

中国物理学会高能物理分会  
HIGH ENERGY PHYSICS BRANCH OF CPS



山东大学  
SHANDONG UNIVERSITY

# TeV物理实验进展综述

刘衍文

中国科学技术大学

感谢梁志均、陈新、李海峰、李数、刘洋、张雷、吴雨生、张华桥、鲁楠、孙小虎、陈明水、李强、易凯、袁丽、陈震宇、肖朦、史欣、杨洪洮、孙勇杰、尤郑昀、赵政国等提供材料

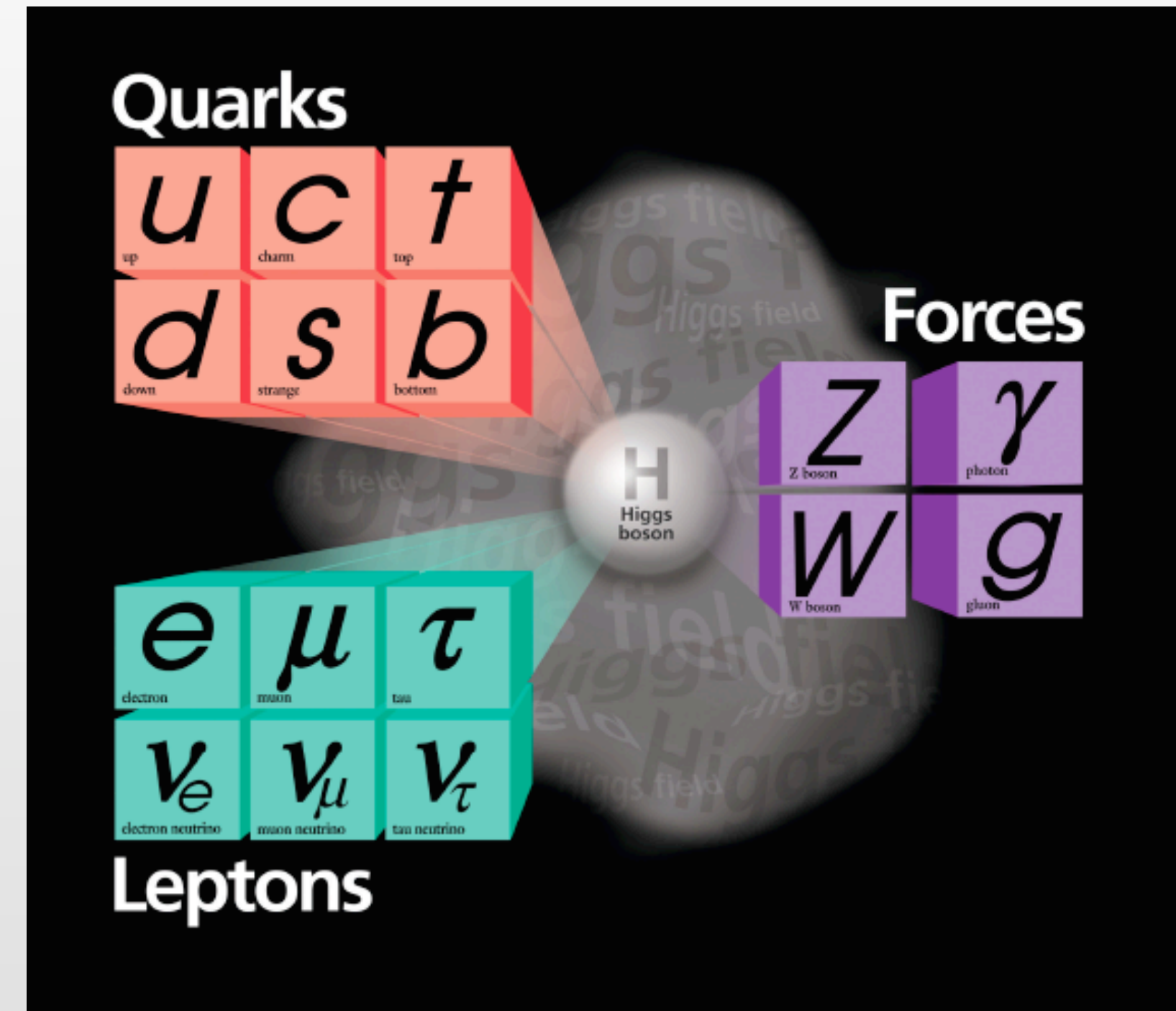
2024-8-16 青岛 第十四届全国粒子物理学术会议

# 报告内容

- 引言
  - TeV 重要的物理问题
  - ATLAS/CMS概况
  - 中国组概况
- 主要物理进展: links to [ATLAS](#) / [CMS](#) Public Results
- 升级关键技术

# 标准模型没有回答的重要物理问题

- 为何基本粒子如此多？ (Who ordered that?)
- 希格斯势能形式？
- 相互作用(EW,Strong,Gravity)是否能统一？
- 时空只有4维？
- 为何反物质如此罕见？
- 中微子质量从何而来？
- 暗能量、暗物质的基本粒子构成什么？
- ...

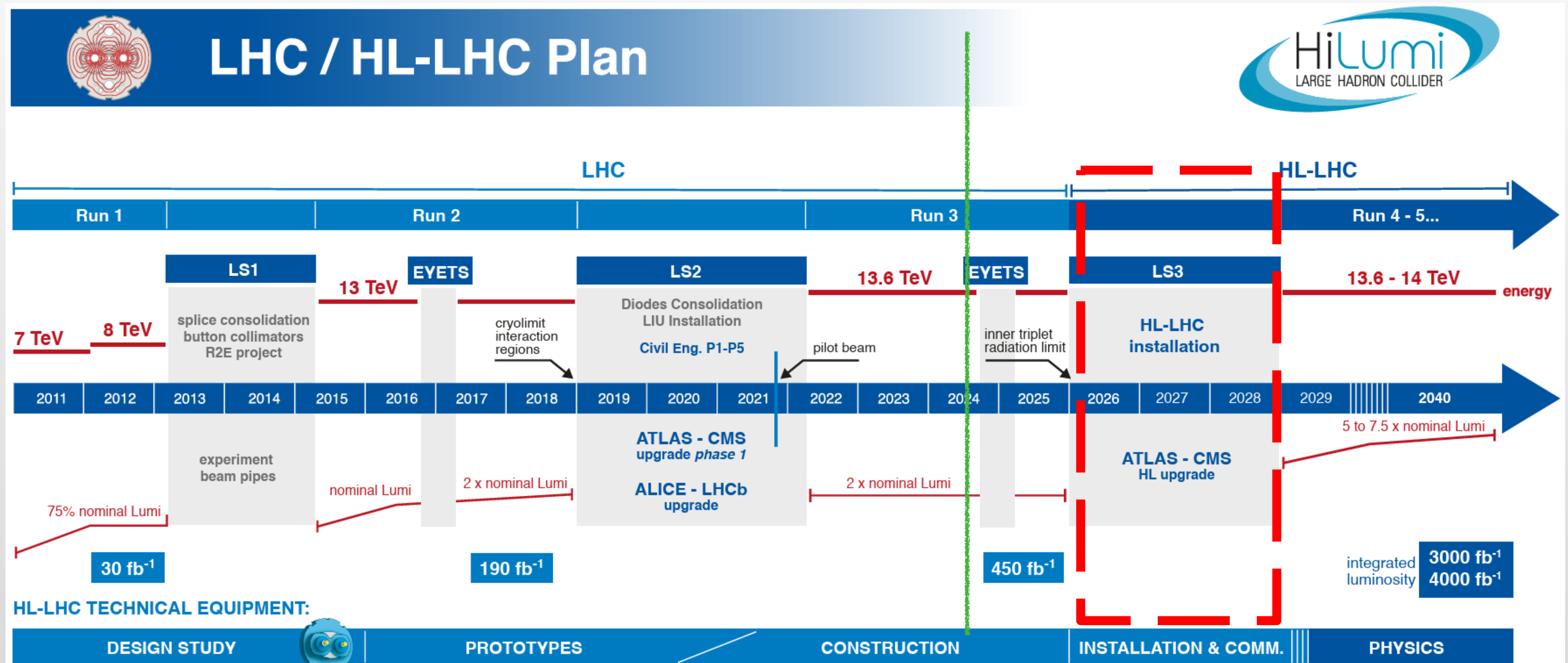


# LHC ATLAS/CMS的物理目标

- 希格斯粒子的性质研究（基本粒子的质量起源、希格斯势能形式）
- 精确测量电弱、强相互作用，检验标准模型的自洽性，寻找BSM的迹象
  - $W$ 质量和宽度、玻色子散射、多玻色子末态、喷注内部能量关联等
- 寻找特定BSM新粒子、新现象
  - 新共振峰、FCNC、SUSY、Long-Lived Particles(LLP)

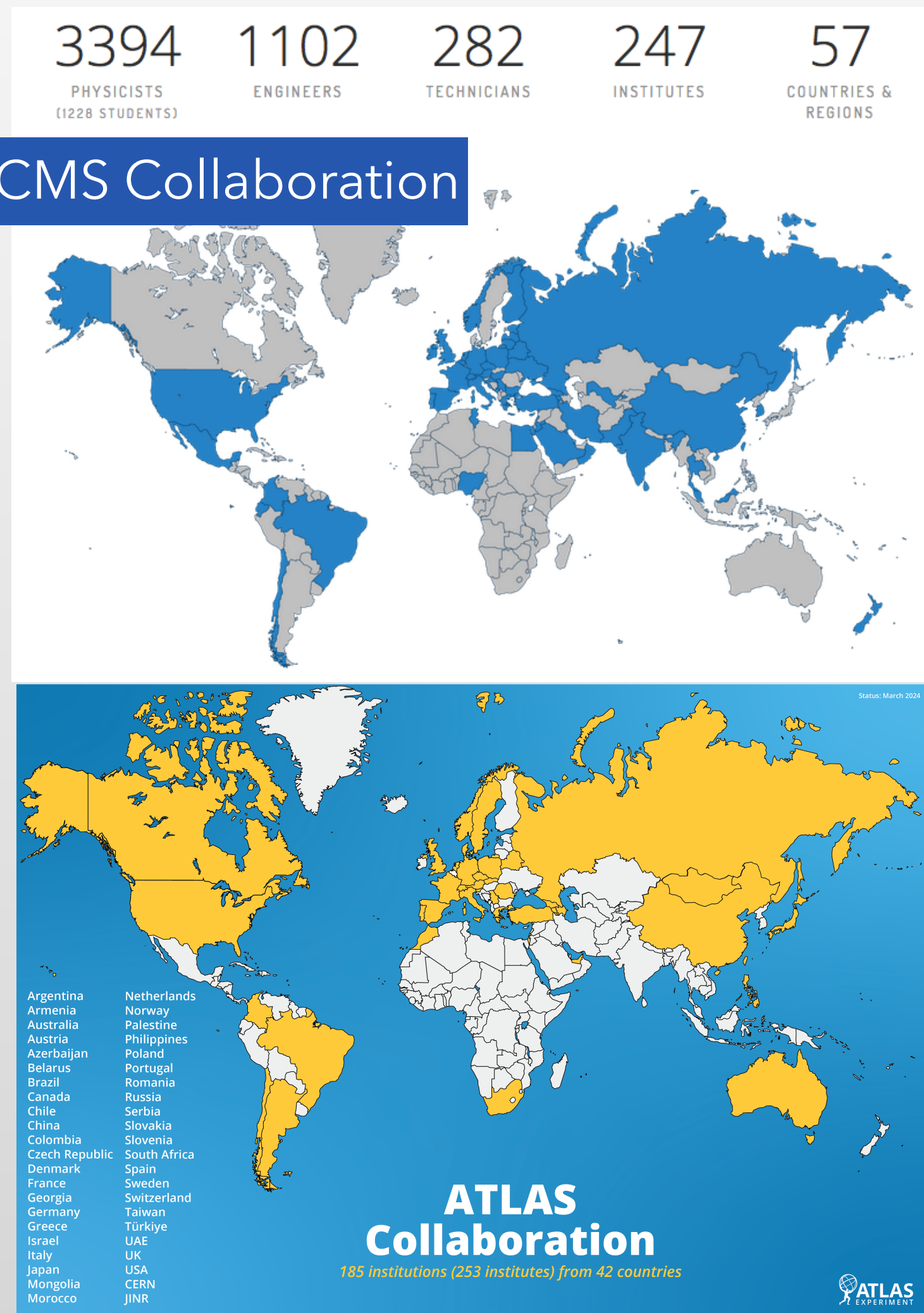
# LHC时间表

~90%数据来自HL-LHC



Nominal luminosity =  $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

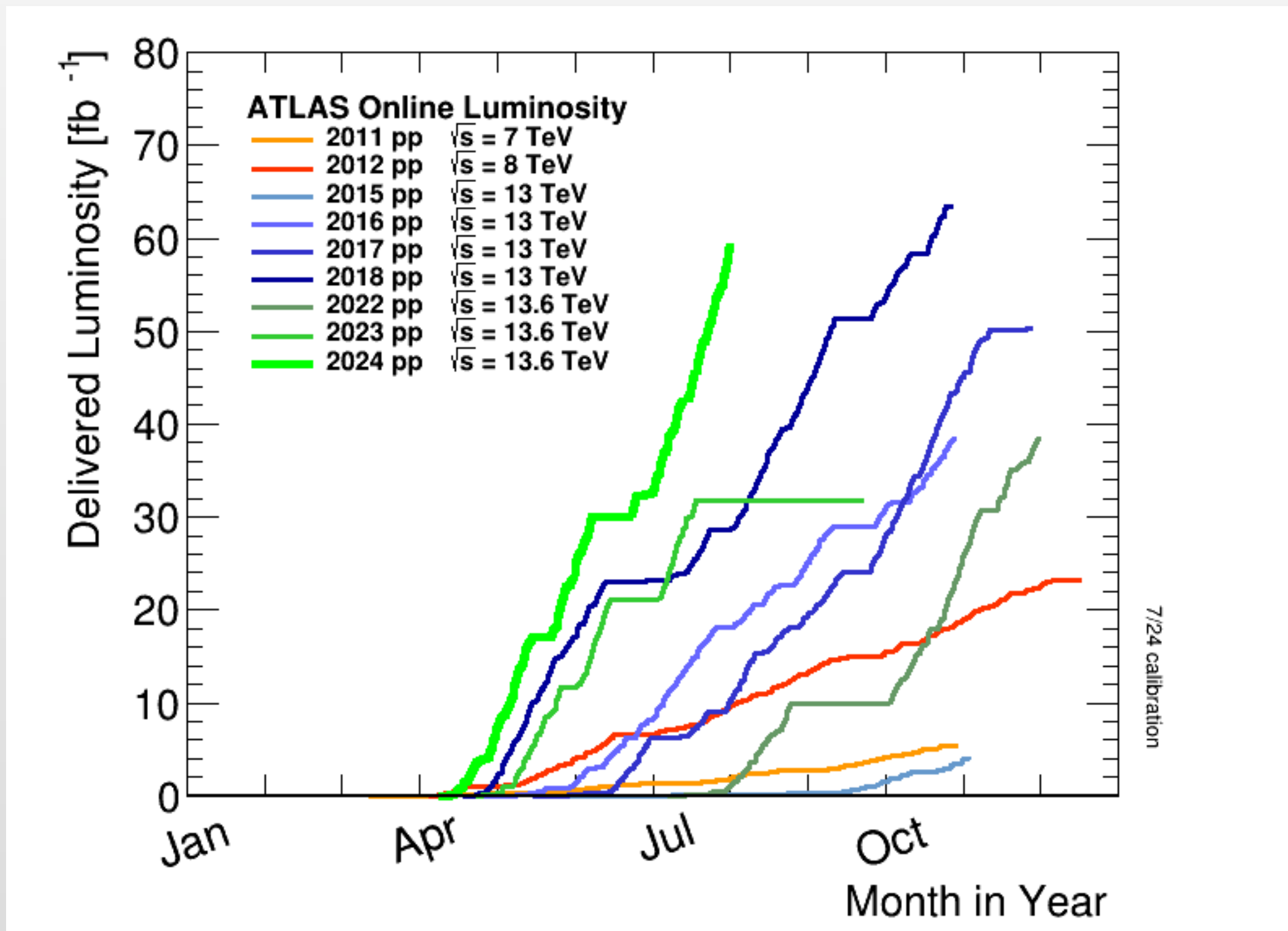
# ATLAS/CMS概况



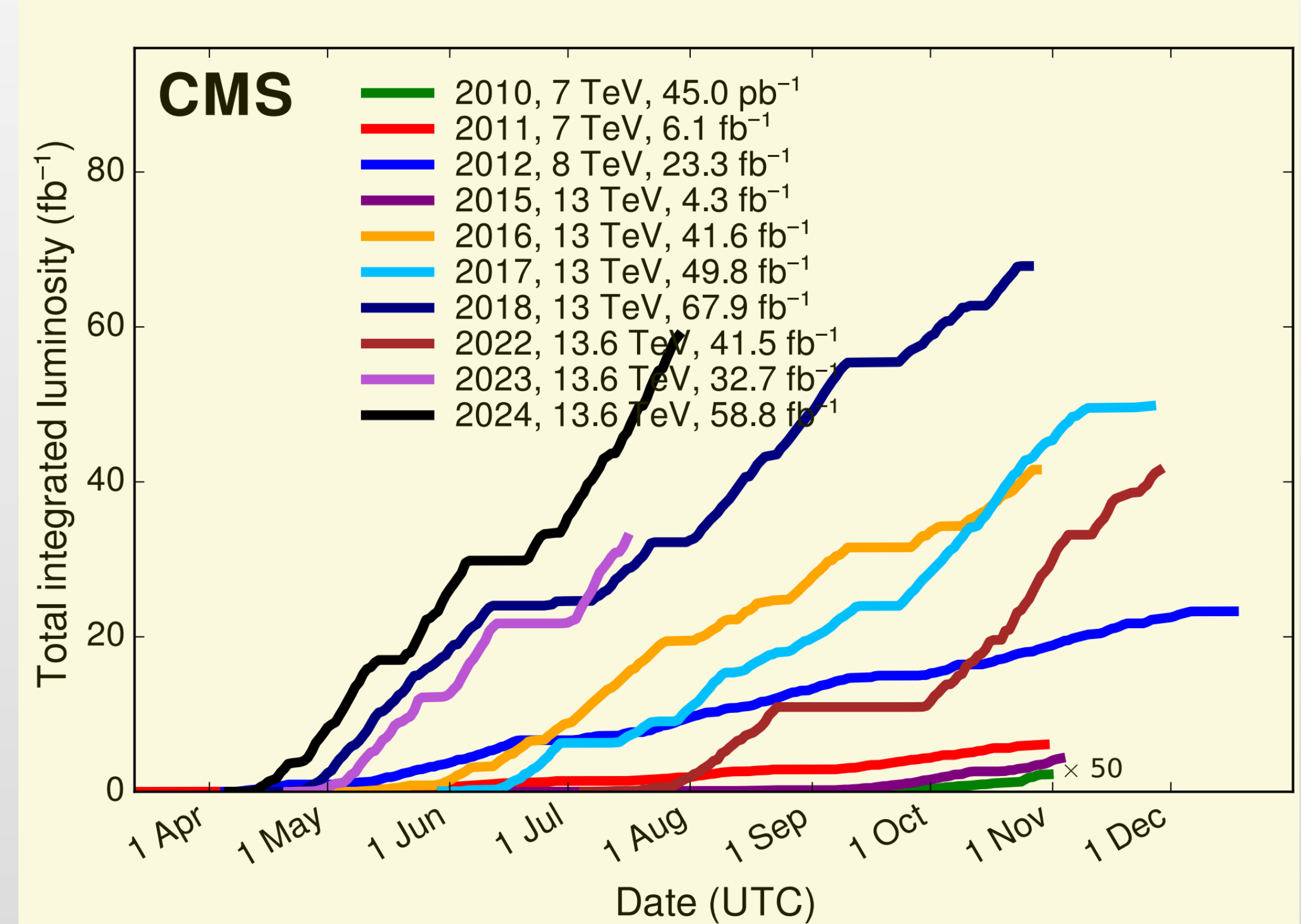
	ATLAS	CMS
<b>中国组单位</b>	<ul style="list-style-type: none"> <li>• 中国科学技术大学</li> <li>• 高能物理研究所</li> <li>• 山东大学</li> <li>• 上海交通大学</li> <li>• 李政道研究所</li> <li>• 南京大学</li> <li>• 中山大学</li> <li>• 清华大学</li> <li>• 郑州大学</li> </ul>	<ul style="list-style-type: none"> <li>• 高能物理研究所</li> <li>• 北京大学</li> <li>• 北京航空航天大学</li> <li>• 清华大学</li> <li>• 中山大学</li> <li>• 浙江大学</li> <li>• 南京师范大学</li> <li>• 复旦大学</li> <li>• 中国科学技术大学</li> <li>• 山东大学</li> <li>• 华南师范大学</li> </ul>
<b>单位数</b>	9	11
<b>署名作者数*</b>	131	50
<b>作者数在合作组占比</b>	4%	2%

# 取数情况

## ATLAS luminosity



## CMS luminosity



Run 2: 目前主要物理成果  $\sim 140 \text{ fb}^{-1}$

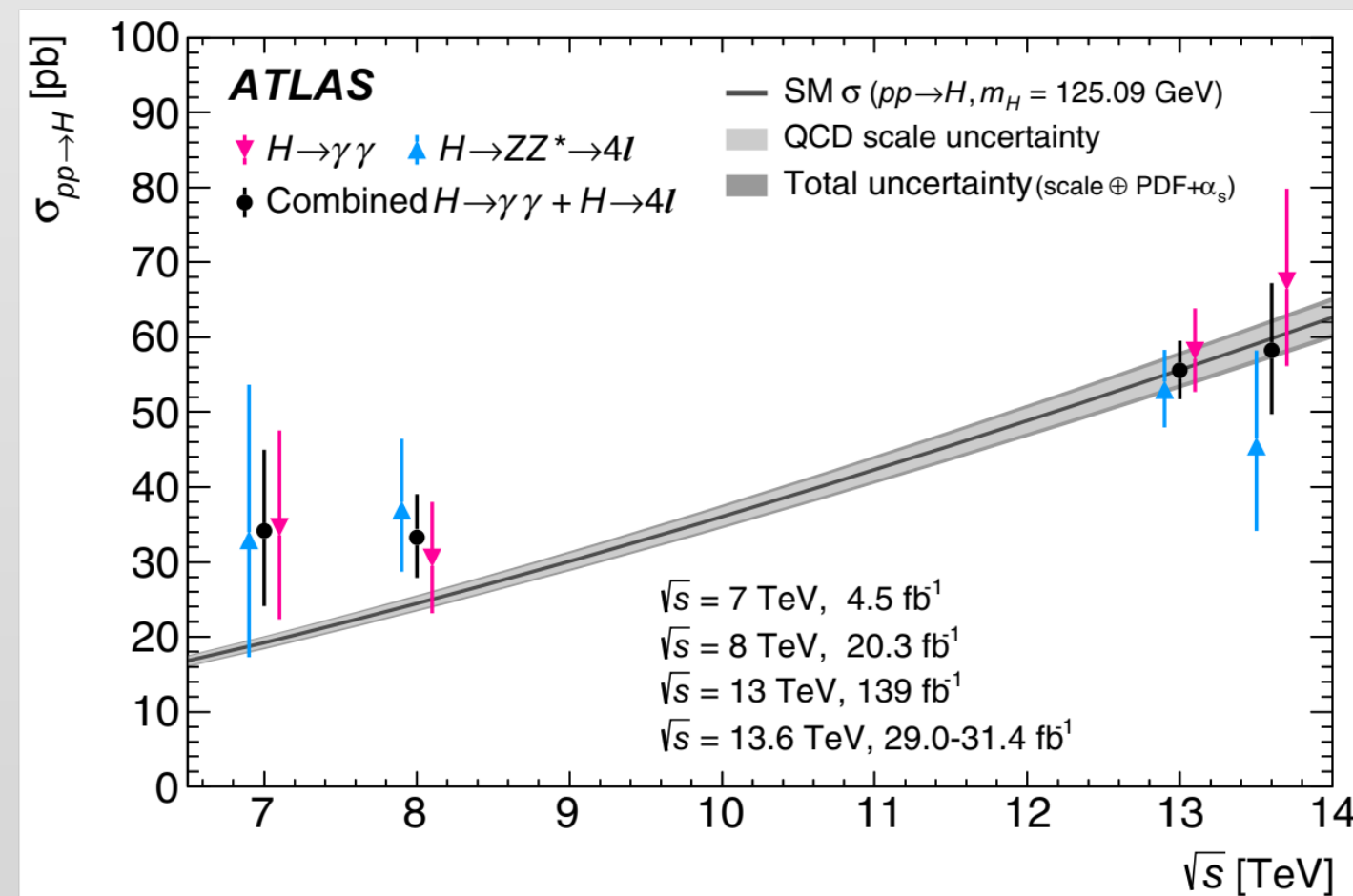
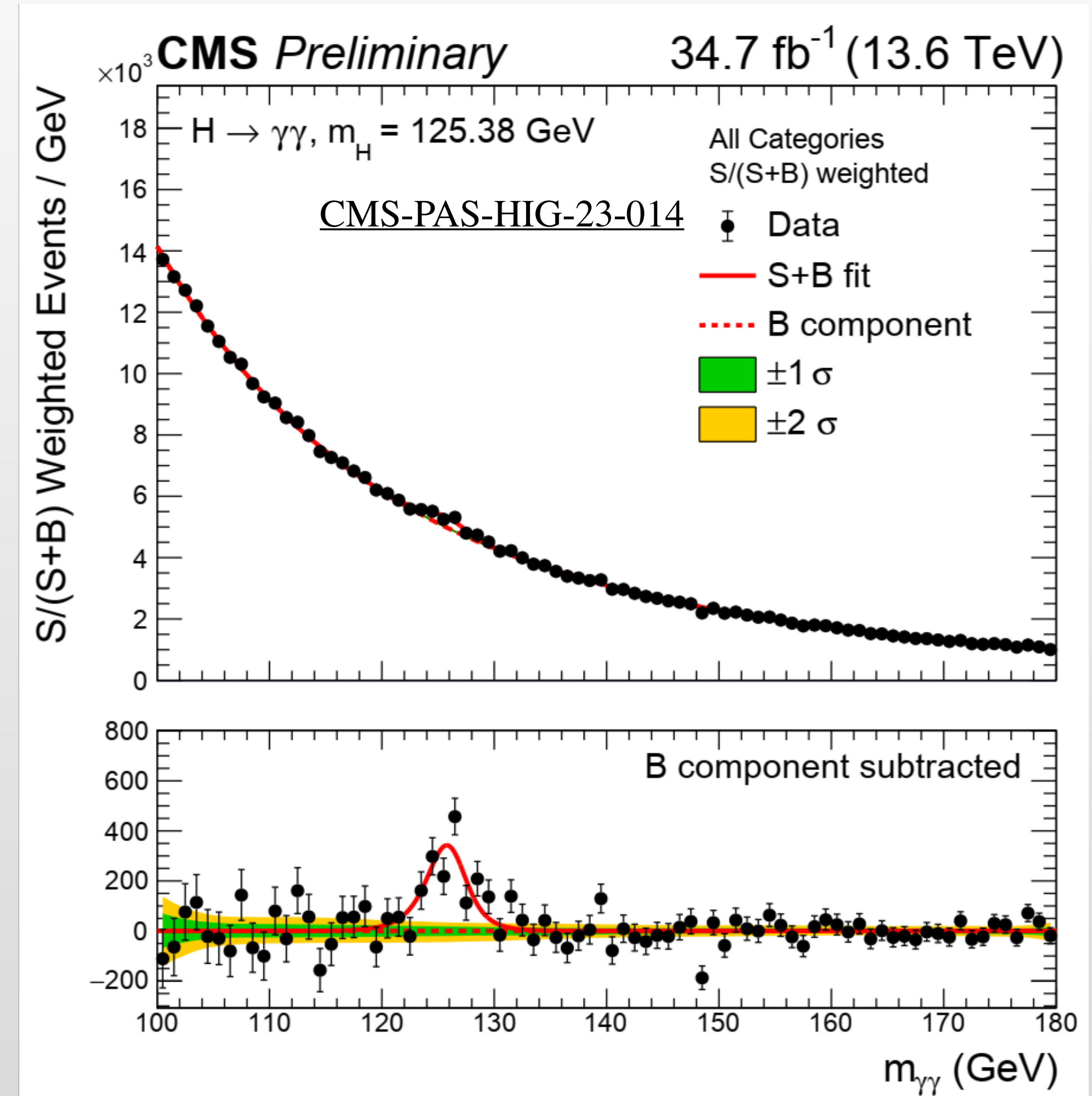
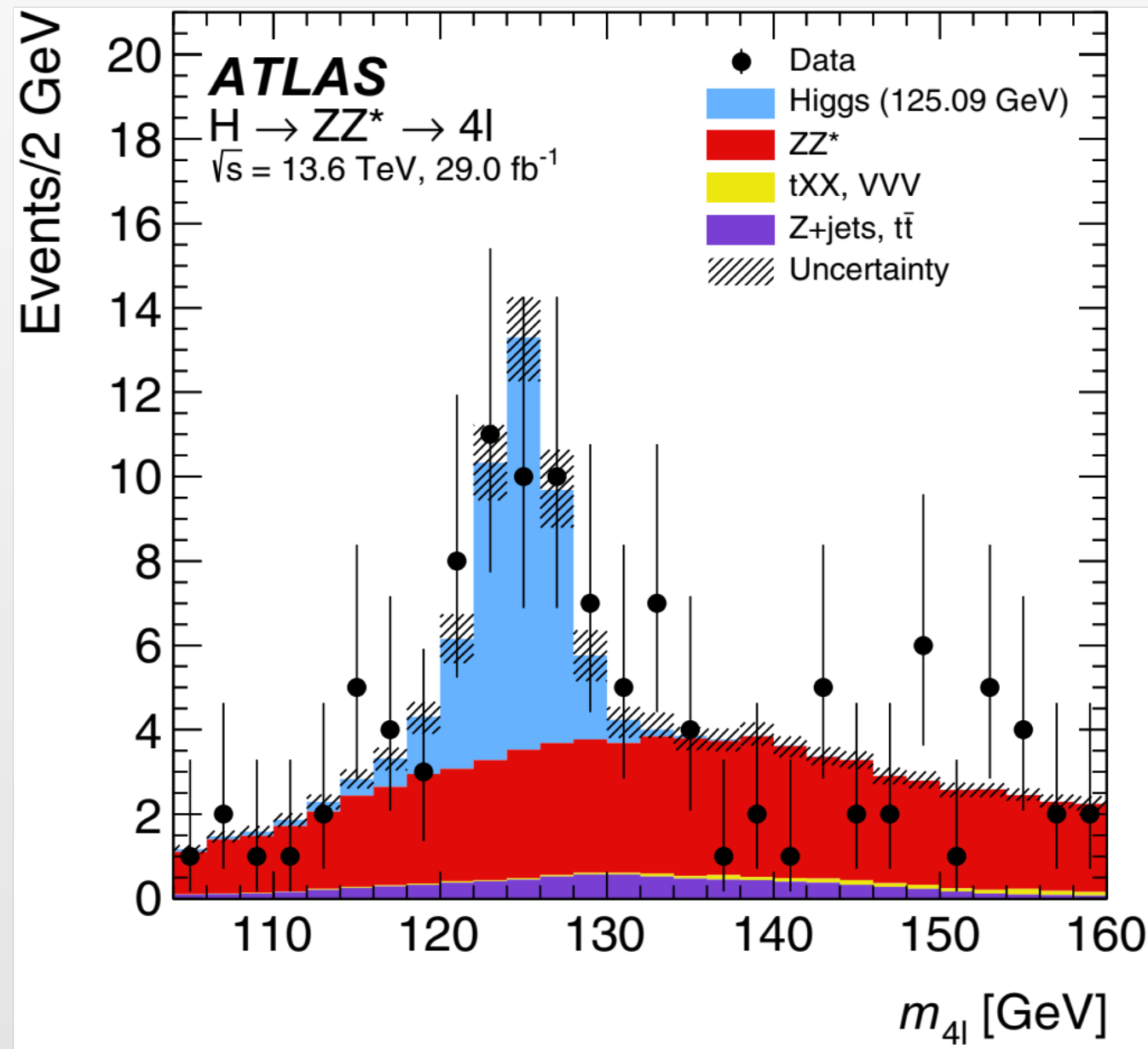
Run 3已经获取积分亮度  $\sim 130 \text{ fb}^{-1}$

# 希格斯粒子性质研究进展



# Run 3中的希格斯粒子

EPJC84(2024)78



详见8.15 Tahir J.报告

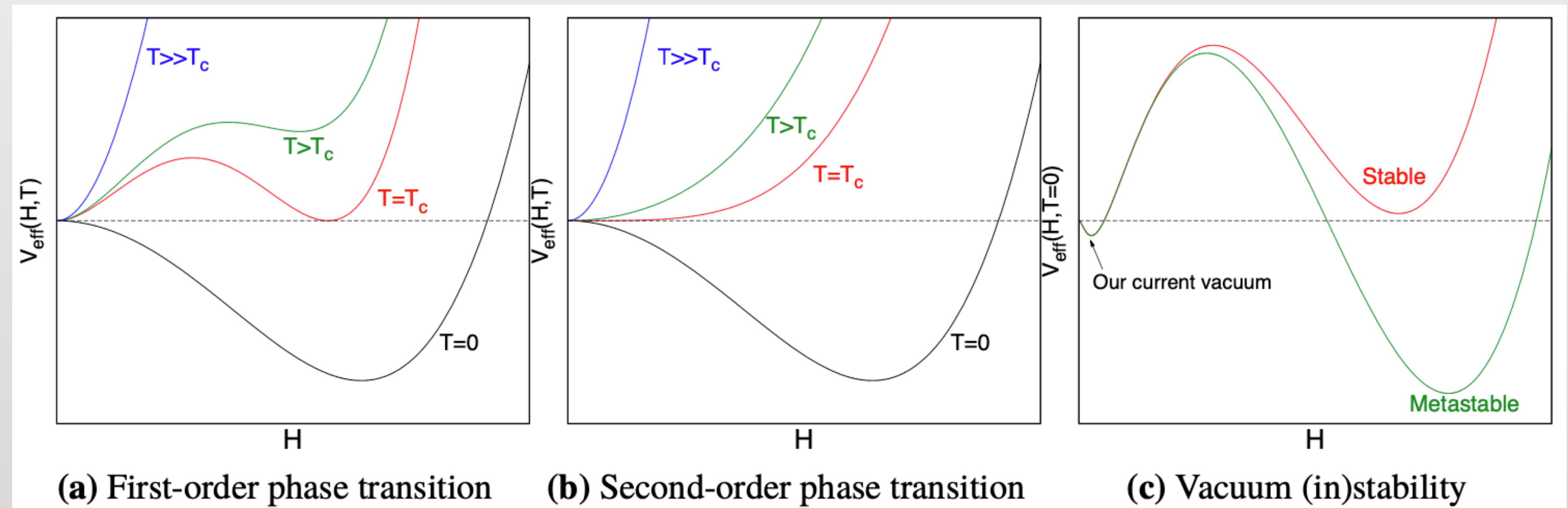
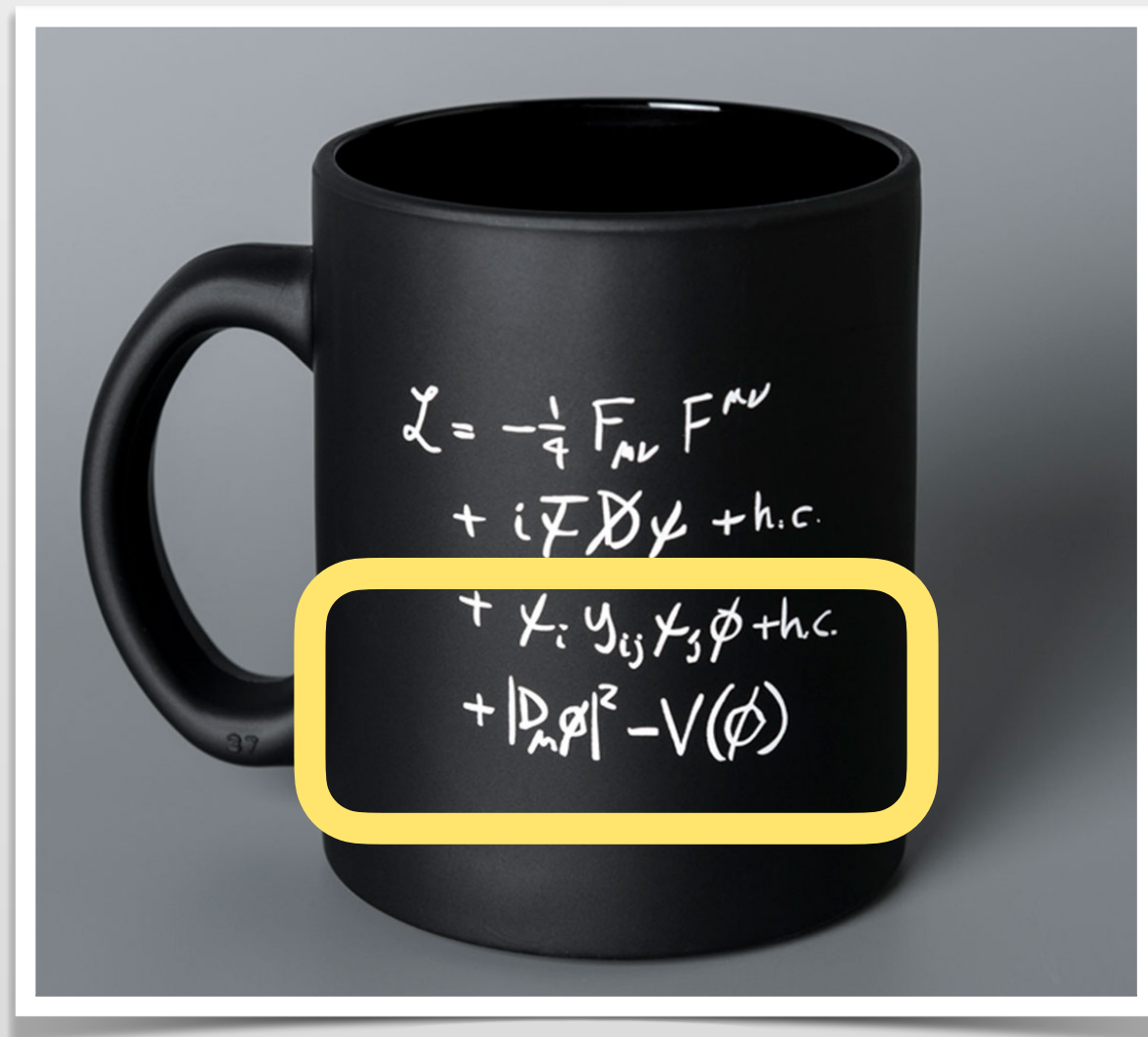
ATLAS:IHEP,NJU,USTC...  
 CMS:BUAA,IHEP,PKU,USTC...

# 希格斯粒子性质

希格斯粒子是标准模型中唯一的标量粒子，是探索新物理的重要工具

- ◎希格斯势能形式不受规范对称性约束，质量受量子修正影响(fine-tuning)
- ◎所有费米子的质量由Yukawa耦合描述
- ◎或与宇宙演化息息相关：电弱相变、真空稳定性...

$$\text{SM: 电弱能标下 } V(H, H^\dagger) = -\mu^2 \Phi^\dagger \Phi + \frac{1}{2} \lambda (\Phi^\dagger \Phi)^2$$



# 希格斯粒子的质量和宽度

PDG live (2024)

$H$   $J=0$

was  $H^0$

In the following  $H$  refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of  $H$  and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below. Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ( $H^\pm$  and  $H^{\pm\pm}$ )", respectively.

