Does it rock?

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

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16/9/24 FCC Physics Performance Meeting

Once upon a time. . . . .

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

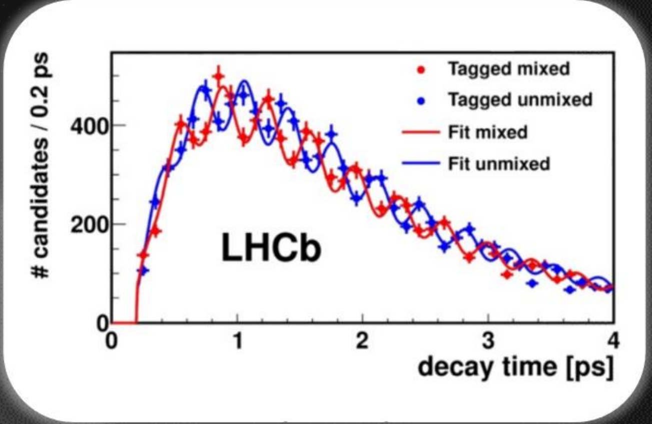
[Matter » Anti-matter]

Sakharov Condition (within Baryogenesis):

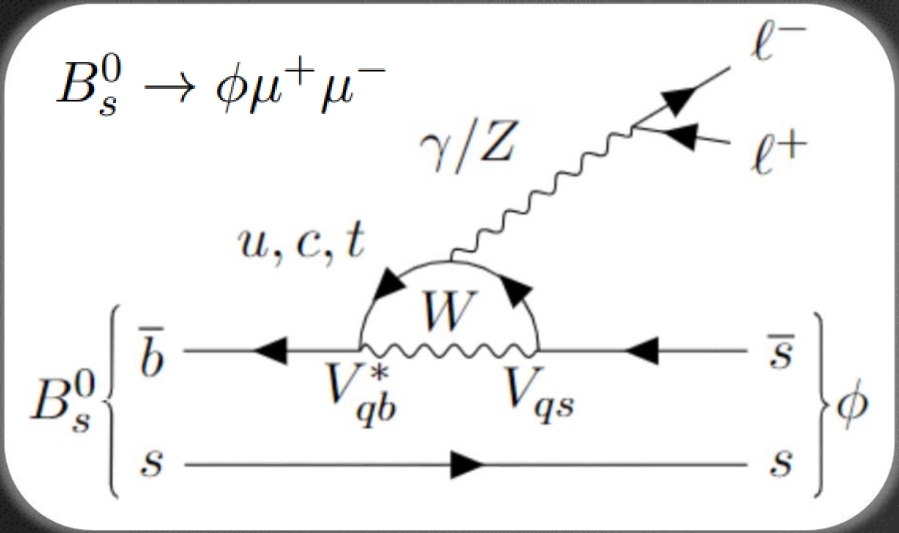
- Baryon number violation
- Interactions out of thermal equilibrium
- <u>C, CP violation</u>

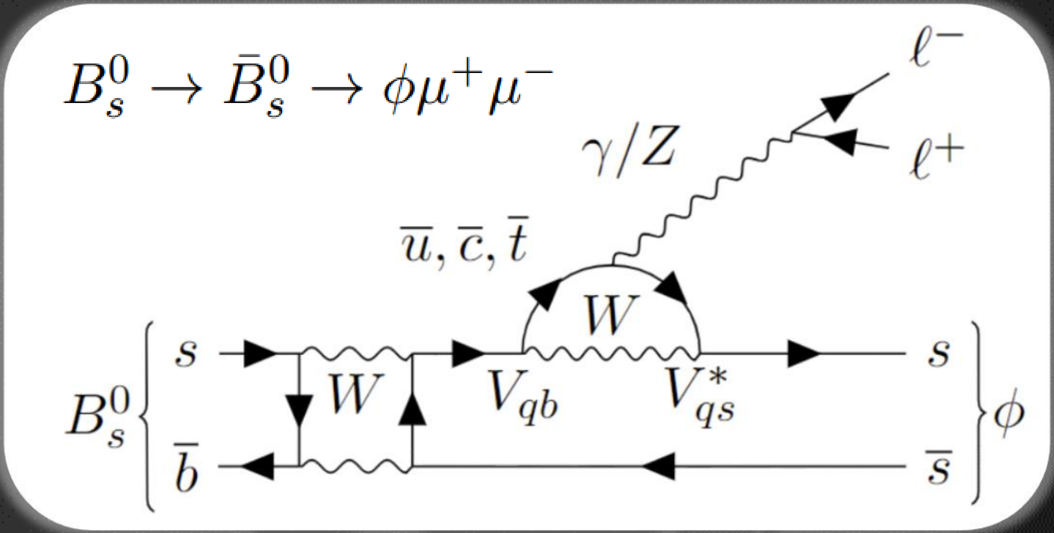
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

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



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





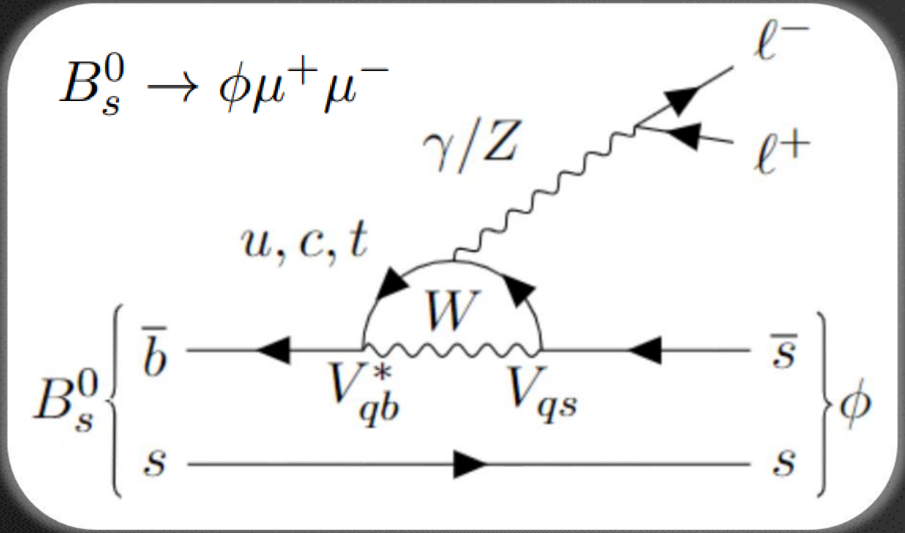
Just an example, there are more diagrams

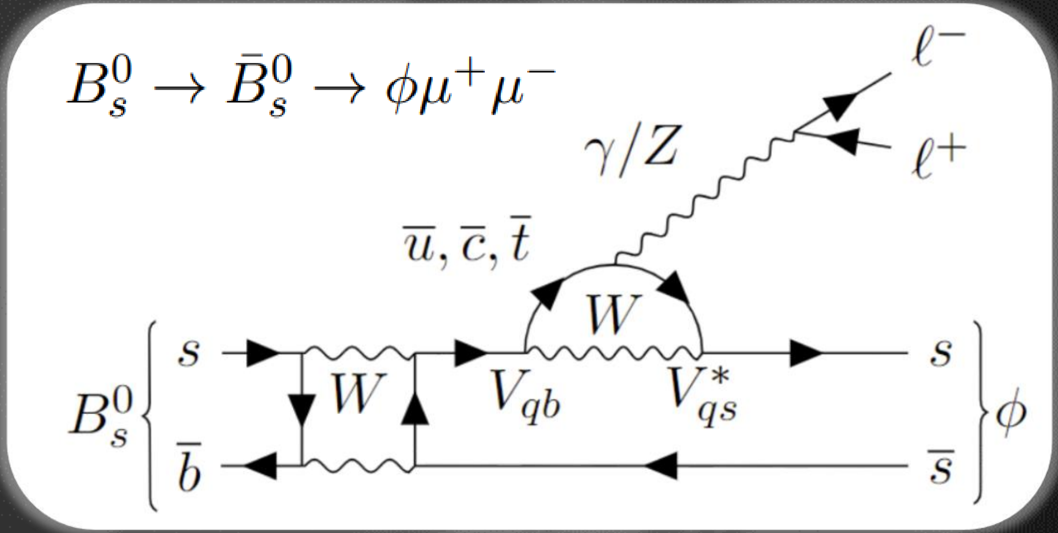
We look at. . . . . (CPV from NP?)

