A_{CP} in $K_S \to \mu\mu$

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A_{CP} in $K_S \to \mu\mu$

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$$\left(\frac{d\Gamma}{dt}\right) = N_f f(t), \quad f(t) = C_L e^{-\Gamma_L t} + C_S e^{-\Gamma_S t} + 2 C_{Int.} \cos(\Delta m t - \varphi_0) e^{-\Gamma t}$$

A. Dery, KAONS@JPARC

$A_{CP}(t\sim 0) \sim -2C_{int} \cos(\varphi_0) / (C_L + C_S)$

$$(C_L^{K^0})_{SM} = |A_0^{\text{CP-even}}|^2 \equiv 1,$$
$$(C_S^{K^0})_{SM} = |A_0^{\text{CP-odd}}|^2 + \beta_\mu^2 |A_1^{\text{CP-even}}|^2 \approx 0.43,$$
$$(C_{Int.}^{K^0})_{SM} = |A_0^{\text{CP-even}}||A_0^{\text{CP-odd}}| \approx 0.12,$$

https://arxiv.org/abs/2104.06427

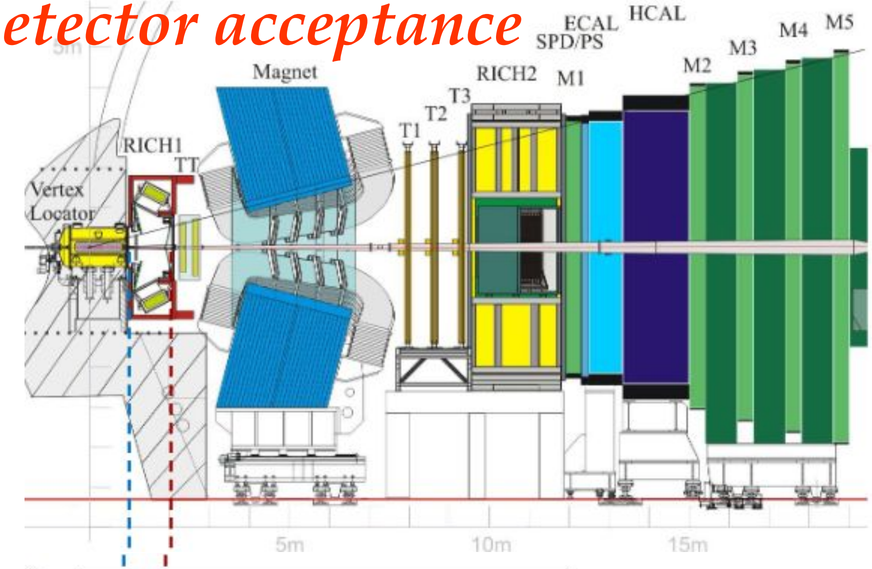
$$\cos^2 \varphi_0 = 0.96 \pm 0.02_{\text{exp}} \pm 0.02_{\text{th}}\,.$$

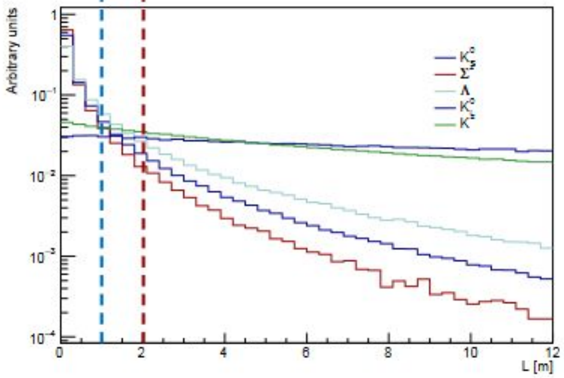
https://arxiv.org/pdf/2211.03804

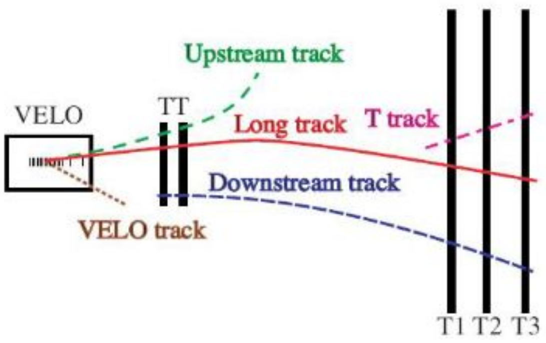
$|A_{CP}(0)|^{SM} \sim 16\%$

Sign depends on sign(Aγγ)

