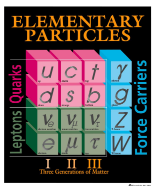
What makes things so hard?

KAST
Minho Son

BSM

SM



+

Quantum gravity

Inflation

Dark Matter

particle-anti-particle asymmetry

Solution on hierarchy problem
(is it really problem ?)

...

Shit!, no unique guiding principle
Nightmare!!

Need more input from data
measure
measure
measure

Flavor-precision at high-E hadron colliders

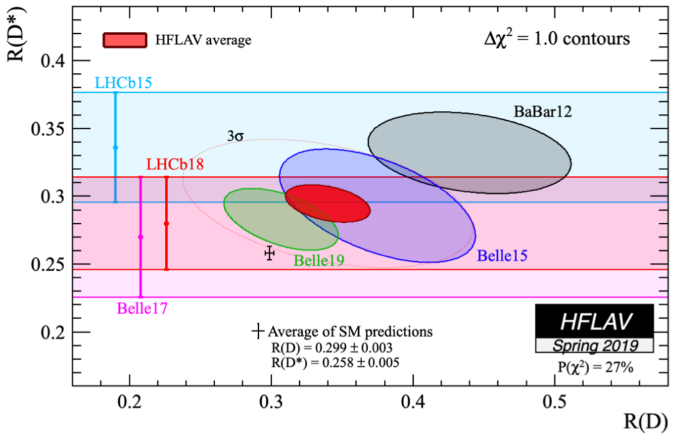


Illustration using B-anomaly example

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}l\nu_l)}$$

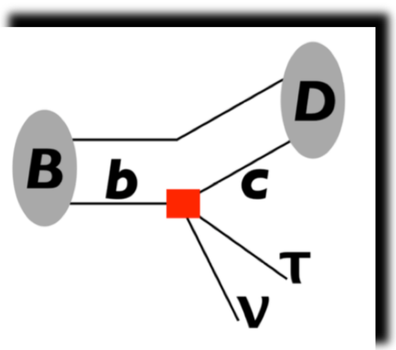
Bottom-flavored Mono-Tau Tails at the LHC

Marzocca, Ui, **SON** JHEP 2020

Low-E experiment

: probe through semileptonic decay

✓ accessible to only one op



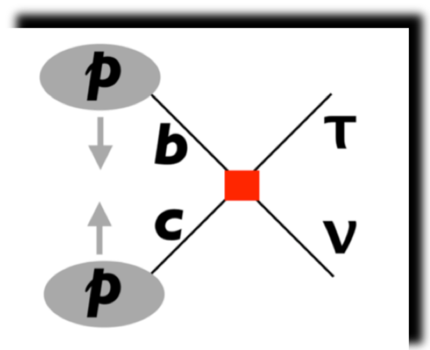
$$\bar{c}_i \frac{\mathcal{O}_i^{(d=6)}}{v^2}$$

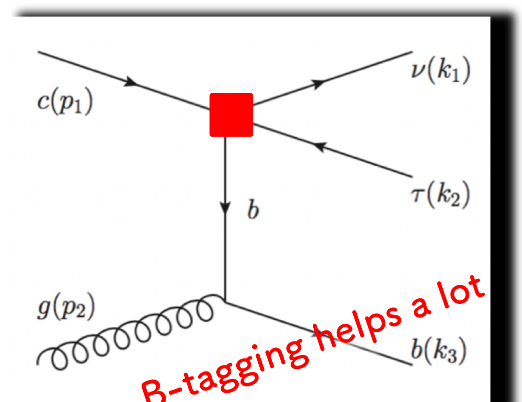
$$\bar{c}_i \frac{E^2}{v^2} \leq \Delta_{exp} \quad \to \quad \bar{c}_i \leq \Delta_{exp} \frac{v^2}{E^2}$$

High-E experiment

: through collision of quarks from PDF

✓ accessible to only linear comb of ops





$$\Delta_{exp} \quad \times \quad \frac{v^2}{E^2}$$

: poor at the LHC : suppression at high–E tail

$$q_i \to \left(\left(V^{+}u\right)_i, d_i\right)^T = \left(V^*_{ji}u_j, d_i\right)^T$$

: from UV origin   : PMNS matrix   : from CKM matrix

v

$$\Delta\mathcal{L}(\Lambda) = -\frac{1}{v^2}\left[C^{(3)}_{lq}\right]_{ijkl}\left(\bar{l}_i\gamma_\mu\sigma^I l_j\right)\left(\bar{q}_k\gamma^\mu\sigma^I q_l\right) + \cdots$$

Match to SU(2)xU(1) invariant operators above EW scale

SU(2)xU(1) symmetry spits out more operators in the low energy

m_b

$$\mathcal{O}_{VL} = [\bar{c}\gamma^\mu b][\bar{l}\gamma_\mu P_L \nu]$$

$$\mathcal{O}_{AL} = [\bar{c}\gamma^\mu\gamma_5 b][\bar{l}\gamma_\mu P_L \nu]$$

… … . .