ATLAS: 改进了  $H \rightarrow \gamma\gamma$ , 联合  $4l$  (Run1, Run2)  
 $m_H = 125.11 \pm 0.11$  GeV (stat. 0.09, syst. 0.06)

[PRL131\(2023\)251802](#)

CMS: 最精确的单通道( $4l$ )测量  $\Gamma_H = 2.9^{+2.3}_{-1.7}$  MeV  
 $m_H = 125.04 \pm 0.11 \pm 0.05$  GeV

[CMS-PAS-HIG-21-019](#)

ATLAS 由  $4l$  得到的宽度:  $\Gamma_H = 4.5^{+3.0}_{-2.5}$  MeV

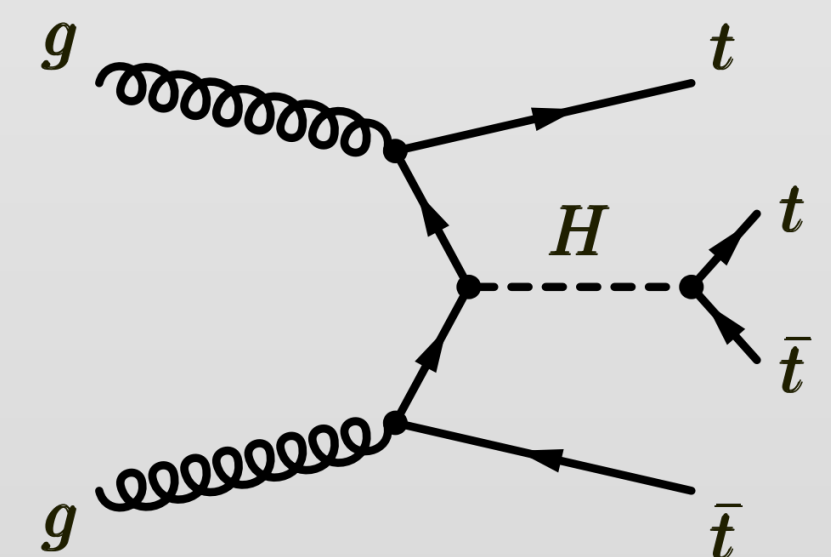
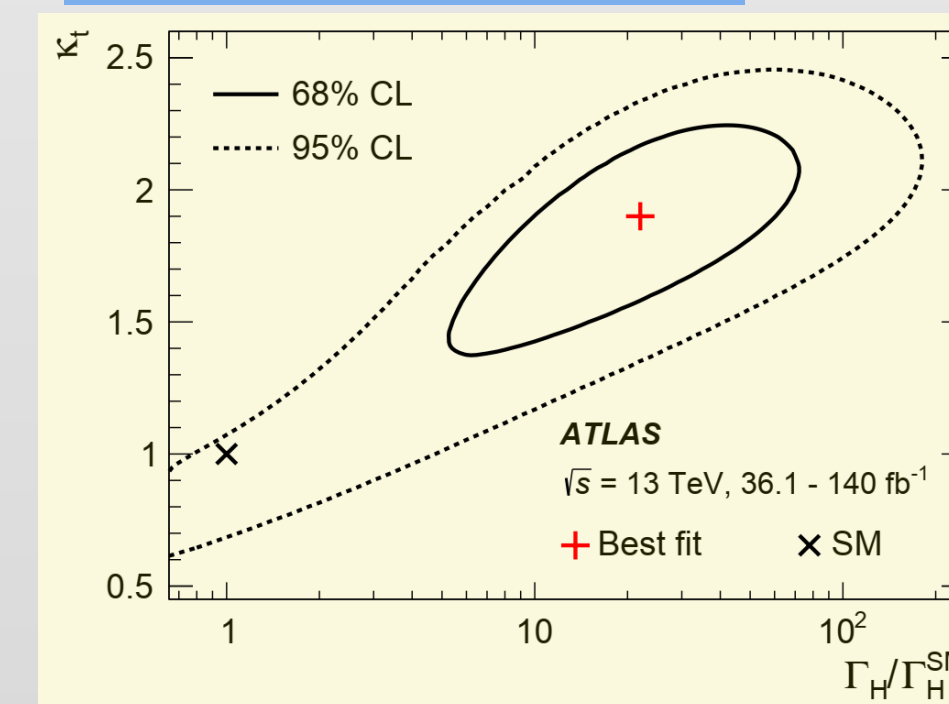
[PLB846\(2023\)138223](#)

[Corrigendum](#)

新宽度测量: 利用  $t\bar{t}t\bar{t}$  测量离壳截面

$\Gamma_H = 86^{+110}_{-49}$  MeV

[arxiv:2407.10631](#)



$H$ MASS	$125.20 \pm 0.11$ GeV ( $S = 1.4$ )
$H$ SPIN AND $CP$ PROPERTIES	
$H$ DECAY WIDTH	$3.7^{+1.9}_{-1.4}$ MeV
$H$ SIGNAL STRENGTHS IN DIFFERENT CHANNELS	
Combined Final States	$1.03 \pm 0.04$
$WW^*$ Final State	$1.00 \pm 0.08$
$ZZ^*$ Final State	$1.02 \pm 0.08$
$\gamma\gamma$ Final State	$1.10 \pm 0.06$
$c\bar{c}$ Final State	$< 14$ CL=95.0%
$b\bar{b}$ Final State	$0.99 \pm 0.12$

on-shell

$\sigma_{pp \rightarrow H \rightarrow ZZ}^{\text{on-shell}} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H \Gamma_H}$

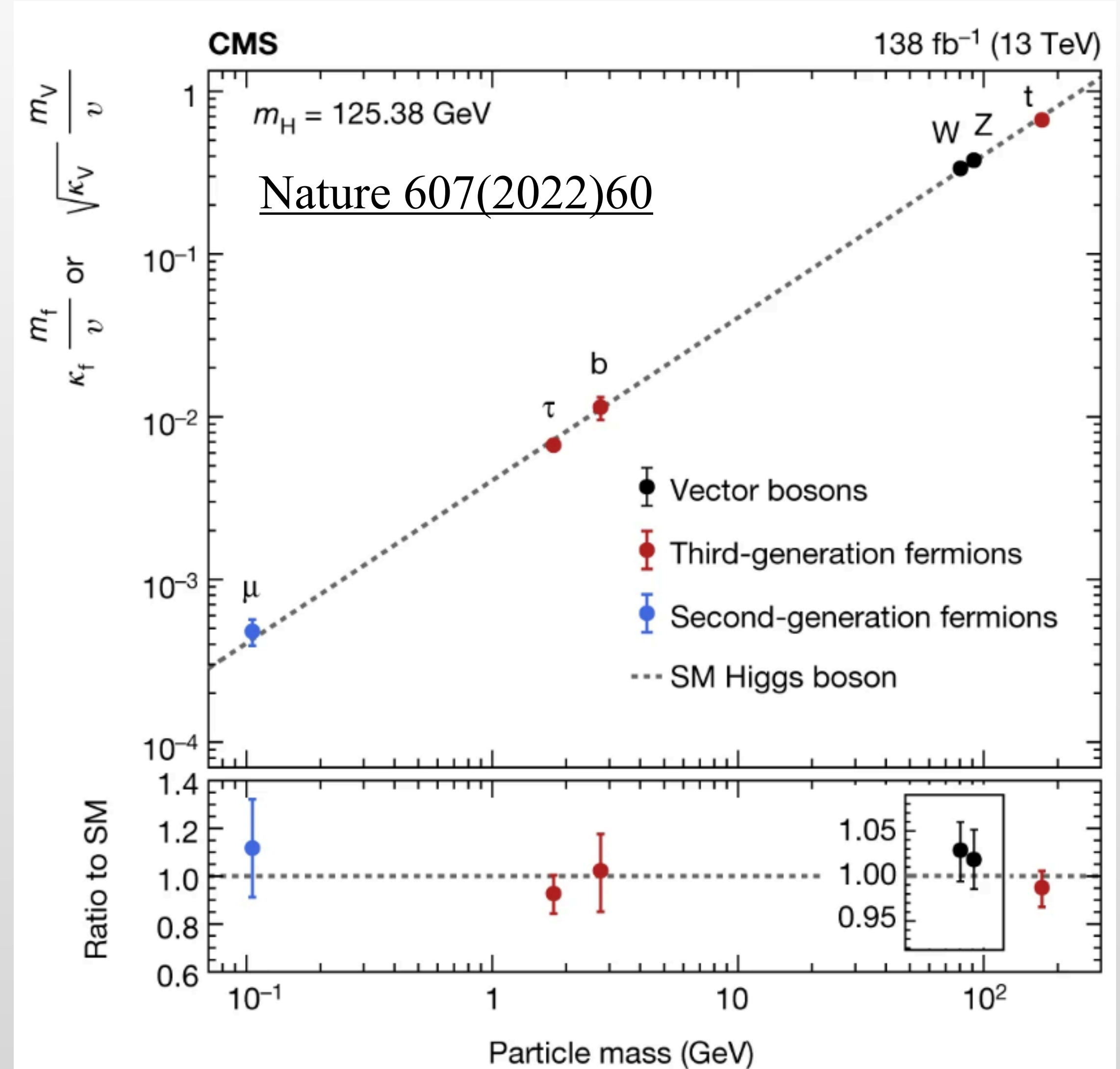
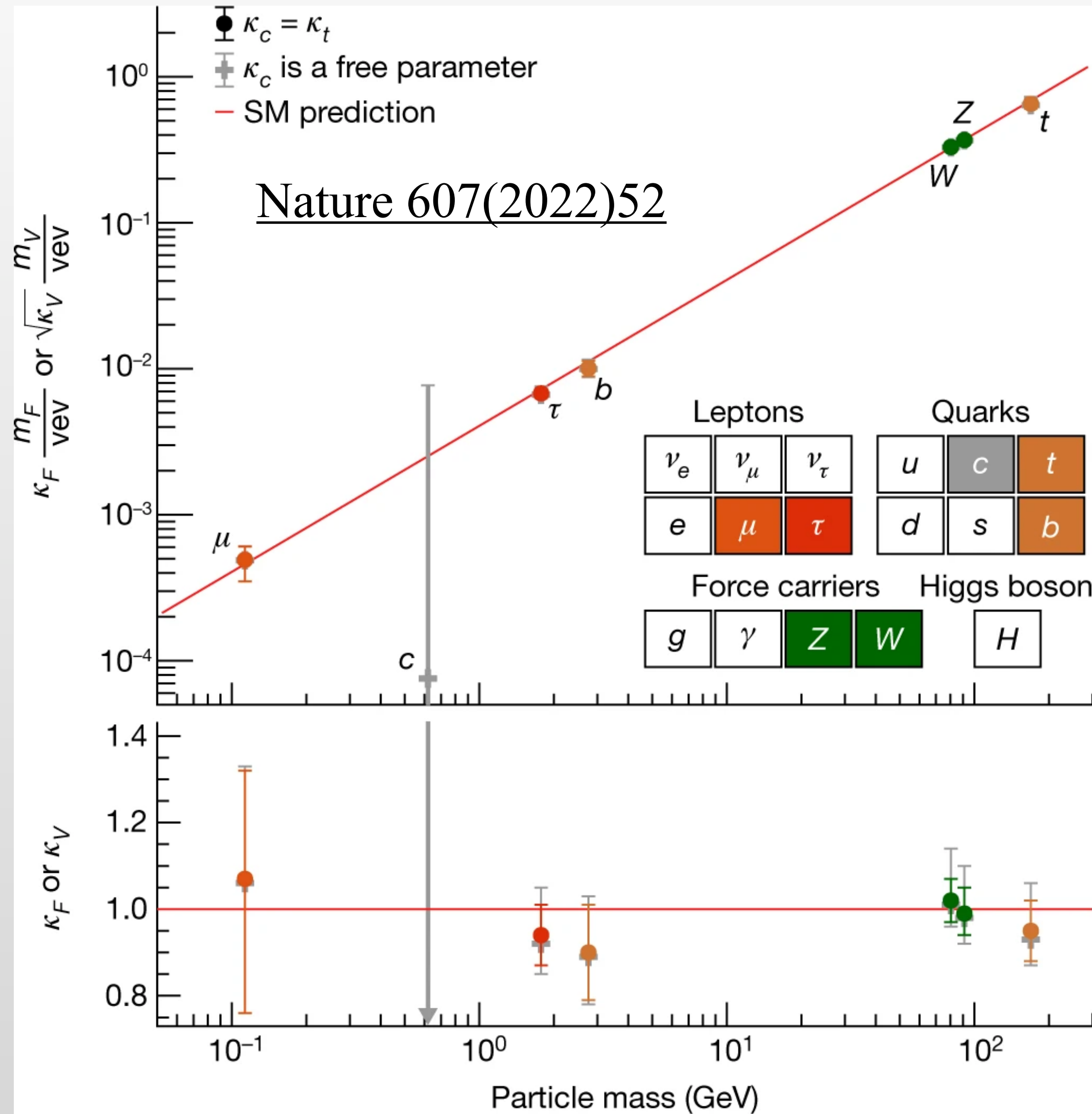
off-shell

$\frac{d\sigma_{pp \rightarrow H \rightarrow ZZ}}{dm_{ZZ}} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$

$\frac{d\sigma_{\text{off-shell}}^{pp \rightarrow H \rightarrow ZZ}}{dm_{ZZ}} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2}$

CMS: BUAA, IHEP, PKU, ...  
 ATLAS: IHEP, NJU, SDU, SJTU (TDLI), USTC...

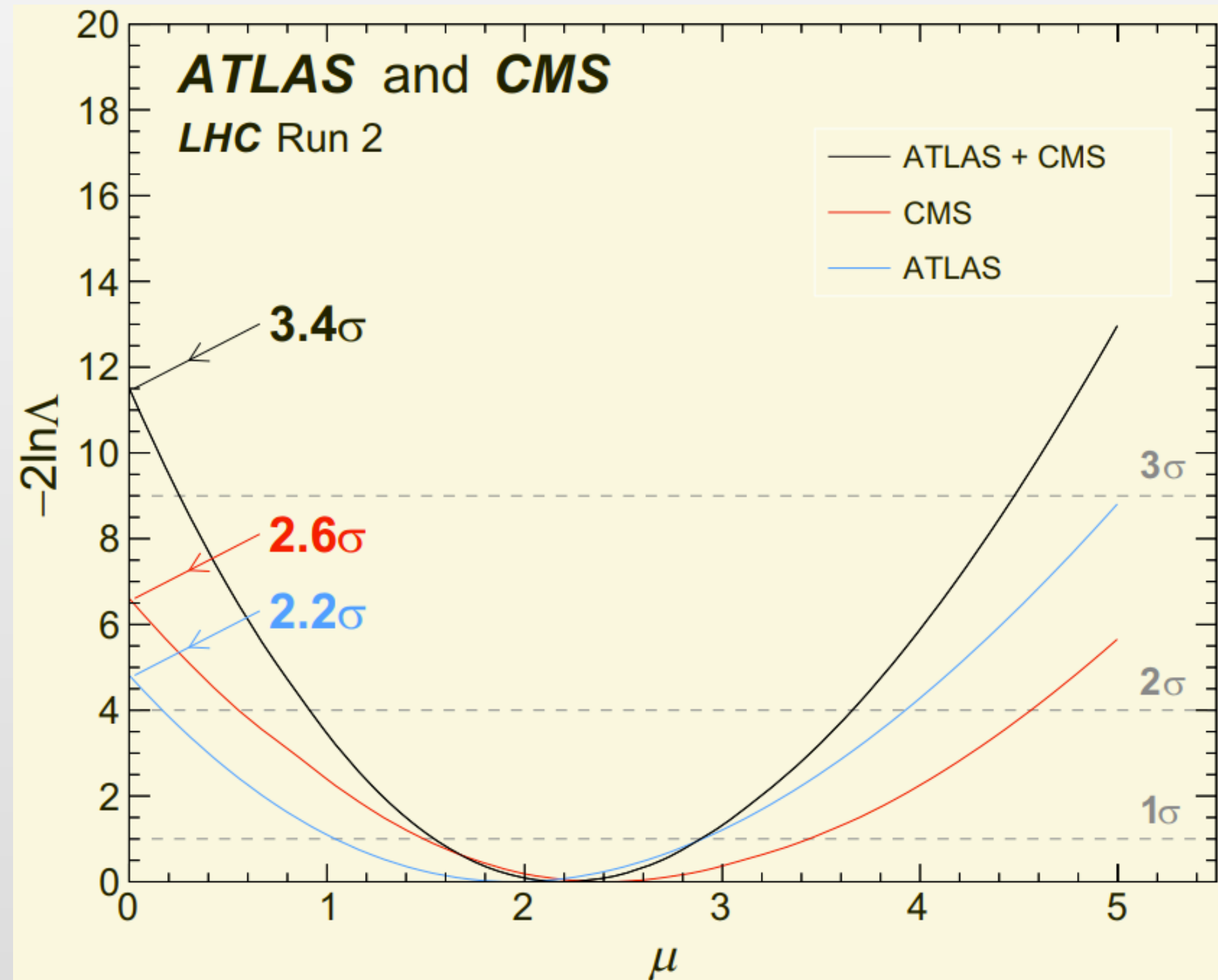
# 希格斯耦合概览



# 希格斯粒子性质新进展

PRL132(2024)021803 Editors' Suggestion

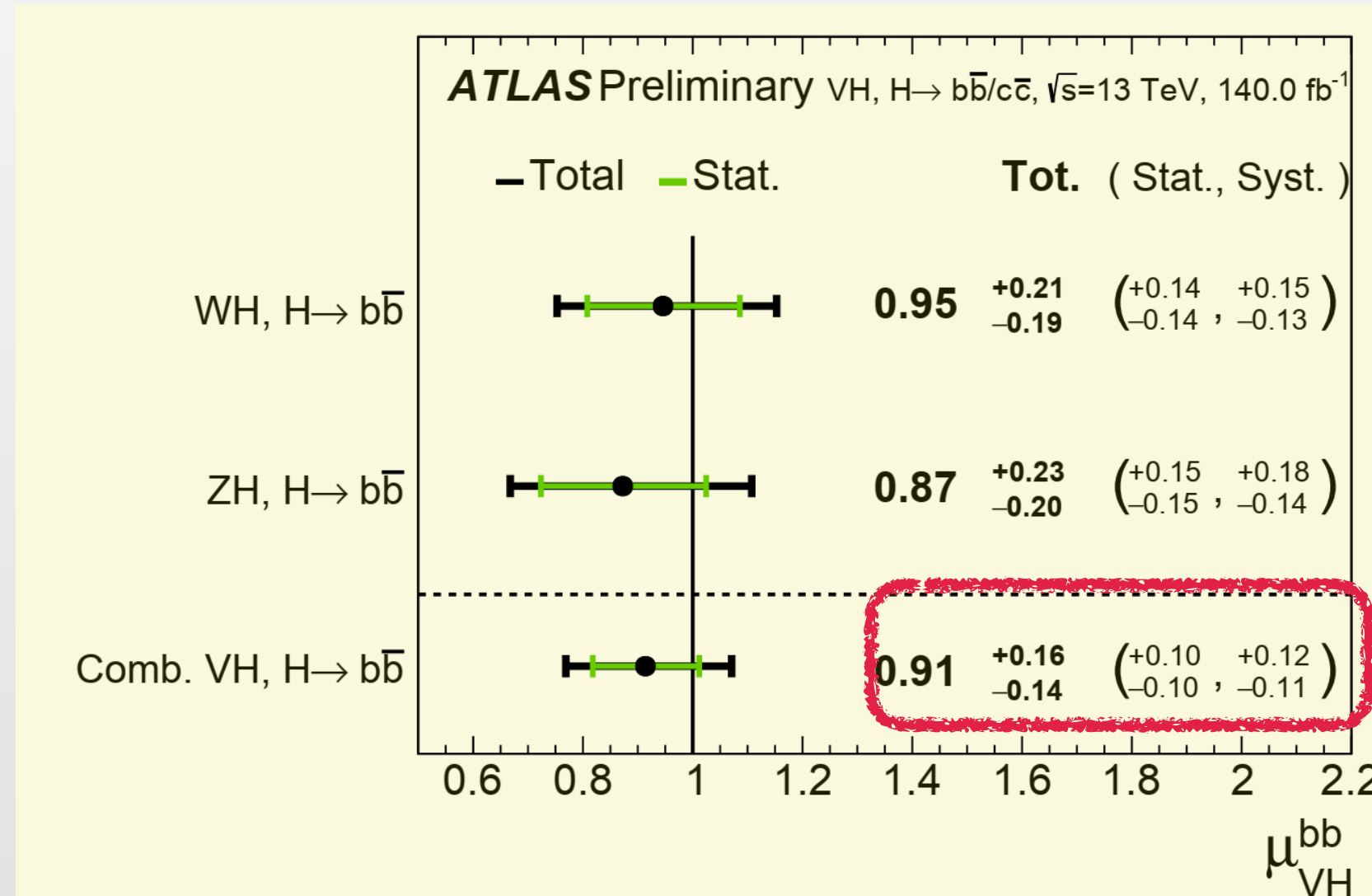
$$H \rightarrow Z\gamma : \mu = 2.2 \pm 0.7$$



ATLAS-CONF-2024-010

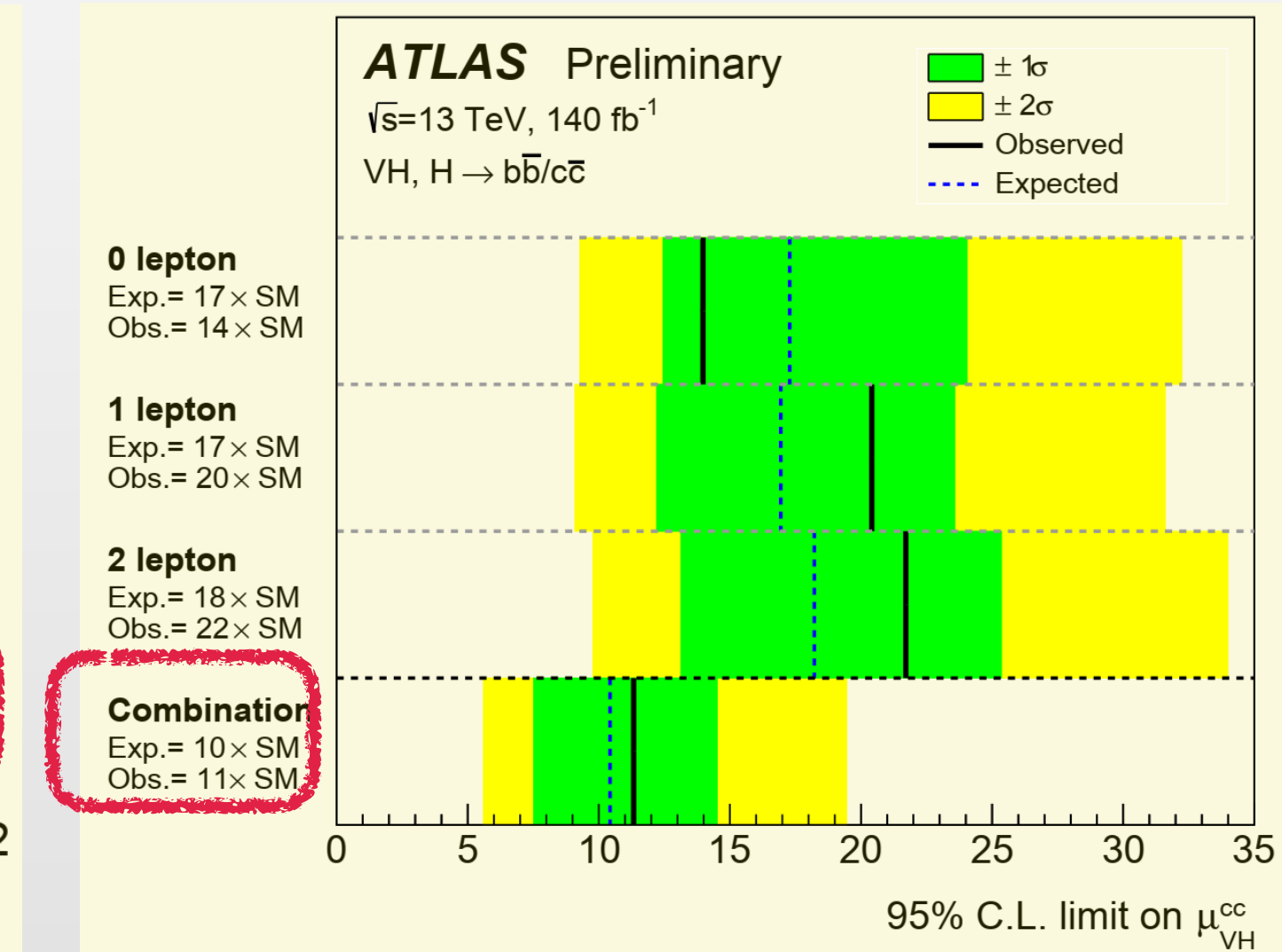
ATLAS Briefing

$$H \rightarrow b\bar{b}, c\bar{c}$$



上一轮结果: EPJC 81(2021)178:1.02<sup>+0.18</sup><sub>-0.17</sub>

提高15%

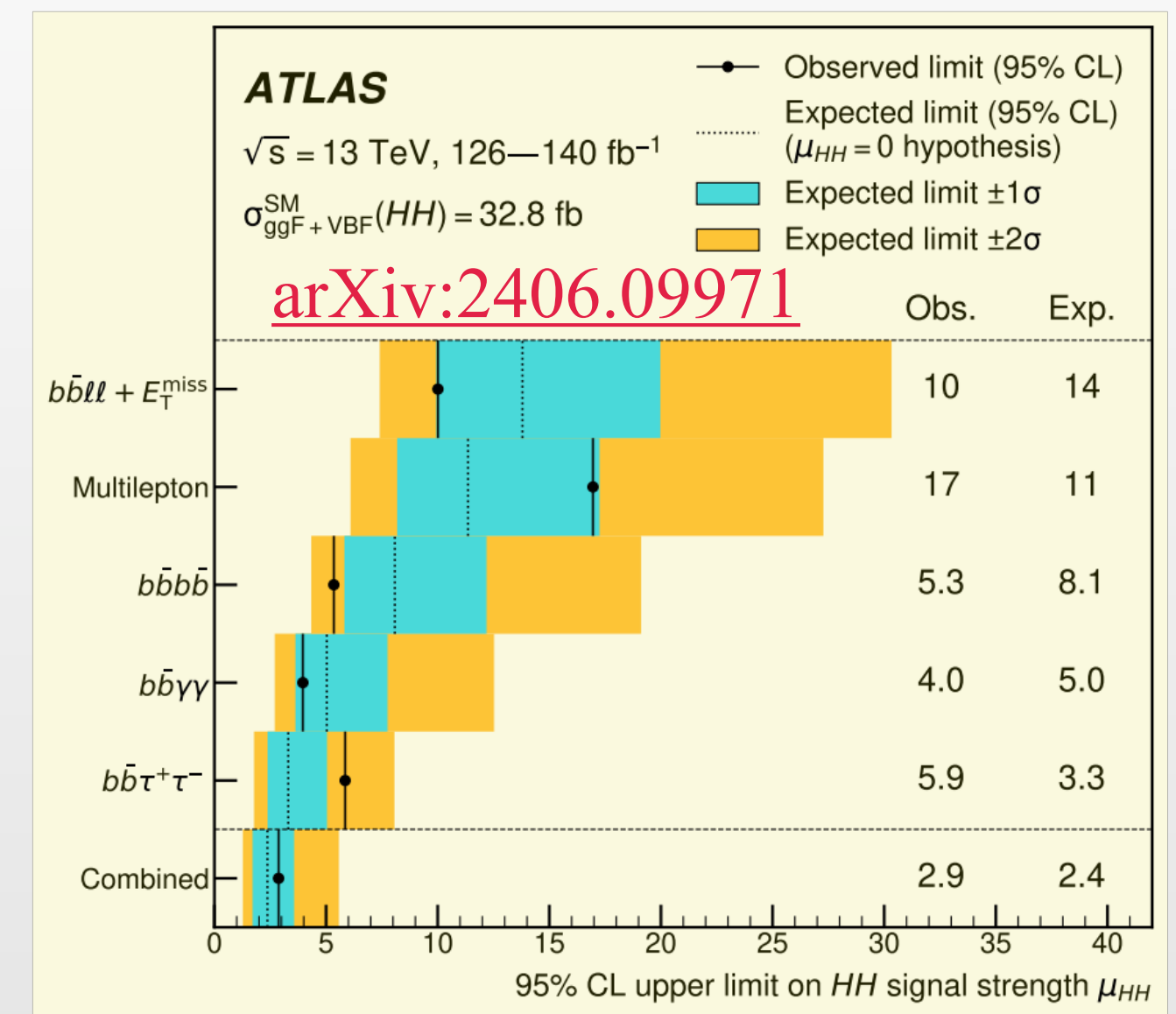
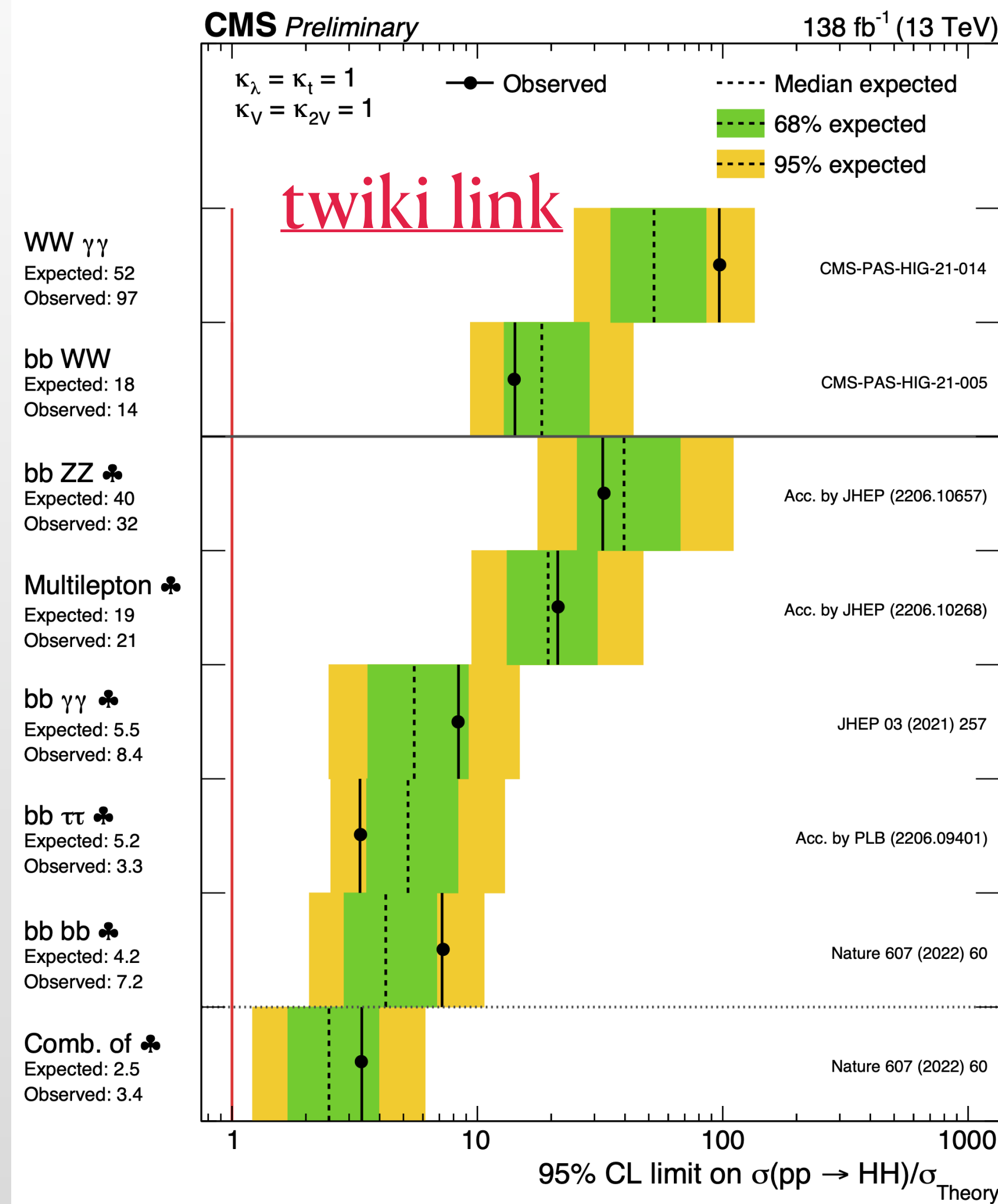
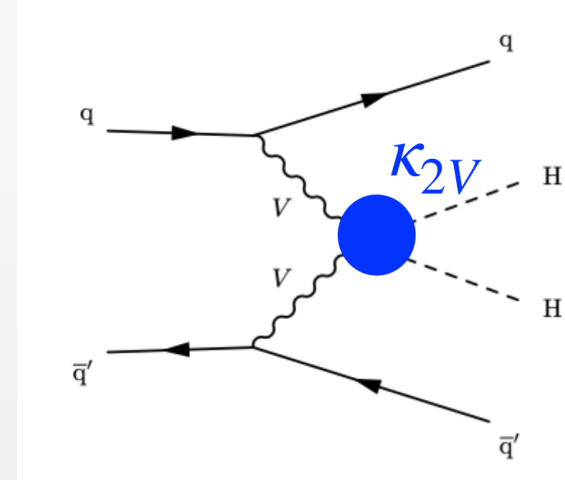
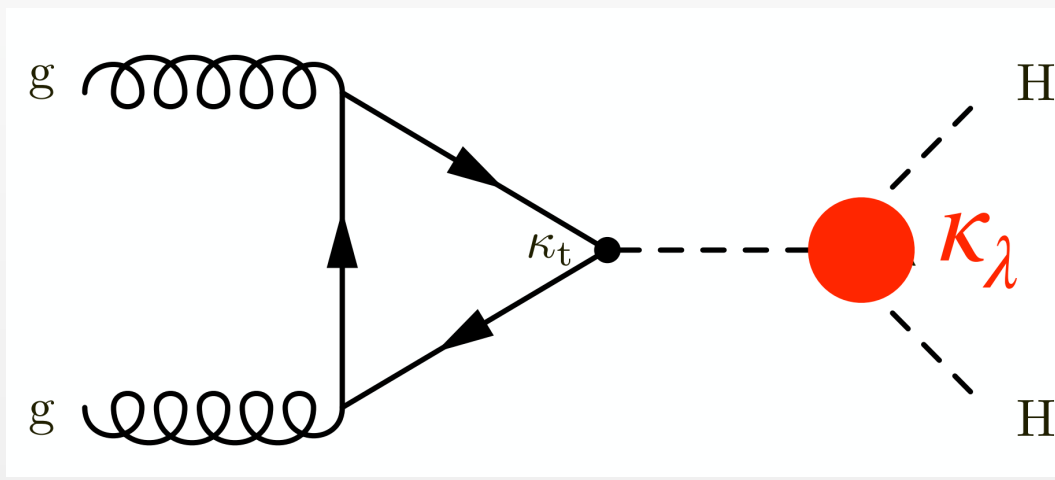


CMS, PRL131(2023)061801  $\mu < 14 \times \text{SM}$

ATLAS, EPJC82(2022)717  $\mu < 26 \times \text{SM}$

提高约3倍

# 希格斯粒子对(HH)的产生



	$b\bar{b}$	$WW_{>=1\ell}$	$WW_{4q}$	$\tau\tau$	ZZ	$\gamma\gamma$
$b\bar{b}$	34%					
$WW_{>=1\ell}$	13.4%	1.3%				
$WW_{4q}$	11.6%	1.1%	2.1%			
$\tau\tau$	7.3%	1.4%	1.2%	0.39%		
ZZ	3.1%	0.6%	0.2%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.05%	0.04%	0.028%	0.012%	0.0005%

Rarer decay ↓

→ Rarer decay

灵敏度逼近标准模型

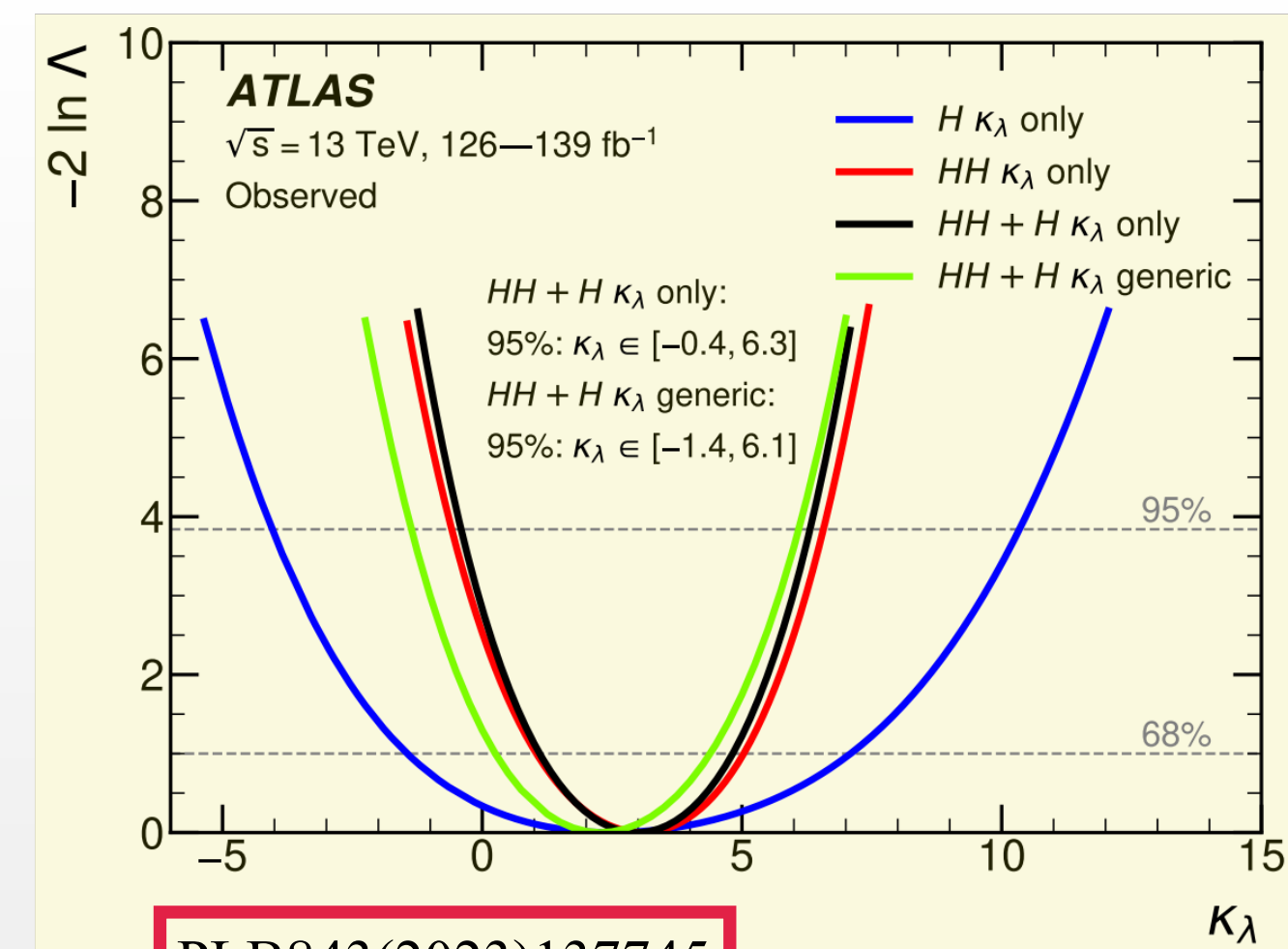
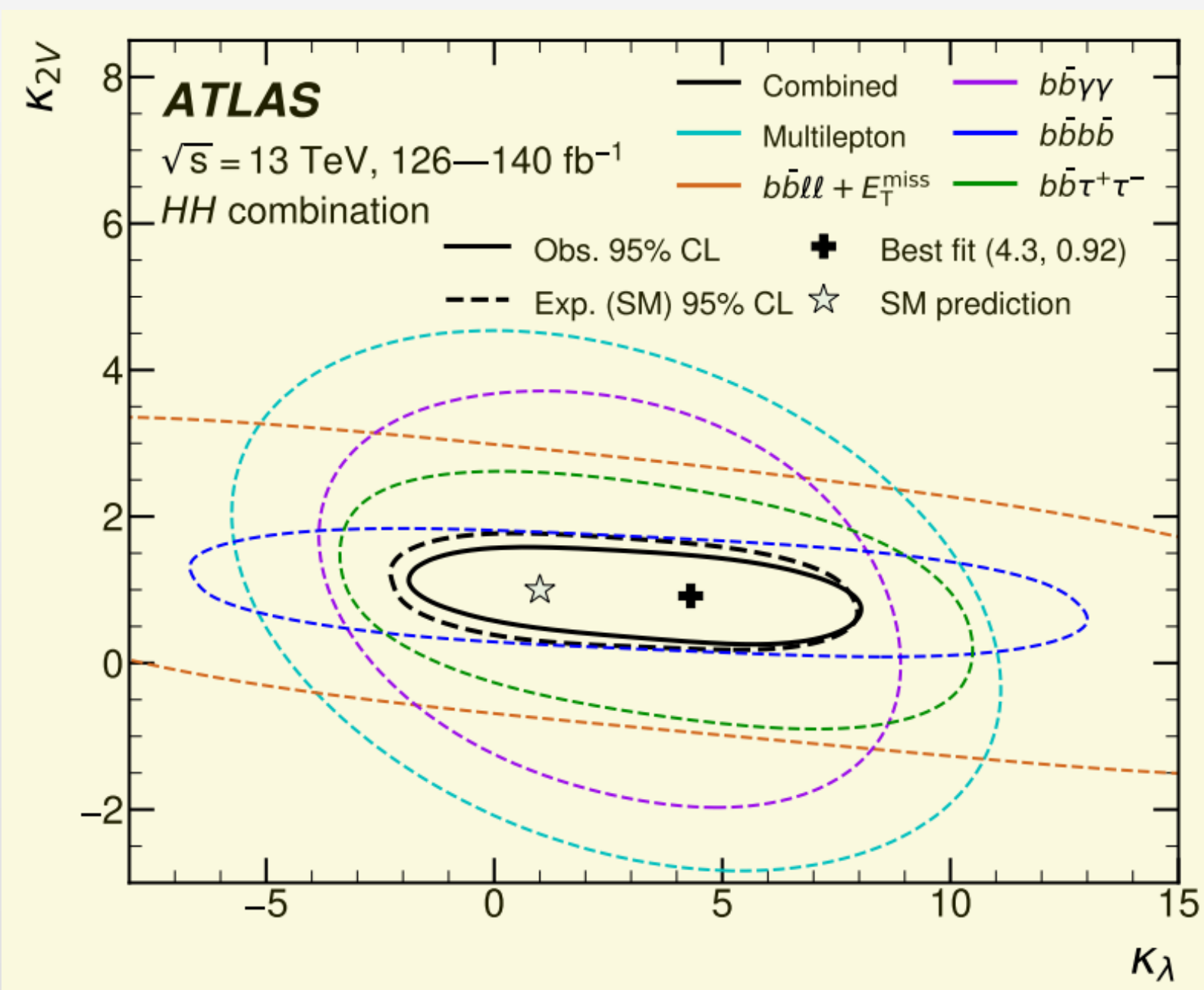
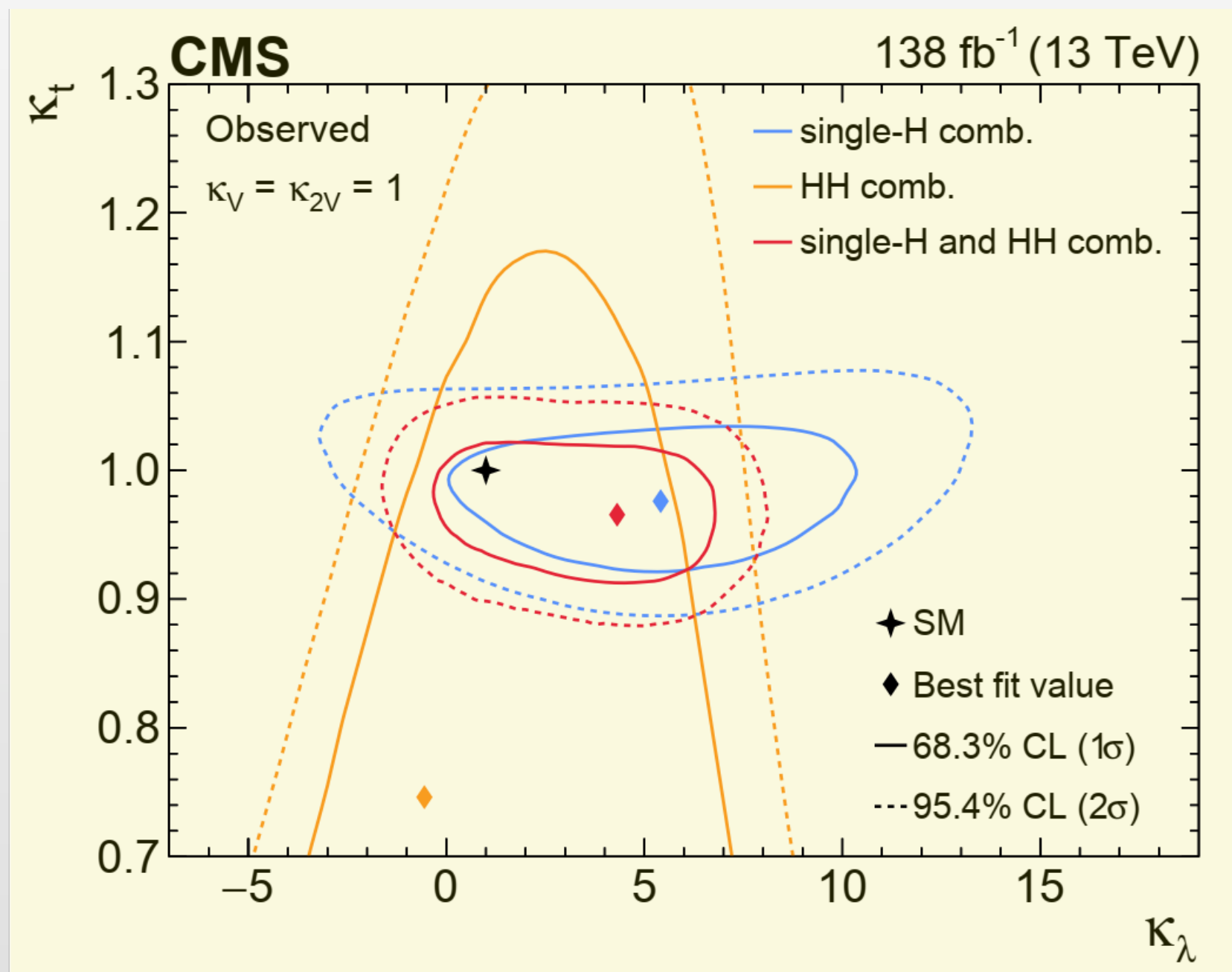
CMS:BUAA,IHEP,PKU...  
ATLAS:IHEP,NJU,SDU,SJTU(TDLI),USTC...