Detector acceptance







K→ μμ 50% Long 50% downstream

But only long are used

Lifetime acceptance and $K_L \to \mu\mu$

K_L and K_S are distinguishable only by the decaytime…
… and that is in theory. In practice, LHCb decaytime acceptance is not great for kaons

With β 5xΓs (>> Γ_L).

This makes the two lifetime distributions to look similar

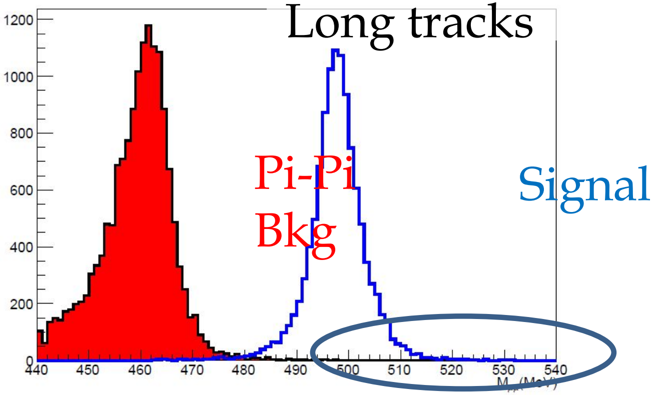
But the overall efficiency ratio is of course different

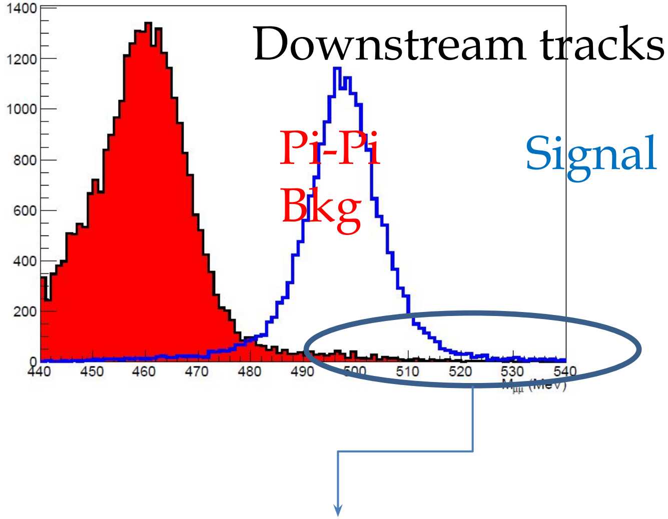
$$\frac{\epsilon_{K^0_{\rm L}}}{\epsilon_{K^0_{\rm S}}} = \frac{\Gamma_L \int_{0.1\tau_S}^{1.45\tau_S} e^{-t(\Gamma_S+\beta)} dt}{\Gamma_S \int_{0.1\tau_S}^{1.45\tau_S} e^{-t(\Gamma_L+\beta)} dt} \approx 2.2 \times 10^{-3}$$

$$\beta \sim 86\,\mathrm{ns}^{-1}$$

And makes K_L □μμ contribution to be "only" 3 times larger than the KS→ μμ signal

