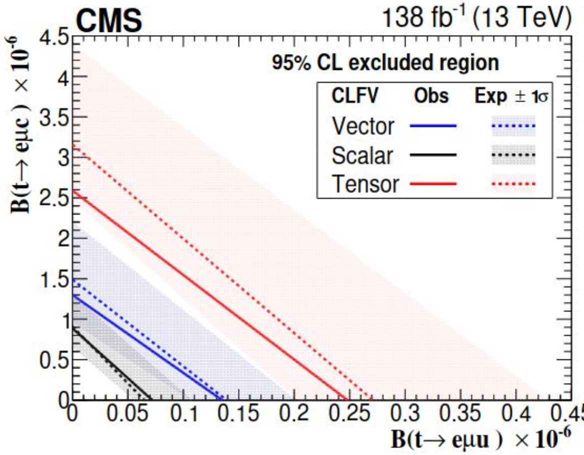
138/fb	SUSY RPV $\tilde{\nu}_\tau$ ($\lambda = \lambda' = 0.1$)	QBH (ADD, n=4)	Z’ (Br = 10%)
$e\mu$	4.2 TeV	5.6 TeV	5.0 TeV
$e\tau$	3.7 TeV	5.2 TeV	4.3 TeV
$\mu\tau$	3.6 TeV	5.0 TeV	4.1 TeV







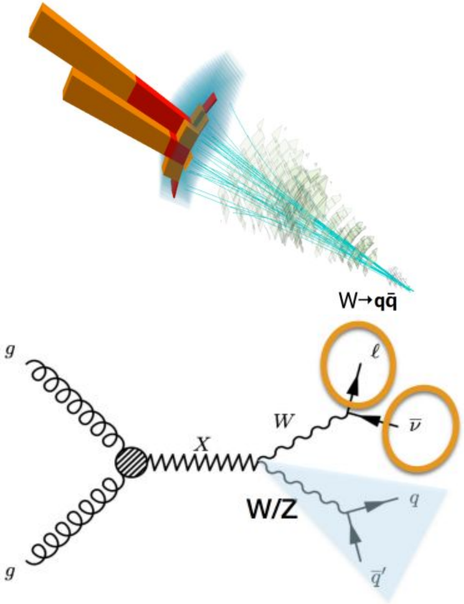
Top quark related CLFV also explored

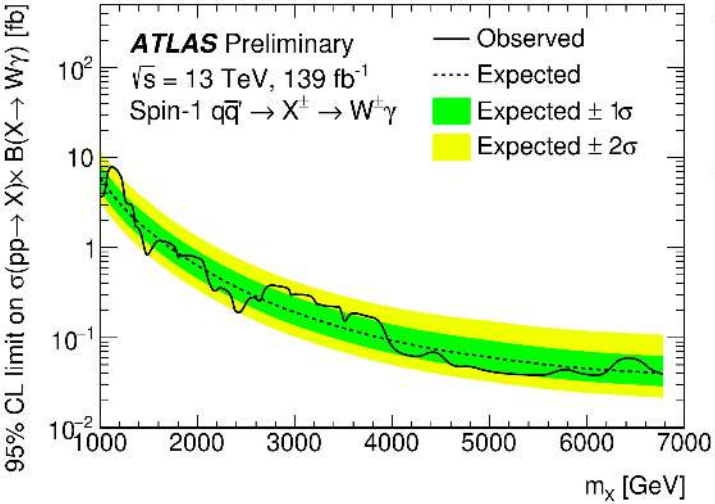


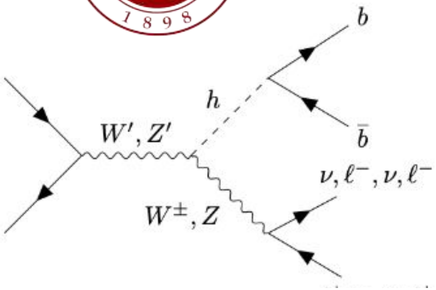
Di-boson Resonances

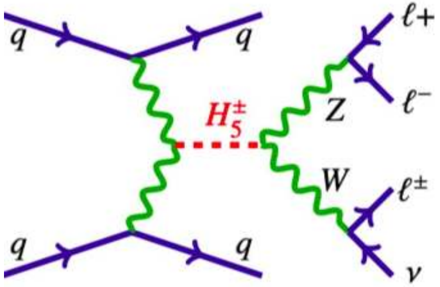
PRD 105 (2022) 032008 ATLAS-CONF-2021-041 2207.00230 2207.03925

New Particle decays into Diboson favored in various models:
Extra Dimension, Heavy Vector Triplet, 2HDM, Georgi Machacek …
<u>Rich developments and applications</u> of advanced technique on (boosted) jet in last years:
PileUp Per Particle Identification (PUPPI); W/H tagging; Nsubjettiness; Softdrop; Grooming; Deep learning tagger (DeepAK, ParticleNet)









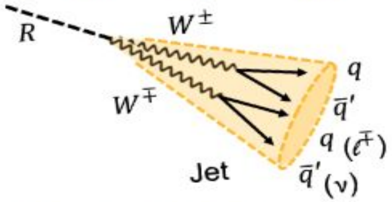
Tri-boson Resonances

PRL129 (2022) 021802 PRD 106 (2022) 012002

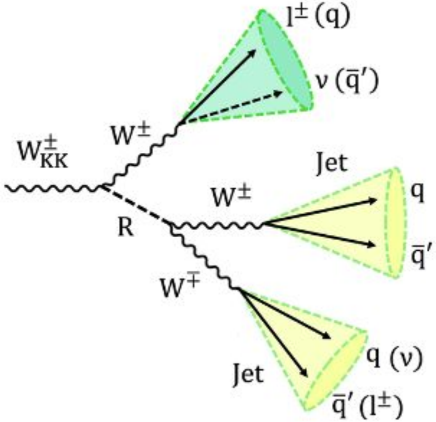
First tri-heavy W boson resonance search

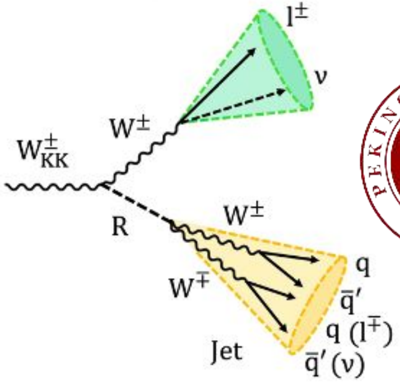
Novel tagging and calibration method for 3/4 prone quark Fat jets

