Does it rock?

Time-dependent Measurement of $B_s > \phi(KK)\mu\mu$ Decay at FCC-ee

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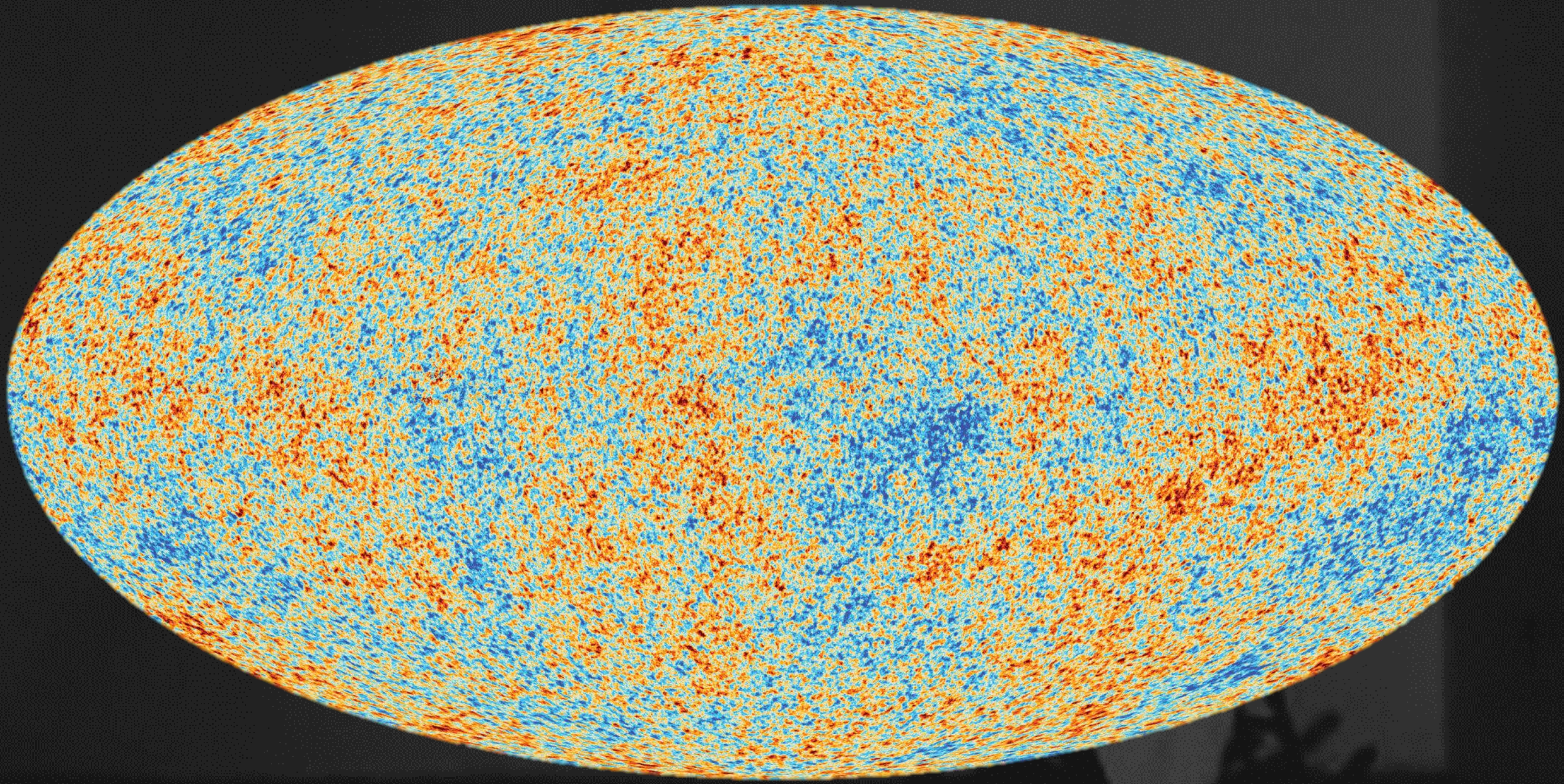
WARNING

This presentation contains preliminary results.
Do NOT take it super seriously,
some numerical values may be updated in later stage.


Once upon a time..........

Once upon a time. . . . .



Once upon a time. . . . .

Cosmological measurement shows: $(n_{baryon}-n_{anti\text{-}baryon})/n_{photon} \sim 10^{-9}$

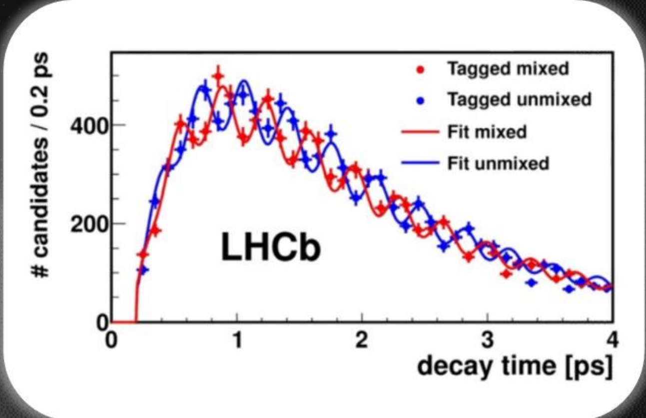
[Matter >> Anti-matter]

Sakharov Condition (within Baryogenesis):

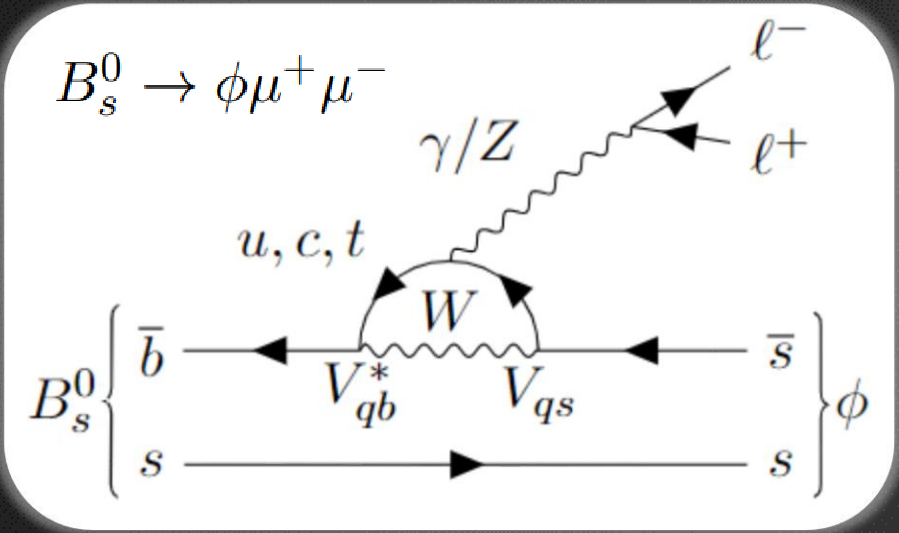
- Baryon number violation
- Interactions out of thermal equilibrium
- <u>C, CP violation</u>

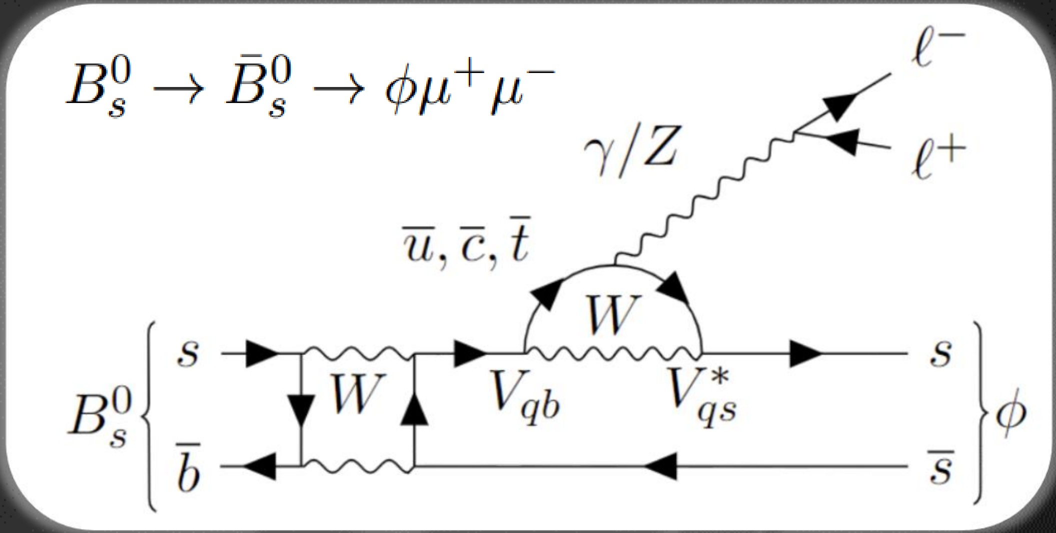
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

We have CPV in SM!
But not enough
[Mostly CPV in non-leptonic decay]



We look at. . . . . (CPV from NP?)





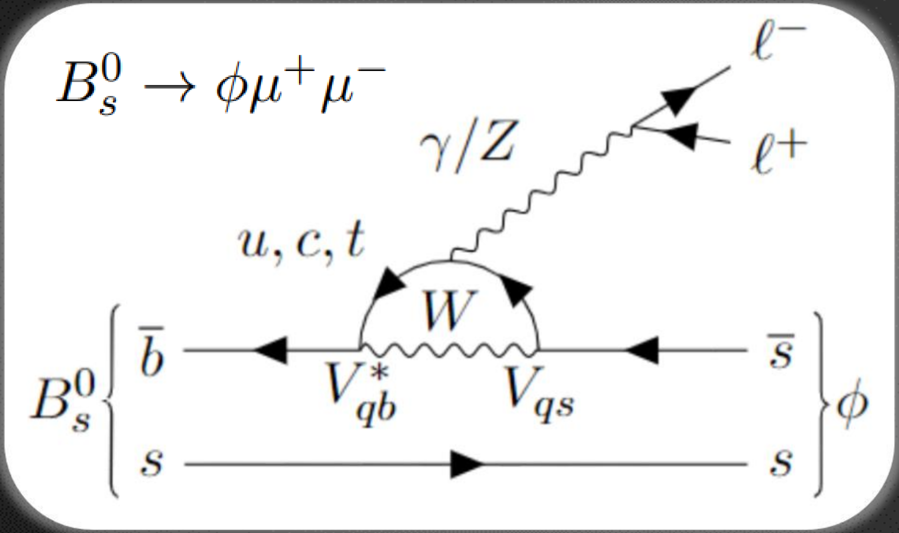
Just an example, there are more diagrams

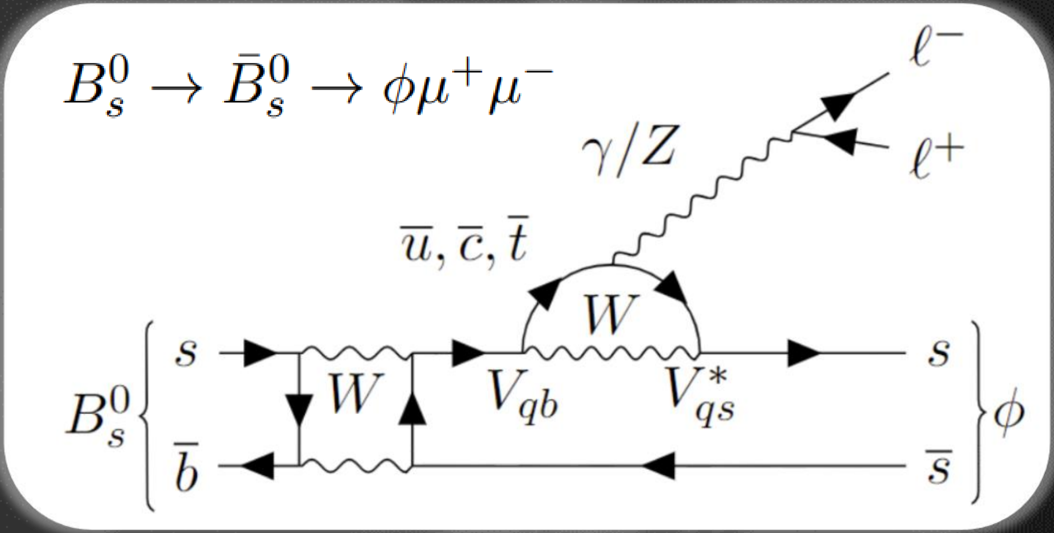
We look at. . . . . (CPV from NP?)