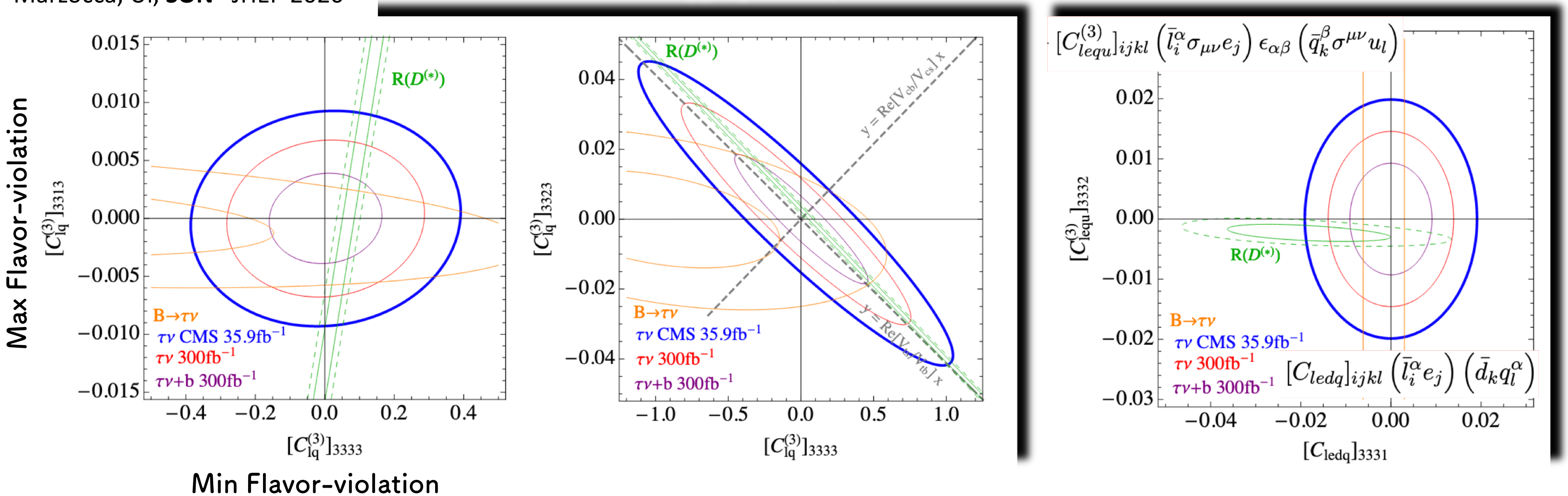
Rich phenomenology

$$-\sum_{f=u,c,t}\left[\frac{2\mathcal{C}_{fb}}{v^2}(\bar{\tau}\gamma_\mu\nu_\tau)(\bar{f}\gamma^\mu b) + \cdots\right]$$

$$\mathcal{C}_{fb} = \left[C^{(3)}_{lq}\right]_{3313}V_{fd} + \left[C^{(3)}_{lq}\right]_{3323}V_{fs} + \left[C^{(3)}_{lq}\right]_{3333}V_{fb}$$

✓ B-tagging has equivalent benefit as increasing luminosity by 10x

Marzocca, Ui, **SON** JHEP 2020

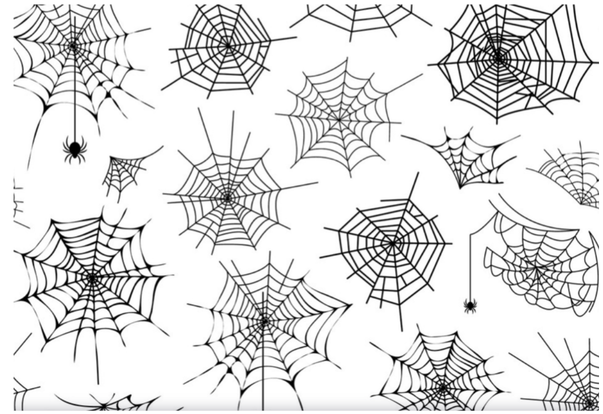


With more data at HL-LHC, FCC-hh

Extension to 2-to-3

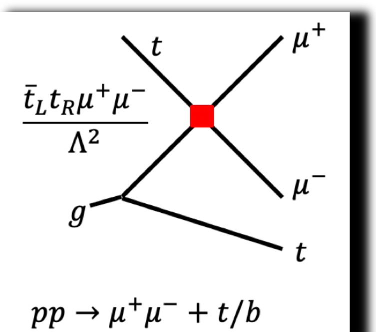
- ✓ More differential distributions
- ✓ Fully covering independent test of EFT/leptoquark approach for B-anomaly and muon g-2

2-to-3 processes are unique opportunity in constructing complete Flavor-Precision-Net for NP

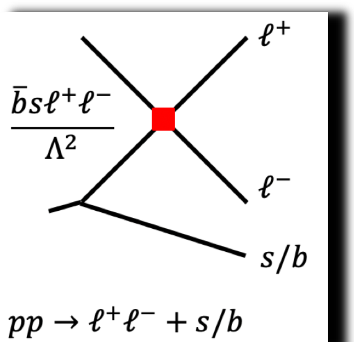


Let me use anomalies to illustrate the strategy.

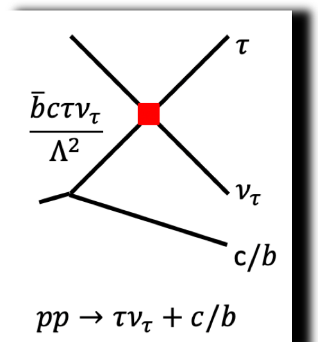
$(g-2)_\mu: \ \frac{a_\mu}{m_\mu} \sim \frac{1}{16\pi^2}\frac{m_\mu}{\Lambda^2} \times \frac{m_t}{m_\mu}$



