OPPORTUNITIES FOR FLAVOUR PHYSICS @ HI-LUM/HI-ENERGY HADRON COLLIDERS

Luca Silvestrini
INFN, Rome

- Introduction
- First ideas on the impact of a flavour experiment with ab^{-1} @ a hadron collider
- Conclusions and Outlook

INTRODUCTION

- Most of the discoveries of the past 45 years anticipated by arguments or indirect evidence:
  - Ioffe&Shabalin, GIM: NP (charm) @ GeV
  - Unitarization of Fermi theory: NP at 10^2 GeV
  - KM: 3^{rd} generation
  - Flavour, EW fit: m_t~170 GeV
  - EW fit: m_H=100±30 GeV

INTRODUCTION II

- Now we are left with arguments only:
  - Hierarchy problem: NP close to EW scale
  - WIMP miracle: NP close to EW scale
  - gauge coupling unification: NP (SUSY) close to EW scale
- In parallel with increasing the energy probed by direct search, seek for indirect evidence!

WHY FLAVOUR?

- No tree-level flavour changing neutral currents in the SM
- GIM suppression of FCNC @ the loop level
- Tiny CP violation in K and D mesons due to small CKM angles
- Unobservable LFV & EDM's

⇒ Flavour & CP violation ideal places to get indirect evidence of NP

ROLE OF FLAVOUR

- In the framework of future experimental developments, Flavour physics should:
- Guarantee that the flavour structure of any directly discovered NP can be efficiently probed, and/or
- Push the NP scale that can be indirectly probed up by (at least) one order of magnitude (ε_K now at 5 10^5 TeV)

- A generic FCNC amplitude has the form

$$A_{SM}+A_{NP}=K_{SM}\frac{\alpha_W}{4\pi}\frac{F_{CKM}}{M_W^2}+K_{NP}L\frac{F_{NP}}{\Lambda^2}$$

where L is a possible loop factor, F_{NP} denotes the NP flavour coupling and $K_{NP} \geq K_{SM}$.

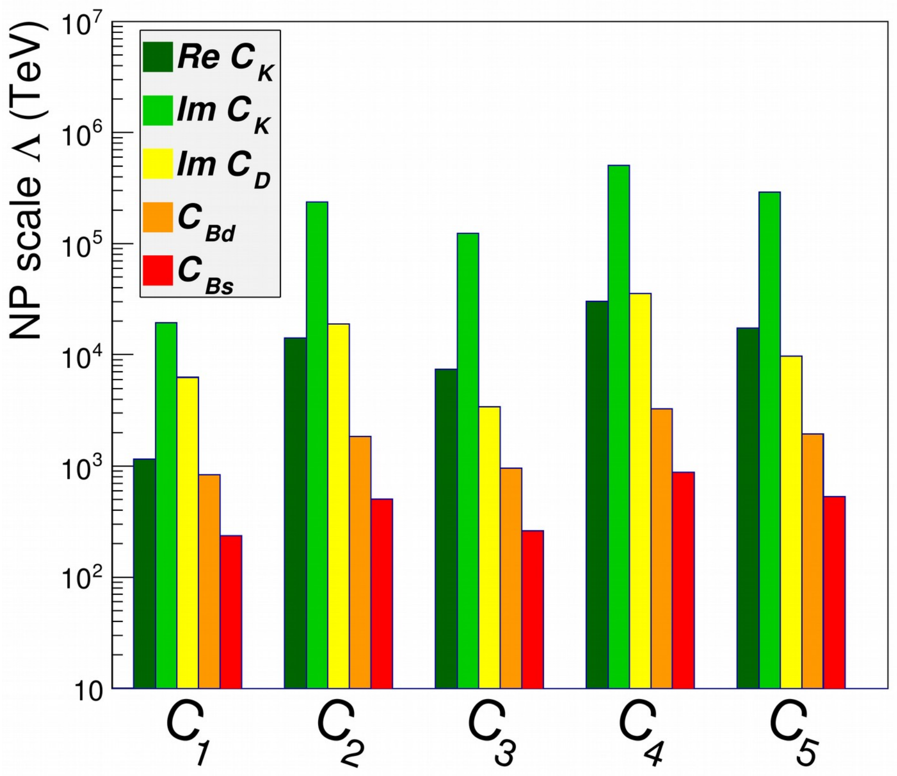
- For any directly observed NP, we know Λ and L and can extract F_{NP}