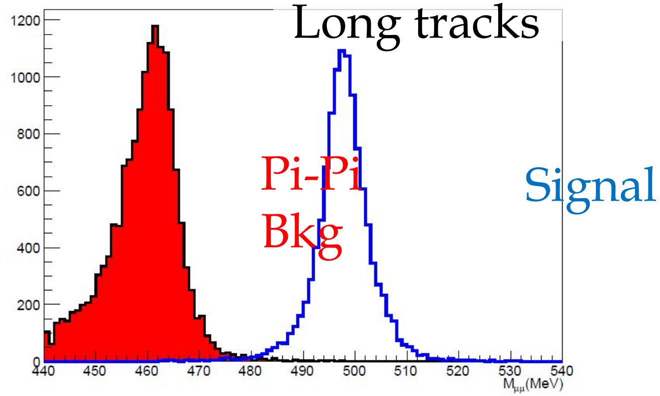
Long vs Downstream

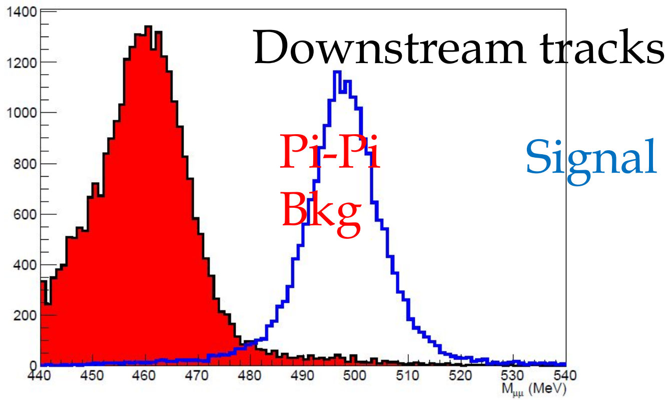


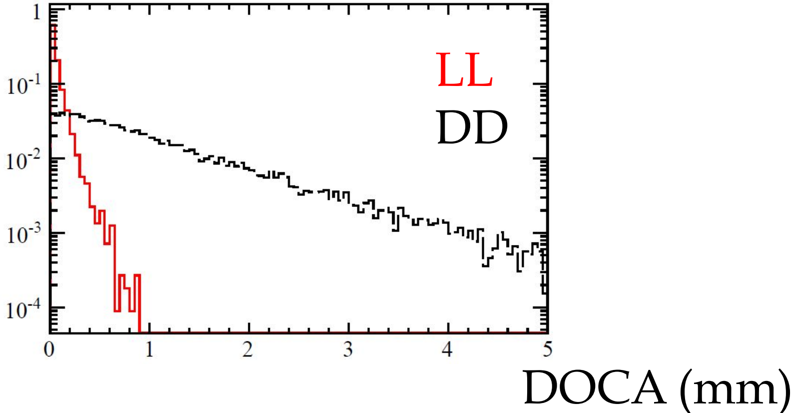


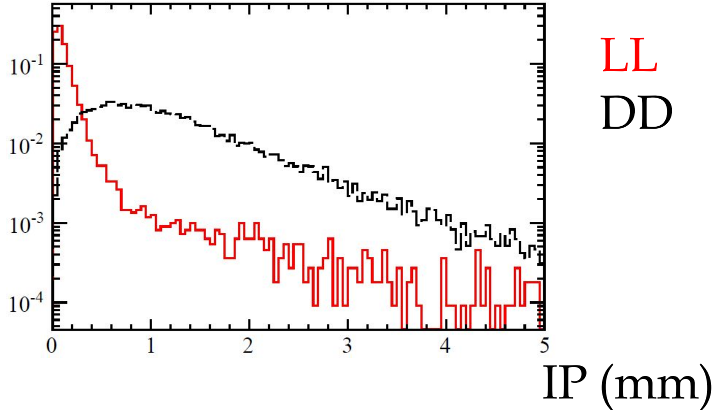
Signal over misid background is worse by a factor ~~10
(Accurate number would depend on selection/trigger/etc…)

Long vs Downstream









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Prospects and what could be done for ACP

