JENNIFER 2

EU grant n.822070

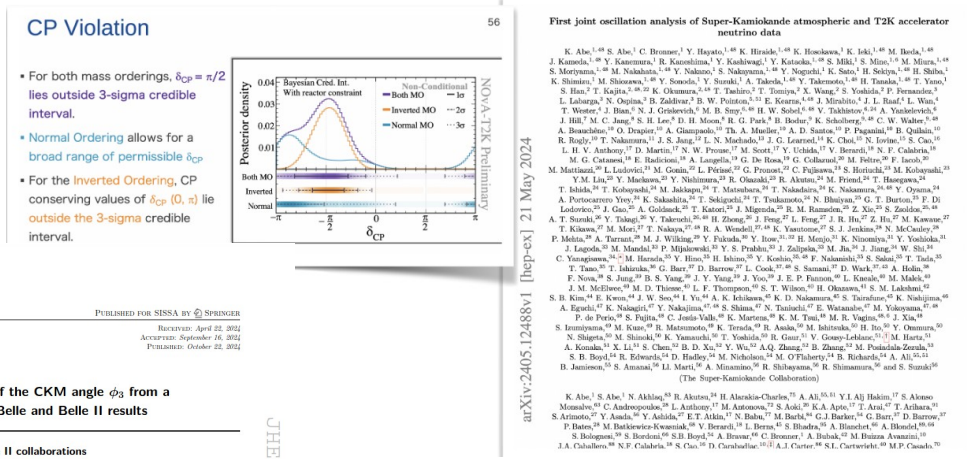
WP5 Common tools: combination of experiments

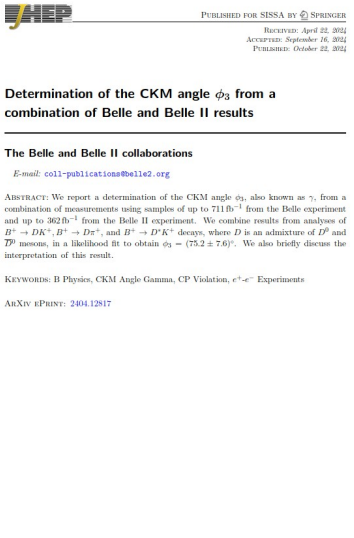
JENNIFER2 final meeting
(April 2025, Pisa)

S.Bolognesi (CEA Saclay)

Combination of experiments

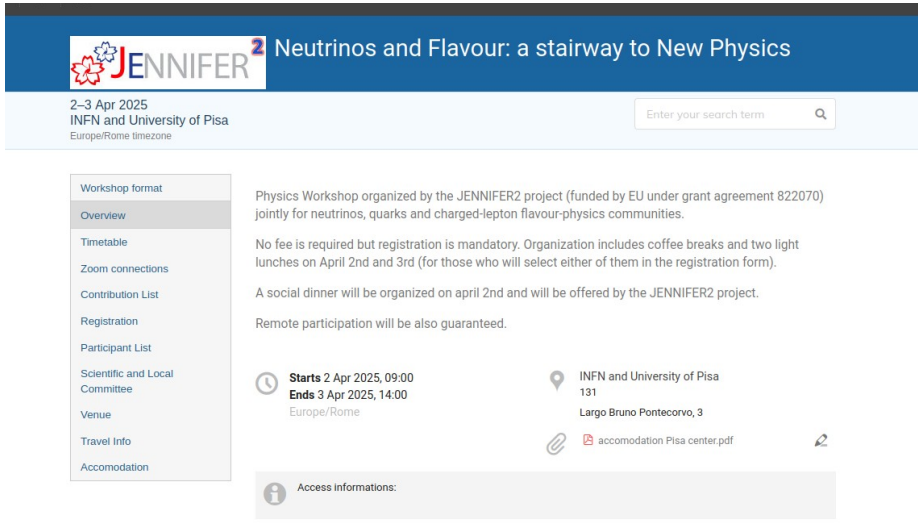
The Jennifer2 era has been the years if ‘combination’ both for **Belle2 (+Belle)** and for **T2K (+SK, +NOVA)** communities!