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]

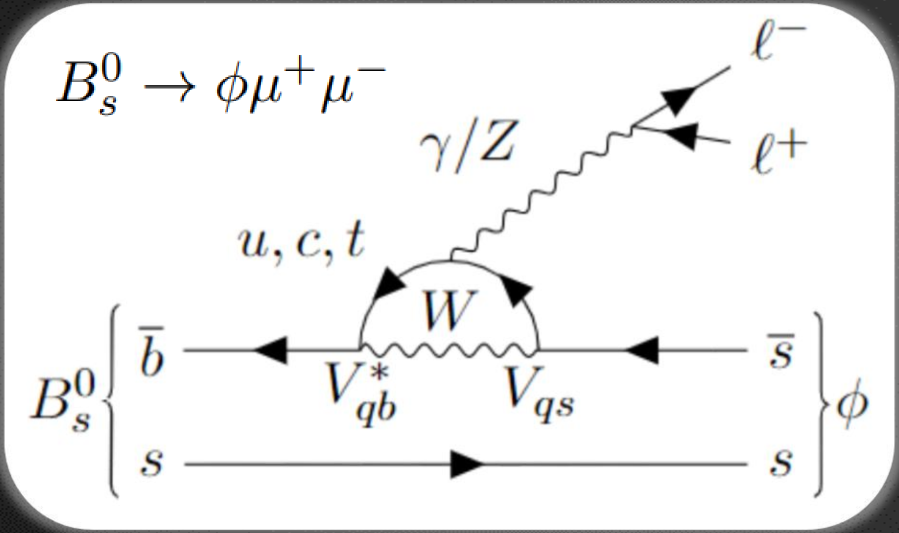


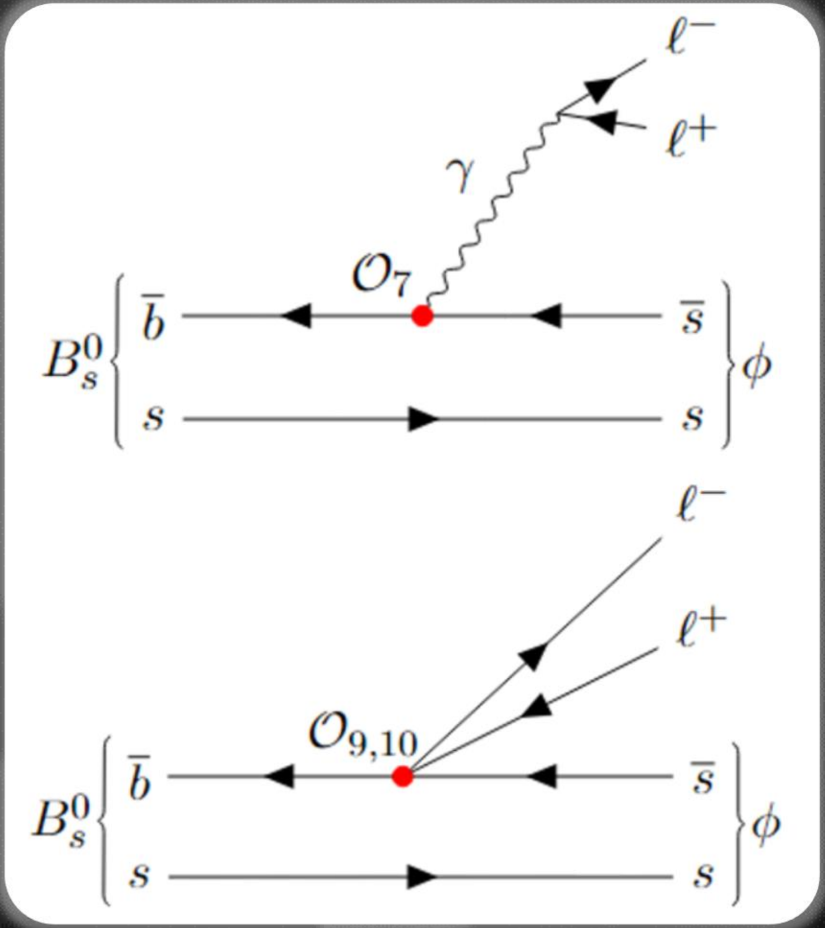


Just an example, there are more diagrams

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

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





Just an example, there are more diagrams

Why FCC-ee . . . .?

FCC-ee at Z-pole

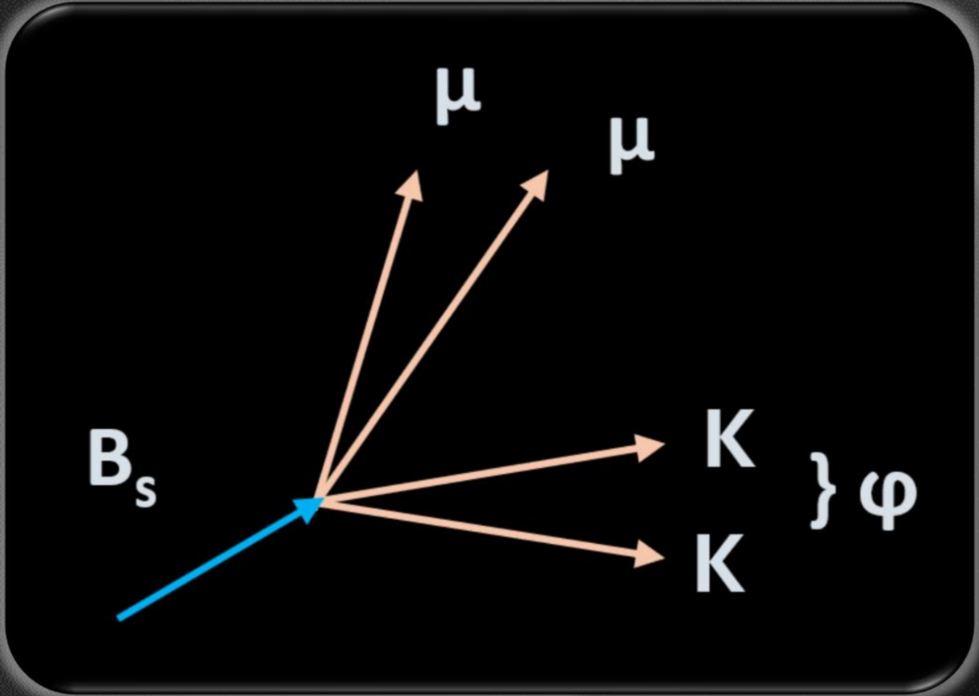
b-hadron	Belle II	LHCb	FCC-ee
B^0, $\bar{B}^0$	5.3×10^{10}	6×10^{13}	7.2×10^{11}
$B^{\pm}$	5.6×10^{10}	6×10^{13}	7.2×10^{11}
B^0_s, $\bar{B}^0_s$	5.7×10^{8}	2×10^{13}	1.9×10^{11}
$B^{\pm}_c$	...	4×10^{11}	1.1×10^{9}
Λ^0_b, $\bar{\Lambda}^0_b$	...	2×10^{13}	1.5×10^{11}

Genève

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

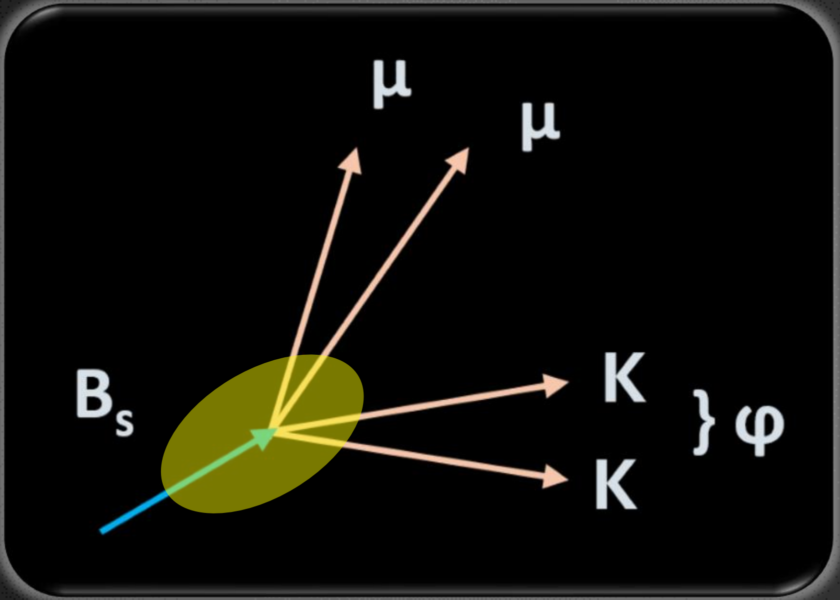
- Clean (vs LHCb)
- Good Flavor Tagging (vs LHCb)
- Large Stat. (vs Belle II)
- Good Vertexing (vs Belle II)
- ...

Cartoon Diagram of Signal. . . . . . .