$K_S \to \mu\mu$ latest result

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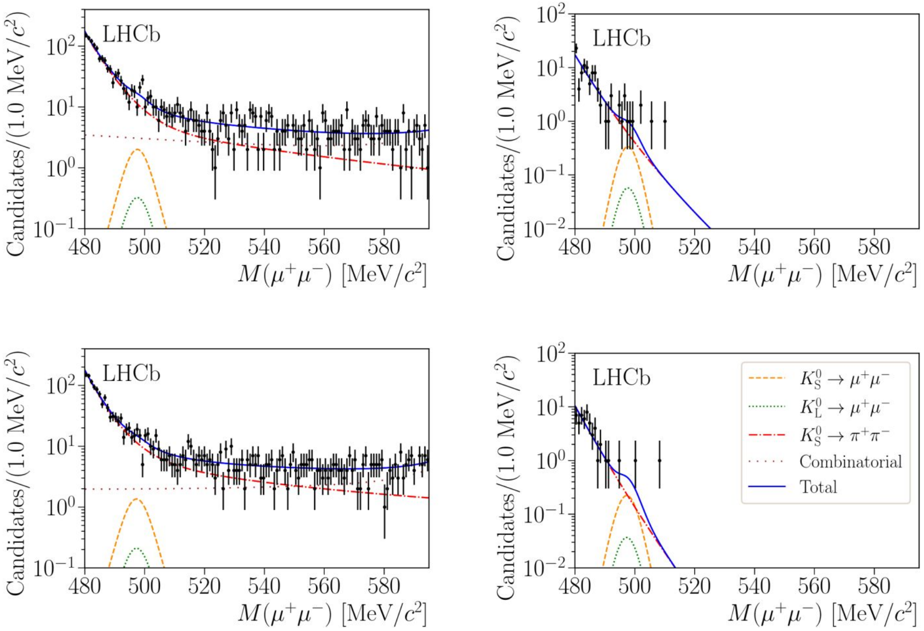
LHCb-PAPER-2019-038
arXiv: 2001.10354
PRL 125, 231801 (2020)



- Full dataset analysed (9 fb^{-1})
- No evidence for signal (1.4σ)

BR(K_S□$\mu\mu$) < 2.1×10^{-10} @ 90% CL

$K_S \to \mu\mu$: prospects

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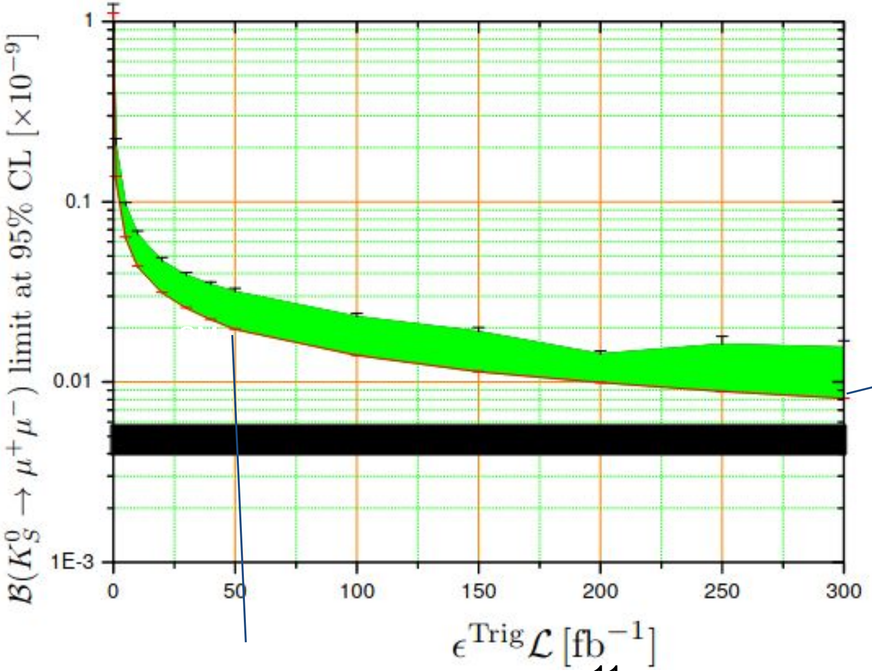
arXiv: 1808.03477