详见8.14 刘彦麟、莫岑、郭佳林  
8.15Wu S., Wang Z.,张翼翔 等人报告

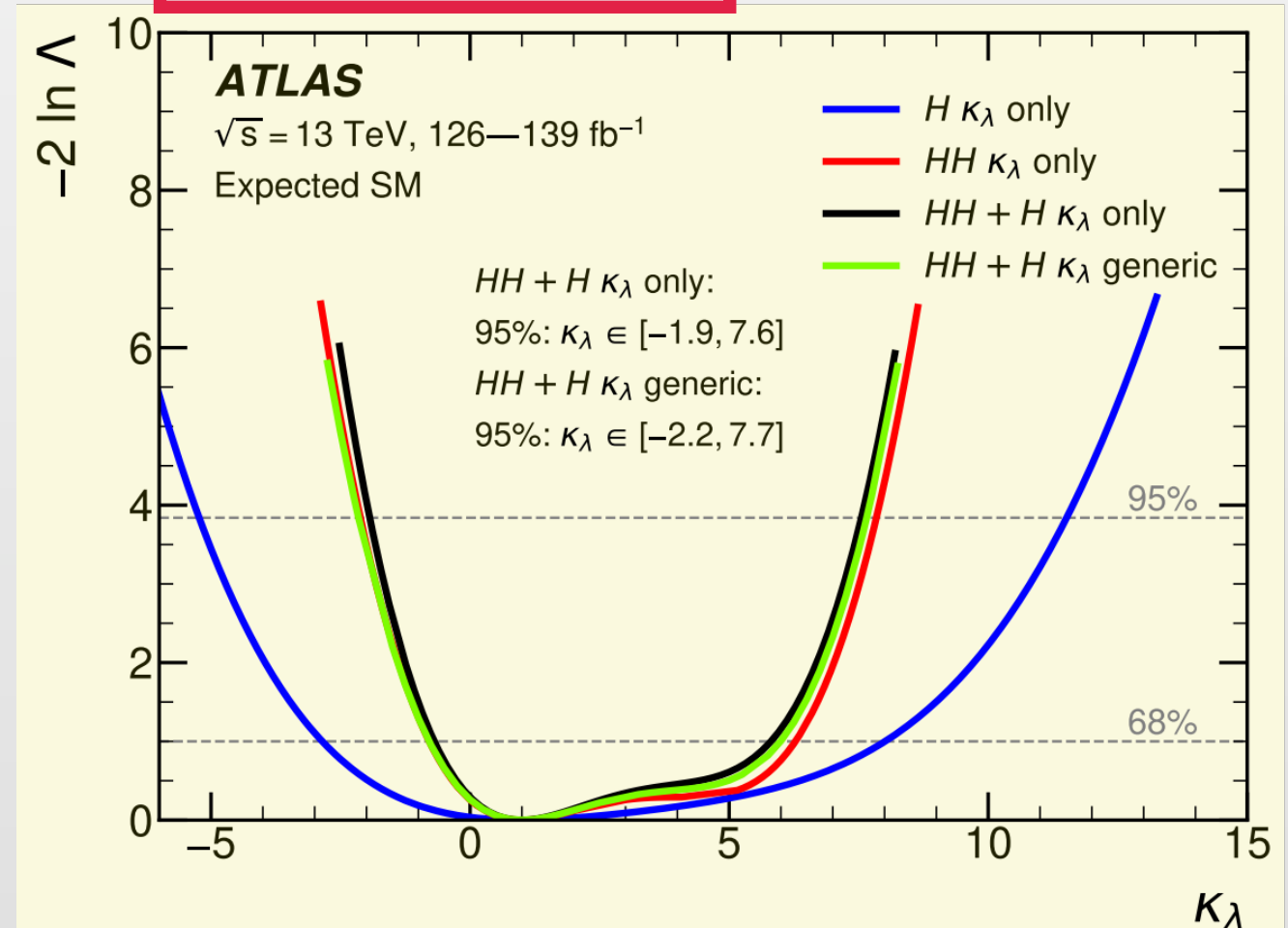
# 希格斯自耦合

arXiv:2407.13554

arXiv:2406.09971



PLB843(2023)137745



CMS:  $\kappa_\lambda$  “单参数”分析:

ATLAS:  $\kappa_\lambda$  “单参数”分析:

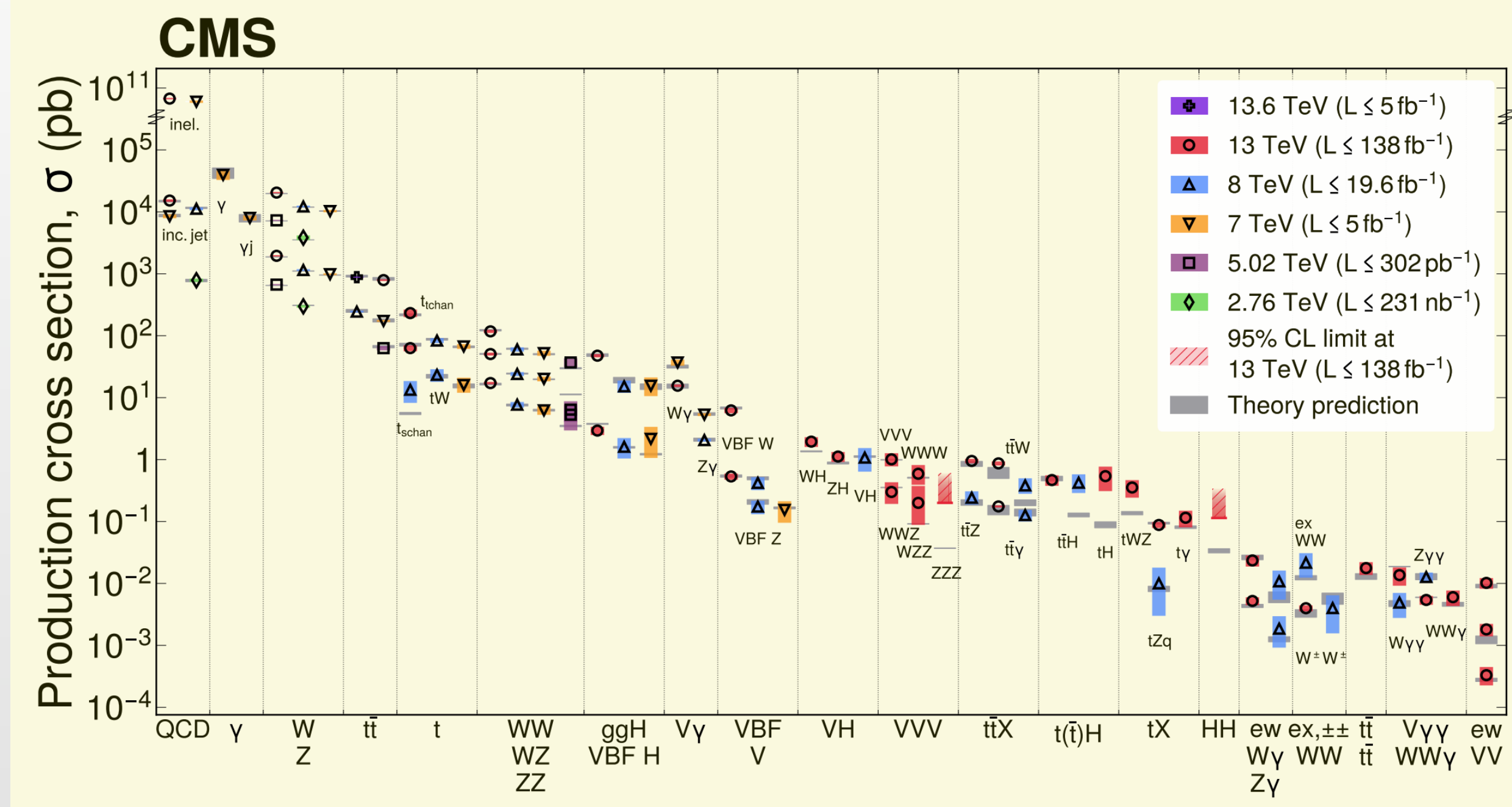
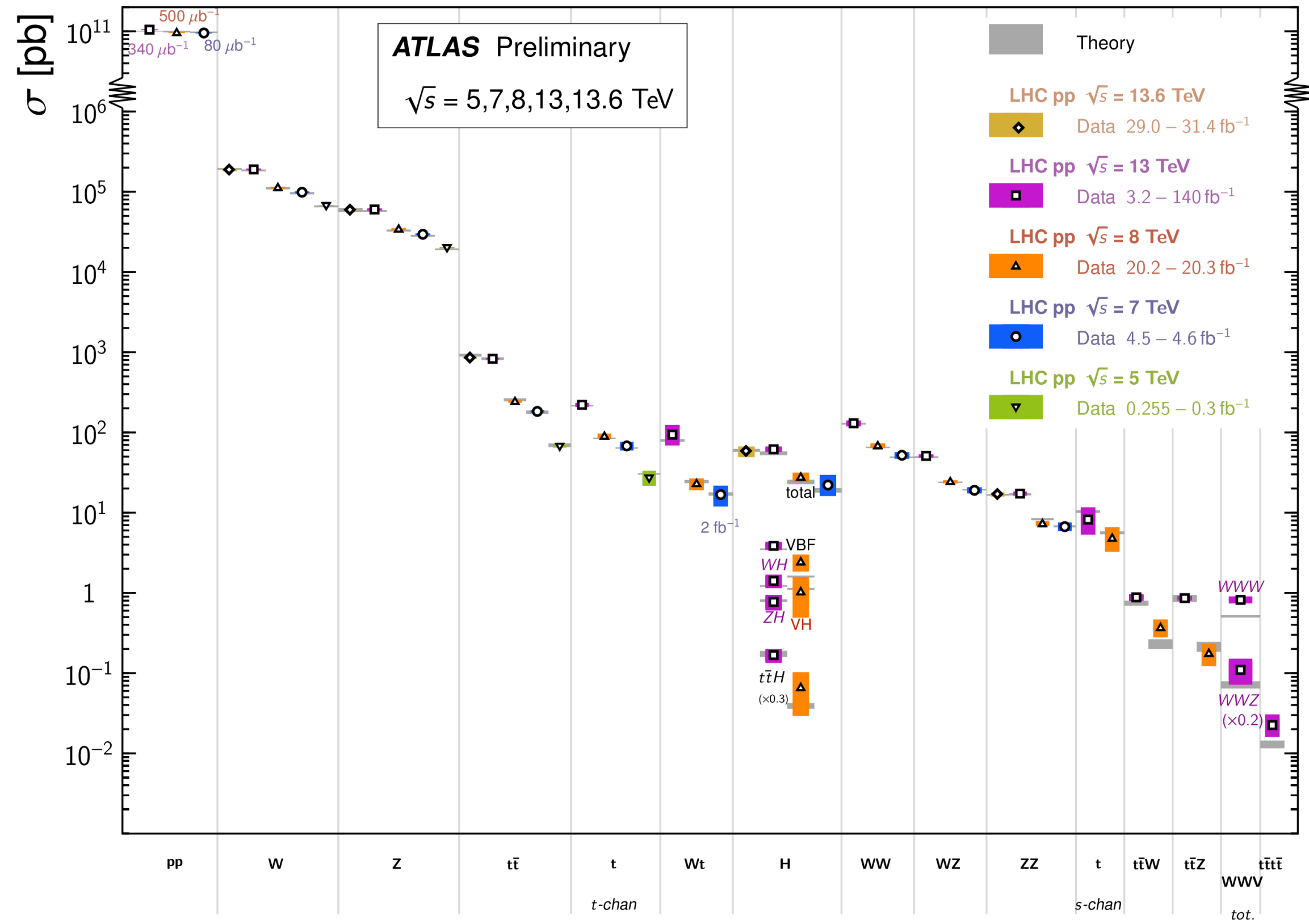
“Generic”: float  $\kappa_t, \kappa_b, \kappa_V, \kappa_\tau$

$2\sigma(95.4\%)$  C.I.  $[-1.2, 7.5]$  ( $[-2.0, 7.7]$ ) 95% C.I.  $[-1.2, 7.2]$  ( $[-1.6, 7.2]$ )

$$\lambda^{\text{SM}} = \frac{m_H^2}{2v^2} \approx 0.13$$

# Standard Model Total Production Cross Section Measurements

Status: June 2024

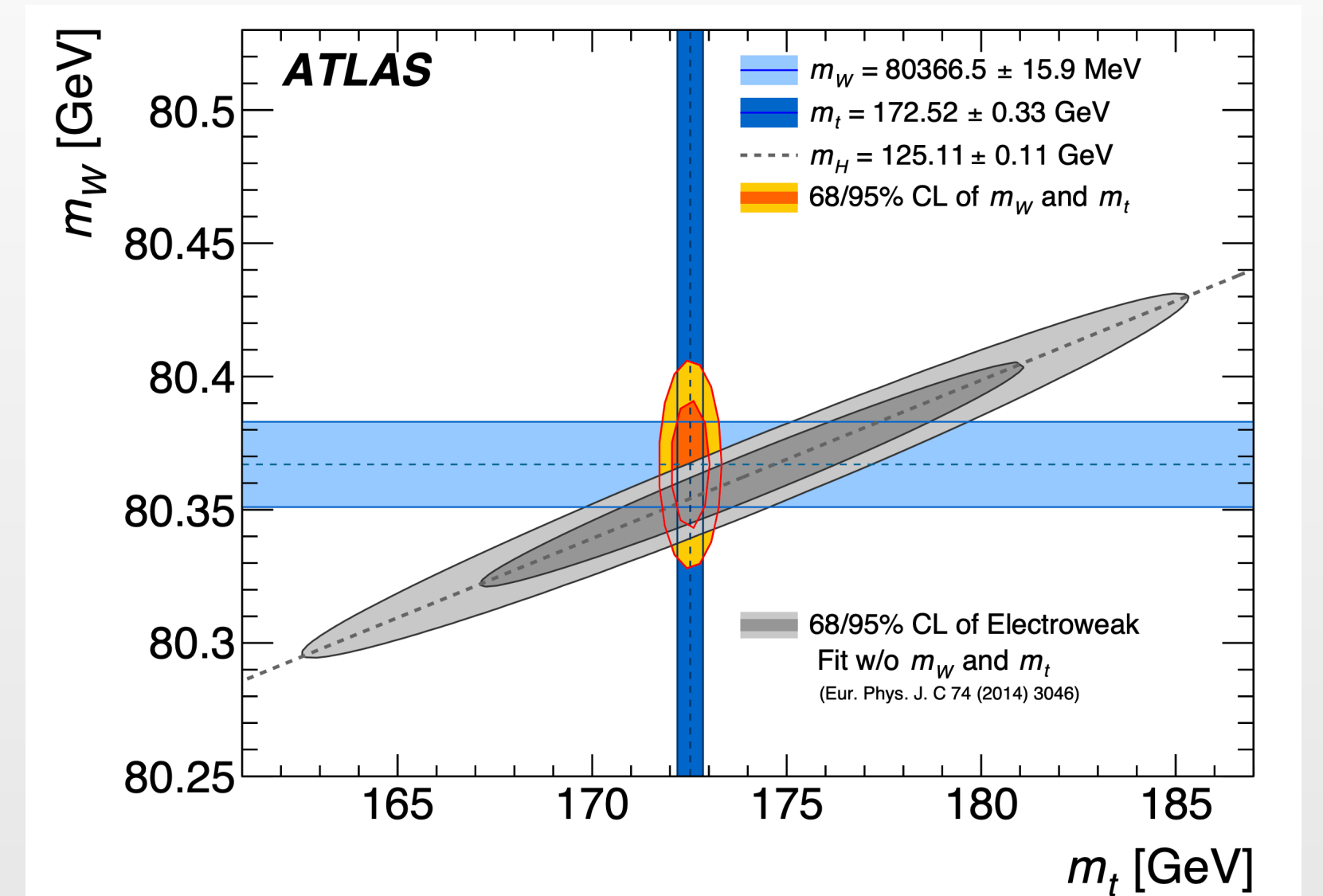
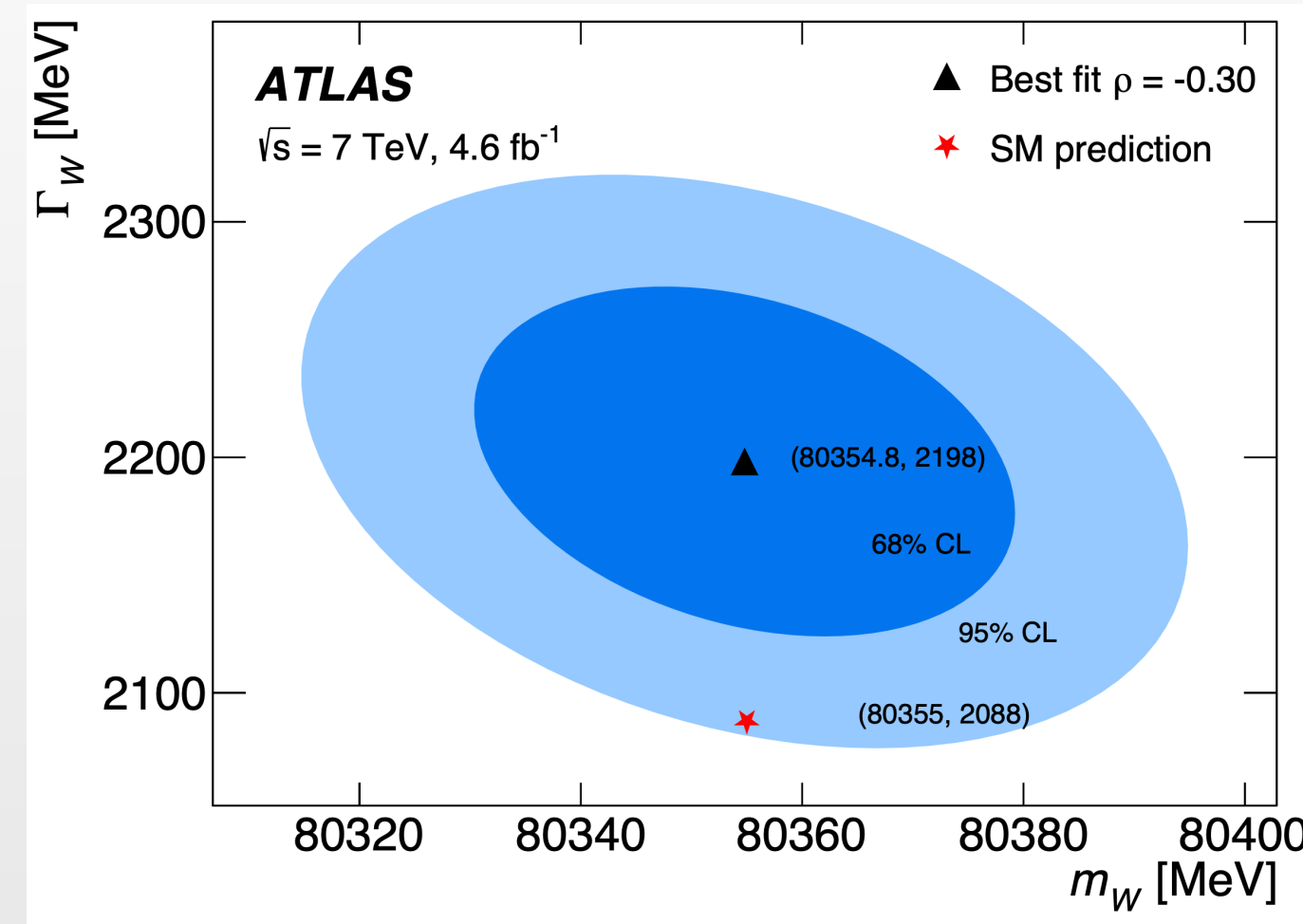
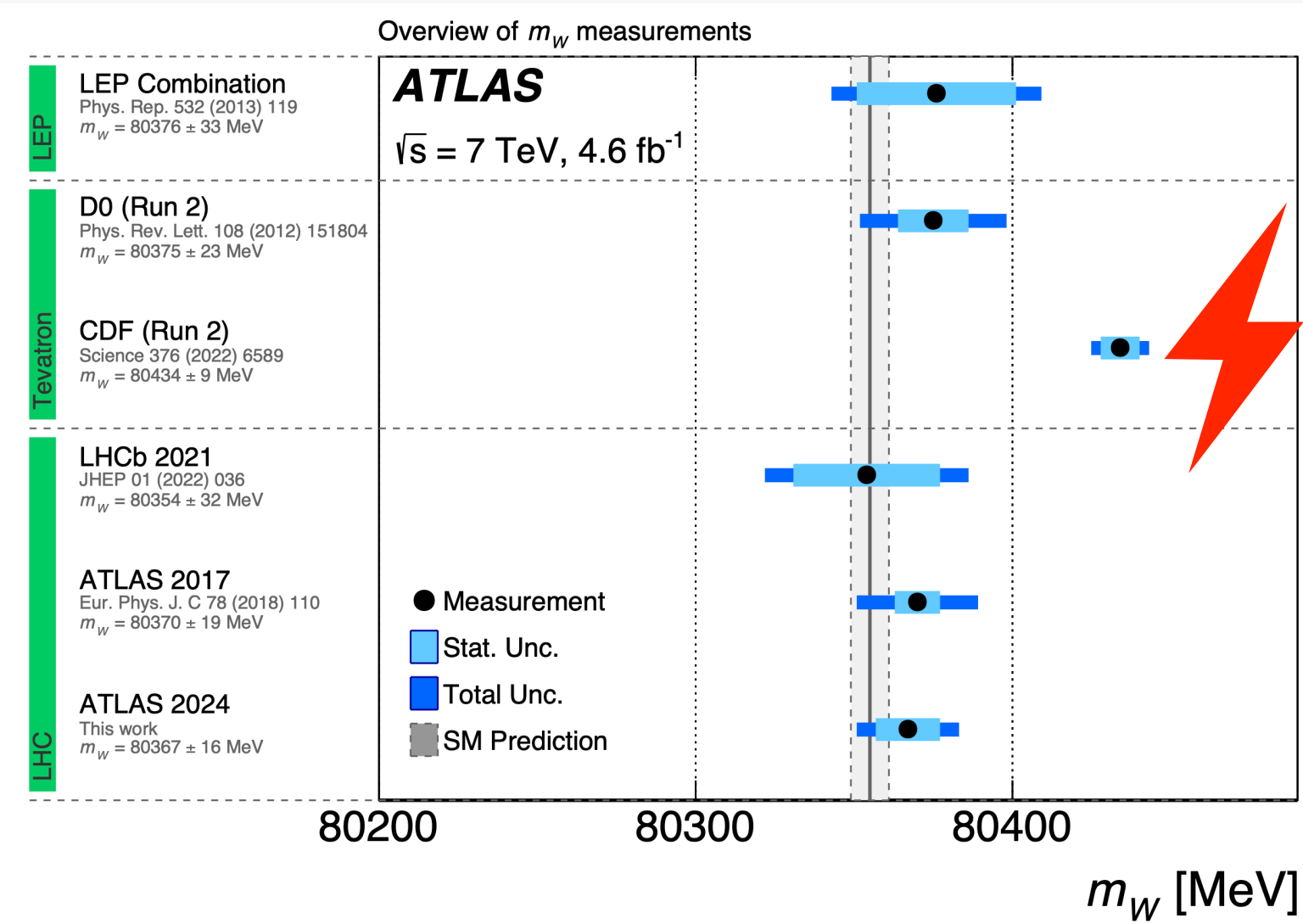


# 标准模型精确检验进展

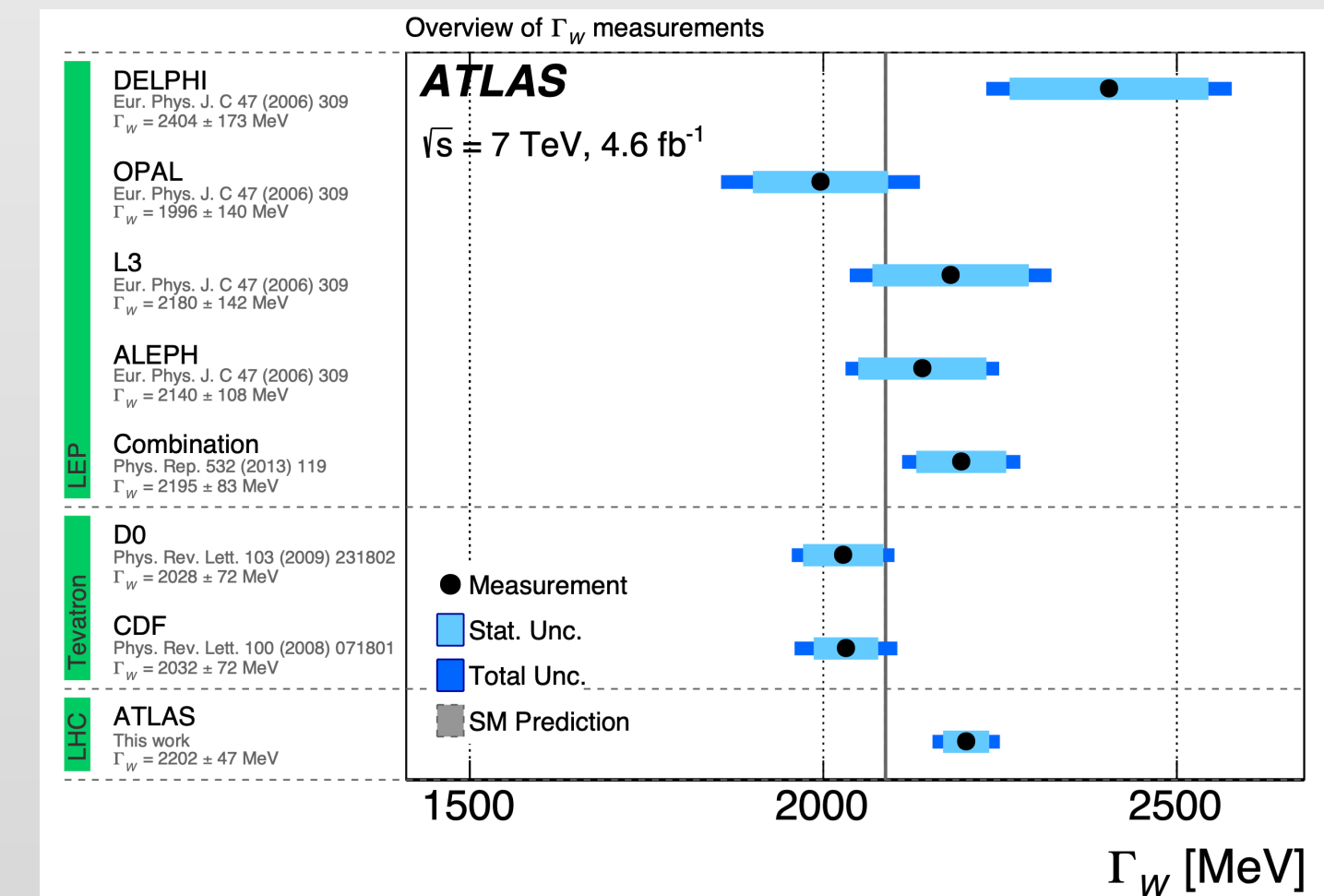


# $W$ 粒子质量与宽度的测量 (Run 1 数据)

arXiv:2403.15085

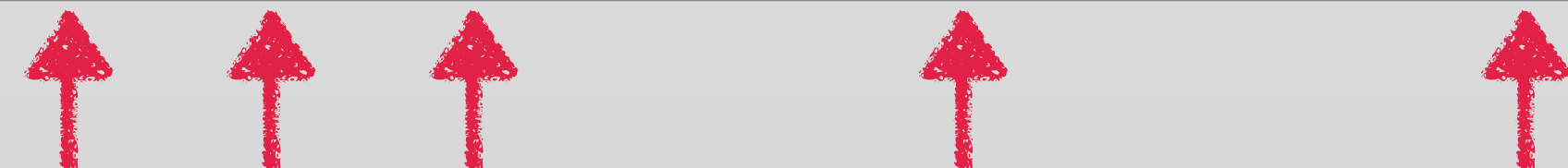


EW global fit: PRD 106 (2022) 033003



## $W$ 质量测量误差分解

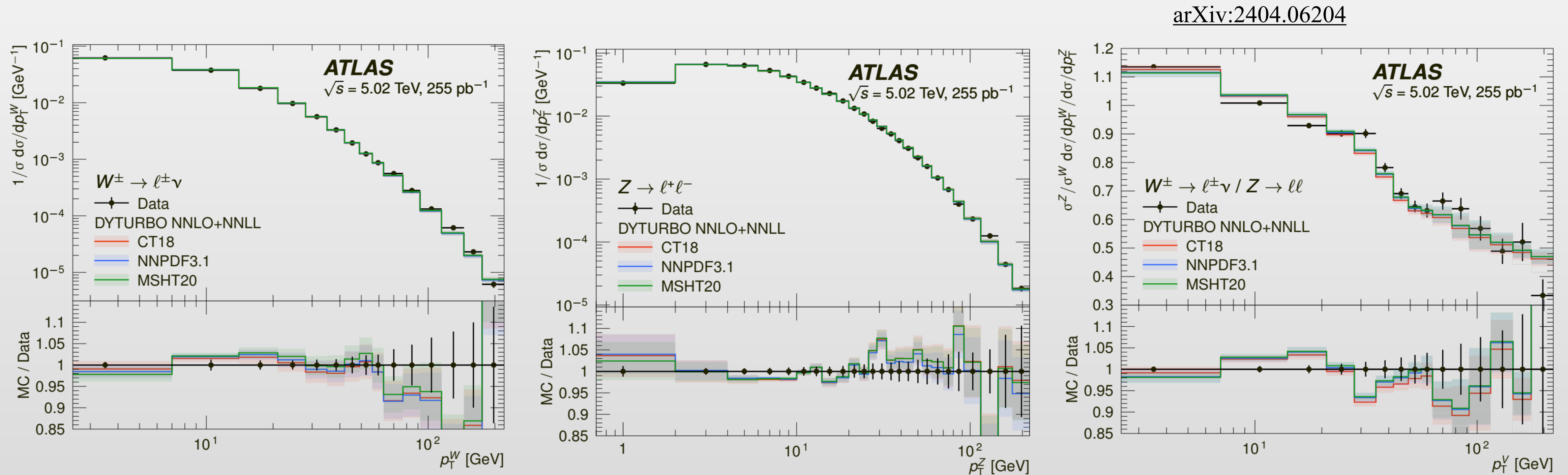
Unc. [MeV]	Total	Stat.	Syst.	PDF	$A_i$	Backg.	EW	$e$	$\mu$	$u_T$	Lumi	$\Gamma_W$	PS
$p_T^\ell$	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
$m_T$	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3



# 利用低瞬时亮度数据测量 $W/Z$ 横动量

LHC 上的 $W/Z$ 横动量分布是测量QCD效应的探针(高阶微扰修正、PDF、初态 $k_T$ 等非微扰效应)

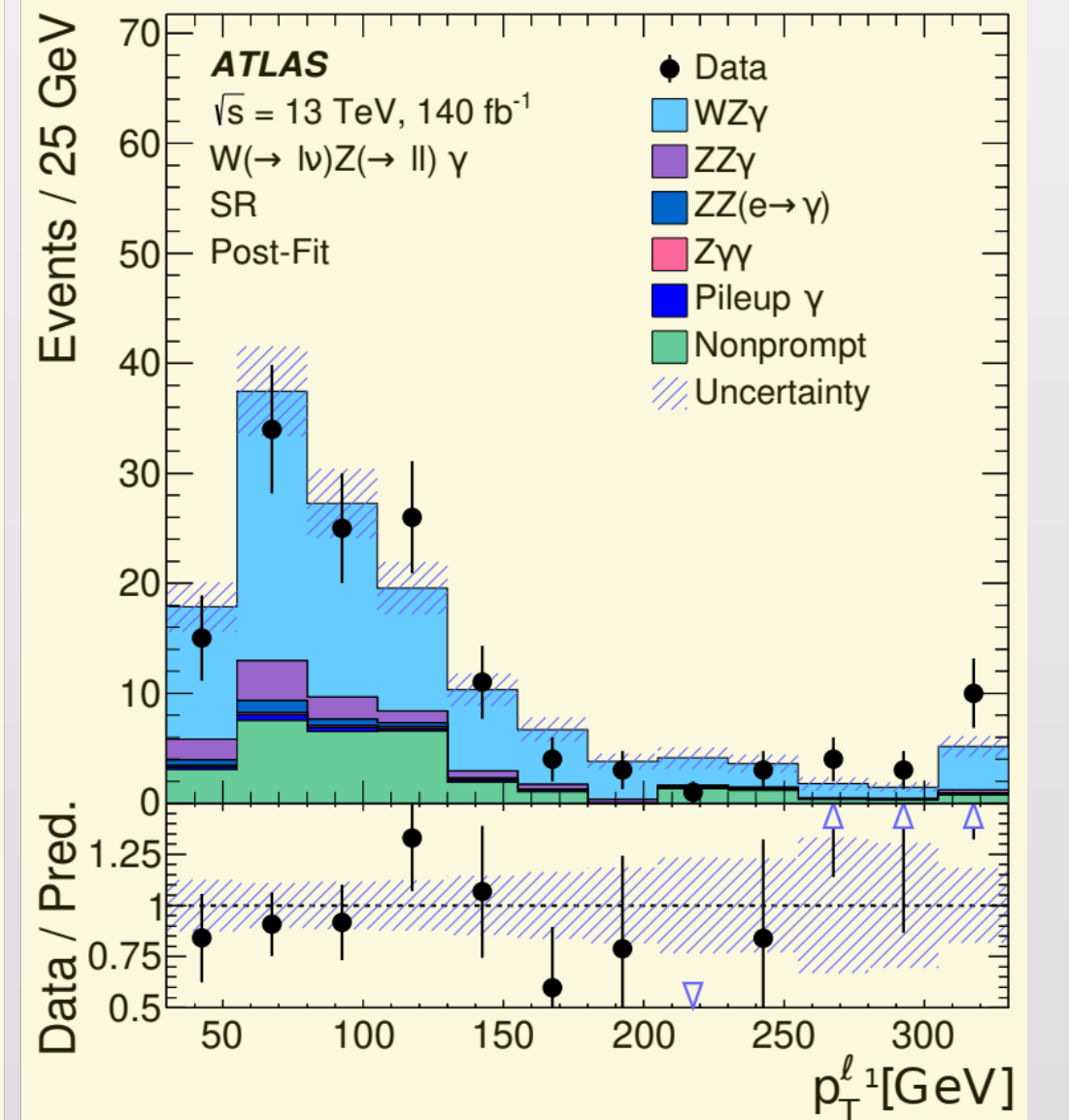
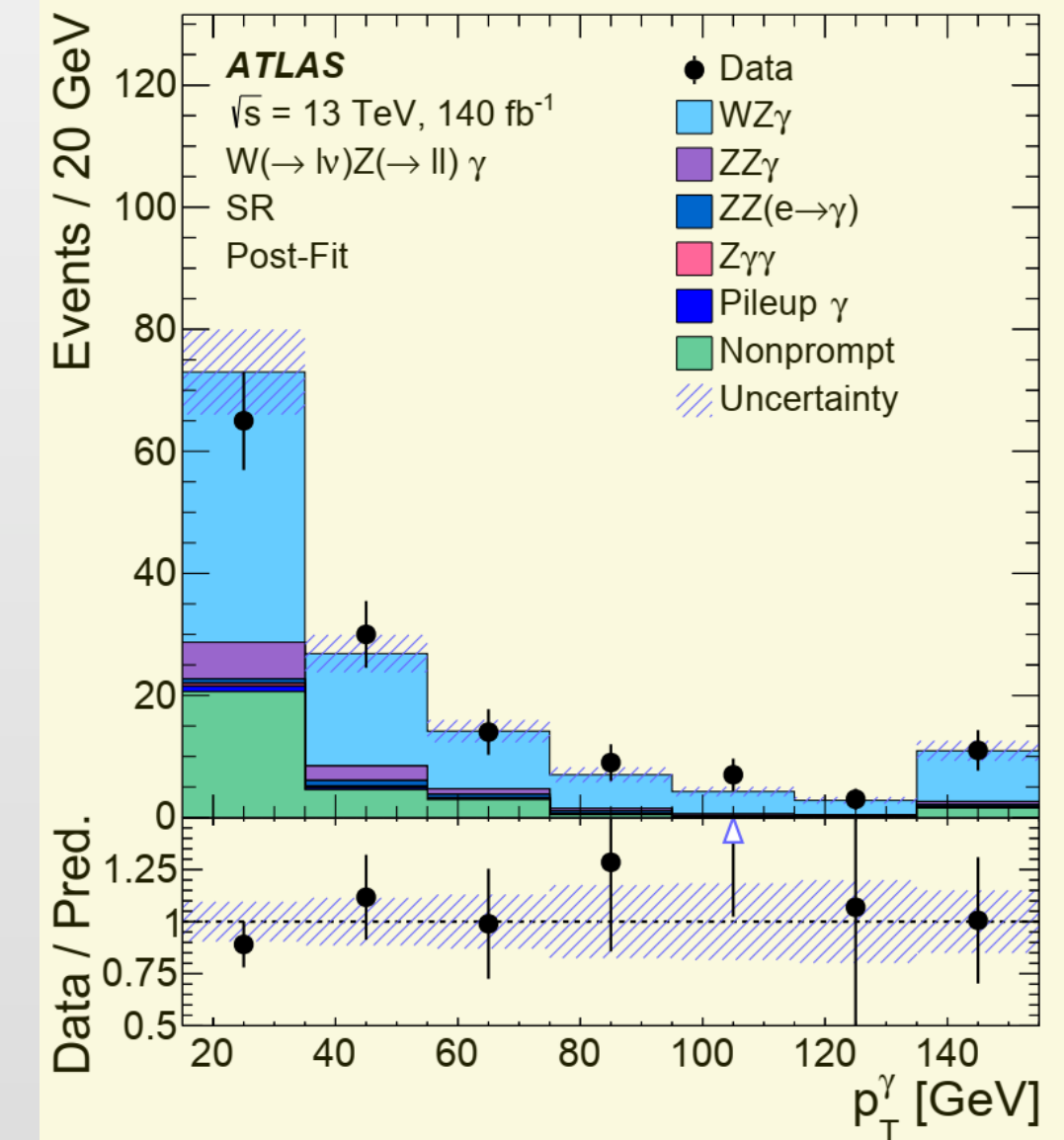
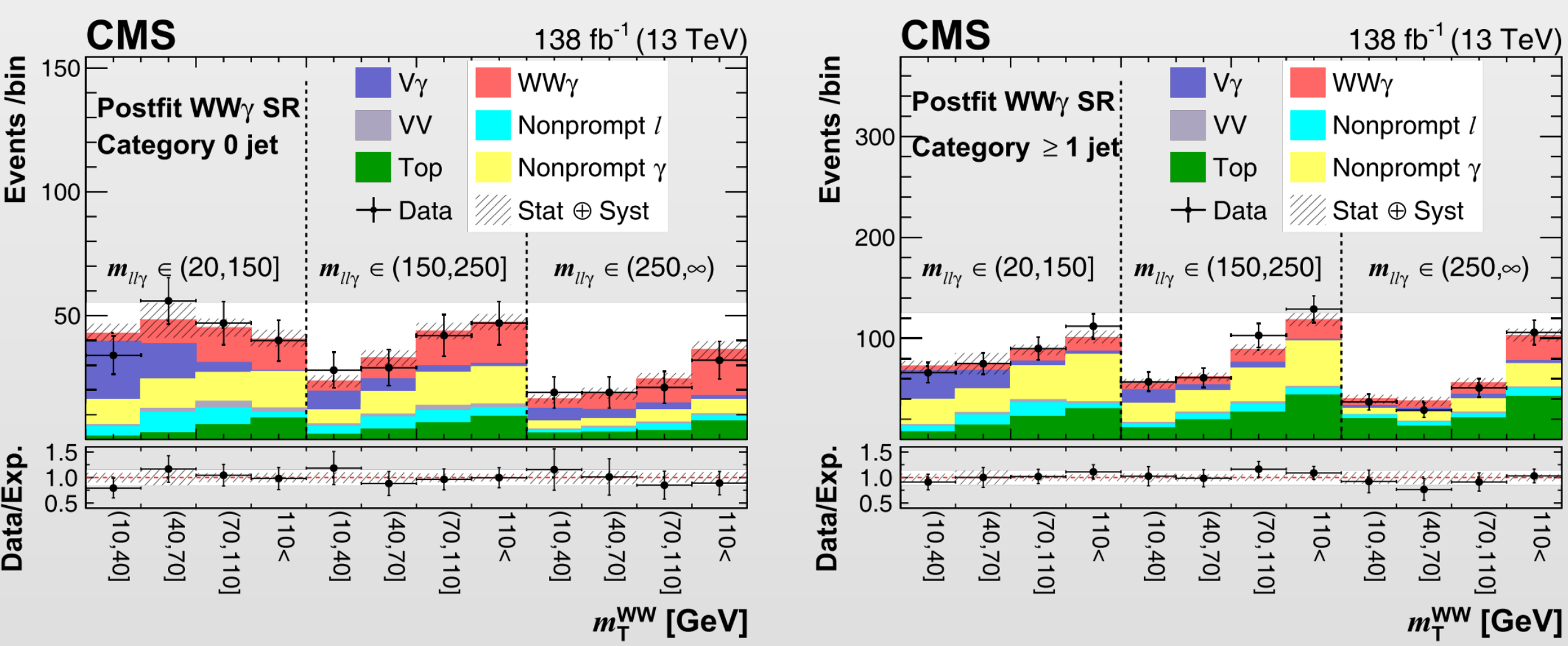
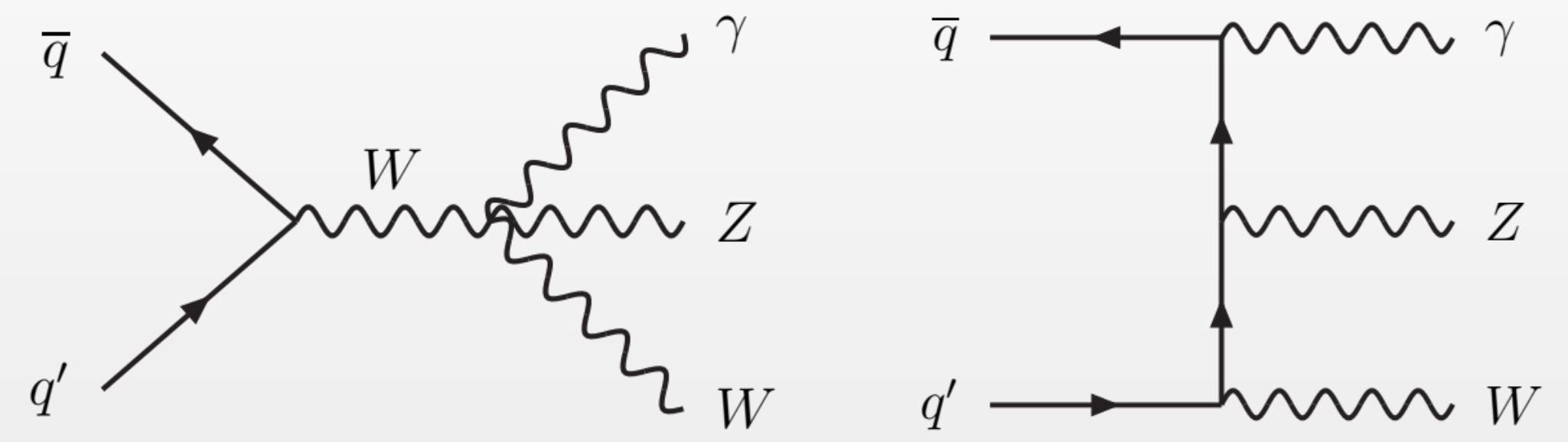
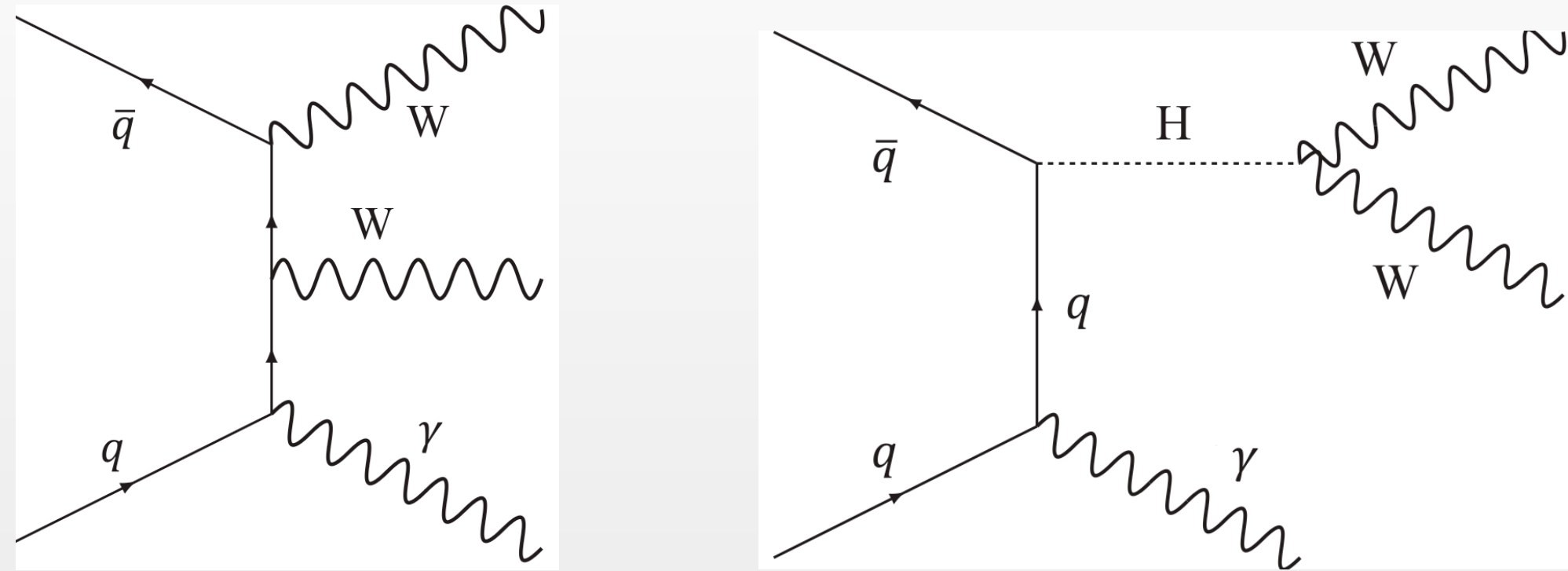
$W/Z$ 横动量的精确测量是 $W$ 质量测量的重要环节