It is FCNC!!! Loop suppressed: BR~8x10^{-7}

(BR measurement done by LHCb in 2021 [arXiv:2105.14007])

[Leptonic CPV is not yet fully explored]

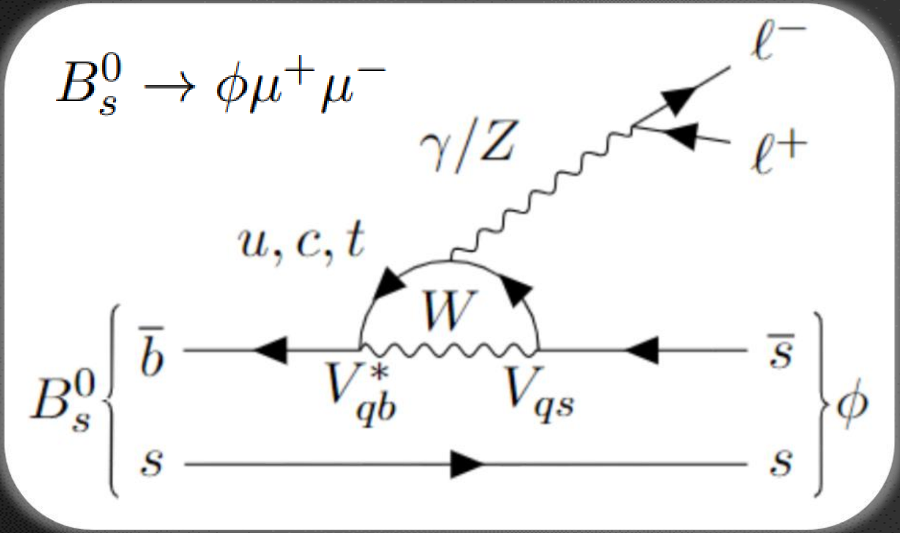


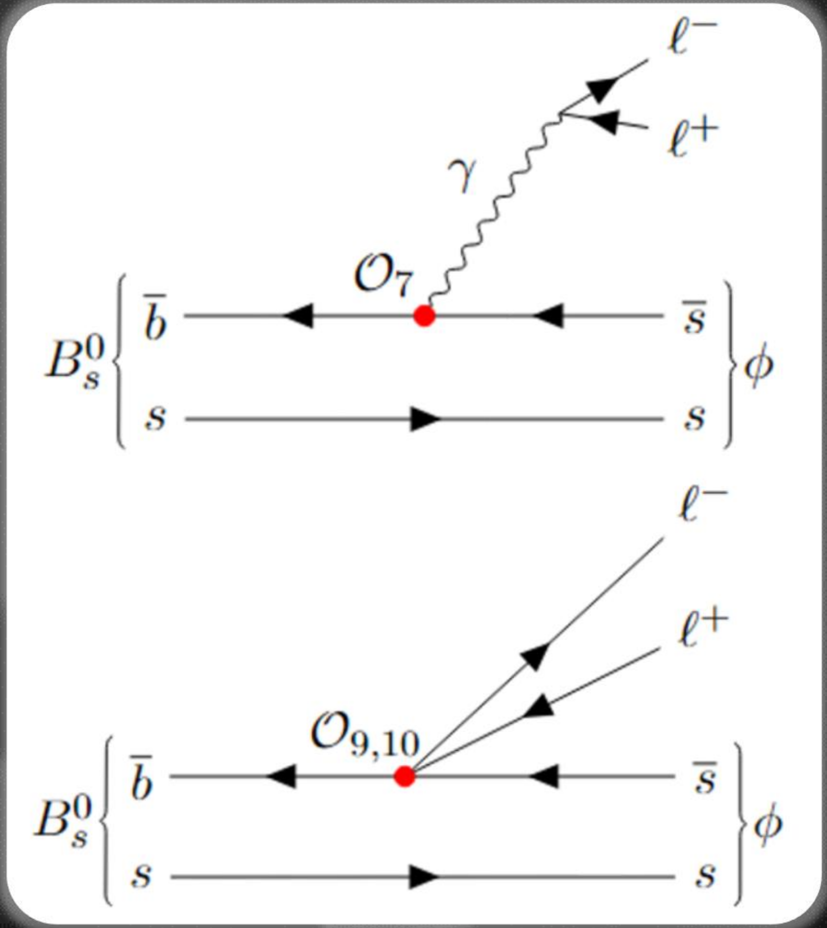


Just an example, there are more diagrams

We look at. . . . . (CPV from NP?)

BSM could introduce CPV in FCNC operators:
time-dependent measurements are sensitive to $\mathrm{Im}[C_{7,9,10}]$





Just an example, there are more diagrams

Why FCC-ee . . . . ?

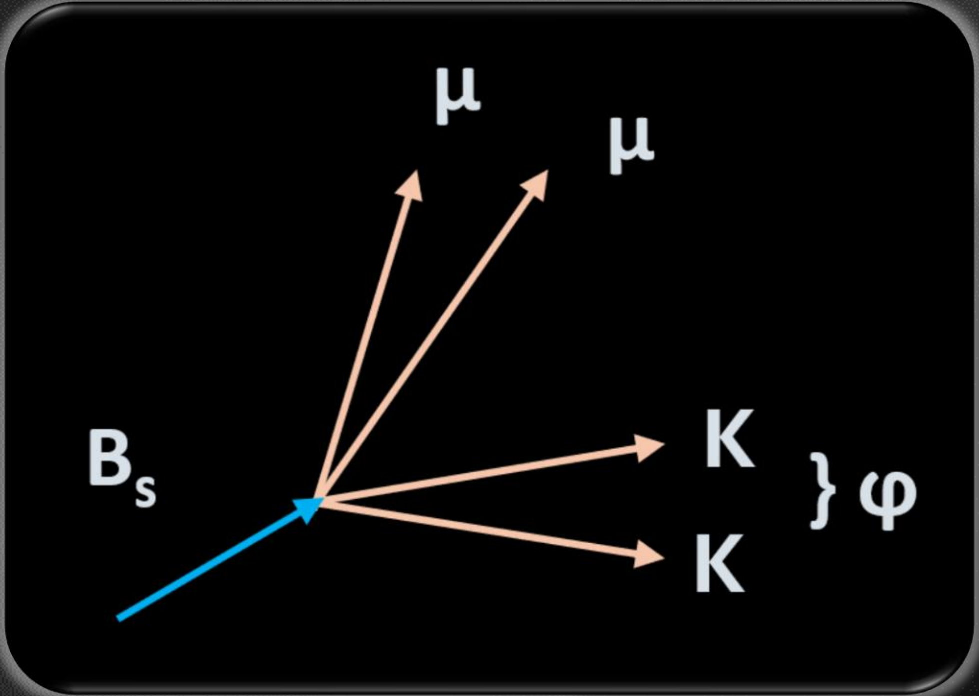
FCC-ee at Z-pole

b-hadron	Belle II	LHCb	FCC-ee
B^0, $\bar{B}^0$	5.3×10^{10}	6×10^{13}	7.2×10^{11}
$B^\pm$	5.6×10^{10}	6×10^{13}	7.2×10^{11}
B^0_s, $\bar{B}^0_s$	5.7×10^8	2×10^{13}	1.9×10^{11}
$B^\pm_c$	...	4×10^{11}	1.1×10^9
Λ^0_b, $\bar{\Lambda}^0_b$	...	2×10^{13}	1.5×10^{11}

In general (you all know better than I do):

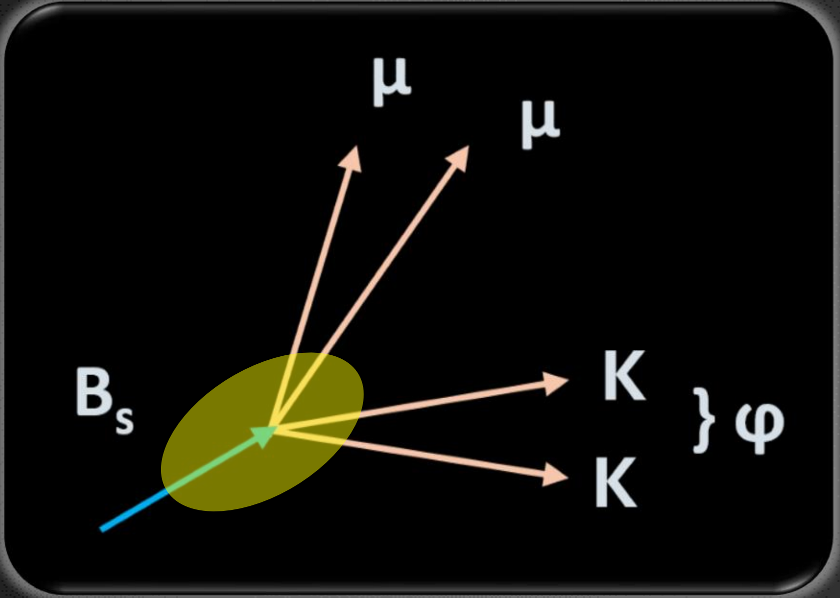
- Clean (vs LHCb)
- Good Flavor Tagging (vs LHCb)
- Large Stat. (vs Belle II)
- Good Vertexing (vs Belle II)
- …

Cartoon Diagram of Signal. . . . . . .

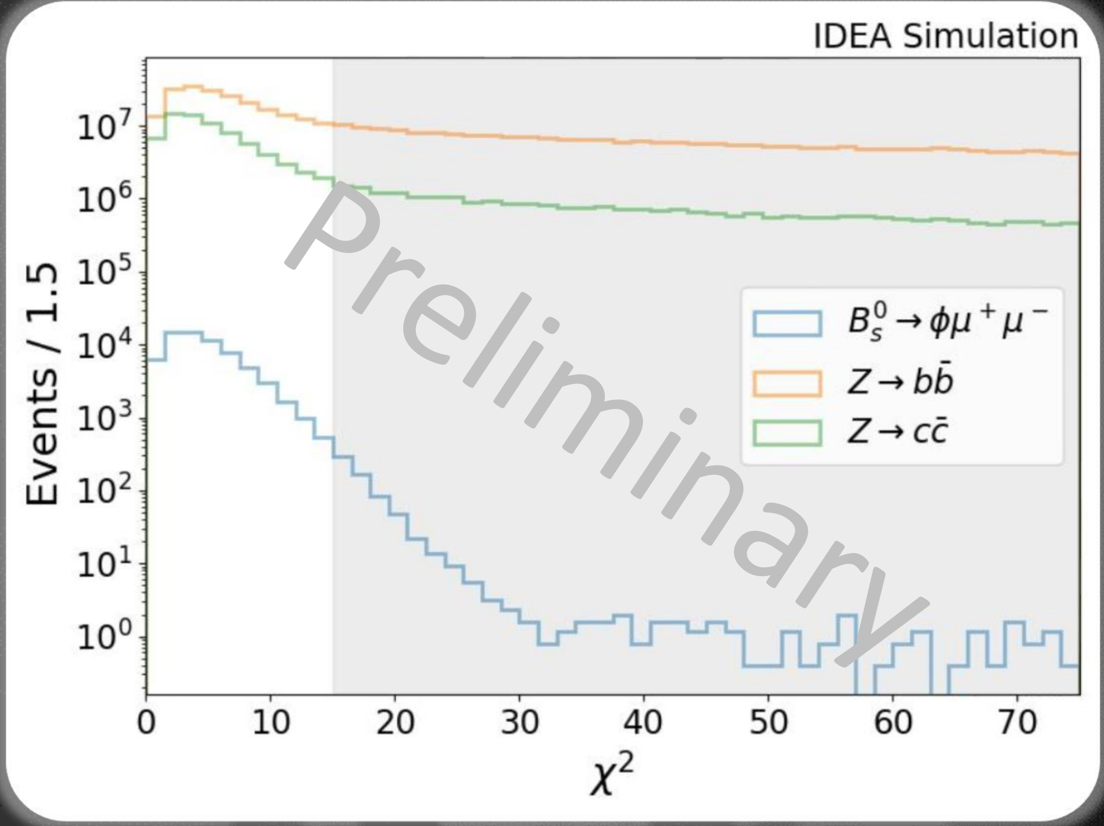


We use Pythia + Delphes (IDEA) for simulating signal & backgrounds

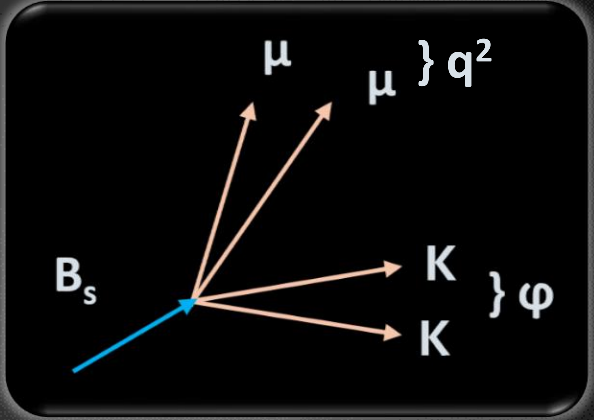
Some Physics of Signal. . . . .



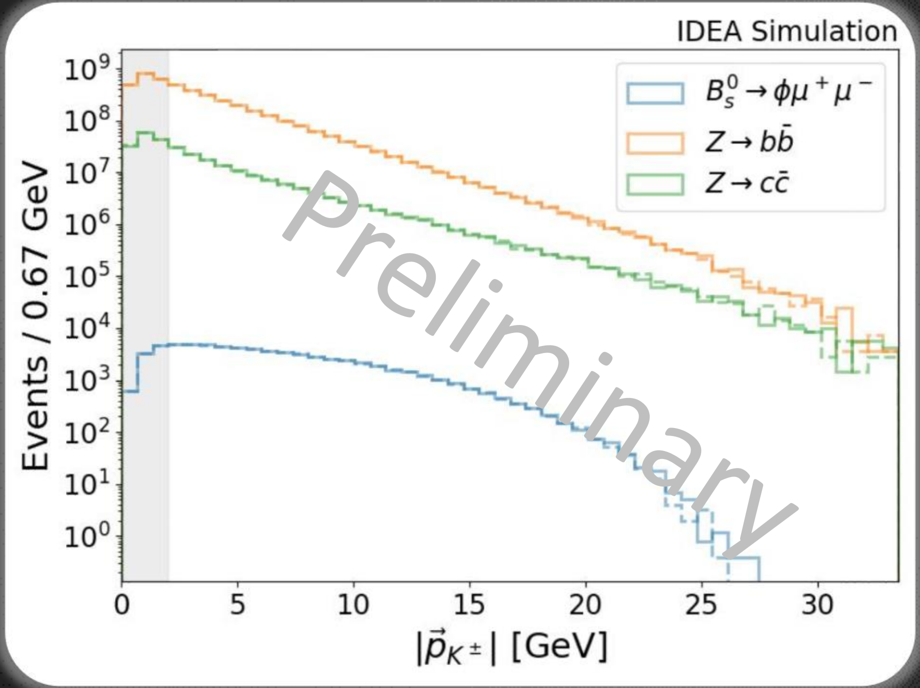
Vertex Fit



Some Physics of Signal. . . . .