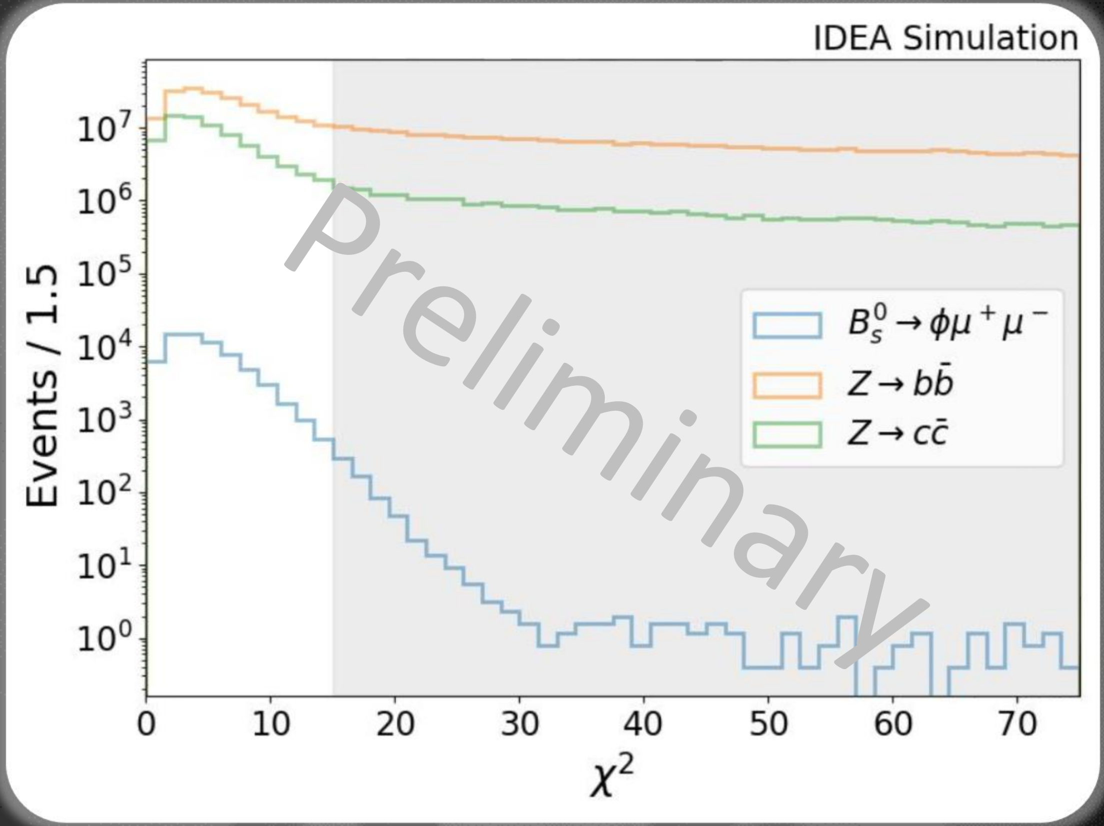


We use Pythia + Delphes (IDEA) for simulating signal & backgrounds

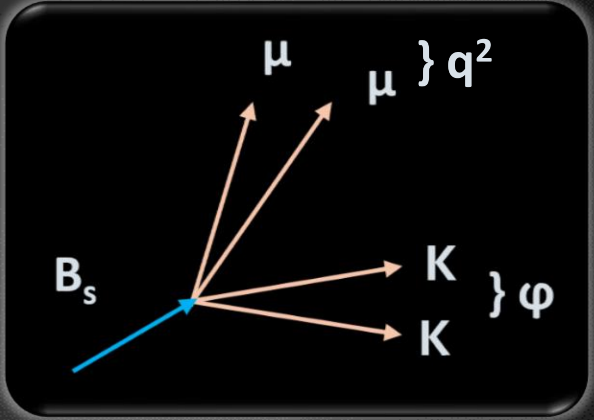
Some Physics of Signal. . . . .



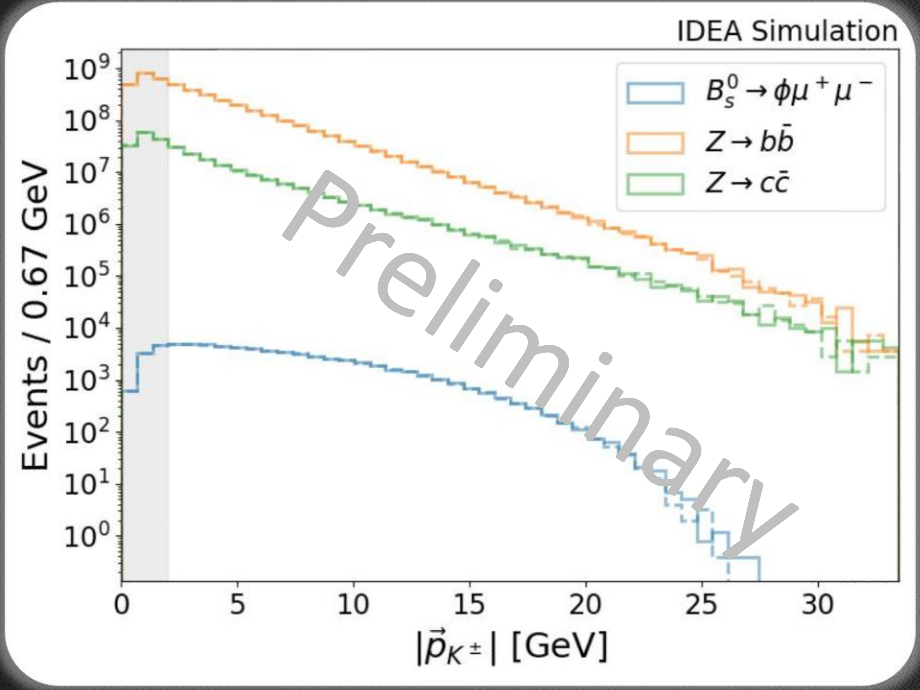
Vertex Fit



Some Physics of Signal. . . . .

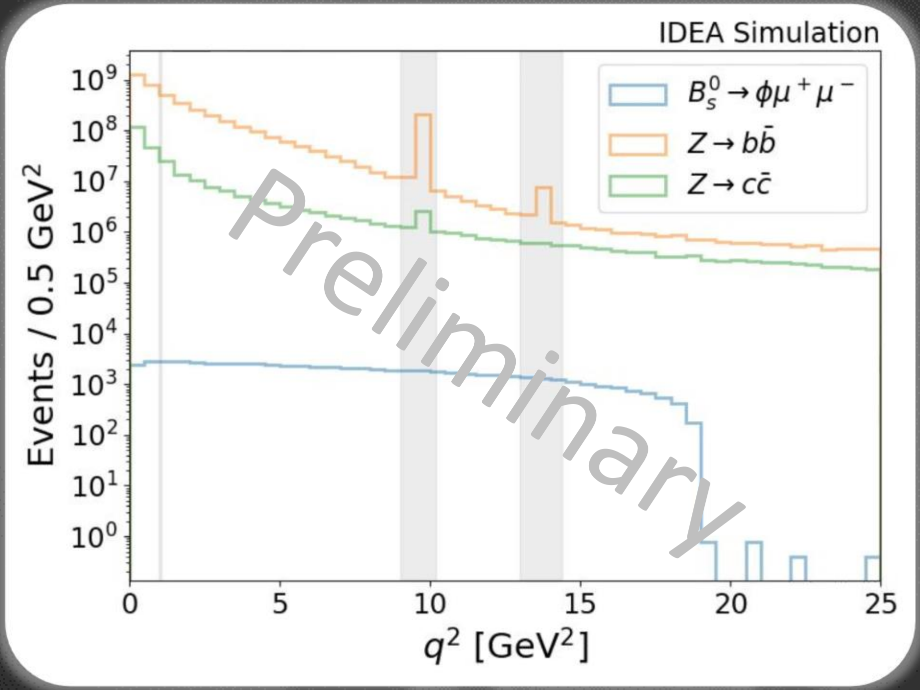


Kinematics

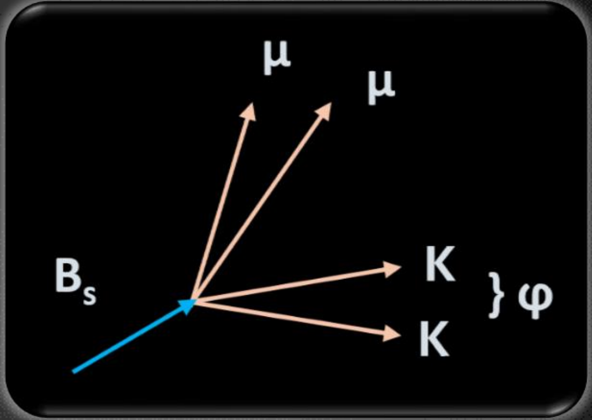


Resonances

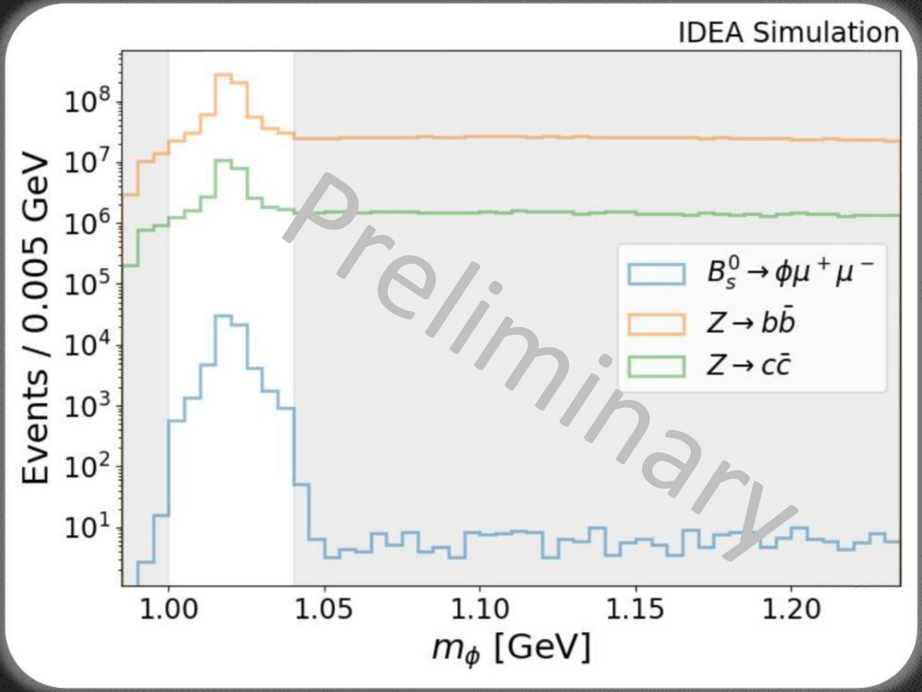
(momentum transferred to dimuon system)



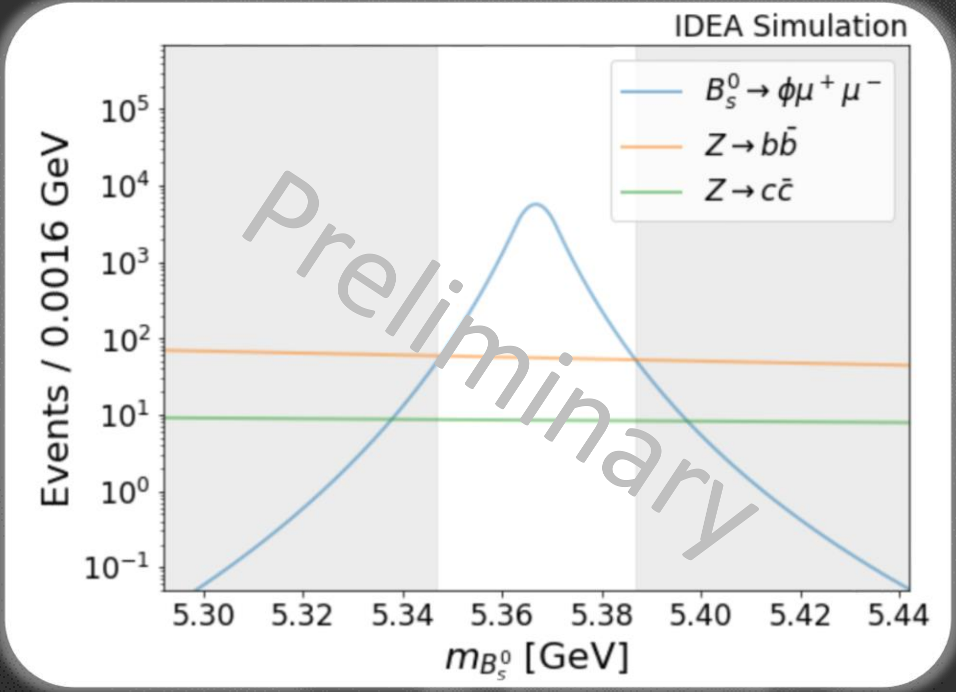
Some Physics of Signal. . . . .



