

Testing CKM Unitarity via W^+W^- production at the LHC and future colliders

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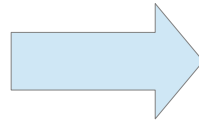
in collaboration with: Luca Marzola and Kristjan Mürsepp

based on: 2405.14585 [hep-ph]

- Weak Charged currents interactions in the SM

$$\mathcal{L}^{cc} = -\frac{g}{\sqrt{2}} (\bar{u}_L, \bar{c}_L, \bar{t}_L) \gamma^\mu W_\mu^+ V_{\text{CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.$$

CKM matrix



$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitarity of CKM matrix (implicit by construction in the SM) requires

$$\sum_i V_{ij} V_{ik}^* = \delta_{jk} \quad \text{or} \quad \sum_j V_{ij} V_{kj}^* = \delta_{ik}$$



9 independent constraints
6 represented as triangle in
complex plane

- New Physics can break CKM Unitarity

- Models including new fields that mix with quarks in CC weak interactions entail violation of CKM unitarity at energies below NP mass scale
- **Examples:** heavy fourth-generation, **vector-like quarks** → mixing with SM via Yukawa interactions: **universal-see-saw models** and their **LR symmetric extension**

Current measurements

First two rows : up, charm

$$\begin{aligned} |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 &= 0.9985 \pm 0.0007, \\ |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 &= 1.001 \pm 0.012, \end{aligned}$$

PDG 2022

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.002 \pm 0.027$$

First two columns: down, strange

$$\begin{aligned} |V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 &= 0.9972 \pm 0.0020 \\ |V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 &= 1.004 \pm 0.012. \end{aligned}$$

PDG 2022

CKM unitarity violation parametrization

$$\delta_q \equiv \begin{cases} |V_{qd}|^2 + |V_{qs}|^2 + |V_{qb}|^2 - 1 & \text{for } q = u, c \\ |V_{uq}|^2 + |V_{cq}|^2 + |V_{tq}|^2 - 1 & \text{for } q = d, s, b \end{cases}$$

- All CKM unitarity tests in good agreement with SM
- except δ_u showing a 2.2σ tension $\Rightarrow$ Cabibbo angle anomaly
- mainly due to $|V_{ud}|$ recent determination from 20 superallowed $0^+ \rightarrow 0^+$ nuclear beta-decays
J.C. Hardy, I.S. Towner, PRC 102 (2020), 4, 045501
- $\delta_u = -0.00151(53)$ $\Rightarrow$ 2.85σ if measurements of V_{ud} , V_{us} are added to the global fit
Cirigliano et al, PLB 838 (2023) 137748
Crivellin et al, JHEP 03 (2023) 234

New Physics interpretations of Cabibbo Anomaly...

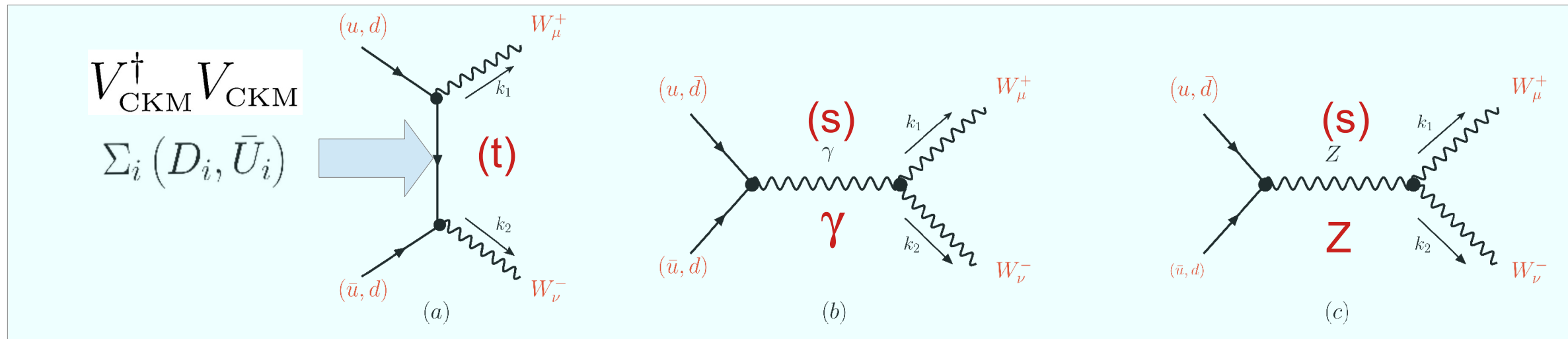
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Motivations

