Contact interactions from high-mass Drell-Yan tails

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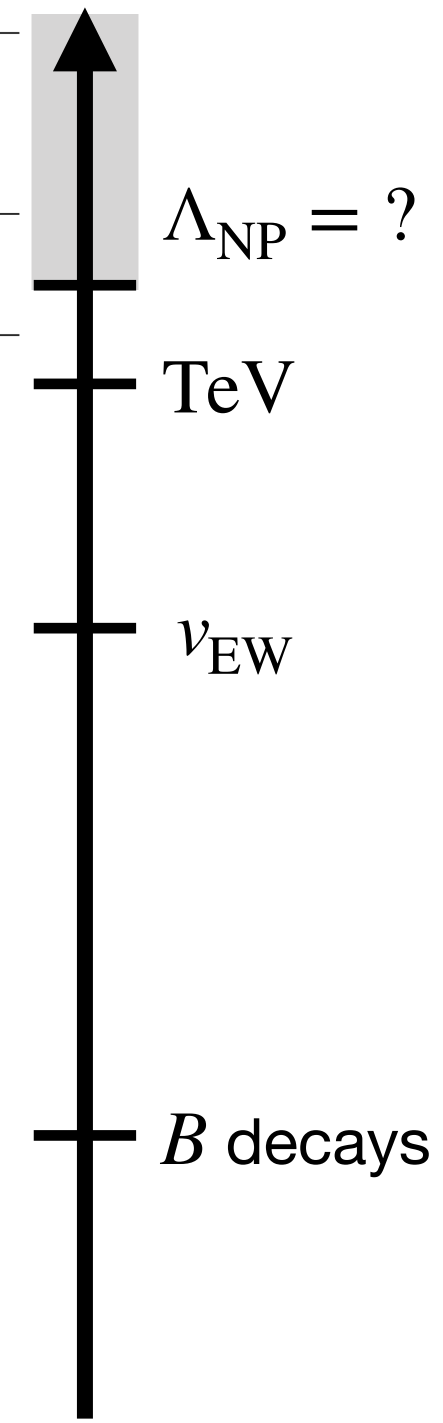
Based on w.i.p. with A. Greljo, J. Salko and P. Stangl

E.g. B. Grzadkowski et al. - *JHEP* 10 (2010) 085

SMEFT

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2} \sum_i C_i Q_i$$

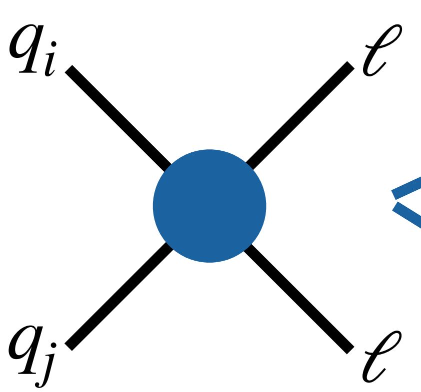
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \sigma^i l_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

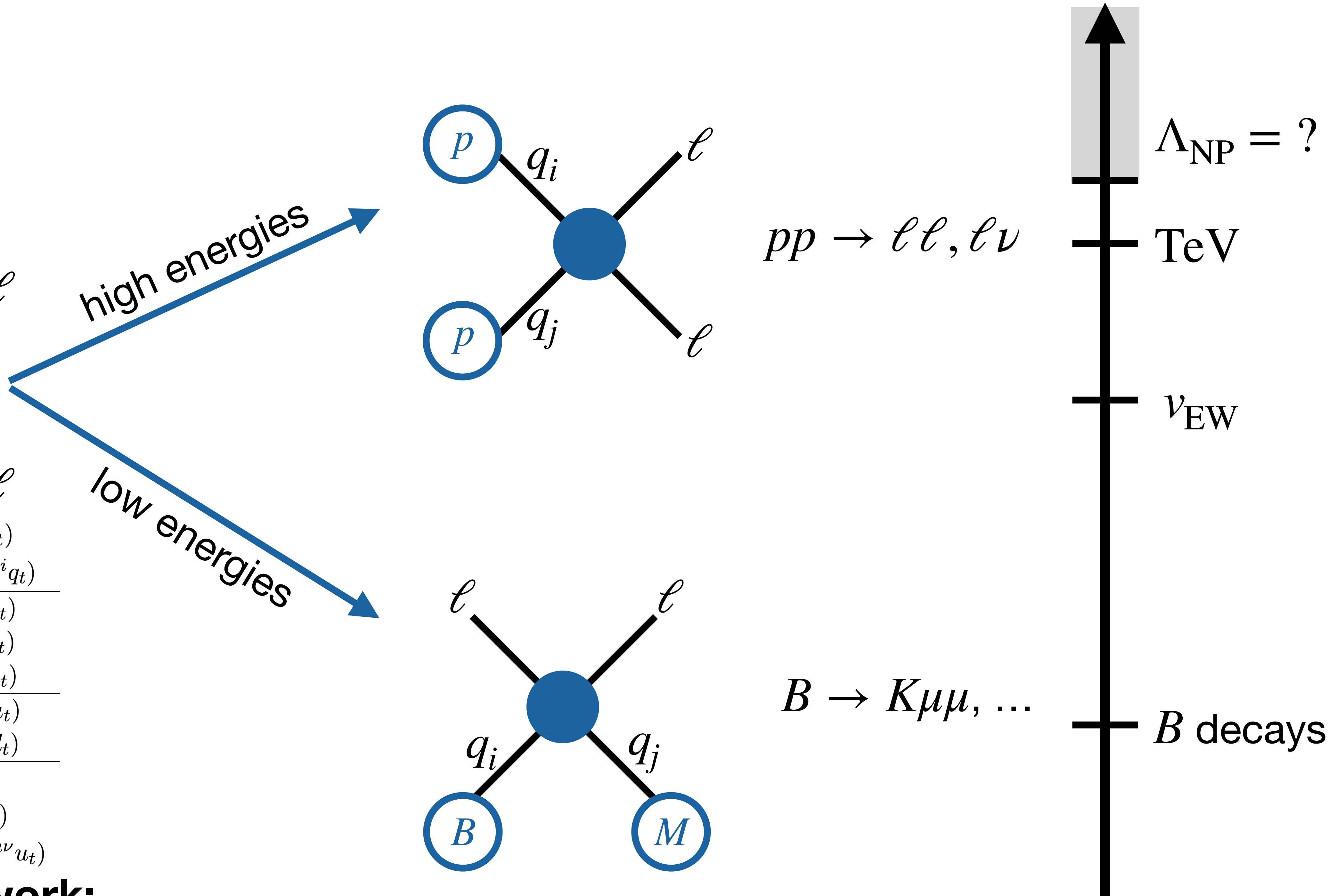


- Absence of NP in direct searches suggests a mass gap between v_{EW} and Λ_{NP}
- SMEFT: Low energy limit of generic heavy NP
- 59 operators for a single generation at dim. 6
- Flavour opens a huge parameter space: 1350 real + 1149 complex parameters
- Overarching goal:
  efficient scanning, over-constraining the parameter space to learn about NP

Focus of this work:
Dim. 6 contact interactions entering high mass Drell-Yan tails and interplay with low-energy B decays to light leptons

Drell-Yan vs B-decays





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A word about flavio

- Open-source python package **flav-io.github.io**
- Calculator of hundreds of observables in the SM and in dim. 6 EFTs
- Contains a large database of experimental measurements, allows for easy construction of likelihoods
- Interface with wilson for running and matching of WCs above and below the EW scale
- Basis of smelli - package providing a global SMEFT likelihood

Our contributions:

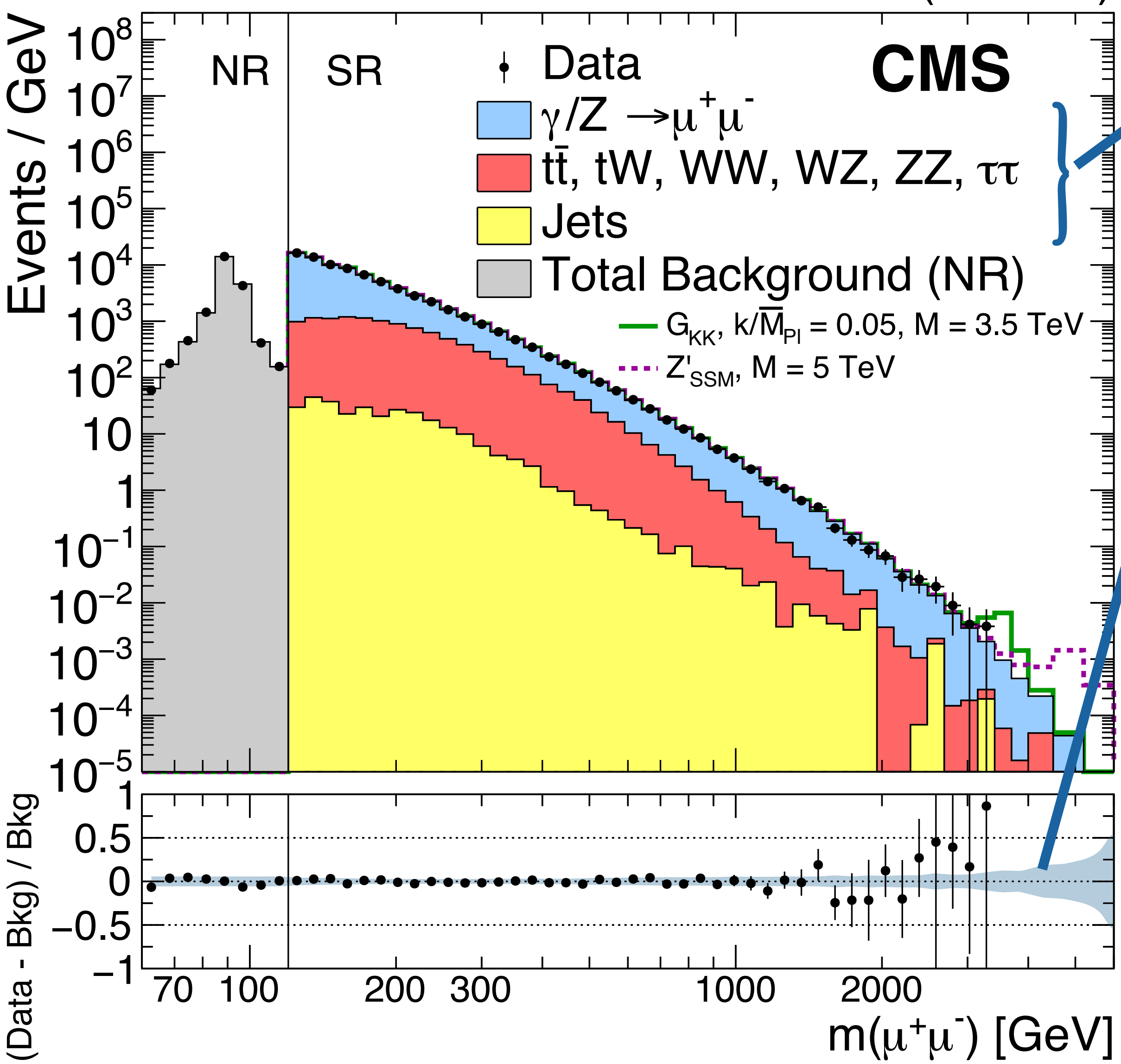
- **Implementation of** theoretical predictions (dim. 6 in SMEFT) and latest experimental measurements of **neutral and charged current high-mass Drell-Yan** with light leptons $\ell = e, \mu$
- **Implementation and update of various $b \to d$ predictions and measurements**

Implementation of Drell-Yan

Experimental measurements:

We implement data (~140fb^{-1}) from latest CMS and ATLAS searches:

	$pp \to \ell\ell$	$pp \to \ell\nu$
CMS	2103.02708	2202.06075
ATLAS	2006.12946	1906.05609



[m_T in CC]

A. Greljo and D. Marzocca: 1704.09015

Expected # of events @ (N)NLO in QED(QCD) including $N_{DY}^{\rm SM}$

Systematic errors provided

Likelihood:

Poisson convolved with Normal (systematics)

For predictions:

We reweigh the reported expected number of DY events with ratio

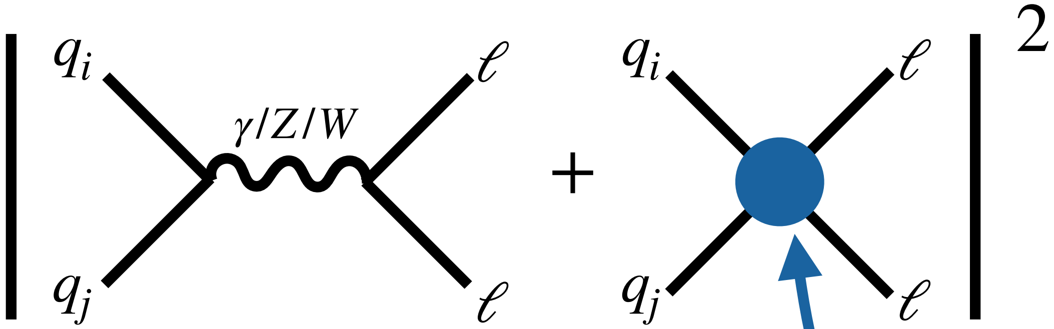
$$N_{DY}^{\rm NP+SM} = \frac{\sigma^{\rm SM+NP}}{\sigma^{\rm SM}} N_{DY}^{\rm SM}$$

$\Rightarrow$implement analytical predictions of $d\sigma(pp \to \ell\ell, \ell\nu)/dm$

Implementation of Drell-Yan

- Partonic cross-sections including all Lorentz structures, chiralities
- Implementation of PDFs in flavio (NNPDF 4.0), convolution of σ_{part} with luminosity functions

$$\sigma_{\text{part}}^{q\bar{q}} \sim \sum_{\bullet} \Big| \quad \Big|^2$$



$$\sigma_{\text{had}} \sim \sum_{q\bar{q}} \mathscr{L}_{q\bar{q}} * \sigma_{\text{part}}^{q\bar{q}}$$

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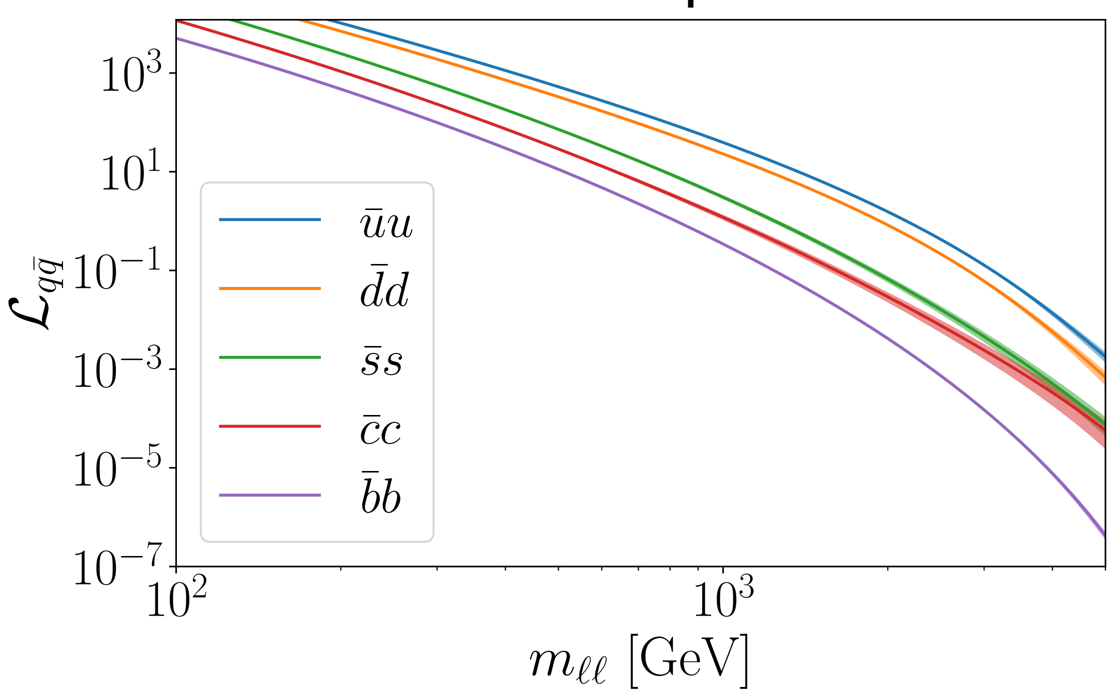
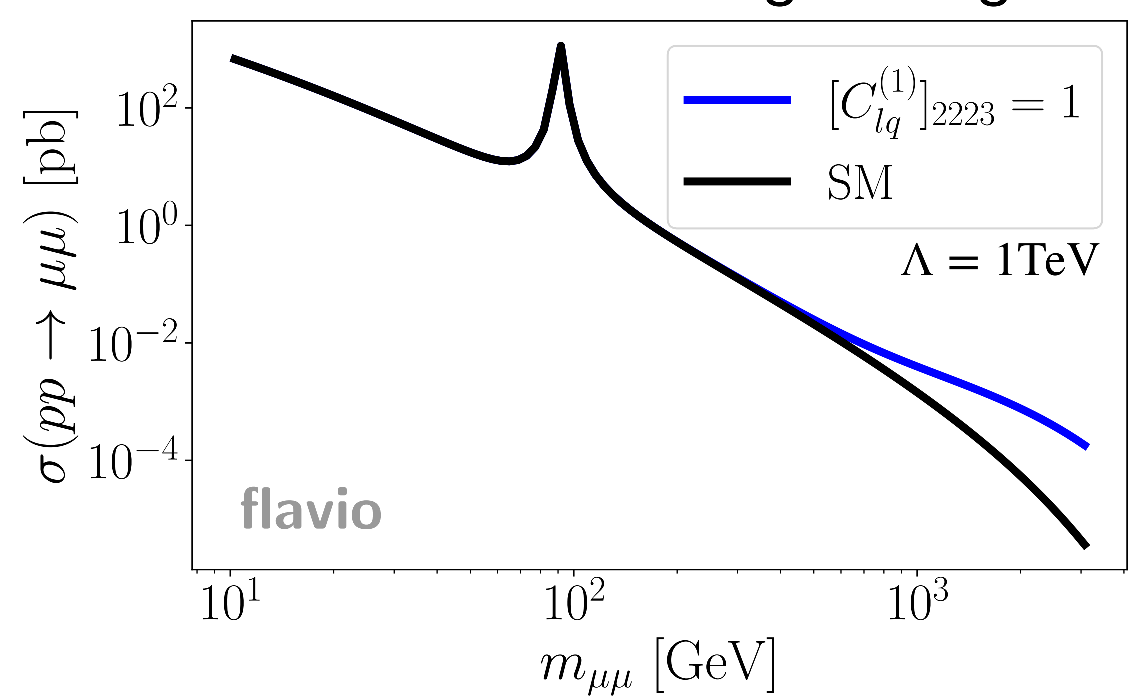
sensitive to five quark flavours



EFT enhanced at high energies



Thorough validations against Monte Carlo simulations using Madgraph

Status of $b \to q\ell\ell$ in flavio

Current and **newly implemented** processes

$b \to s\mu\mu$

Various branching ratios, angular observables, and other observables, measured in many modes: $B \to K^{(*)}\mu\mu$, $B_s \to \phi\mu\mu$, $B_s \to \mu\mu$, $\Lambda_b \to \Lambda\mu\mu$

$b \to see$

Upper limit on $B_s \to ee$ [LHCb 2020]

Inclusive $B \to X_s ee$ [BaBar 2013]

($B \to K^* ee$ at very low q^2 - LHCb)

+ LFUV ratios $R_{K^{(*)}}$

$b \to d\mu\mu$

Upper limit on $B^0 \to \mu\mu$ [LHCb, ATLAS, CMS]

Branching ratio of $B \to \pi\mu\mu$ *[LHCb 2015]

Branching ratio of $B_s \to K^*\mu\mu$ **[LHCb 2018]

$b \to dee$

Upper limit on $B^0 \to ee$ [LHCb 2020]

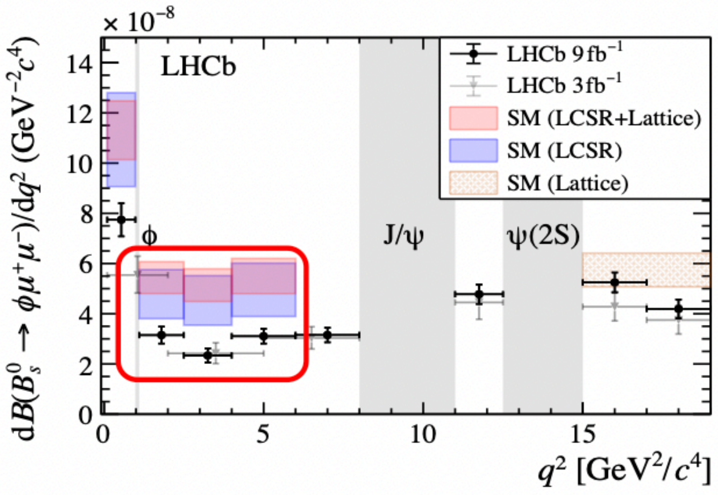
Upper limit on $B \to \pi ee$ *[Belle 2008]

*we update $B \to \pi$ **form factors** from *D. Leljak et al* (2102.07233) (lattice+LCSR)

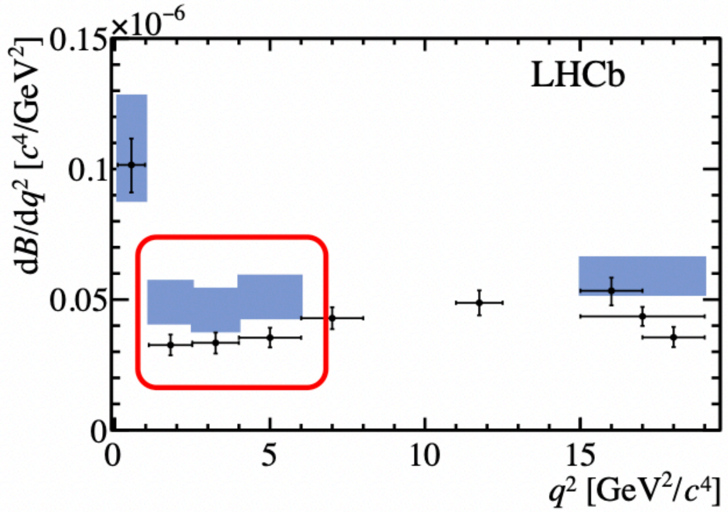
**we follow closely *R. Bause et al* (2209.04457) for treatment of resonant regions

$b \to s\mu\mu$ anomalies…

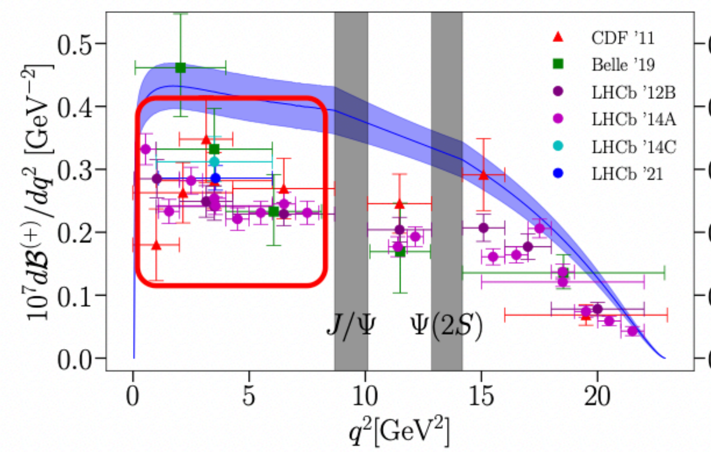
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



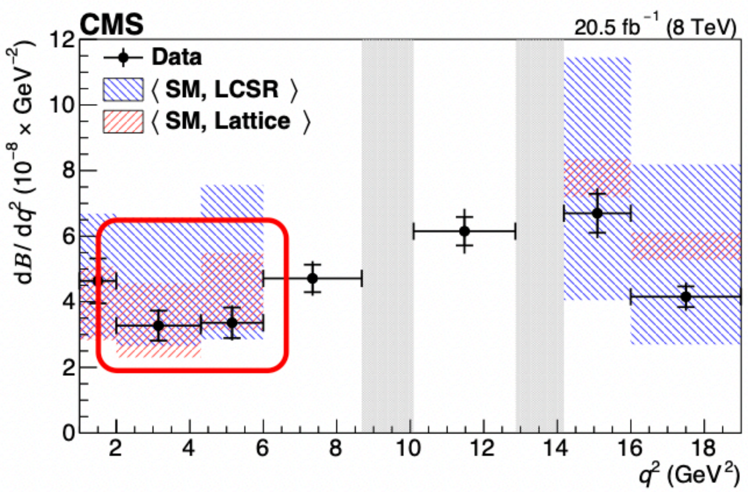
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