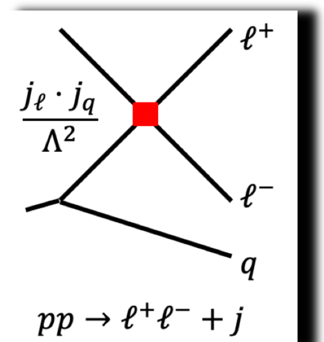
$R_{K^{(*)}}$



$R_{D^{(*)}}$

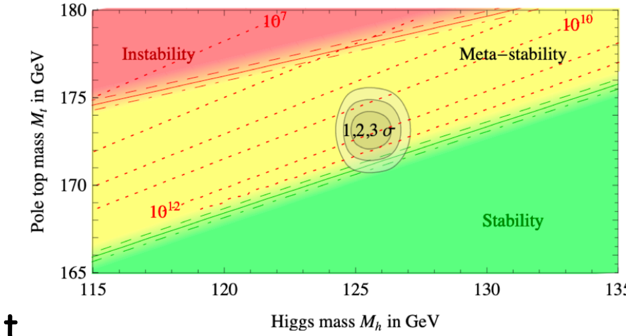


W, Y-precision



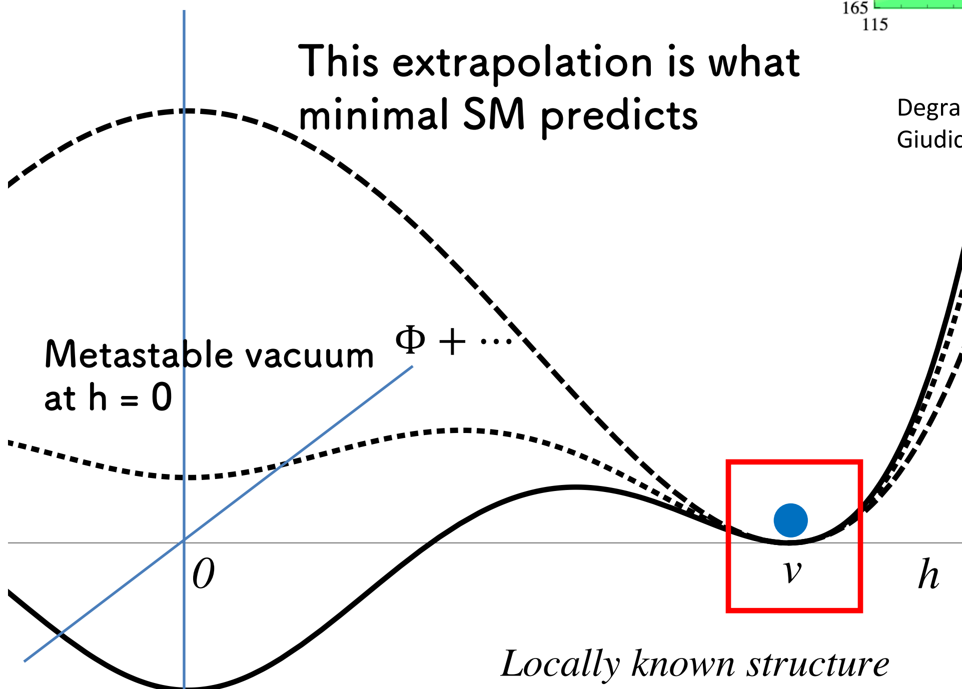
+ s-channel (not same as ISR-jet tagging!)

Global structure of Higgs potential I



Degrassi, Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia, 13'

This extrapolation is what minimal SM predicts



Instability at a large Higgs field might imply a new global vacuum

$$V_{\rm eff}(h) \sim \frac{\lambda_{\rm eff}(h)}{4} h^4$$

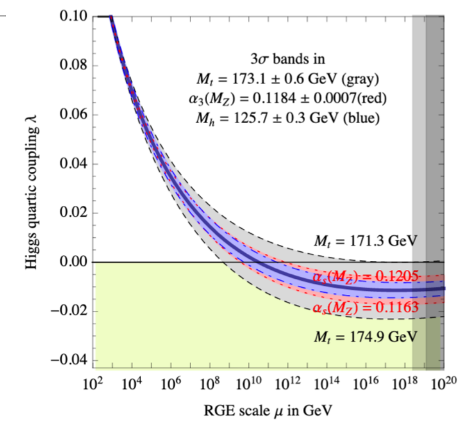
Less explored,
Not ruled out yet

Global vacuum
at h = 0

Locally known structure

v=246 GeV, m_h^2=(125 GeV)^2

Typically taken as global vacuum

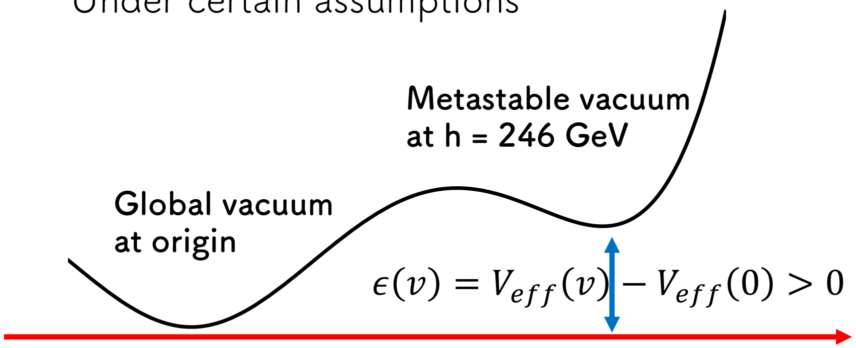


Bai, Lee, SON, Ye JHEP 2021

From the viewpoint of Landscape of many vacua, e.g. in string theory, it might be more natural if our current Universe turns out to be sitting at a metastable vacuum

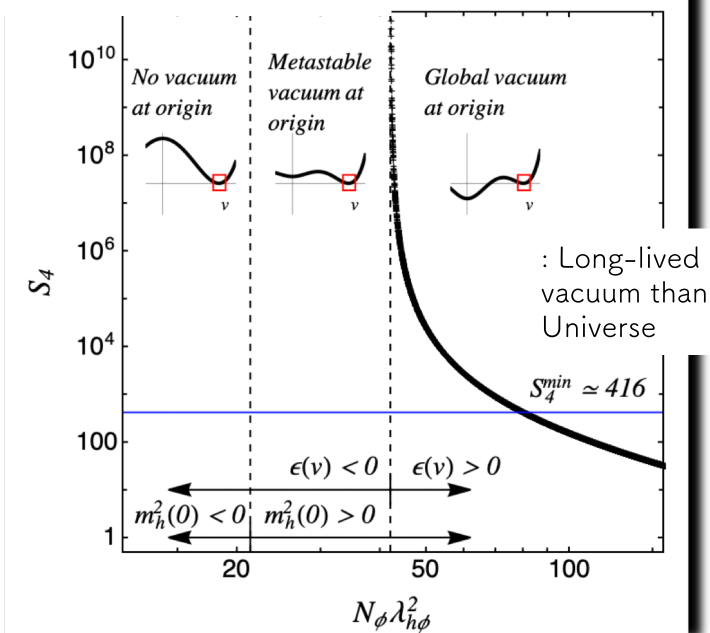
Global EWS vacuum at h = 0 in Higgs portal with ϕ via $\lambda_{h\phi}$