Inv. mass (Dikaon)



Inv. Mass (Dikaon + Dimuon)



Cut Flow. . . . .

Cut Flow. . . . .

Channel	$B_s^0 \to \phi\mu^+\mu^-$	$Z \to b\bar{b}$	$Z \to c\bar{c}$
Events at FCC-ee	7.19×10^4	9.07×10^{11}	7.22×10^{11}
N_{FS}	6.72×10^4	4.34×10^9	2.82×10^8
N_{χ^2}	6.61×10^4	2.15×10^8	7.25×10^7
$N_{\lvert\vec{p}\rvert}$	4.25×10^4	5.98×10^7	2.25×10^6
N_{m_ϕ}	4.23×10^4	3.21×10^7	3.64×10^5
N_{q^2}	3.66×10^4	1.24×10^7	3.13×10^6
$N_{m_{B_s^0}}$	3.62×10^4	1.39×10^3	2.13×10^2

Precision: ~0.5% (vs LHCb: ~2.6%)

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. . . . . ?

Fact Sheet on "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

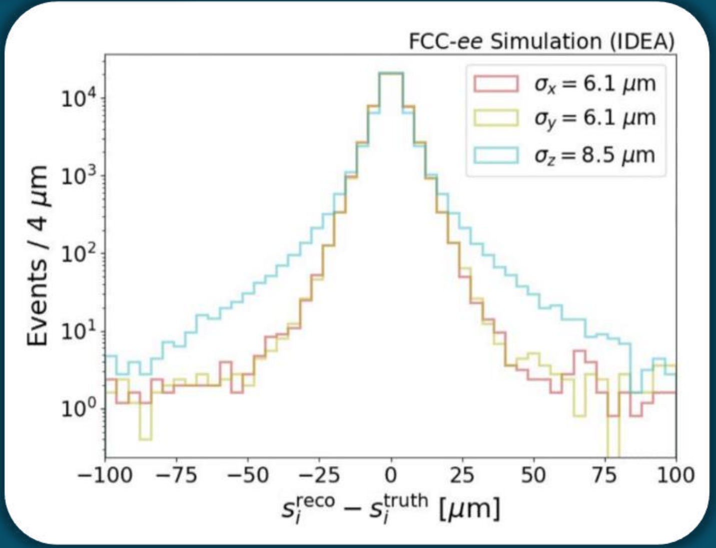
Uncert. ~ 1/sqrt{Tag Power}

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

Fact Sheet on "Timing"

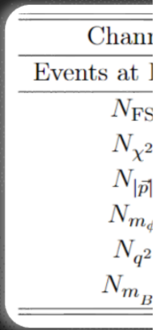
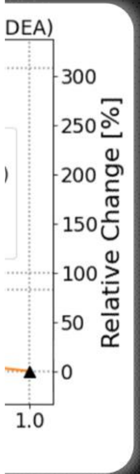
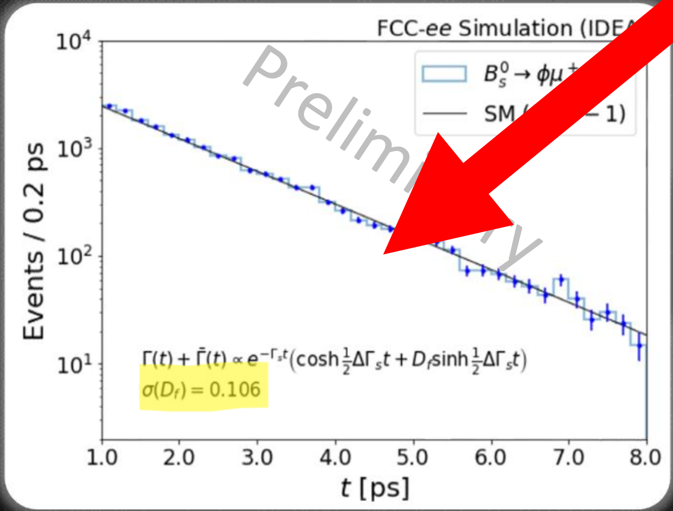
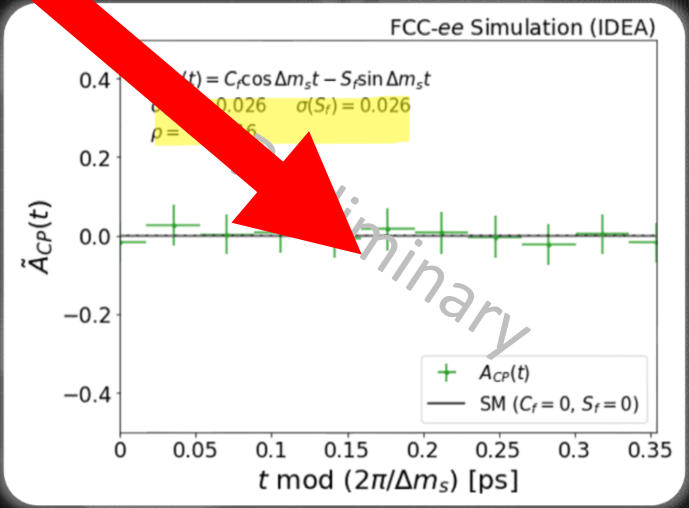
Time resolution effect: dilution factor (~0.995)

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



What Can We Measure. . . . . ?

"Tagging":
Tell they're from B or anti-B
Uncert. ~ 1/sqrt{Tag Power}

	Untagged	Tagged
Time-independent		
Time-dependent		

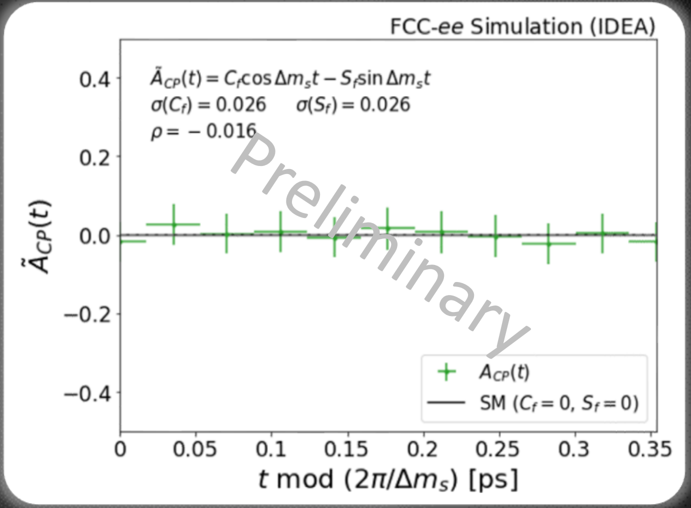
LHCb may measure untagged time-dependent

BUT

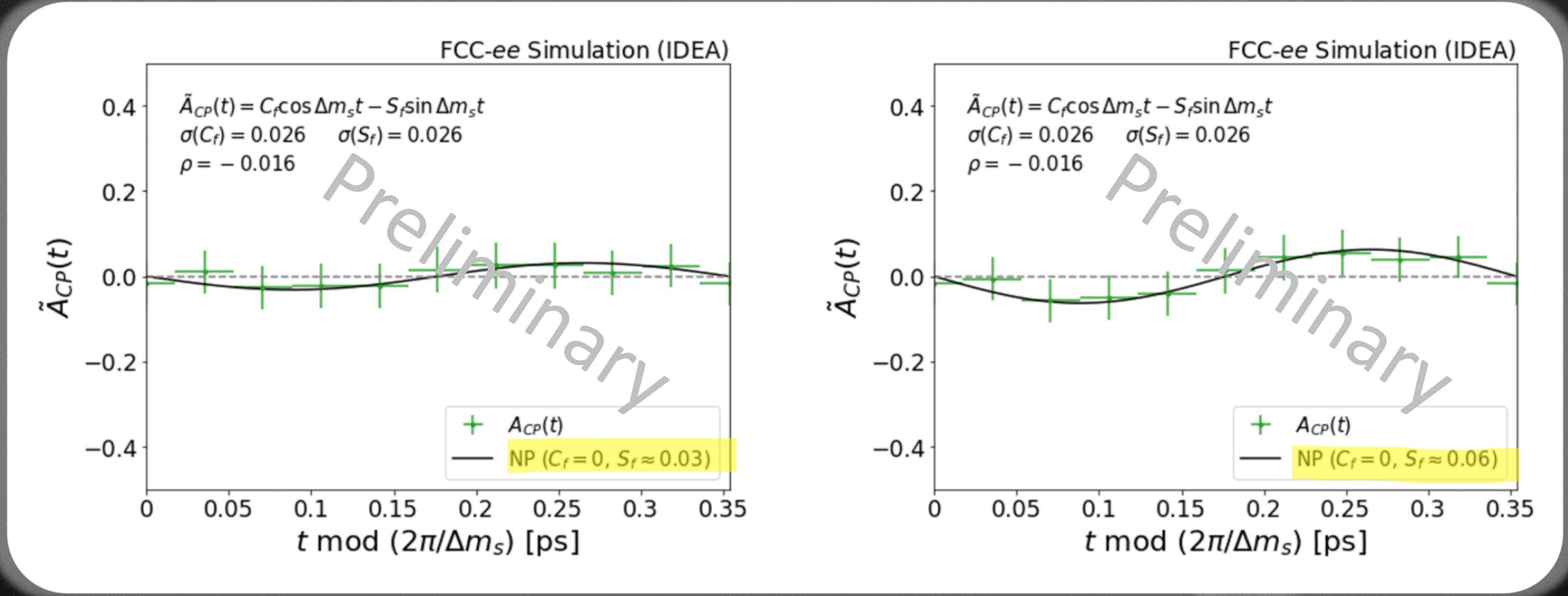
FCC-ee is really (almost) the only one can measure tagged time-dependent

If NP exists. . . . . ?