- All tests of CKM unitarity are based on **low energy observables** of Flavor physics
- No corresponding tests at high energy are available at moment
- CKM unitarity violation $\rightarrow$ can break unitarity of S-matrix at high energy
- inducing anomalous energy behavior in related cross sections at some energy scale Λ
- signaling the presence of NP $\rightarrow$ required to recover unitarity above Λ scale
- **WW production** (currently measured at the LHC) is a golden process for testing CKM unitarity at the **LHC**, **HL-LHC** and future colliders as **FCC-hh**

W^+W^- production at hadron colliders



Quantum amplitude

$$\mathcal{M}^{q\bar{q}} = -ie^2 \left[\bar{v}(p_1) \Gamma_{\mu\nu}^q u(p_2) \right] \varepsilon^\mu(k_1)^* \varepsilon^\nu(k_2)^*$$

$$\Gamma_{\mu\nu}^{q=u,c} = \frac{1}{s} \left(\gamma^\alpha \bar{g}_V^q - \gamma^\alpha \gamma_5 \bar{g}_A^q \right) V_{\alpha\nu\mu}(p, -k_2, -k_1) + \frac{\xi_q}{4ts_W^2} \gamma_\nu (\not{p}_2 - \not{k}_1) \gamma_\mu (1 - \gamma_5)$$

trilinear-gauge-boson
vertex

$$\delta_q$$

$$\xi_q \equiv \sum_{U=u,c,t} [V_{Uq}^* V_{Uq}] = 1 + \delta_q \quad \text{SM}$$

breaks unitarity at $\sqrt{s} \gg M_W$

$$q \bar{q} \rightarrow W^+ W^-$$

$$|\overline{\mathcal{M}}^{q\bar{q}}|^2(\delta_q) = |\overline{\mathcal{M}}_{\text{SM}}^{q\bar{q}}|^2 + \delta_q \Delta \overline{\mathcal{M}}_1^{q\bar{q}} + \delta_q^2 \Delta \overline{\mathcal{M}}_2^{q\bar{q}}$$

$s/M_W^2 \gg 1$ expansion

(see paper for exact expression)

$$\Delta \overline{\mathcal{M}}_1^{q\bar{q}} \simeq \frac{\alpha_W^2 \pi^2}{6N_c} \left(\frac{s}{M_W^2} \right) s_\Theta^2 \left[6 - \frac{M_Z^2}{M_W^2} (3 - 4x_q s_W^2) \right]$$

$$\Delta \overline{\mathcal{M}}_2^{q\bar{q}} \simeq \frac{\alpha_W^2 \pi^2}{4N_c} \left[\left(\frac{s^2}{M_W^4} \right) s_\Theta^2 + \left(\frac{s}{M_W^2} \right) 4 (3 + c_\Theta^2) \right]$$

$$\Theta \longrightarrow \text{Scattering angle in WW center of mass}$$

$$x_q = 1, 1/2 \longrightarrow \text{For } q=\text{Up, Down}$$

$$s_\Theta = \sin \Theta$$

$$c_\Theta = \cos \Theta$$

terms proportional to δ_q grow quadratically with energy $\rightarrow$ **breaking unitarity**

pp → WW cross section

$$\frac{d^2\sigma}{d\Omega dm_{WW}} = \frac{\beta_W}{64\pi^2 m_{WW}^2} \sum_{q=u,d,s,c,b} |\overline{\mathcal{M}}^{q\bar{q}}|^2 L^{q\bar{q}}(\tau)$$

$$\beta_W = \sqrt{1 - 4M_W^2/m_{WW}^2}, \quad \tau = m_{WW}/\sqrt{S} \longrightarrow \text{pp cm energy}$$