Under certain assumptions



$$m_h^2(0) = \left.\frac{d^2V_{eff}}{dh^2}\right|_{h=0} > 0$$

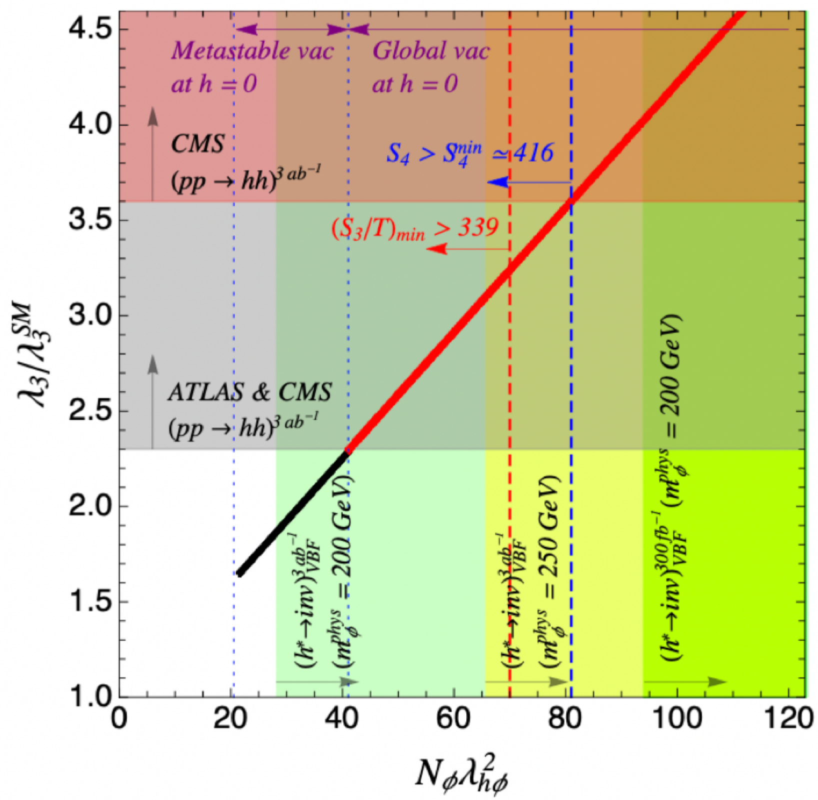
Classification at T ~ 0



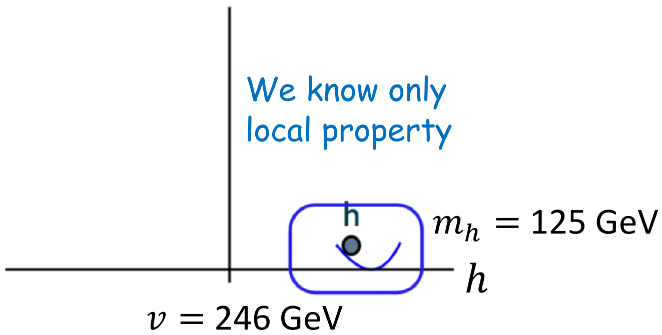
: Long-lived enough vacuum than age of Universe

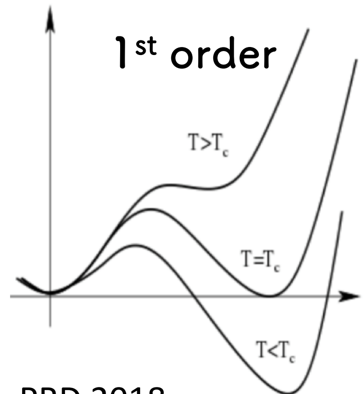
How to test at the LHC ?

Higgs cubic self-coupling
Missing Et + jets



Global structure of Higgs potential II



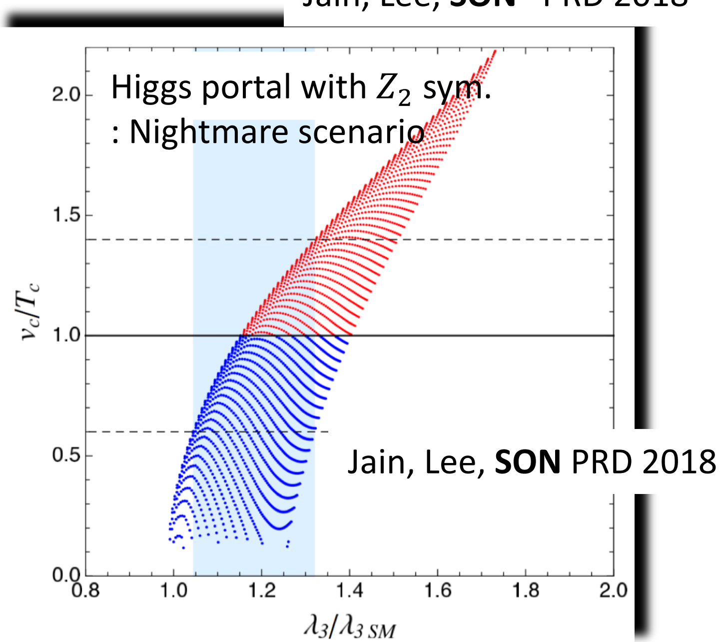


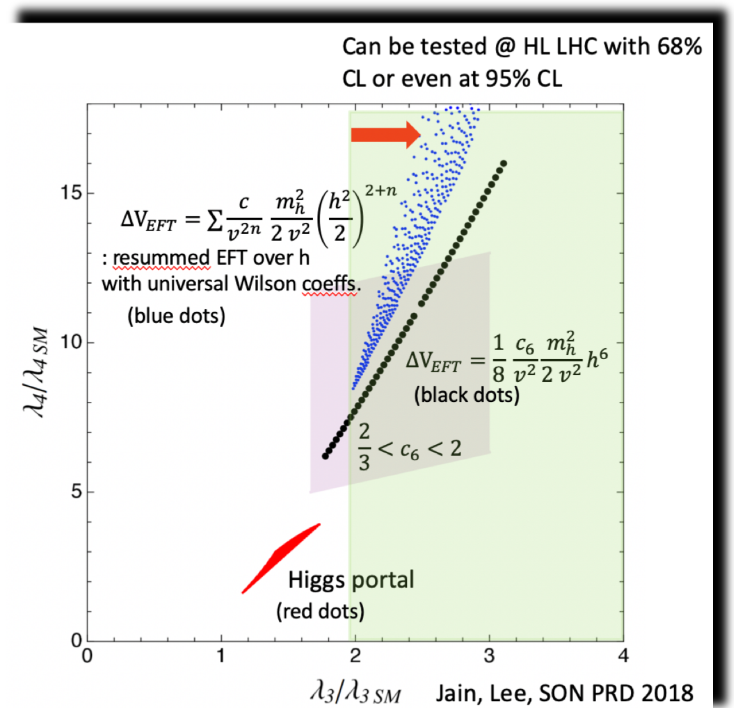
Baryogenesis based on strong 1st order EWPT