$R \approx R^{4q} + R^{3q} + R^{lqq}$

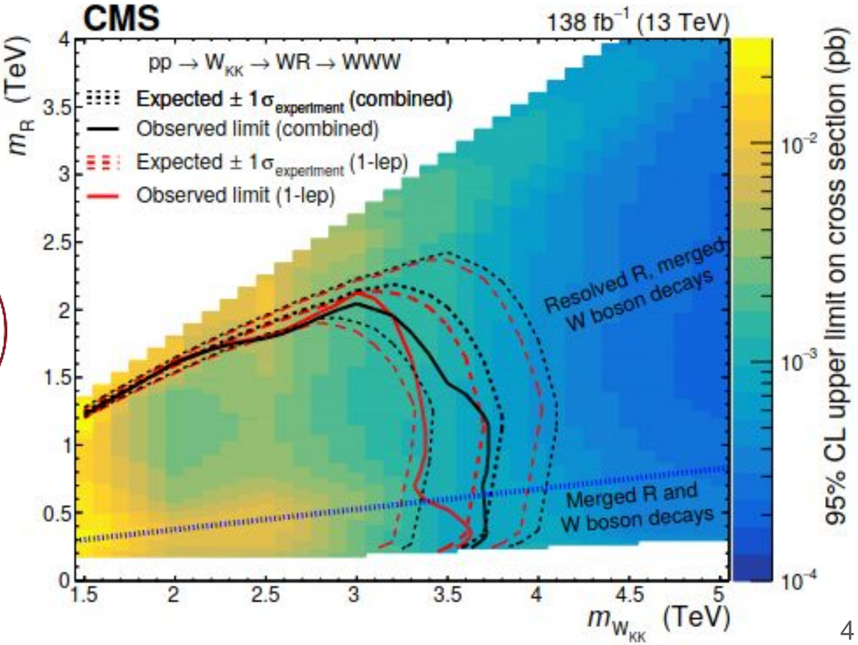


We do NOT have standard candle in SM to calibrate all these





CMS Physics Briefing
https://cms.cern/news/wwwtribosoncms-0



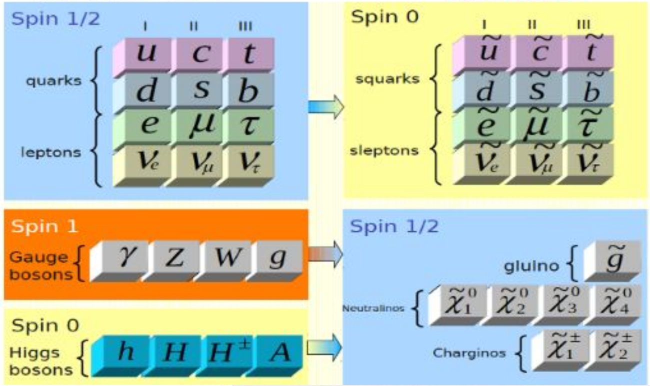
SUSY

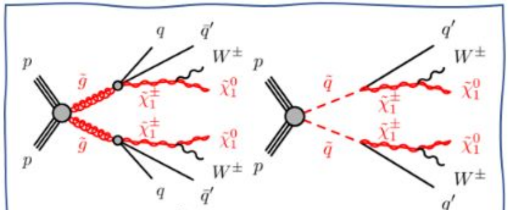
EPJC 81 (2021) 600　ATLAS-CONF-2022-042

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

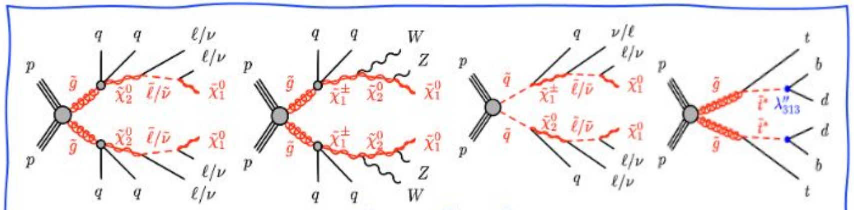
强作用产生过程 squark，gluino 粒子	弱作用产生过程 gaugino，slepton 粒子	总结性文章
1. 1轻子末态~q/~g寻找 Eur. Phys. J. C 81 (2021) 600	3. Tau末态stau寻找 *ANA-SUSY-2019-17	8. EWK Combination *ANA-SUSY-2020-05
	4. Tau末态gaugino寻找 ATL-CONF-2022-045	
2. 同号2轻子和3轻子末态~q/~g寻找 *ANA-SUSY-2020-27	5. 1轻子末态gaugino寻找 *ANA-SUSY-2019-19	9. Grand pMSSM Scan *ANA-SUSY-2020-14
	6. 同号2轻子和3轻子末态gaugino寻找 *ANA-SUSY-2019-22	
	7. 0轻子末态紧致gaugino寻找 *ANA-SUSY-2020-04	

我们的世界…　　新世界?

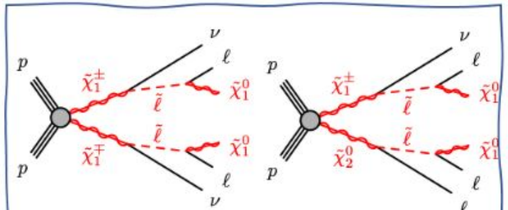




一轻子



同号两轻子或三轻子



Via slepton decay

Eur. Phys. J. C 81 (2021) 600

Heavy Neutrino

arXiv:2206.08956 ~ accepted by PRL

arXiv > hep-ph > arXiv:0901.3589

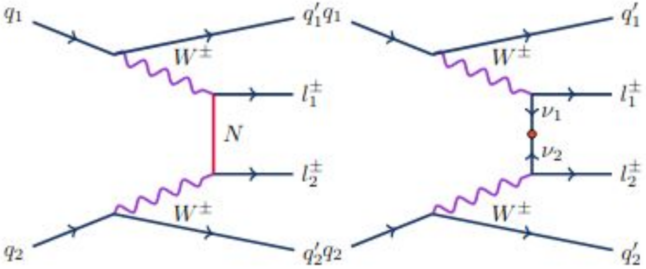
High Energy Physics - Phenomenology

[Submitted on 23 Jan 2009 (v1), last revised 7 May 2009 (this version, v2)]

The Search for Heavy Majorana Neutrinos

Anupama Atre, Tao Han, Silvia Pascoli, Bin Zhang

First Search through VBS channel



- Address neutrino mass

✓ Heavy Majorana neutrino HMN (see-saw) → neutrinoless VBF t-channel (high mass sensitivity, new!)

✓ Effective field theory (EFT): dim-5 Weinberg operator (WO) → m_ν with no new fields

→ Analogous to neutrinoless double β decay, but with μ (instead of e)

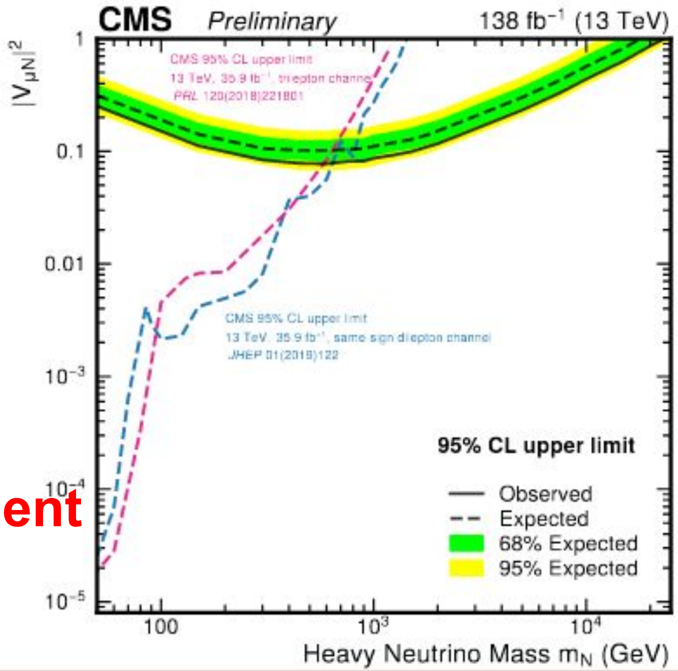
- Final state: two same sign $\mu\mu$ and VBF jets
- Dedicated studies to identify high-p_T μ

~23TeV!

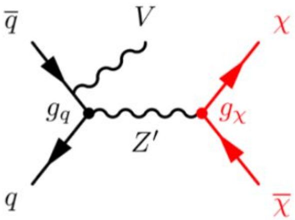
0νμμ experiment

- Limits exclude
  - HMN up to $m_N = 23$ TeV
  - Effective Majorana mass up to $m_{\ell\ell} = 10.84$ GeV

  → First constraints for this process!

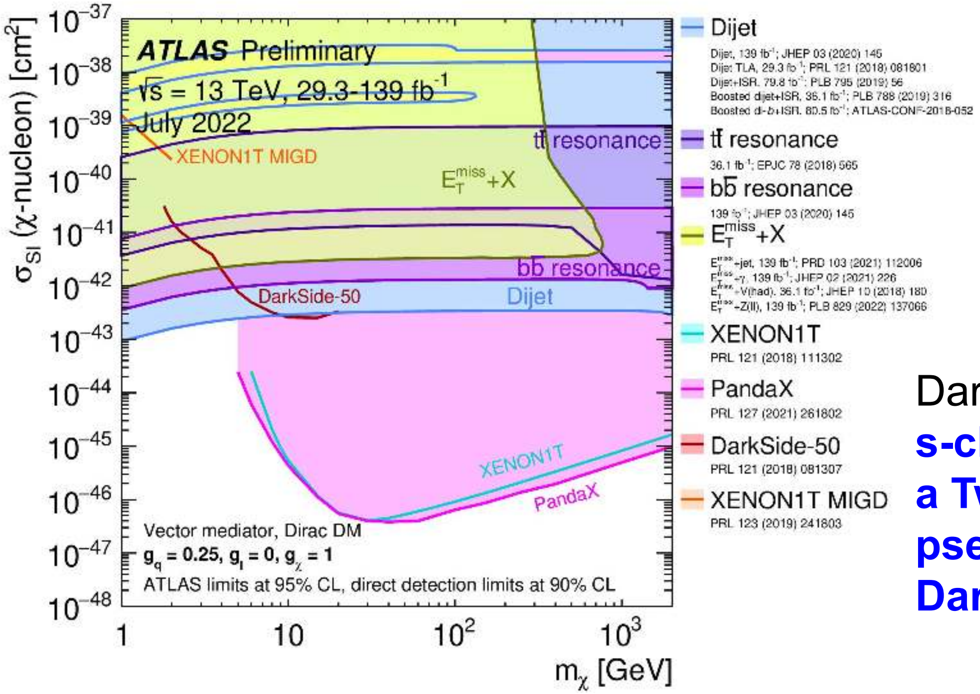


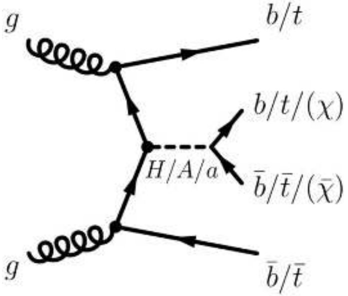
Dark matter [ATLAS-CONF-2021-036](#) [ATL-PHYS-PUB-2022-036](#)

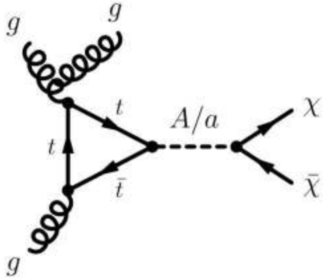


李政道研究所 TSUNG-DAO LEE INSTITUTE

MET+H(bb), and MET+Z(ll) searches. **Reinterpreted** in a common benchmark model: a Two-Higgs-Doublet Model with a pseudoscalar mediator.