Extrapolations from Run1

Upgrade-II: Get close to the SM

Upgrade-I: few x 10^{-11}

$K_S \rightarrow \mu\mu$: prospects

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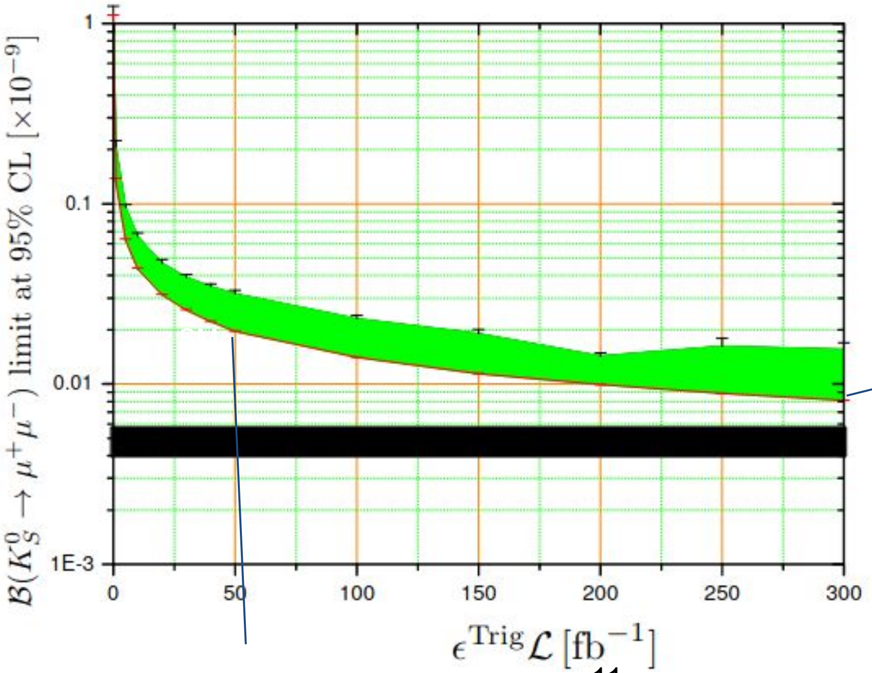
arXiv: 1808.03477



Upgrade-I: few x 10^{-11}

Extrapolations from Run1

Upgrade-II: Get close to the SM

Naive extrapolation (1/√L) from **Run2**:

BR< ~ 6.4x10^{-12} @ 95% CL
(or better, if some 1/L effect is still there)

Studying CP asymmetries in LHCb

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We could measure CP asymmetries in K0 decays at LHCb at t~0 (LHCb acceptance), if:

- Have a sizeable K^0 production asymmetry
  - It is **not** the case, ~ few %
  - Still, can try to exploit differences in η, pT → eg, valence quarks can be part of a K^0, but not of a K^0.

- We tag the K0 meson at production time
  - A promising way seems to be $pp \rightarrow K^0 K^- X$

$$pp \rightarrow K^0 K^- X,\ pp \rightarrow K^{*+} X \rightarrow K^0 \pi^+ X \text{ and } pp \rightarrow K^0 \Lambda^0 X.$$

Studying CP asymmetries in LHCb

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Evaluate tagging power for kaon events using Fast Simulation of LHCb upgrade

- Tracking system https://arxiv.org/abs/2012.02692 → Quite ok for efficiencies, resolutions
- Added on top PID efficiency, $\pi \rightarrow K$ misid from tabulated numbers

→ Got 3% tagging power for SSK : a bit on the optimistic side, but right ballpark
→Without much tuning on the K+ selection cuts , obtained:

$\varepsilon = 62\%$

D = ~~75%~~ 60%

→ tagging power for K^0's of ~~~35%~~ >> SSK for Bs

22%

$K_S \to \mu\mu$: prospects

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What do we need to estimate the sensitivity to A_{CP}?

⇒ Effective yield, $\mathbf{Y_{eff} \sim T_P S^2/(S+B)}$,

Tagging power: $\varepsilon_{Tag} D^2$

Tagging efficiency

Dilution

Fast simulation:

$T_P \sim 22\%$ (if one trusts Pythia)

$K_S \to \mu\mu$: prospects

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What do we need to estimate the sensitivity to A_{CP}?

$\Rightarrow$ Effective yield, $\mathbf{Y_{eff} \sim T_P S^2/(S+B)}$,

Signal and background in a narrow window around the K^0 peak

$K_S \to \mu\mu$: prospects

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What do we need to estimate the sensitivity to A_{CP}?