FYI: SM is like:

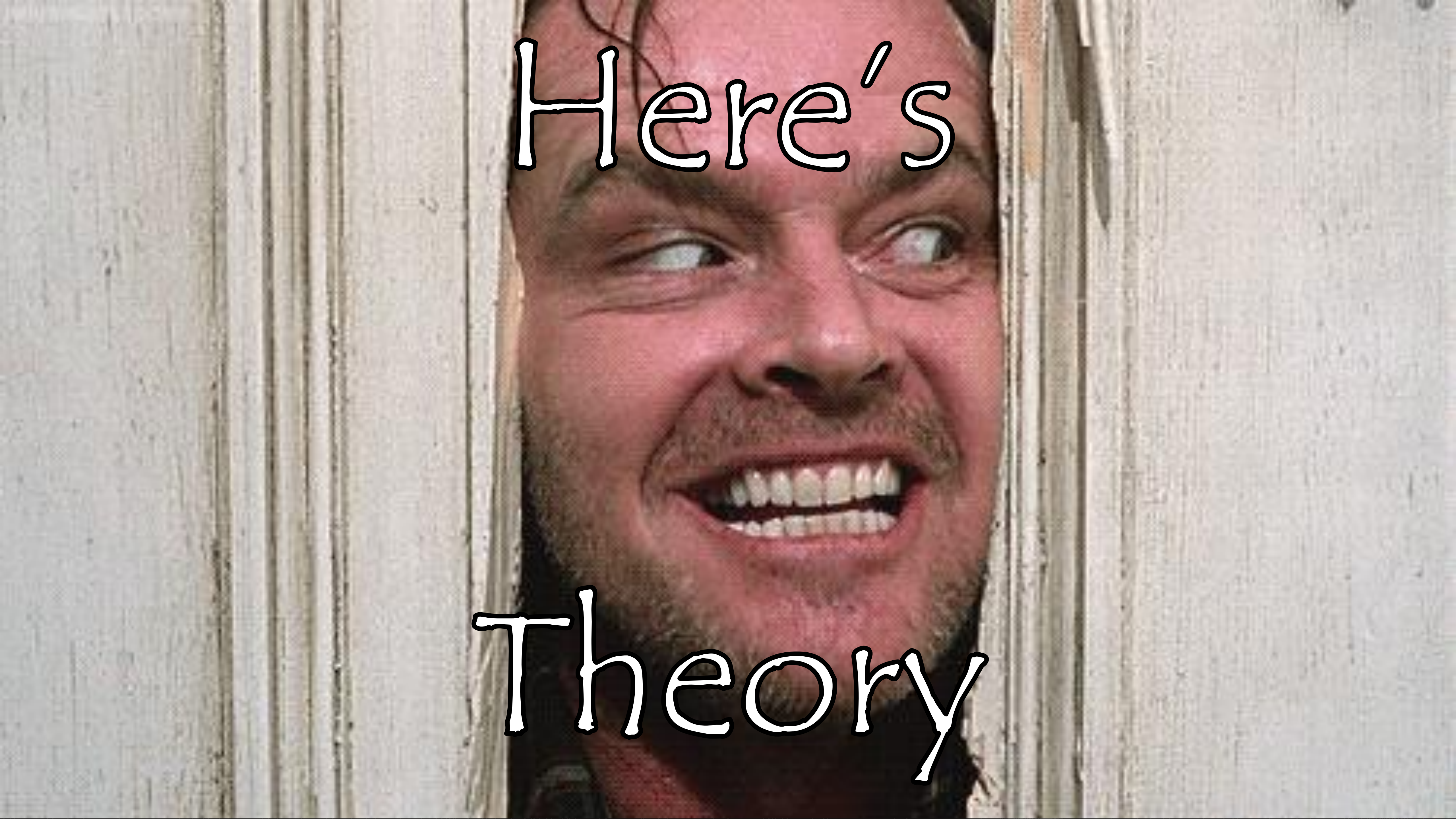


If there are $\mathrm{Im}[C_{NP}]$



Conclusion (Analysis Part):

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

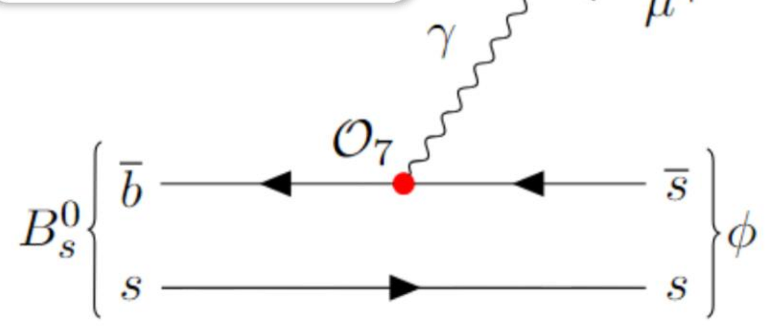

Here's
Theory

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

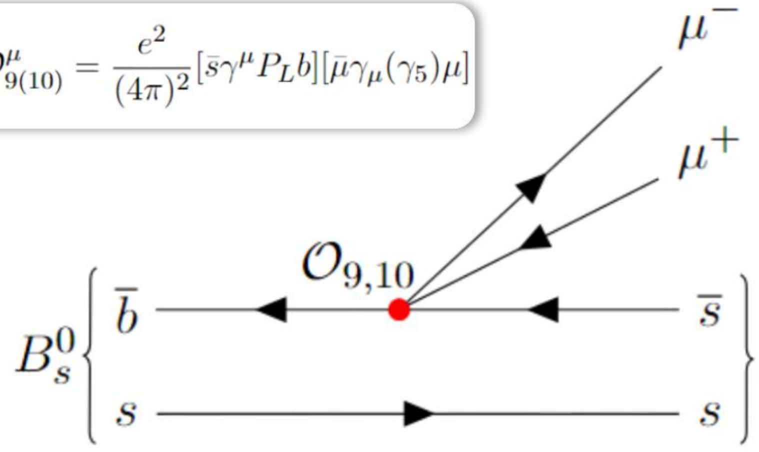
$$\mathcal{H}^{\text{eff}} \supset -\frac{4G_F V_{tb} V_{ts}^*}{\sqrt{2}} \left(\sum_{i=1}^{8} \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right) + \sum_{i=9}^{10} \left(C_i \mathcal{O}_i^{\mu} + C_i' \mathcal{O}_i^{\mu\prime} \right) \right) + \text{h.c.}$$

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). . . . . . .

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

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

Observable as function of C's

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

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

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

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

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

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

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

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

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

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

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

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

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

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

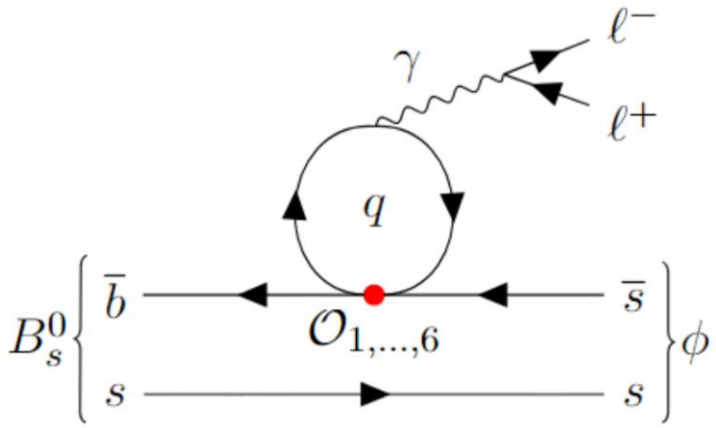
Our projection is pushing theory limit

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. . . . .