- Assuming a value for $L \geq \alpha_W/4\pi$ and $F_{NP} \geq F_{SM}$, we can extract the NP scale Λ

- Need to improve A_{exp} & A_{SM} (where present)

PRESENT BOUNDS ON NP

Bounds from $\Delta F=2$ processes



$\Delta F=2$ processes scale as $1/\Lambda^2$

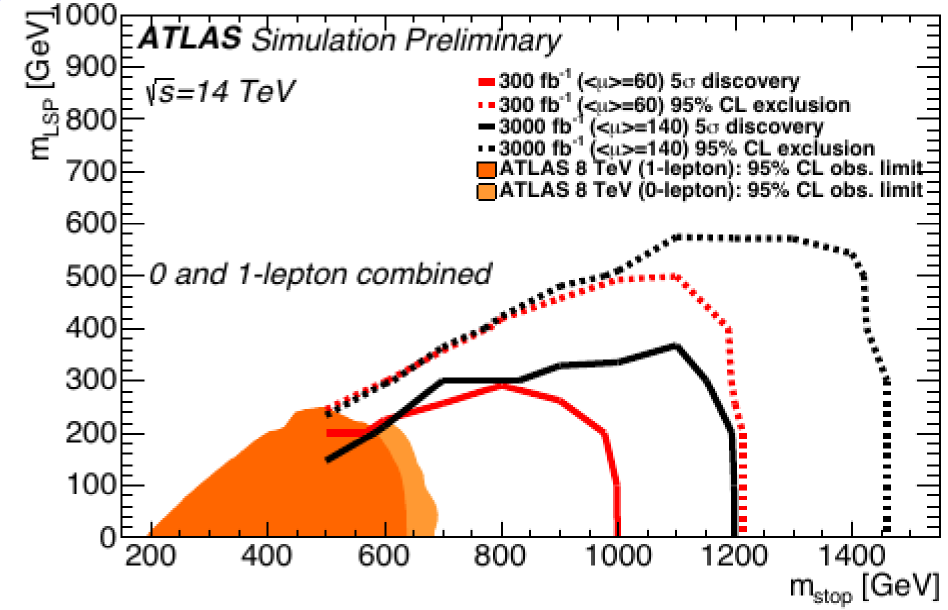
- Best bound from ε_K, dominated by CKM error
- CPV in charm mixing follows, exp error dominant
- Best CP conserving from Δm_K, dominated by long distance
- B_d and B_s behind, error from both CKM and B-params

INTERPRETING THE BOUNDS

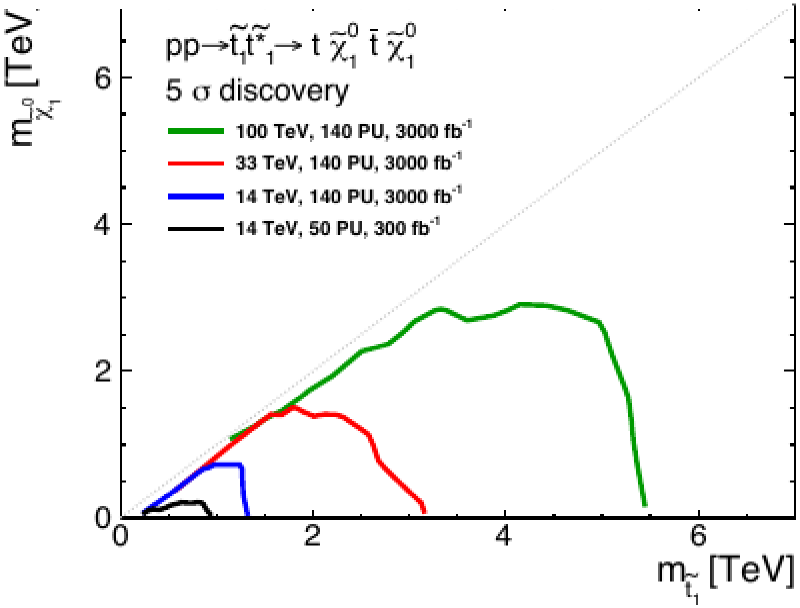
- generic case (no loop, no flavour suppression, all chiral structures): $\Lambda > 3\ 10^5$ TeV
- Extra-Dim case (no loop suppression, CKM suppression, all chiral structures): $\Lambda > 70$ TeV
- MFV case (no loop suppression, CKM suppression, only left-handed): $\Lambda > 7$ TeV
- weakly-interacting MFV case (EW loop & CKM suppression, left-handed): $\Lambda > 200$ GeV