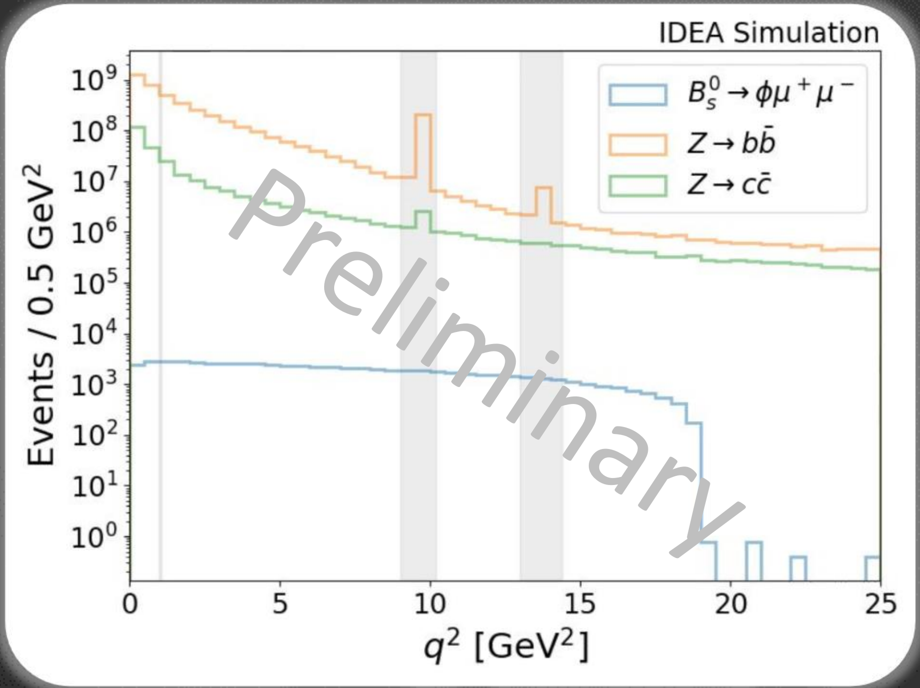


Kinematics

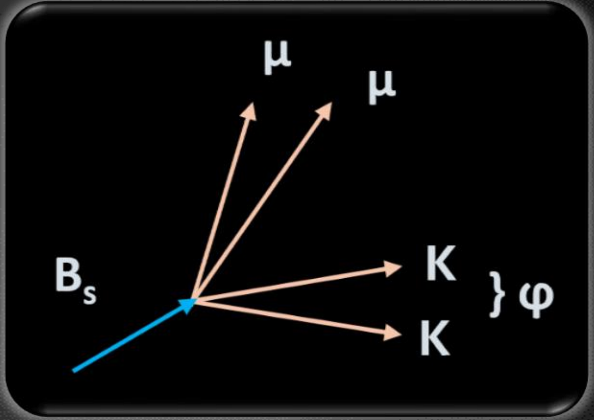


Resonances

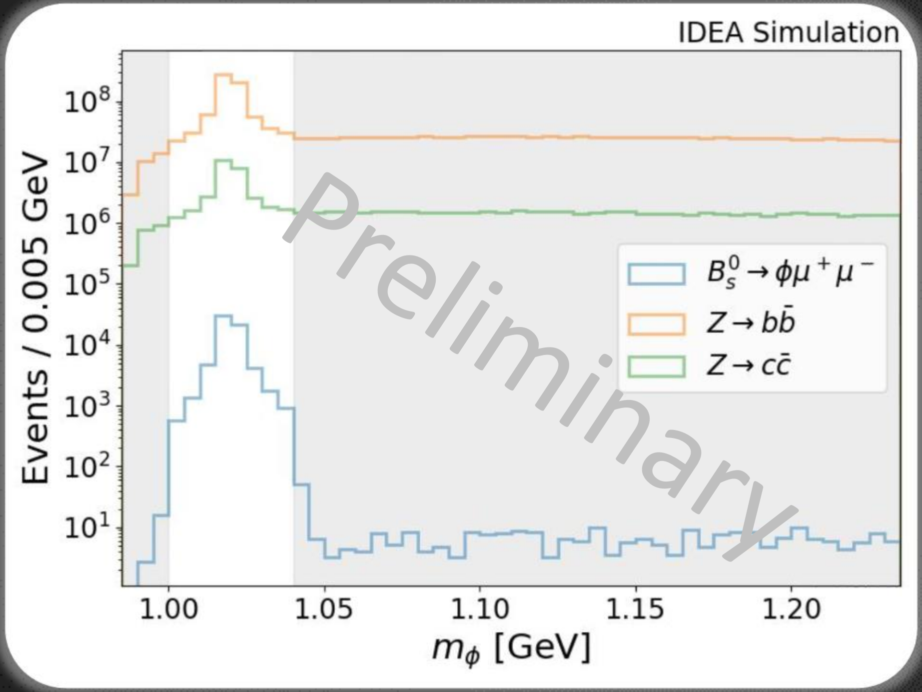
(momentum transferred to dimuon system)



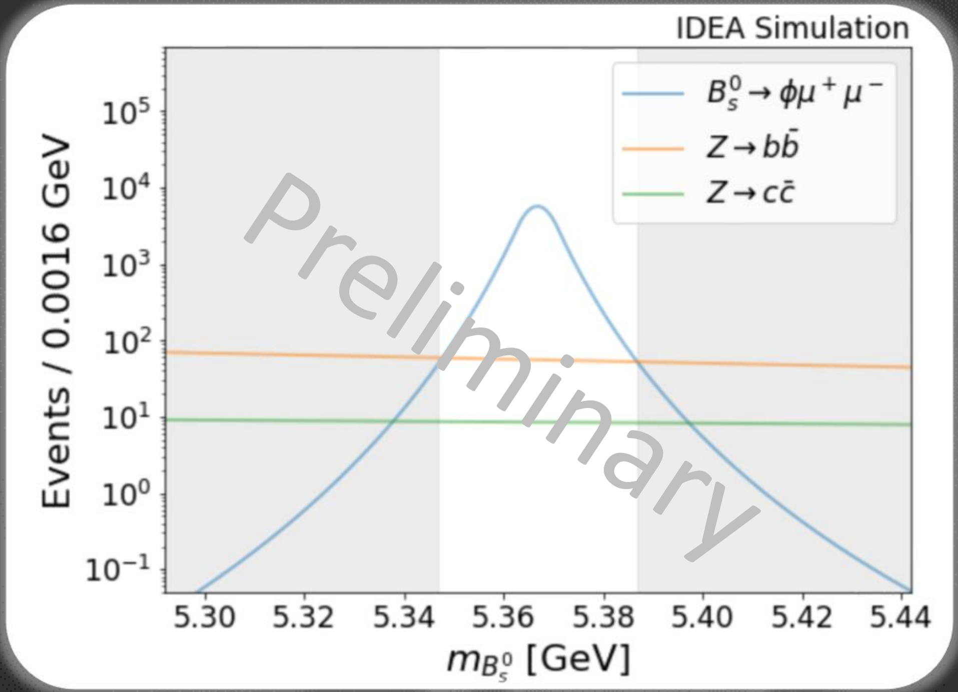
Some Physics of Signal. . . . .



Inv. mass (Dikaon)



Inv. Mass (Dikaon + Dimuon)



Cut Flow. . . . .

Cut Flow. . . . .

Cut Flow........

Channel	$B_s^0 \to \phi\mu^+\mu^-$	$Z \to b\bar{b}$	$Z \to c\bar{c}$
Events at FCC-*ee*	1.25×10^5	9.07×10^{11}	7.22×10^{11}
N_{FS}	1.16×10^5	4.34×10^9	2.82×10^8
N_{χ^2}	1.15×10^5	2.15×10^8	7.25×10^7
$N_{\|\vec{p}\|}$	7.35×10^4	5.98×10^7	2.25×10^6
N_{m_ϕ}	7.32×10^4	3.21×10^7	3.64×10^5
N_{q^2}	6.33×10^4	1.24×10^7	3.13×10^6
$N_{m_{B_s^0}}$	6.27×10^4	1.39×10^3	2.13×10^2

Precision: ~0.4% (vs LHCb: ~2.6%)

What Can We Measure. . . . . ?

	Untagged	Tagged
Time-independent		
Time-dependent		

What Can We Measure. . . . . ?

Fact Sheet: "Tagging"

Tell they're from B or anti-B

Tag eff.: How often we can tell something
Tag Rate: How often we get it right

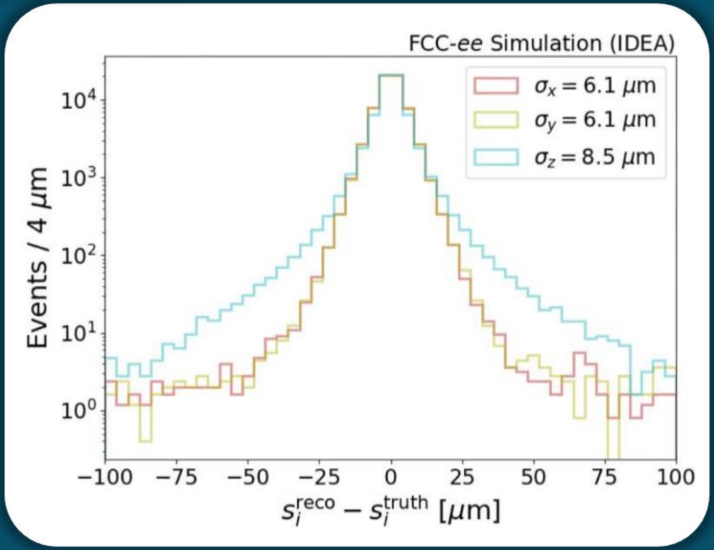
Uncert. ~ 1/sqrt{Tag Power}

	LEP	Belle II	BaBar	LHCb
P_{tag}	$25-30\%$	30%	30%	6%

Fact Sheet: "Timing"

Time resolution effect: dilution factor (~0.995)

Function of: PV, SV, Boost
[Dominated by SV resolution]



What Can We Measure. . . . . ?

	Untagged	Tagged
Time-independent	Branching Ratio	Time-integrated CP-asymmetry $\langle A_{CP}\rangle = \frac{\Gamma_{B_s^0\to\phi\mu^+\mu^-} - \Gamma_{\bar{B}_s^0\to\phi\mu^+\mu^-}}{\Gamma_{B_s^0\to\phi\mu^+\mu^-} + \Gamma_{\bar{B}_s^0\to\phi\mu^+\mu^-}}$
Time-dependent	Time-dependent Decay Rate $\Gamma_{B_s^0\to\phi\mu^+\mu^-}(t) + \Gamma_{\bar{B}_s^0\to\phi\mu^+\mu^-}(t) \propto e^{-\Gamma_s t}\left(\cosh\frac{1}{2}\Delta\Gamma_s t + D_f \sinh\frac{1}{2}\Delta\Gamma_s t\right)$	Time-dependent CP-asymmetry $A_{CP}(t) = \frac{C_f \cos\Delta m_s t - S_f \sin\Delta m_s t}{\cosh\frac{1}{2}\Delta\Gamma_s t + D_f \sinh\frac{1}{2}\Delta\Gamma_s t}$

What Can We Measure. . . . . ?