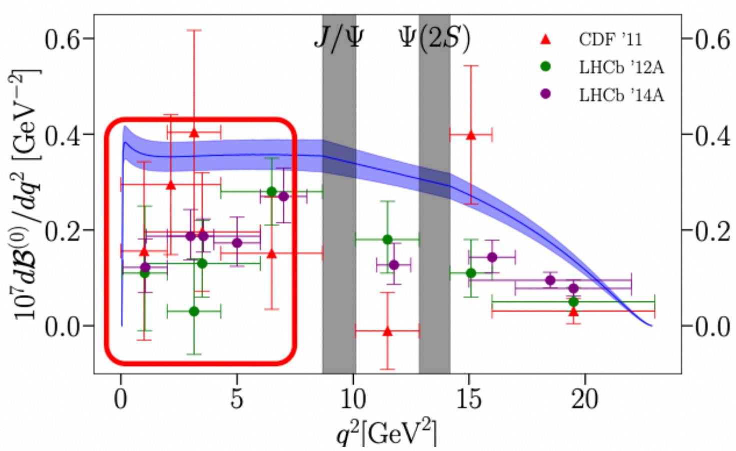
Lattice $B^+ \to K^+\mu^+\mu^-$ [arXiv:2207.13371]



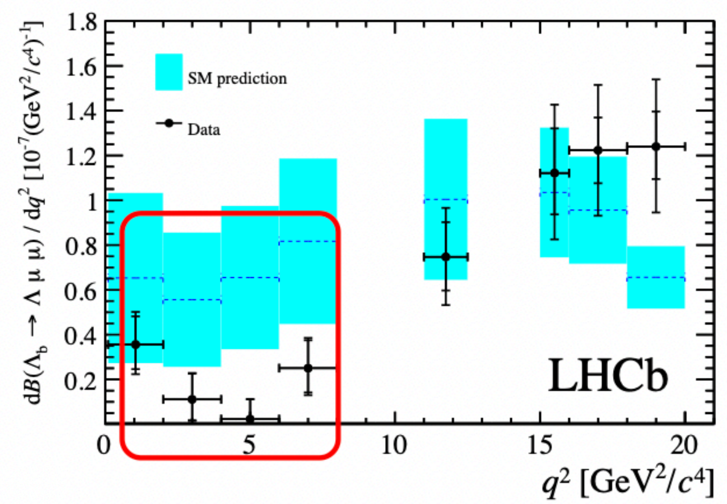
CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



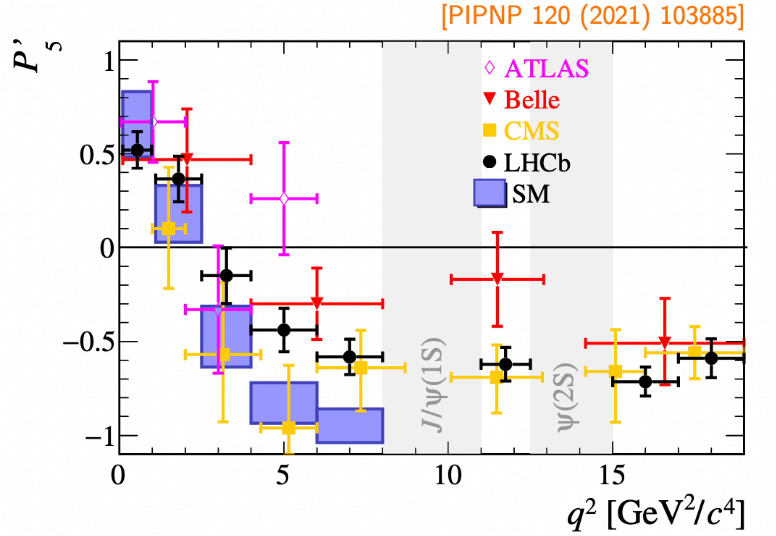
Lattice $B^0 \to K^0\mu^+\mu^-$ [arXiv:2207.13371]

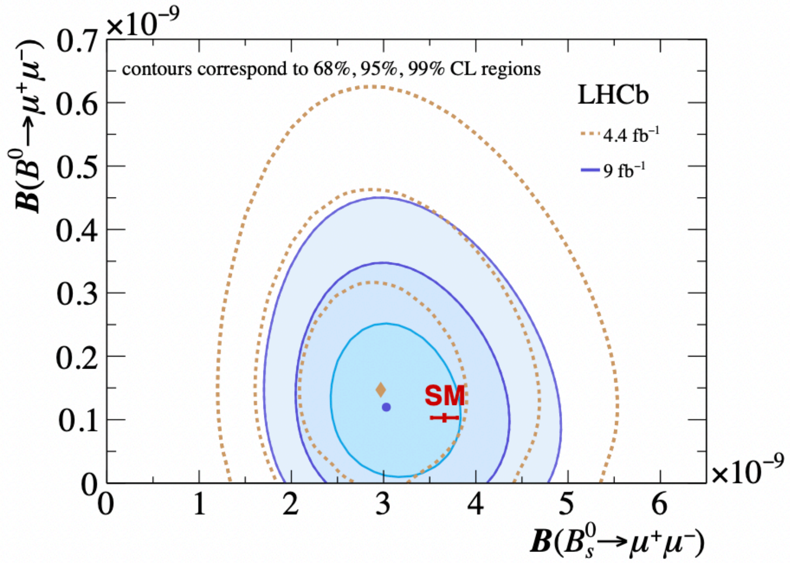


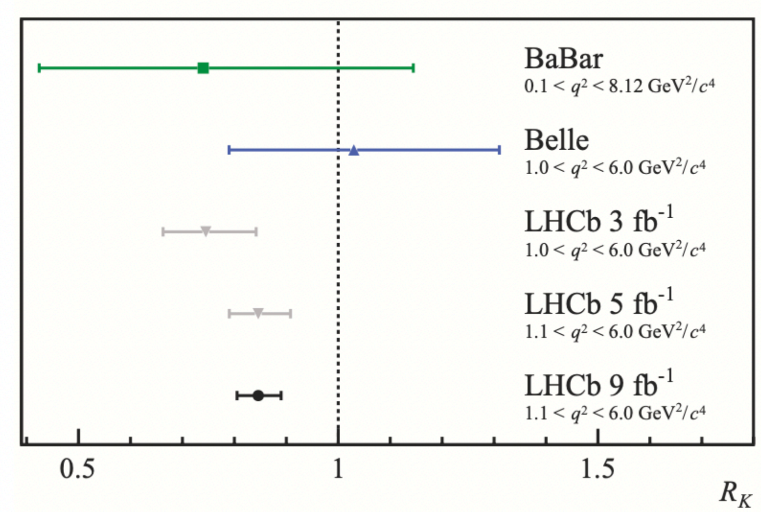
LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



[PIPNP 120 (2021) 103885]





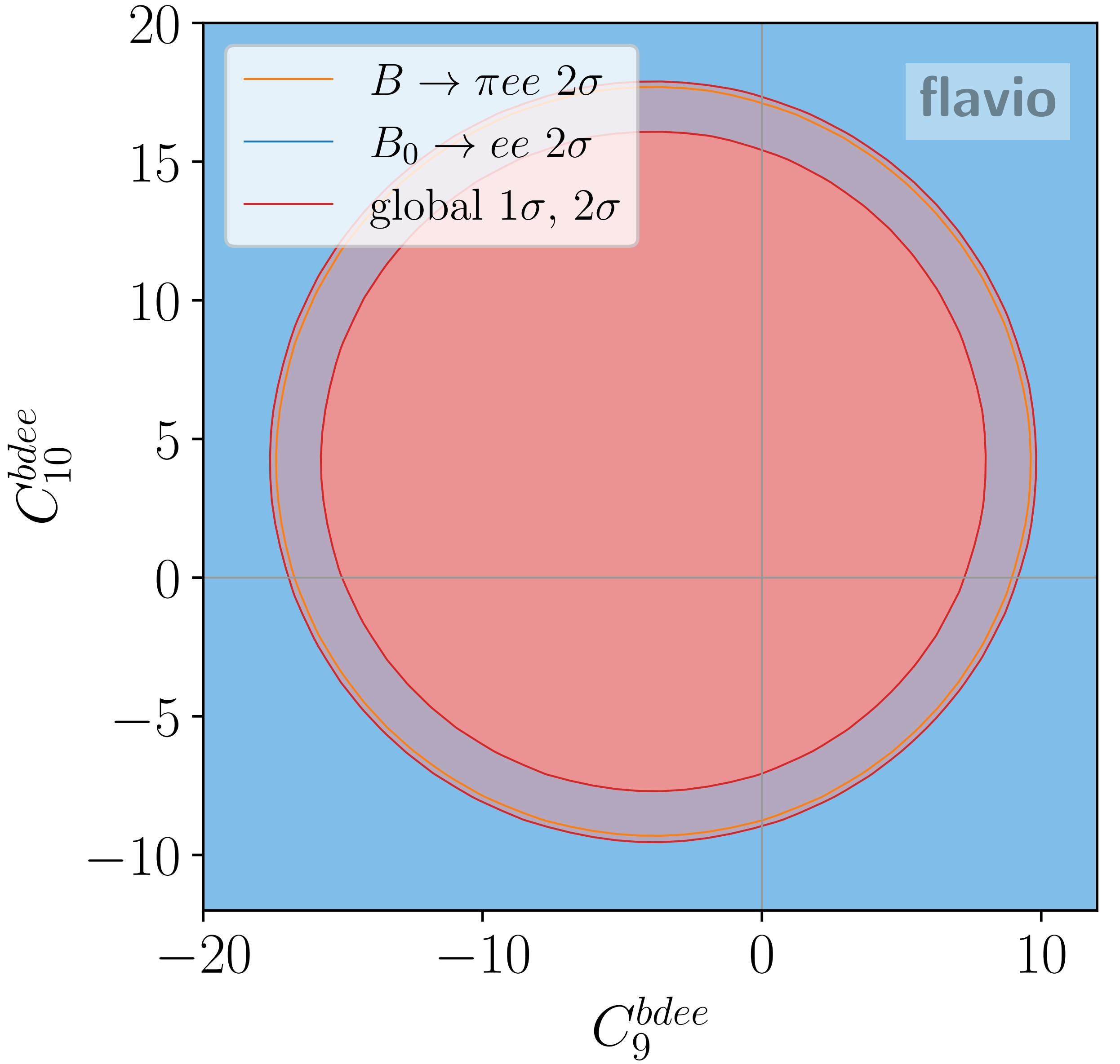


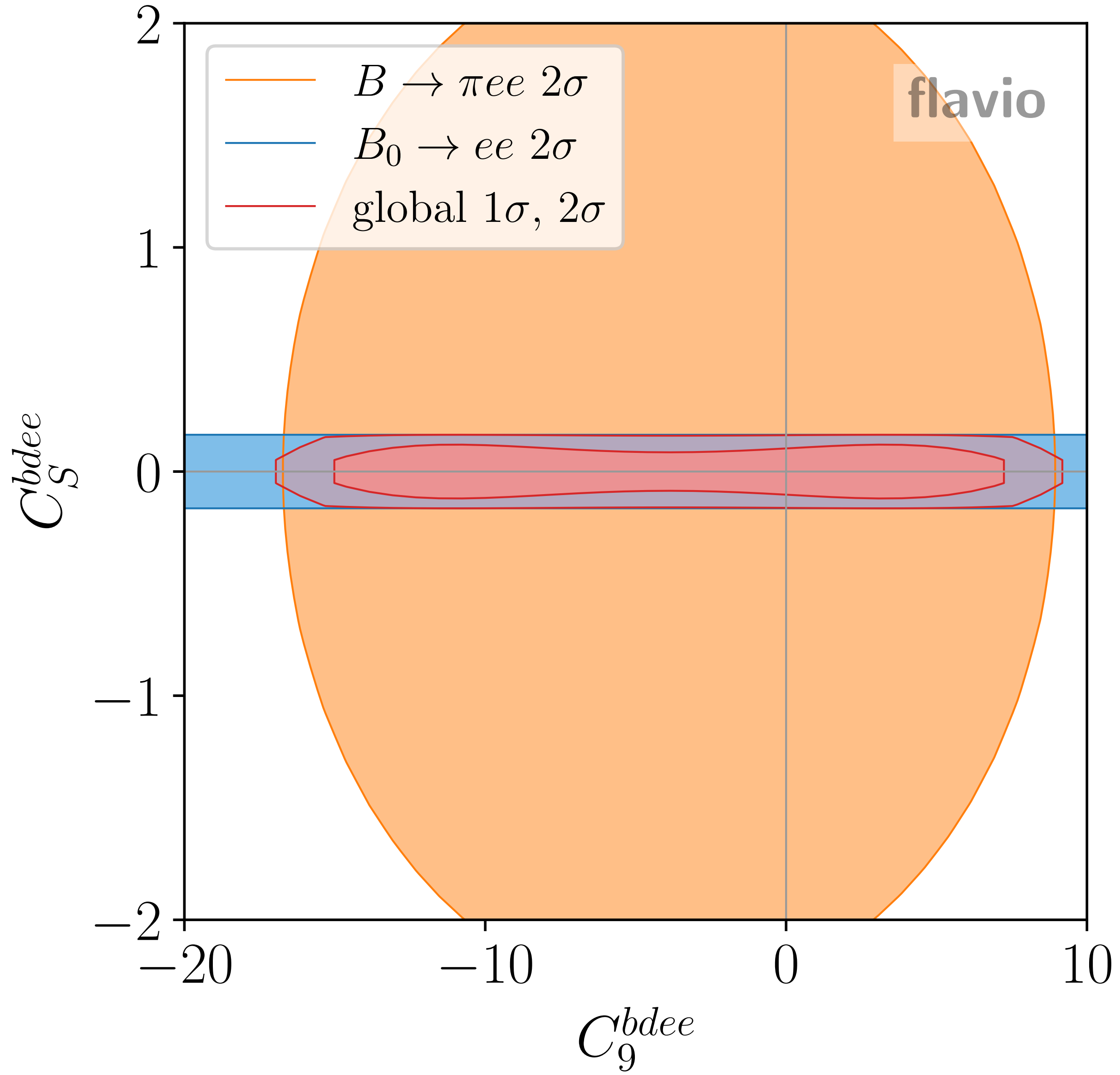
... but let us focus on $b \to dee$ for now