Simple criteria on how strong :

$$\frac{v_c}{T_c} \gtrsim 0.6 - 1.4$$

Jain, Lee, **SON** PRD 2018





$$\delta\left({}^{\lambda_3}/_{\lambda_3^{SM}}\right) \sim [5, 32]\% \text{ for } {}^{v_c}/_{T_c} \geq [0.6, 1.4]$$

Only 100 TeV FCC-hh vs other option ? to rule out this possibility

Light particle frontier

Provided by Seung J. Lee

Generic prediction in Axiverse, Photiverse etc

Is it meta-science or something real? Remains to be clarified, but ideas are being developed

New Particle	Comes from	Couples to
Axion and Axion Like Particles	Topology of Extra Dimensions	Spin and Mass density, Light in a background field
Dilatons, Moduli, radion	Geometry of Extra Dimensions	Mass density, Fundamental constants
Dark Photons	Topology of Extra Dimensions	Mixes with the photon
Higher Dimensional Graviton	Extra Dimensions	Just like the graviton

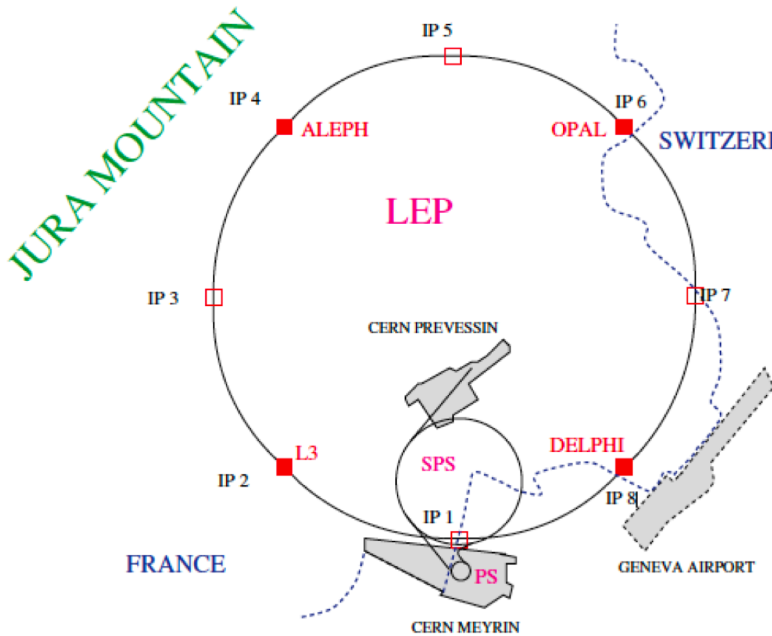
Extra slides for discussion

Legacy of Effective Field Theory approach

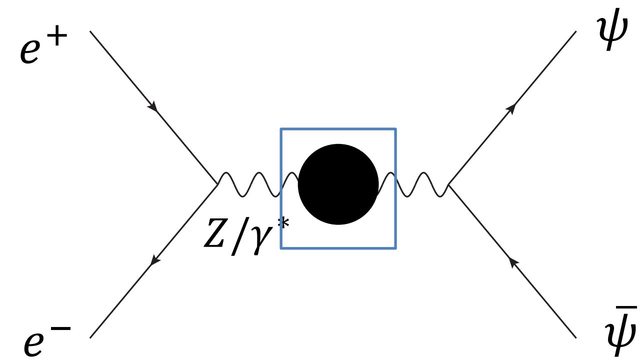
Related topic to Jae-sik Lee

LEP (Large Electron Positron)

1989-2000

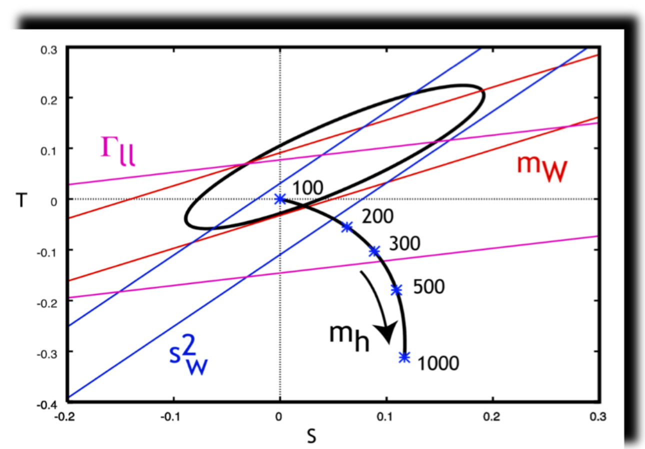


EWPT at LEP



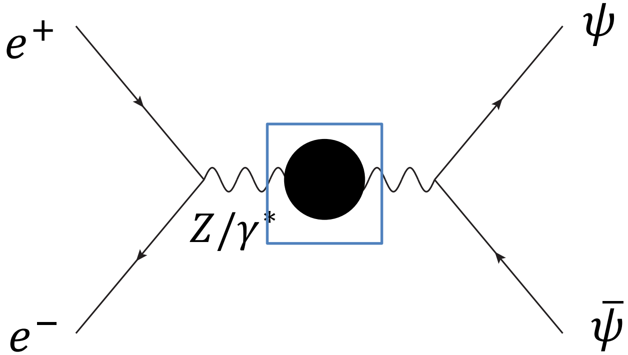
$$\Pi_{VV}(q^2) = \Pi_{VV}^{(0)}(m_Z^2) + \frac{q^2}{\Lambda_{\text{new}}^2}\Pi_{VV}^{(1)}(m_Z^2) + \cdots$$