COMPLEMENTARITY WITH DIRECT SEARCHES

- The weakly-interacting MFV case provides a lower bound on NP contribution to flavour observables (worst-case scenario)
- This often corresponds to worst-case scenarios for direct searches as well
- Keep the two reaches in sync so that we can see flavour effects of any directly visible NP



T. Lari
LTS1
Elba



NEAR FUTURE

- Belle II/SuperB scenario has been studied in detail, for example for the UT analysis in the NP scenario one has an order-of-magnitude improvement, leading to a factor of three in the NP scale ⇒ worst-case Λ>600 GeV

Parameter	New Physics fit today	New Physics fit at Super$B$
$\overline{\rho}$	0.187 ± 0.056	± 0.005
$\overline{\eta}$	0.370 ± 0.036	± 0.005
α $(^\circ)$	92 ± 9	± 0.85
β $(^\circ)$	24.4 ± 1.8	± 0.4
γ $(^\circ)$	63 ± 8	± 0.7

PROSPECTS FOR HI-LUM

- A very interesting possibility has been put forward: collect 100x the LHCb upgrade luminosity
- A detailed study of the impact of such possibility should be carried out to assess its full physics potential.
- I'll just briefly flash a few items to make you interested

ASSESSING THE IMPACT OF A HI-LUM FLAVOUR EXP

- Determine expected exp and th uncertainties on the widest spectrum of observables
- Extrapolate accuracy in CKM determination in the presence of NP
- Assess the NP reach in all sectors and various scenarios

I follow Vittorio Lubicz's Appendix in the SuperB CDR (2007 -> 2015)

(and Stephen Sharp's talk at *Lattice QCD: Present and Future* (Orsay, 2004))

Values of the simulation parameters (N_{conf}, a, m_l, L) to achieve a certain accuracy (1%, 0.5%, 0.1%)

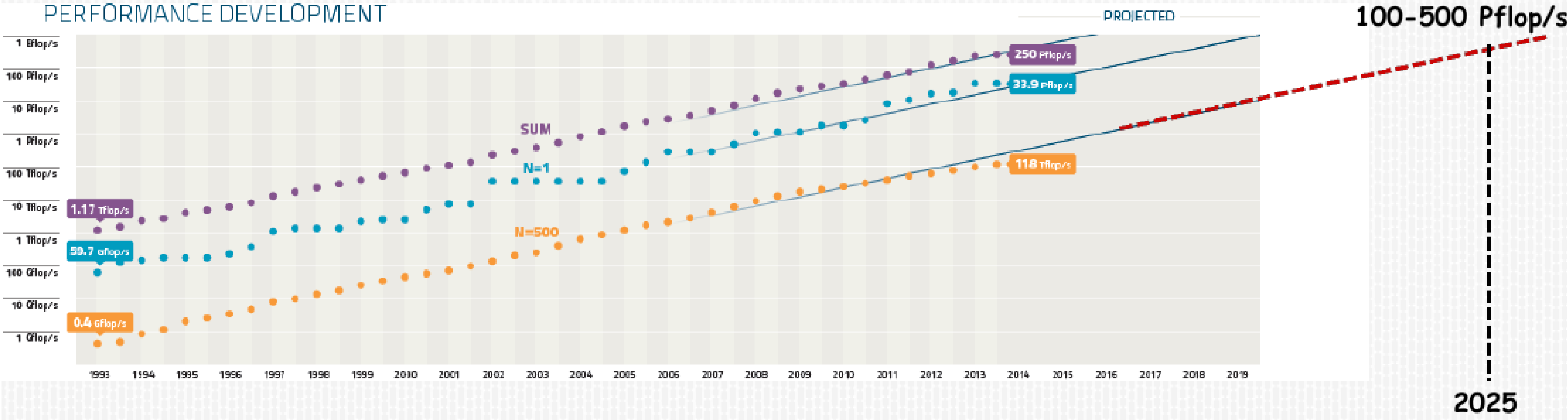
Computational cost of the corresponding simulation