Minimalistic flavour scenario

consider only coefficients relevant for a certain decay

In WET:

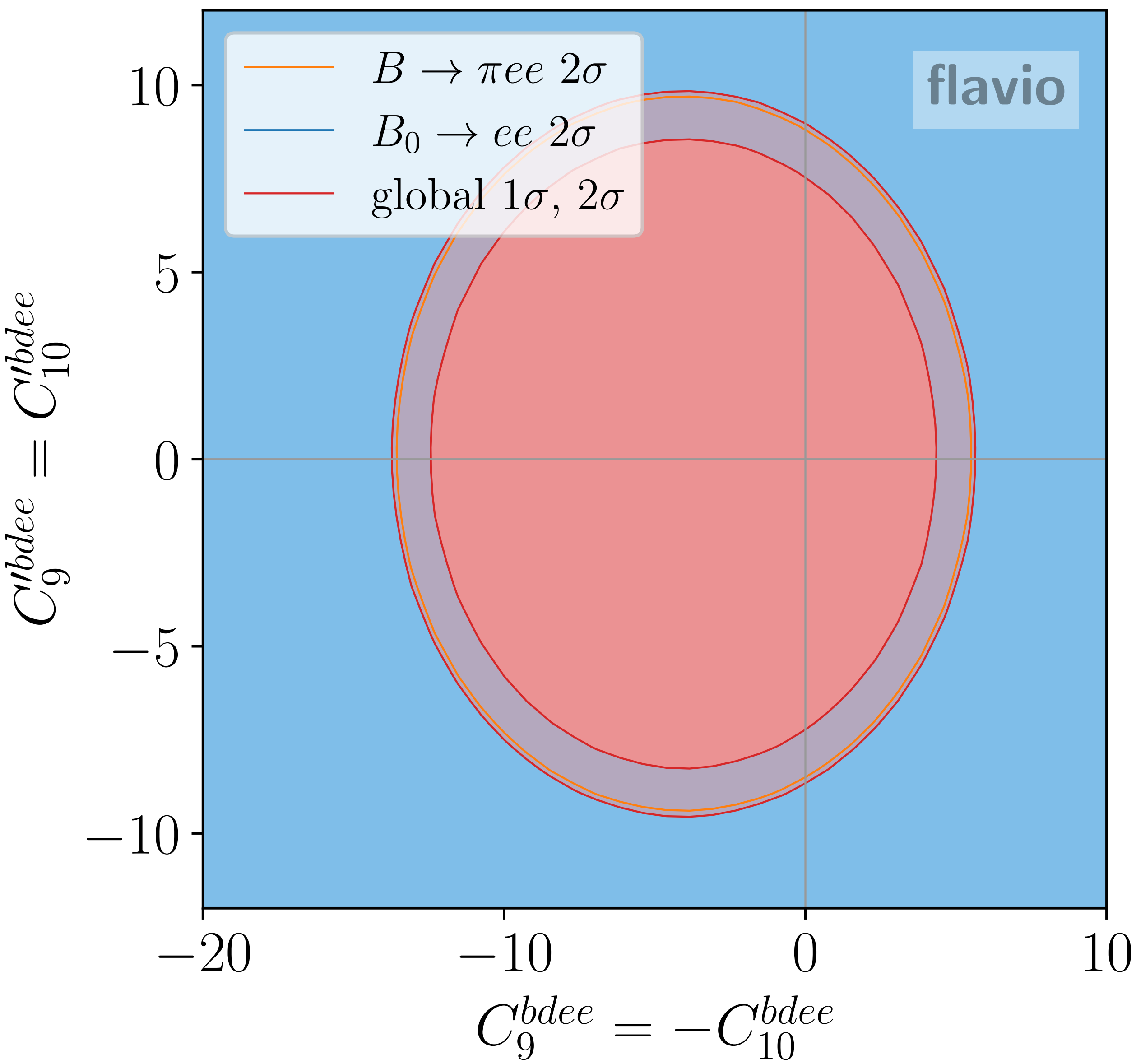




$O_{9(10)}^{[\prime]ijkk} \sim (\bar{q}^j_{L[R]}\gamma^\mu q^i_{L[R]})(\bar{\ell}^k\gamma_\mu(\gamma_5)\ell^k)$

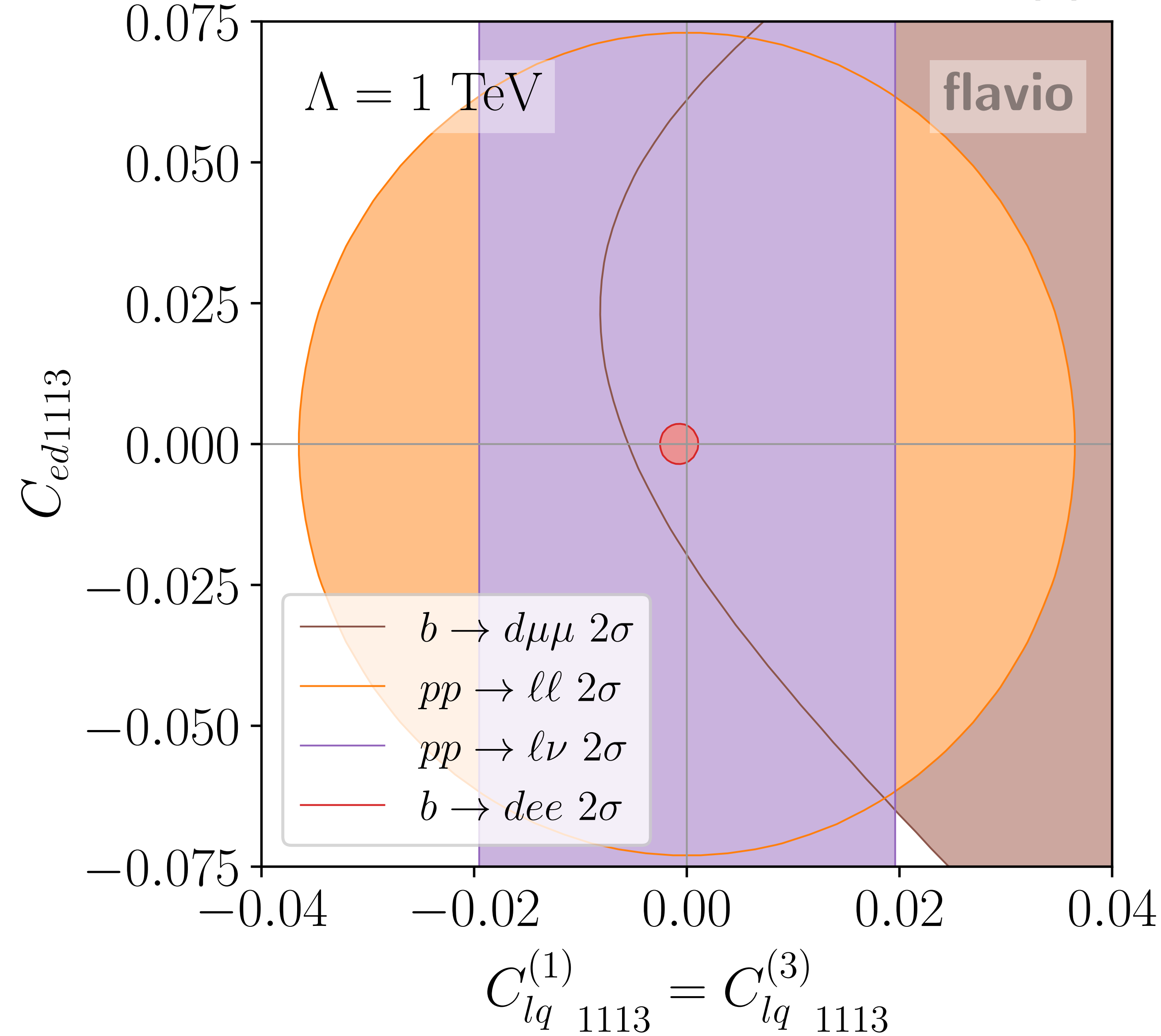
$O_S^{ijkk} \sim (\bar{q}^j_L q^i_R)(\bar{\ell}^k\ell^k)$

In SMEFT, confronting with high-mass Drell-Yan and $b \to q\nu\nu$ ($B \to K, \pi, \rho$)



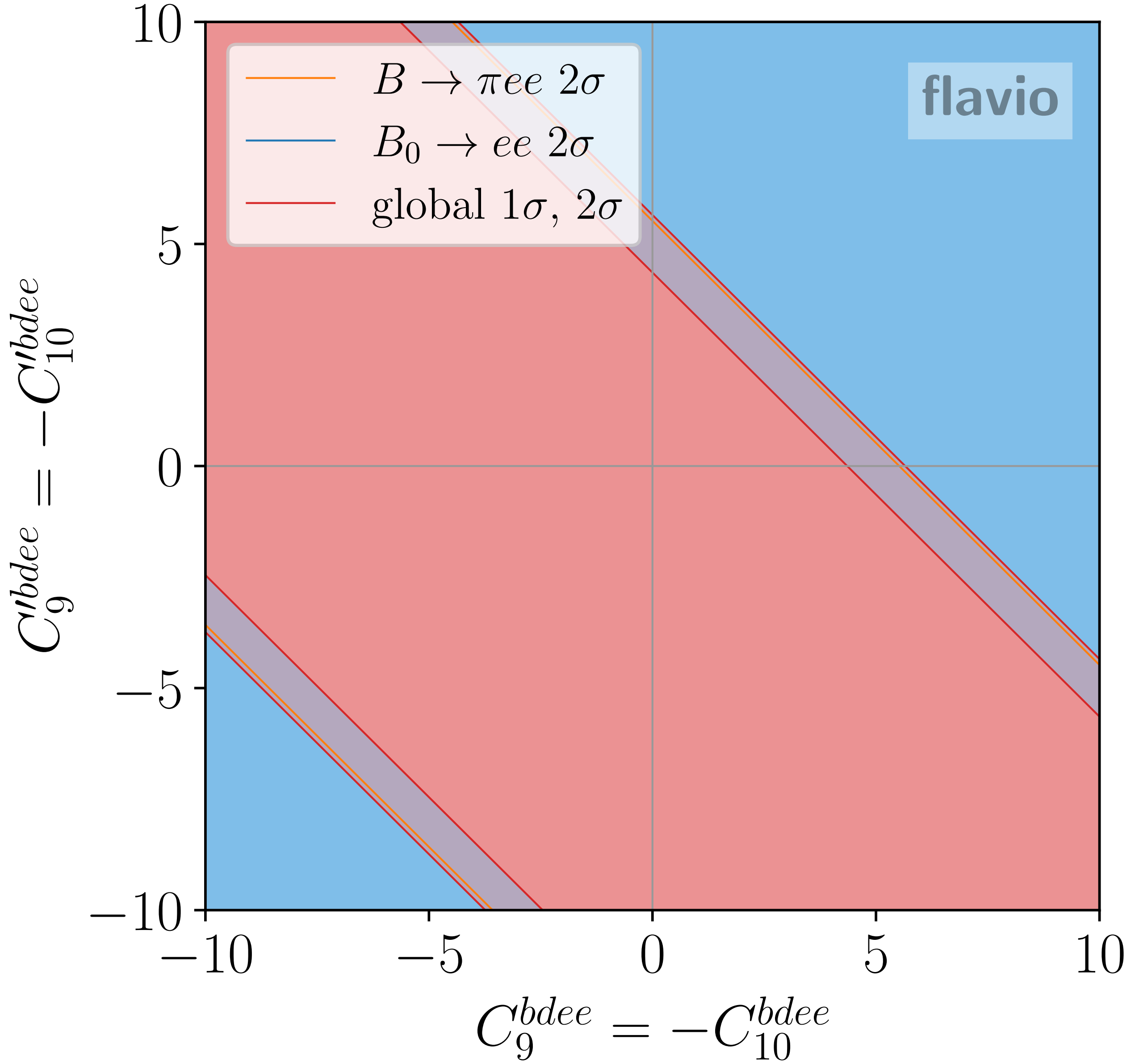
$$O_{9(10)}^{[\prime]ijkk} \sim (\bar{q}^j_{L[R]}\gamma^\mu q^i_{L[R]})(\bar{\ell}^k\gamma_\mu(\gamma_5)\ell^k)$$