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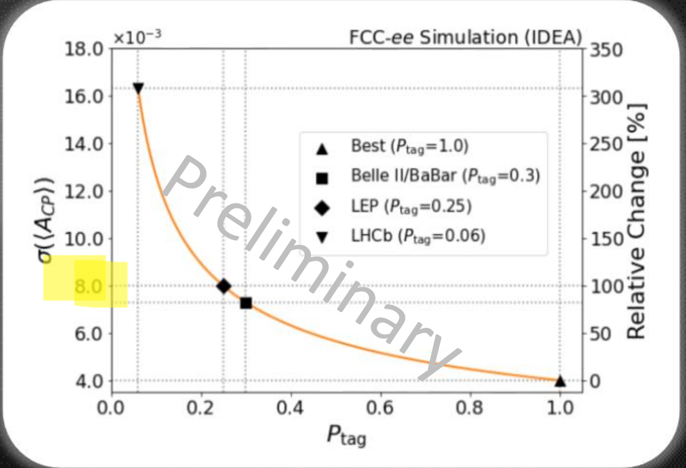
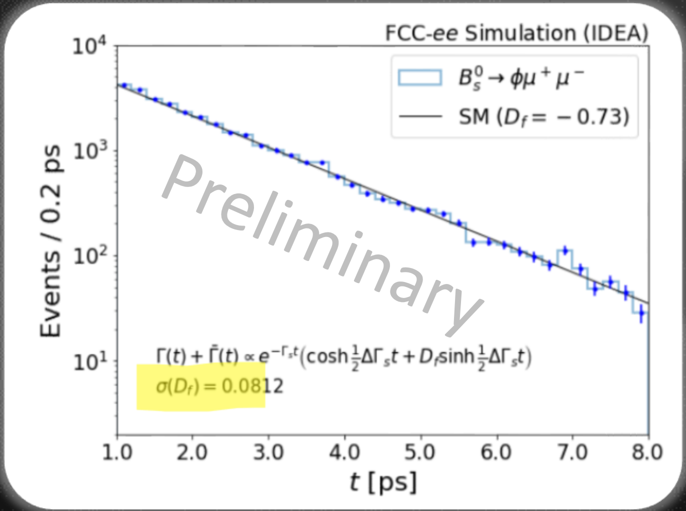
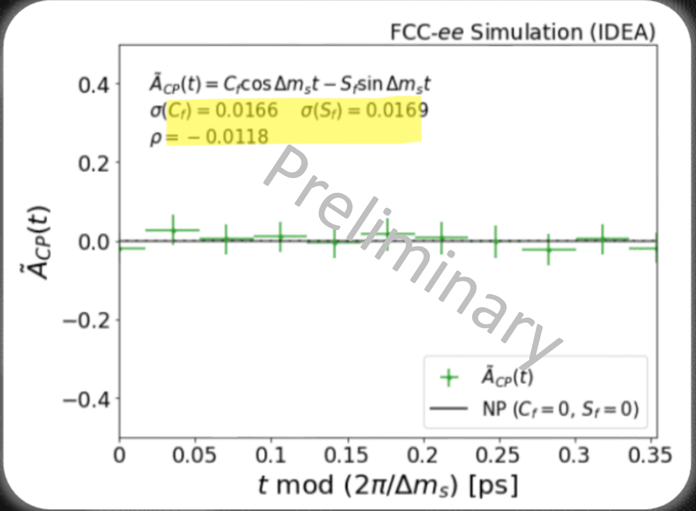
Precision: ~0.4%

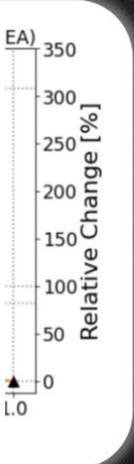






What Can We Measure. . . . . ?

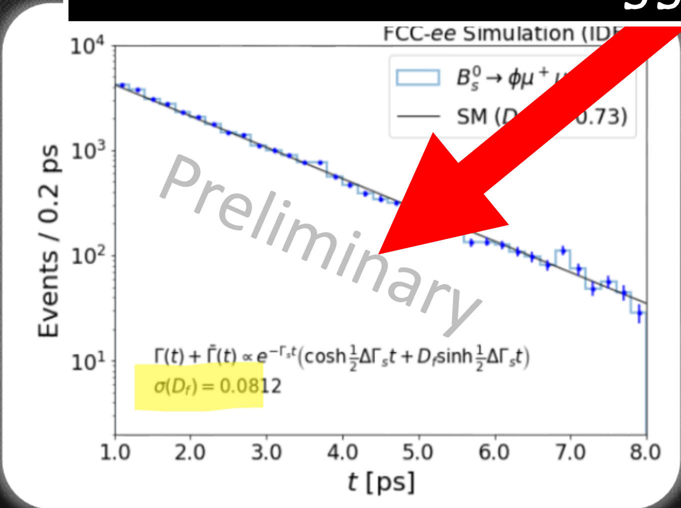
	Untagged	Tagged
Time-independent		
Time-dependent		

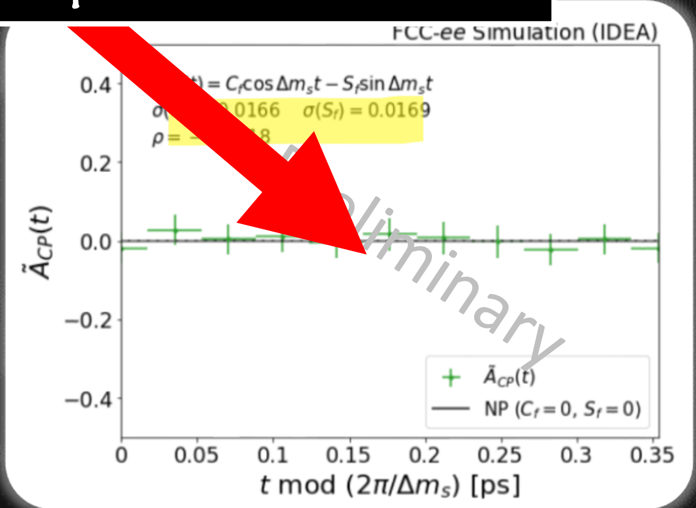


LHCb may measure untagged time-dependent

BUT

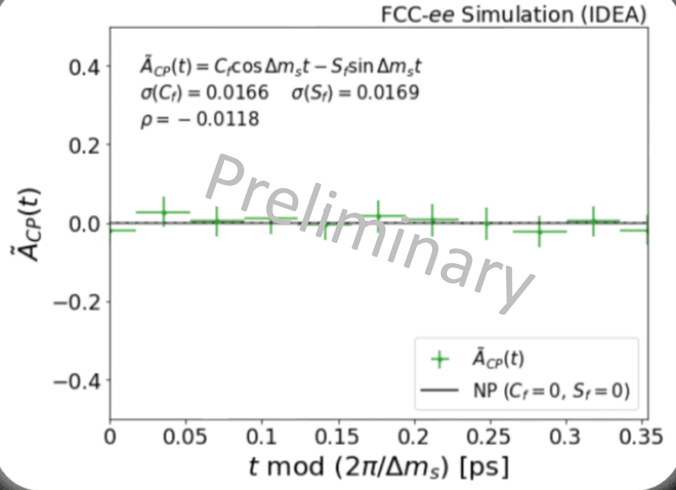
FCC-ee is really (almost) the only one can measure tagged time-dependent



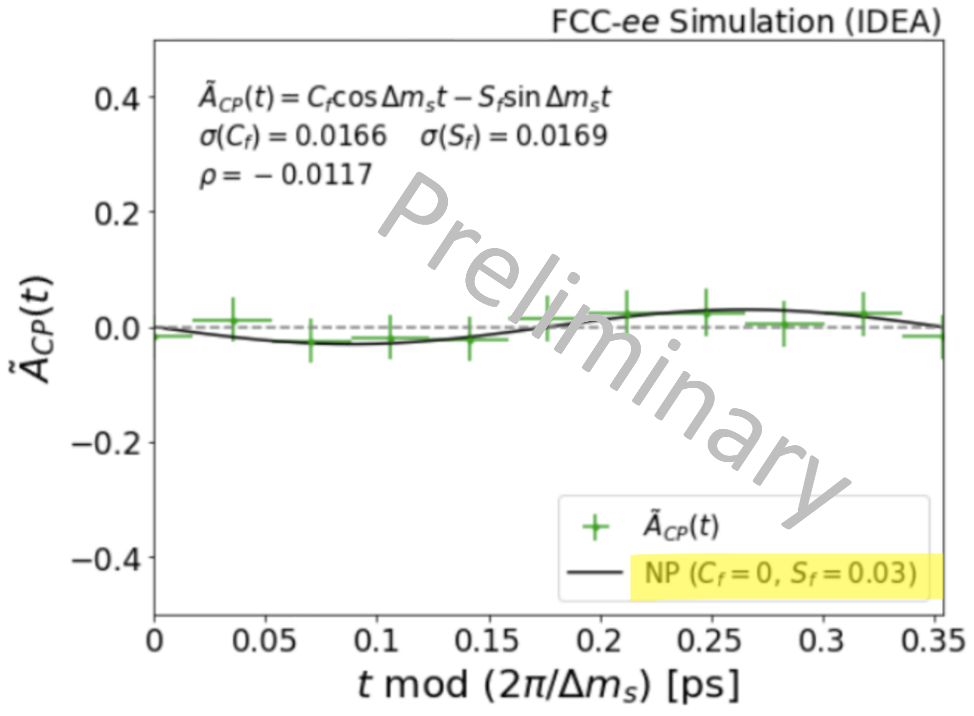


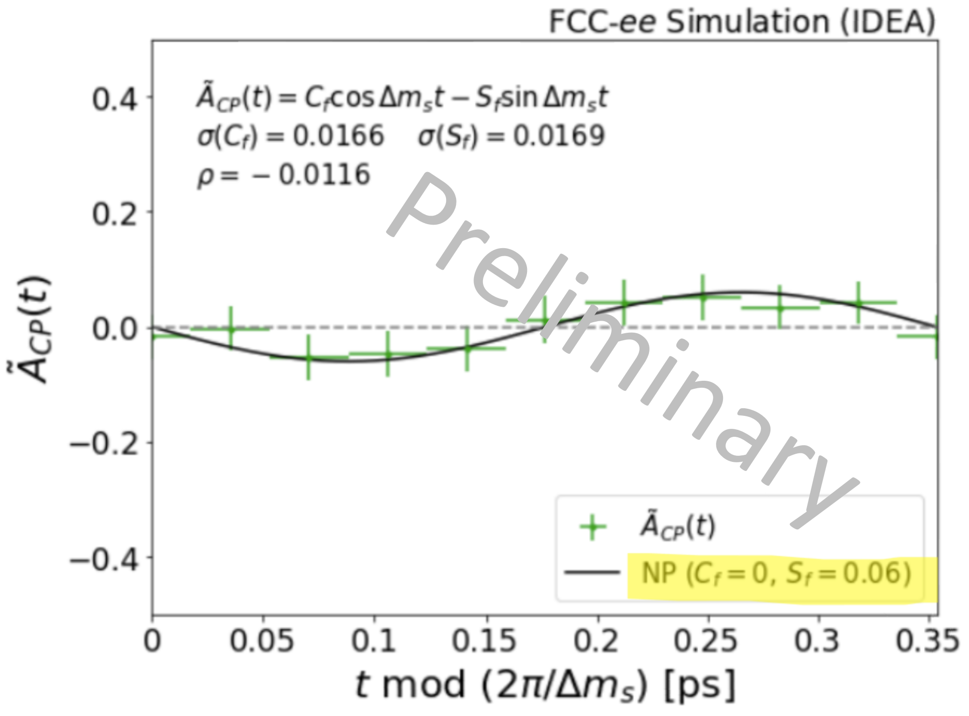
If NP exists. . . . . ?

FYI: SM is like:



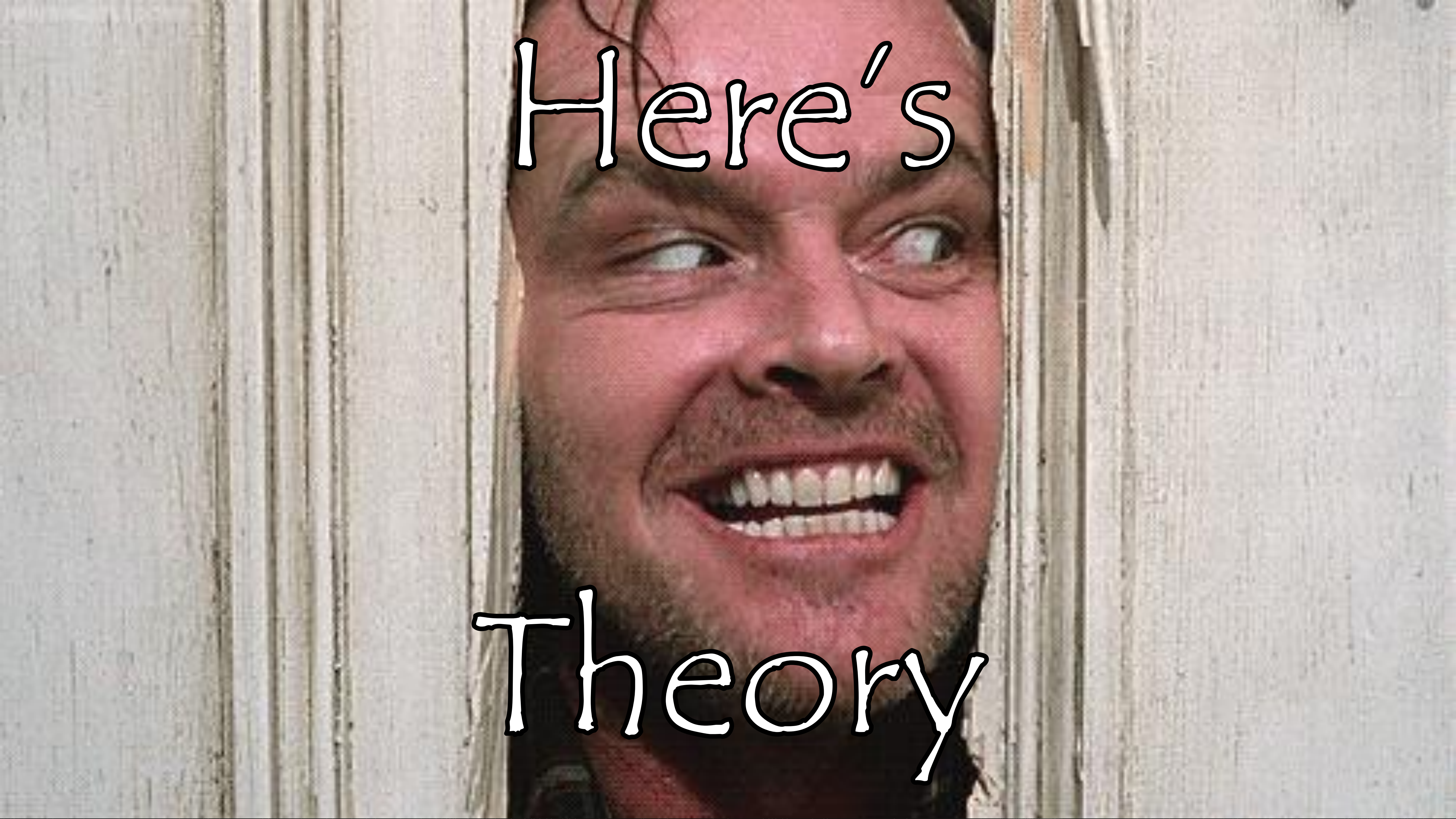
If there are $Im[C_{NP}]$



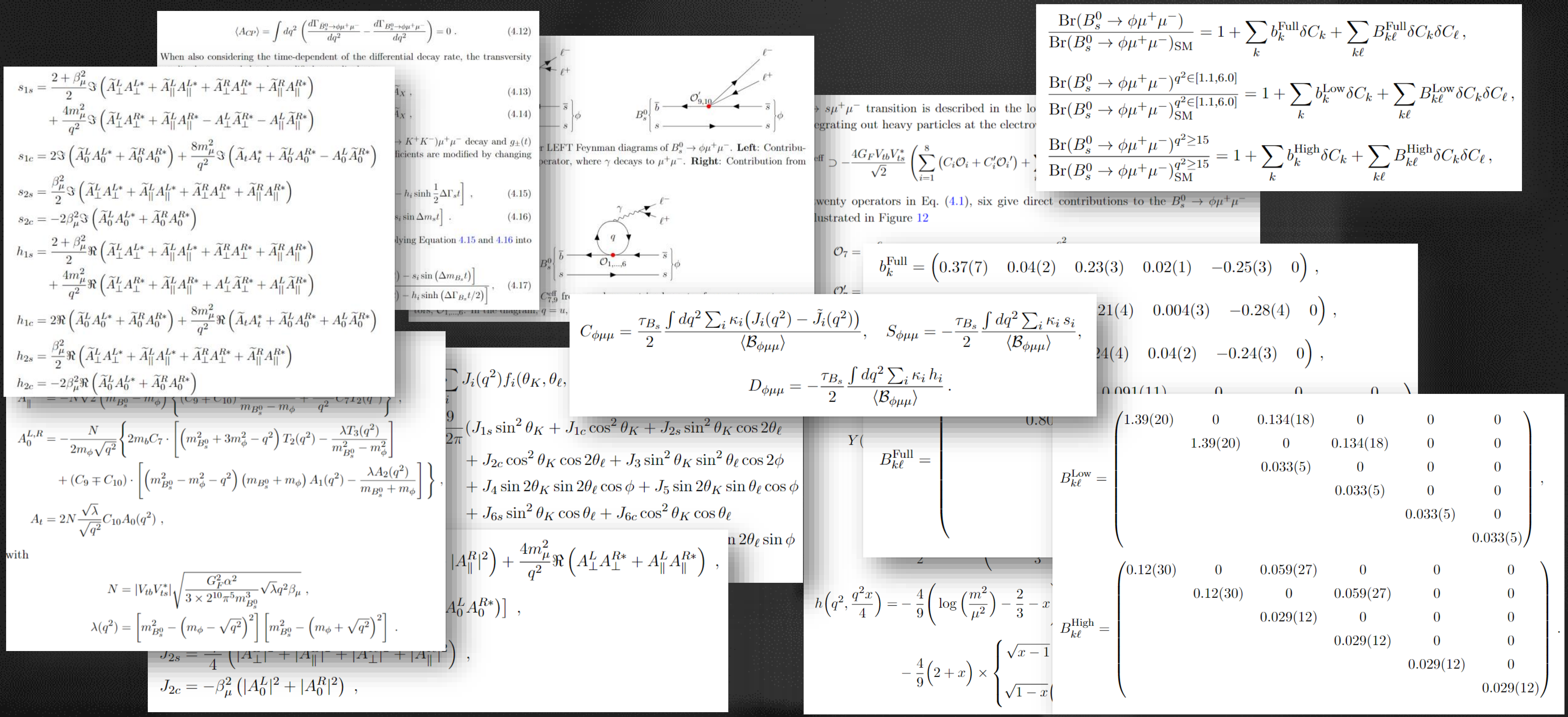


Conclusion (Analysis Part):

Now (we think) we know
what we can measure. . . . .


Here's
Theory

Interpretation In A Nutshell. . . . .

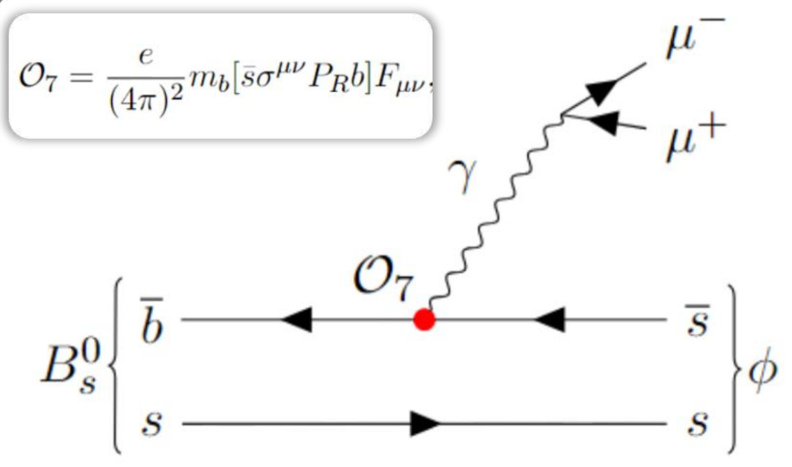


Model-independent Way (EFT). . . . .

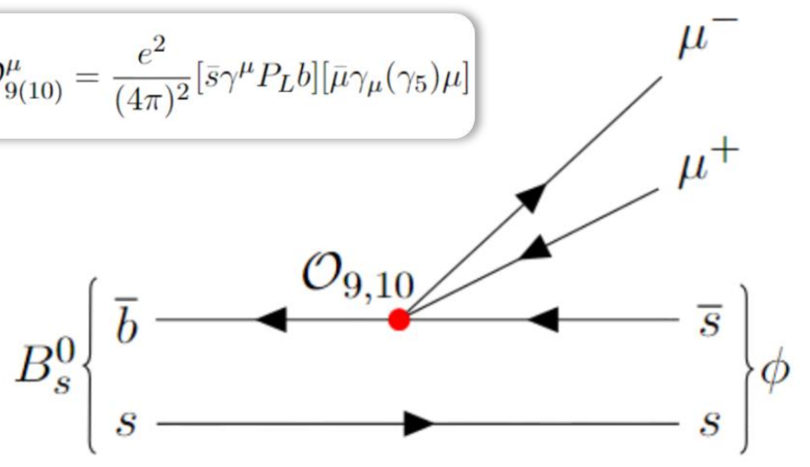
$$\mathcal{H}^{\text{eff}} \supset -\frac{4G_F V_{tb} V_{ts}^*}{\sqrt{2}} \left(\sum_{i=1}^{8} (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') + \sum_{i=9}^{10} (C_i \mathcal{O}_i^{\mu} + C_i' \mathcal{O}_i^{\mu\prime}) \right) + \text{h.c.}$$

Want to see how Wilson Coefficients (C_i) deviate from SM value

$$\mathcal{O}_7 = \frac{e}{(4\pi)^2} m_b [\bar{s}\sigma^{\mu\nu} P_R b] F_{\mu\nu}$$



$$\mathcal{O}^{\mu}_{9(10)} = \frac{e^2}{(4\pi)^2} [\bar{s}\gamma^{\mu} P_L b][\bar{\mu}\gamma_{\mu}(\gamma_5)\mu]$$



Connecting EXP-TH (An Example). . . . . . .

$$C_{\phi\mu\mu} = \frac{\tau_{B_s}}{2}\frac{\int dq^2 \sum_i \kappa_i \big(J_i(q^2) - \tilde{J}_i(q^2)\big)}{\langle \mathcal{B}_{\phi\mu\mu}\rangle}, \quad S_{\phi\mu\mu} = -\frac{\tau_{B_s}}{2}\frac{\int dq^2 \sum_i \kappa_i\, s_i}{\langle \mathcal{B}_{\phi\mu\mu}\rangle},$$

$$D_{\phi\mu\mu} = -\frac{\tau_{B_s}}{2}\frac{\int dq^2 \sum_i \kappa_i\, h_i}{\langle \mathcal{B}_{\phi\mu\mu}\rangle}.$$

Observable as function of C's

Link observables to J's, h's, s's

$$J_{1s} = \frac{(2+\beta_\mu^2)}{4}\left(|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right) + \frac{4m_\mu^2}{q^2}\Re\left(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}\right),$$

$$J_{1c} = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\Re\left(A_0^L A_0^{R*}\right)\right],$$

$$J_{2s} = \frac{\beta_\mu^2}{4}\left(|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right),$$

$$J_{2c} = -\beta_\mu^2\left(|A_0^L|^2 + |A_0^R|^2\right),$$

$$h_{1s} = \frac{2+\beta_\mu^2}{2}\Re\left(\tilde{A}_\perp^L A_\perp^{L*} + \tilde{A}_\parallel^L A_\parallel^{L*} + \tilde{A}_\perp^R A_\perp^{R*} + \tilde{A}_\parallel^R A_\parallel^{R*}\right) + \frac{4m_\mu^2}{q^2}\Re\left(\tilde{A}_\perp^L A_\perp^{R*} + \tilde{A}_\parallel^L A_\parallel^{R*} + A_\perp^L \tilde{A}_\perp^{R*} + A_\parallel^L \tilde{A}_\parallel^{R*}\right)$$

$$h_{1c} = 2\Re\left(\tilde{A}_0^L A_0^{L*} + \tilde{A}_0^R A_0^{R*}\right) + \frac{8m_\mu^2}{q^2}\Re\left(\tilde{A}_t A_t^* + \tilde{A}_0^L A_0^{R*} + A_0^L \tilde{A}_0^{R*}\right)$$

$$h_{2s} = \frac{\beta_\mu^2}{2}\Re\left(\tilde{A}_\perp^L A_\perp^{L*} + \tilde{A}_\parallel^L A_\parallel^{L*} + \tilde{A}_\perp^R A_\perp^{R*} + \tilde{A}_\parallel^R A_\parallel^{R*}\right)$$

$$h_{2c} = -2\beta_\mu^2\Re\left(\tilde{A}_0^L A_0^{L*} + \tilde{A}_0^R A_0^{R*}\right)$$

$$A_\perp^{L,R} = N\sqrt{2\lambda}\left\{(C_9 \mp C_{10})\frac{V(q^2)}{m_{B_s^0} + m_\phi} + \frac{2m_b}{q^2}C_7 T_1(q^2)\right\},$$