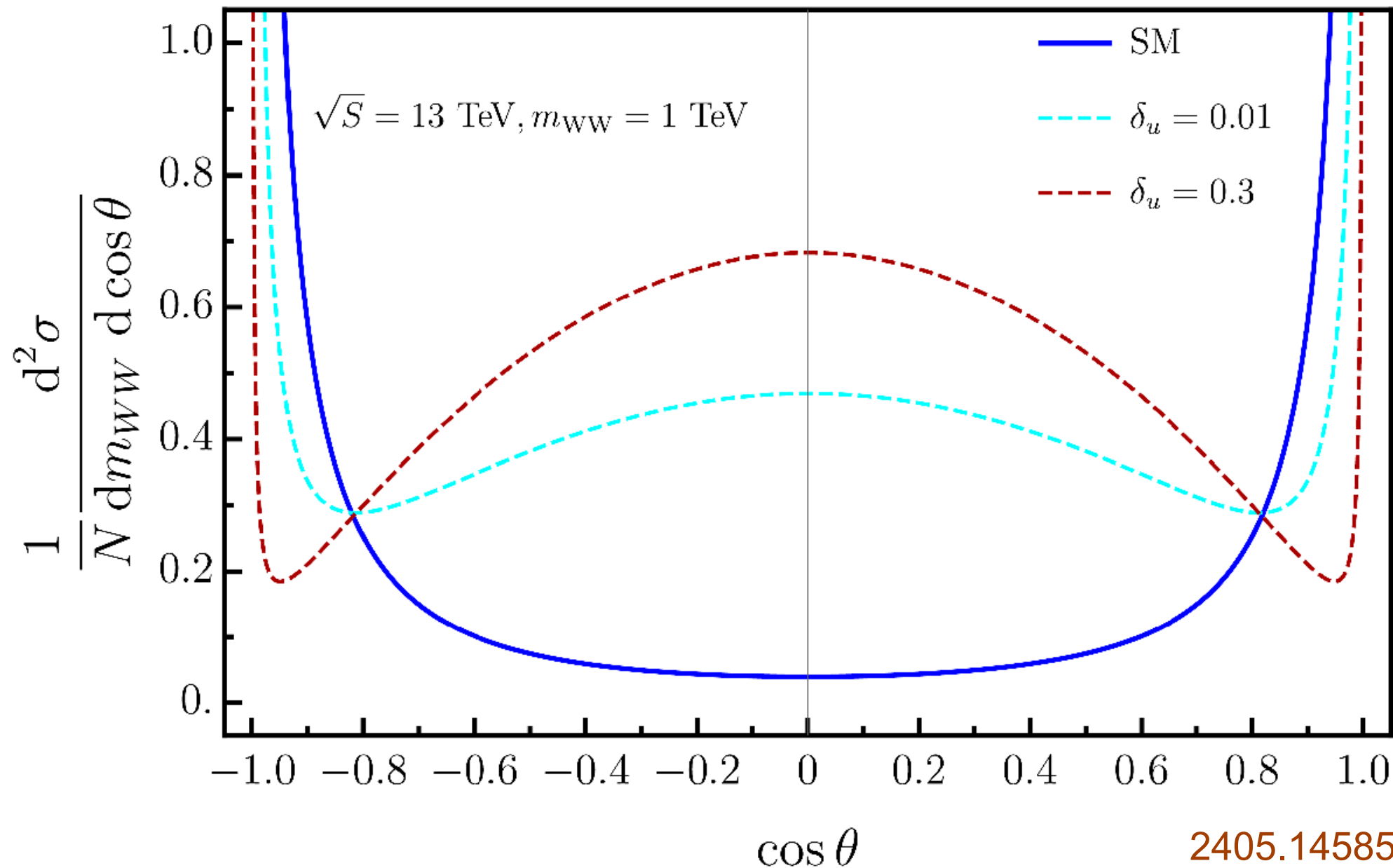
$\Omega \longrightarrow$ solid scattering angle
in WW cm frame