RGE effects: $b \to d\mu\mu$



Dominated by B decays

In SMEFT, confronting with high-mass Drell-Yan and $b \to q\nu\nu$ ($B \to K, \pi, \rho$)



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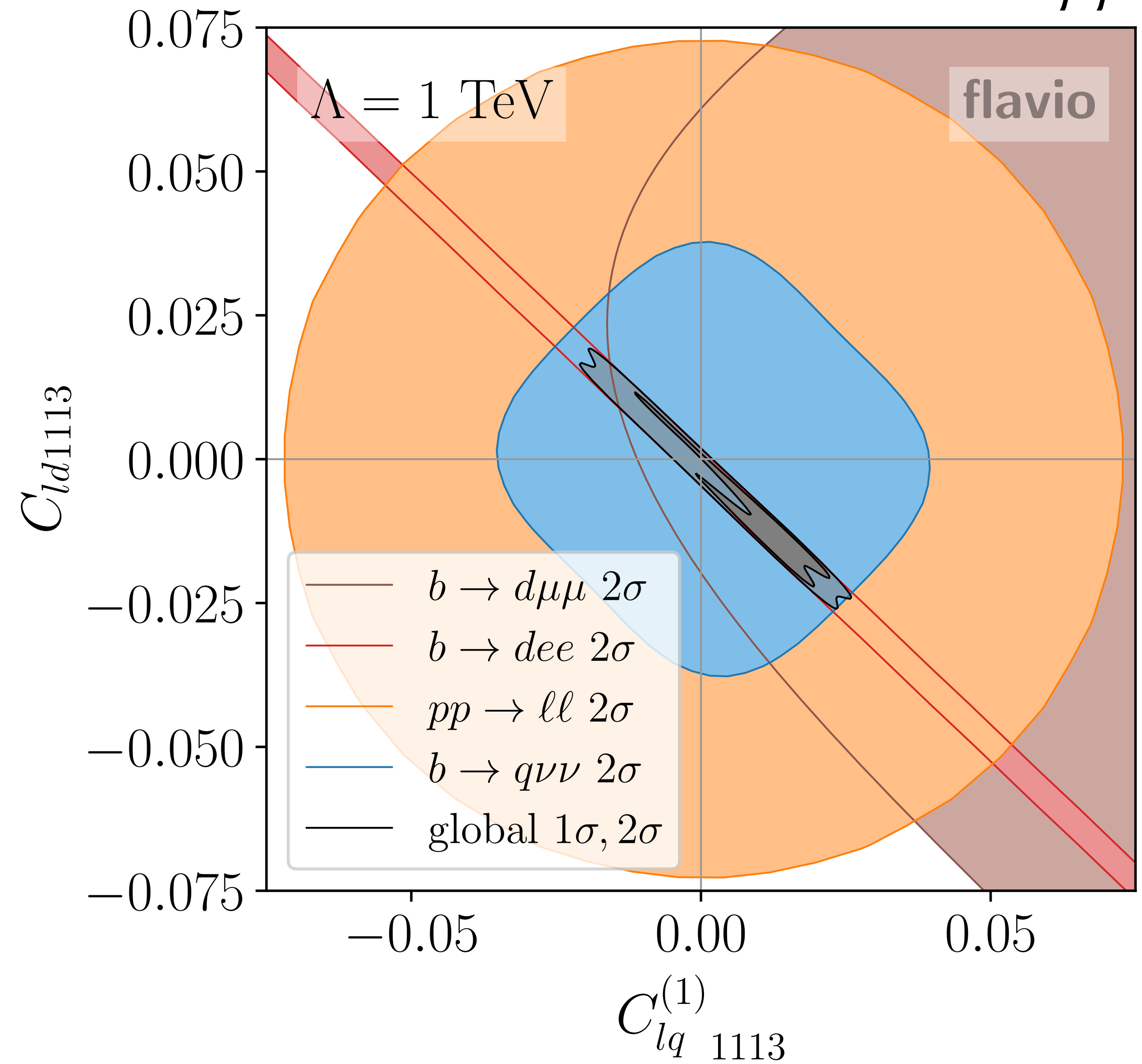
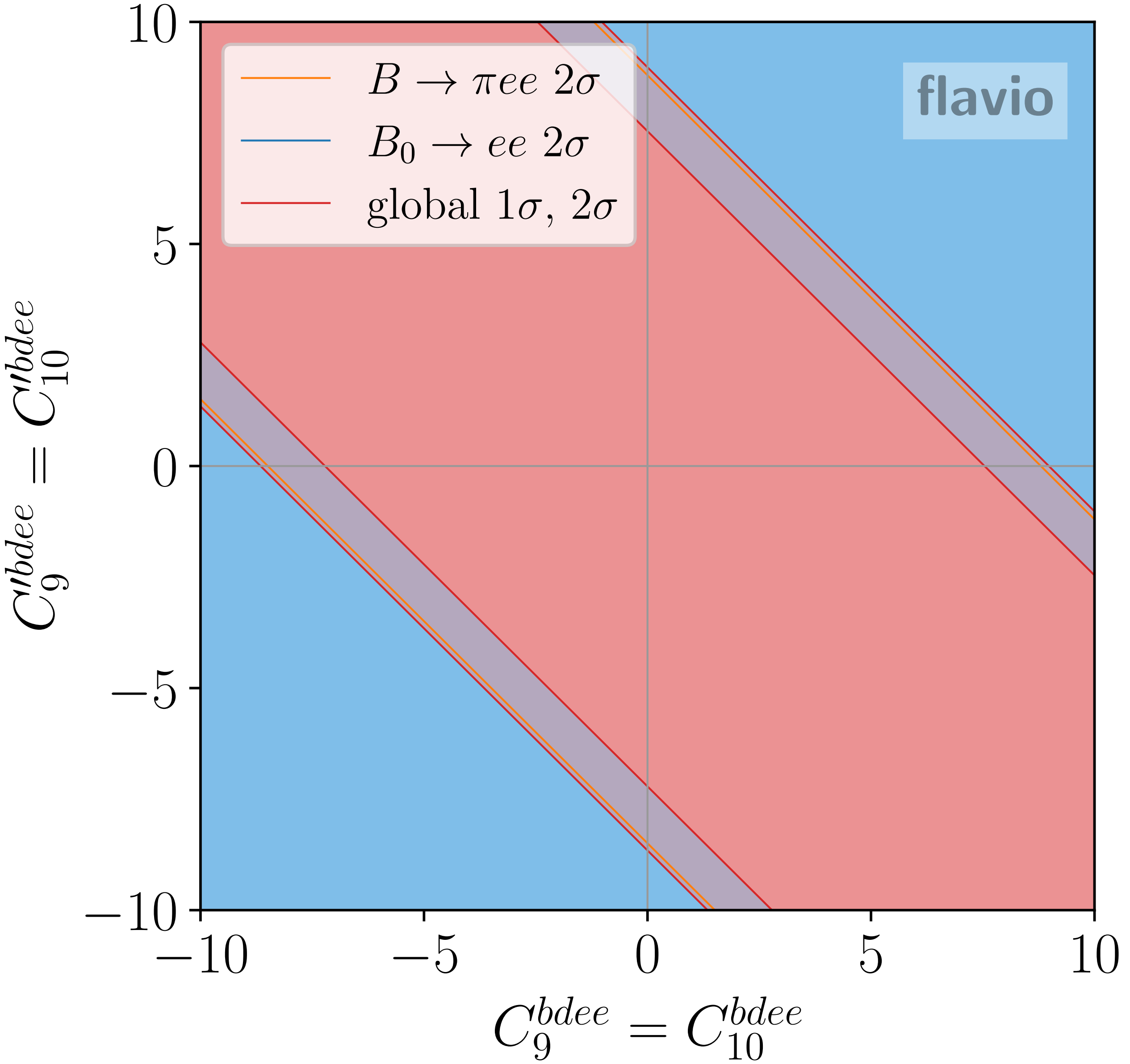


Closed by $b \to q\nu\nu$

In SMEFT, confronting with high-mass Drell-Yan and $b \to q\nu\nu$ ($B \to K, \pi, \rho$)



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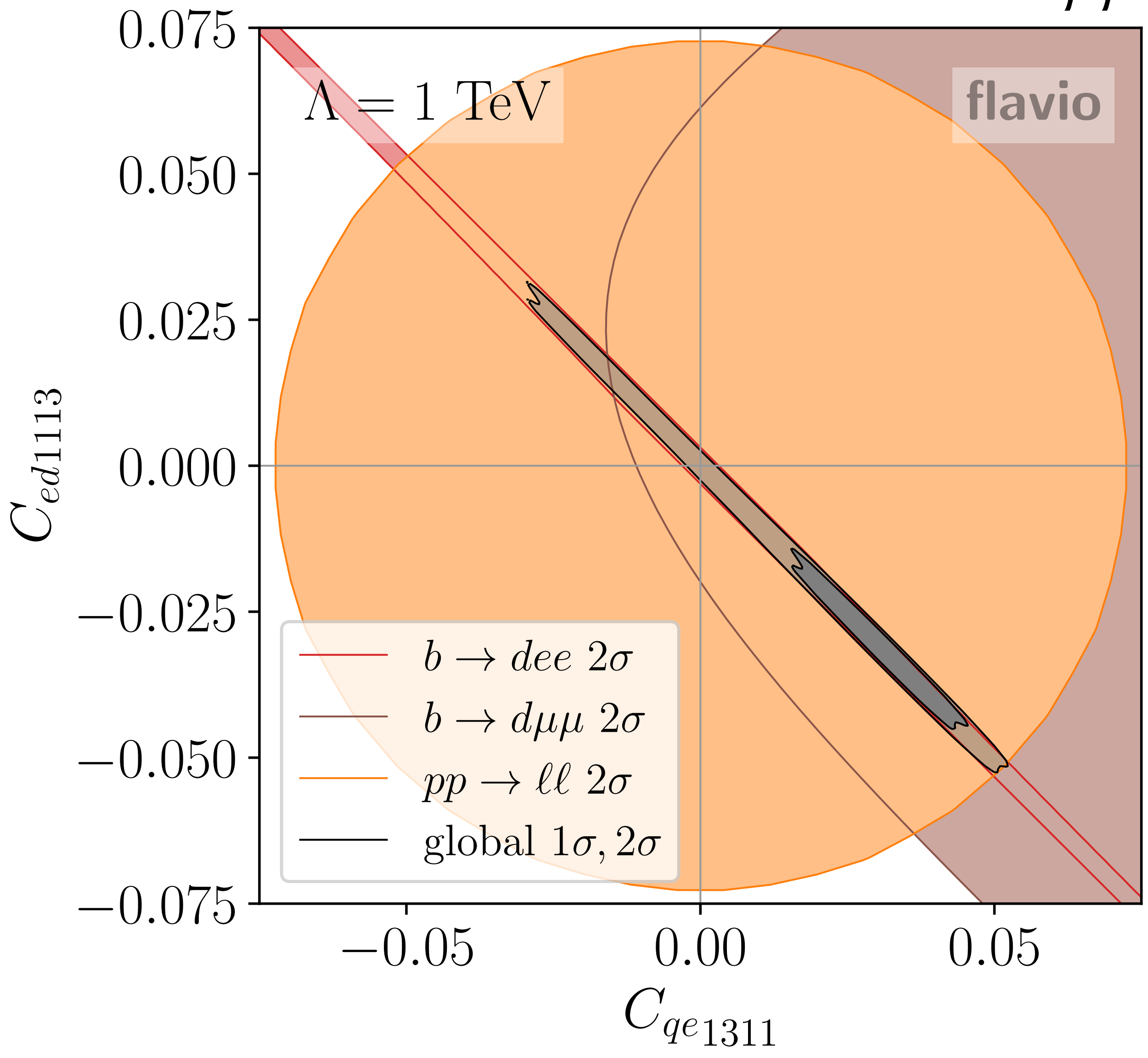