$\rightarrow$ **S, T, U, ⋯**



We knew Higgs has to be light! before the Higgs discovery

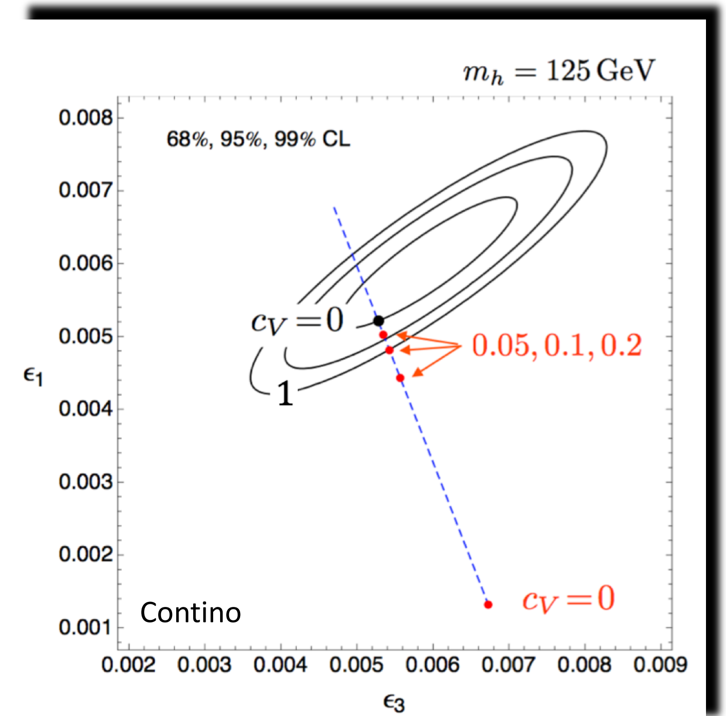
EWPT at LEP



$$\Pi_{VV}(q^2) = \Pi_{VV}^{(0)}(m_Z^2) + \frac{q^2}{\Lambda_{\rm new}^2}\Pi_{VV}^{(1)}(m_Z^2) + \cdots$$

→ S, T, U, ⋯

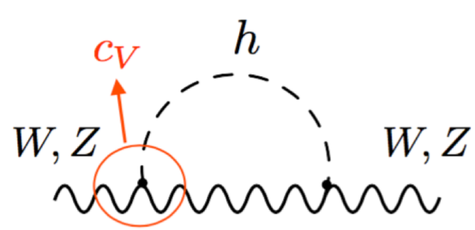
$$\epsilon_1 = \epsilon_1^{SM} + \alpha\, T$$

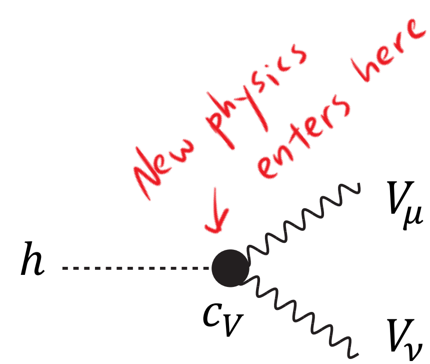


$$\epsilon_3 = \epsilon_3^{SM} + \frac{\alpha}{4\sin^2\theta_W} S$$

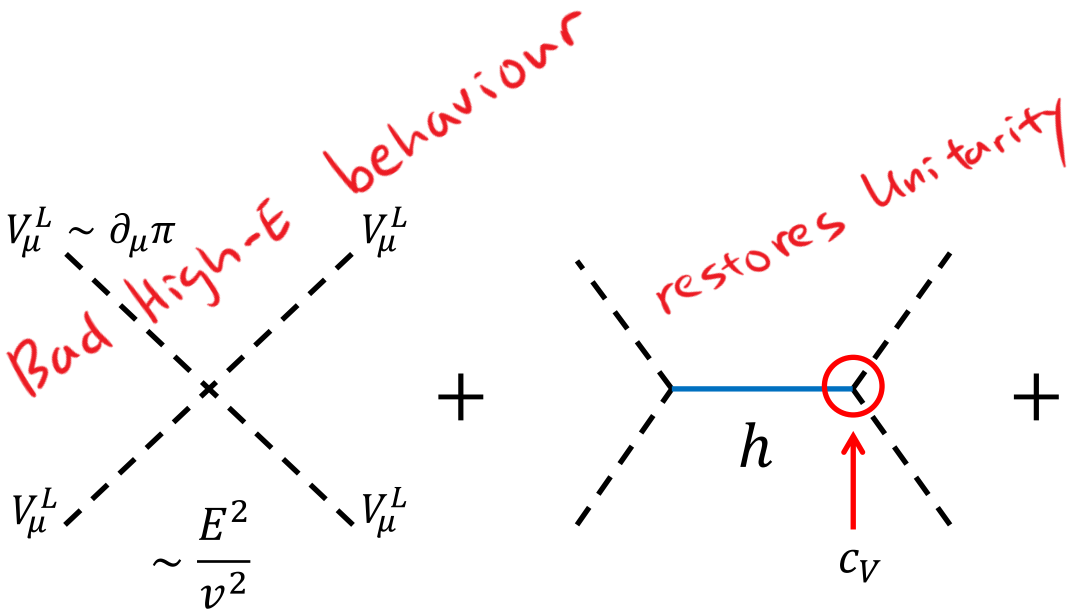
Since Higgs discovery

"**Varying Higgs mass**" to "**varying Higgs coupling**"

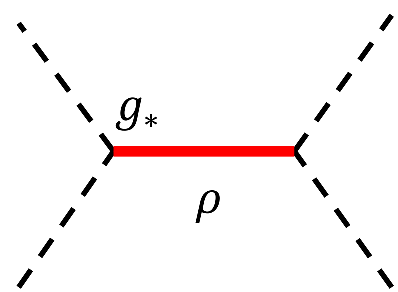




VV-VV scattering



NP needs to kick in at $E \sim \frac{v}{\sqrt{\delta}}$ to save us again



$$A(s) = \frac{s}{v^2}(1 - c_V^2) - c_V^2 \frac{m_h^2}{v^2} \frac{s}{s - m_h^2 + i\,\Gamma\, m_h}$$

$s \sim E^2$

In SM limit ($c_V = 1$) $\longrightarrow \sim \frac{m_h^2}{v^2}$

E-growing parts are perfectly canceled and saturated at weak coupling!