$\downarrow$ WW invariant mass

$$L^{q\bar{q}}(\tau) = \frac{4\tau}{\sqrt{S}} \int_{\tau}^{1/\tau} \frac{dz}{z} q_q(\tau z) q_{\bar{q}}\left(\frac{\tau}{z}\right) \longrightarrow \text{Parton luminosity}$$

For PDF we used PDF4LHC21

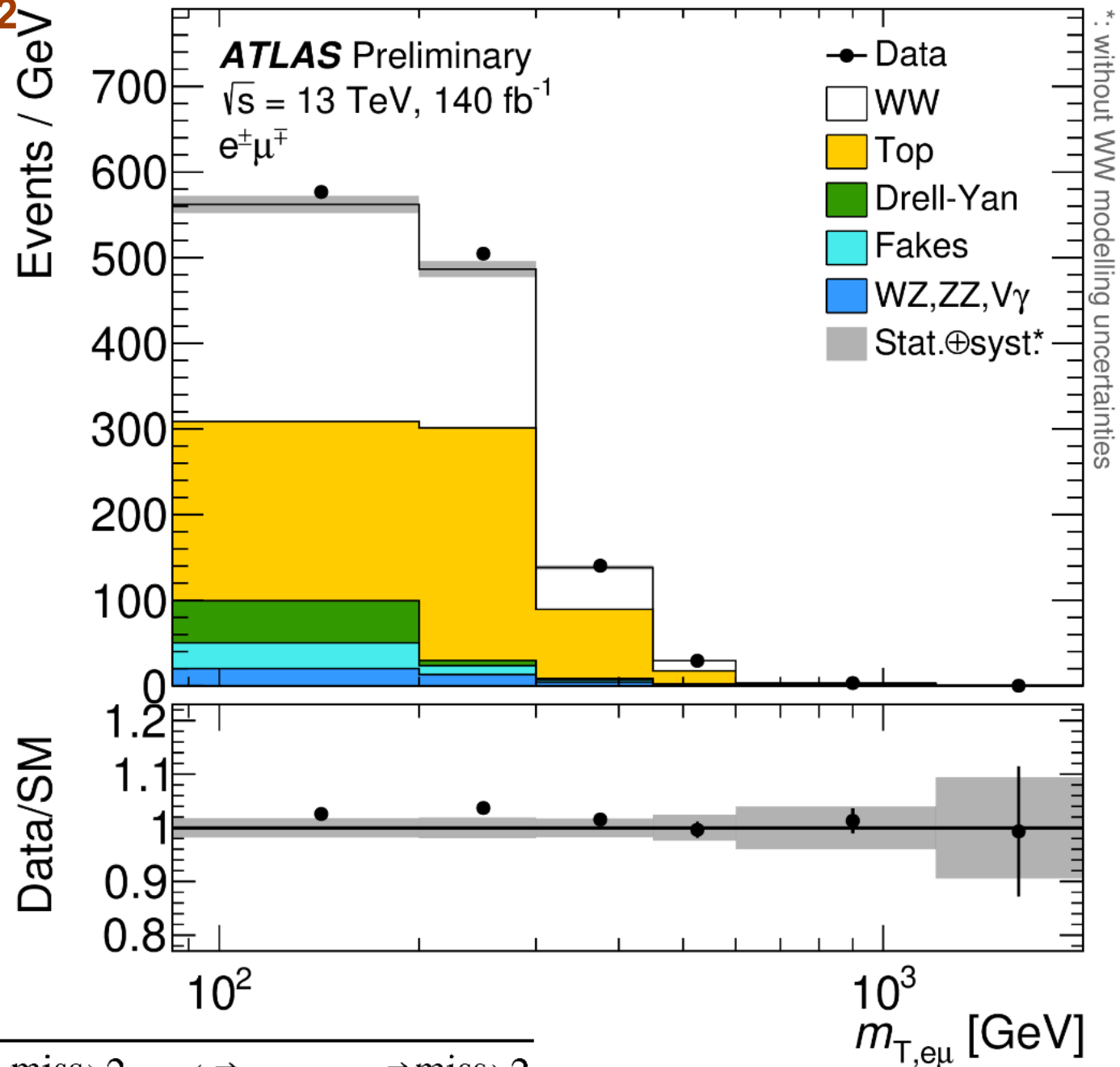
- NNLO QCD corrections included with **K-factor = 1.72** @ $\sqrt{S} = 13$ TeV
- we assume K-factor the same for the NP contribution