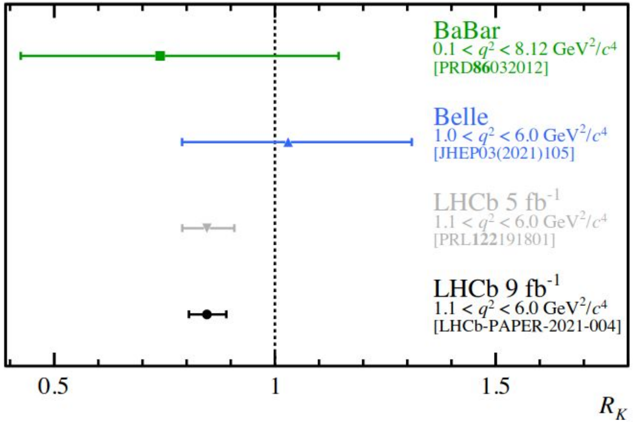


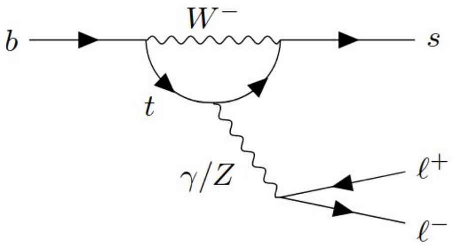


Dark matter simplified models with **s-channel Spin-1 and Spin-0 mediators, a Two-Higgs-Doublet model with a pseudoscalar mediator (2HDM+a) and Dark Higgs model**

LFUV related Leptoquark, VLL, VLq

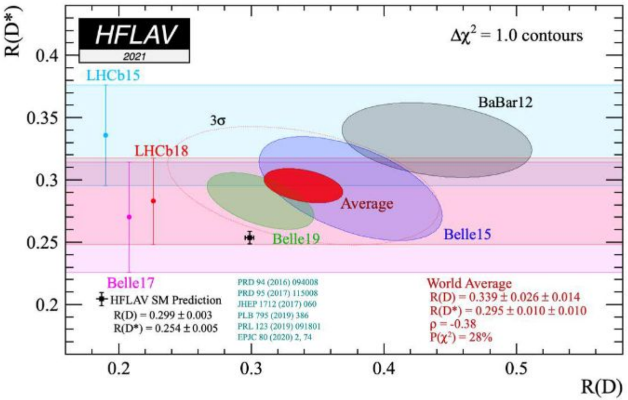
More details@LF(U)V Workshop: July 04-06, 2022 Zurich and 110th Plenary ECFA

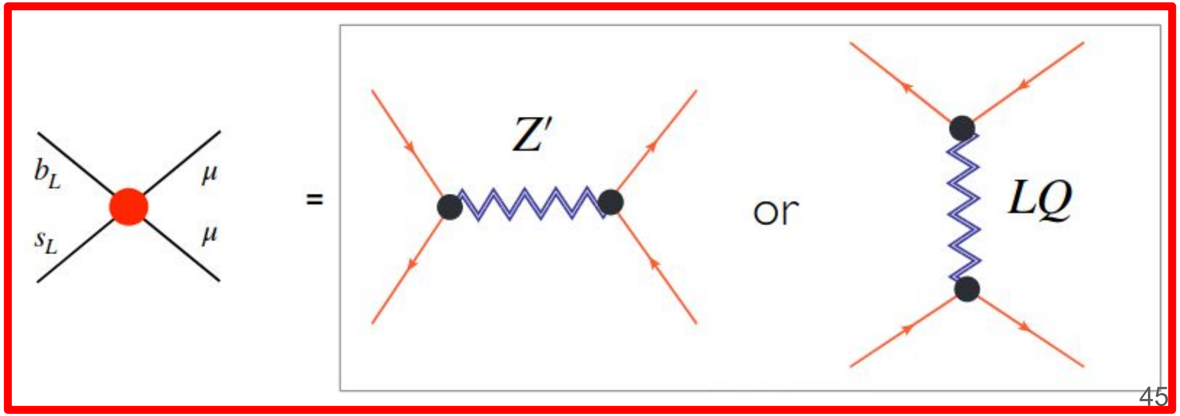




$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

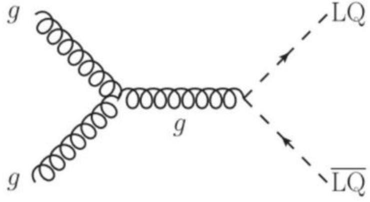
At high energy probe: Z', leptoquark, or more complete New Physics models

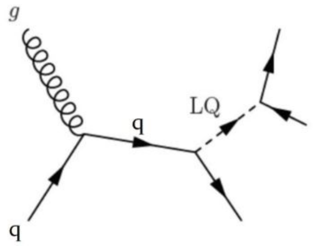




LFUV related Leptoquark, VLL, VLq

Search for singly and pair-produced leptoquarks coupling to 3rd generation fermions





PLB 819 (2021) 136446


A report from the CMS experiment

News · News · Topic: Physics

CERN News

Voir en français

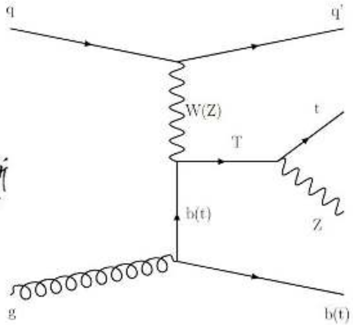
CMS sets new bounds on the mass of leptoquarks

The bounds are some of the tightest yet on the existence of third-generation leptoquarks

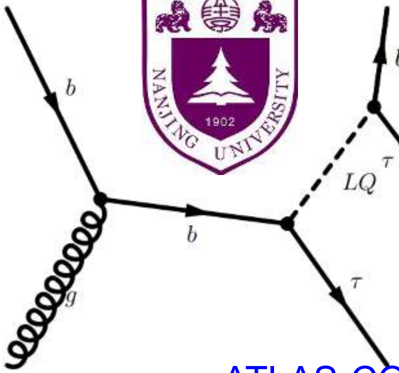
18 DECEMBER, 2020 | By Ana Lopes

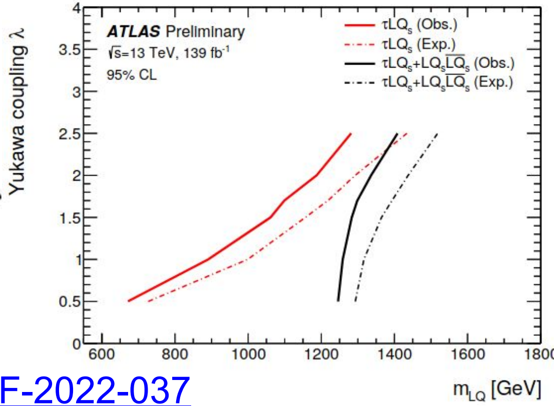
single production of a vector-like T quark decaying to a top and a Z boson