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



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

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

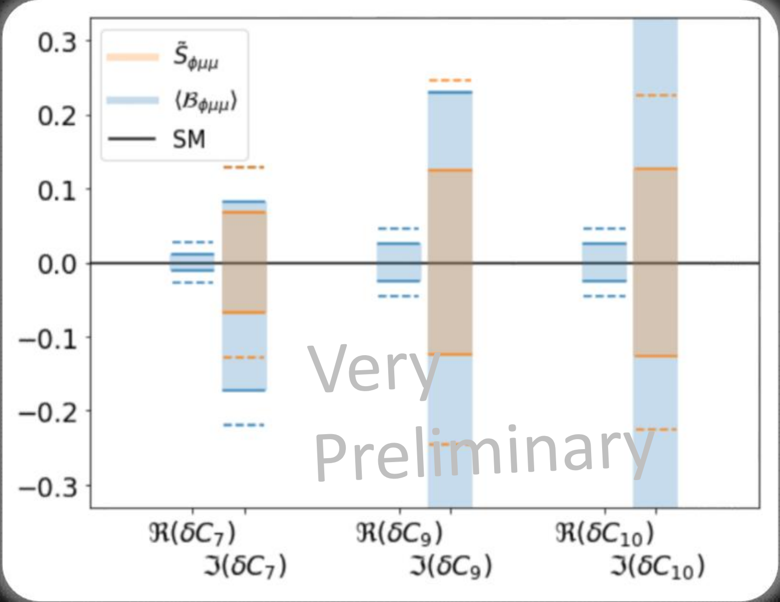
Money Plot (In Construction)…….

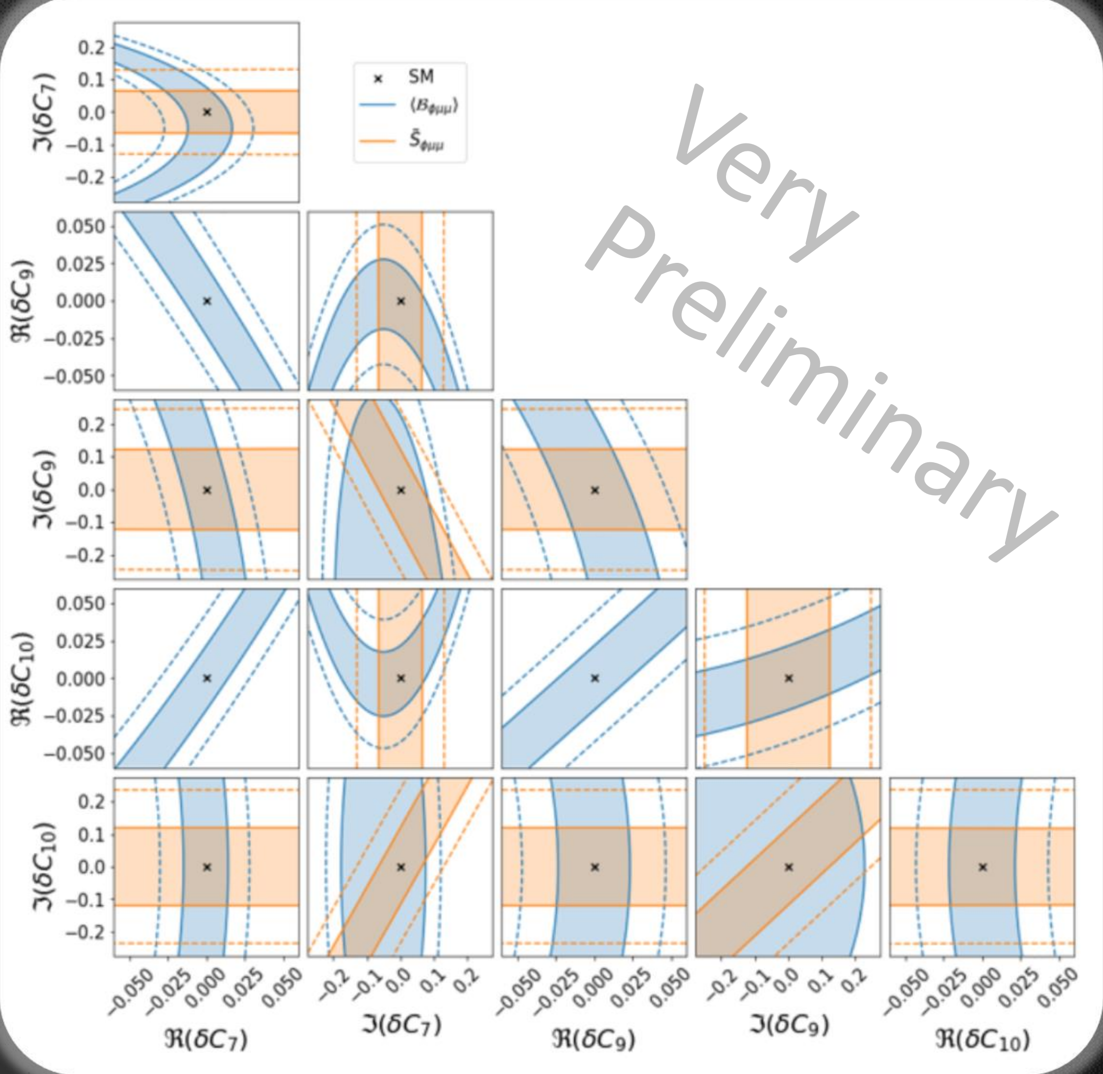
$$\frac{\mathrm{Br}(B_s^0 \to \phi\mu^+\mu^-)}{\mathrm{Br}(B_s^0 \to \phi\mu^+\mu^-)_{\mathrm{SM}}} = 1 + \sum_k b_k^{\mathrm{Full}} \delta C_k + \sum_{k\ell} B_{k\ell}^{\mathrm{Full}} \delta C_k \delta C_\ell \,,$$

$$\frac{\mathrm{Br}(B_s^0 \to \phi\mu^+\mu^-)^{q^2\in[1.1,6.0]}}{\mathrm{Br}(B_s^0 \to \phi\mu^+\mu^-)_{\mathrm{SM}}^{q^2\in[1.1,6.0]}} = 1 + \sum_k b_k^{\mathrm{Low}} \delta C_k + \sum_{k\ell} B_{k\ell}^{\mathrm{Low}} \delta C_k \delta C_\ell \,,$$

$$\frac{\mathrm{Br}(B_s^0 \to \phi\mu^+\mu^-)^{q^2\geq 15}}{\mathrm{Br}(B_s^0 \to \phi\mu^+\mu^-)_{\mathrm{SM}}^{q^2\geq 15}} = 1 + \sum_k b_k^{\mathrm{High}} \delta C_k + \sum_{k\ell} B_{k\ell}^{\mathrm{High}} \delta C_k \delta C_\ell \,,$$

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





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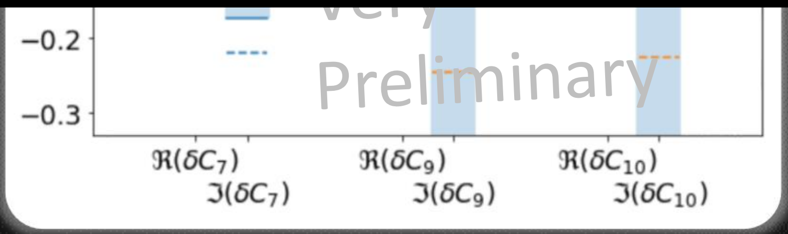
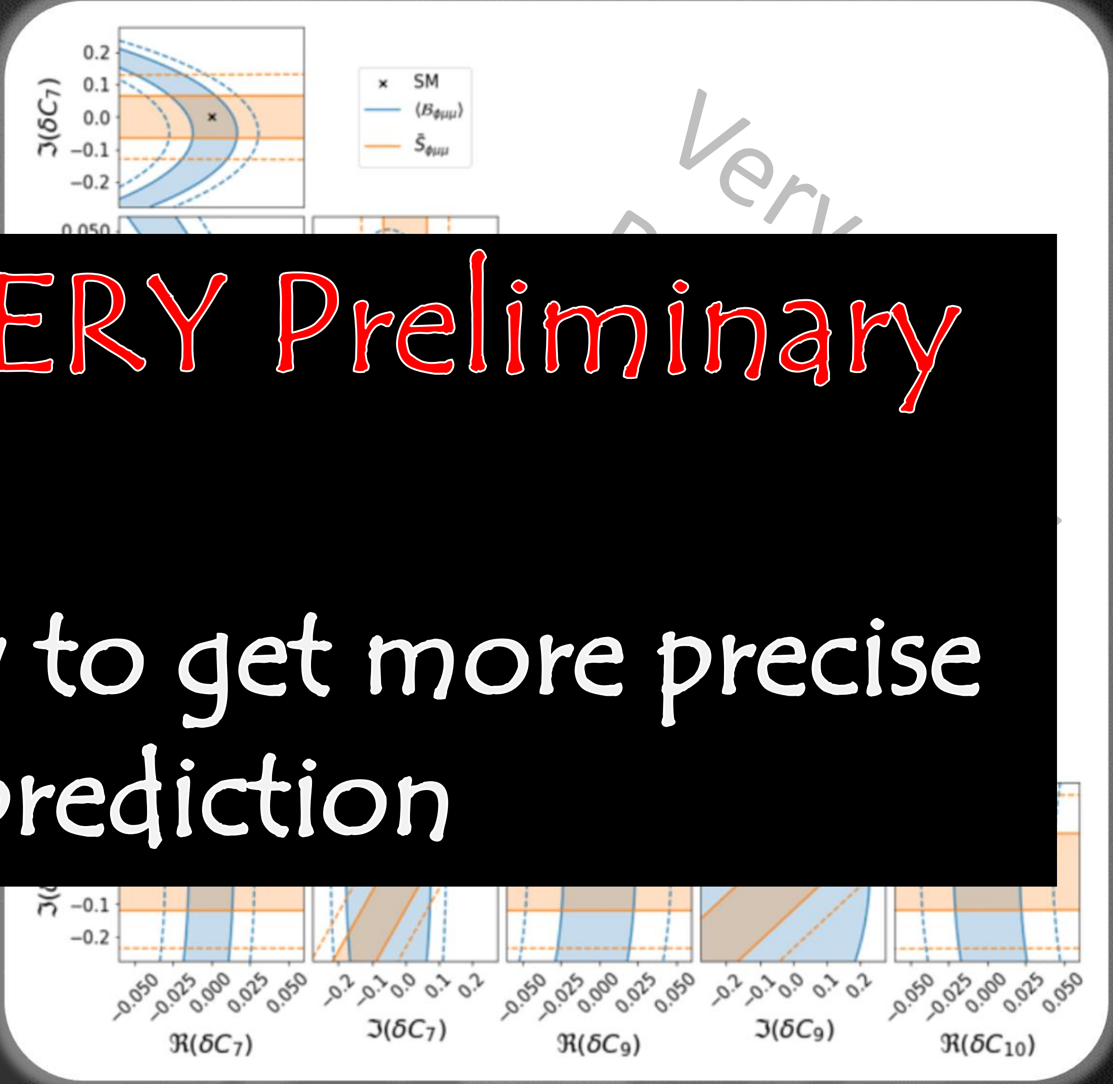
$$\frac{\mathrm{Br}(B_s^0\to\phi\mu^+\mu^-)^{q^2\in[1.1,6.0]}}{\mathrm{Br}(B_s^0\to\phi\mu^+\mu^-)_{\mathrm{SM}}^{q^2\in[1.1,6.0]}} = 1+\sum_k b_k^{\mathrm{Low}}\delta C_k + \sum_{k\ell} B_{k\ell}^{\mathrm{Low}}\delta C_k\delta C_\ell\,,$$





WARNING: VERY Preliminary

Still discussing how to get more precise theory prediction

Form Factor Uncertainties. . . . .