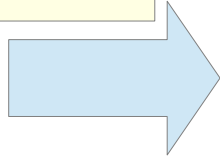
2405.14585 [hep-ph]

NP contribution is enhanced in the **central region**, where SM is suppressed.

- $pp \rightarrow W^+ W^-$ cross section recently measured by
ATLAS: [arXiv:1905.04242] and ATLAS-CONF-2023-012
CMS : [arXiv:2009.00119] and CMS-PAS-SMP-24-001
- Using LHC Run 2 $\rightarrow \mathcal{L} \sim 140 \text{ fb}^{-1}$ (ATLAS) $\mathcal{L} \sim 36 \text{ fb}^{-1}$ (CMS)
- Good agreement with SM predictions
- NP effect of **CKM violation** is sensitive to large **WW invariant masses**
- strong constraints arise from regions of $M(WW) > 1 \text{ TeV}$
- We used ATLAS results in **1905.04242** to set bounds on δ_q



we compare
 (SM+CKMV)/SM
 against Data/SM



$$m_{T,e\mu} = \sqrt{(E_{T,e\mu} + E_T^{\text{miss}})^2 - (\vec{p}_{T,e\mu} + \vec{p}_T^{\text{miss}})^2}$$

coincides with our m_{WW} in the WW CM frame

Analysis @ LHC: run2 and HL phase

We consider the following **m_{WW}** bins (same as ATLAS analysis)

$$\Delta_i = \left\{ [2M_W/\text{GeV}, 200], [200, 300], [300, 450], [450, 600], [600, 1200], [> 1200] \right\}$$

and perform a χ^2 test at **95% CL**

$$\chi^2(\delta_q) = \sum_{i=1}^6 \frac{\left(\alpha_i \bar{\sigma}_i(\delta_q) - r_i \right)^2}{\varepsilon_i^2} \leq 12.592$$

central values for
Data/SM

Experimental errors

$$\bar{\sigma}_i(\delta) \equiv \int_{\Delta_i} \frac{d\sigma(\delta)}{dm_{WW} d\Omega} dm_{WW} d\Omega$$

$$\alpha_i \equiv r_i / \bar{\sigma}_{\text{SM}} \longrightarrow \text{correct for the normalization used in the exp. data}$$