Institute of High Energy Physics
Chinese Academy of Sciences



JHEP 05 (2022) 093

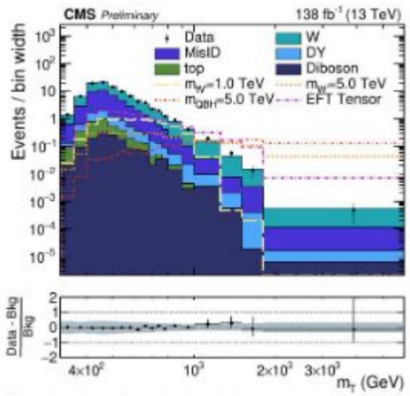


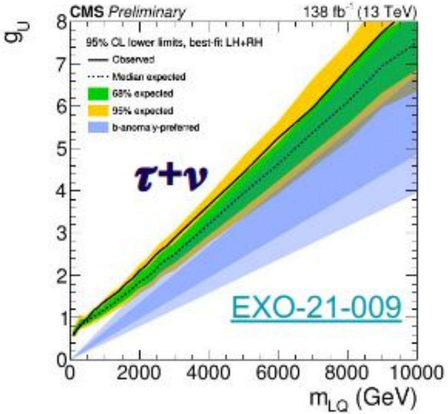


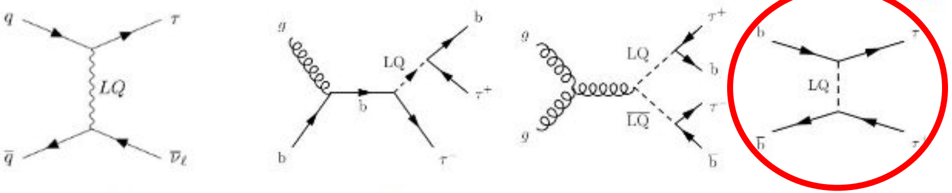
ATLAS-CONF-2022-037

Searches related to b-anomalies with τ

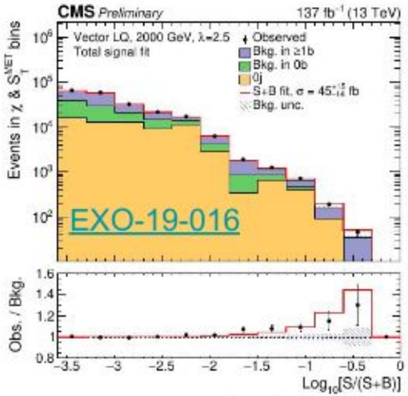
New@ICHEP

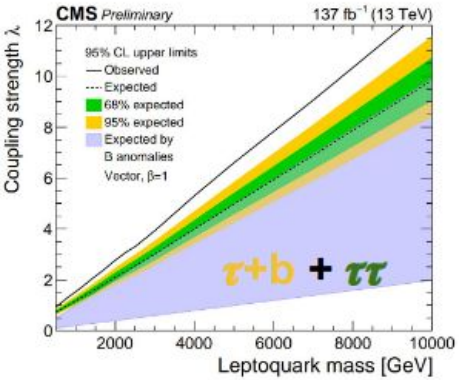


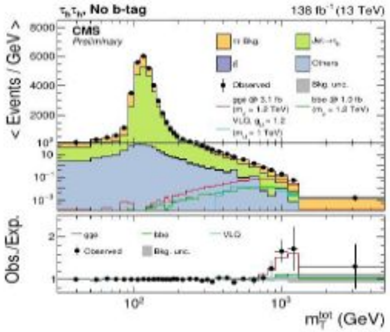


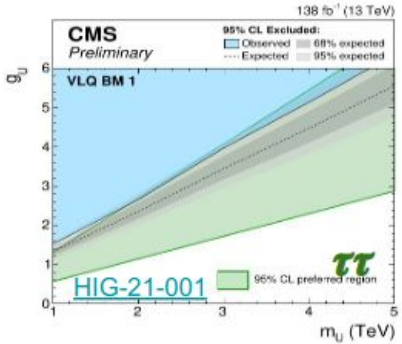


- Final states with **τ+ν**, **τ+b** and **ττ** are investigated
- Good probe of models **related to b-anomalies** (e.g. leptoquark)
- Sensitivity approaching the "preferred" region from b-anomalies in some LQ models
- Some sizeable excess in non-resonant **ττ** final state (seen by two different analyses)





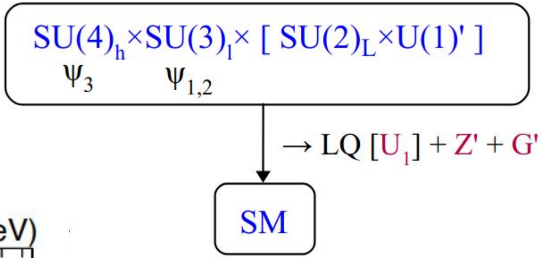




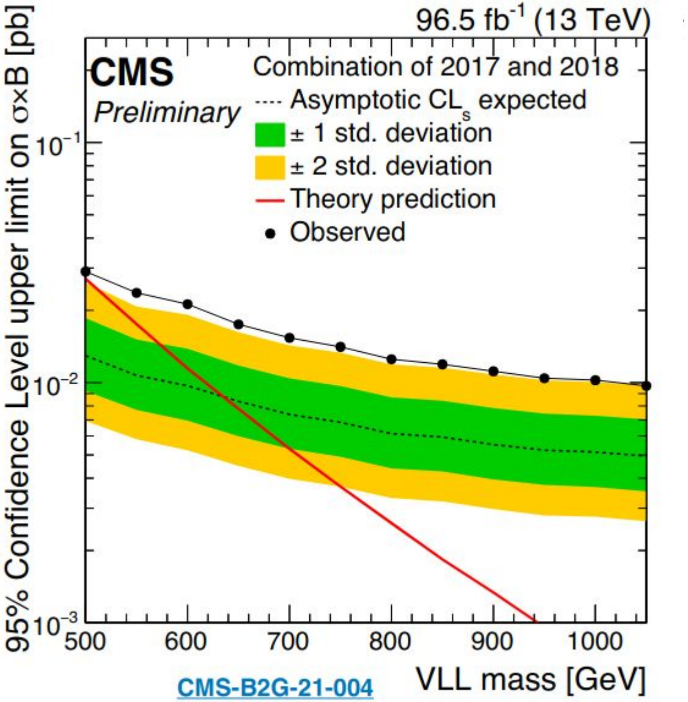
17

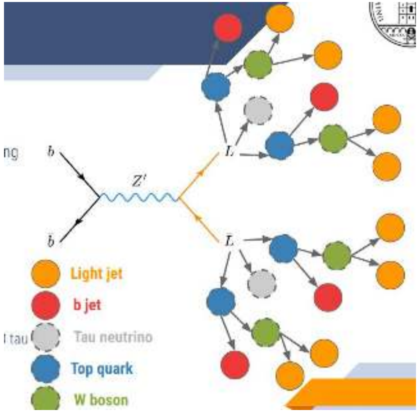
Searches with UV Complete Model containing LQ

CMS-PAS-B2G-21-004

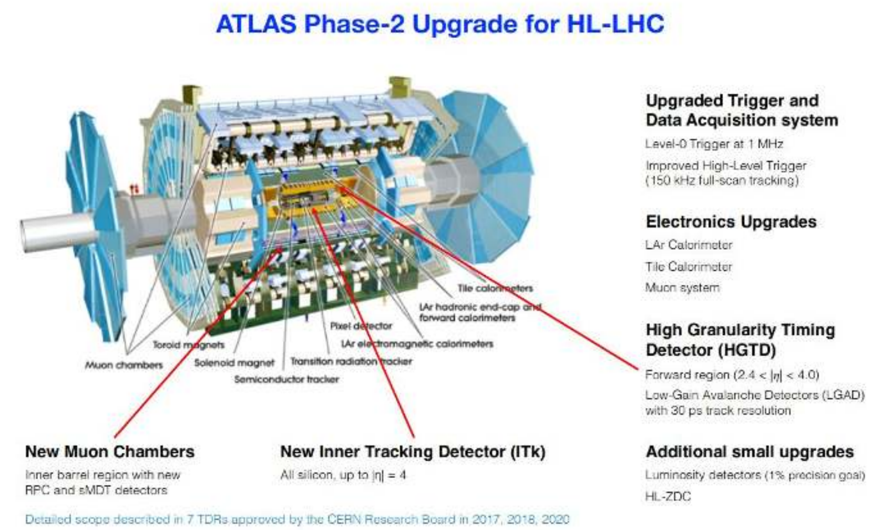


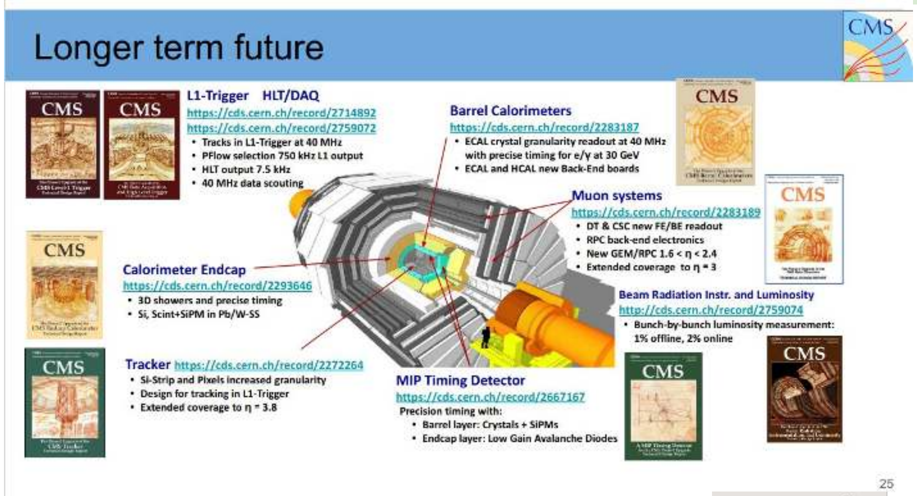
- A structured explanation of the anomalies (e.g., 4321 model) imply a SUSY-like scenario
  - production of heavy colored particles
  - cascade decays to lighter states
  - multi-body final states with quarks and leptons
  - expected third-generation dominance





Hardware Upgrade





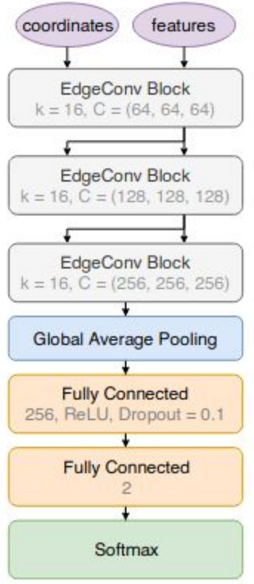
- 高能所、清华ATLAS团队参与硅微条内径迹探测器升级，承担重要任务。
- 高能所、中科大、南京大学、山东大学等ATLAS团队，在高颗粒度高时间分辨探测器（HGTD）项目中占主导地位，担任项目经理等多个管理职务。
- 中科大、山大、上交ATLAS团队在缪子探测器升级上起重要作用。
- 高能所、清华、复旦、浙大等国内CMS团队参与高粒度量能器项目，通过模块集成中心认证。
- 高能所CMS团队在RPC后端触发电子学，北大、北航、清华、中山CMS团队在GEM升级项目等起了重要作用。CMS中国团队拓展参与MTD升级项目。

Summary

- **LHC has great potential and future**
  - More Higgs to be produced and explored
  - Large Photon Collider & Large Boson Collider
  - Going Deeper
  - **More mysteries to be explored**
    - LFUV, W mass, Neutrino mass, dark matter, muon g-2…
- **Chinese Groups have made many contributions in various aspects.**
  - From Higgs to X
- **Run 3 is ongoing. Keep Tuned!**
  - Join us!:)

LHC: the Large gauge Bosons Collider

LHC: the Large pHoton Collider



(a) ParticleNet

tantalizing

PUT IT UNDER MICROSCOPE
STUDY IT TO DEATH!