Using interpolated results from Lattice QCD + Light-cone Sum Rules

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

$$b_k^{\mathrm{Full}} = \big(0.37(7) \quad 0.04(2) \quad 0.23(3) \quad 0.02(1) \quad -0.25(3) \quad 0\big)$$

Theoretical uncertainty is NOT neglectable!!!

$$\begin{matrix} 0.030(4) & 0 & 0 \\ & 0.030(4) & 0 \\ & & 0.030(4) \end{matrix}$$

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 just theoretical uncert. suppressed to similar order of magnitude]
In Progress	Include the theoretical uncert. in the fit

Conclusion

Big Question	Why matter » antimatter?
Exact Problem	Do we have CPV from NP
	[If just theoretical uncert. suppressed to similar order of magnitude]
In Progress	Include the theoretical uncert. in the fit

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

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	Armin Ilg

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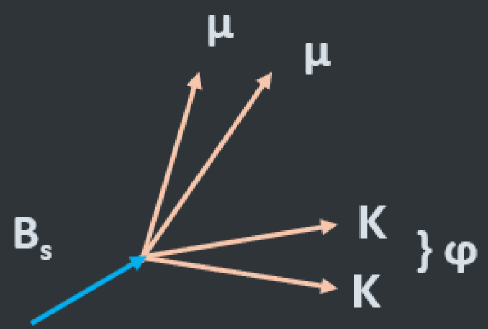
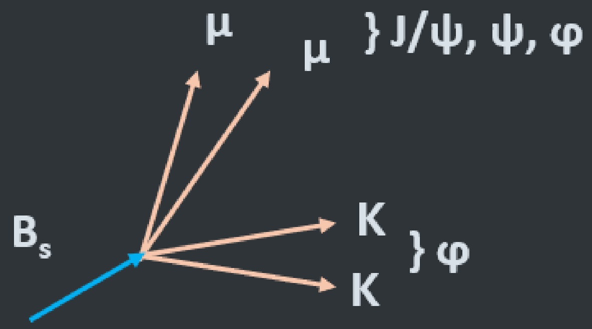
Backups. . . . .

What background types do we have?

Signal

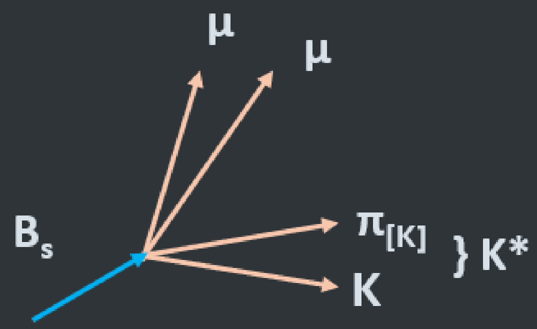


Resonance



- m(μμ) != m(J/ψ), m(ψ), m(φ)

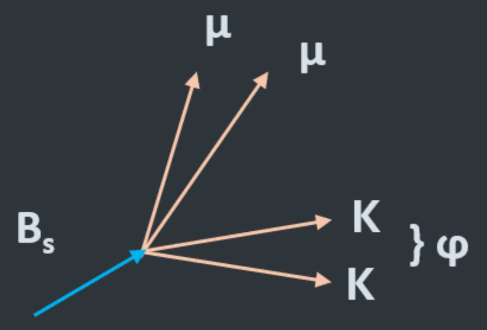
Peaking (misID)



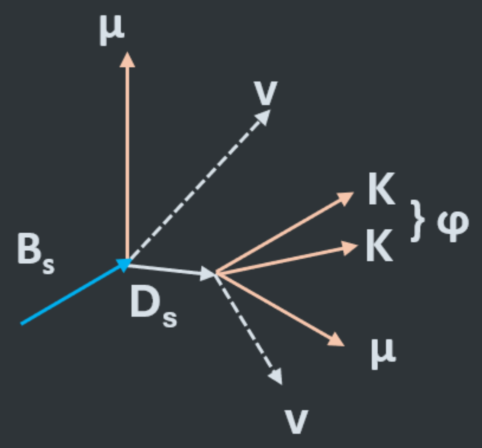
- m(K π[K]) != m(φ)
- O(1%) misID rate

What background types do we have?

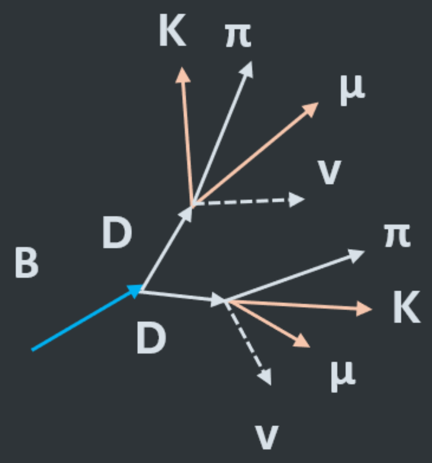
Signal



Z>bb Cascade

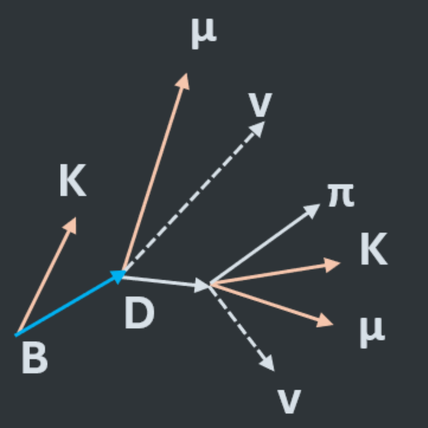


- KKμμ don't form a vertex
- m(KKμμ) != m(B_s)



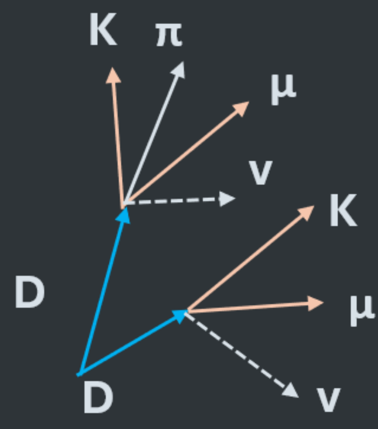
-m(KK) != m(φ)

Z>bb Comb.



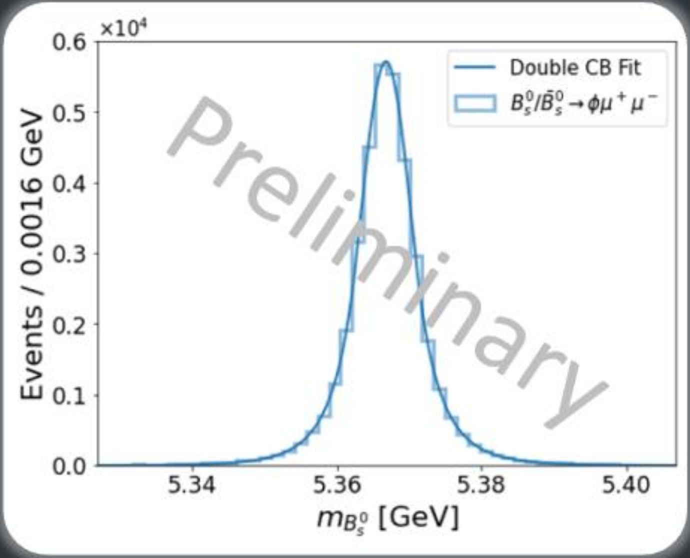
- KKμμ don't form a vertex
- m(KKμμ) != m(B_s)
- m(KK) != m(φ)

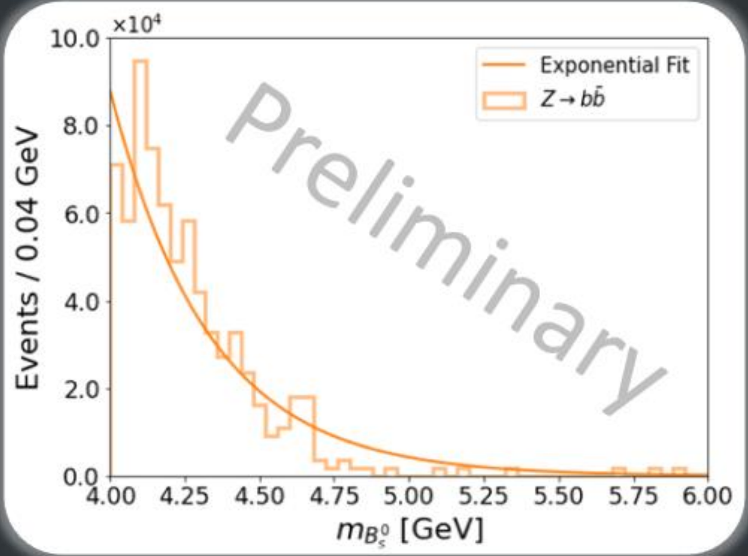
Z>cc Comb.