Closed by $b \to d\mu\mu$ and tails

Minimalistic flavour: B decays mostly more constraining, but now always

Towards realistic flavour

Similar to SM, NP most likely has *a* flavour structure

With a **flavour assumption** we correlate various SMEFT Wilson coefficients and decrease the number of free parameters

Minimal flavour violation:
assume SM Yukawa couplings are the only source of flavour breaking also in NP

$$G_F = U(3)_Q \times U(3)_u \times U(3)_d$$

$$Q \sim (3,1,1) \quad u \sim (1,3,1) \quad d \sim (1,1,3) \quad \Rightarrow \quad Y_u \sim (3,\bar{3},1) \quad Y_d \sim (3,1,\bar{3})$$

Then we can decompose coefficients with spurion insertions:

$$\sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$

$$[C_{lq}^{(1)}]_{iist}\bar{L}_i\gamma_\mu L_i\bar{Q}_s\gamma^\mu Q_t \to [C_{lq}^{(1)}]_{iist} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}$$

(and similar for other operators involving $\bar{Q}Q$)

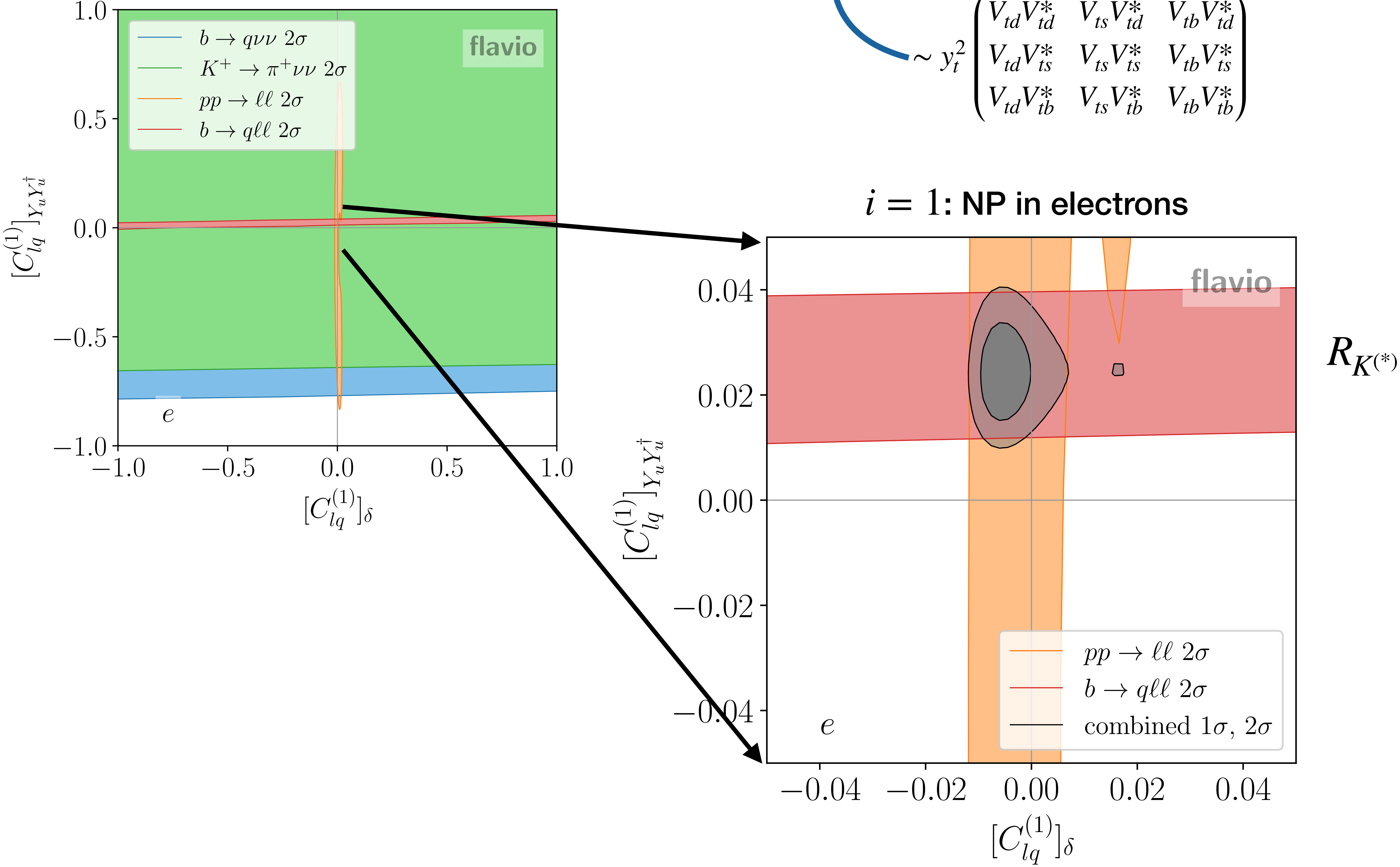
$$\sim y_b y_t^2 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$

$$[C_{ledq}]_{iist}(\bar{L}_ie_i)(\bar{d}_sQ_t) \to [C_{ledq}]_{iist} = (Y_d^\dagger)_{st}[C_{ledq}]_{Y_d} + (Y_d^\dagger Y_u Y_u^\dagger)_{st}[C_{ledq}]_{Y_d^\dagger Y_u Y_u^\dagger}$$

*all results in down-diagonal Warsaw basis

$$[C_{lq}^{(1)}]_{iist}\bar{L}_i\gamma_\mu L_i\bar{Q}_s\gamma^\mu Q_t \to [C_{lq}^{(1)}]_{iist} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}$$

$$(Y_uY_u^\dagger) \sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$



Realistic flavour: B decays and tails complementary

$$[C_{lq}^{(1)}]_{iist}\bar{L}_i\gamma_\mu L_i\bar{Q}_s\gamma^\mu Q_t \to [C_{lq}^{(1)}]_{iist} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}$$

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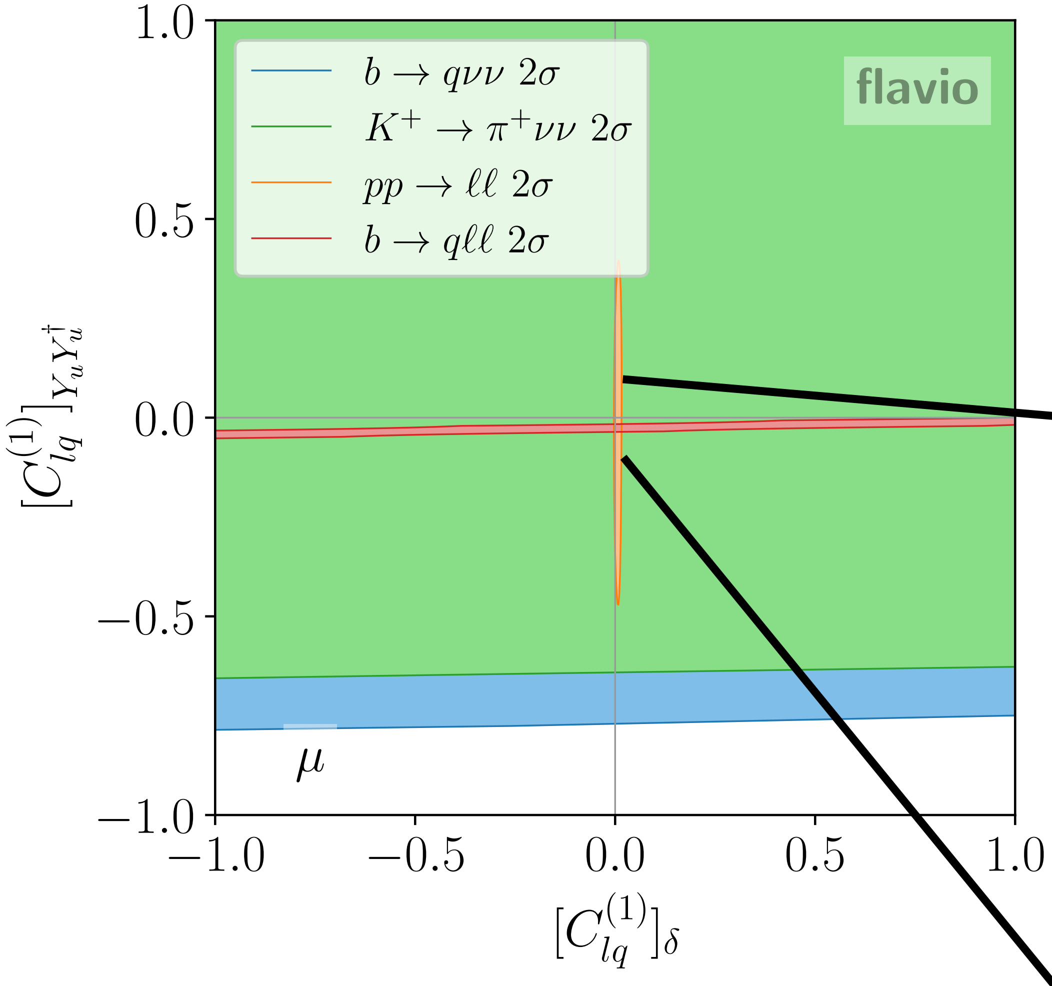
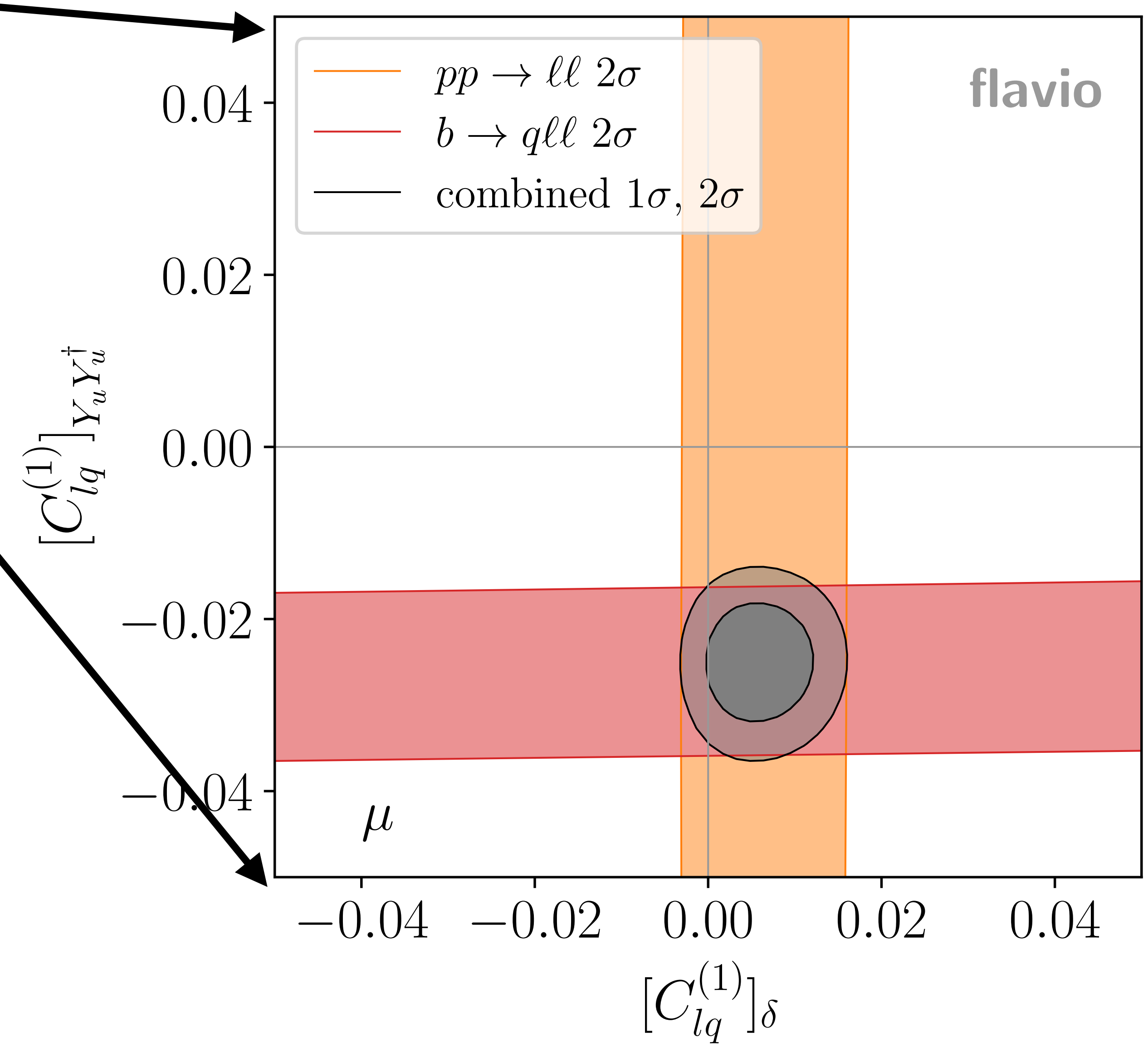