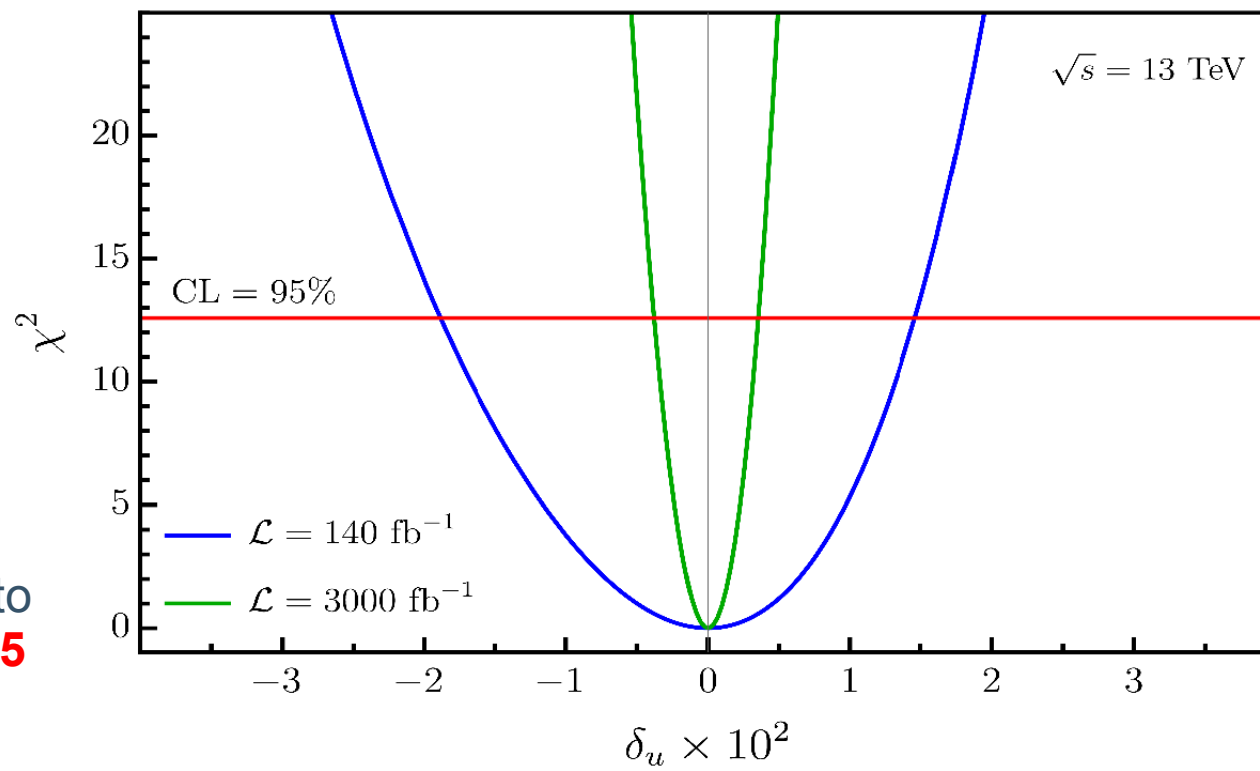
Δ_i	r_i	ϵ_i
$[2M_W/\text{GeV}, 200]$	1.026	0.013
$[200, 300]$	1.037	0.014
$[300, 450]$	1.015	0.013
$[450, 600]$	0.997	0.017
$[600, 1200]$	1.013	0.023
$[> 1200]$	0.994	0.120

→ extracted from the plot → not still available by ATLAS collaboration

- We assume the parameters δ_q are independent quantities and perform the χ^2 test by retaining only one non-vanishing contribution at a time.
- The projections for HL-LHC are obtained upon a rescaling of the exp. errors by

$$\epsilon_i \rightarrow \sqrt{\mathcal{L}_{\text{LHC}}/\mathcal{L}_{\text{HL}}} \epsilon_i$$

$$\begin{aligned}\mathcal{L}_{\text{LHC}} &= 140 \text{ fb}^{-1} \\ \mathcal{L}_{\text{HL}} &= 3000 \text{ fb}^{-1}\end{aligned}$$



Passing from LHC run2 to HL we expect a factor **4-5** improvement for **u,d,s** and **3-4** for **c,b** limits