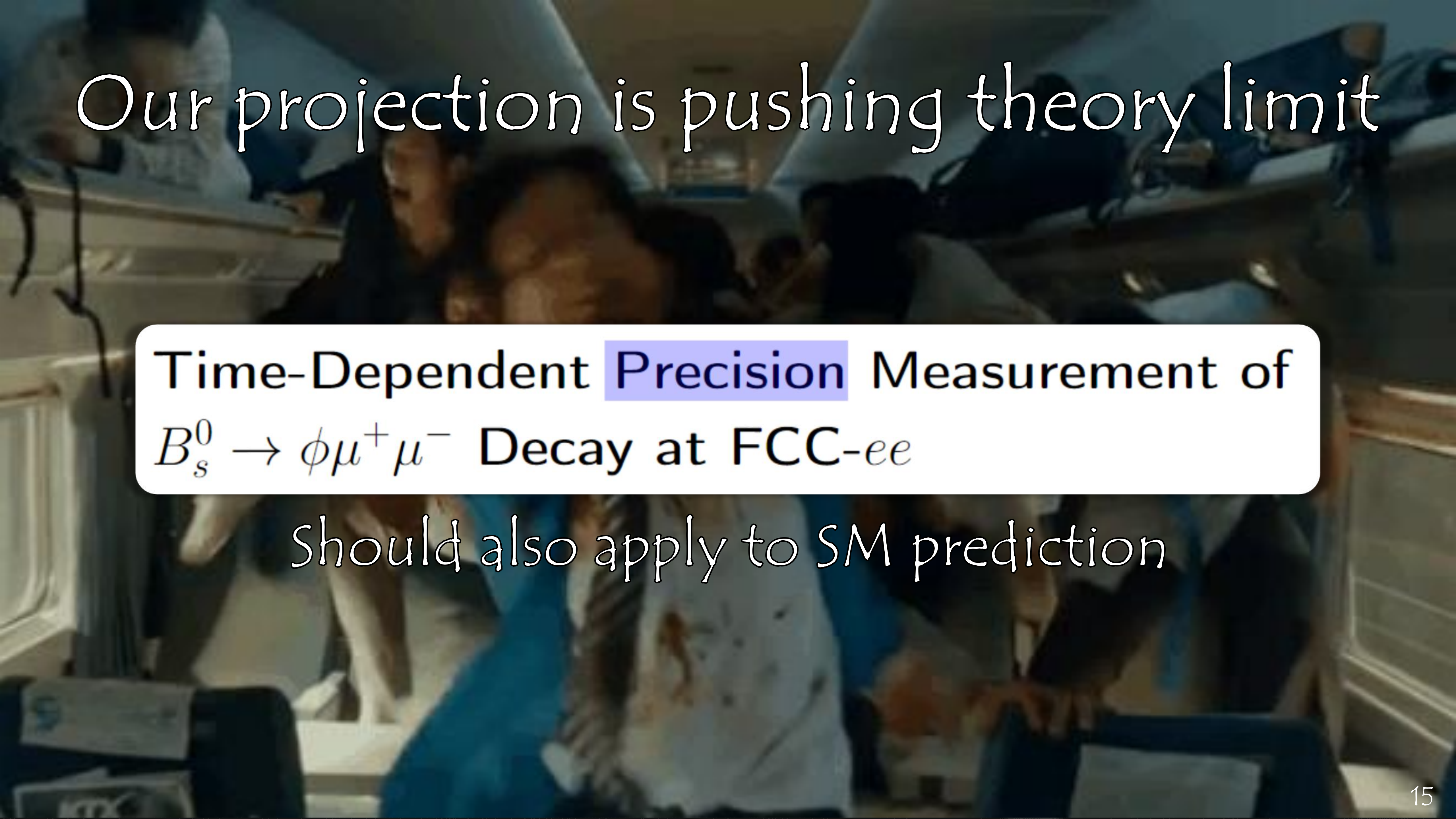
$$A_\parallel^{L,R} = -N\sqrt{2}\left(m_{B_s^0}^2 - m_\phi^2\right)\left\{(C_9 \mp C_{10})\frac{A_1(q^2)}{m_{B_s^0} - m_\phi} + \frac{2m_b}{q^2}C_7 T_2(q^2)\right\},$$

$$A_0^{L,R} = -\frac{N}{2m_\phi\sqrt{q^2}}\left\{2m_b C_7 \cdot \left[\left(m_{B_s^0}^2 + 3m_\phi^2 - q^2\right)T_2(q^2) - \frac{\lambda T_3(q^2)}{m_{B_s^0}^2 - m_\phi^2}\right] + (C_9 \mp C_{10}) \cdot \left[\left(m_{B_s^0}^2 - m_\phi^2 - q^2\right)\left(m_{B_s^0} + m_\phi\right)A_1(q^2) - \frac{\lambda A_2(q^2)}{m_{B_s^0} + m_\phi}\right]\right\},$$

$$A_t = 2N\frac{\sqrt{\lambda}}{\sqrt{q^2}}C_{10}A_0(q^2),$$

J's, h's, s's functions of Amplitudes

Our projection is pushing theory limit

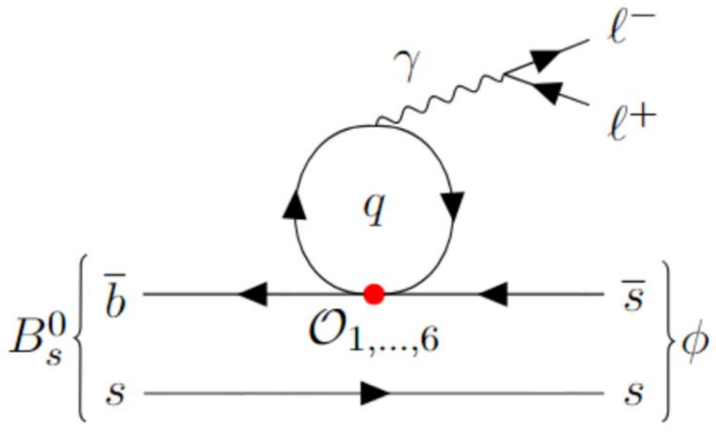


Time-Dependent Precision Measurement of $B_s^0 \to \phi\mu^+\mu^-$ Decay at FCC-ee

Should also apply to SM prediction

Long-distance Effects. . . . .

$$C_7^{\text{eff}} = C_7 - \frac{1}{3}C_3 - \frac{4}{9}C_4 - \frac{20}{3}C_5 - \frac{80}{9}C_6\,, \quad C_9^{\text{eff}} = C_9 + Y(q^2)\,,$$



$$\begin{aligned} Y(q^2) =& \frac{4}{3}C_3 + \frac{64}{9} + \frac{64}{27}C_6 - \frac{1}{2}h(q^2,0)\left(C_3 + \frac{4}{3}C_4 + 16C_5 + \frac{64}{3}C_6\right) \\ &+ h(q^2, m_c)\left(\frac{4}{3}C_1 + C_2 + 6C_3 + 60C_5\right) \\ &- \frac{1}{2}h(q^2, m_b)\left(7C_3 + \frac{4}{3}C_4 + 76C_5 + \frac{64}{3}C_6\right), \end{aligned}$$

$$\begin{aligned} h\left(q^2, \frac{q^2 x}{4}\right) =& -\frac{4}{9}\left(\log\left(\frac{m^2}{\mu^2}\right) - \frac{2}{3} - x\right) \\ &- \frac{4}{9}(2+x) \times \begin{cases} \sqrt{x-1}\arctan\frac{1}{\sqrt{x-1}} & , x > 1 \\ \sqrt{1-x}\left(\log\frac{1+\sqrt{1-x}}{\sqrt{x}} - \frac{i\pi}{2}\right) & , x \leq 1 \end{cases}. \end{aligned}$$

Then we can write, *e.g.*:

Expanding into 2nd order

$$\frac{\mathrm{Br}(B_s^0 \to \phi\mu^+\mu^-)}{\mathrm{Br}(B_s^0 \to \phi\mu^+\mu^-)_{\mathrm{SM}}} = 1 + \sum_k b_k^{\mathrm{Full}} \delta C_k + \sum_{k\ell} B_{k\ell}^{\mathrm{Full}} \delta C_k \delta C_\ell \,,$$

$$\tilde{C}^I_{\phi\mu\mu} = \sum_k \gamma_k^I \, \delta C_k + \sum_{k\ell} \Gamma^I_{k\ell} \, \delta C_k \delta C_\ell \,,$$

$$\tilde{S}^I_{\phi\mu\mu} = \sum_k \sigma_k^I \, \delta C_k + \sum_{k\ell} \Sigma^I_{k\ell} \, \delta C_k \delta C_\ell \,,$$

$$\tilde{D}^I_{\phi\mu\mu} = \tilde{D}^I_{\phi\mu\mu,\mathrm{SM}} + \sum_k \delta_k^I \, \delta C_k + \sum_{k\ell} \Delta^I_{k\ell} \, \delta C_k \delta C_\ell \,,$$

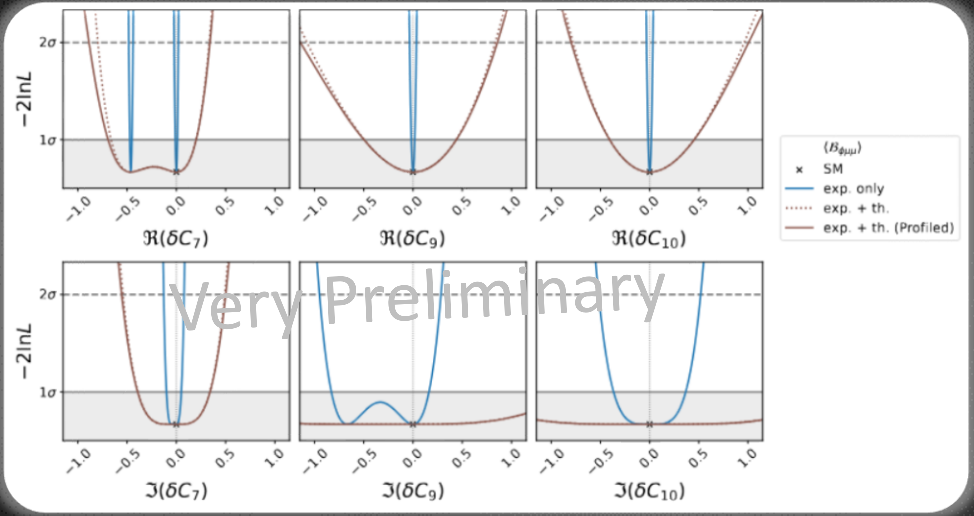
~10% theoretical uncertainty!!!

$$b_k^{\mathrm{Full}} = \begin{pmatrix} 0.37(7) & 0.04(2) & 0.23(3) & 0.02(1) & -0.25(3) & 0 \end{pmatrix} \,,$$

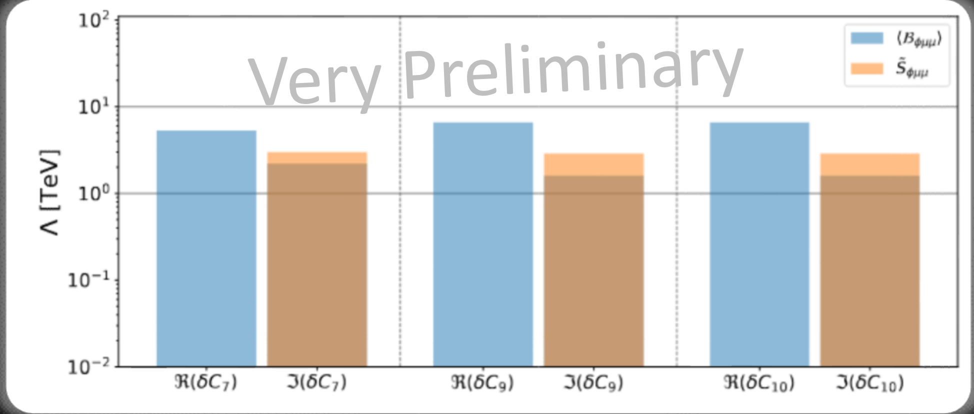
$$B_{k\ell}^{\mathrm{Full}} = \begin{pmatrix} 0.80(11) & 0 & 0.091(11) & 0 & 0 & 0 \\ & 0.80(11) & 0 & 0.091(11) & 0 & 0 \\ & & 0.030(4) & 0 & 0 & 0 \\ & & & 0.030(4) & 0 & 0 \\ & & & & 0.030(4) & 0 \\ & & & & & 0.030(4) \end{pmatrix} \,,$$

Money Plot (In Construction). . . . . . .

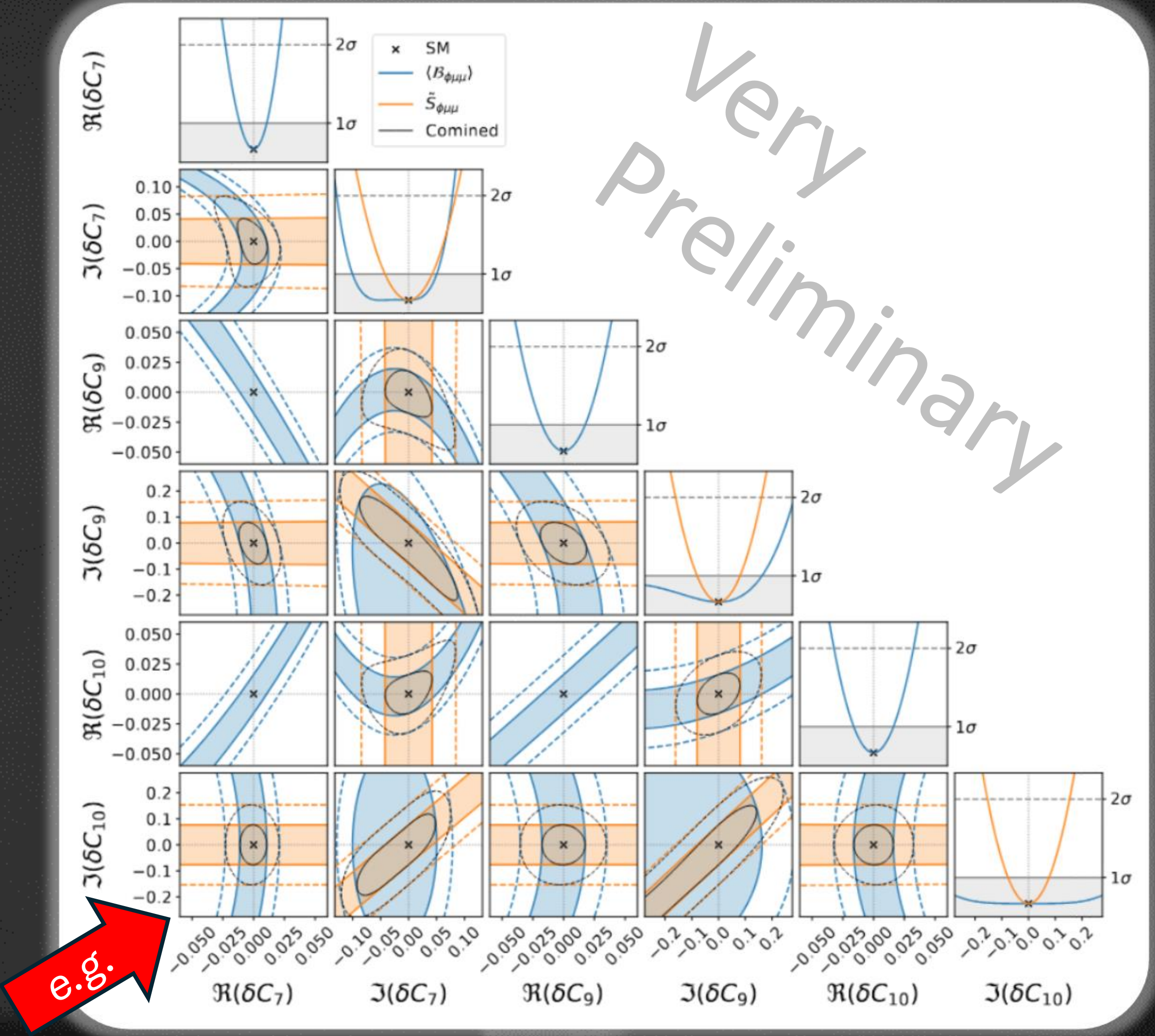
With Th. Uncert.: Th. Uncert. » Exp. Uncert.