$$\sqrt{s} = 5.02 \text{ TeV}, 255 \text{ pb}^{-1} \quad \langle \mu \rangle \approx 2$$

$$\sqrt{s} = 13 \text{ TeV}, 338 \text{ pb}^{-1}$$

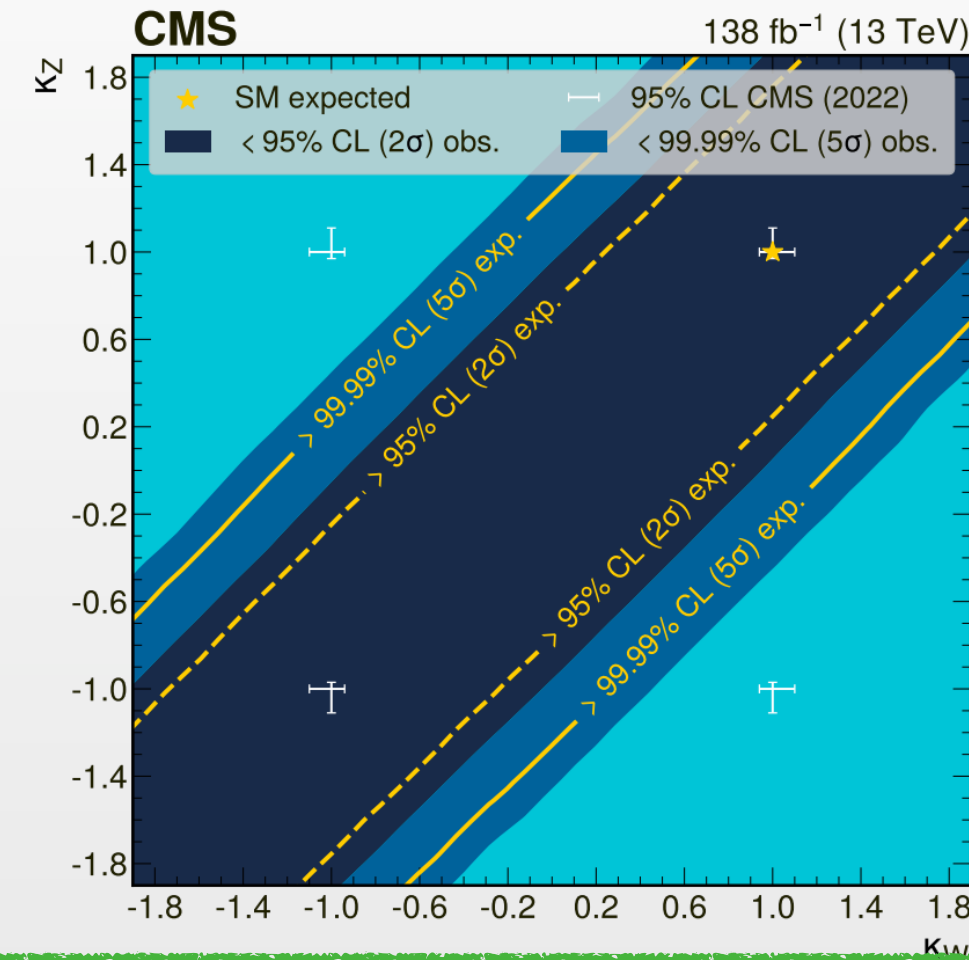
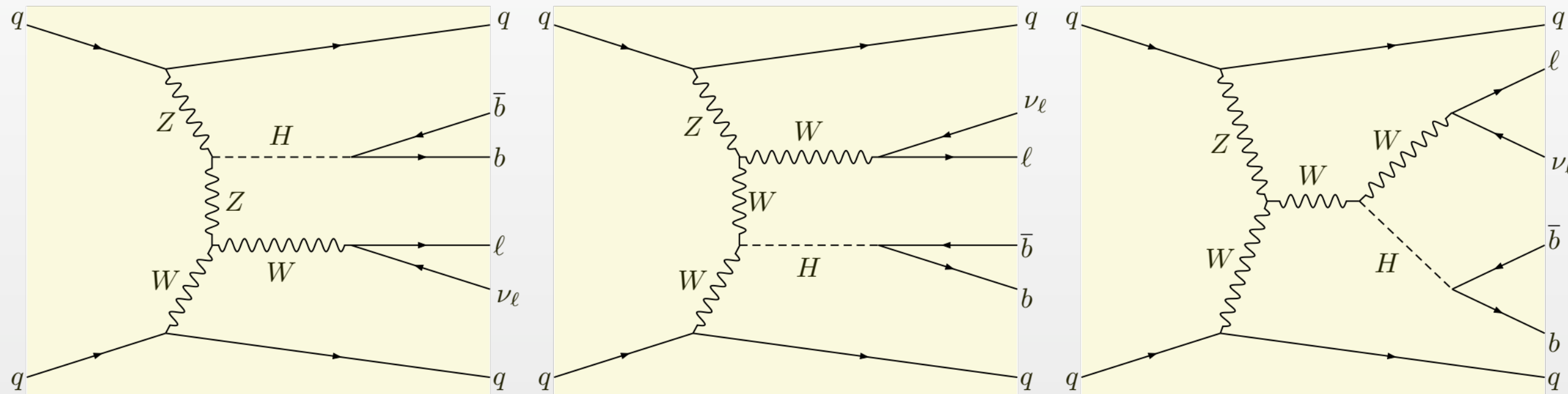
# 多玻色子末态



统计显著性:  $5.6(5.1)\sigma$ . 限制  $u, d, c, s$  汤川耦合  
 $\sigma_{WW\gamma} = 5.9 \pm 0.8(\text{stat.}) \pm 0.8(\text{syst.}) \pm 0.7(\text{mod.}) \text{ fb}$

统计显著性:  $6.3(5.0)\sigma$   
 $\sigma_{WZ\gamma} = 2.01 \pm 0.30(\text{stat.}) \pm 0.16(\text{syst.}) \text{ fb}$

# 其他电弱检验



arXiv:2405.16566

$WZ \rightarrow WH$

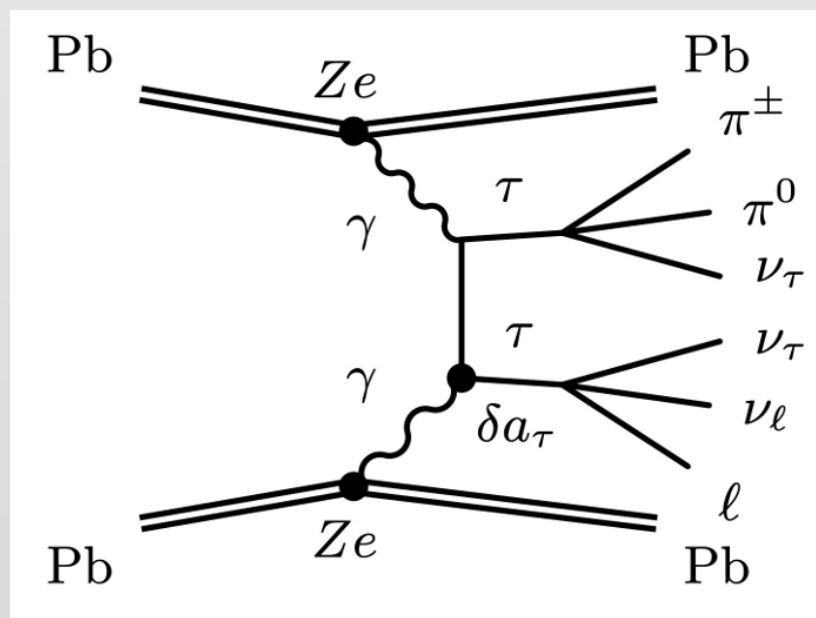
确定  $\kappa_W * \kappa_Z > 0$

PKU...

Editors' suggestion

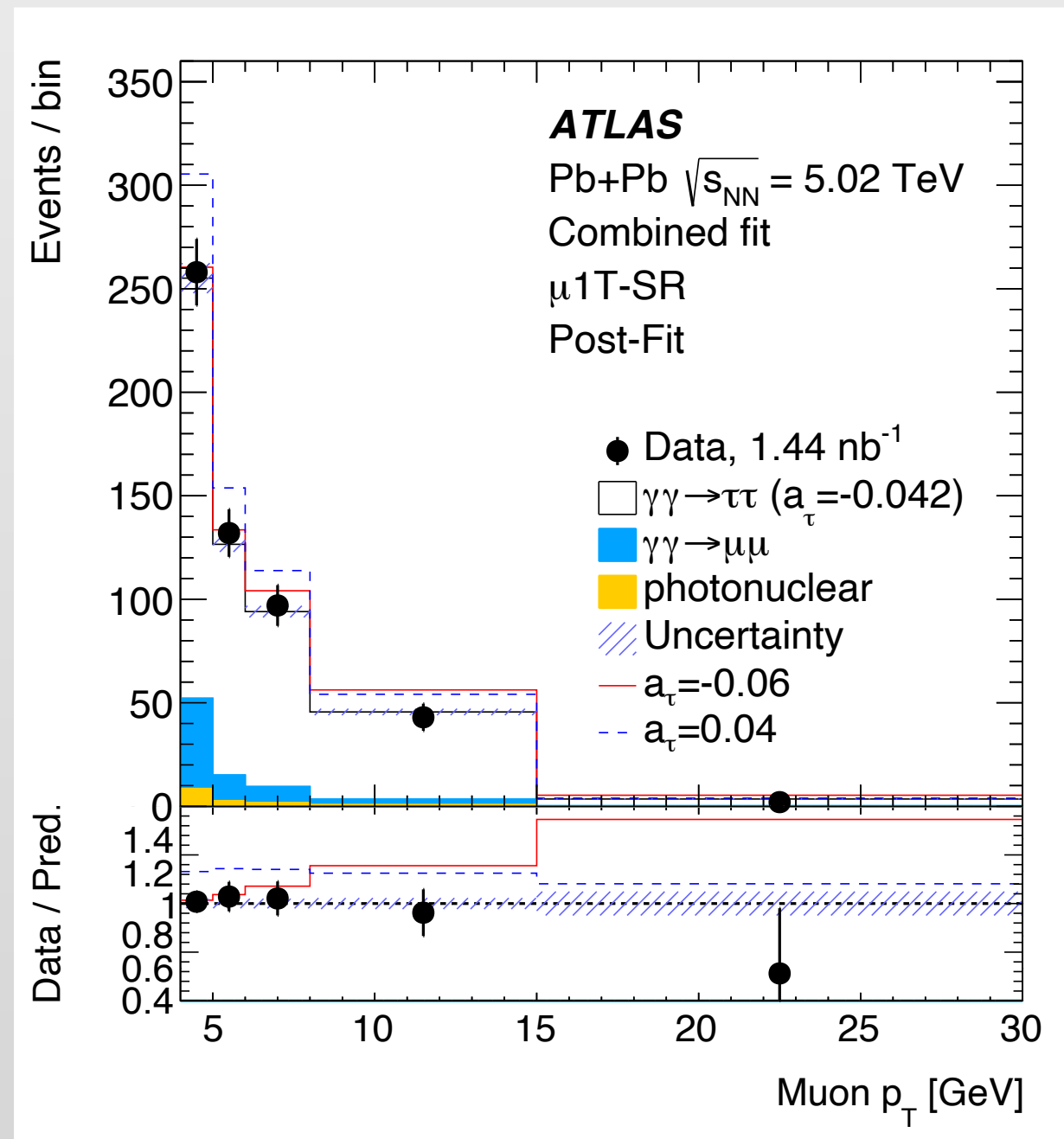
PRL131(2023)151802

$-0.057 < a_\tau < 0.024 @ 95\% \text{ CL}$



SDU...

CMS  $\gamma\gamma \rightarrow \tau\tau$  in pp



VBS ZZ: [Nature Physics 19\(2023\) 237](#)

VBS Zgamma: [PLB846\(2023\)138222](#)

VBS Wgamma: [arXiv:2403.02809](#)

Z\_L Z\_L: [JHEP 12 \(2023\) 107](#)

WZ RAZ: [arXiv:2402.16365](#)

Z+b/c: [arXiv:2403.15093](#)

ttW: [JHEP05\(2024\)131](#)

SDU,SJTU/TDLI,USTC...

IHEP,TDLI...

SJTU/TDLI...

SDU,SJTU/TDLI,USTC...

USTC...

USTC...

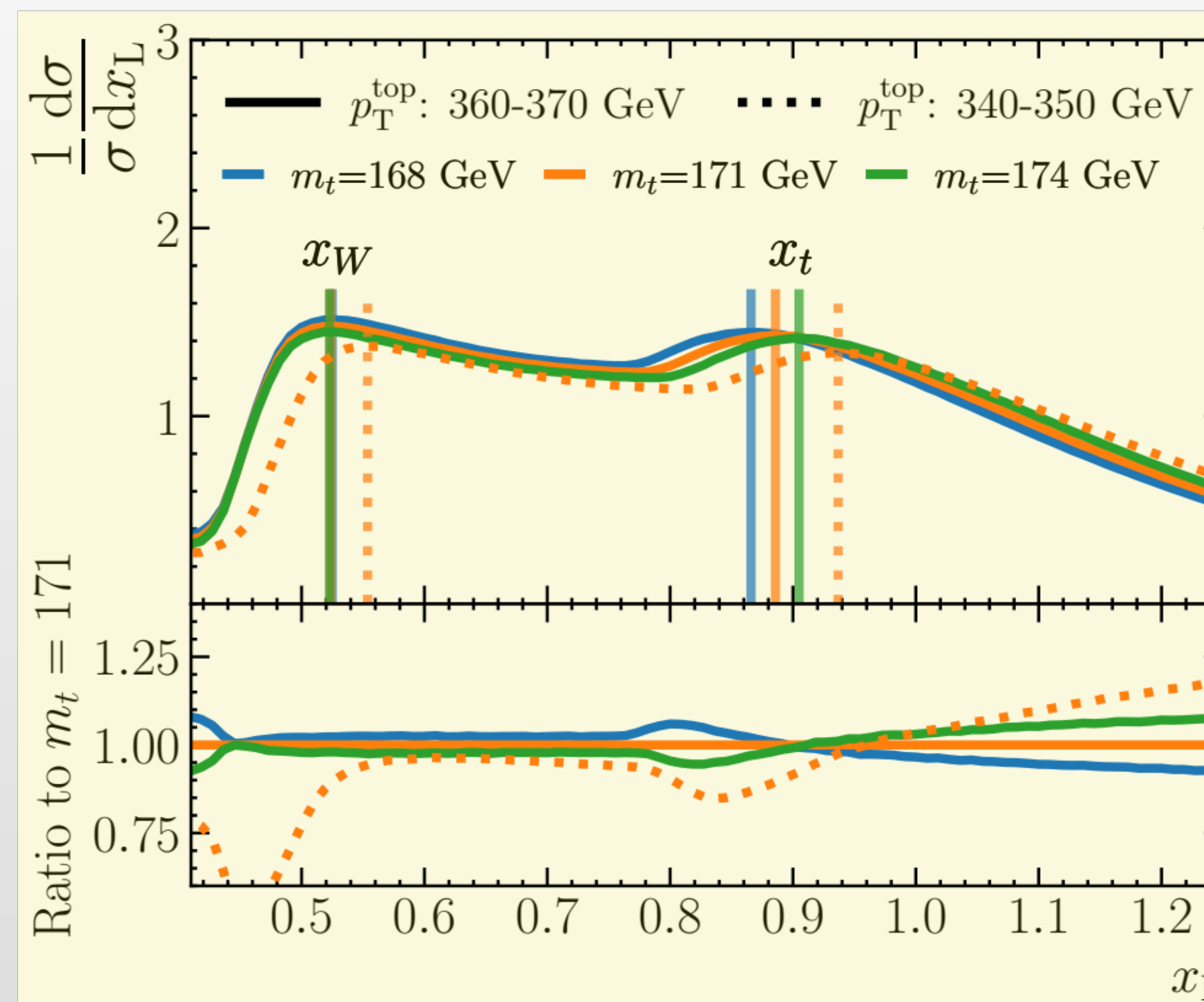
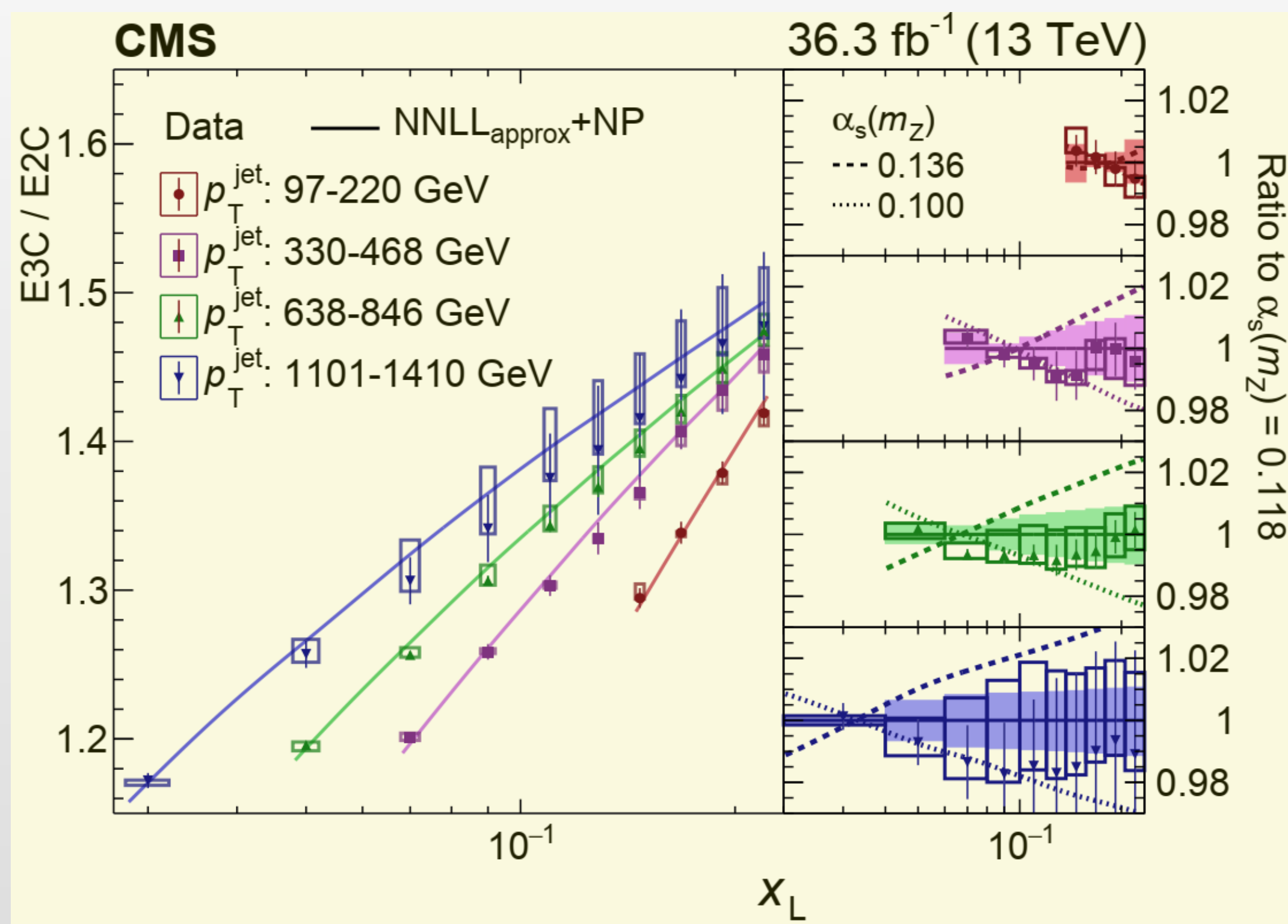
SDU,SJTU/TDLI,USTC...

详见8.14 下午吴雨生、陈婧、李家琳及8.15下午杨轩等人报告

# 喷注内部能量关联:E3C/E2C

arXiv:2402.13864

arXiv:2405.20001



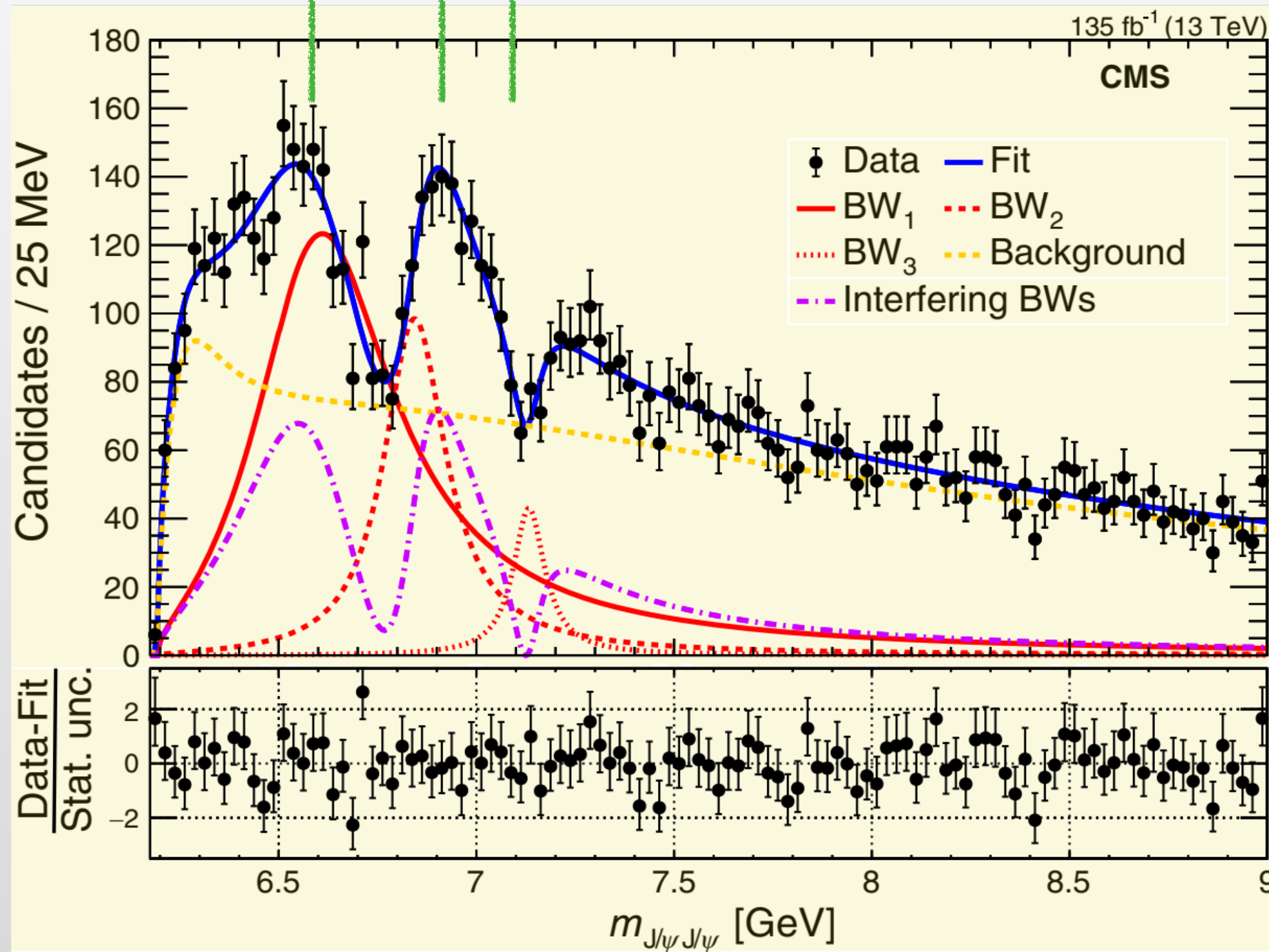
测得:  $\alpha_s(M_Z) = 0.1229^{+0.0040}_{-0.0050}$

$$E3C = \frac{d\sigma}{dx_L} = \sum_{i,j,k} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{ij}, \Delta R_{ik}, \Delta R_{jk}))$$

详见8.14 下午林桢报告

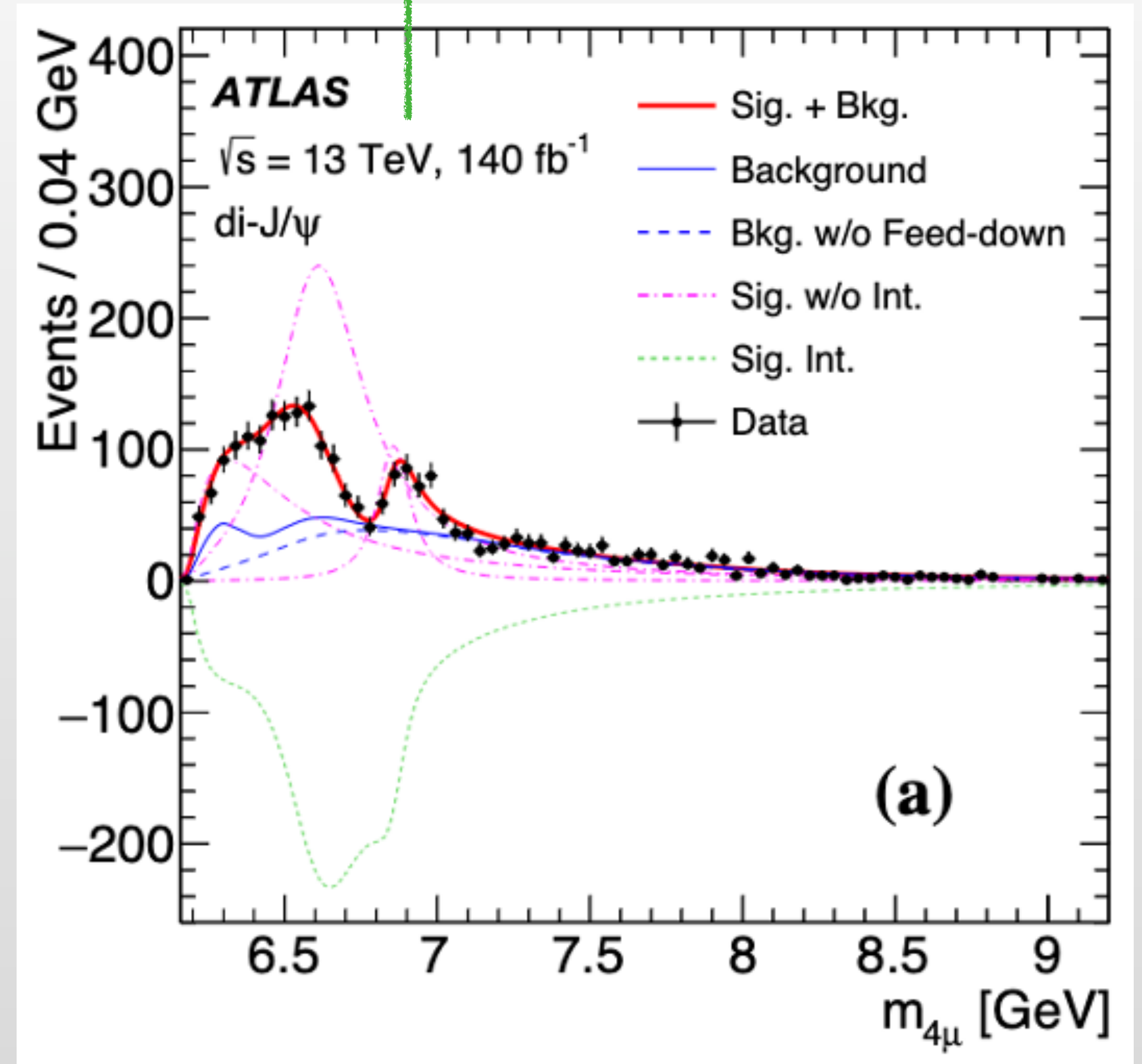
# $J/\psi J/\psi(4\mu)$ 共振峰

X(6600) X(6900) X(7100)



PRL132(2024)111901 Editors' Suggestion

X(6900)



PRL131(2023)151902 Editors' Suggestion

# ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1} \quad \sqrt{s} = 13 \text{ TeV}$$

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	$M_D$ 11.2 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	$2 \gamma$	-	-	36.7	$M_S$ 8.6 TeV $n=3$ HLZ NLO
	ADD QBH	-	$2 j$	-	139	$M_{th}$ 9.4 TeV $n=6$
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{th}$ 9.55 TeV $n=6, M_D = 3 \text{ TeV, rot BH}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	139	$G_{KK}$ mass 4.5 TeV $k/\overline{M}_{Pl} = 0.1$
Gauge bosons	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK}$ mass 2.3 TeV $k/\overline{M}_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$G_{KK}$ mass 3.8 TeV $\Gamma/m = 15\%$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	$Z'$ mass 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	-	36.1	$Z'$ mass 2.42 TeV
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	36.1	$Z'$ mass 2.1 TeV
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$Z'$ mass 4.1 TeV
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	$W'$ mass 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	$1 \tau$	-	Yes	139	$W'$ mass 5.0 TeV
	SSM $W' \rightarrow tb$	-	$\geq 1 b, \geq 1 J$	-	139	$W'$ mass 4.4 TeV
	HVT $W' \rightarrow WZ$ model B	$0-2 e, \mu$	$2 j / 1 J$	Yes	139	$W'$ mass 4.3 TeV
	HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \nu'$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	$W'$ mass 340 GeV
	LRSM $W_R \rightarrow WW$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	$Z'$ mass 3.9 TeV
CI	CI $qqqq$	-	$2 j$	-	37.0	$\Lambda$ 21.8 TeV $\eta_{LL}$
	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	$\Lambda$ 35.8 TeV $\eta_{LL}$
	CI $e e b s$	$2 e$	$1 b$	-	139	$\Lambda$ 1.8 TeV $g_s = 1$
	CI $\mu\mu b s$	$2 \mu$	$1 b$	-	139	$\Lambda$ 2.0 TeV $g_s = 1$
	CI $t t t t$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\Lambda$ 2.57 TeV $ C_{4\ell}  = 4\pi$
DM	Axial-vector med. (Dirac DM)	-	$2 j$	-	139	$m_{med}$ 3.8 TeV $g_a = 0.25, g_t = 1, m(\chi) = 10 \text{ TeV}$
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	$m_{med}$ 376 GeV $g_a = 1, g_t = 1, m(\chi) = 1 \text{ GeV}$
	Vector med. $Z'$ -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	$m_{Z'}$ 3.0 TeV $\tan\beta = 1, g_Z = 0.8, m(\chi) = 100 \text{ GeV}$
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	$m_a$ 800 GeV $\tan\beta = 1, g_t = 1, m(\chi) = 10 \text{ GeV}$
LQ	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 j$	Yes	139	LO mass 1.8 TeV $\beta = 1$
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 j$	Yes	139	LO mass 1.7 TeV $\beta = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$1 \tau$	$2 b$	Yes	139	LO <sup>u</sup> mass 1.49 TeV $\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	LO <sup>d</sup> mass 1.24 TeV $\mathcal{B}(LQ_3^d \rightarrow \nu\tau) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$\geq 2 e, \mu, \geq 1 \tau$	$\geq 1 j, \geq 1 b$	-	139	LO <sup>s</sup> mass 1.43 TeV $\mathcal{B}(LQ_3^s \rightarrow \tau\tau) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$0 e, \mu, \geq 1 \tau$	$0-2 j, \geq 2 b$	Yes	139	LO <sup>s</sup> mass 1.26 TeV $\mathcal{B}(LQ_3^s \rightarrow b\nu) = 1$
	Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	LO <sup>u</sup> mass 2.0 TeV $\mathcal{B}(\tilde{U}_i \rightarrow t\mu) = 1, \text{Y-M coupl.}$
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu \geq 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass 1.46 TeV SU(2) doublet
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$
	VLQ $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	T mass 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$
	VLQ $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$
	VLQ $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1 j, \geq 1 J$	-	139	B mass 2.0 TeV SU(2) doublet, $\kappa_B = 0.3$
Excit. ferm.	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	q* mass 6.7 TeV only $u'$ and $d'$ , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 j$	-	36.7	q* mass 5.3 TeV only $u'$ and $d'$ , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	139	b* mass 3.2 TeV
	Excited lepton $\tau^*$	$2 \tau$	$\geq 2 j$	-	139	$\tau^*$ mass 4.6 TeV $\Lambda = 4.6 \text{ TeV}$
Other	Type III Seesaw	$2,3,4 e, \mu$	$\geq 2 j$	Yes	139	$N_R^0$ mass 910 GeV
	LRSM Majorana $\gamma$	$2 \mu$	$2 j$	-	36.1	$N_R$ mass 3.2 TeV
	Higgs triplet $H^{\pm\pm} \rightarrow W^+ W^+$	$2,3,4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2,3,4 e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV
Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	

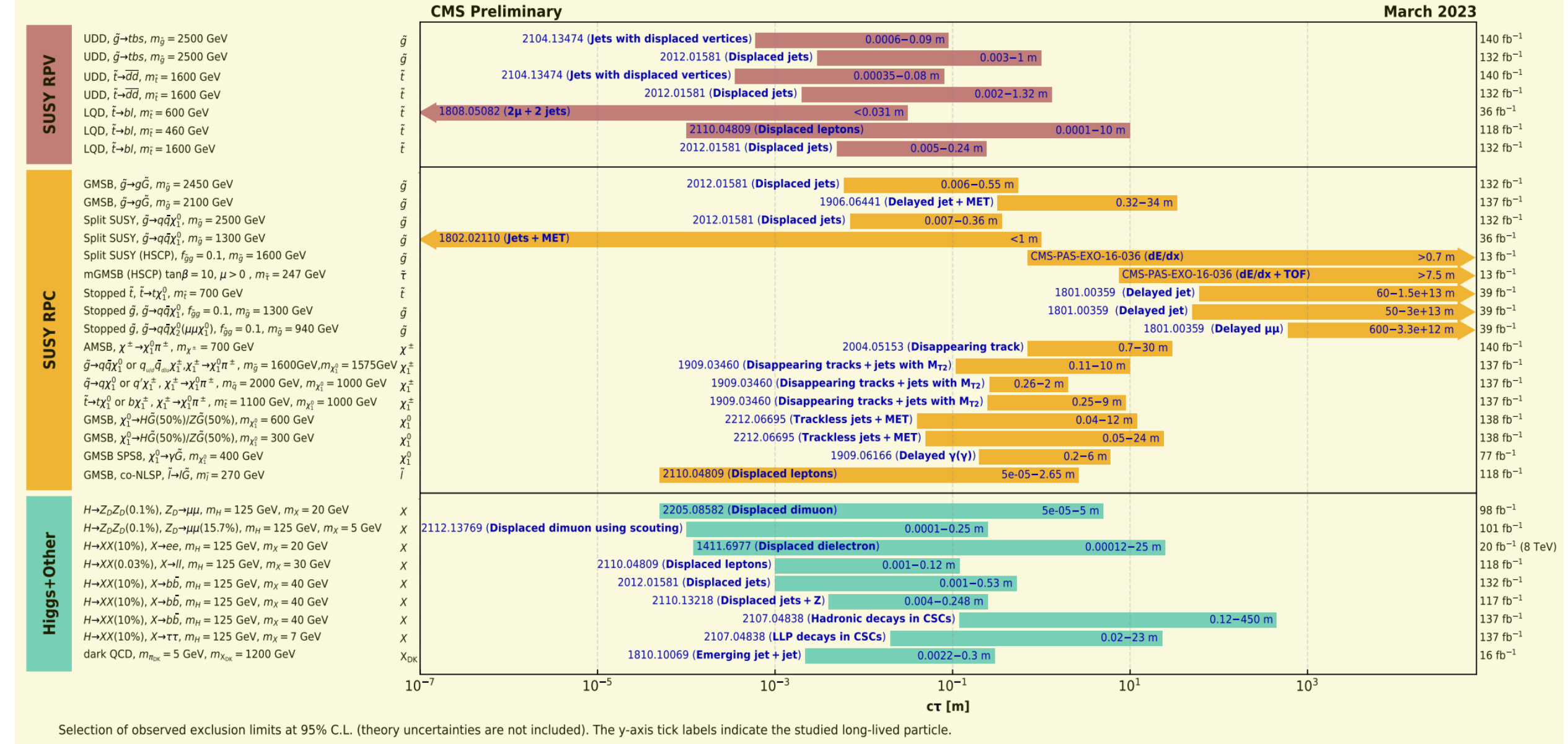
$\sqrt{s} = 13 \text{ TeV}$   
partial data

$\sqrt{s} = 13 \text{ TeV}$   
full data

\*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

## Overview of CMS long-lived particle searches



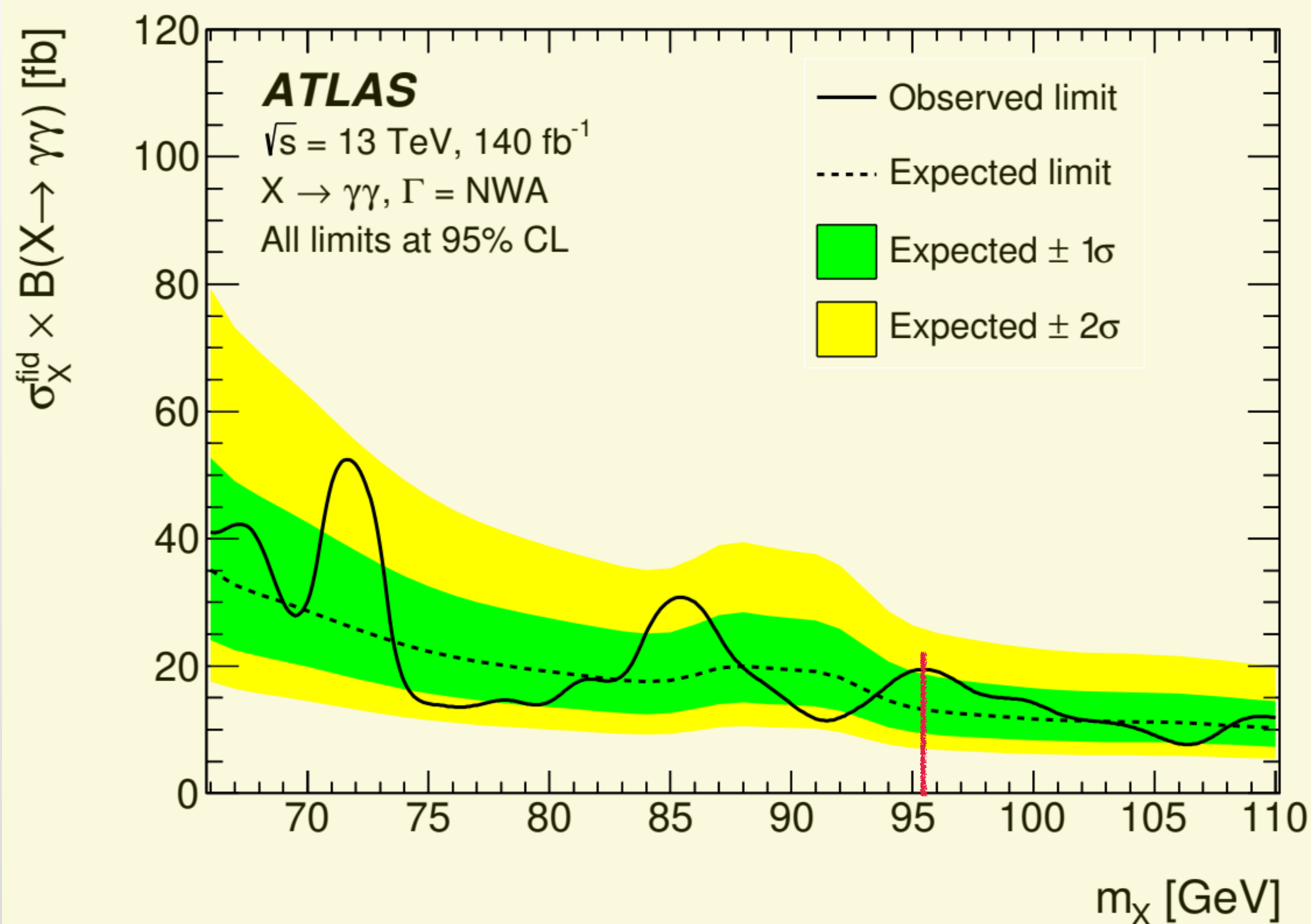
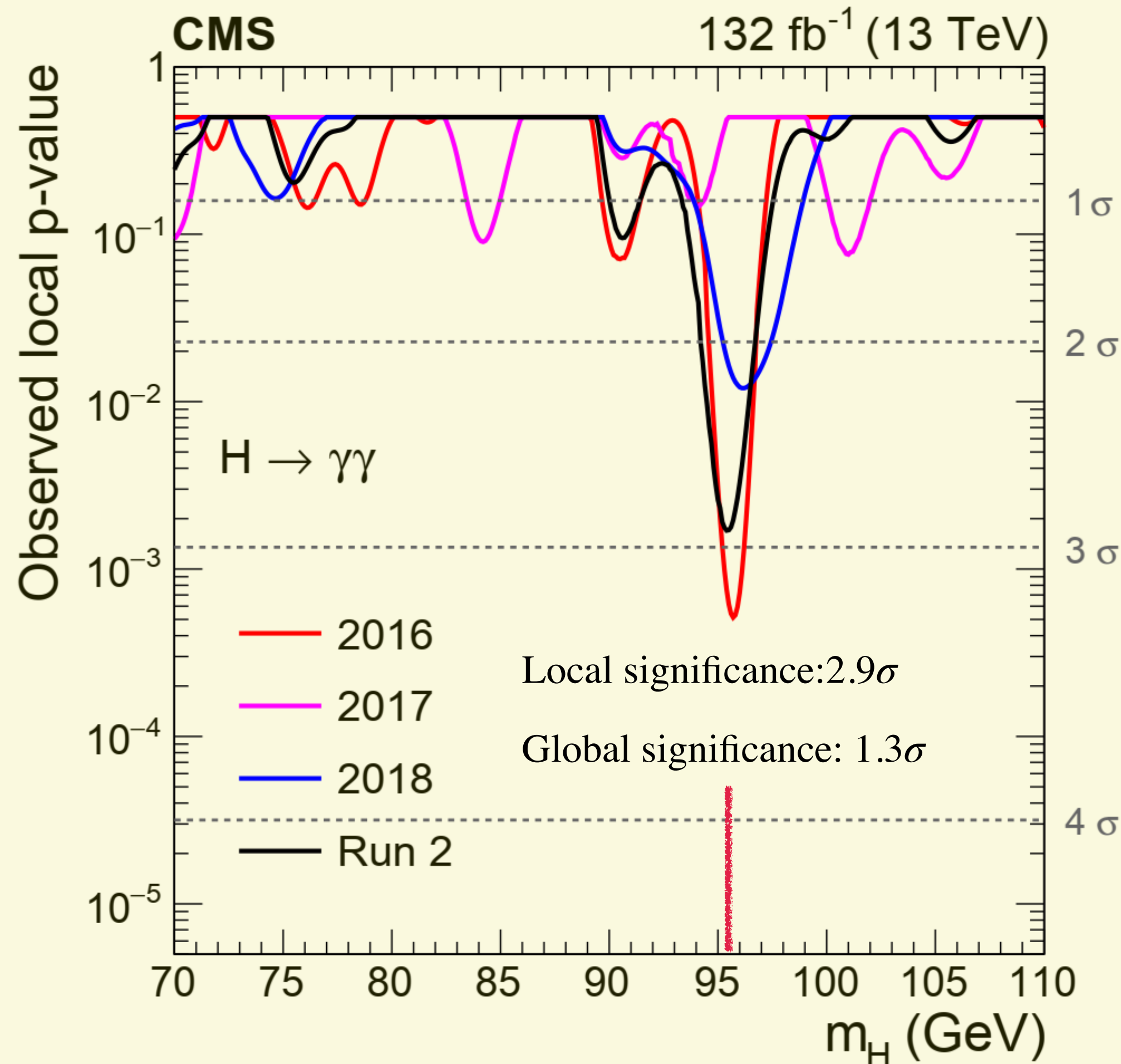
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