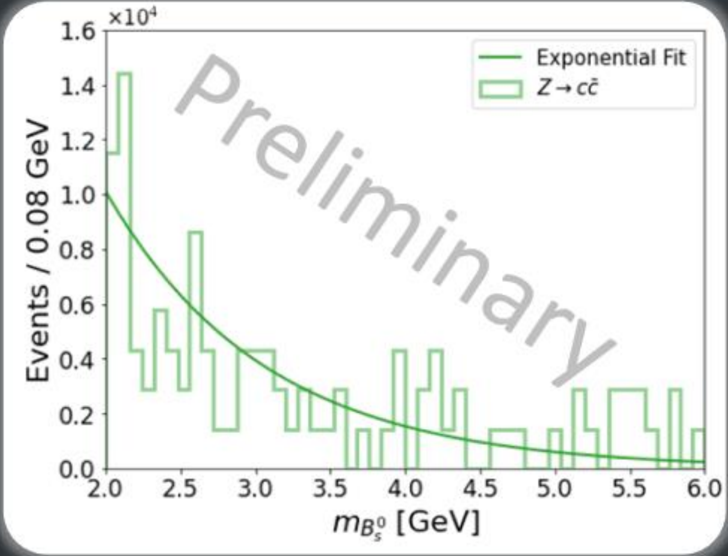


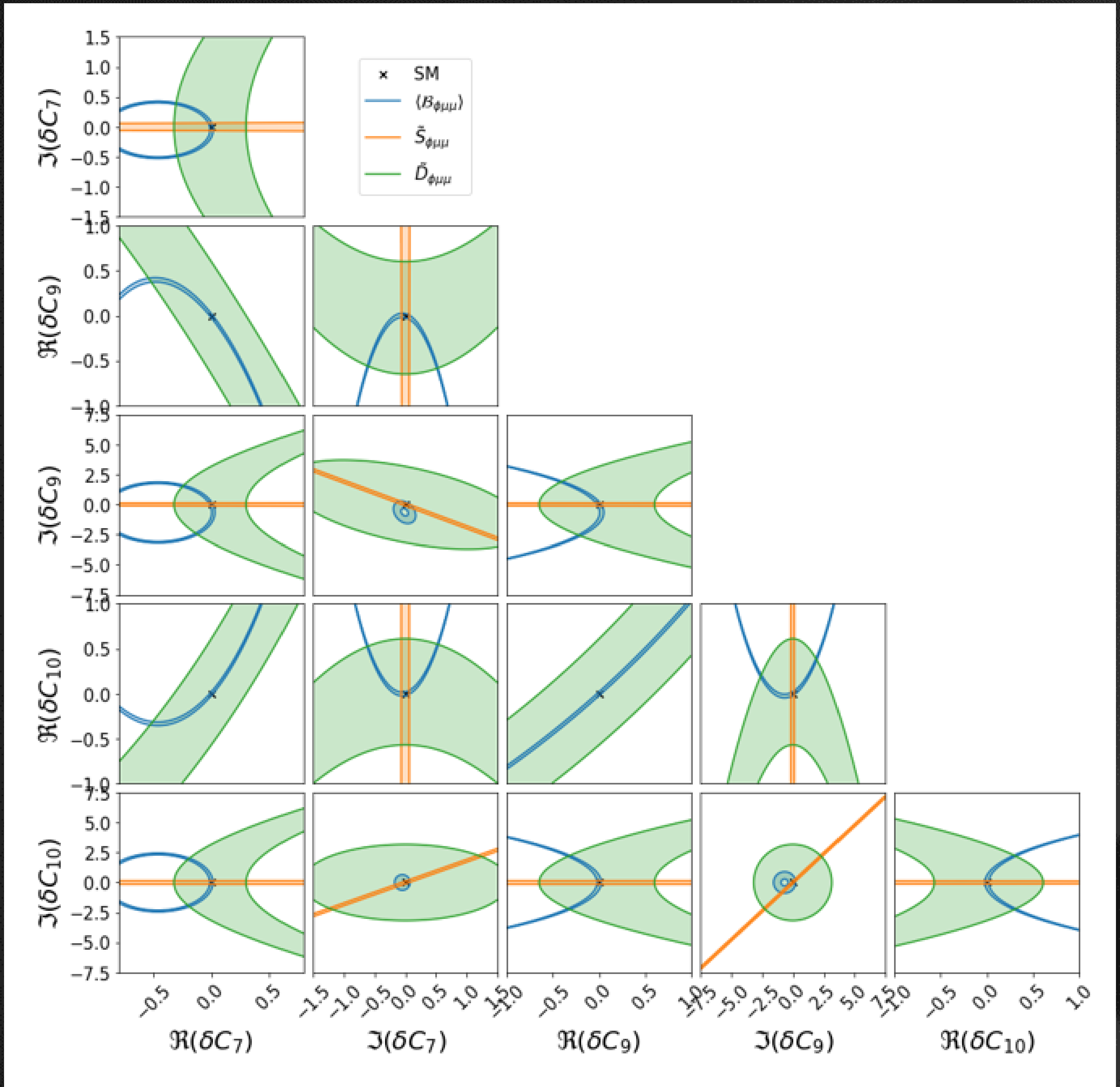
- KKμμ don't form a vertex
- m(KKμμ) != m(B_s)
- m(KK) != m(φ)

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





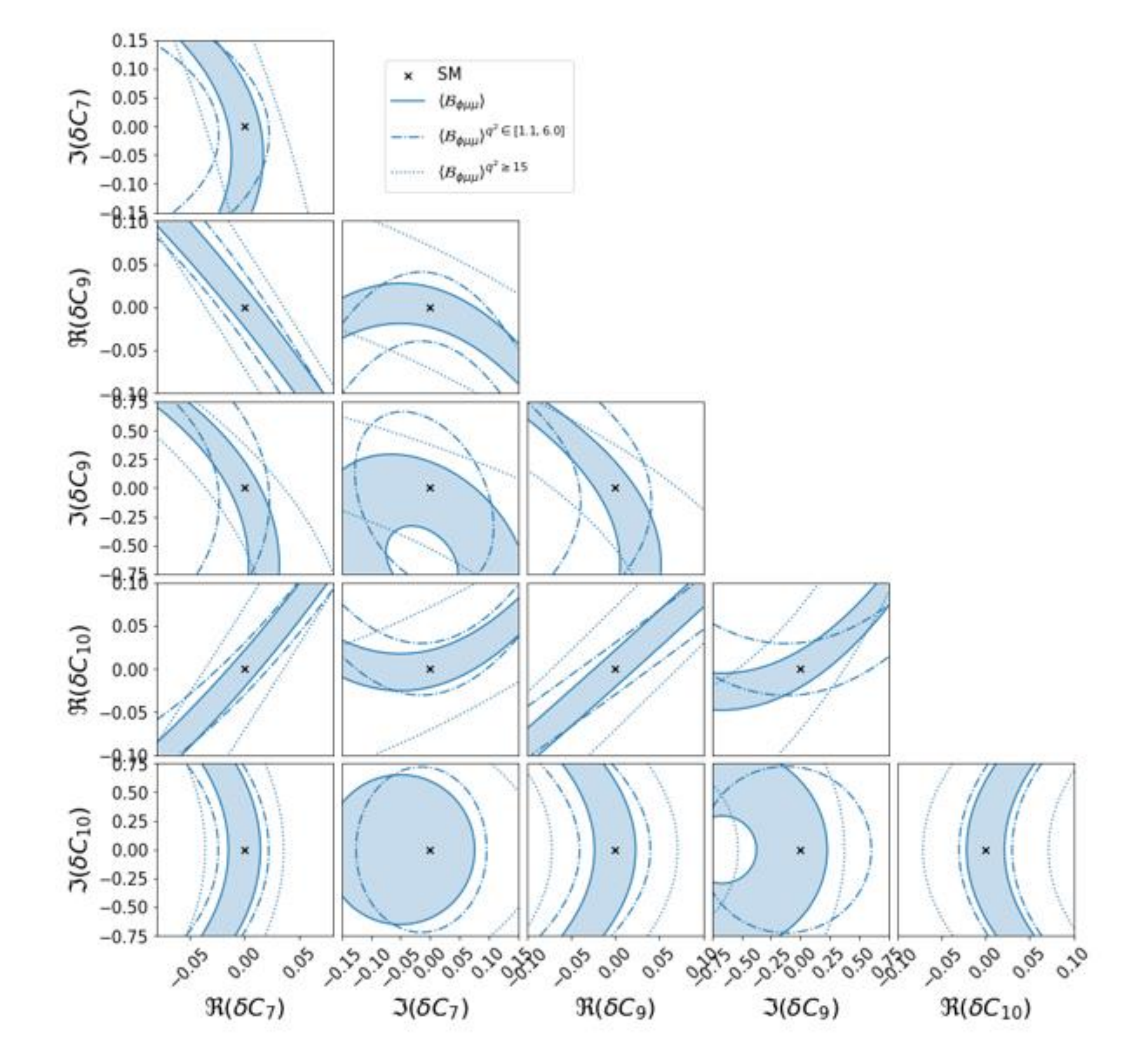




Why D_f measurement is not included?

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