$i = 2$: NP in muons



$R_{K^{(*)}}$, $b \to s\mu\mu$

Realistic flavour: B decays and tails complementary

$$[C_{lq}^{(1)}]_{iist}\bar{L}_i\gamma_\mu L_i\bar{Q}_s\gamma^\mu Q_t \to [C_{lq}^{(1)}]_{iist} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}$$

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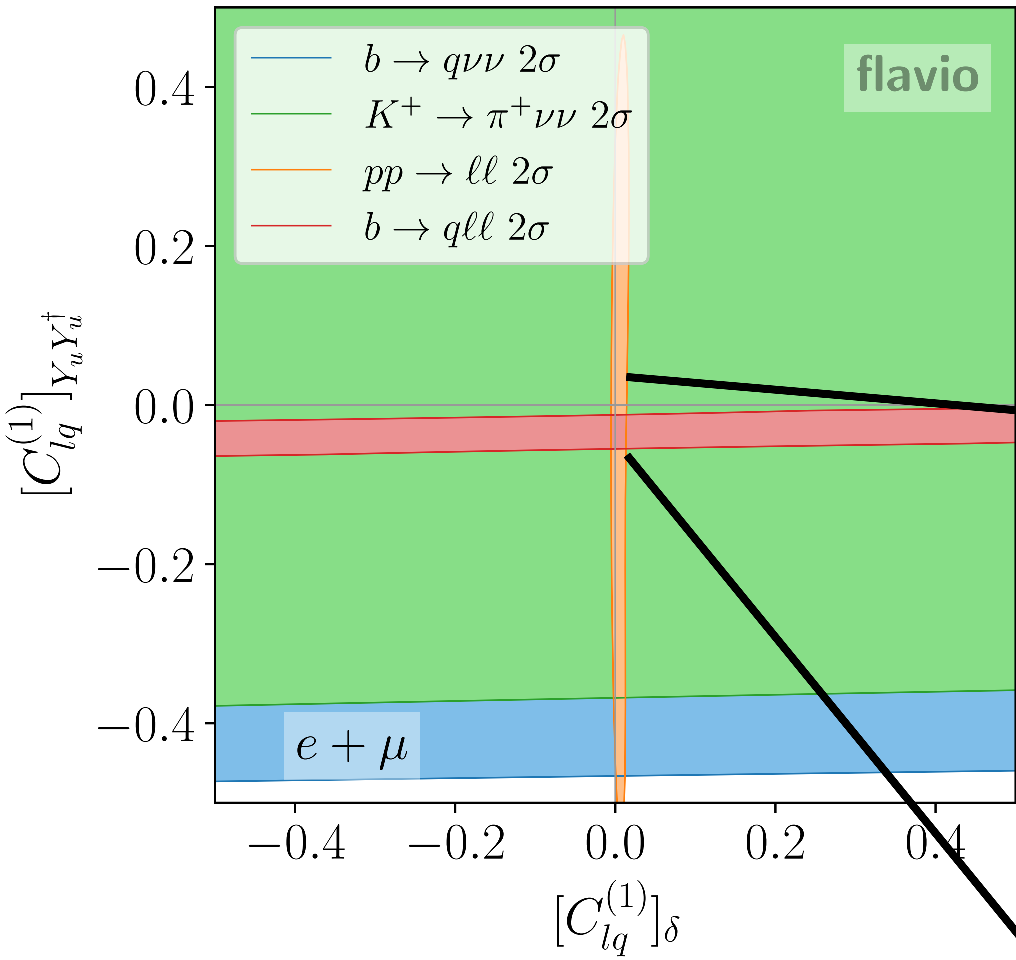
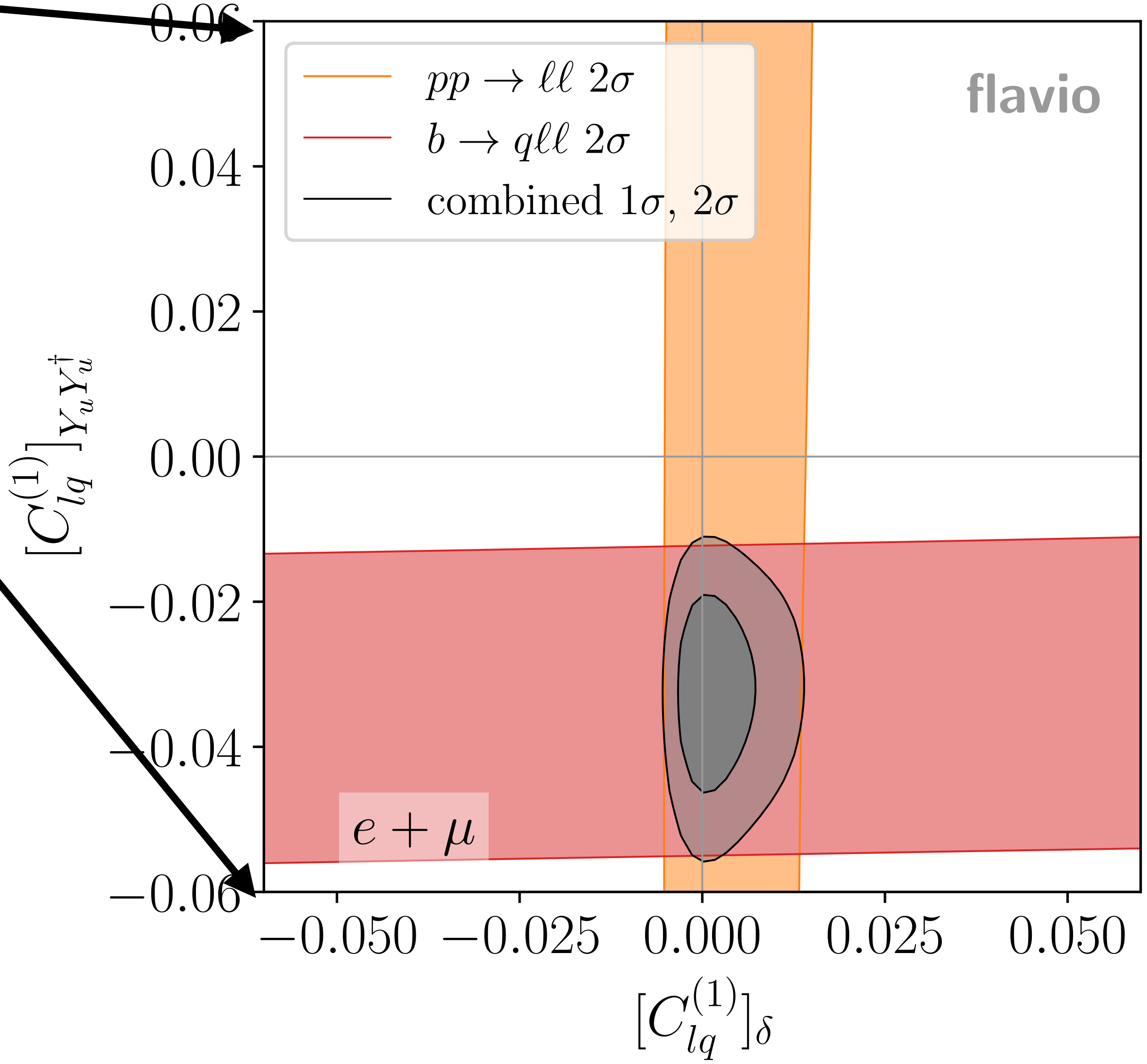


$i = 1,2$: universal NP



$b \to s\mu\mu$

Realistic flavour: B decays and tails complementary

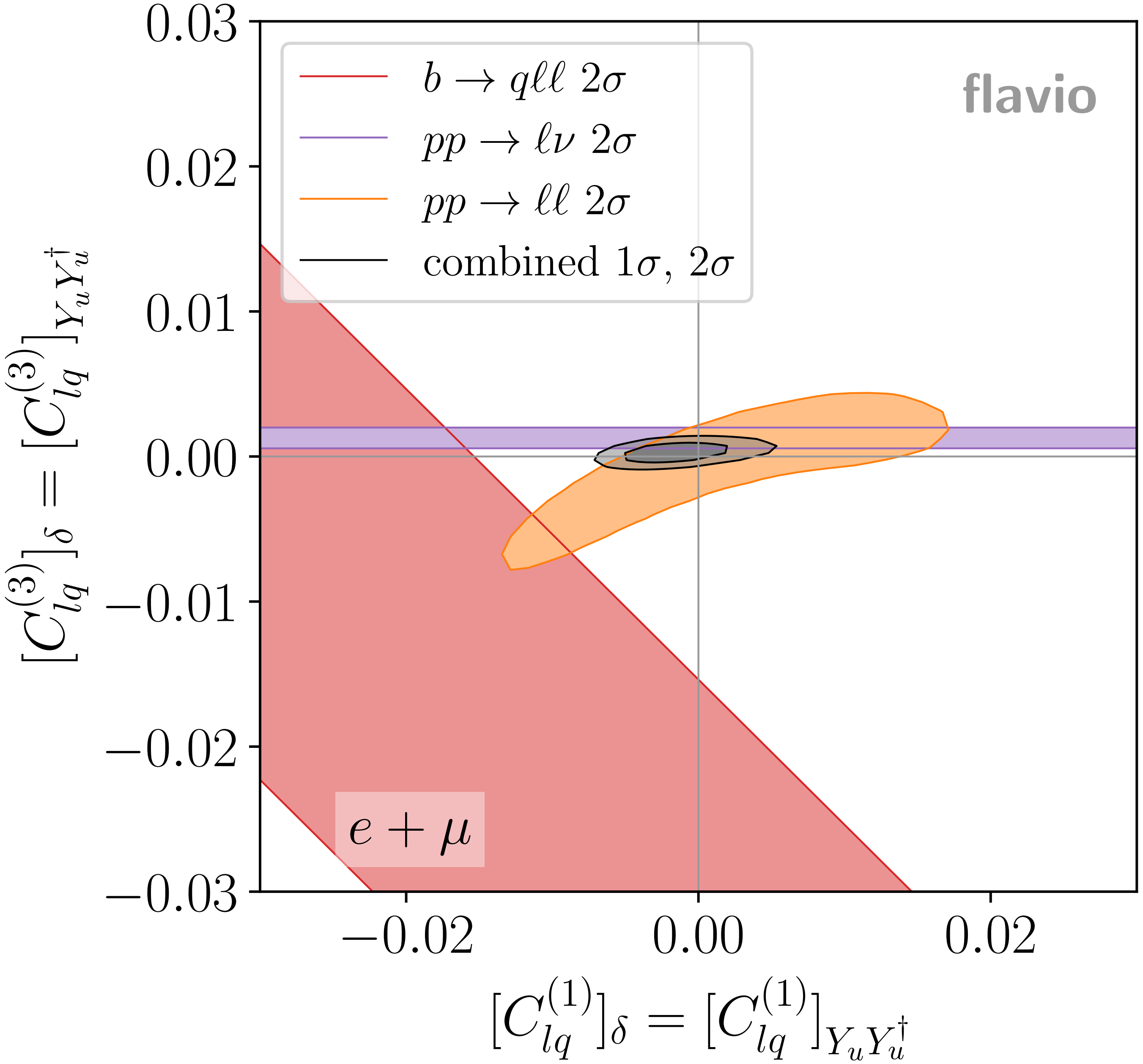
$$[C_{lq}^{(1)}]_{iist}\bar{L}_i\gamma_\mu L_i\bar{Q}_s\gamma^\mu Q_t \to [C_{lq}^{(1)}]_{iist} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}$$