In BSM case ($1 - c_V^2 = \delta$) $\longrightarrow \sim \frac{m_h^2}{v^2} + \boxed{\frac{E^2}{v^2}\delta} + \Delta(BSM)$

See Jae-sik Lee for precision at FCC-ee

Strong Magnets at FCC-hh

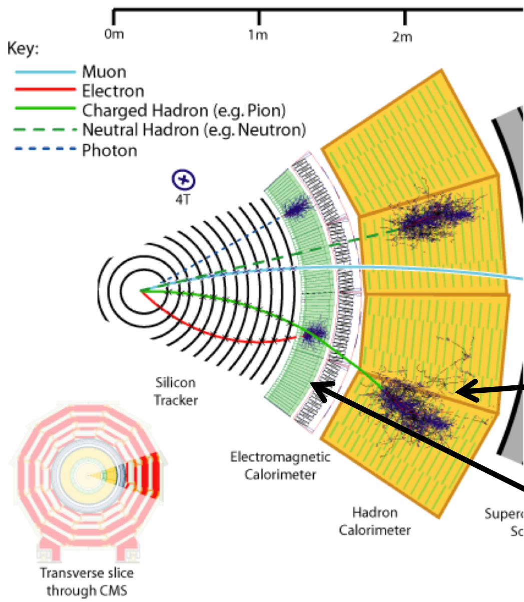
✓ Beneficial to high-p_T physics. It hurts low-p_T physics

	CMS: 4T, 1.5m	FCC: 6T, 6m
$p_{T\,crit} = 0.15\times\left(\frac{\mathrm{B}}{\mathrm{T}}\right)\times\left(\frac{\mathrm{r}_{cal}}{m}\right)$	~ 0.9 GeV	~ 5.4 GeV

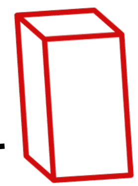
- This implies that $O(100\ \mathrm{GeV})$ process such as Higgs physics becomes low-p_T physics at 100 TeV!

  E.g. $H \rightarrow b\bar{b}$ with low p_T will be significantly under-reconstructed due to lost tracks (We need to make sure that we are capable of restoring the lost tracks back to our jets via track reconstruction, e.g. particle-flow)

Detector at 14 TeV: instrumental challenge

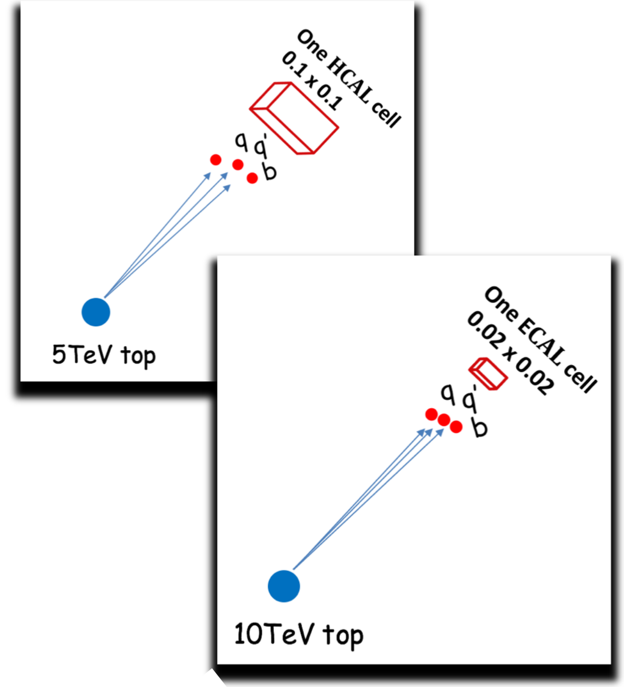


Detector granularity becomes a biggest problem at some point



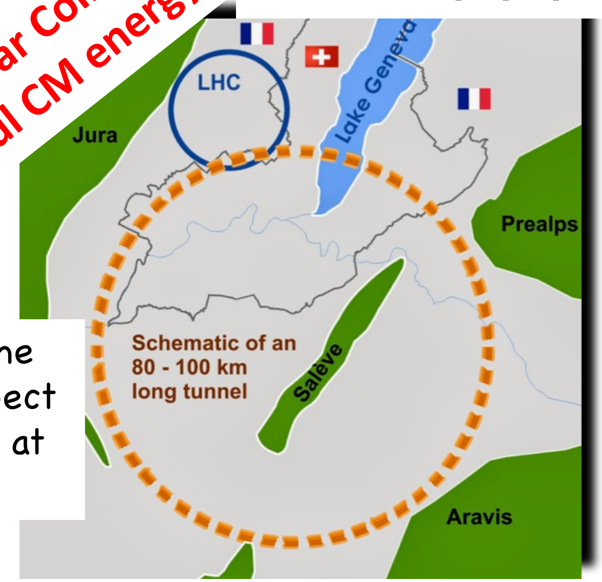
One HCAL cell
0.1 x 0.1

One ECAL cell
0.02 x 0.02



Future Circular Collider
7x powerful CM energy

100 TeV 가속기



3 TeV top at the LHC would expect 20 TeVish tops at 100 TeV

Other than Higgs discovery at the LHC, We haven't answered for any big questions

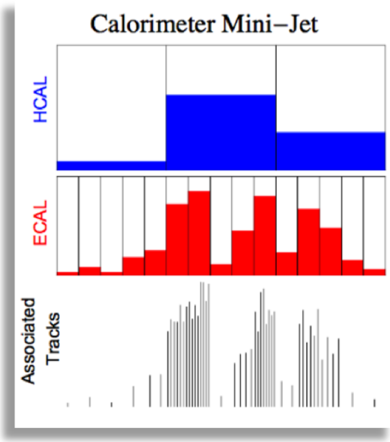
If we build up 100 TeV collider,
can detector catch up with it ?