Can learn NP up to O(10 TeV) [Stat. only]

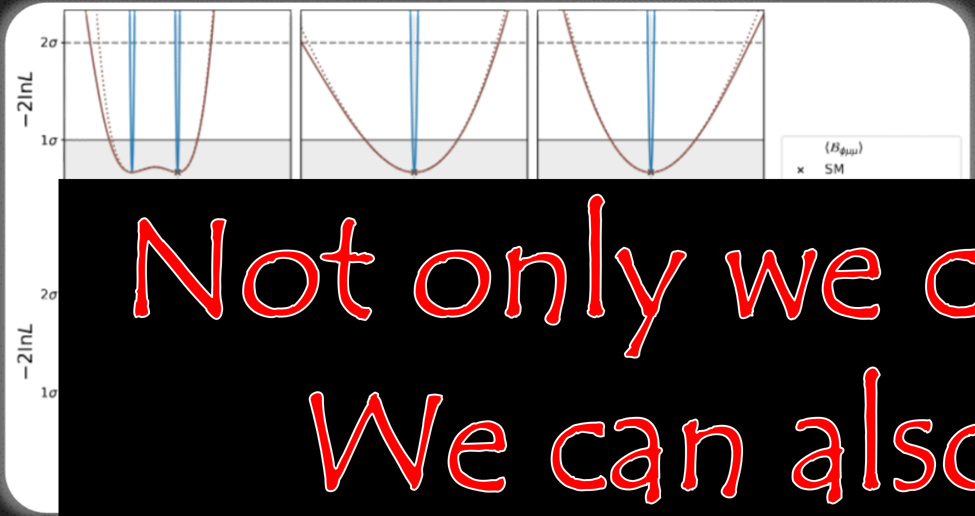


Complementary: Re and Im parts

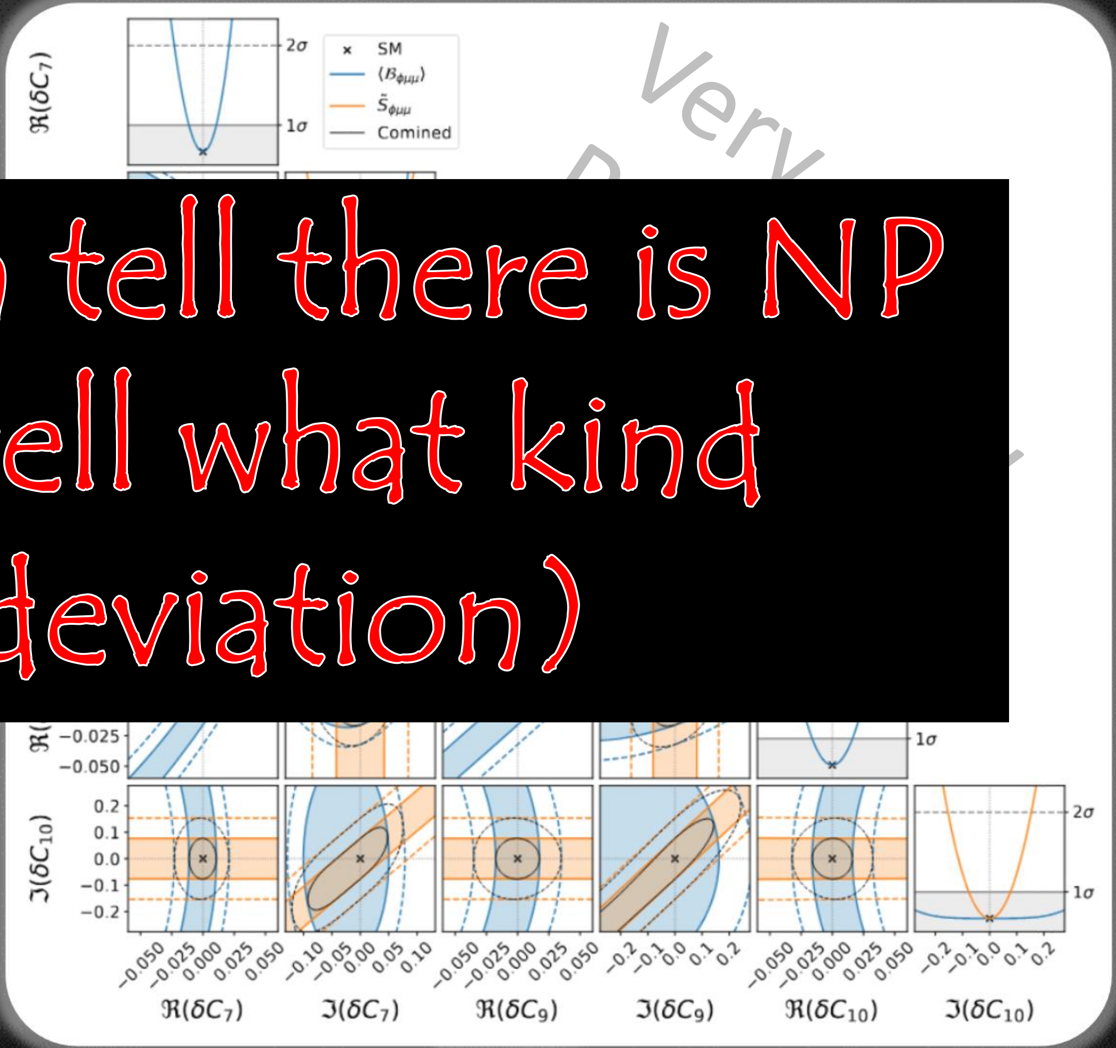


Money Plot (In Construction). . . . . . .

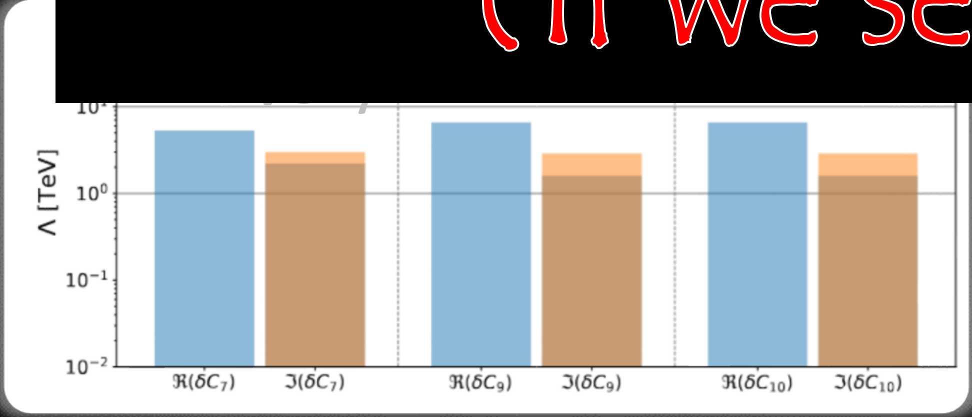
With Th. Uncert.: Th. Uncert. » Exp. Uncert.



Complementary: Re and Im parts



Not only we can tell there is NP
We can also tell what kind
(If we see deviation)



Conclusion

Big Question	Why matter » antimatter?
Exact Problem	Do we have CPV from NP (in leptonic rare, FCNC, decay)?
Where do we test it	FCC-*ee* : Ideal to test rare process! [Clean, Good Vertexing, …]
How to Interpret it	EFT: Tell how (NP) complex phase affects experimental measurements
What can we learn	Can probe NP up to O(10 TeV) [If th. uncert. suppressed to similar order of magnitude] We should push th. calculation

Conclusion

Big Question	Why matter » antimatter?
Exact Problem	Do we have CPV from NP

There is only one way to find out if it oscillates!
MEASURE IT!

[If th. uncert. suppressed to similar order of magnitude]
We should push th. calculation

Crew

--- alphabetical ---

Theoretical Part	Jason Aebischer
Experimental Part (Boss)	Ben Kilminster
Experimental Part	Anson Kwok
Experimental Part	Valeriia Lukashenko
Theoretical Part	Zach Polonsky

Special Thank

Useful Discussions and Feedbacks	Gino Isidori
	Armin Ilg
	Franco Grancagnolo
	Margherita Primavera
	Lingfeng Li

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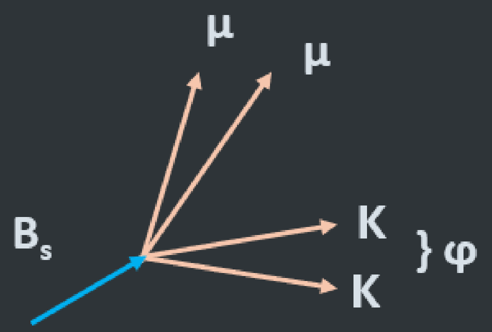
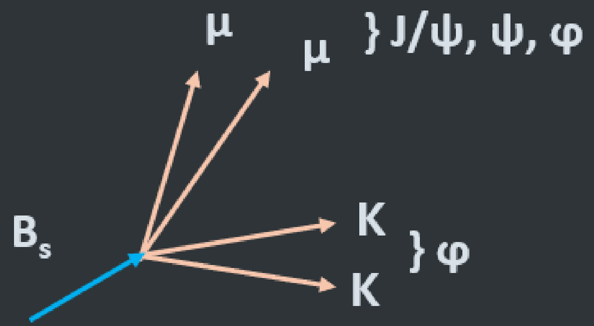
Backups. . . . . . .

What background types do we have?

Signal

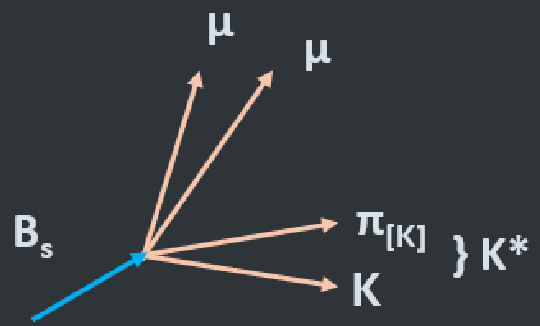


Resonance



- m(μμ) != m(J/ψ), m(ψ), m(φ)

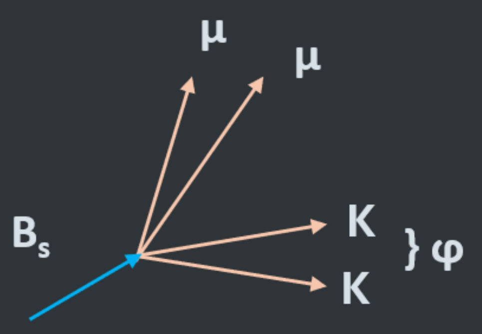
Peaking (misID)



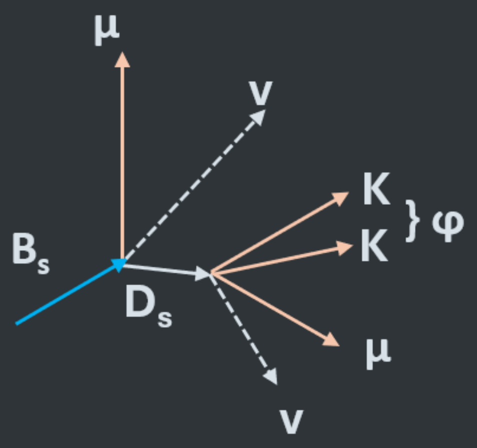
- m(K π[K]) != m(φ)
- O(1%) misID rate

What background types do we have?