Comparison to the expected future computational power

History (and prediction) of the computational power
from Moore's Law (1965):

The number of transistors on integrated circuits doubles approximately every two years
(thanks to miniaturization)

Performance improvement of $O(10^3)$ every 10 years



Lattice collaborations typically have at hand per year a computational power similar to the 500° most powerful computer (0.1-0.5 Pflops-years in 2014 → 100-500 Pflops-years in 2025)

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Computational cost of a Lattice Simulation as a function of the parameter values (e.g. Wilson-like fermions, $N_f=2$)

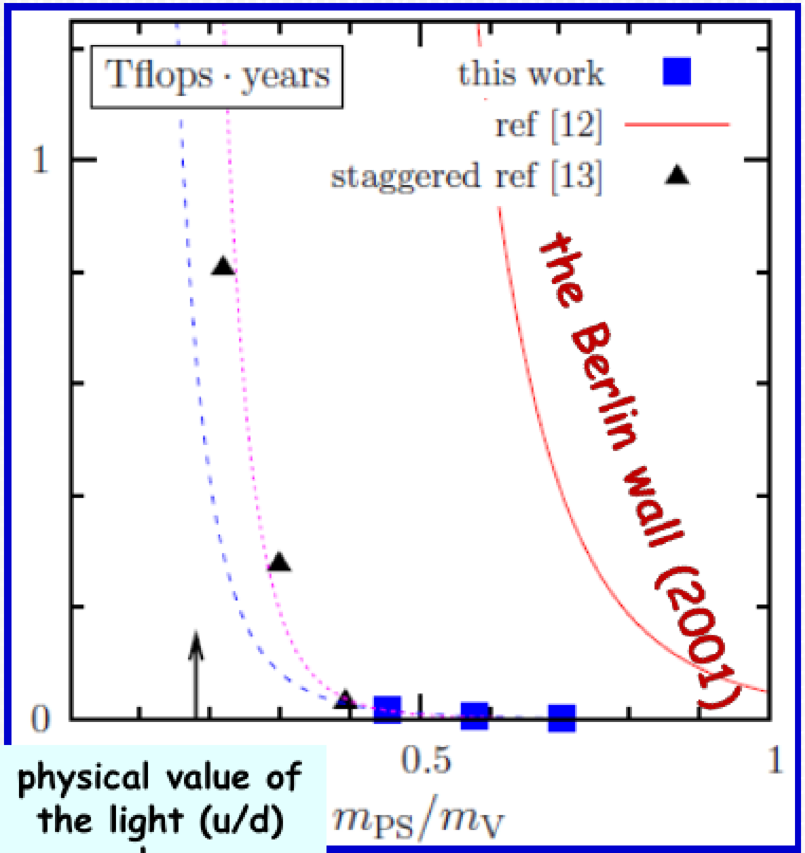
Del Debbio, Giusti, Luscher, Petronzio, Tantalo, hep-lat/0610059

$$\text{TFlops} - \text{years} \simeq 0.03 \left(\frac{N_{\rm conf}}{100}\right)\left(\frac{L_s}{3\ \text{fm}}\right)^5\left(\frac{L_t}{2L_s}\right)\left(\frac{0.2}{\hat{m}/m_s}\right)\left(\frac{0.1\ \text{fm}}{a}\right)^6$$