Nima Arkani-Hamed 奋斗到底

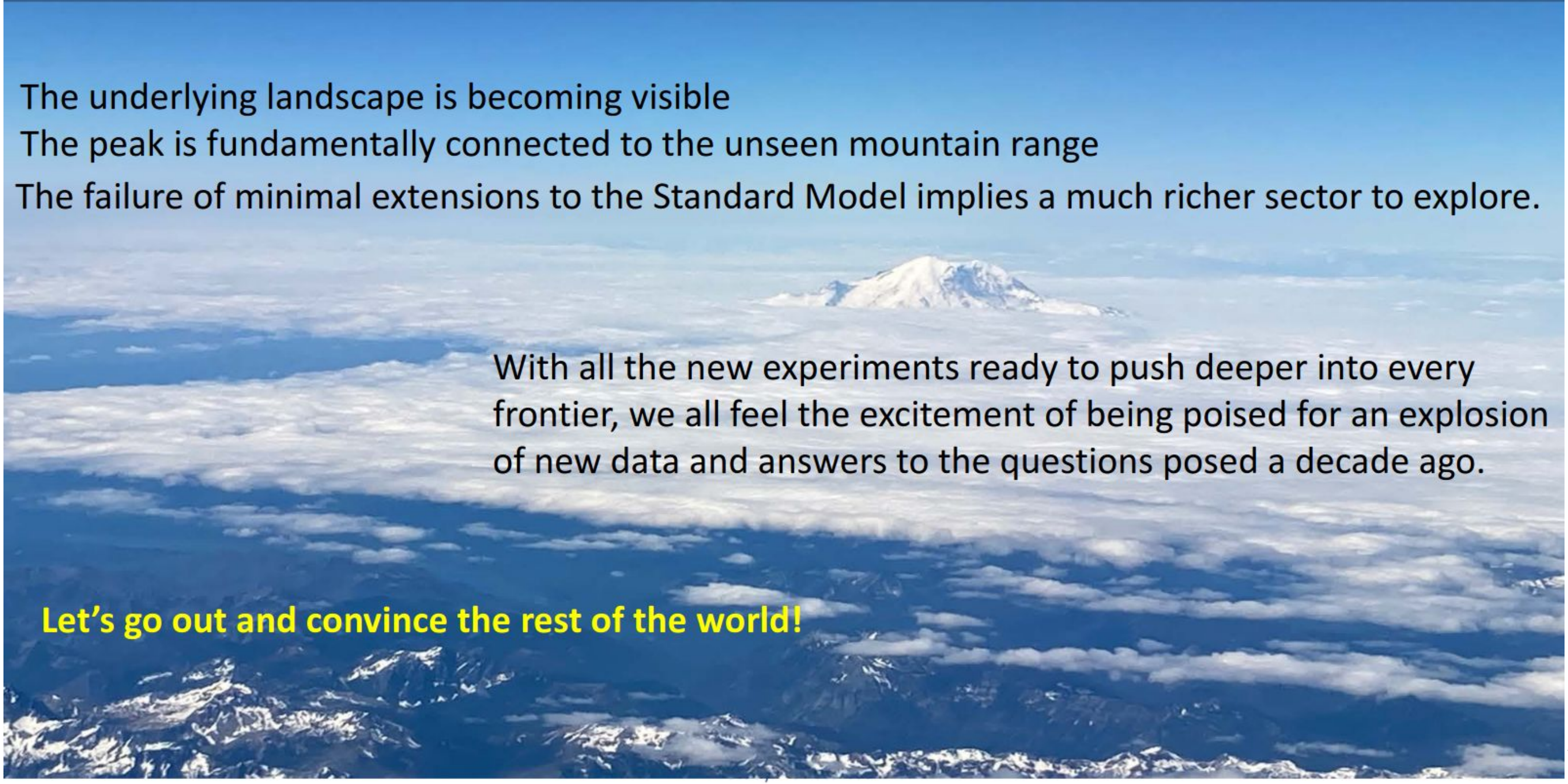
"If at the end of Run-2 you will see no 3 sigma deviations, you will never discover anything new, until at least HL-LHC" (anonymous)

- => multiple 2-3 sigma tensions, it will be fun understanding what they are (Bad background models? Statistical fluctuations? New physics?)

Andrea Rizzi 反常可期

https://indico.fnal.gov/event/22303/contributions/246087/attachments/158149/207438/Cushman_Distillation.pdf

The Beginning of a new era




P
+
BACKUP

https://indico.fnal.gov/event/22303/contributions/246087/attachments/158149/207438/Cushman_Distillation.pdf

The Science Message

The 2014 P5 Physics Drivers

- Use the **Higgs boson** as a new tool for discovery.
- Pursue the physics associated with **neutrino mass.**
- Identify the new physics of **dark matter.**
- Understand **cosmic acceleration**: dark energy and inflation.
- **Explore the unknown**: new particles, interactions, physical principles

These are STILL the physics drivers because we have not answered ANY of the questions we posed in Snowmass 2013.

All that money and you still don't know the answers?

Potential pitfall if we concentrate only on BSM physics, rather than on our achievements in measuring Standard Model parameters and expanding our dizzying array of new detectors, accelerators, and cosmic probes.

The 2013 Snowmass Summary Questions

1. How do we understand the Higgs boson? What principle determines its couplings to quarks and leptons? Why does it condense and acquire a vacuum value throughout the Universe? Is there one Higgs particle or many? Is the Higgs particle elementary or composite?

2. What principle determines the masses and mixings of quarks and leptons? Why is the mixing pattern apparently different for quarks and leptons? Why is there CP violation in quark mixing? Do leptons violate CP?

3. Why are neutrinos so light compared to other matter particles? Are neutrinos their own antiparticles? Are their small masses connected to the presence of a very high mass scale? Are there new interactions that are invisible except through their role in neutrino physics?

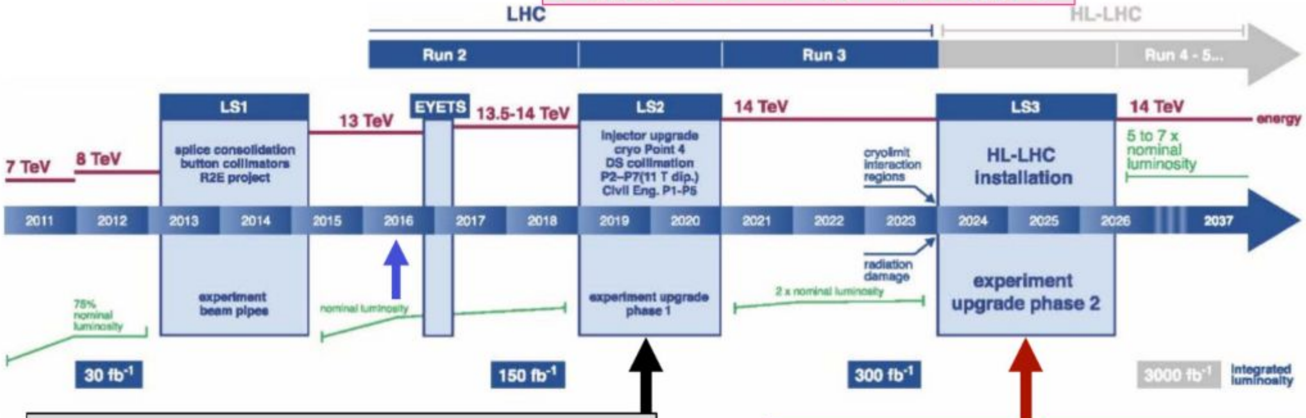
4. What mechanism produced the excess of matter over anti-matter that we see in the Universe? Why are the interactions of particles and antiparticles not exactly mirror opposites?

5. Dark matter is the dominant component of mass in the Universe. What is the dark matter mad
What principle d
Are the dark mat
or are they part o

The landscape has changed,
but the fundamental physics drivers have not

Paradigms have shifted, requiring new search strategies

具体请参考王建春老师的报告



LS2 (2019-2020):
- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

Atlas：
NSW: 科大/山大

LS3 (2024-2026):
- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

ATLAS：
ITK：高能所/南大/清华
缪探测器RPC：科大/交大/山大
HGTD：所有7家单位

CMS：
HGCal：高能所/浙大/复旦/清华/南师
GEM升级：北大/清华/中大/北航/南师
iRPC/RPC系统backend电子学：高能所

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https://indico.ihep.ac.cn/event/10906/session/13/contribution/377/material/slides/0.pdf https://indico.cern.ch/event/1135177/contributions/4764266/attachments/2474228/4248469/Higgs10_CERN_Tanaka.pdf