# 寻找BSM进展

# 双光子共振峰

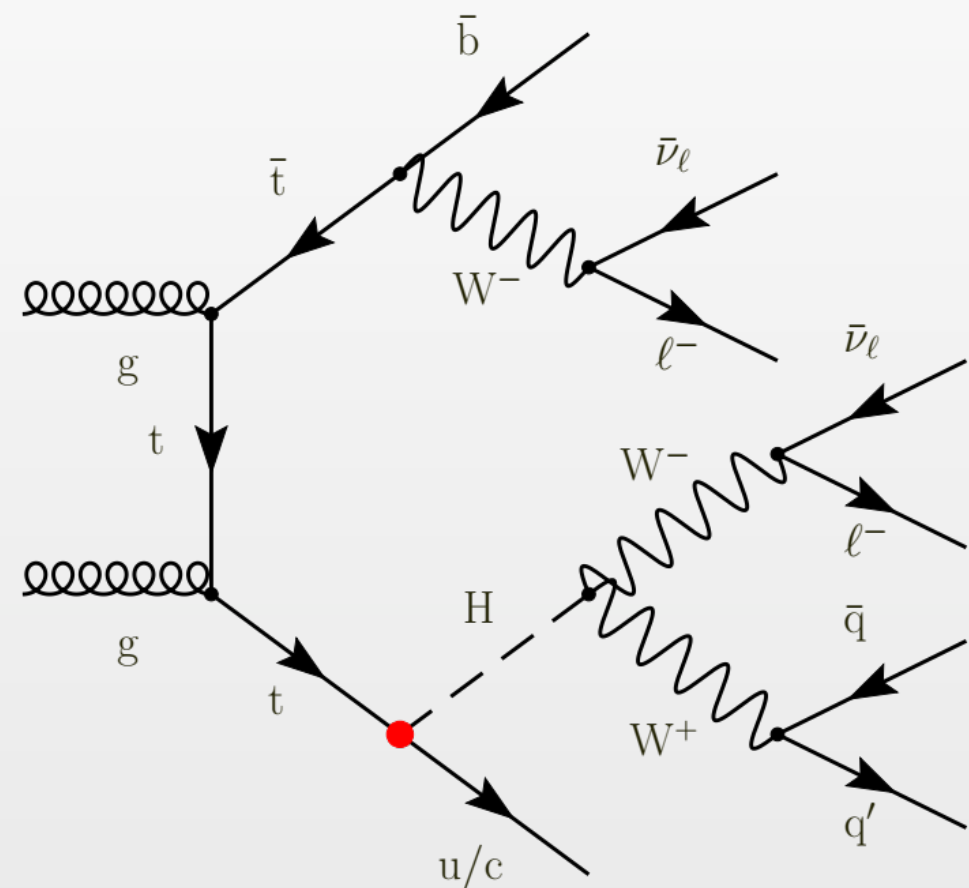
arXiv:2405.18149

arXiv:2407.07546

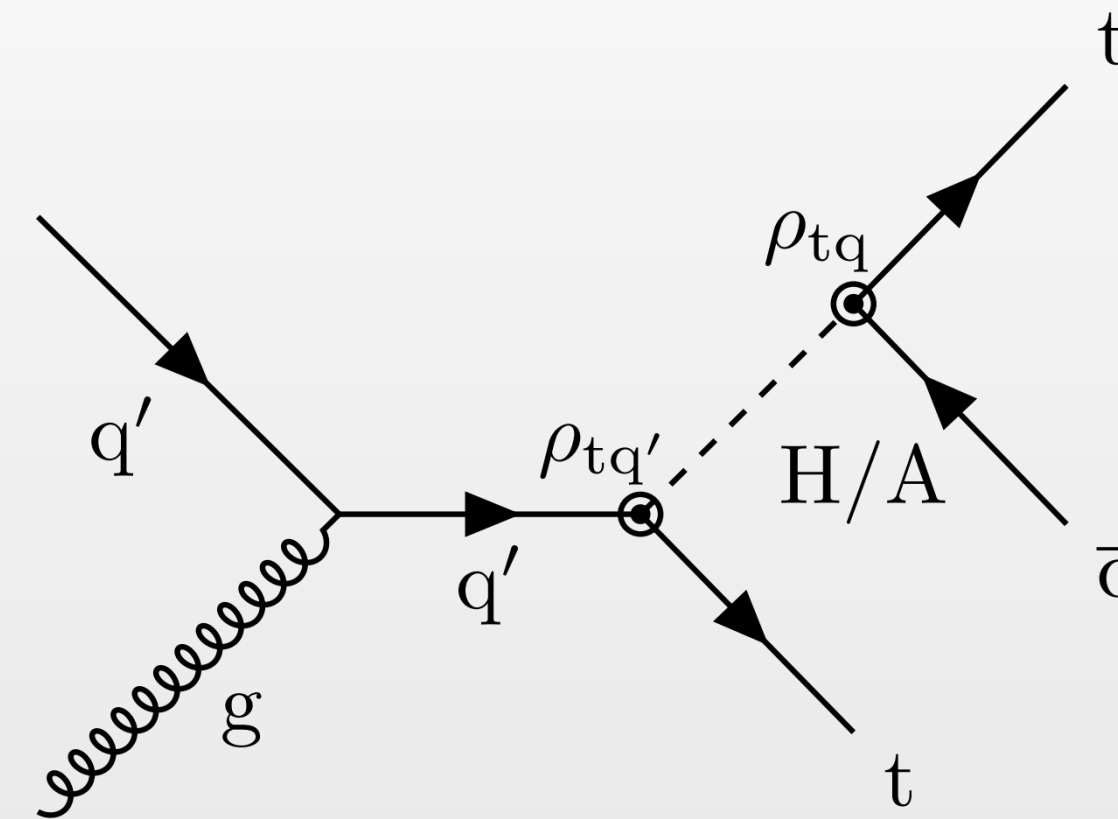




# 利用top夸克寻找新物理(FCNC)

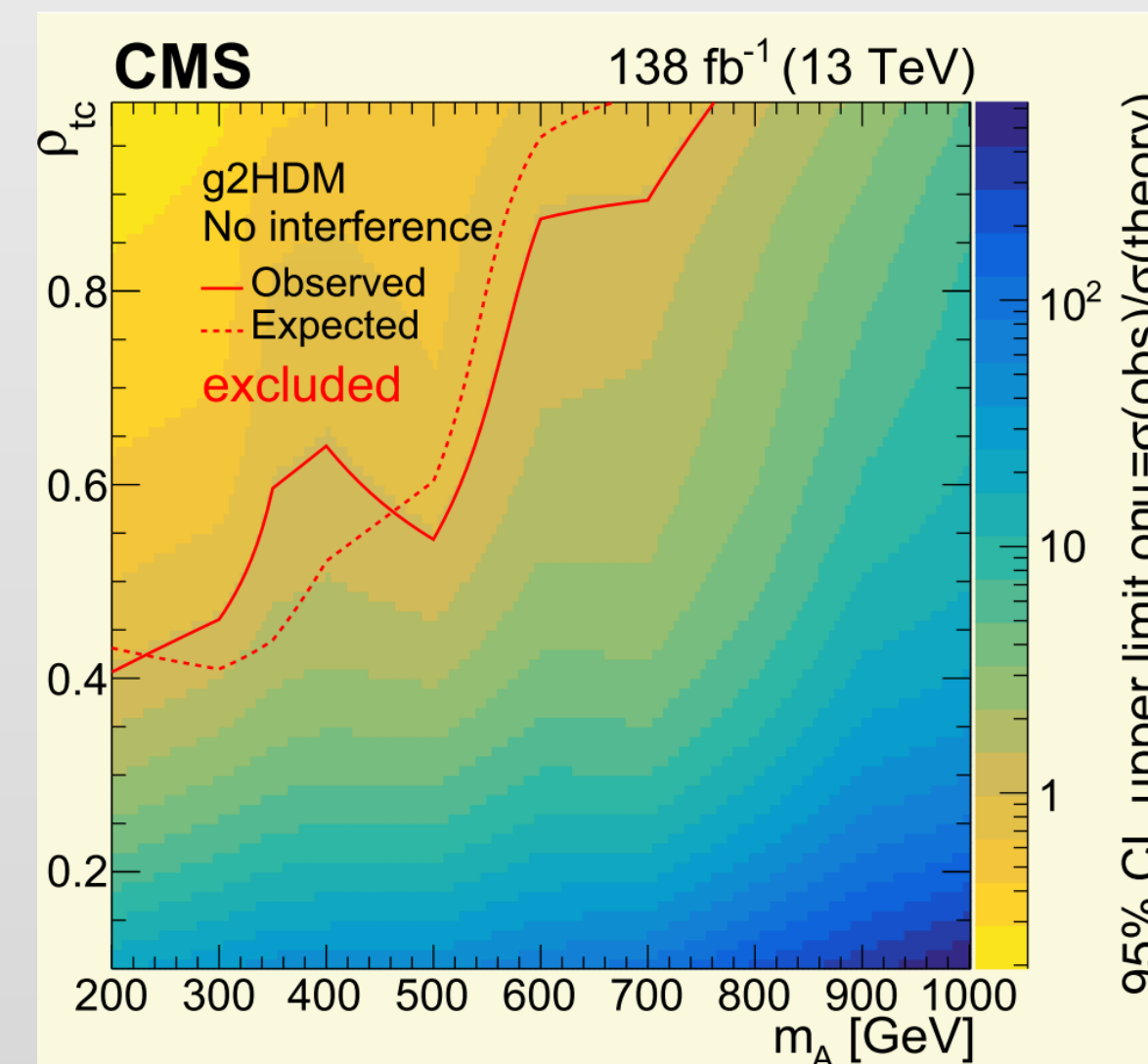
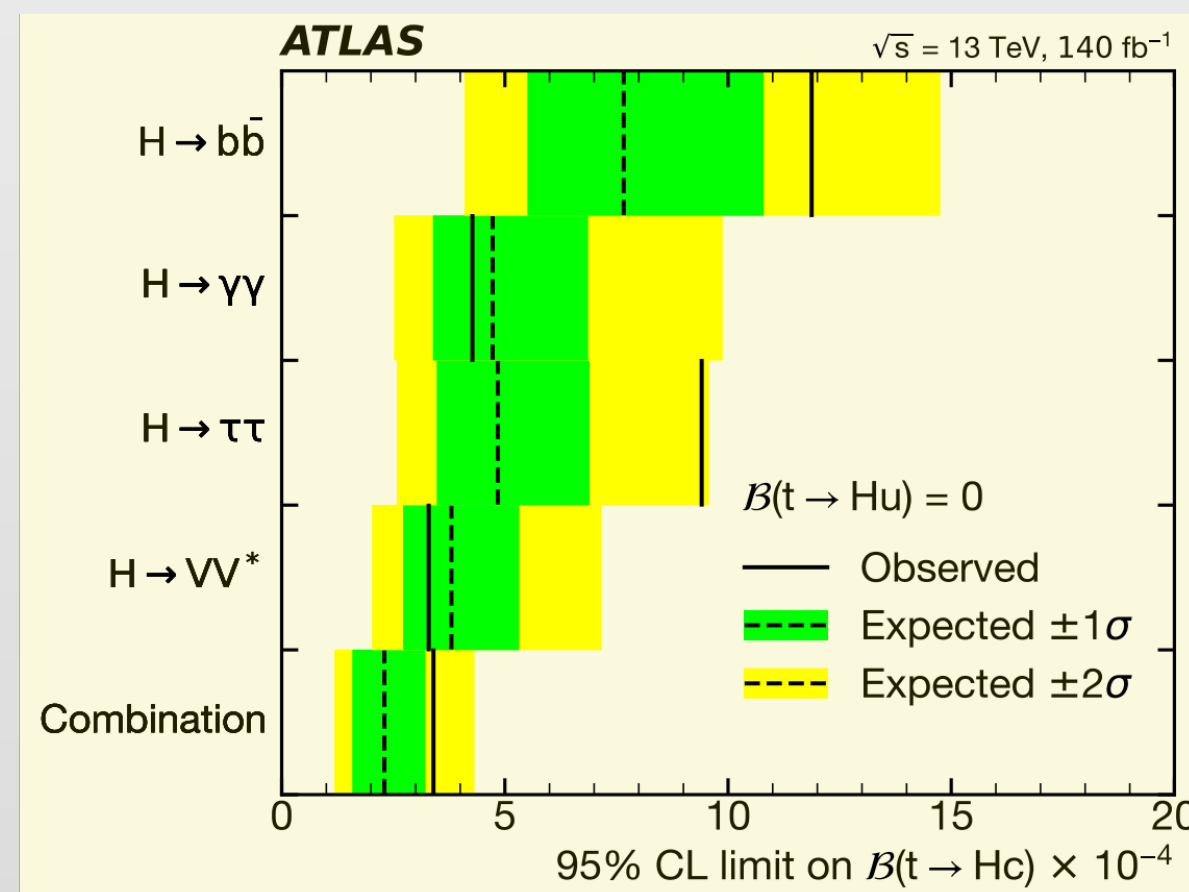
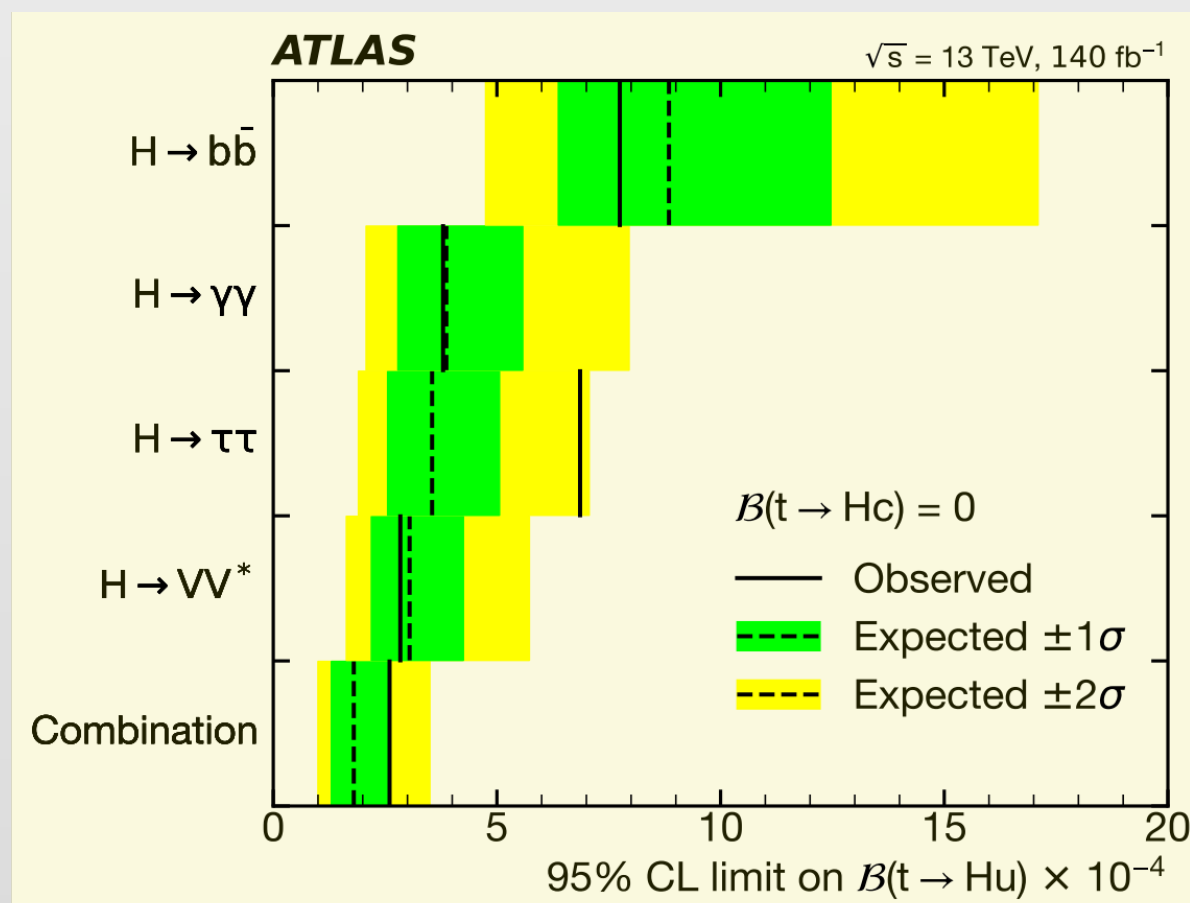


[arXiv:2404.02123](https://arxiv.org/abs/2404.02123)



[arXiv:2404.02123](https://arxiv.org/abs/2404.02123)

g2HDM



$$\mathcal{B}(t \rightarrow Hu) < 2.6(1.8) \times 10^{-4} @ 95 \% \text{ CL}$$

$$\mathcal{B}(t \rightarrow Hc) < 3.4(2.3) \times 10^{-4} @ 95 \% \text{ CL}$$

ATLAS: THU...

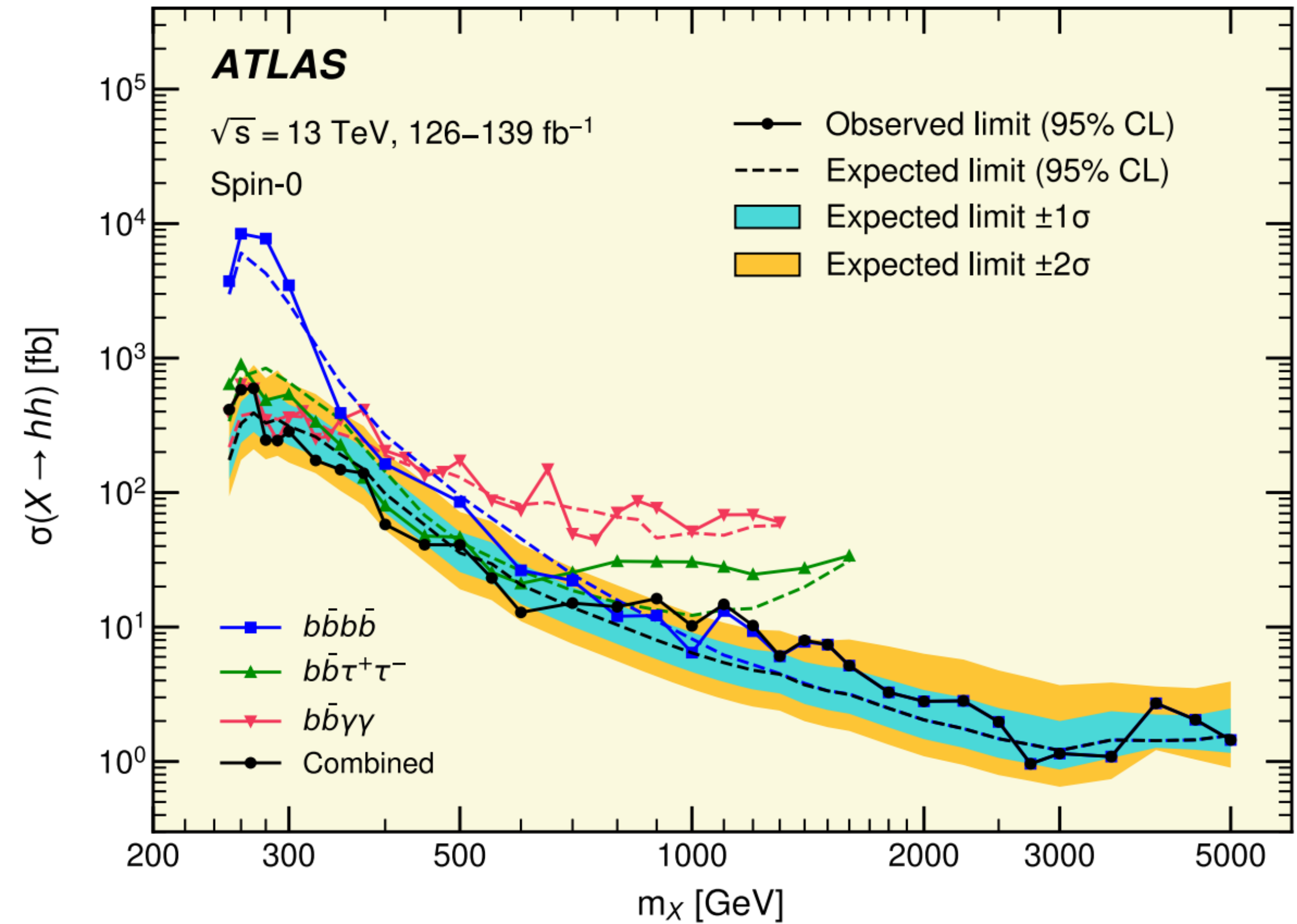
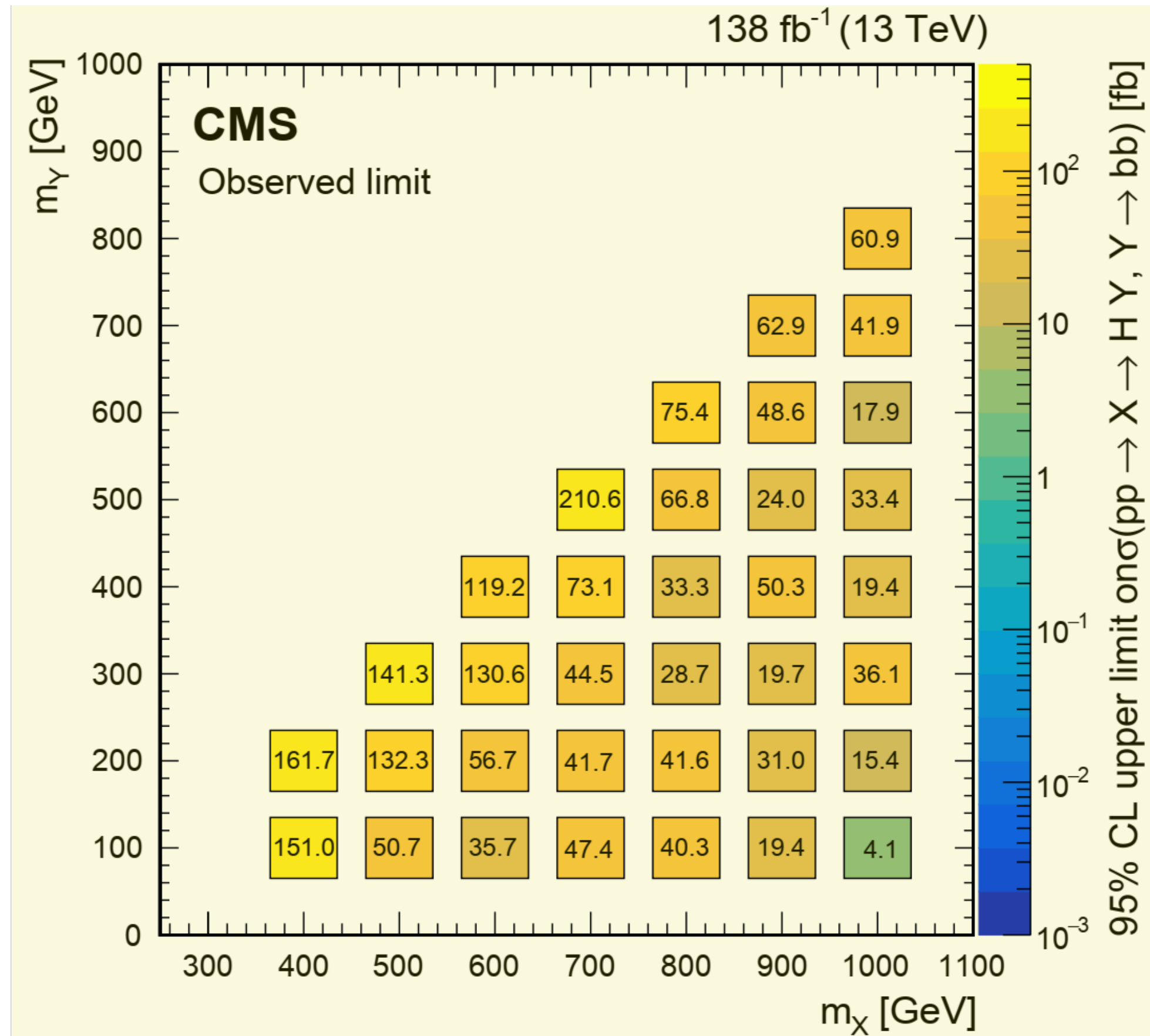
详见8.16上午尤郑昀报告

CMS: PKU, SYSU...

# 寻找 $X \rightarrow YH/HH$

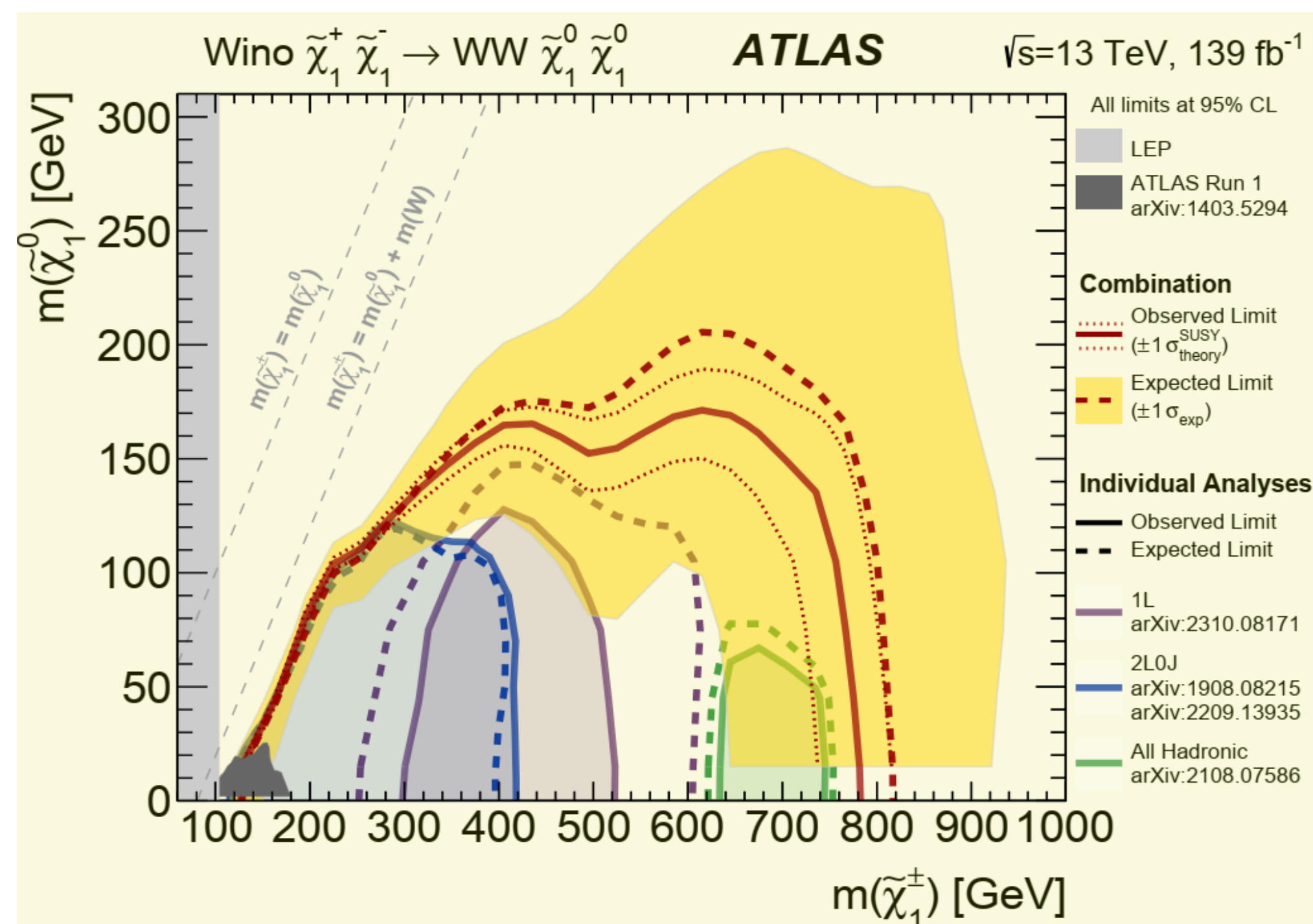
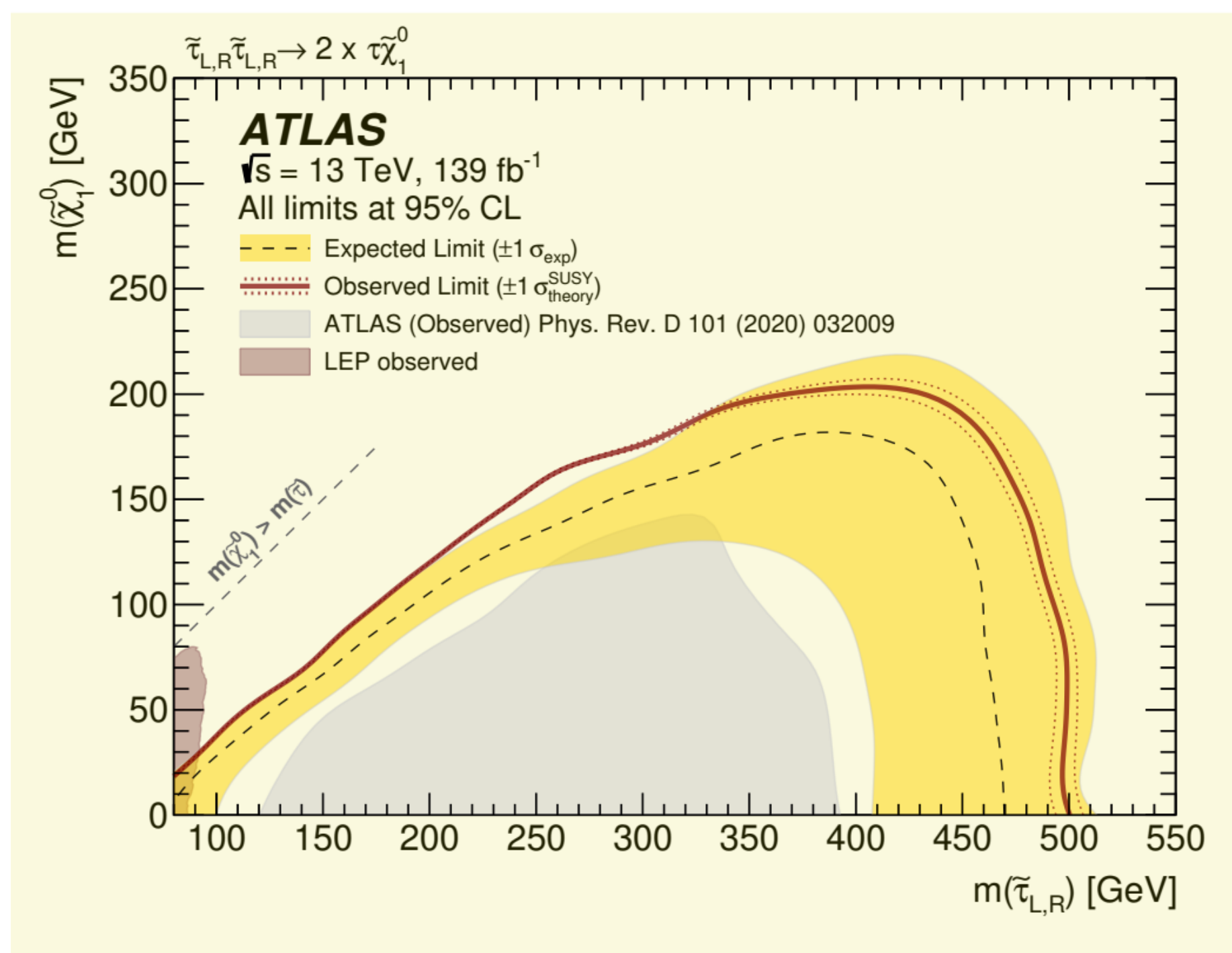
arXiv:2403.16926 Submitted to Phys. Rept.

PRL132(2024)231801



# 寻找SUSY

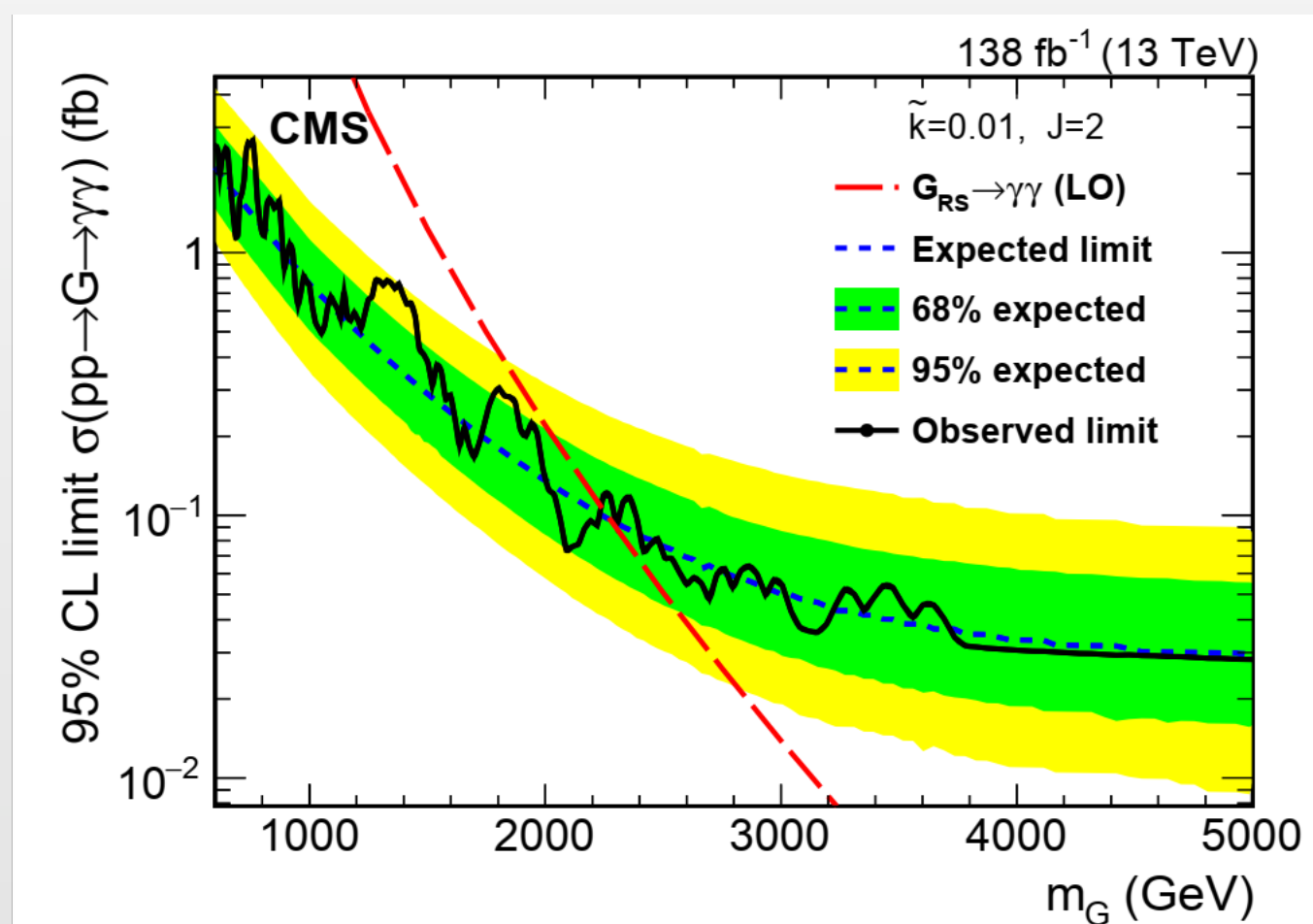
- 利用强相互作用过程寻找 $\tilde{g}, \tilde{q}$ , 质量下限分别达到2.2 TeV, 1.7 TeV [JHEP02\(2024\)107](#)
- 利用Wh、WW、WZ、多轻子等末态寻找 $\tilde{\tau}$ , gaugino, [JHEP05\(2024\)150](#), [JHEP12\(2023\)167](#), [JHEP11\(2023\)150](#)
- 综述、参数空间扫描、不同末态的统计联合分析 [arXiv:2402.08347](#)(PRL接收), [JHEP05\(2024\)106](#), [ATL-PHYS-PUB-2024-007](#), [PLB846\(2023\)138172](#)



# 其他BSM

arXiv:2405.09320

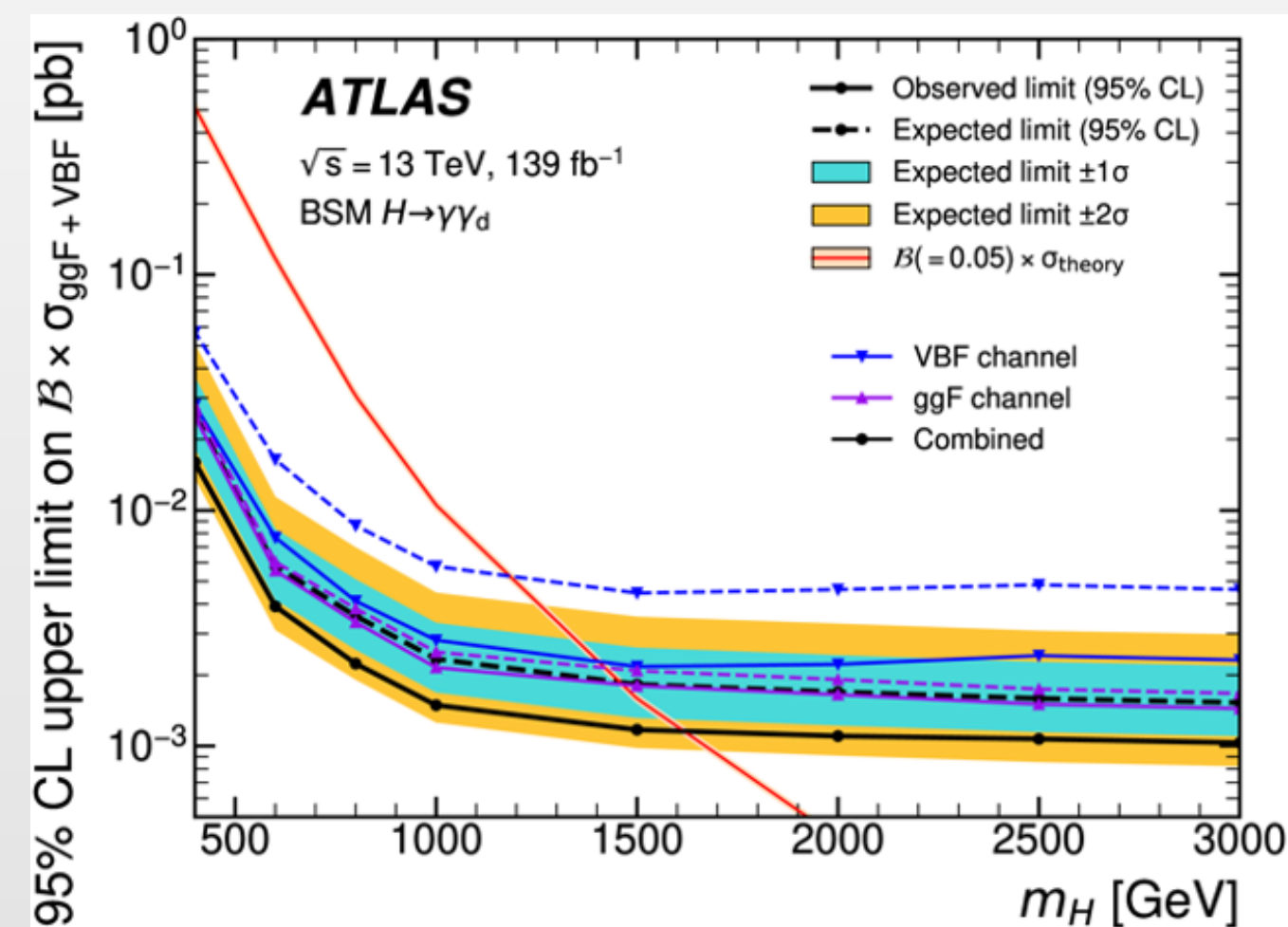
IHEP...