0.03 →0.1 [N_f=2+1]
→0.05 [O(a)-improved]
→0.3-1.0 [Ginsparg-Wilson]

x3 of overhead (less expensive simulations to perform continuum extrapolation…)

(We will see if a more detailed study of recent simulations provides a more optimistic estimate)



physical value of the light (u/d) quark mass

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The wall fall ($1/m_l^3 \to 1/m_l$) is an important example of how unpredictable (theoretical and algorithmic) developments can have a significant impact

Therefore, my tentative (INACCURATE!) estimates are:

Hadronic parameter	L.Lellouch ICHEP 2002 [hep-ph/0211359]	FLAG 2013 [1310.8555]	2025 [What Next]
$f_+^{K\pi}(0)$	- First Lattice result in 2004 [0.9%]	[0.4%]	[0.1%]
$\hat{B}_K$	[17%]	[1.3%]	[0.1-0.5%]
f_{Bs}	[13%]	[2%]	[0.5%]
f_{Bs}/f_B	[6%]	[1.8%]	[0.5%]
$\hat{B}_{Bs}$	[9%]	[5%]	[0.5-1%]
B_{Bs}/B_B	[3%]	[10%]	[0.5-1%]
$F_{D*}(1)$	[3%]	[1.8%]	[0.5%]
$B\to\pi$	[20%]	[10%]	$[\gtrsim 1\%]$

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More unpredictable but more surprising progresses can occur for the observables that today are very difficult (or infeasible): $K\to\pi\nu\bar{\nu}$, $K\to\pi l^+ l^-$, $K\to\pi\pi$, Δm_K

CHARM CPV EXTRAPOLATED

- SM contribution to ϕ_{M12} negligible, while one could envisage $\phi_{\Gamma12}$ O(1°) due to LD penguins
- Present fit:
  - ϕ_{M12} = [-4,12]° @ 95% prob., no reach on $\phi_{\Gamma12}$
  - $\Lambda > 3.5\ 10^4$ TeV
- LHCb upgrade / τ-c factory:
  - $\delta\phi_{M12} = \pm\ 1°$ and $\delta\phi_{\Gamma12} = \pm\ 2°$ @ 95% prob.
  - $\Lambda > 10^5$ TeV

CHARM CPV EXTRAPOLATED

- HI-LUM (very preliminary and very naïve: just scaled LHCb upgrade estimates for $K_S\pi\pi$ and y_{CP}, A_Γ):
  - $\delta\phi_{M12} = \pm\, 0.1°$ and $\delta\phi_{\Gamma 12} = \pm\, 0.2°$ @ 95% prob.
  - $\Lambda > 3\ 10^5$ TeV, close to the bound from ε_K

$B_{d,s} \to \mu^+\mu^-$

- One could reach an uncertainty on $\frac{BR(B_d \to \mu\mu)}{BR(B_s \to \mu\mu)}$ at the level of few percent, allowing for a very stringent test of NP and of its flavour structure, without hitting the th error wall
- A time-dependent analysis of the B_s channel also very interesting with very high accuracy
- Very clean probe of NP

CONCLUSIONS

- In a global strategy for NP searches, improving the accuracy on FCNC and CPV processes has a key role to ensure that:
  - we are able to determine the flavour structure of any NP directly seen, and hopefully understand its origin; roughly 3x in M_{NP} ⇔ 10x in exp & th ⇔ 100x in L
  - we increase the sensitivity of indirect searches (flavour has the lead in this field) and maybe detect an indirect NP signal

CONCLUSIONS II

- A global assessment of the physics potential of a very HI-LUM flavour experiment requires extensive studies, including, on the theory side:
    - extrapolation of lattice errors;
    - evaluation of uncertainties in the UTA;
    - projection of NP sensitivities in all sectors
- A very interesting and exciting perspective