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Signal and background in a narrow window around the K^0 peak

BR< ~ 6.4×10^{-12} @ 95% CL

\+ Plots from CERN-THESIS-2020-101 Appendix E

<u>Single bin similar experiment:</u>

$S(K_S \to \mu\mu)_{SM} \sim 450$ for $B \sim 50\,000$

$S(K^0 \to \mu\mu)_{SM} \sim 1900$

$K_S \to \mu\mu$: prospects

What do we need to estimate the sensitivity to A_{CP}?

⇒ Effective yield, $\mathbf{Y_{eff} \sim T_P S^2/(S+B)}$ ~ 15 events for 300 fb^{-1} → σ_{ACP} ~ 26%

How to improve it:

→ Increase T_P (unlikely big effects, already using an optimistic value)
→ Increase S (R&D on beam side → 350fb^{-1} ?)

$K_S \to \mu\mu$: prospects

What do we need to estimate the sensitivity to A_{CP}?

$\Rightarrow$ Effective yield, $\mathbf{Y_{eff} \sim T_P S^2/(S+B)}$ ~ 15 events for 300 fb^{-1} $\to$ σ_{ACP} ~ 26%

How to improve it:

→ Increase T_P (unlikely big effects, already using an optimistic value)
→ Increase S (Downstream tracks Upstream Pixel in Upgrade-II → ~2x?)

(These will have longer lifetimes, so not t ~ 0 simplification may not be ok here)

$K_S \to \mu\mu$: prospects

What do we need to estimate the sensitivity to A_{CP}?

$\Rightarrow$ Effective yield, $\mathbf{Y_{eff} \sim T_P S^2/(S+B)}$ ~ 15 events for 300 fb^{-1} $\to$ σ_{ACP} ~ 26%

How to improve it:

→ Increase T_P (unlikely big effects, already using an optimistic value)
→ Increase S
→ Reduce B ?

$K_S \to \mu\mu$: prospects

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→ Reduce B ?

- Analysis so far optimized against combinatorial
- Analysis so far optimized for a >> SM signal
- Few handles to kill $Ks \to \pi\pi$ misid
    - More stringent muon ID
    - Per event mass uncertainty

Invariant mass resolution is not a constant, depends on particle kinematics → this can be used to kill events in the far tails of $K_S \to \pi\pi$

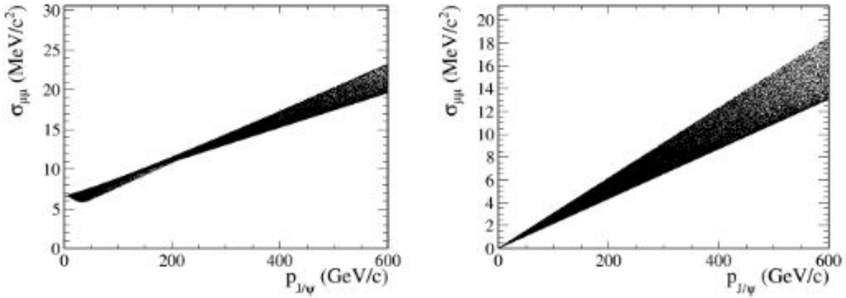

Figure 7: Per-event mass uncertainty versus J/ψ momentum. Left: with multiple scattering. Right: only detector resolution.

https://arxiv.org/pdf/1312.5000

$K_S \to \mu\mu$: prospects

→ Reduce B ?