额外维模型中的引力子

arXiv:2406.01656

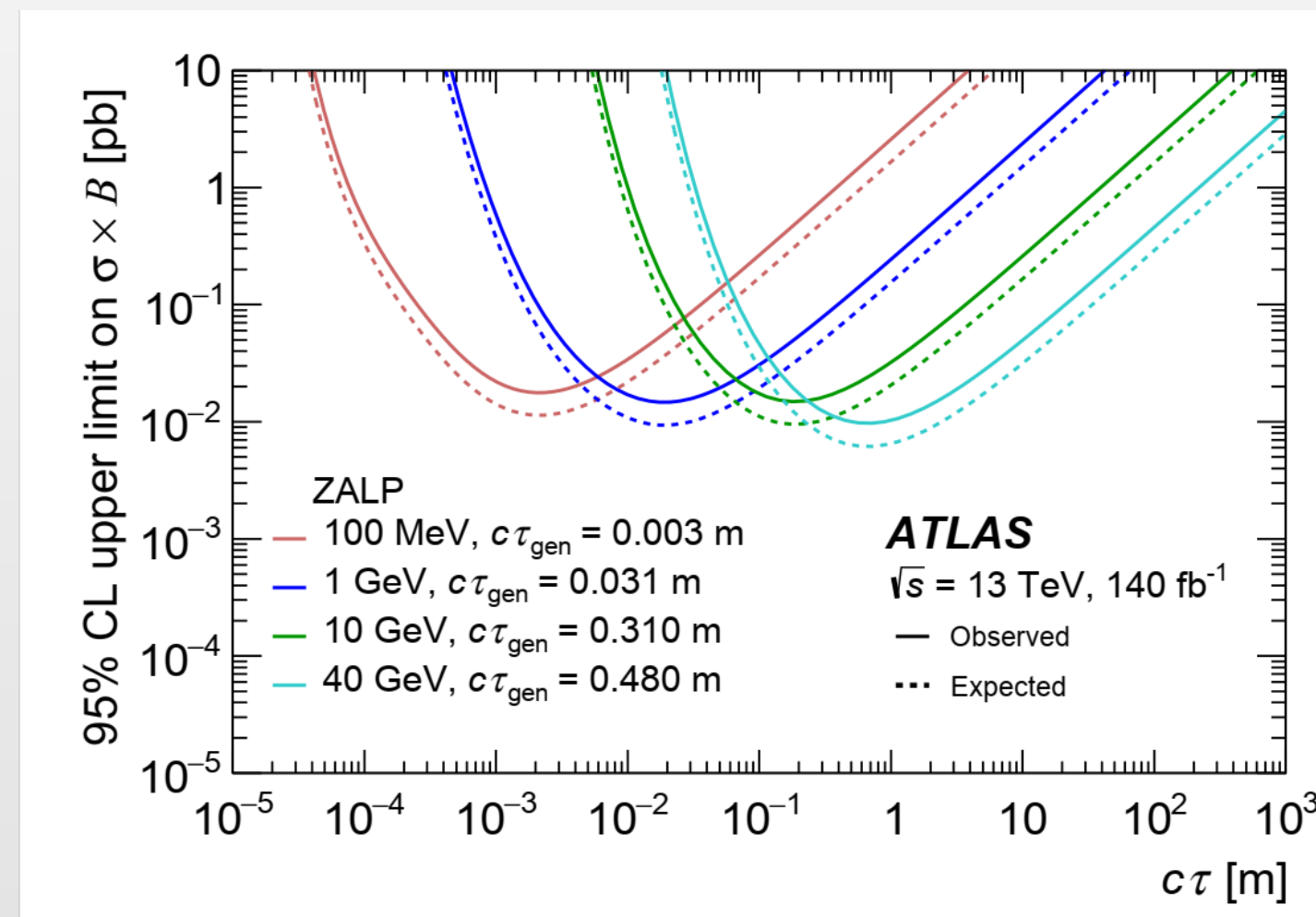
IHEP,SJTU...



希格斯粒子衰变到暗光子

arXiv:2407.09183

USTC...



长寿命粒子

详见8.15 Vu N.-K. 王泽炳

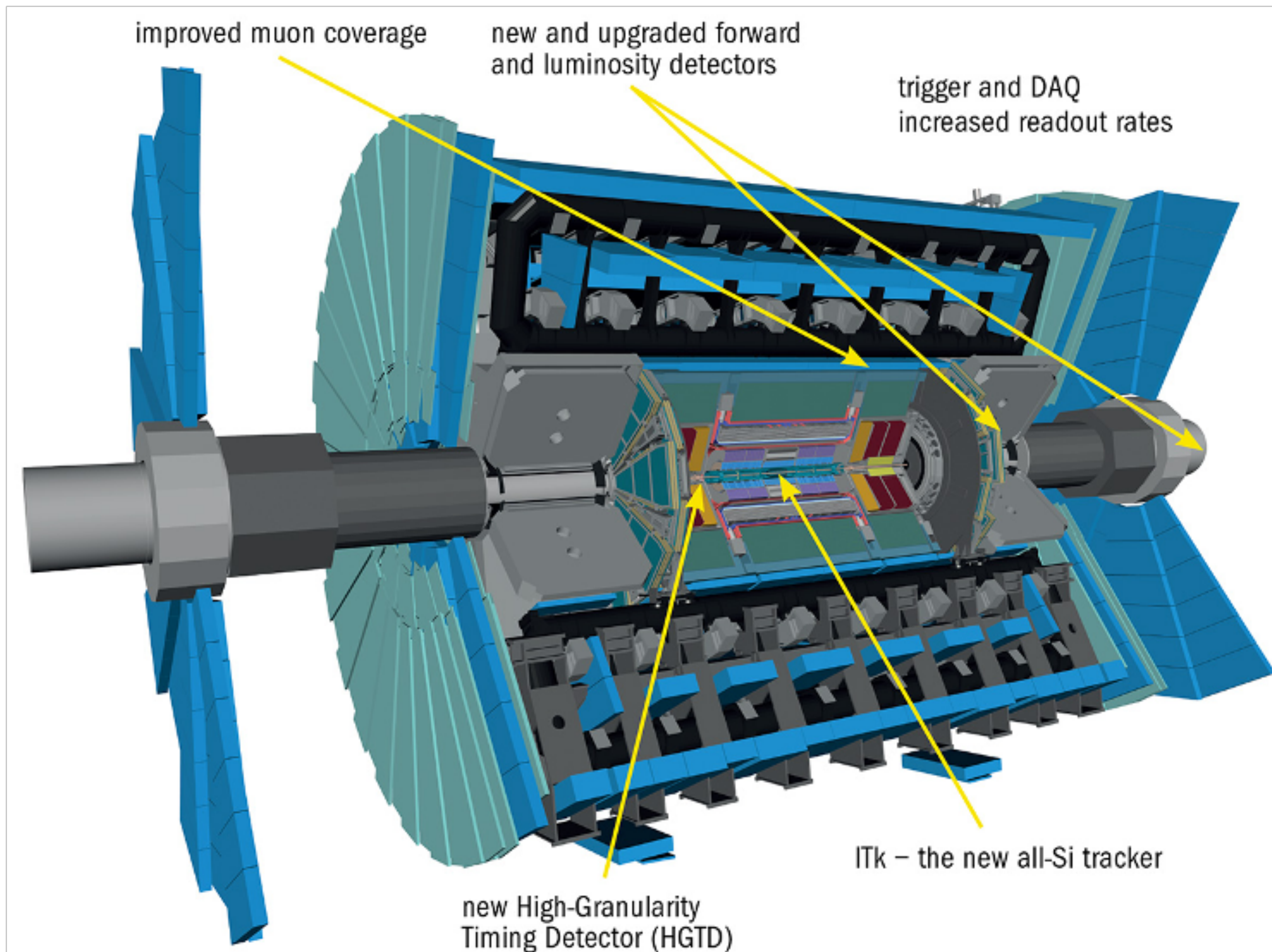
8.16李数、Agapitos A.、袁睿等人报告

# 探测器升级关键技术

# ATLAS/CMS phase 2 升级

- ATLAS和CMS的Phase 2升级是实现LHC物理目标的基础：约90%数据来自HL-LHC
- HL-LHC 对探测器性能提出更严苛的要求：每次束流交汇产生约200个质子-质子反应
- 策略：中国组选择最前沿的技术开展研发，承担或主导有显示度的整块任务
  - 大面积、抗辐照、高空间时间分辨的硅探测器
  - 新型大面积、高计数率、高效率的气体探测器
  - 高颗粒度、高能量分辨、高时间分辨量能器
  - 先进的电子学读出和触发系统
- 掌握前沿探测技术及复杂系统批量制作技术，建设平台，培养人才

# ATLAS升级概览



TDAQ: 单级触发@1 MHz 接收率(FPGA)

内部径迹探测器(ITk): 全部替换为硅探测器

量能器: 前端、后端读出电子学

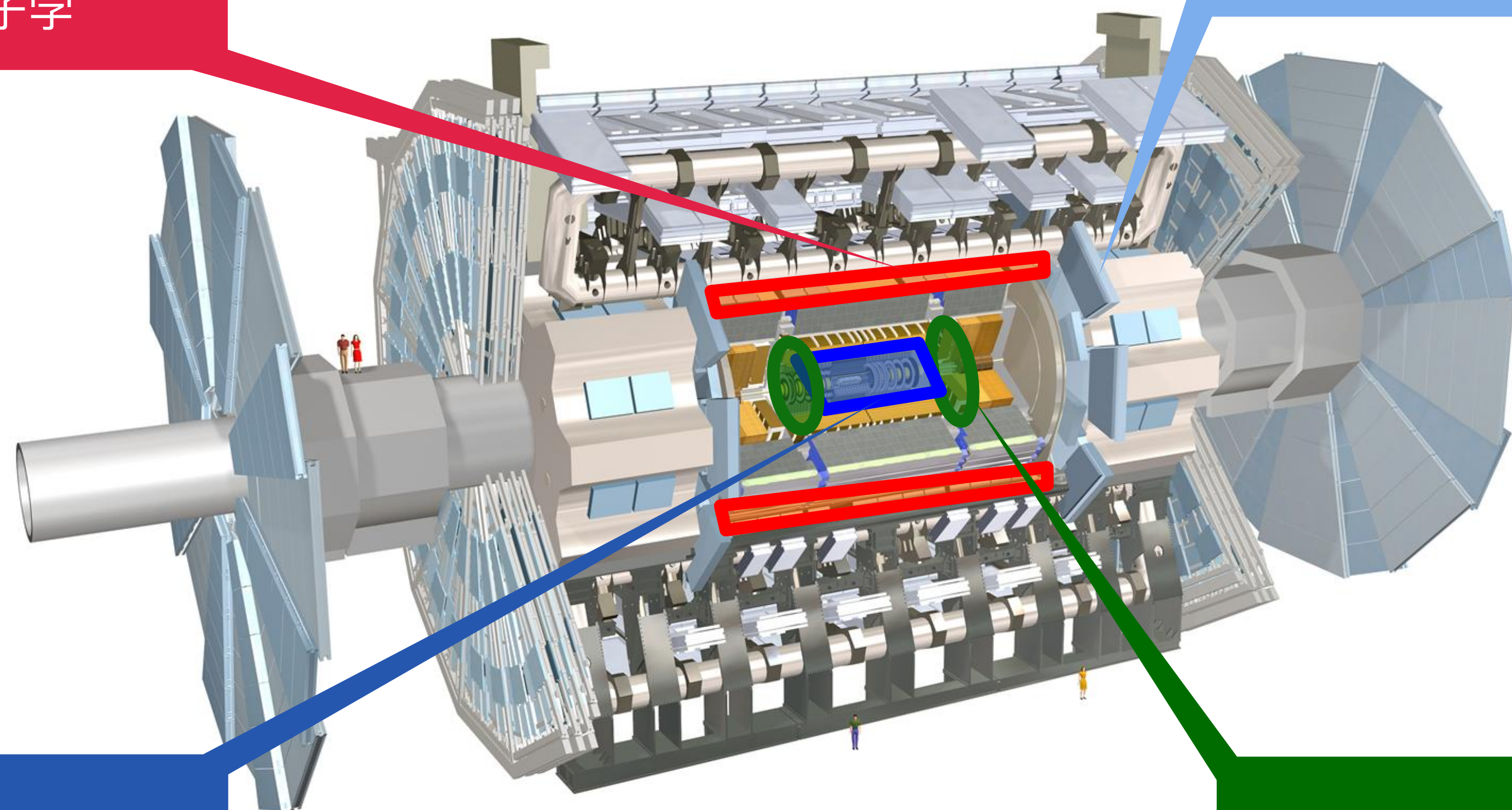
缪子探测器: 桶部内层新RPC, TGC, sMDT

HGTD: 新增飞行时间探测器(30 ps / track)

# ATLAS升级-中国

Phase 2: BI RPC (1mm gap)  
USTC、SJTU、SDU:  
气隙、读出板、电子学

Phase 1: NSW  
SDU、USTC: sTGC探测器和前端电子学

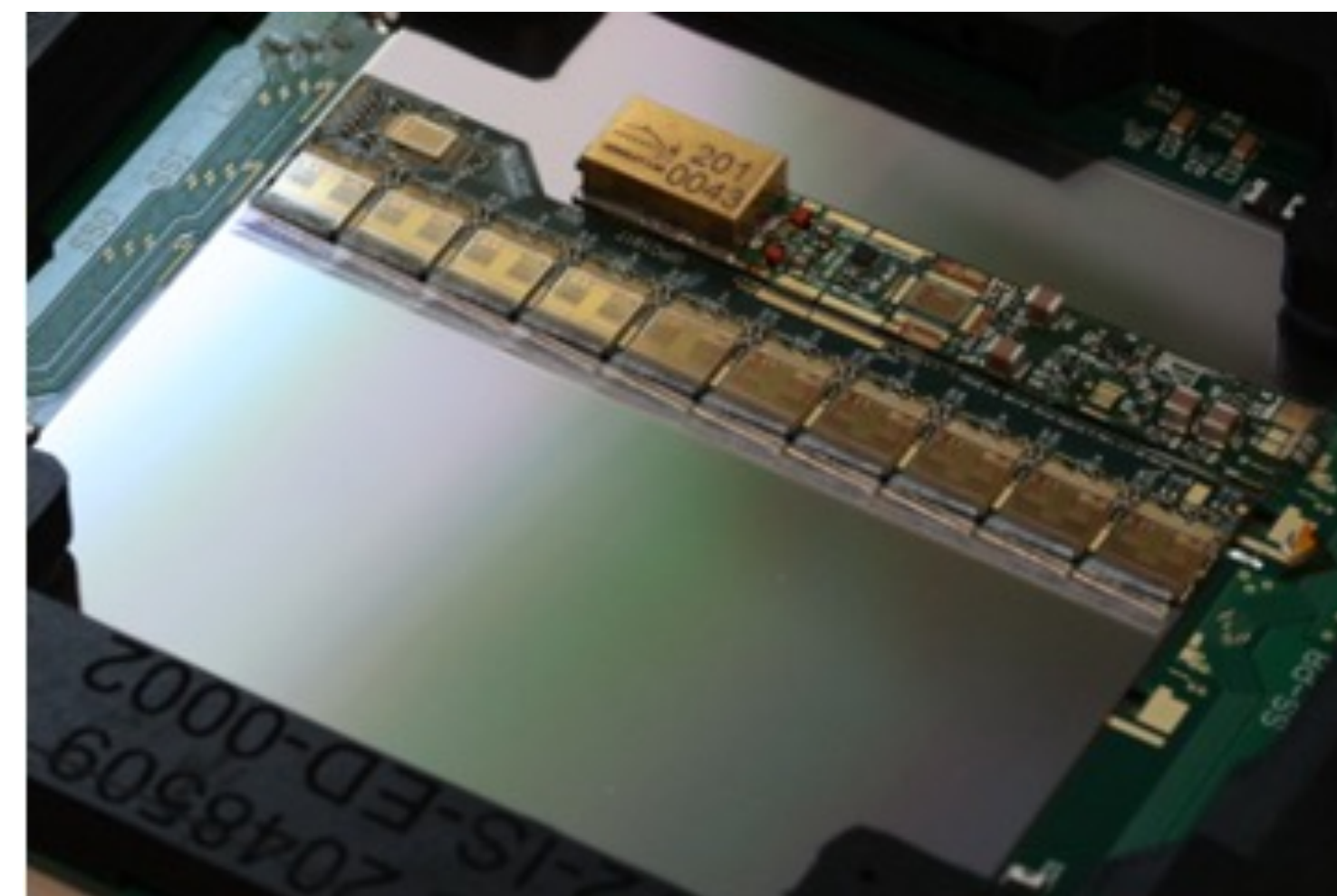
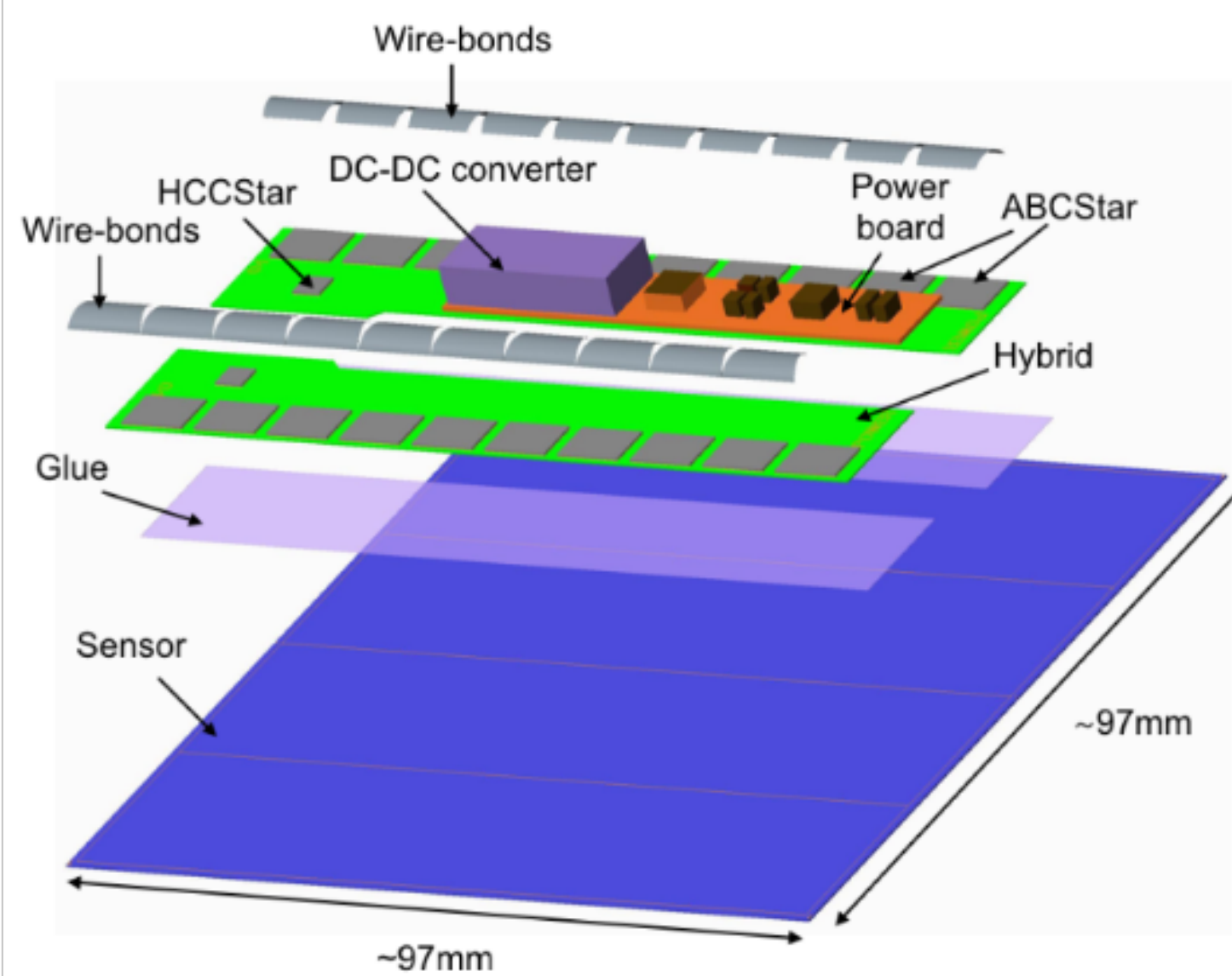
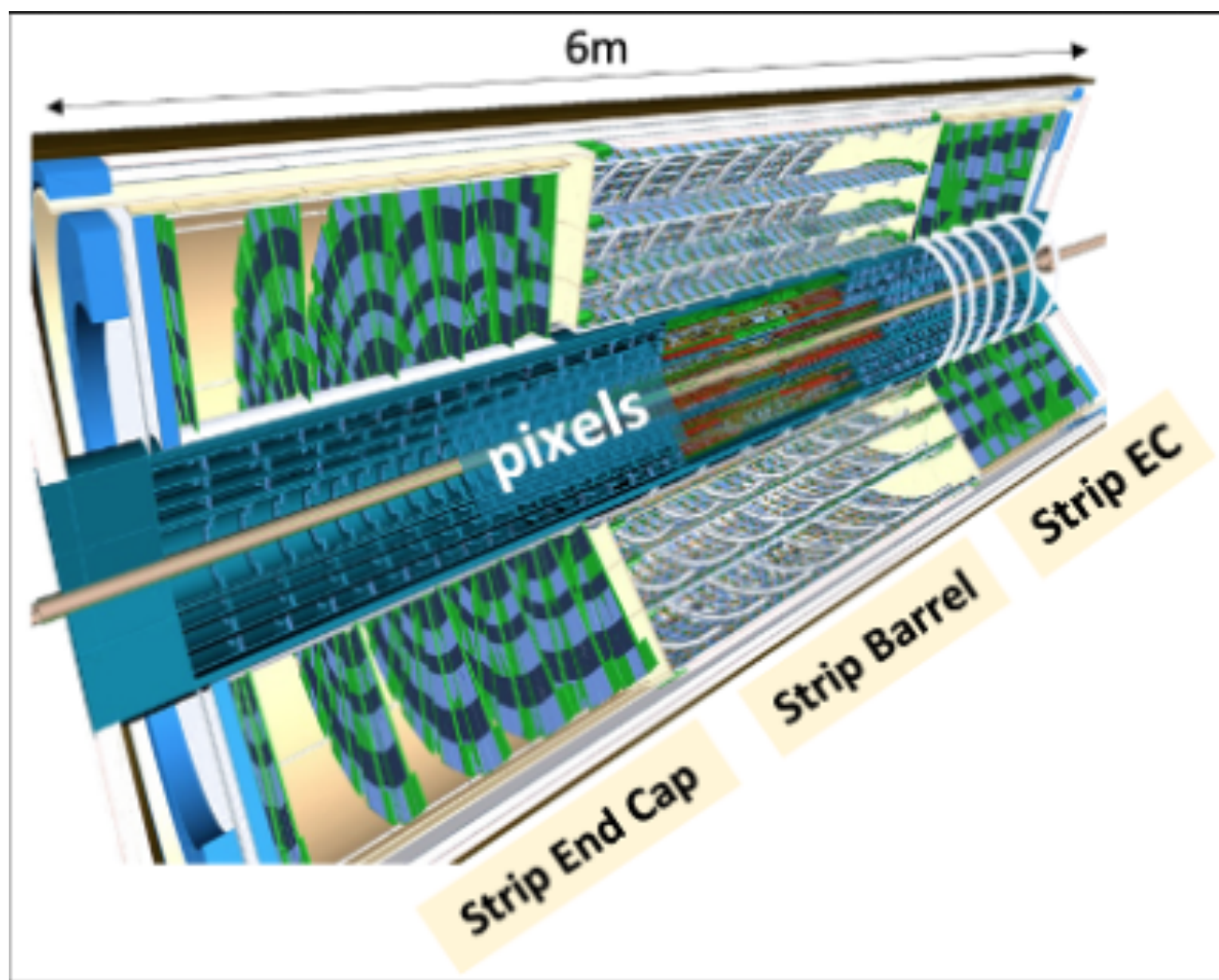


Phase 2: 内部径迹探测器  
IHEP、THU: 桶部硅微条建造

Phase 2: HGTD  
IHEP、USTC、NJU、SDU:  
LGAD、模块组装、外围电子学、高压系统

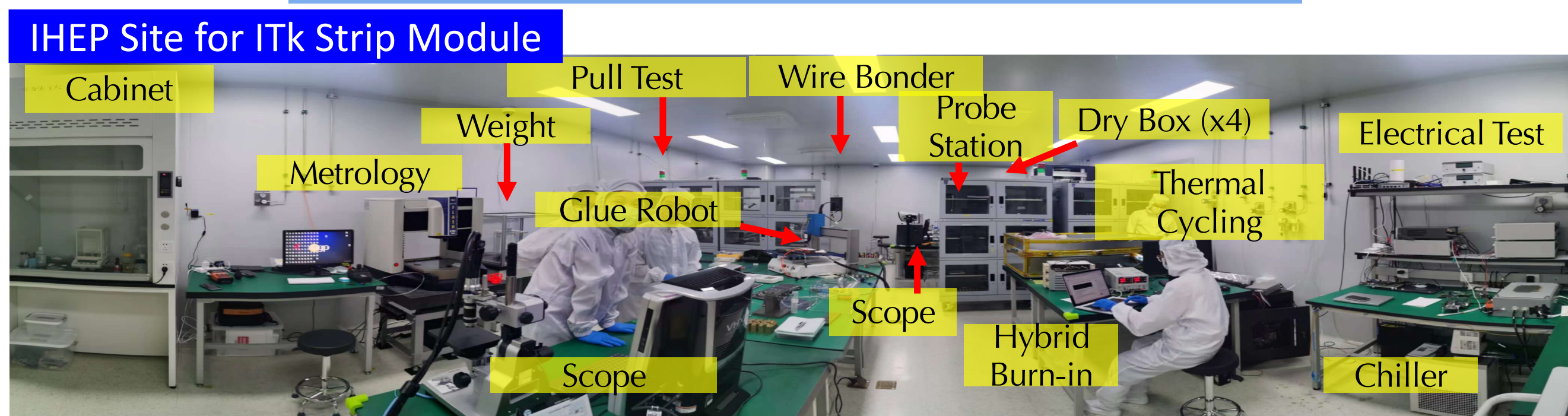


# ATLAS ITk



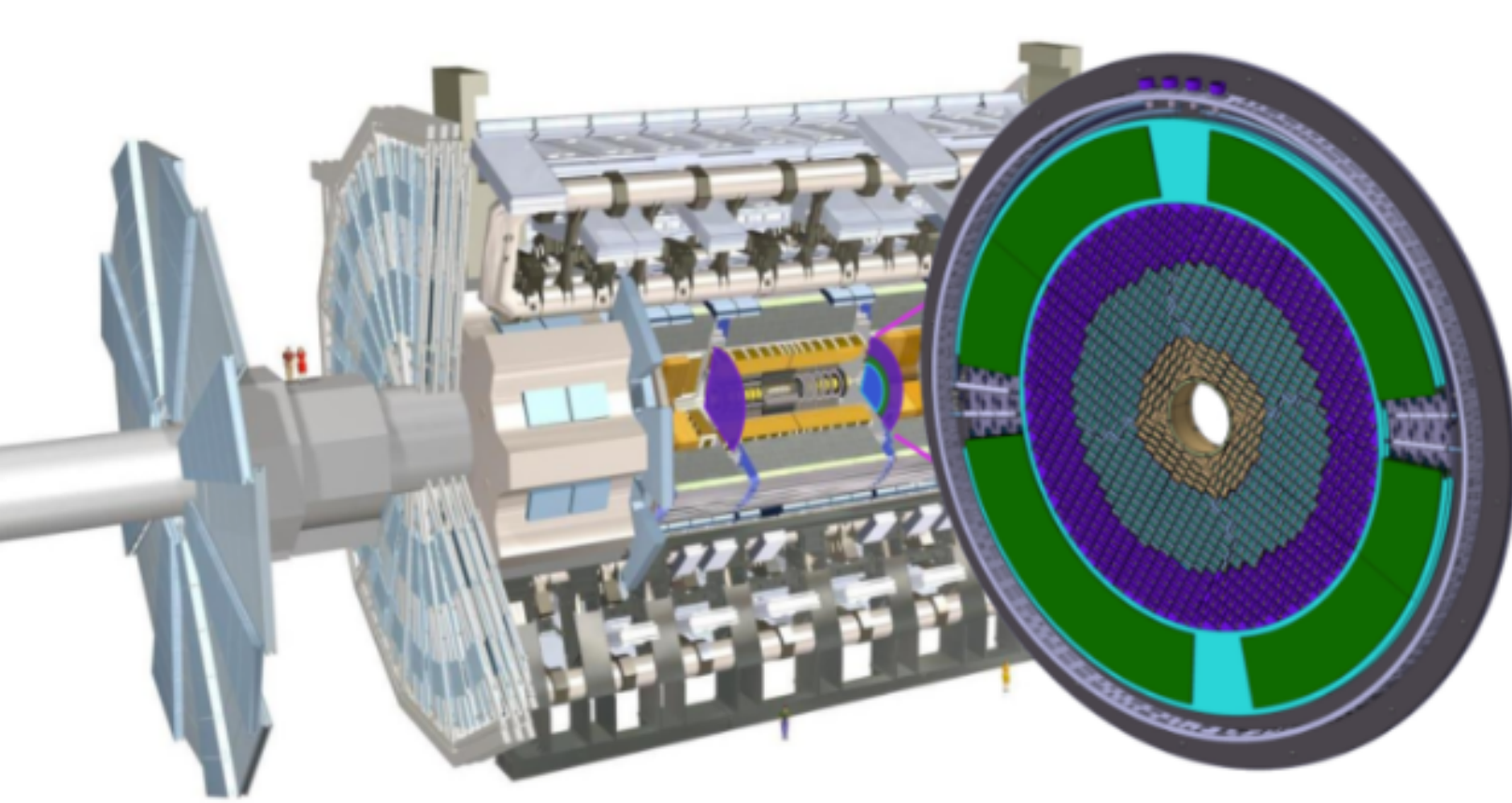
IHEP、THU: 组装10% 硅微条模块(~200个)  
利用X-ray及CSNS质子研究芯片抗辐照性能

- 将内部径迹系统全部用硅探测器替换
- $\eta$  覆盖范围从2.5 增大到 4
- 每条径迹至少9个击中
- 硅像素总面积: 13 m<sup>2</sup> (约50亿通道)
- 硅微条总面积: 165 m<sup>2</sup> (约6千万通道)
- 抗辐照环境: 内部像素NIEL高达  $1 \times 10^{16}$  n<sub>eq</sub>/cm<sup>2</sup>



详见8.14 下午蔡孟珂报告

# ATLAS HGTD

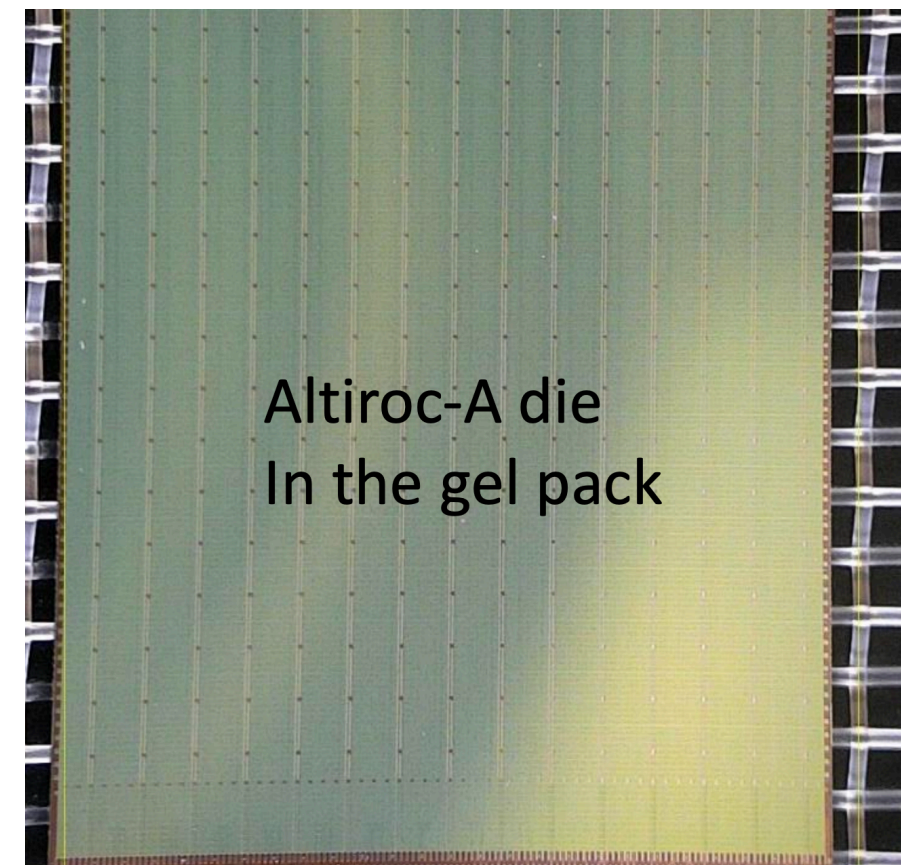
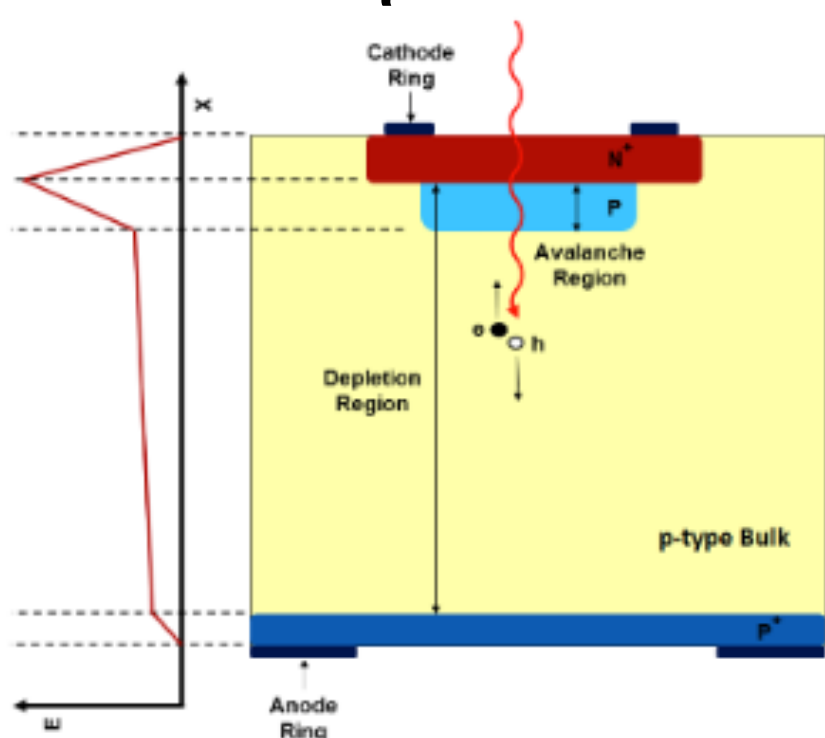


共3.6M通道  
8000模块  
约6 m<sup>2</sup>

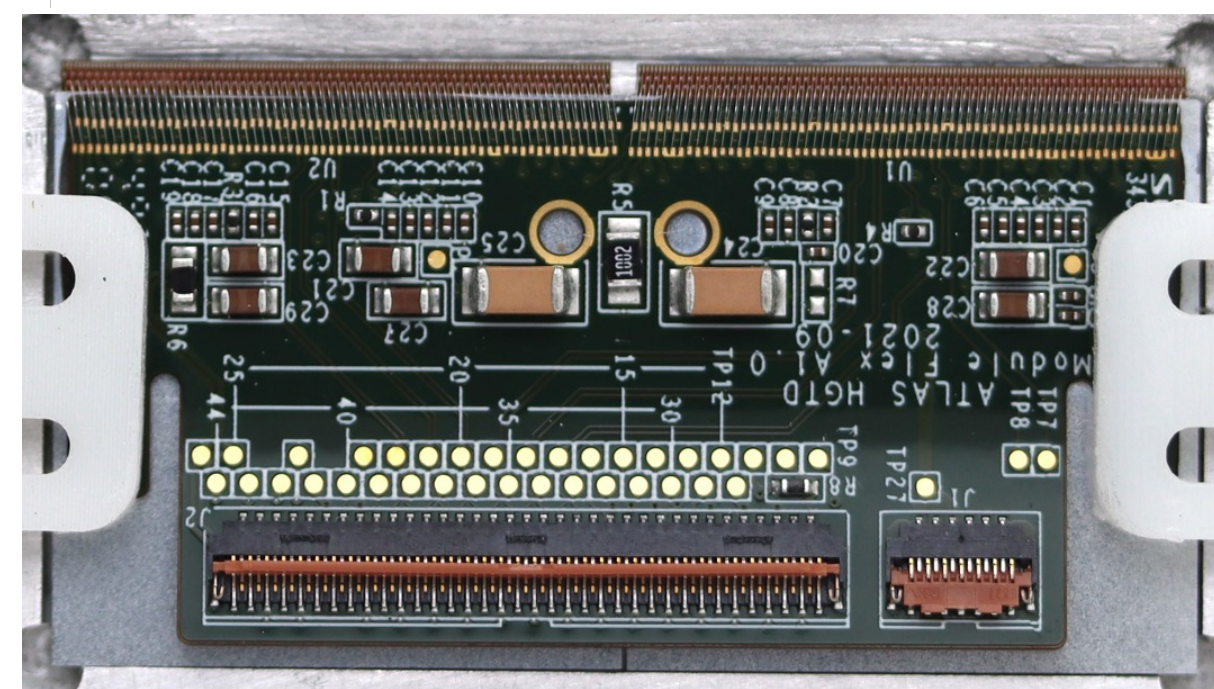
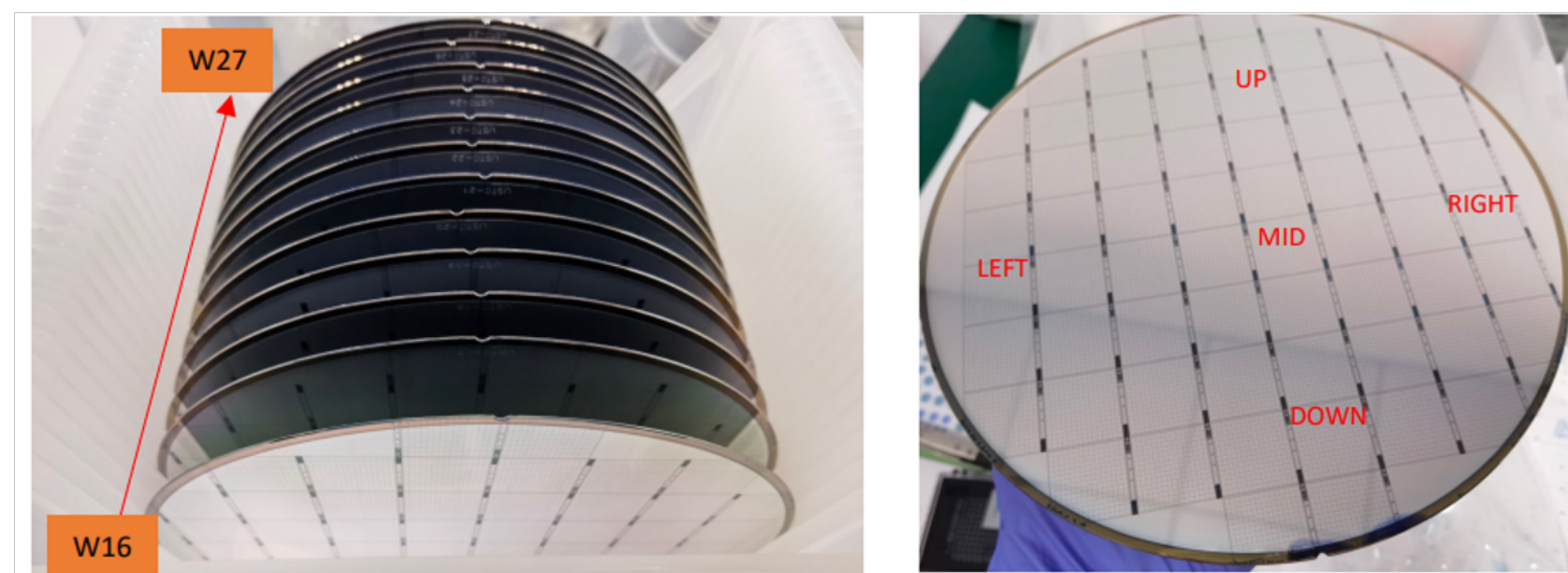
$$z = \pm 3.5 \text{ m}$$

$$0.12 \text{ m} < r < 0.64 \text{ m}$$

$$2.4 < \eta < 4$$



Altiroc-A die  
In the gel pack



HV, LV, Cooling plate prototype  
Electronics : PEB 1F + flex tails + 54 modules mounted on 4 support units (detector unit)

LGAD: 全部(IHEP/USTC设计, IME制作)通过PRR

IHEP: 66%(采购)+24%(实物贡献)

USTC:10%(实物贡献)

探测器模块:

IHEP: 50% hybrid, 100% module PCB,  
34% assembly

USTC: 10% assembly

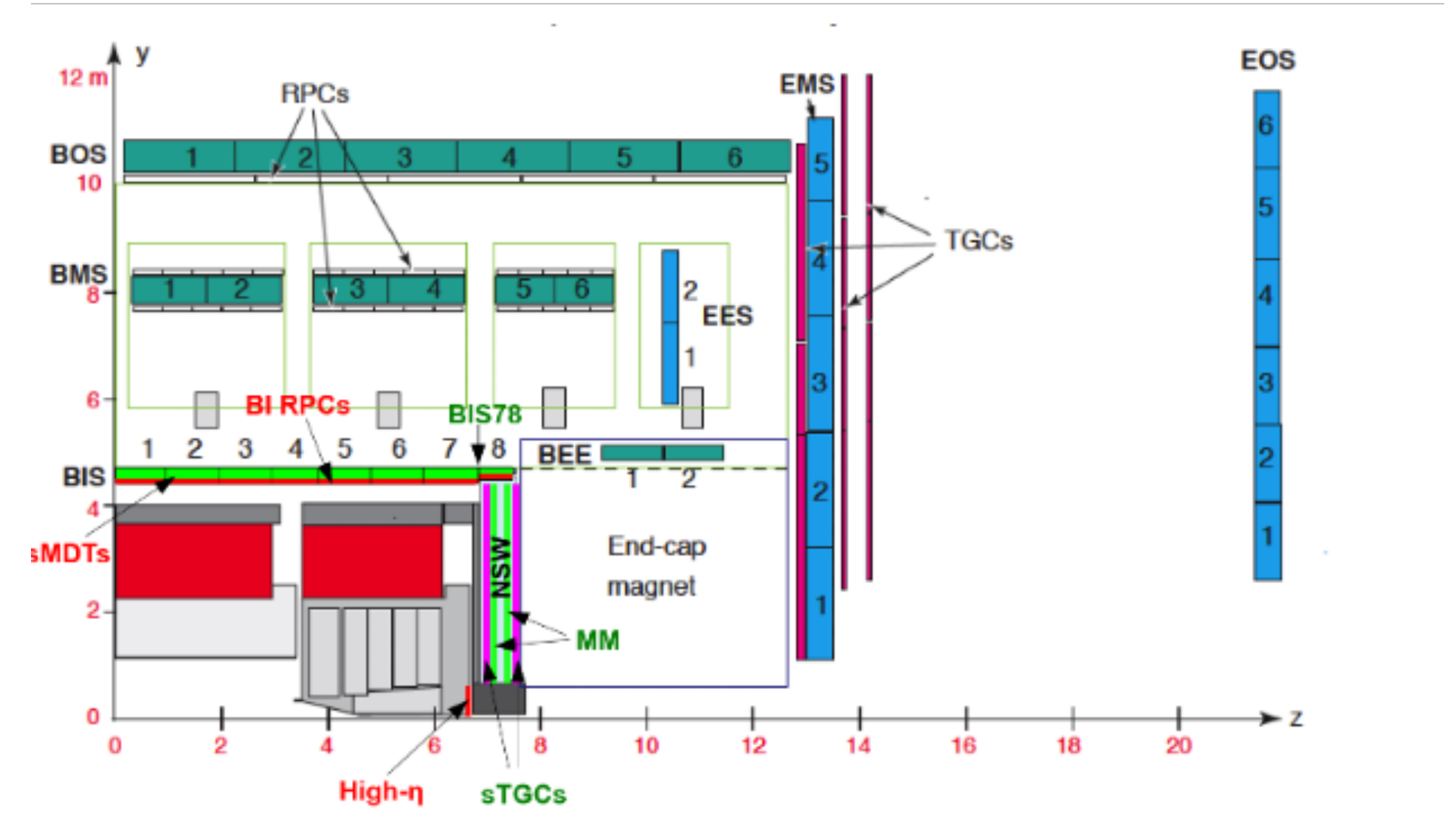
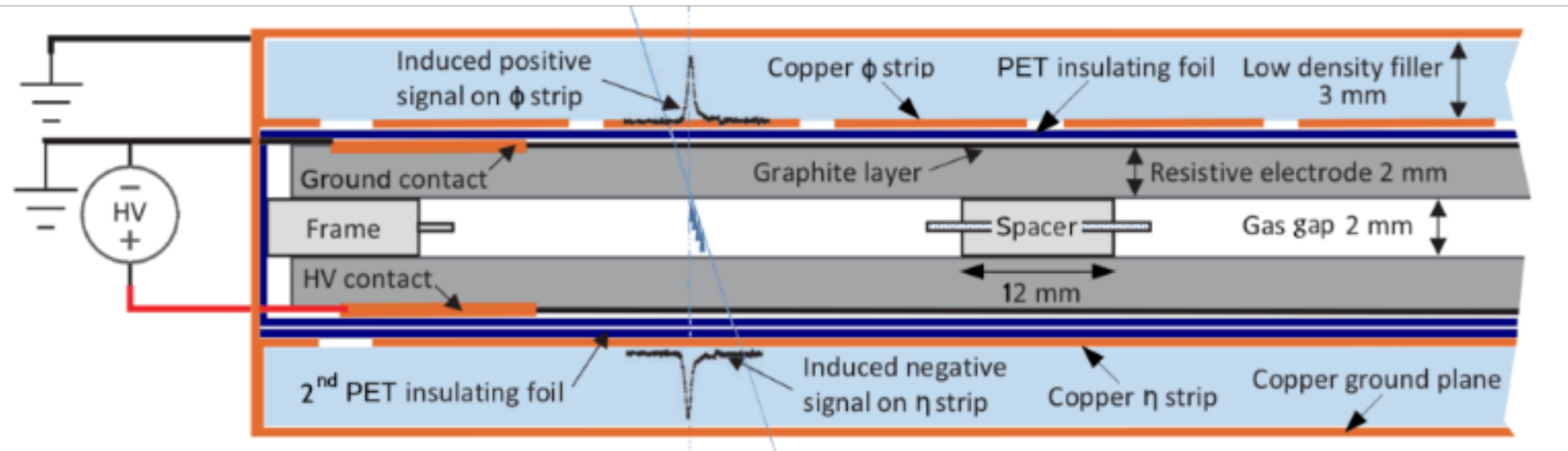
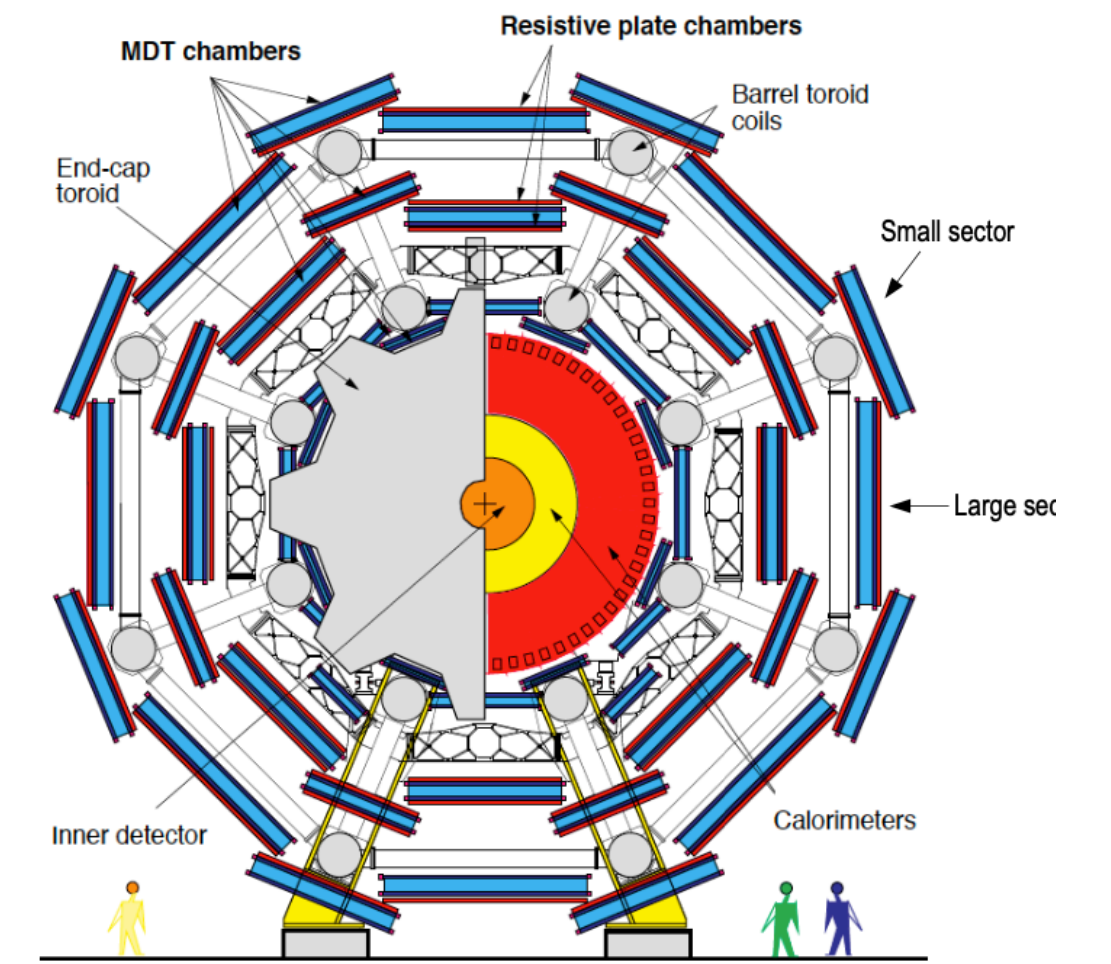
高压系统: IHEP

外围电子学板: IHEP+NJU

详见周四(08/15)上午粒子物理实验技术分会  
(梁志均、赵梅、马阔、黄鑫辉等的报告)

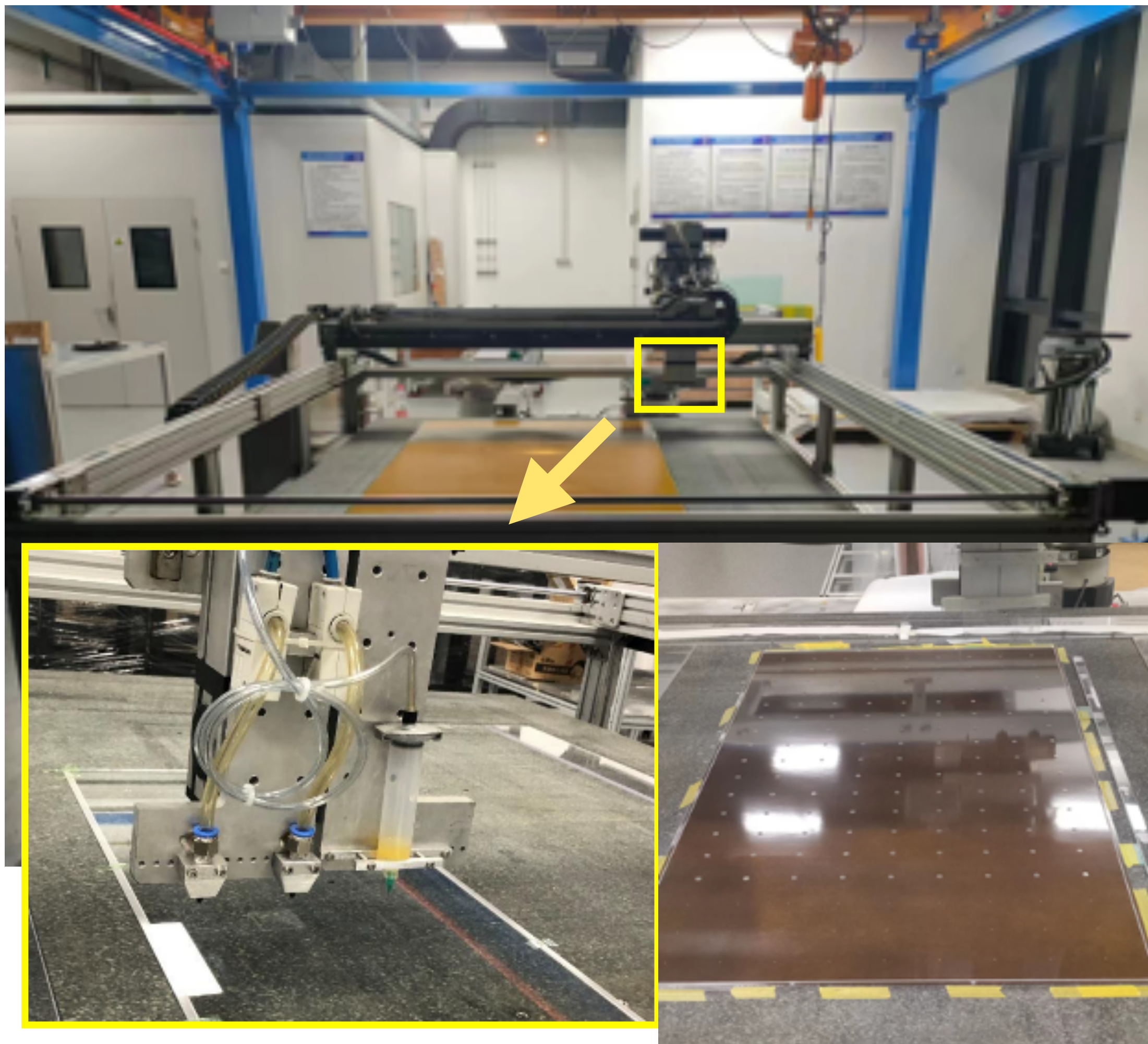
# ATLAS RPC

- 触发和读出电子学：每个BX触发逻辑中用到所有数据(包括sMDT)
- 探测器：新增sMDT, RPC和TGC提高覆盖率和触发选择能力
- 科大-上海交大-山东大学：建造窄气隙RPC
  - ~70 气隙、300单层探测器(全部BIS,占BI 50%)、900读出蜂窝板(50%)、5000前端电子学板(50%)



- ★大尺寸(1.7 m × 1.1 m)
- ★高精度气隙厚度:  $1 \text{ mm} \pm 10 \mu\text{m}$
- ★读出板厚度精度/平整性: 好于  $100 \mu\text{m}$

# RPC 进展情况



读出板制作：已进入工程阶段  
完成约200个合格读出板

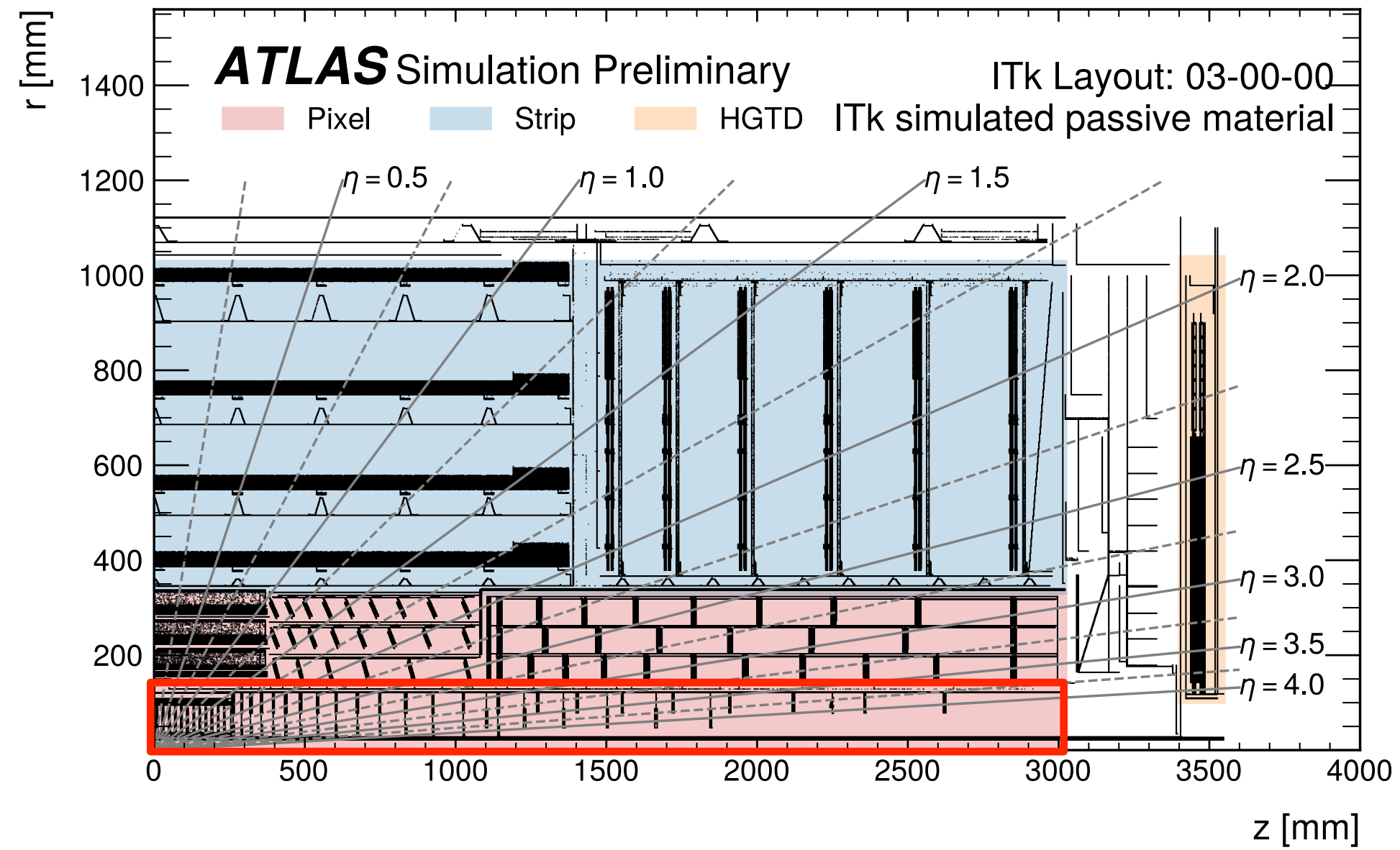
建立测试系统和标准  
(CERN)

详见杜东硕poster

气隙建造：已建立完整工艺，细节待优化

# 高精度时间像素探测器

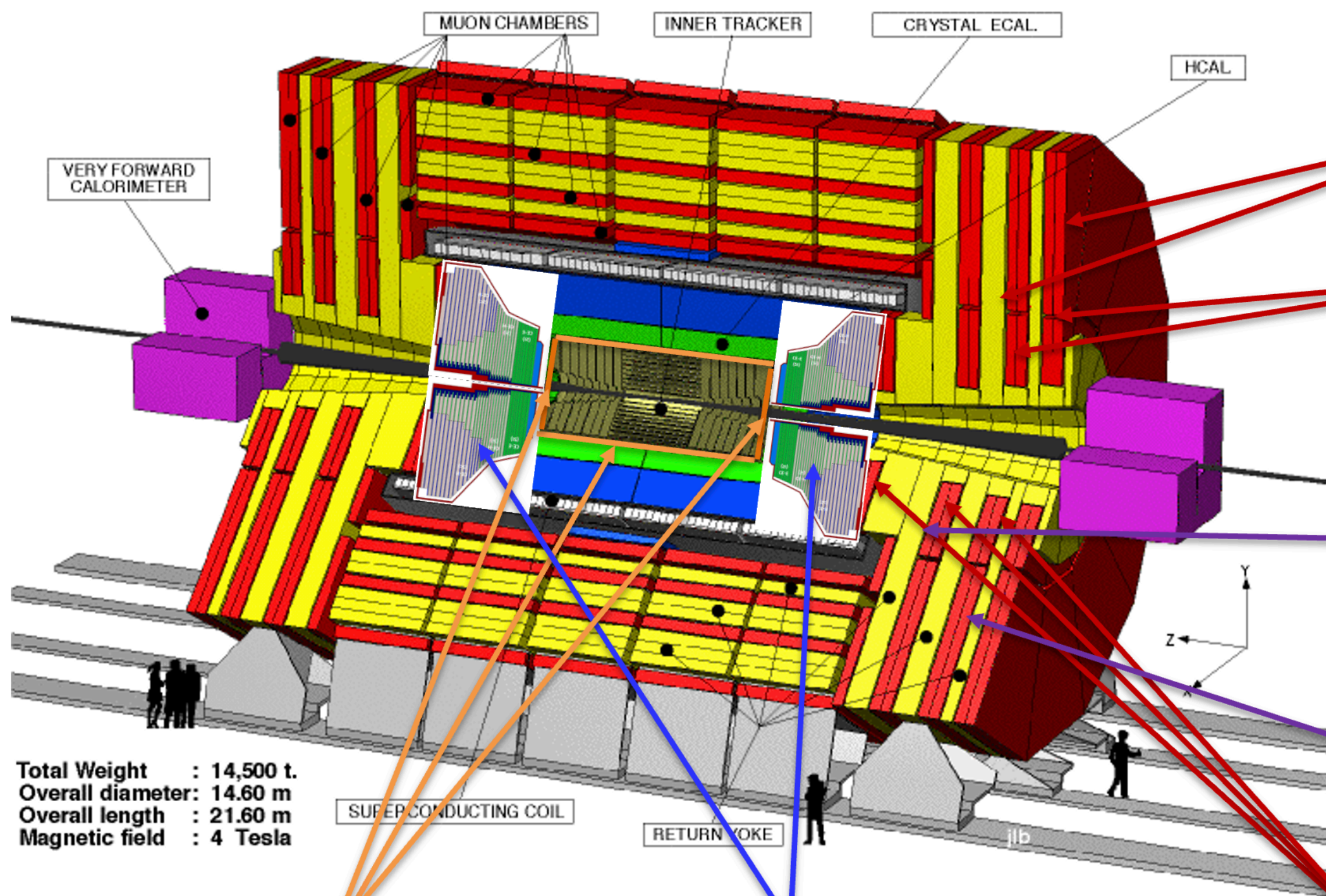
- 按照设计指标，ATLAS ITk像素探测器最内两层在HL-LHC取数至 $2 \text{ ab}^{-1}$ 时需要替换
- 以此为契机，ATLAS中国组已经开始与国际同行（LBNL, CERN, SLAC等）合作研制具有  $\sim 50 \text{ ps/pixel}$  分辨率的高精度时间像素探测器，以促成同时覆盖ATLAS探测器桶部与端盖的四维径迹与顶点重建，减轻HL-LHC上堆积效应的影响
- 中国组目前进展与计划
  - **ASIC**: 正在开展能够完成高精度时间数据高效缓存和快速读出的数字电路设计，未来将与国际合作者设计的模拟前端电路整合完成芯片设计
  - **传感器**: 正在探索碳化硅LGAD、硅基LGAD、3D传感器等多条国内自主研发的技术路线，适时确定最终选择
  - **物理**: 正在开展完整的四维径迹与顶点重建算法研发与测试，计划完整验证其物理及计算潜力



Variable	requirement	result (simulation)
Time resolution	< 50ps	LSB: $\sim 25 \text{ ps}$ noise: $\sim 30 \text{ ps}$ total: $\sim 40 \text{ ps}$
Area	< $20 \times 50 \mu\text{m}$	$15 \times 13 \mu\text{m}$ analog $23 \times 13 \mu\text{m}$ digital (counters) $38 \times 13 \mu\text{m}$ total
Power	< $5 \mu\text{W}$ average	< $5 \mu\text{W}$ during conversion
Range	10 ns	13 ns
Hit rate	$\sim 100 \text{ kHz}$	max conversion time < 2 us (500 kHz)

模拟前端  
仿真结果

# CMS探测器升级概览



Total Weight : 14,500 t.  
 Overall diameter: 14.60 m  
 Overall length : 21.60 m  
 Magnetic field : 4 Tesla

一期: CSC缪子探测器  
 1/3 of CSC for ME4/2

一期: RPC缪子探测器  
 2/3 RPC RE4 (RE4/2, RE4/3)

一期: 一级MUON系统触发电子学  
 Concentrator, Preprocessor and Fan-out system

二期 一级触发电子学:  
 高能所

RPC后端触发电子学

二期时间探测器: 北大, 清华, 北航, 科大, 山大, 华南师大

二期高粒度量能器: 高能所, 清华, 南京师大, 复旦, 浙大

二期GEM缪子探测器: 北大, 清华, 中山大学, 北航

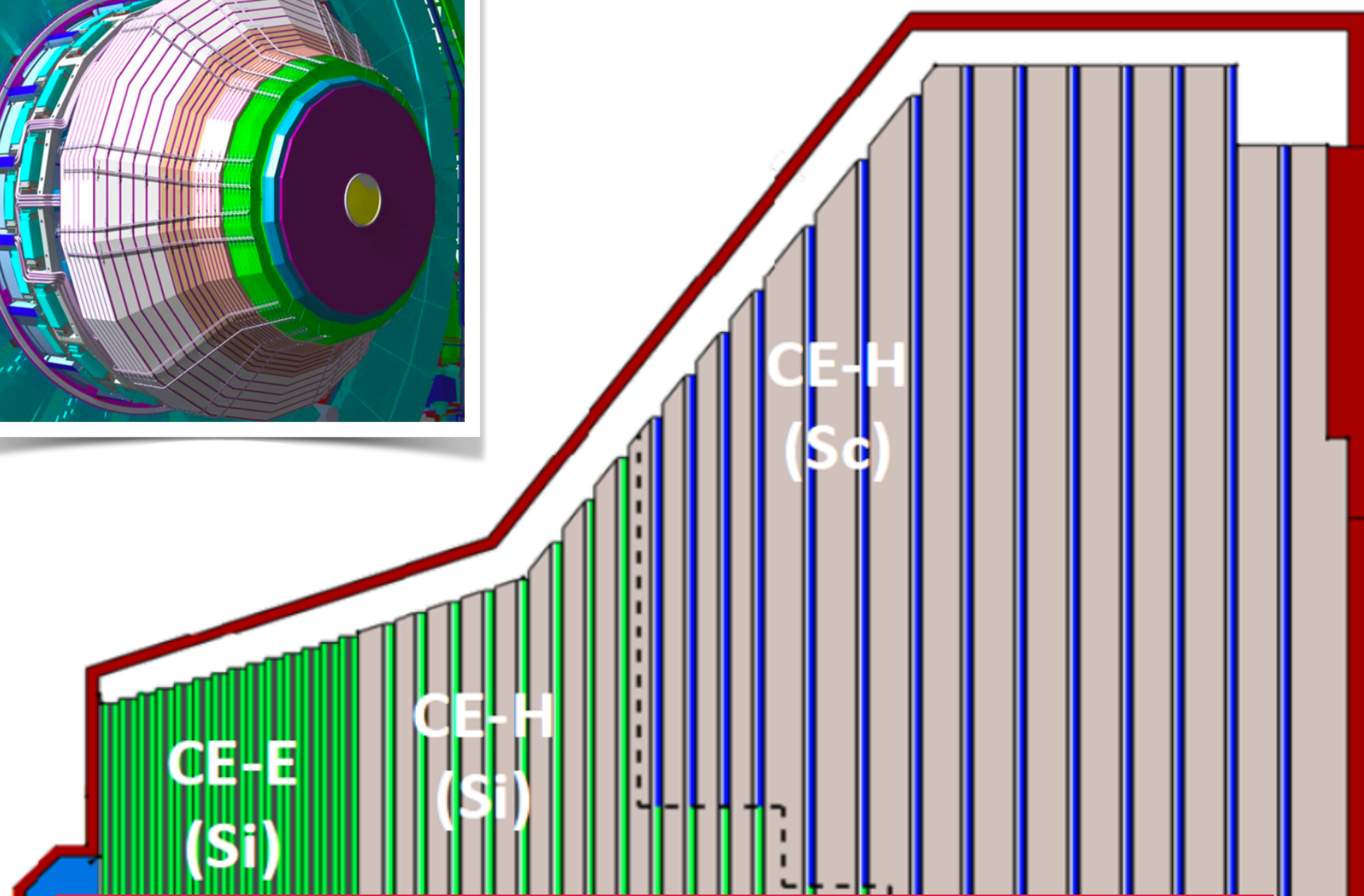
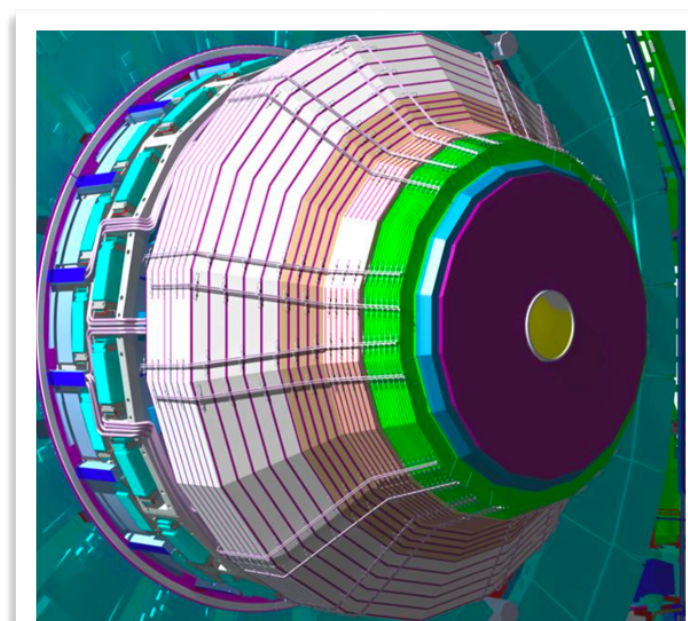
MTD  
 MIP Timing Detector

HGCAL

GEM

# CMS 高颗粒度量能器(HGCal)

中国组承担1/5，IHEP 站点已通过评估，率先完成30 (prototype)+7(pre-prod.)模块

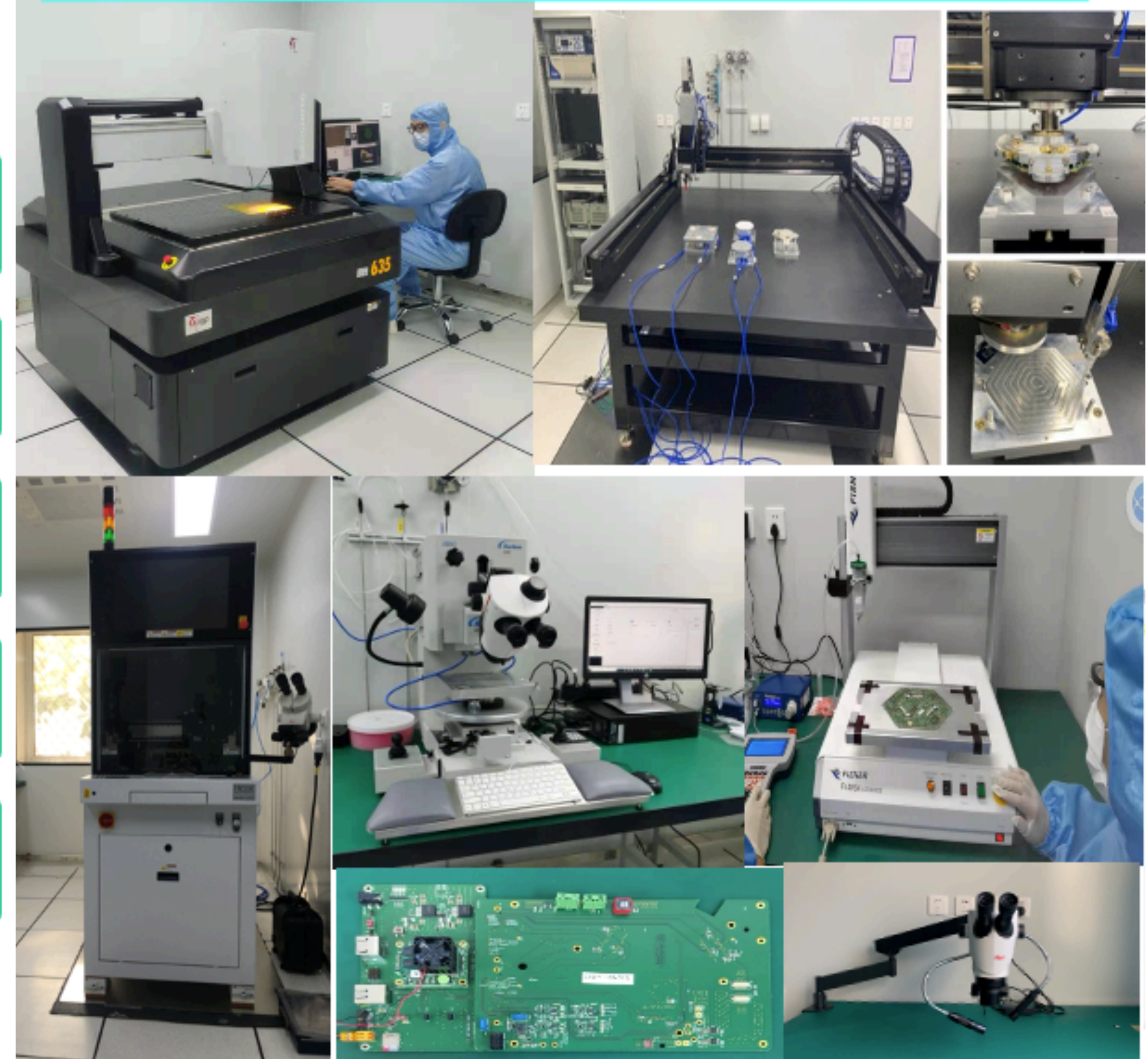


**"5维"信息:**  
能量分辨率:  $25\% \sqrt{E/\text{GeV}} \oplus 1\%$   
时间分辨率: 50 ps  
空间颗粒度: 1 cm<sup>3</sup>  
抗辐照性能:  $1 \times 10^{16} n_{eq}/\text{cm}^2$   
硅探测器: ~26000模块(620m<sup>2</sup> 灵敏区域)

## HGCal硅模块 制作流程

- 元器件/半成品质量控制
- 硅模块集成
- 电子学绑定
- 硅模块封装
- 测试

## Dedicated lab established from scratch for HGCal @ IHEP

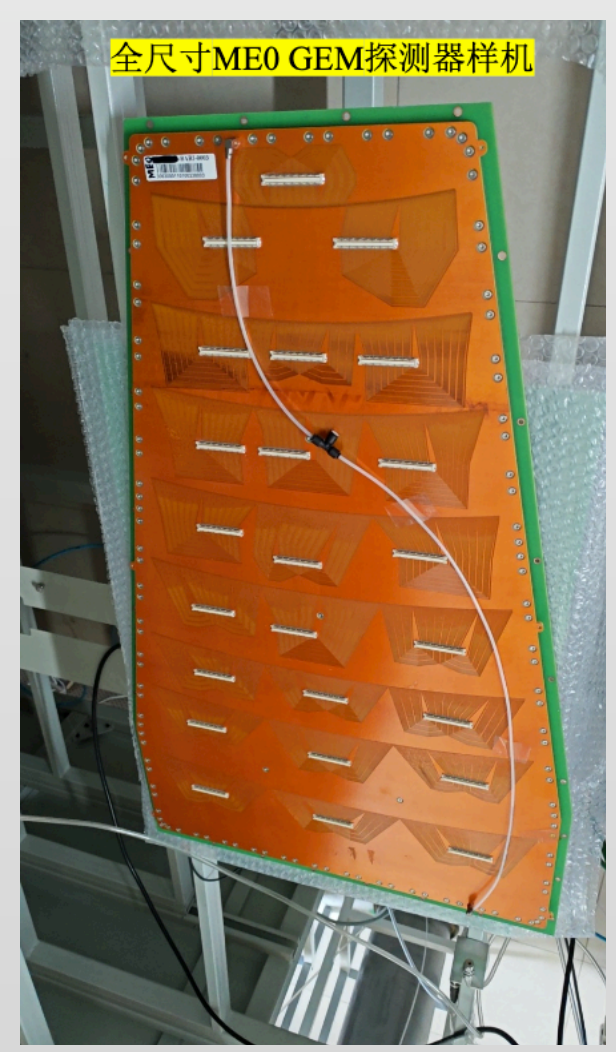
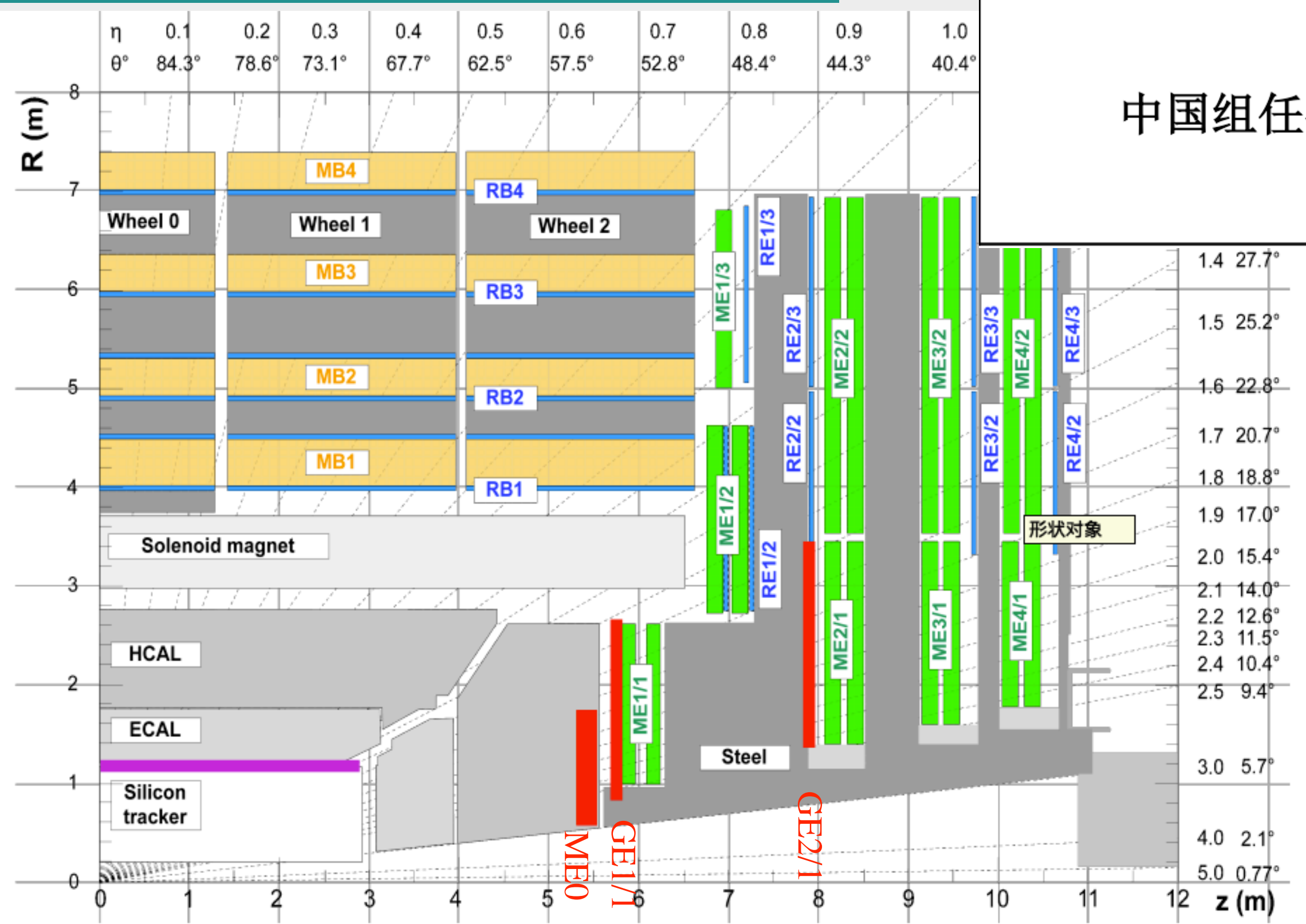


# CMS 缪子谱仪—GEM

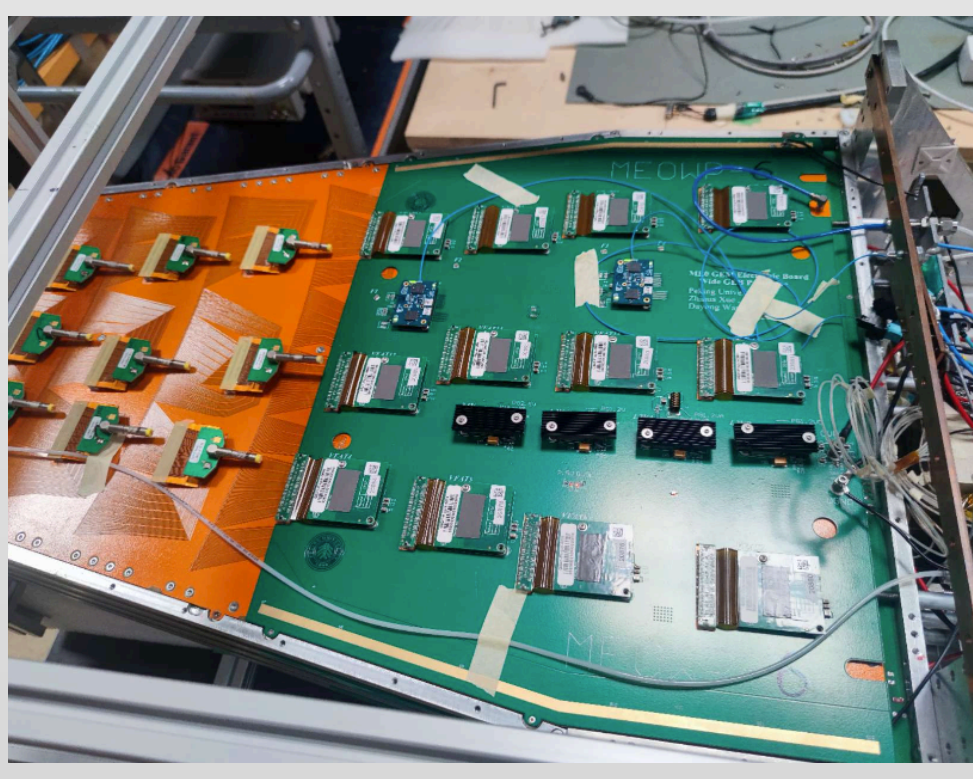
GE1/1: GEM Endcap Station 1 Ring 1  
 ME1/1: Muon Endcap Station 1 Ring 1

GE1/1: 已在取数  
 GE2/1: 前端电子学板已完成, 探测器制作实验室通过认证。  
 ME0: 样机通过测试, 量产准备就绪

升级探测器		GE1/1	GE2/1	ME0
探测器个数*		288 (=2×36×4)	288 (=2×18×8)	216 (=2×18×6)
计划	预研	2013-2017	2014-2022	2014-2023
	批量生产	2017-2019	2022-2026	2024-2025
	安装调试	2018-2020	2026-2027	2025-2027
中国组任务		全部前端电子学板GEB的生产测试, 在CERN的探测器组装测试、安装调试	负责设计研发及生产测试全部GEB, 在北大生产1/8 GEM探测器, 在CERN进行组装测试、安装调试	负责设计研发及生产测试全部GEB, 在北大生产~1/5 GEM探测器, 在CERN进行组装测试、安装调试

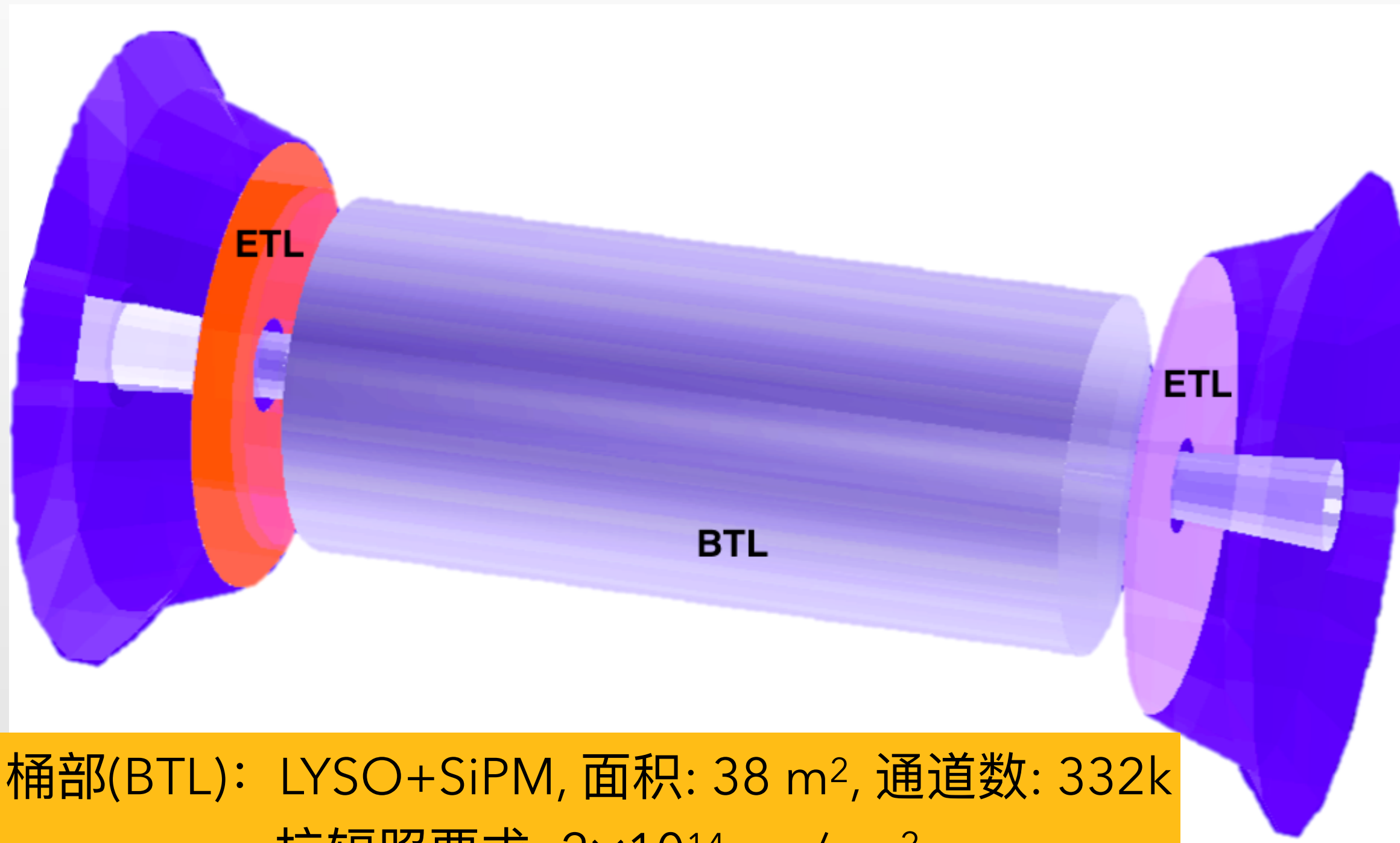


ME0 GEM 测试 @CERN





# CMS 时间探测器(MTD: BTL+ETL)



BTL: PKU、THU、BUAA

详见08/15 王锦报告(1/4 assembly)