Higgs Signal Strength

LO κ-framework

$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

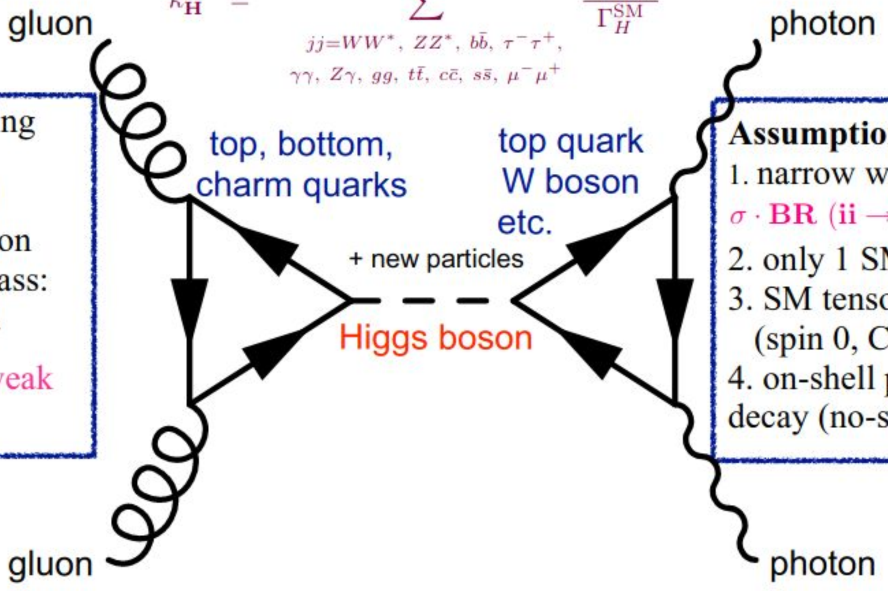
$$\mu = \frac{(\sigma \cdot \mathrm{BR})(gg \to \mathrm{H} \to \gamma\gamma)}{\{\sigma(gg \to \mathrm{H}) \cdot \mathrm{BR}(\mathrm{H} \to \gamma\gamma)\}_{\mathrm{SM}}} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

$$\kappa_{\mathbf{H}}^2 = \sum_{\substack{jj=WW^*,\ ZZ^*,\ b\bar{b},\ \tau^-\tau^+,\\ \gamma\gamma,\ Z\gamma,\ gg,\ t\bar{t},\ c\bar{c},\ s\bar{s},\ \mu^-\mu^+}} \frac{\kappa_j^2 \Gamma_{jj}^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

- Measure with coupling scale factors κ_i.
- The coupling of SM particles to Higgs boson scales with particle mass:

$$g_F = \sqrt{2}\frac{m_f}{v},\ g_V = 2\frac{m_V^2}{v}$$

- Holds up to electroweak effects of O(5-10%).



Assumptions

1. narrow width approx.
$\sigma \cdot \mathbf{BR}\ (\mathbf{ii} \to \mathbf{H} \to \mathbf{ff}) = \frac{\sigma_{\mathbf{ii}} \cdot \Gamma_{\mathbf{ff}}}{\Gamma_{\mathbf{H}}}$
2. only 1 SM-like Higgs
3. SM tensor structure (spin 0, CP-even)
4. on-shell production and decay (no-sense for offshell)

https://indico.cern.ch/event/1135177/contributions/4788686/attachments/2473932/4246031/Higgs10_xsandcouplings_AdeWit_04Jul.pdf

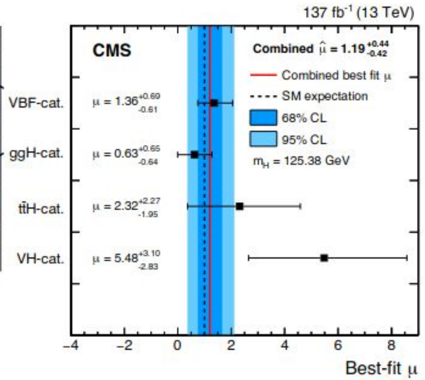
Cross section measurements

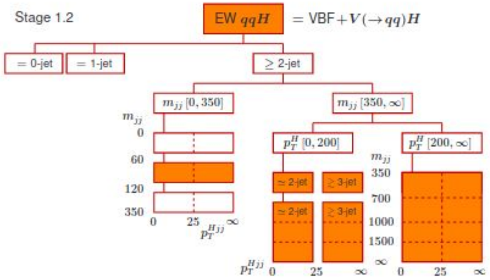
(Inclusive) signal strength or cross section

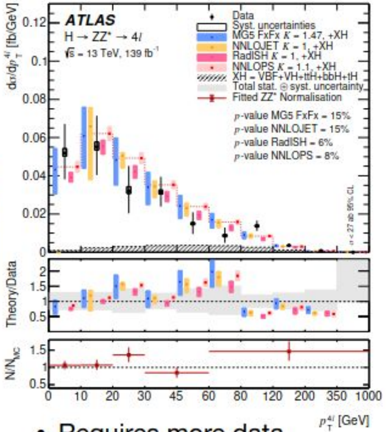
Simplified template cross sections

Differential, fiducial measurements

JHEP01 (2021) 148







EPJC 80 (2020) 942

- First quantity to measure when establishing a channel
- Still powerful with more data: **global** effects

- Requires more data
- Maximise BSM sensitivity / minimising theory dependence ➔ Theory + experiment common ground
- Exploit many variables simultaneously
- Considers inclusive decays - easier combination of channels

- Requires more data
- Generally with fiducial selection for the decay

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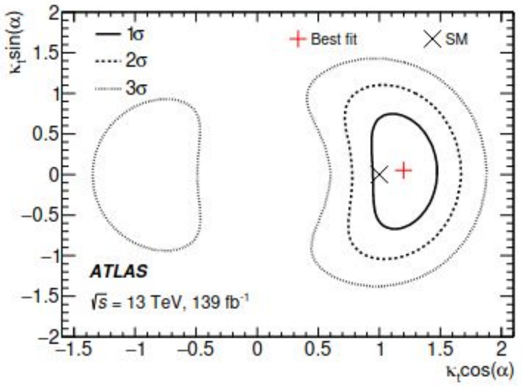
https://indico.cern.ch/event/1135177/contributions/4788685/attachments/2474149/4245835/Delmastro_2022-07-04_Higgs10_MassWidthCP_v3.pdf

CP properties of Higgs-top coupling with ttH

ATLAS ttH H→γγ

Phys. Rev. Lett. 125 (2020) 061802

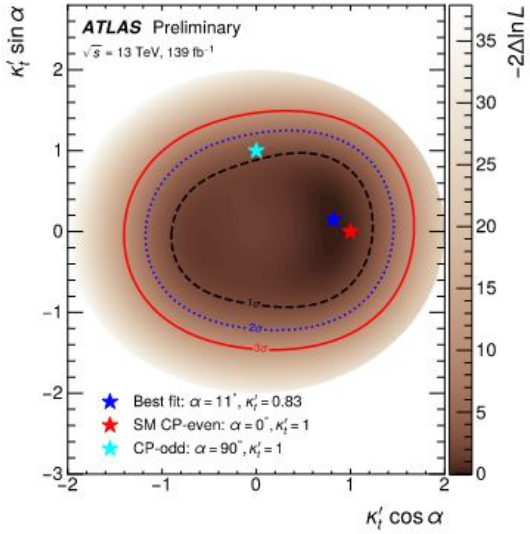


pure CP-odd coupling excluded at 3.9σ

|α| > 43 deg excluded @ 95% CL.

ATLAS ttH H→bb

ATLAS-CONF-2022-016

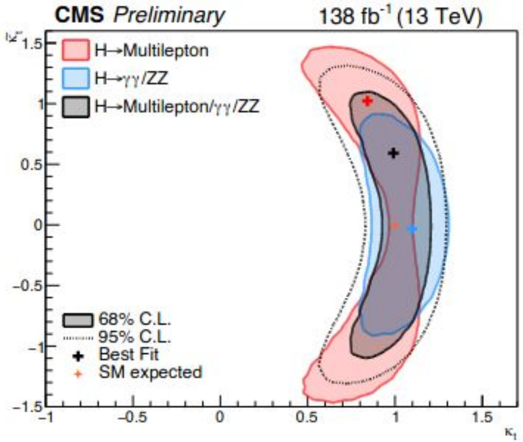


pure CP-odd coupling disfavoured at 1.2σ

$\alpha = 11^{\circ}\,{}^{+55^{\circ}}_{-77^{\circ}}$

CMS ttH H→ML + H→γγ +H→ZZ

PAS HIG-21-006



$$\mathcal{A}(Hff) = \frac{m_f}{v}\bar{\psi}_f(\kappa_t + i\tilde{\kappa}_t\gamma_5)\psi_f$$

pure CP-odd coupling excluded at 3.7σ

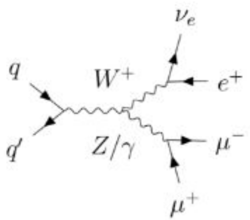
$$f_{CP}^{Htt} = \frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2}$$

$$|f_{Htt}| = (\sin\alpha)^2$$

$|f_{Htt}| = 0.28$ (< 0.55 at 1σ)

https://agenda.infn.it/event/28874/contributions/171901/attachments/94797/130025/ichep-atlas-gu.pdf

Precise studies of rare SM processes: polarization in WZ production

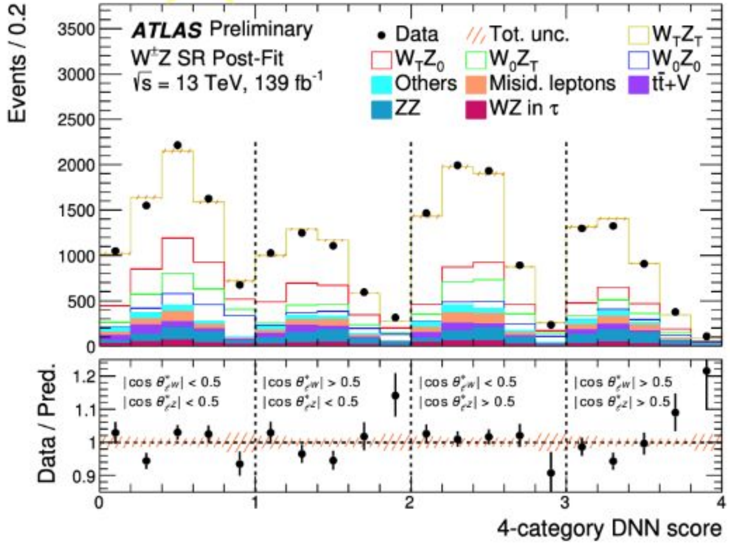


Study W and Z polarisation in WZ events reconstructed in 3l+v decay mode
Joint measurement of W and Z polarisation fraction, using deep neural network
First observation of simultaneous production of longitudinally polarised W and Z bosons with 7.1σ