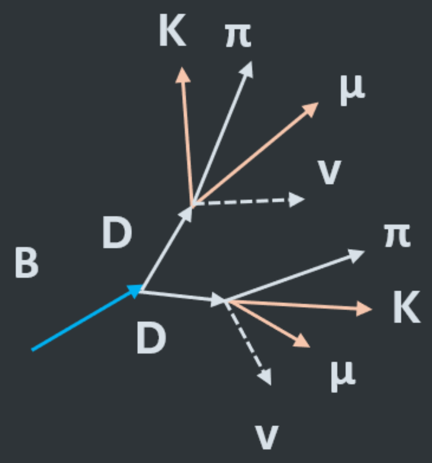
Signal



Z>bb Cascade

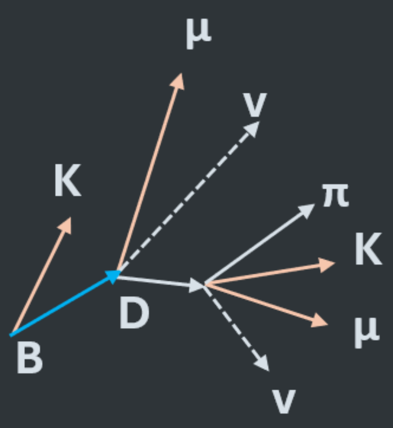


- KKμμ don't form a vertex
- m(KKμμ) != m(B_s)



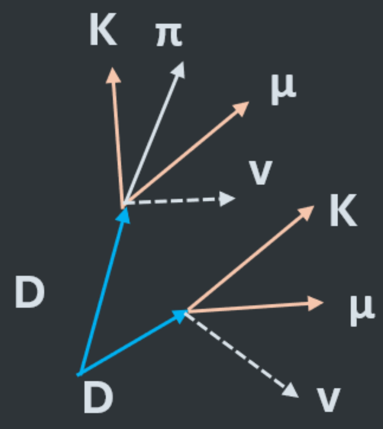
-m(KK) != m(φ)

Z>bb Comb.



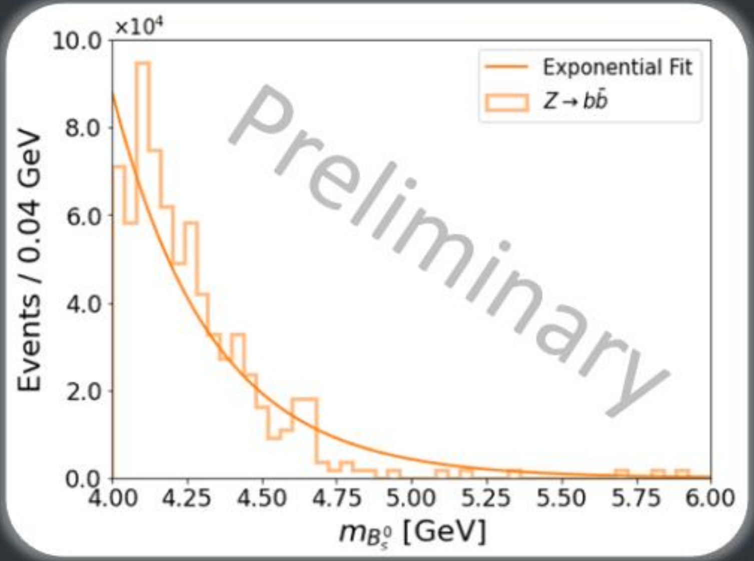
- KKμμ don't form a vertex
- m(KKμμ) != m(B_s)
- m(KK) != m(φ)

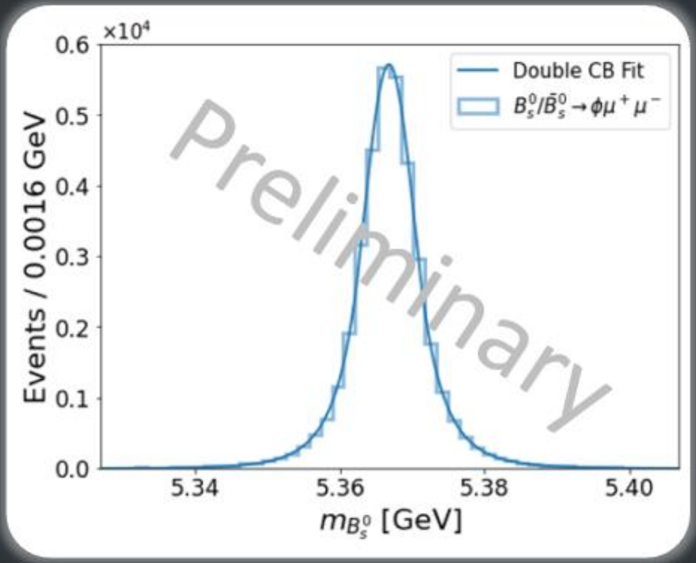
Z>cc Comb.

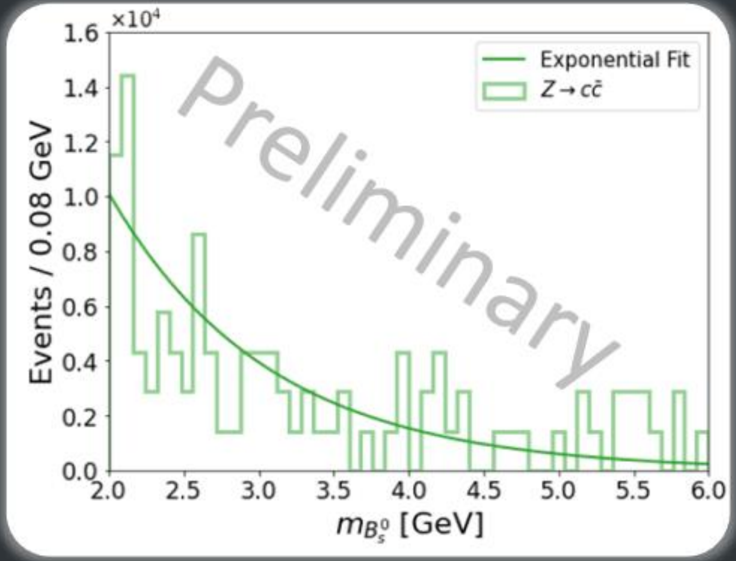


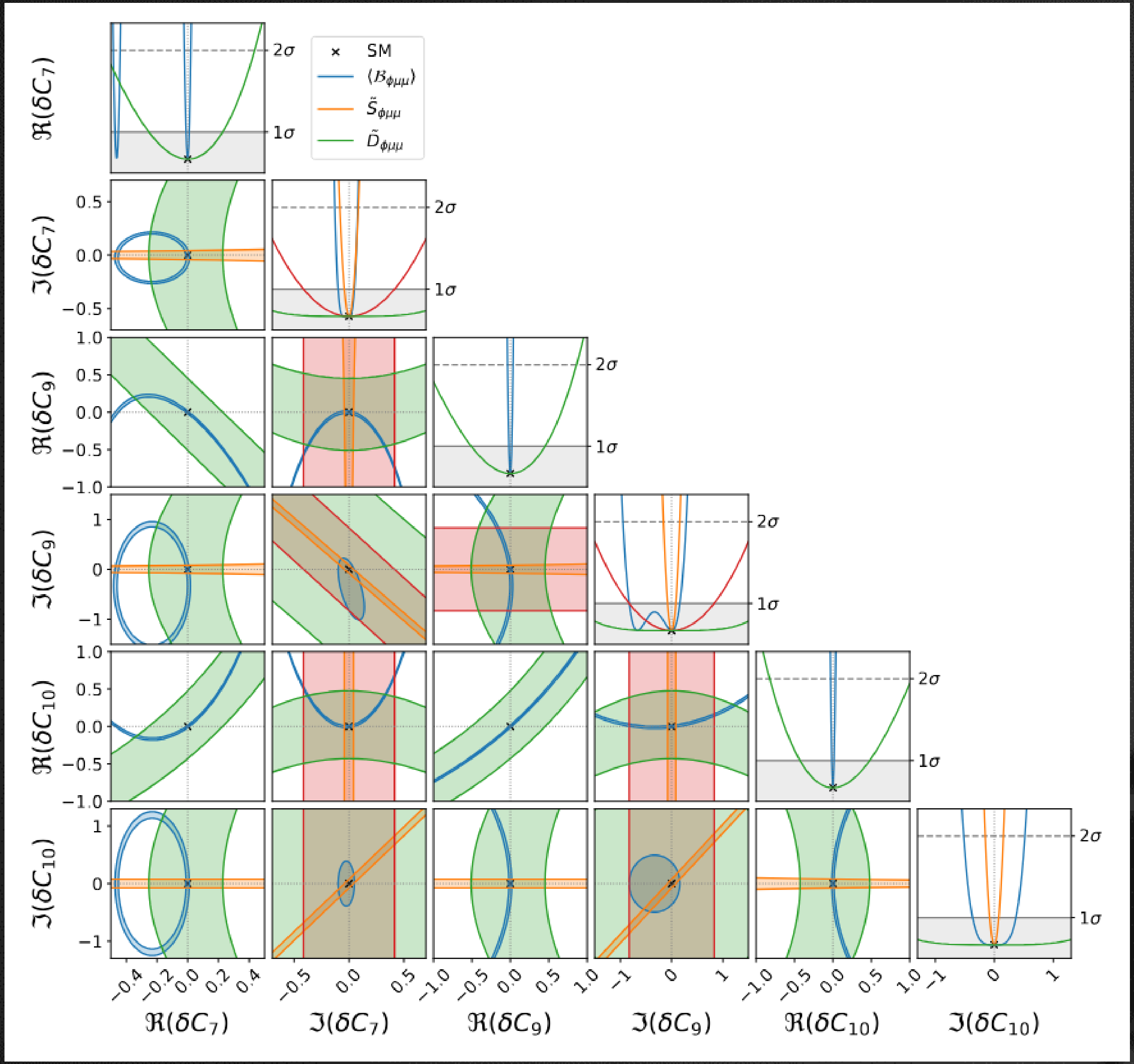
- KKμμ don't form a vertex
- m(KKμμ) != m(B_s)
- m(KK) != m(φ)

Why doing a fit in $m(B_s)$?
Leak of simulation samples





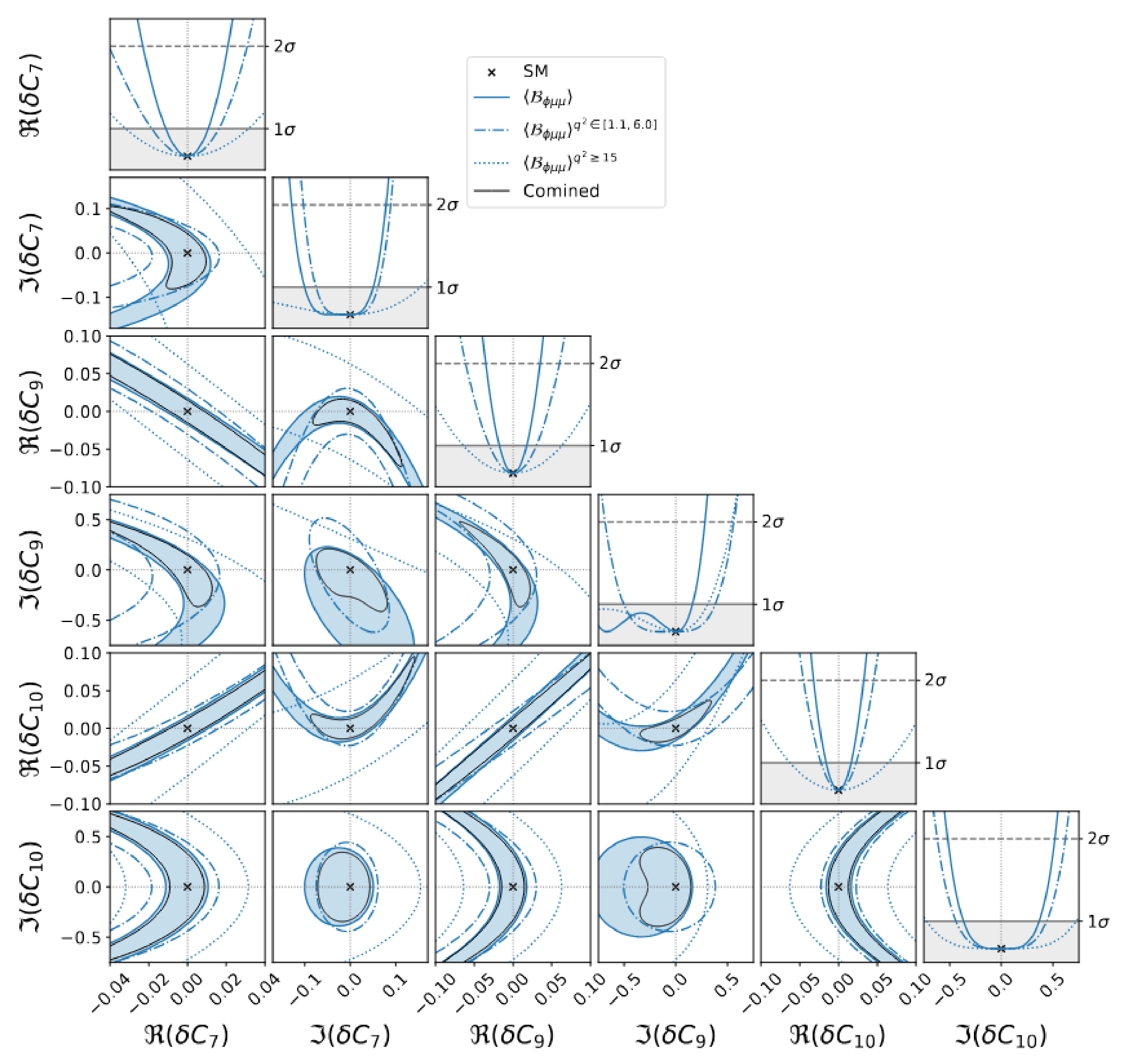




Why D_f, C_f measurement is not included?

Not so sensitive compared to S_f

Extra argument vs LHCb:
They can measure D_f but not much physics can be told from D_f along.



Binned measurements