- Analysis so far optimized against combinatorial
- Analysis so far optimized for a >> SM signal
- Few handles to kill Ks→ ππ misid
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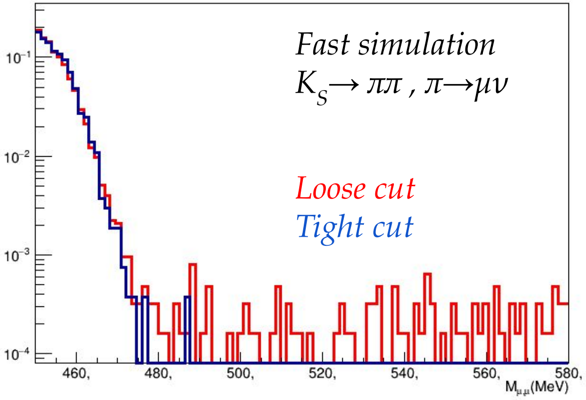
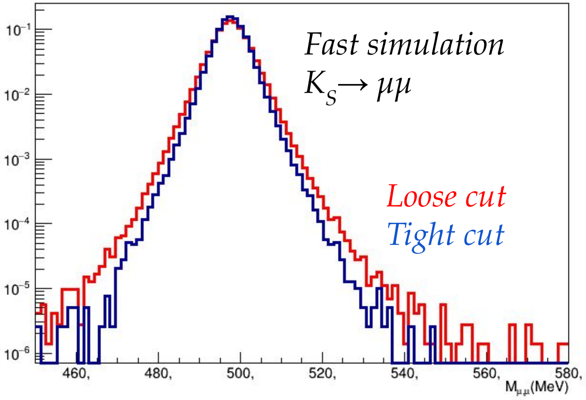
  - Per event mass uncertainty
  - PV - SV- momentum consistency, or other kinematic constraints

(**π→ μν mess up track momentum**)





$K_S \to \mu\mu$: prospects

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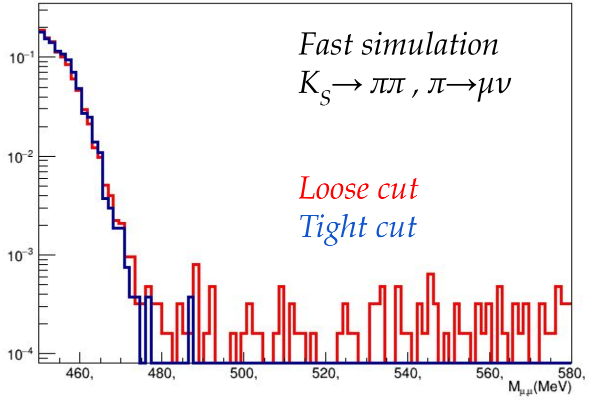

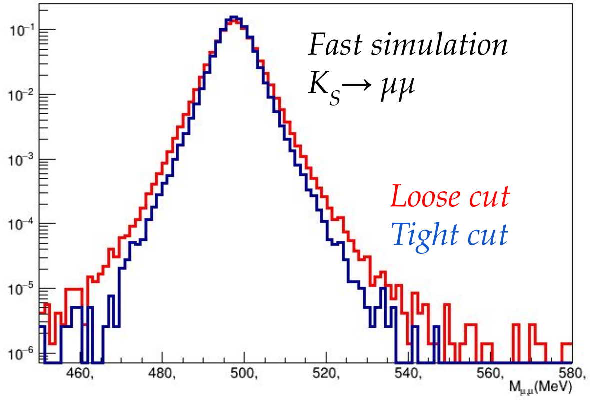

Sacrifice ~50% of signal and reduce B by 90 or 99% may be not a completely crazy hope (but we don't know for sure, this is gambling atm)