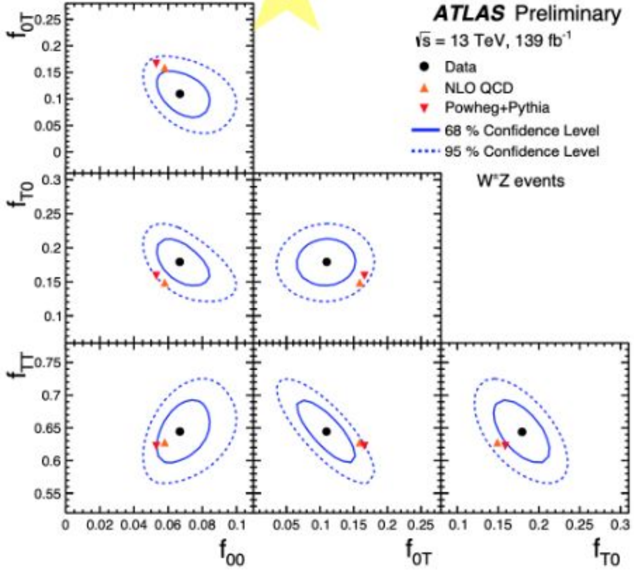
$f_{00} = 0.067 \pm 0.010$

New

ATLAS-CONF-2022-053



New



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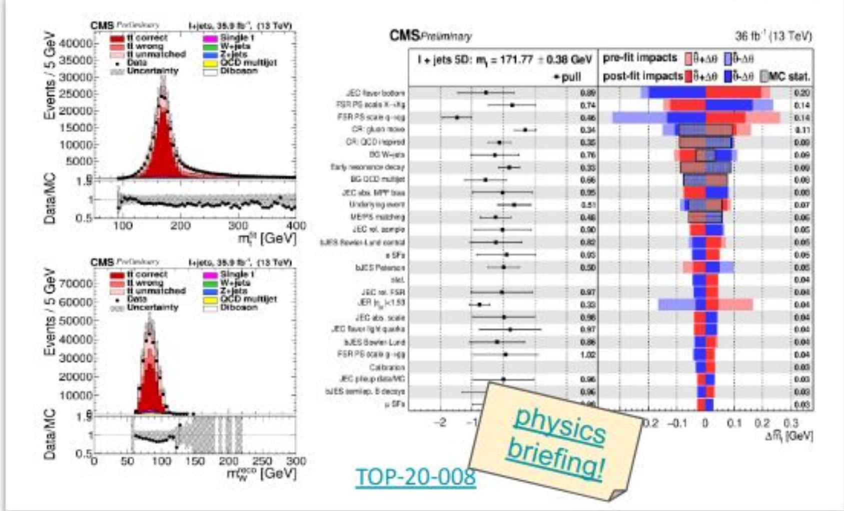
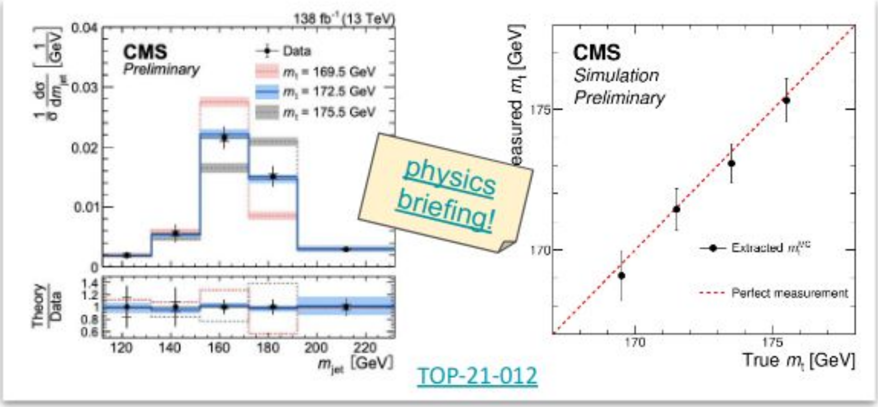
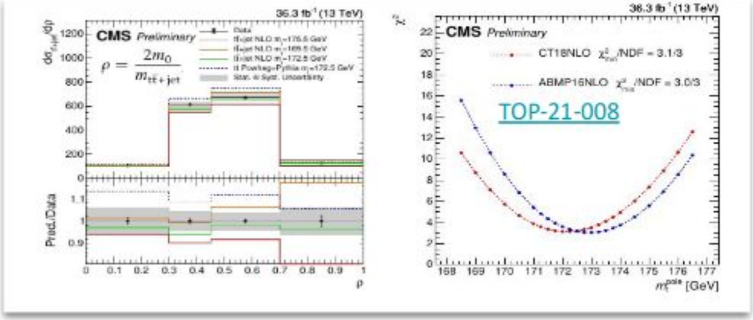
https://agenda.infn.it/event/28874/contributions/171902/attachments/94793/130029/CMS%20Overview%20ICHEP%20%283%29.pdf

Precisely measuring "all" top masses

- Direct measurement with **5D fit** constraining jet uncertainty from **W peak**
  - $m_t = 171.77 \pm 0.38$ GeV
- Measurement from **$t\bar{t}$+jet cross section**
  - $m_t^{pole} = 172.94 \pm 1.37$ GeV
- Measurement of **mass distribution** and m_t in hadronic decay to **boosted jets**
  - $m_t = 172.76 \pm 0.81$ GeV







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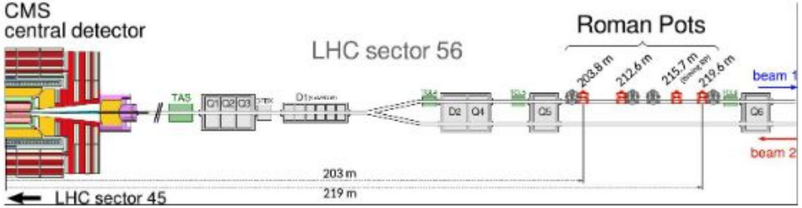
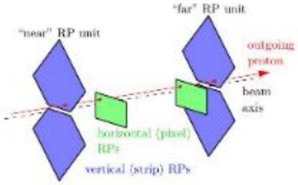
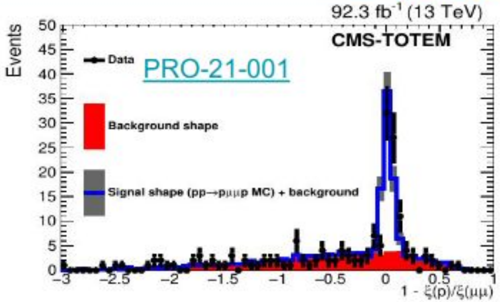
Exploiting the Precision Proton Spectrometer

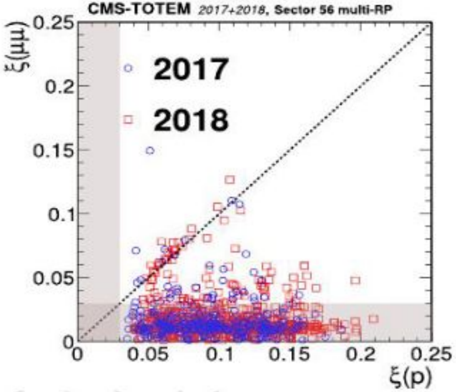
physics briefing



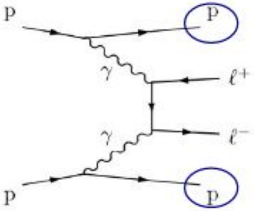




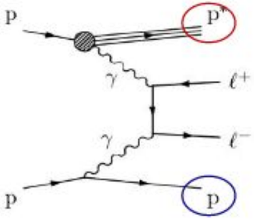
- One or both protons can survive intact after an LHC interaction
- Deviation from LHC orbit allows to measurement momentum loss
- Knowing proton momentum allows to close the event kinematics
- Paper on calibration of the PPS (timing and alignment) recently published by CMS and TOTEM collaborations
- Physics calibration comparing di-lepton events independent reconstruction via PPS and in the central CMS detector



$$\xi = (p_{\rm nom} - p)/p_{\rm nom}$$



Both protons remaining intact



only one proton remaining intact

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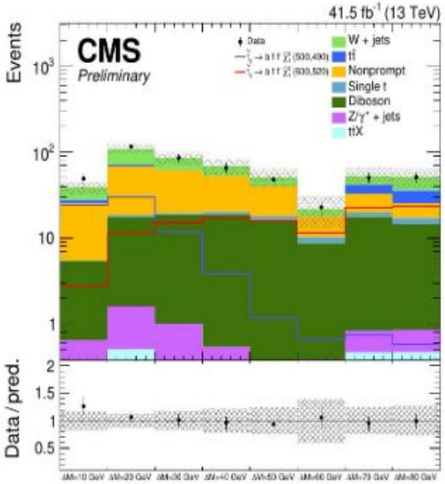
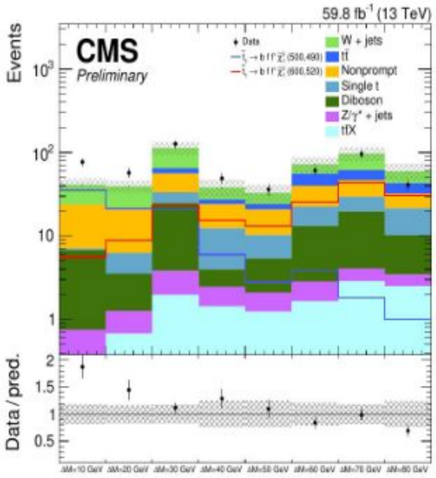
SUSY: compressed stop decays