ETL: USTC、SCNU、SDU

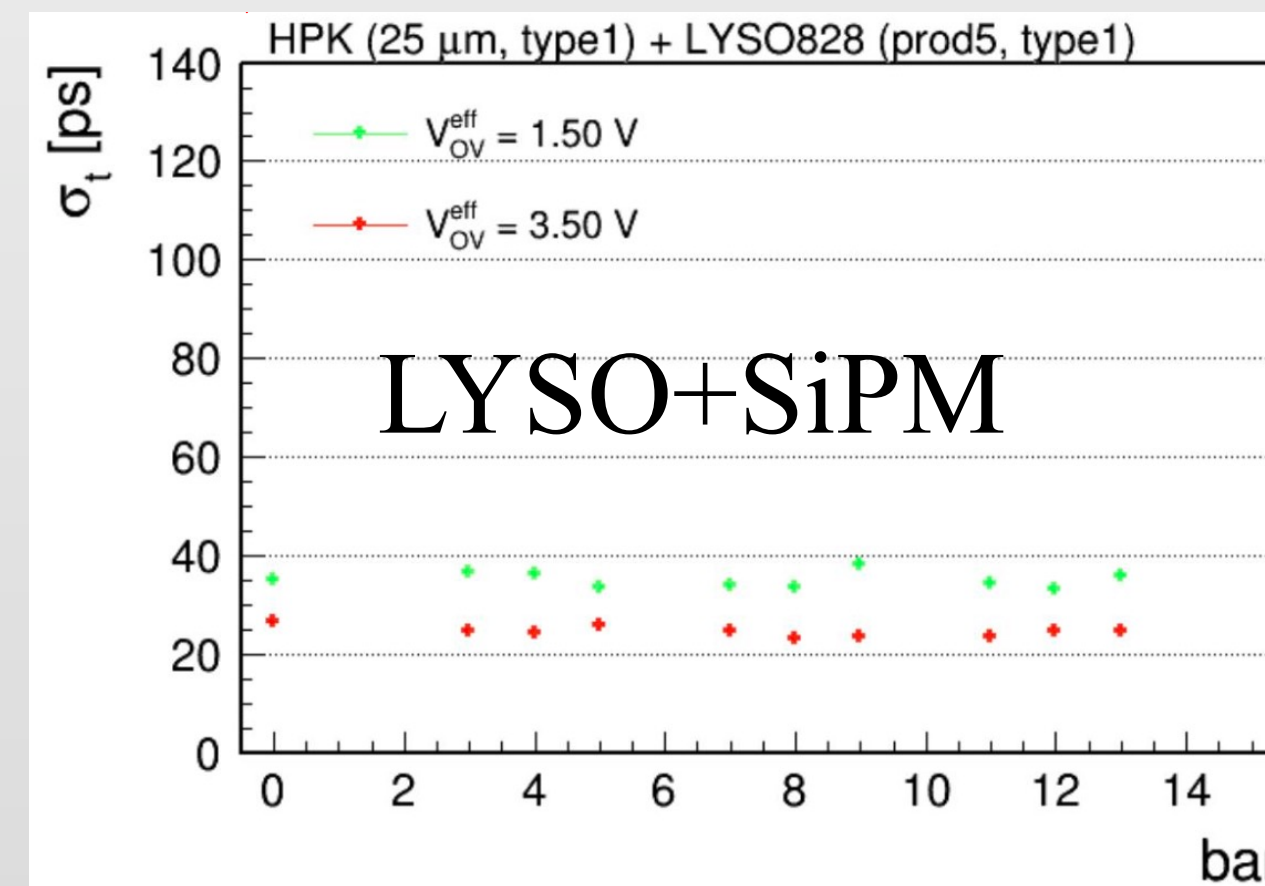
详见08/15 鲁楠报告(sensor QA, post processing)

桶部(BTL): LYSO+SiPM, 面积: 38 m<sup>2</sup>, 通道数: 332k  
抗辐照要求:  $2 \times 10^{14}$  n<sub>eq</sub>/cm<sup>2</sup>

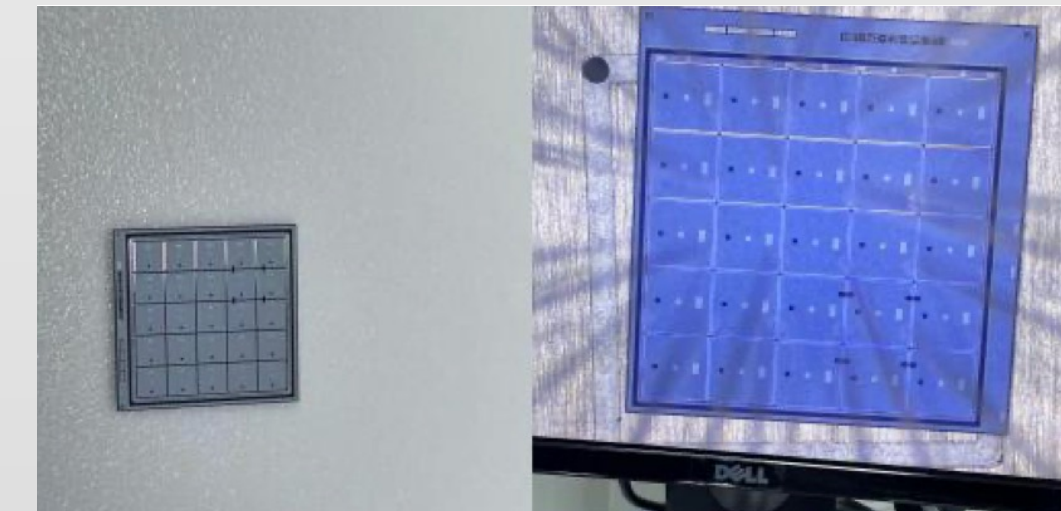
$|\eta| < 1.45$ ,  $z \in [-2.6, 2.6]$  m,  $R = 1.148$  m,  $t = 4$  cm

端盖(ETL): LGAD, 面积: 14 m<sup>2</sup>, 通道数: 8.5M  
抗辐照要求:  $1 \times 10^{15}$  n<sub>eq</sub>/cm<sup>2</sup>

$|\eta| \in (1.6, 3.0)$ ,  $z = \pm 3.0$  m,  $R \in (315, 1200)$  mm,  $t = 4.5$  cm

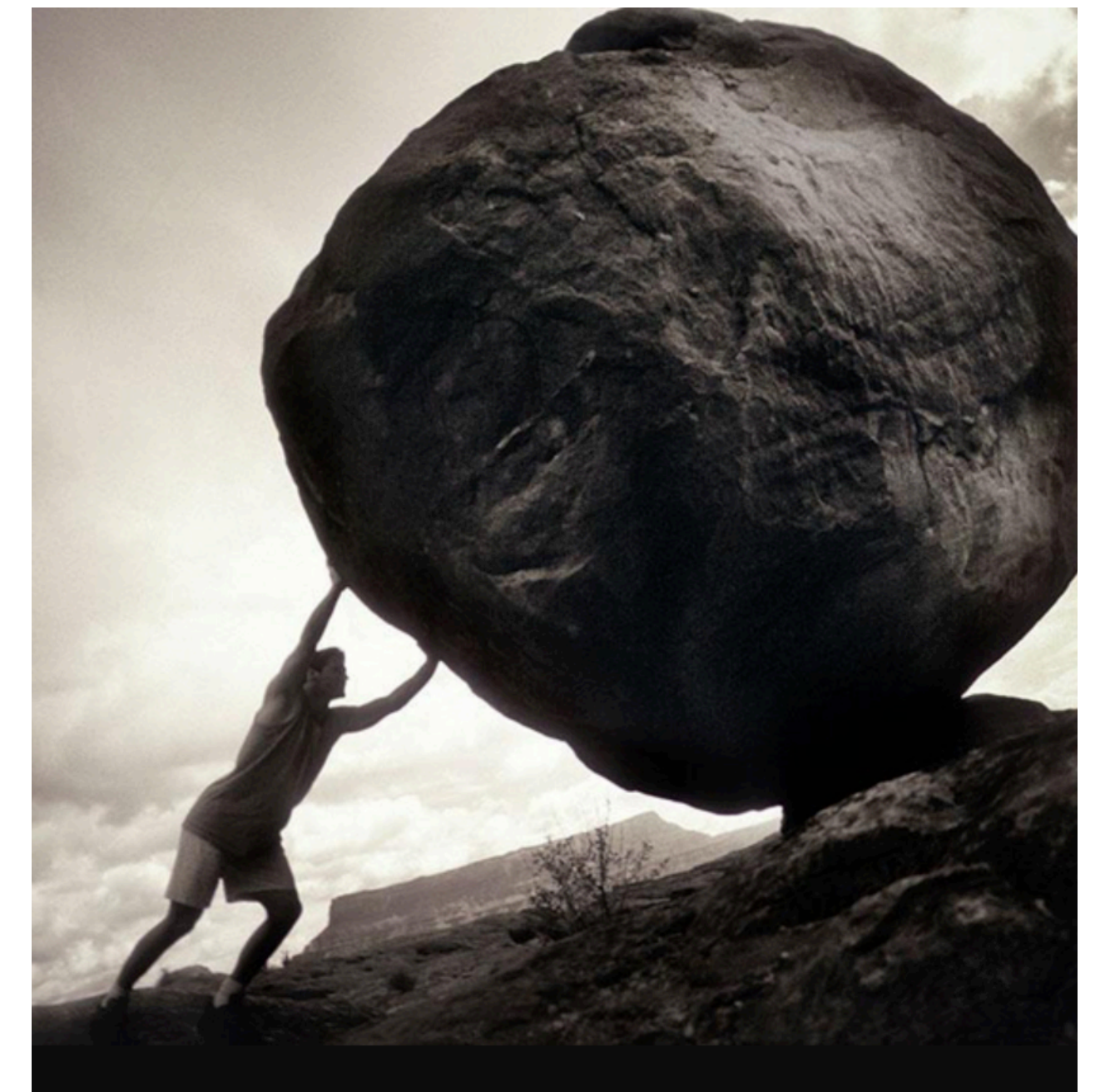


HPK 5x5 LGAD



# 总结

- ATLAS、CMS物理进展
  - 进入希格斯粒子性质精度测量时代，希格斯对产生灵敏度接近标准模型
  - 电弱、强相互作用精确测量取得丰富的结果,检验SM自洽性
  - 寻找BSM: leave no stone unturned
- 为HL- LHC开展探测器升级关键技术研究: 中国组起到举足轻重的作用, 逐步掌握关键技术、建立平台、培养人才



# CLHCP2024 青岛

- 第十届中国LHC物理会议 (CLHCP2024) 将由山东大学承办，中国高等科学技术中心 (CCAST) 与北京大学高能物理研究中心协办
- 会议日期：2024年11月14日至11月17日
- 会议地点：山东省青岛市鳌山湾蓝谷国际酒店
- 会议网址：<https://indico.ihep.ac.cn/event/22941/>
- 注册截止日期：2024年10月8日
- 会议内容包括：希格斯物理、电弱物理、强子物理与味物理、重离子物理、超越标准模型的新物理、探测器与加速器技术等粒子物理高能量与高精度前沿重要基础研究热点方向
- 期待理论与实验交叉对话，共促发展

谢谢!

# CLHCP2024 青岛

第十届中国LHC物理会议  
The 10th China LHC Physics Conference

2024年11月14日-17日

山东省青岛市鳌山湾

<https://indico.ihep.ac.cn/event/22941/>

会议简介：中国LHC物理会议（简称CLHCP）是由中国物理学会高能物理分会牵头的全国性重要学术会议，聚焦于高能量与高精度前沿粒子物理实验与理论的最新研究进展，会议内容包括：希格斯物理、电弱物理、强子物理与味物理、重离子物理、超越标准模型的新物理、探测器与加速器技术等粒子物理高能量与高精度前沿重要基础研究热点方向。会议旨在加强理论物理学家及实验物理学家在高能量前沿、高精度前沿与实验技术前沿领域的交流与合作，引领粒子物理领域国内研究水平的共同进步、推动国内相关研究工作的国际学术影响力、为年轻学者提供交流与合作的舞台。

组织委员会：

PC Chairs: 刘佳 (PKU)、张华桥 (IHEP)

Theory: 王健(SDU)、宋慧超(PKU)、刘佳(PKU)、王玉明(NKU)、于江浩 (ITP)

ALICE: 张晓明 (CCNU)、唐泽波 (USTC)

ATLAS: 李海峰(SDU)、徐来林(USTC)、李敦 (SJTU/TDLI)、张雷(NJU)、徐达 (IHEP)

CMS: 陶军全(IHEP)、袁丽 (BUAA)、张华桥(IHEP)、周辰(PKU)

LHCb: 孙亮 (WHU)、张艳席(PKU)、李一鸣 (IHEP)

Upgrade: 王大勇(PKU)、孙勇杰 (USTC)、徐庆金 (IHEP)

CEPC: 阮曼奇 (IHEP)

LHC Computing: 齐法制(IHEP)

本地组织委员会：

李海峰 (chair)、李冰、刘彦麟、胡坤、马连良、冯存峰、王健、李海涛

主办：中国物理学会高能物理分会

承办：山东大学

协办：中国高等科学技术中心 (CCAST)、北京大学高能物理研究中心

会务：张兰、肖宇

邮箱：[clhcp2024\\_loc@email.sdu.edu.cn](mailto:clhcp2024_loc@email.sdu.edu.cn)

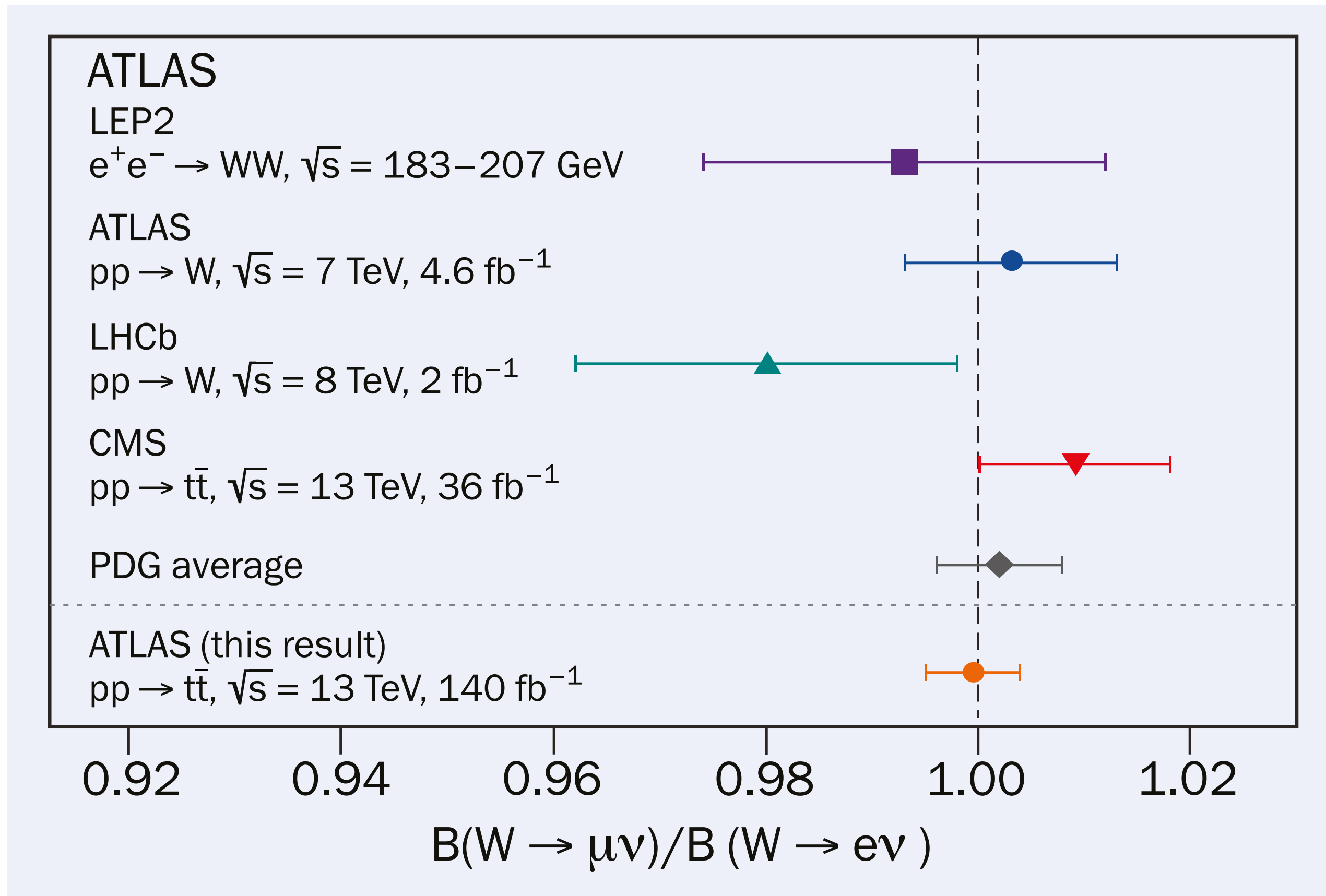


中国高等科学技术中心  
China Center of Advanced Science and Technology



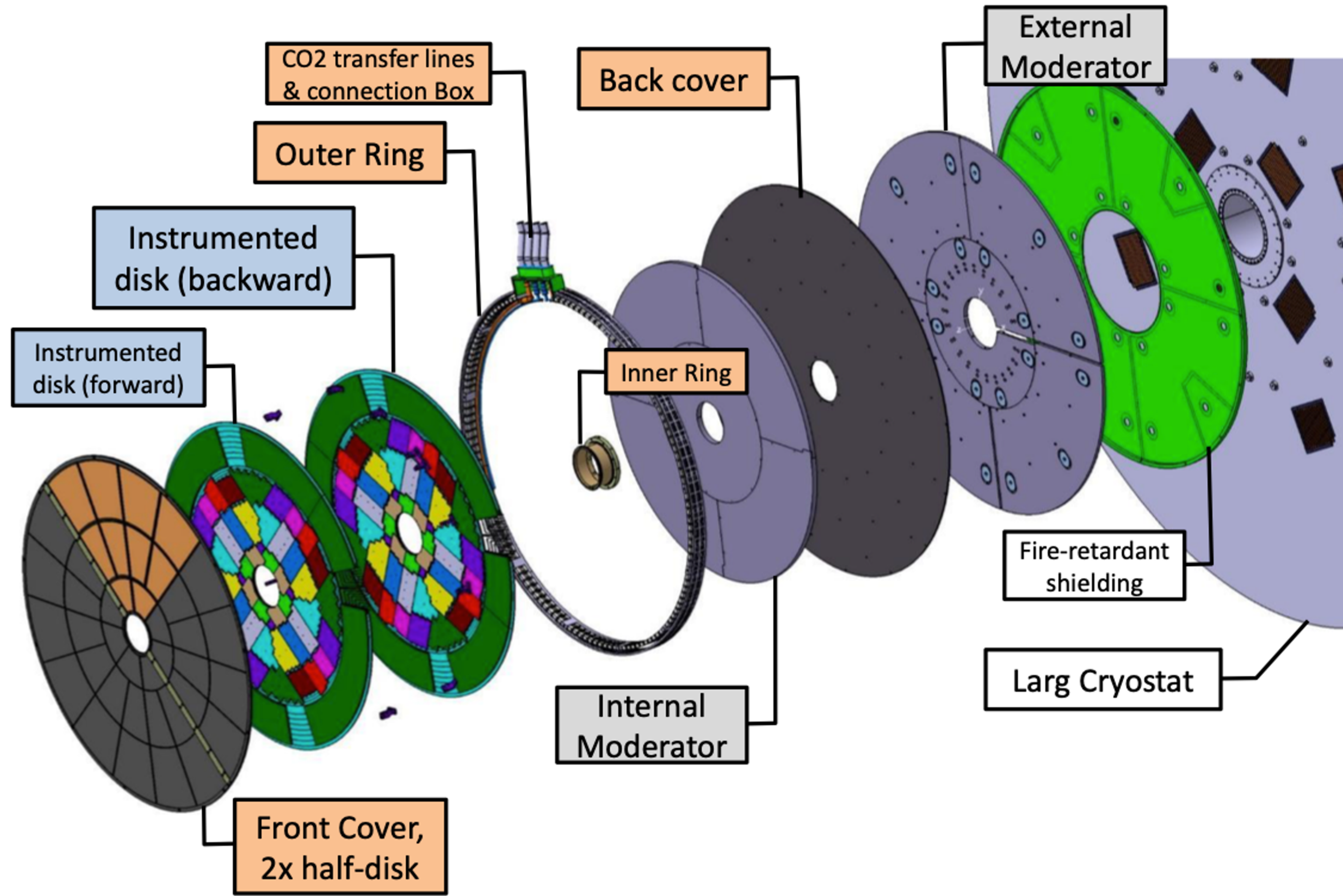
**BACK UP**

# 轻子味普适性(Lepton Flavor Universality)

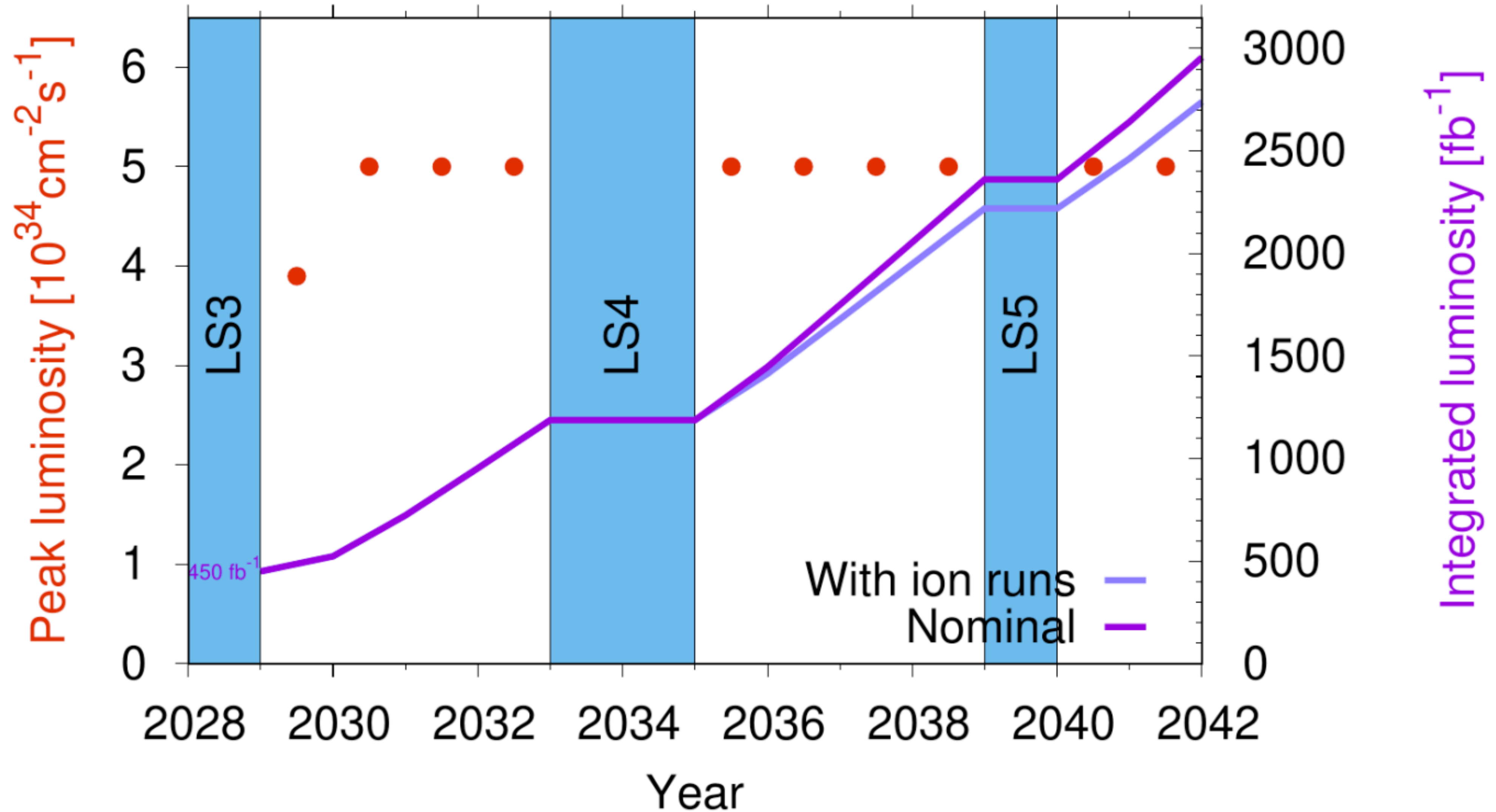


Source: arXiv:2403.02133

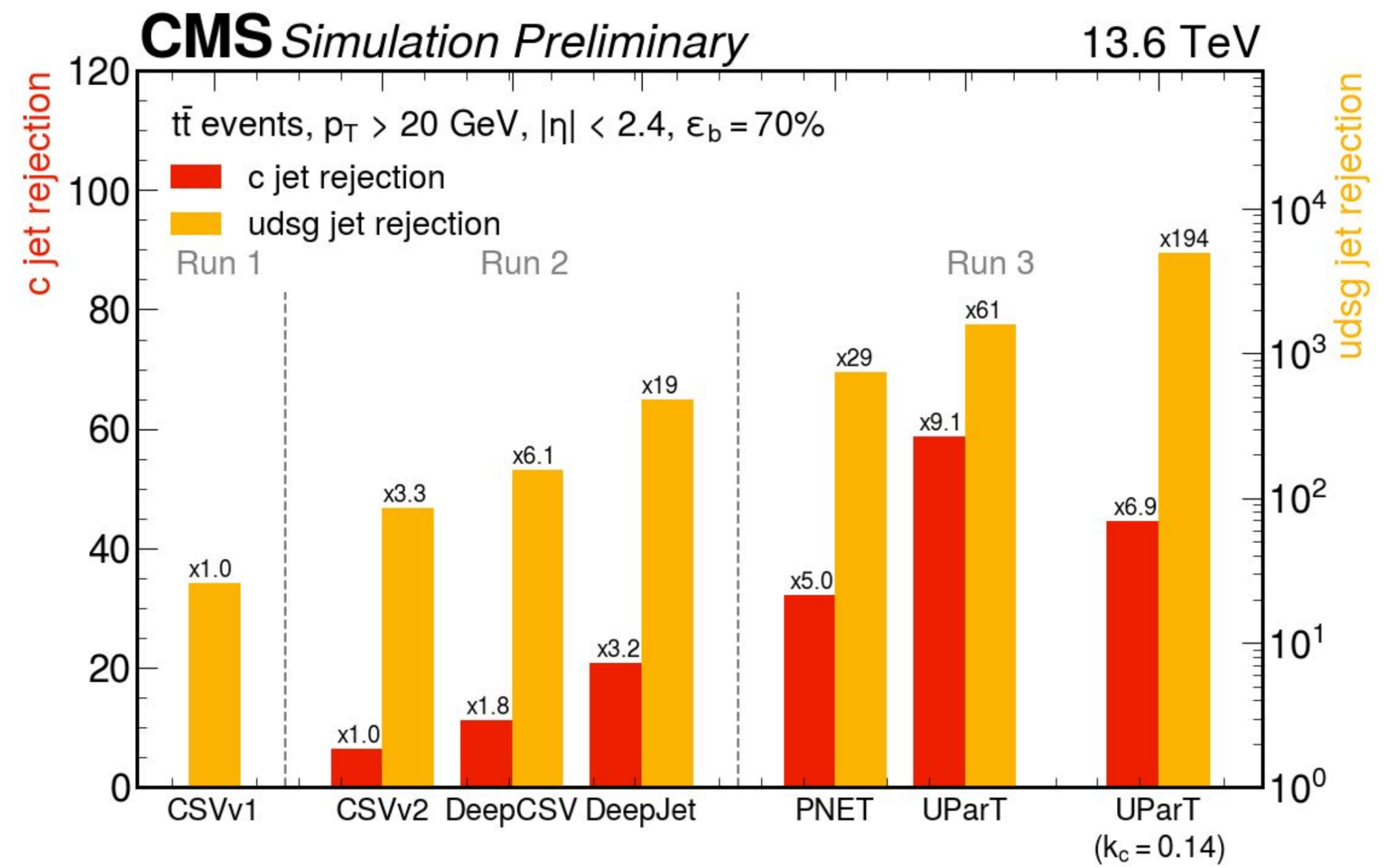
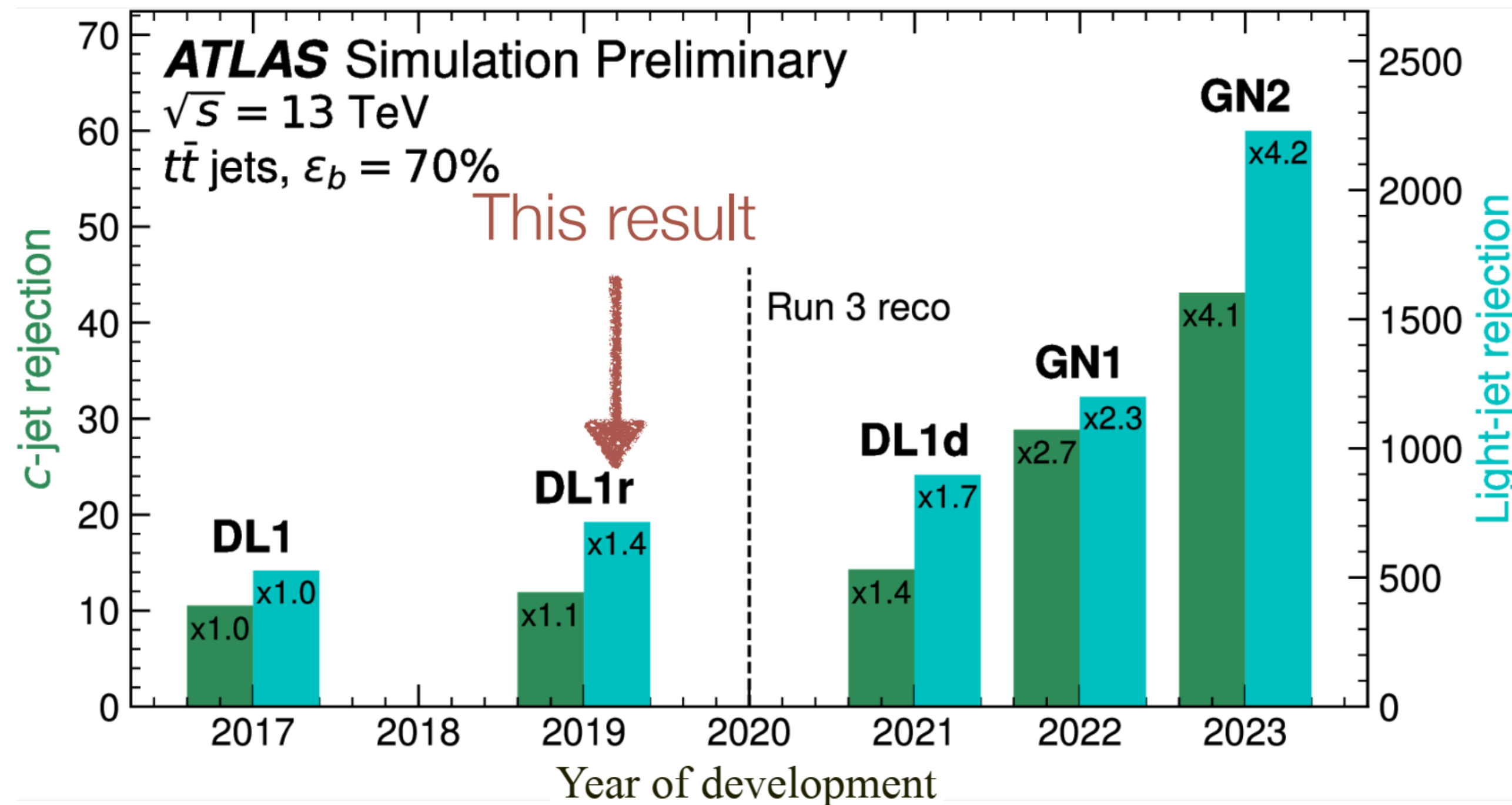
$$R(\mu/e) = 0.9995 \pm 0.0045$$



# HL-LHC luminosity



# Flavor tagging improvements (ML)

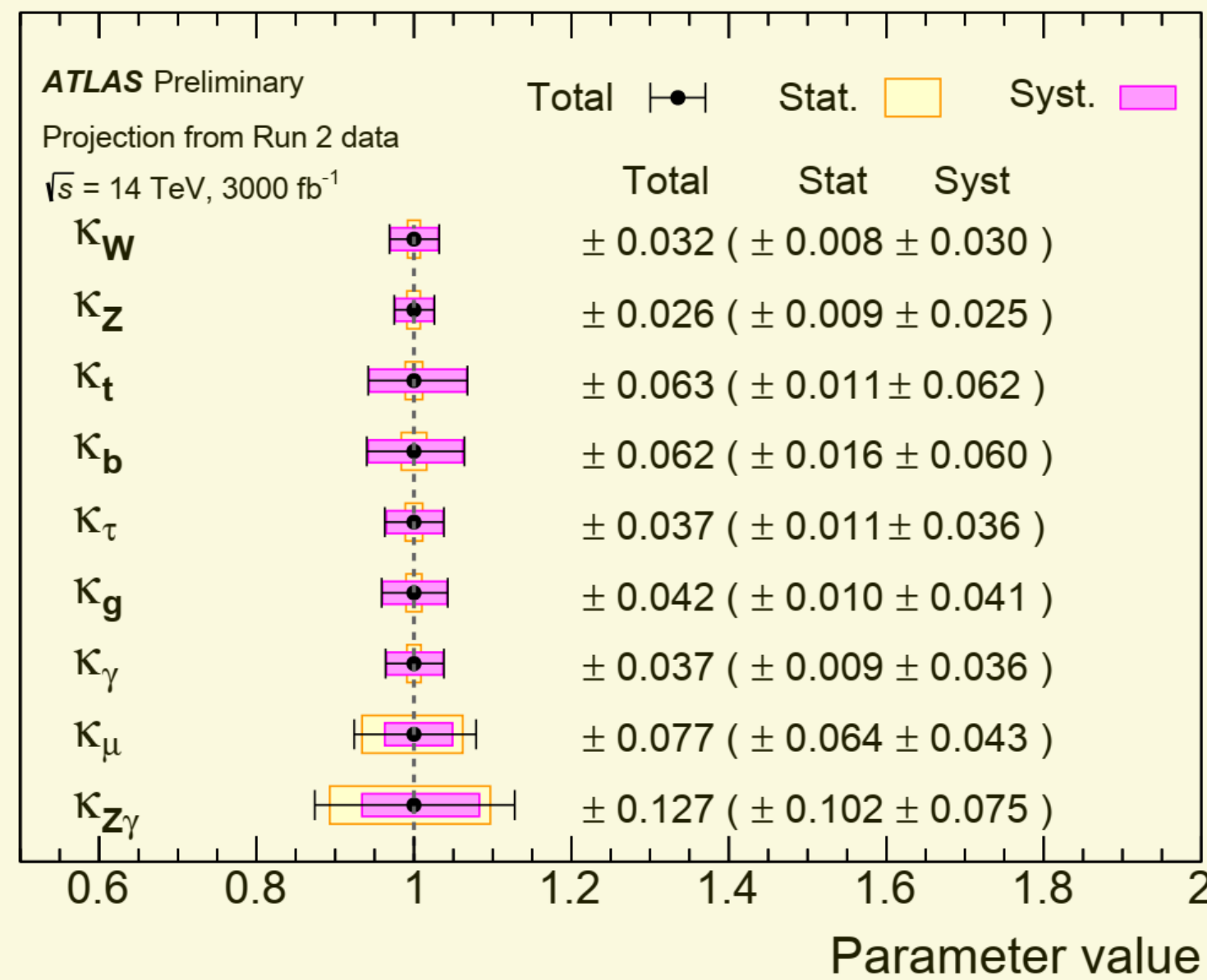


CMS-DP-2024-066

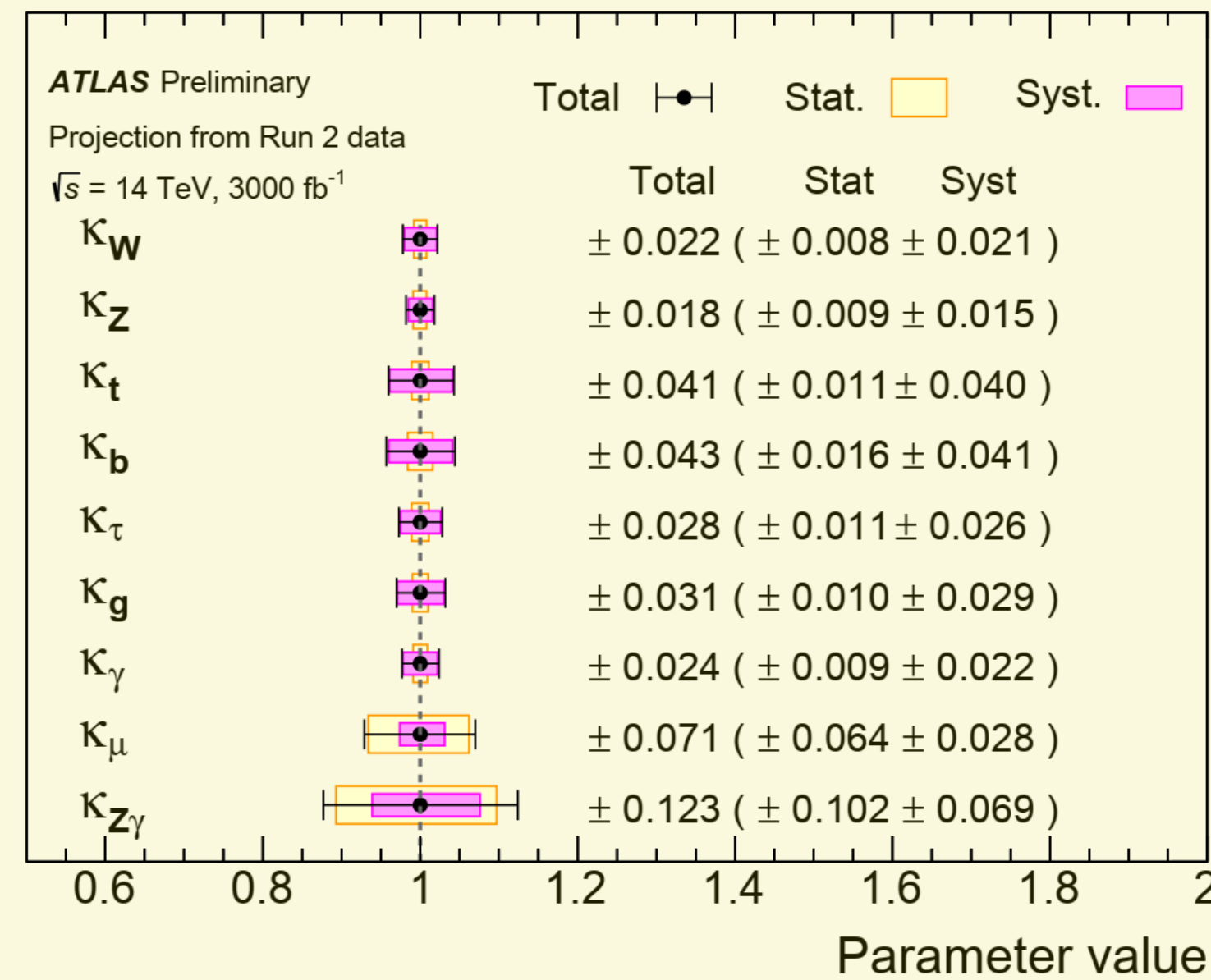


# HL-LHC projections

ATL-PHYS-PUB-2018-054

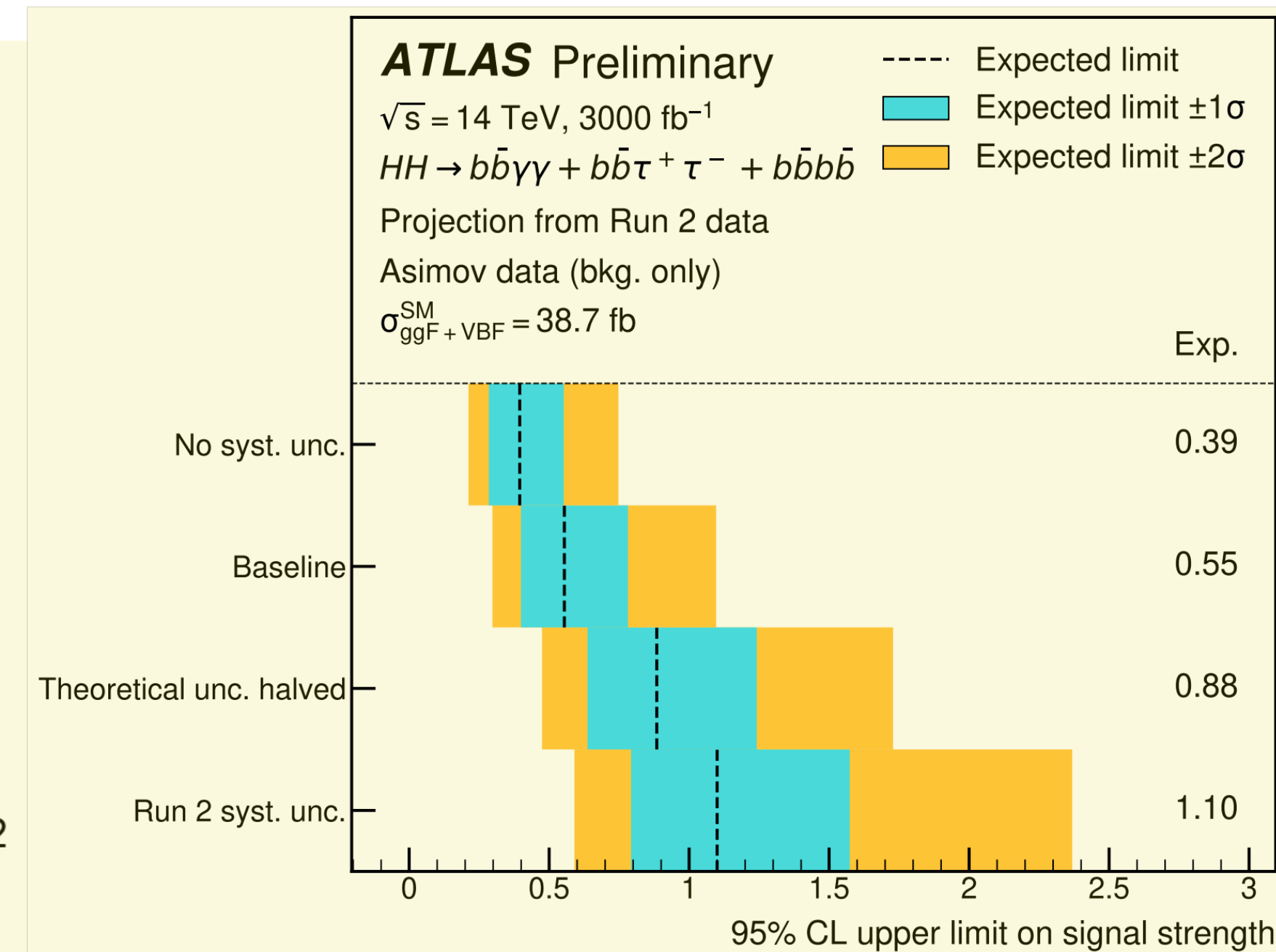


(a) Scenario S1



(b) Scenario S2

ATL-PHYS-PUB-2022-053



# Higgs self-coupling in single Higgs production