95% CL

(run2) $\mathcal{L} = 140 \text{ fb}^{-1}$

(Hi-Lumi) $\mathcal{L} = 3000 \text{ fb}^{-1}$

u →	δ_u	$-1.9 \times 10^{-2} < \delta_u < 1.5 \times 10^{-2}$	$-3.8 \times 10^{-3} < \delta_u < 3.5 \times 10^{-3}$
d →	δ_d	$-3.1 \times 10^{-2} < \delta_d < 2.3 \times 10^{-2}$	$-6.4 \times 10^{-3} < \delta_d < 5.8 \times 10^{-3}$
s →	δ_s	$-1.2 \times 10^{-1} < \delta_s < 7.9 \times 10^{-2}$	$-2.5 \times 10^{-2} < \delta_s < 2.1 \times 10^{-2}$
c →	δ_c	$-2.0 \times 10^{-1} < \delta_c < 1.4 \times 10^{-1}$	$-5.5 \times 10^{-2} < \delta_c < 4.2 \times 10^{-2}$
b →	δ_b	$-3.5 \times 10^{-1} < \delta_b < 2.6 \times 10^{-1}$	$-1.4 \times 10^{-1} < \delta_b < 8.8 \times 10^{-2}$

Future circular collider (FCC-hh)

We consider 9 benchmark m_{WW} bins

$$\sqrt{S} = 100 \text{ TeV}$$

$$\Delta_i^{\text{FCC}} = \left\{ [2M_W/\text{GeV}, 500], [500, 1000], [1000, 1500], [1500, 2000], [2000, 3000], [3000, 4000], [4000, 5000], [5000, 6000], [> 6000] \right\},$$

PDF4LHC21 PDFs QCD NNLO included

$$\mathcal{L} = 30 \text{ ab}^{-1}$$

simplified analysis: assuming only statistical error that dominates

$$\chi^2(\delta_q) = \sum_{i=1}^9 \frac{\left(N_i(\delta_q) - N_i^{\text{SM}} \right)^2}{N_i^{\text{SM}}} \leq 16.919 \quad @ 95\% \text{ CL}$$

N_i = N. of events in the Δ_i^{FCC} bin, with $N_i^{\text{SM}} = N_i(0)$

no fiducial cross sections, no kinematic cuts...consider it as the best limits

95% CL

(FCC-hh) $\mathcal{L} = 30 \text{ ab}^{-1}$

$$\boxed{\delta_u}$$

$$-9.5 \times 10^{-5} < \delta_u < 9.2 \times 10^{-5}$$

$$\boxed{\delta_d}$$

$$-1.3 \times 10^{-4} < \delta_d < 1.3 \times 10^{-4}$$

$$\boxed{\delta_s}$$

$$-2.4 \times 10^{-4} < \delta_s < 2.4 \times 10^{-4}$$

$$\boxed{\delta_c}$$

$$-3.9 \times 10^{-4} < \delta_c < 3.9 \times 10^{-4}$$

$$\boxed{\delta_b}$$

$$-7.4 \times 10^{-4} < \delta_b < 7.3 \times 10^{-4}$$

- Backgrounds, detector efficiency effects are expected to weaken these bounds
- $\delta(u,d,c,s)$ can reach the level of 10^{-4} → competitive with Flavor physics
- No significant bounds for $\delta(b)$ are present from flavor physics
while $pp \rightarrow WW$ @ FCC-hh could reach sensitivity on $\delta(b)$ up to $10^{-3} - 10^{-4}$

Summary

- **WW production** @ LHC is known to be a sensitive process to NP contribution (trilinear WWZ, WW γ couplings, SMEFT operators, etc)

- We show that is is also quite sensitive to CKM violation parameters δ_q

- Using recent ATLAS analysis on WW production based on run2 data we get

$$|\delta_{u,d}| \lesssim \mathcal{O}(10^{-2}) \quad |\delta_{c,s}| \lesssim \mathcal{O}(10^{-1}) \quad @ 95\% \text{ CL}$$

- Limits on $\delta_{u,d,s}$ and $\delta_{c,b}$ expected to be improved by factors of order **4-5** and **3-4** at LHC-HL respectively

- These are new **complementary bounds** to the ones from Flavor physics

- **At future 100 TeV collider, bounds $\mathcal{O}(10^{-4})$ can be reached due to larger $m(WW)$**

- We recommend incorporating CKM violation tests in future analysis of WW production @LHC