BACKUP SLIDES

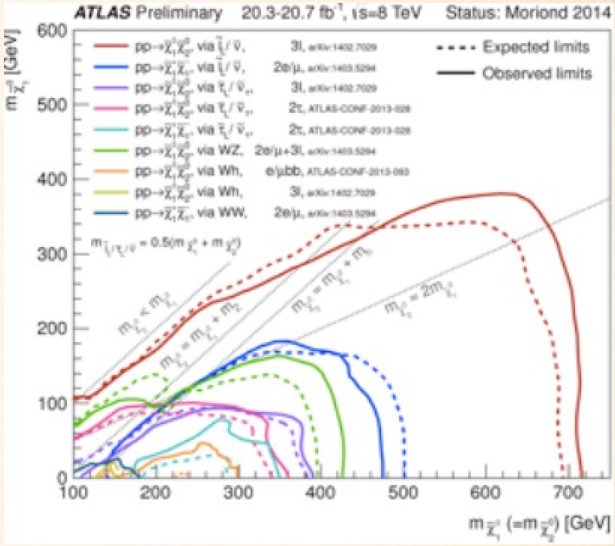
EXP INPUT FOR CHARM MIXING

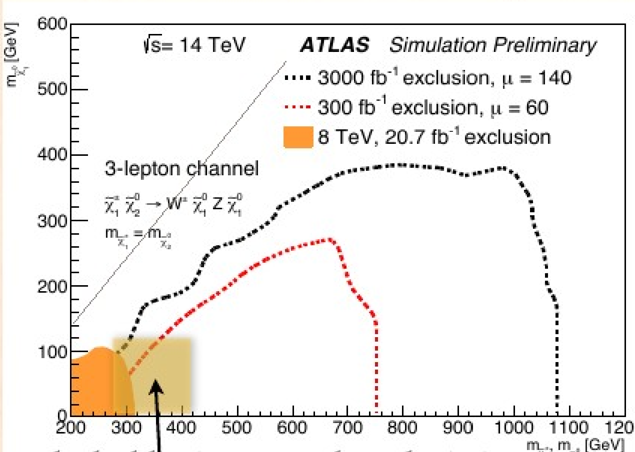
- LHCb upgrade:
  - $\delta x=1.5\ 10^{-4}$, $\delta y=10^{-4}$, $\delta|q/p|=10^{-2}$, $\delta\phi=3°$ (from $K_s\pi\pi$); $\delta y_{CP}=\delta A_\Gamma=4\ 10^{-5}$ (from K^+K^-)
- Cabibbo-Lab τ-c factory:
  - $\delta x=3\ 10^{-4}$, $\delta y=3\ 10^{-4}$, $\delta|q/p|=9\ 10^{-3}$, $\delta\phi=.8°$ (from $K_s\pi\pi$);
- HI-Lumi (LHCb upgrade lumi x 100):
  - $\delta x=1.5\ 10^{-5}$, $\delta y=10^{-5}$, $\delta|q/p|=10^{-3}$, $\delta\phi=.3°$ (from $K_s\pi\pi$); $\delta y_{CP}=\delta A_\Gamma=4\ 10^{-6}$ (from K^+K^-)