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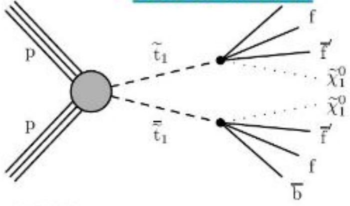
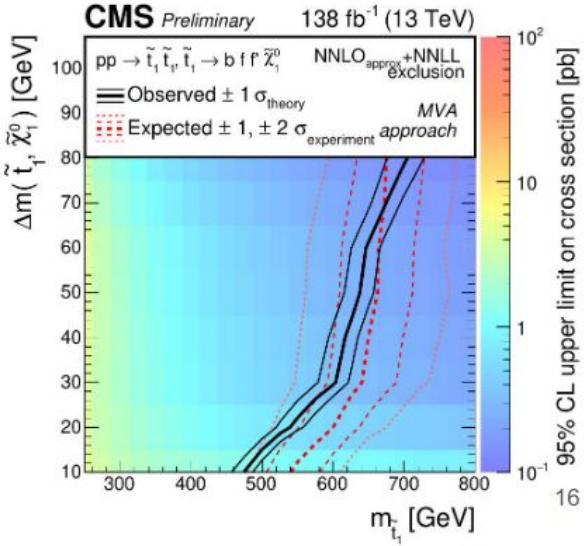




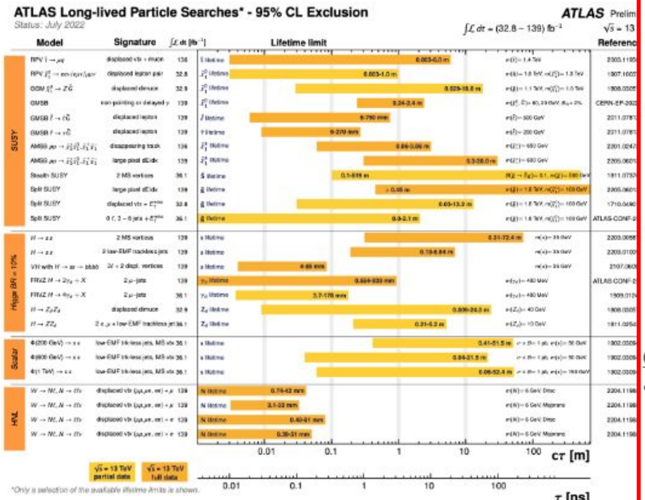
- $\Delta m < m_W \Rightarrow$ four body decay allowed
  - Jet + missing energy + soft leptons
- Trained BDT for different Δm hypotheses
- Slight excess (2.5σ local) at low Δm

https://agenda.infn.it/event/28874/contributions/171901/attachments/94797/130025/ichep-atlas-gu.pdf

Searches for long-lived particles

Large program to search for long-lived particles exploiting a comprehensive set signatures:

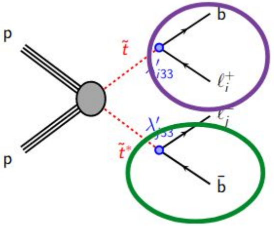
- displaced vertices in inner tracking detector
- lepton not consistent with originating from pp vertex
- decay in the calorimeter or muon spectrometer
- dE/dx measurement for charged metastable particles + multi charge



Search for H or Z produced far from interaction point exploiting shower pointing and time measurements

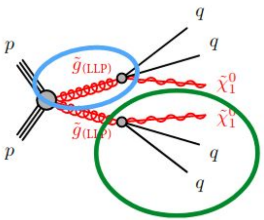
R-Parity violating SUSY

- Small decay couplings



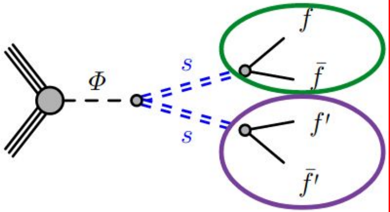
Split-SUSY

- Gluino forms R-hadron



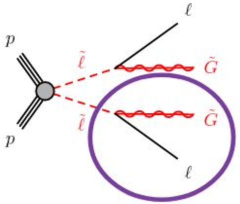
Hidden Sector

- Heavy scalar (Higgs or Φ) decay to long lived scalars



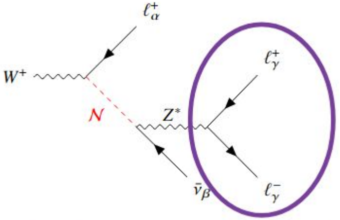
Gauge-Mediated SUSY Breaking

- Small gravitational coupling to lightest gravitino



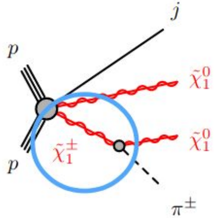
Heavy Neutral Leptons

- Small coupling to neutrino

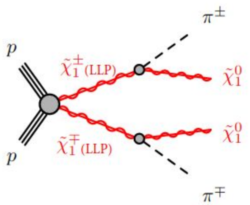


Compressed SUSY

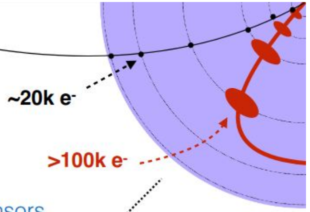
- Small mass splittings



Can produce **displaced / emerging jets**, **displaced ℓ / γ / vertices**, **disappearing tracks** https://indico.cern.ch/event/1083758/contributions/4916615/attachments/2469288/4236053/LLPatLHC_JeffDandoy_SUSY2022_27Jun2022.pdf



Target
$\Delta D > 55$ cm
$m \sim [100 - 3000]$ GeV



- Slow, heavy charged particles deposit more energy in trackers than SM particles
  - Large & long signals from clusters of sensors

MET trigger

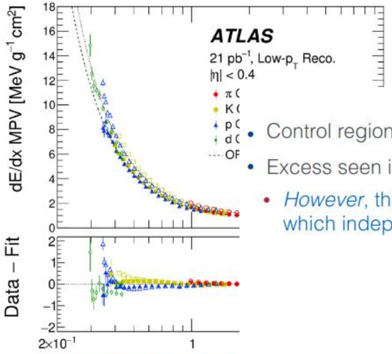
⟨dE/dx⟩ ← Measured ionization loss in Pixel tracker

↓ Bethe-Bloch relation, calibrated w/ SM particles

$\beta\gamma$

↓ $m = \frac{p}{\beta\gamma(\langle dE/dx \rangle)}$

LLP mass

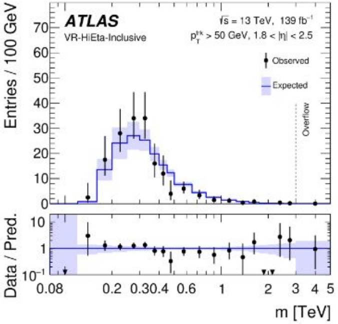


Bethe-Bloc relatior

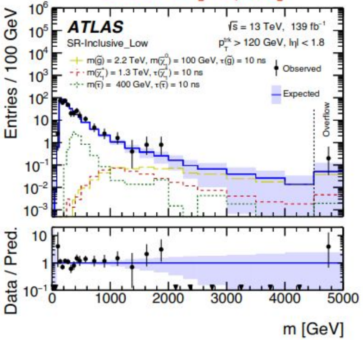
- Control regions (low dE/dx, low E_T^{miss}) for data-driven track-mass templates
- Excess seen in high dE/dx region above 1 TeV
  - *However*, these charged particles are seen in calo & muon systems which independently estimate β~1 (inconsistent w/ signal model)

SEE TALK FRIDAY BY LEONARDO ROSSI

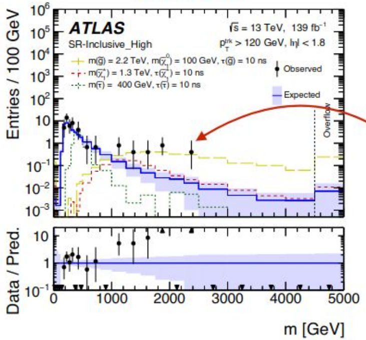
Validated in low p$_T$ & forward regions



dE/dx in [1.8, 2.4]



dE/dx > 2.4



3.3 σ global excess

At high mass, 7 events observed for 0.7±0.4 events expected

- 5 of them have muons
- 3 of them have 2 muons
- **3.6σ local, 3.3σ global**