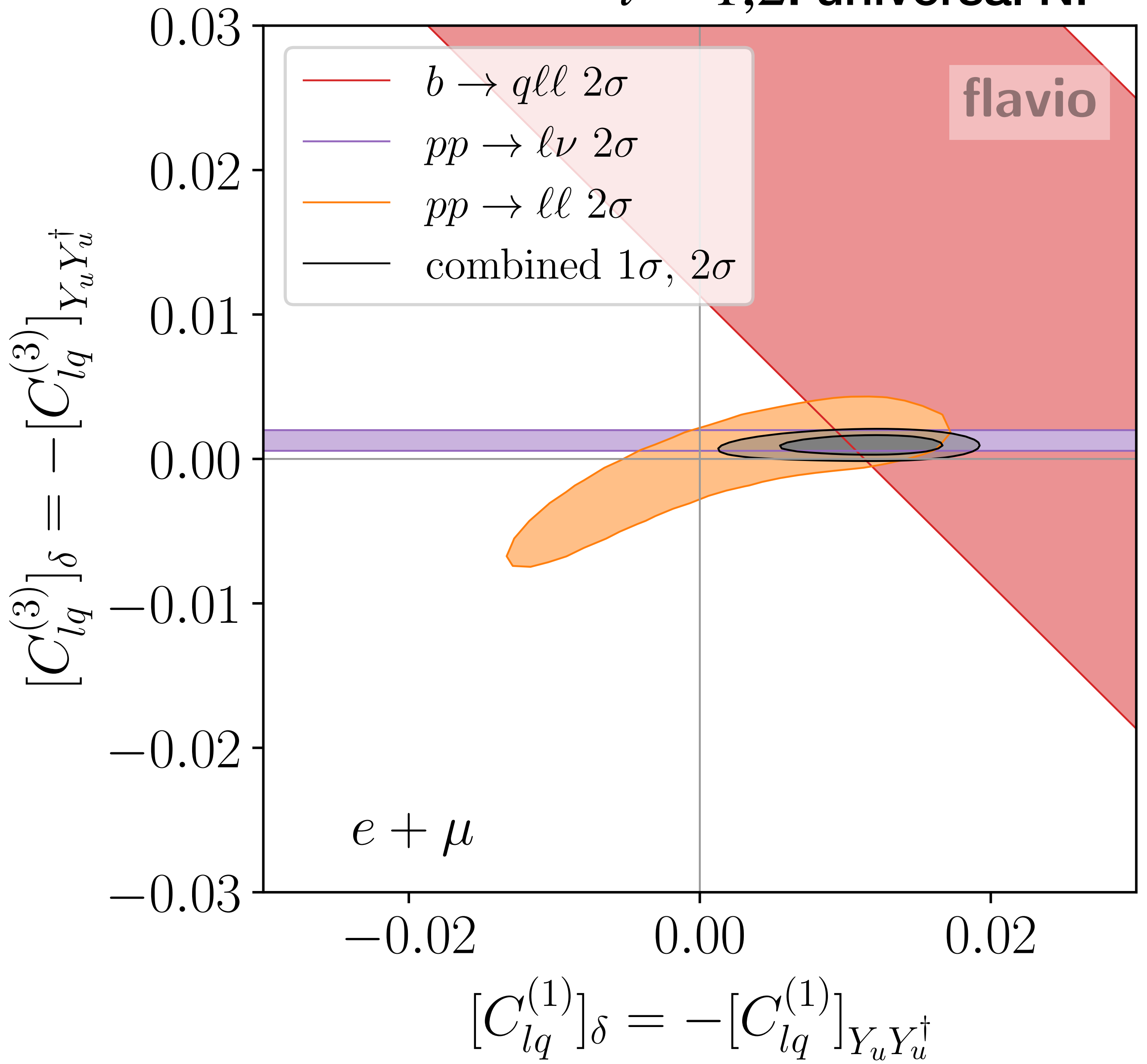
$$\sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$

Equating the coefficients with different signs

$b \to s\mu\mu$ anomalies

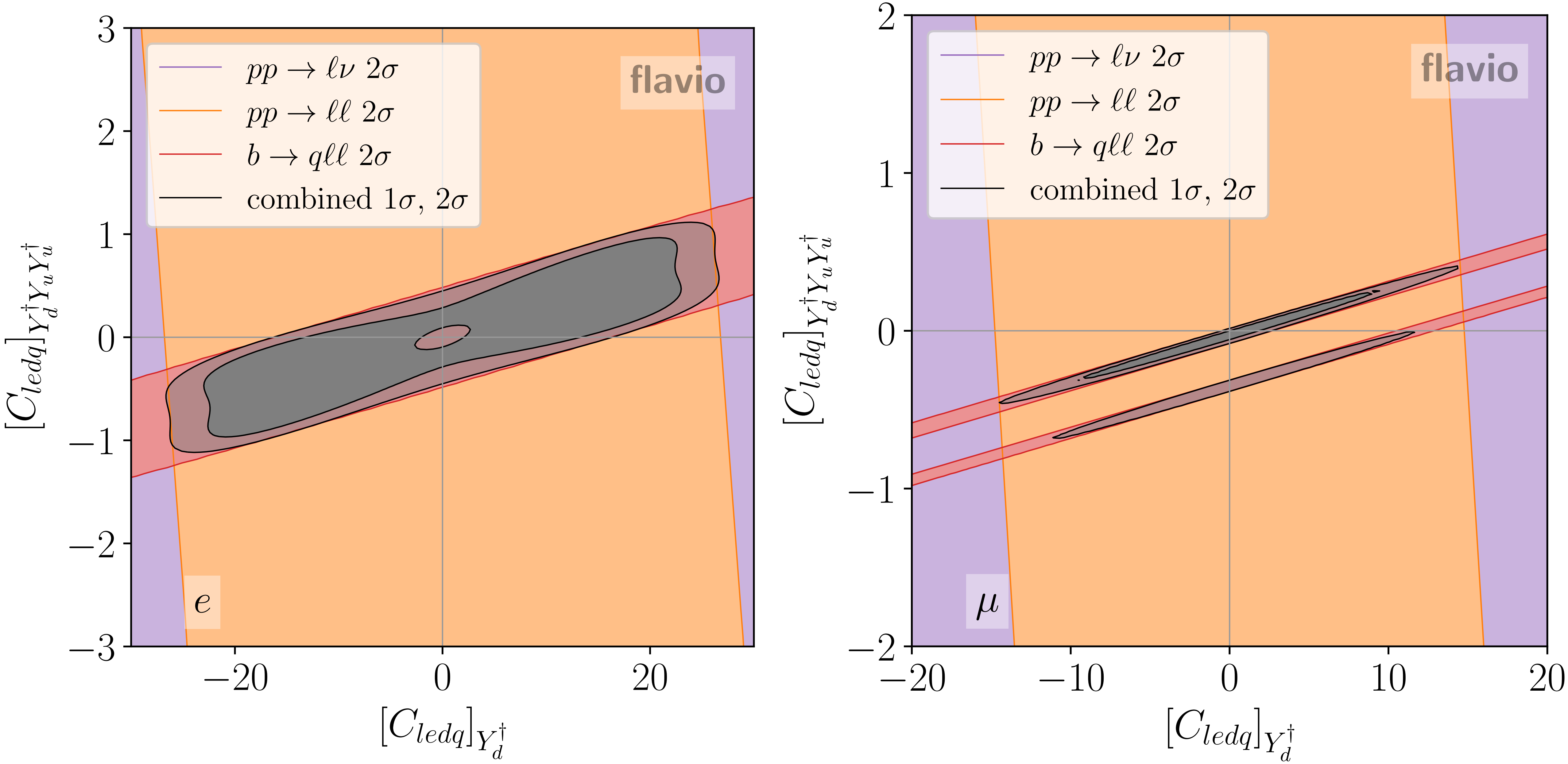
$i = 1,2$: universal NP





$$[C_{ledq}]_{iist}(\bar{L}_i e_i)(\bar{d}_s Q_t) \to [C_{ledq}]_{iist} = (Y_d^\dagger)_{st}[C_{ledq}]_{Y_d} + (Y_d^\dagger Y_u Y_u^\dagger)_{st}[C_{ledq}]_{Y_d^\dagger Y_u Y_u^\dagger}$$

$$\sim y_b y_t^2 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$



At low energies dominated by $B_s \to ee, \mu\mu$

Summary and outlook

- We implement neutral and charged current high-mass Drell-Yan tails into the well established flavio framework

- We analyse the interplay between low-energy B-meson decays into light leptons and high-mass Drell-Yan constraints in the SMEFT

- B decays offer excellent constraining power, especially dominating in minimalistic flavour scenarios, more data in $b \to d\ell\ell$, $b \to see$ welcome

- High complementarity between Drell-Yan and meson decays in realistic flavour scenarios

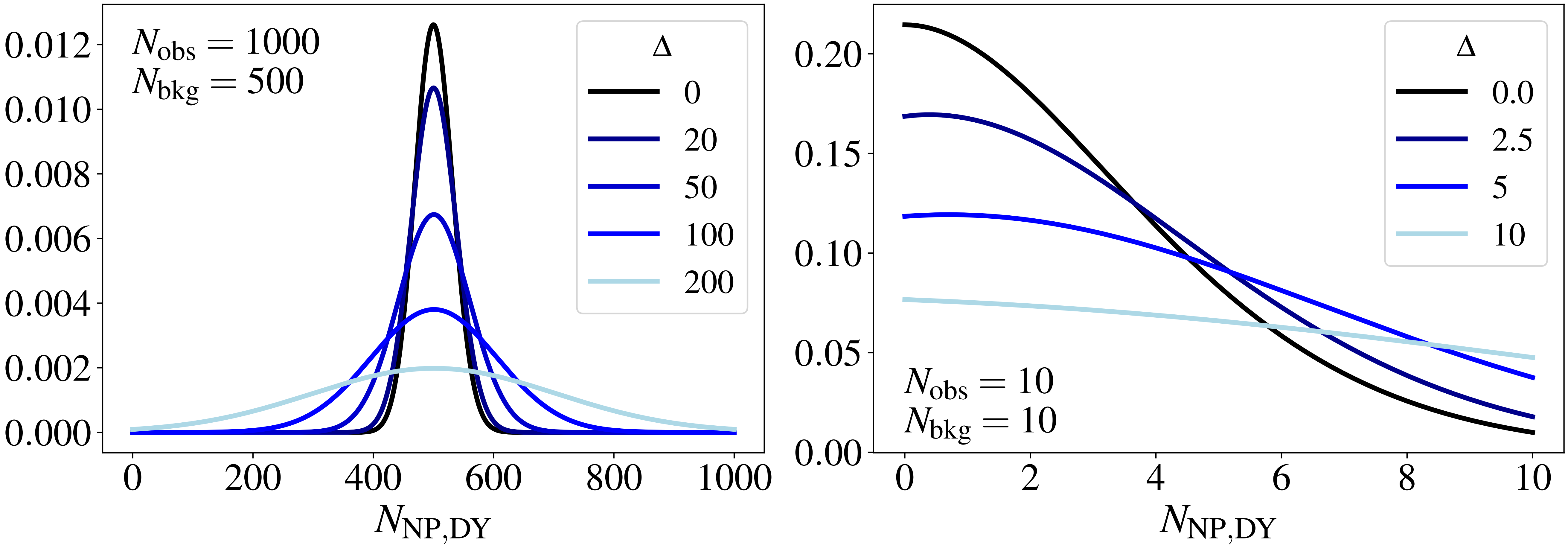
- Stay tuned for more interesting examples and scenarios
  Updated flavio coming soon!

Implementation of Drell-Yan

Experimental likelihood:

- Assume events in each bin independent, following the Poisson distribution
- Systematic uncertainties included by convolving with a Gaussian
- Number of expected events: $N_{\rm tot} = N_{\rm NP,DY} + N_{\rm bkg}$
- Number of observed events: $N_{\rm obs}$

$$f(N_{\rm NP,DY}\,|\,N_{\rm obs}) = \int d\tau \frac{(N_{\rm tot}+\tau)^{N_{\rm obs}} e^{-(N_{\rm tot}+\tau)}}{N_{\rm obs}!} \mathcal{N}(0,\Delta)(\tau)$$



Sensitivity of Drell-Yan