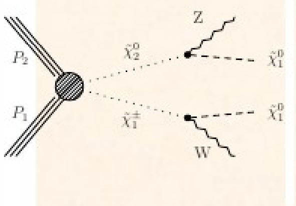
Parameter	95% allowed range (GeV^{-2})	Lower limit on Λ (TeV) for arbitrary NP	Lower limit on Λ (TeV) for NMFV
$\mathrm{Re}C_K^1$	$[-6.8, 7.5] \cdot 10^{-13}$	$1.2 \cdot 10^3$	0.4
$\mathrm{Re}C_K^2$	$[-5.0, 4.6] \cdot 10^{-15}$	$14.2 \cdot 10^3$	3.9
$\mathrm{Re}C_K^3$	$[-1.7, 1.8] \cdot 10^{-14}$	$7.4 \cdot 10^3$	2.0
$\mathrm{Re}C_K^4$	$[-1.0, 1.1] \cdot 10^{-15}$	$30.3 \cdot 10^3$	7.3
$\mathrm{Re}C_K^5$	$[-3.1, 3.3] \cdot 10^{-15}$	$17.4 \cdot 10^3$	4.1
$\mathrm{Im}C_K^1$	$[-1.9, 2.6] \cdot 10^{-15}$	$19.5 \cdot 10^3$	6.4
$\mathrm{Im}C_K^2$	$[-1.8, 1.3] \cdot 10^{-17}$	$237.0 \cdot 10^3$	60.5
$\mathrm{Im}C_K^3$	$[-4.8, 6.6] \cdot 10^{-17}$	$123.5 \cdot 10^3$	31.7
$\mathrm{Im}C_K^4$	$[-2.9, 3.9] \cdot 10^{-18}$	$506.1 \cdot 10^3$	113.2
$\mathrm{Im}C_K^5$	$[-8.8, 11.8] \cdot 10^{-18}$	$291.2 \cdot 10^3$	64.5
$\mathrm{Im}C_D^1$	$[-8.7, 25.2] \cdot 10^{-15}$	$6.3 \cdot 10^3$	2.0
$\mathrm{Im}C_D^2$	$[28.2, 9.7] \cdot 10^{-16}$	$18.8 \cdot 10^3$	4.6
$\mathrm{Im}C_D^3$	$[-3.0, 8.6] \cdot 10^{-14}$	$3.4 \cdot 10^3$	1.1
$\mathrm{Im}C_D^4$	$[-2.7, 8.0] \cdot 10^{-16}$	$35.4 \cdot 10^3$	8.5
$\mathrm{Im}C_D^5$	$[-3.6, 10.6] \cdot 10^{-15}$	$9.7 \cdot 10^3$	2.7
$\lvert C_{B_d}^1\rvert$	$< 1.4 \cdot 10^{-12}$	833.3	7.1
$\lvert C_{B_d}^2\rvert$	$< 2.9 \cdot 10^{-13}$	$1.8 \cdot 10^3$	13.0
$\lvert C_{B_d}^3\rvert$	$< 1.1 \cdot 10^{-12}$	954.8	6.7
$\lvert C_{B_d}^4\rvert$	$< 9.3 \cdot 10^{-14}$	$3.3 \cdot 10^3$	20.9
$\lvert C_{B_d}^5\rvert$	$< 2.6 \cdot 10^{-13}$	$2.0 \cdot 10^3$	12.8
$\lvert C_{B_s}^1\rvert$	$< 1.8 \cdot 10^{-11}$	235.8	9.5
$\lvert C_{B_s}^2\rvert$	$< 3.9 \cdot 10^{-12}$	506.4	17.1
$\lvert C_{B_s}^3\rvert$	$< 1.4 \cdot 10^{-11}$	262.6	8.9
$\lvert C_{B_s}^4\rvert$	$< 1.3 \cdot 10^{-12}$	877.1	27.0
$\lvert C_{B_s}^5\rvert$	$< 3.6 \cdot 10^{-12}$	529.3	16.8

DIRECT EWKINO SEARCHES

- Dark Matter requires a weakly interacting **lightest** supersymmetric particle. Natural models have light higgsinos (related to Higgs mass at tree level).
- Hadron collider can look for neutralino to gravitino + X, with X=Z, h, or γ. If neutralino LSP, they can see heavier ewkinos decay, like N2C1 to WZN1N1 or hZN1N1. Luminosity significantly extends the reach
- For the natural spectrum with light Higgsinos (nearly degenerate N1,N2,C1) and out-of-reach heavier winos/zinos lepton colliders would be best. With high luminosity, theory papers suggest LHC should have sensitivity to higgsino production with ISR monojet or with VBF production for 100-200 GeV







excluded by improved analysis in paper w.r.t. the preliminary results