Optimistic (but still reasonable) scenarios

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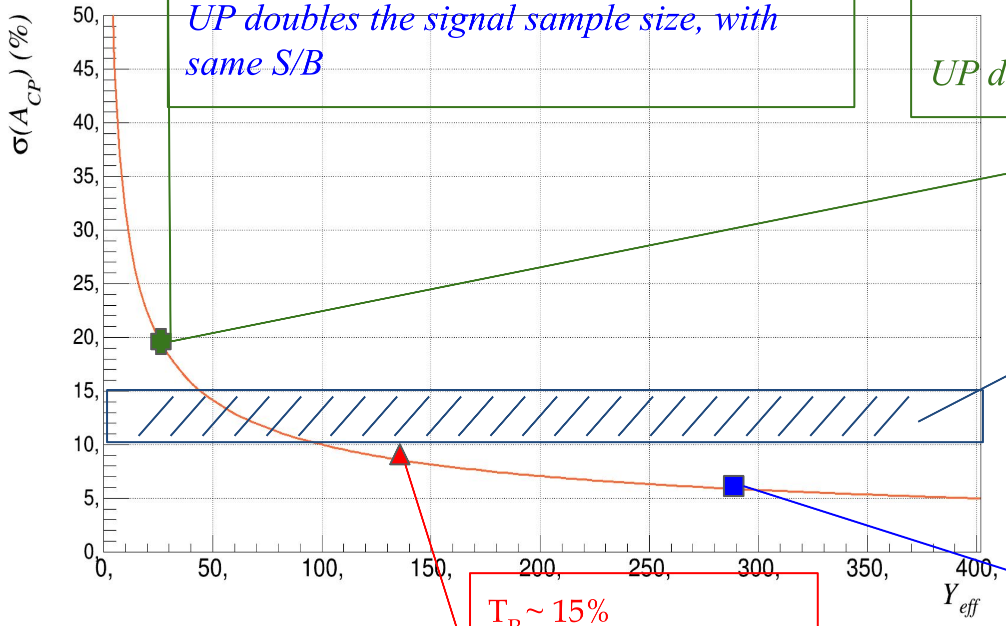

Pessimistic tagging , T_P ~ 2%

Collect ~1000 (long) signal for ~500 bkg

UP doubles the signal sample size, with same S/B

Optimistic tagging , T_P ~ 22%

Collect ~1000 (long) signal for ~8,000 bkg

UP does not help

Resolve Aγγ sign ambiguity at 2 or 3σ ?

T_P ~ 15%
S ~ 1000 B ~ 1000
UP + 70%
U-II takes 330 fb^{-1}

Optimistic tagging , T_P ~ 22%

Collect ~1000 (long) signal for ~500 bkg

UP doubles the signal sample size, with same S/B

$$Y_{eff} \sim T_P S^2/(S+B)$$

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How if we go full crazy… ?

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Optimistic tagging , $T_P \sim 22\%$

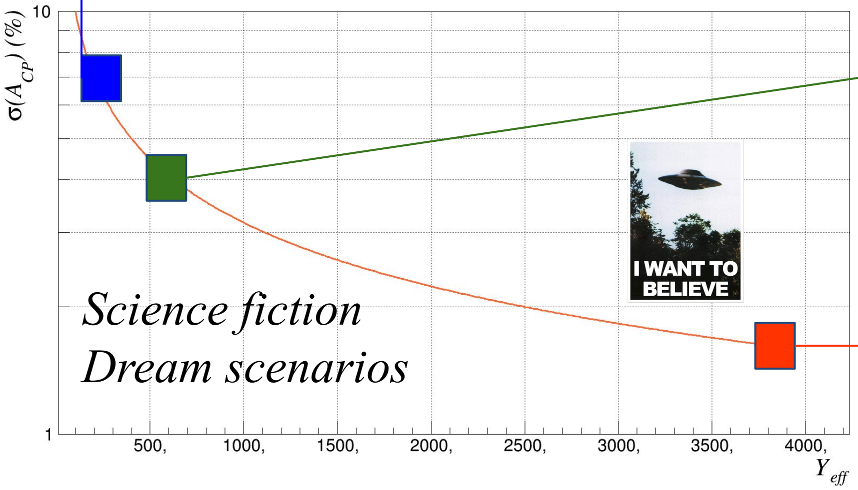
Collect ~1000 (long) signal for ~500 bkg

UP doubles the signal sample size, with same S/B

Perfect tagging , $T_P \sim 50\%$

Collect ~1000 (long) signal for ~500 bkg

UP doubles the signal sample size, with same S/B



$Y_{eff} \sim T_P S^2/(S+B)$

Perfect tagging , $T_P \sim 50\%$

Keep most signal while rejecting all $K \to \pi\pi$ background

UP doubles the signal sample size, still no bkg

LHCb upgrade collects 350 fb^{-1}

Conclusions

With huge efforts and quite some optimism, reaching a precision to at least resolve the SM sign is not impossible

Otherwise (still with huge efforts), at least BSM constraints