Combining information is not unique

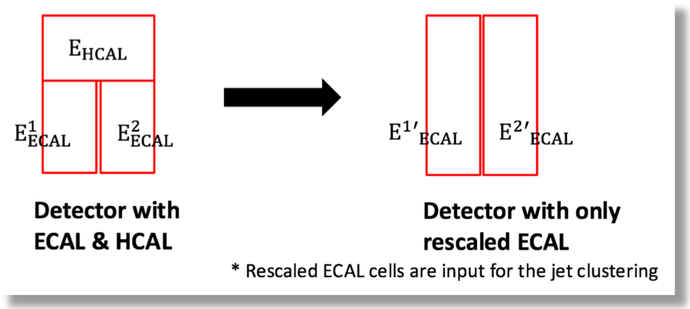
❑ EM-flow

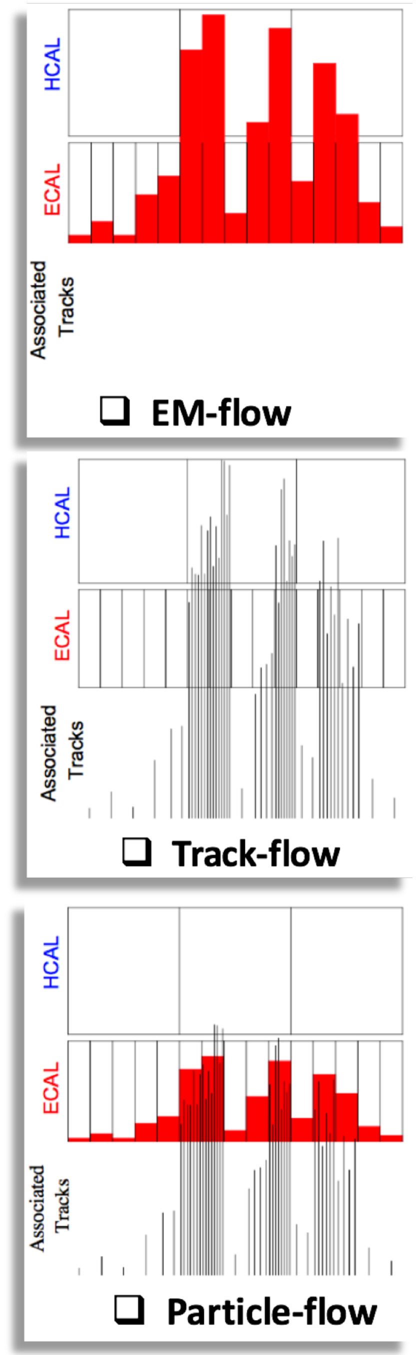
Katz, SON, Spethmann, Tweedie 2011, 2012

Pseudo-CMS type Event



Rescale ECAL cells by $\frac{E_{ECAL}+E_{HCAL}}{E_{ECAL}}$





❑ Track-flow

Similarly rescale tracks by $\frac{E_{ECAL}+E_{HCAL}}{E_{tracks}}$

Schatzel, Spannowsky 2014
Larkoski, Maltoni, Selvaggi 2015

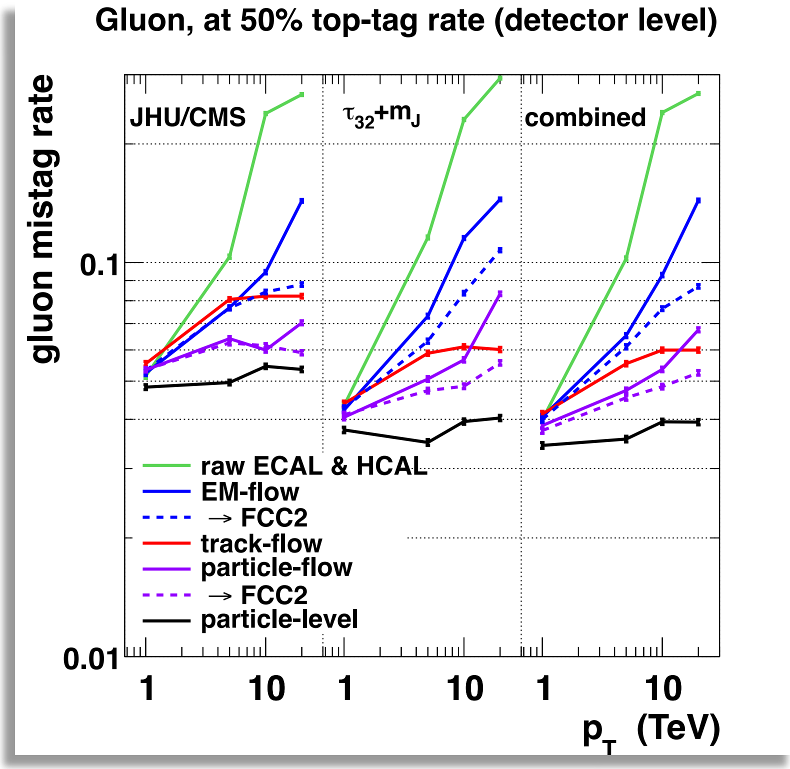
❑ Particle-flow

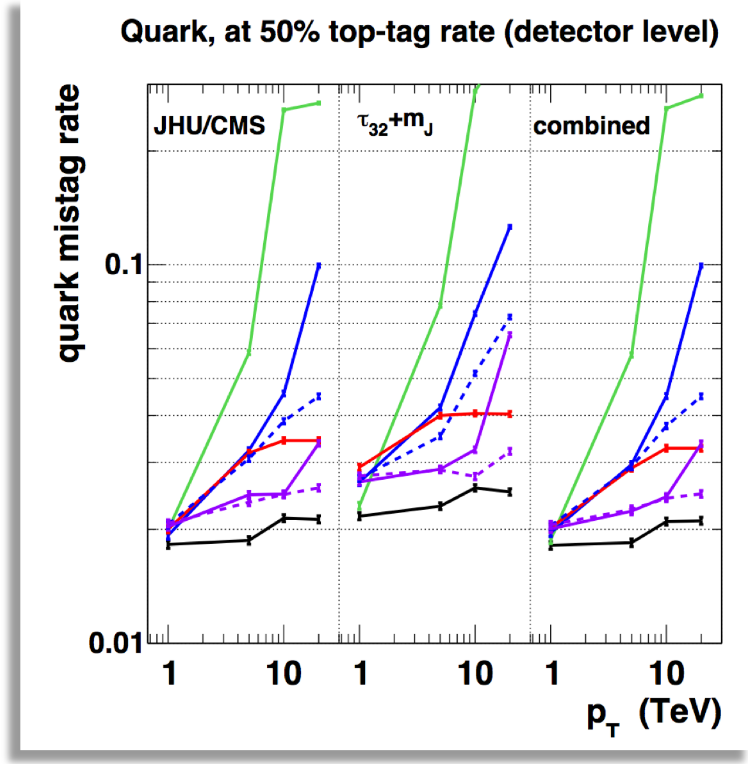
Rescale tracks by $\frac{E_{HCAL}}{E_{tracks}}$ and leave E_{ECAL} as-is

- PERFECT tracking efficiency is assumed. Reality is worse than this perfect case compared to CMS-type ECAL, HCAL

FCC1 : ECAL 2x, HCAL 2x (default)

FCC2 : ECAL 4x, HCAL 2x





Naïve exp when doing nothing

Improvement using our idea

- ✓ EM-flow looks very promising.
- ✓ It can solely cover up to 20TeV tops assuming FCC2 configuration (ECAL 4x, HCAL 2x)