A lot of results from combination of experiments with pivotal participation from Jennifer2 members!

Workshop (2/3 April, Pisa)



Session dedicated to combination of experiments for neutrino and quark flavour

The final word on the achievements during the **Jennifer2 era**
→ **important learned lesson for the future**

The future precision era / New Physics Searches will be dominated by combinations!

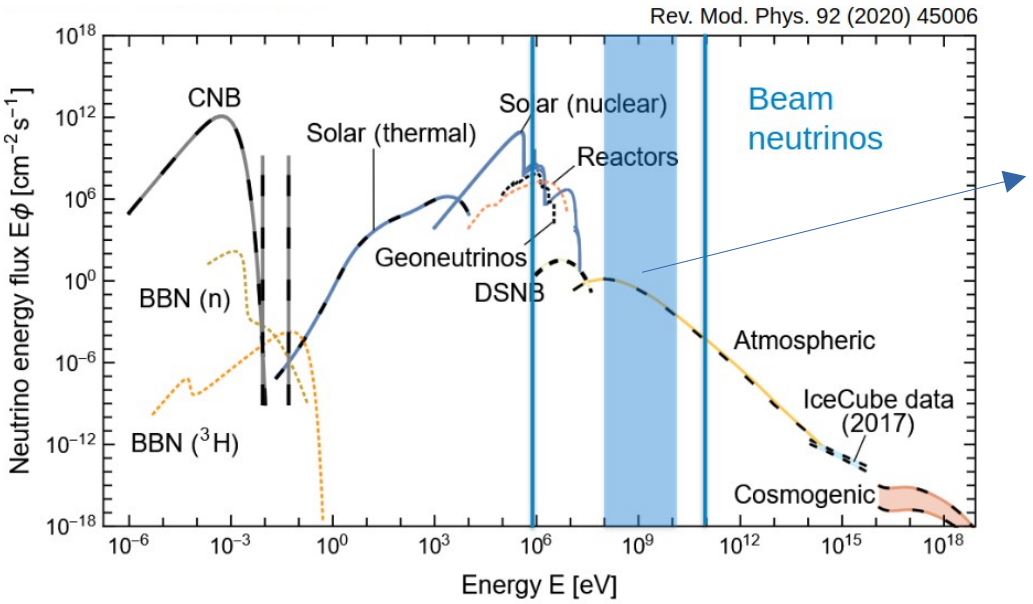
(Big and personal thanks to the speakers for the great talks!
Here just a summary of their inputs)

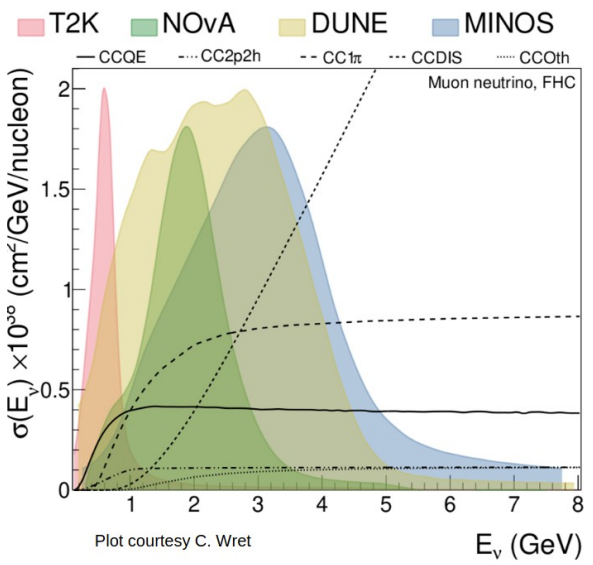
Neutrino oscillations

Many experiments to enjoy (oscillation focus)

Different channels ($\nu_\alpha \rightarrow \nu_\beta$: 3x3) at different energies

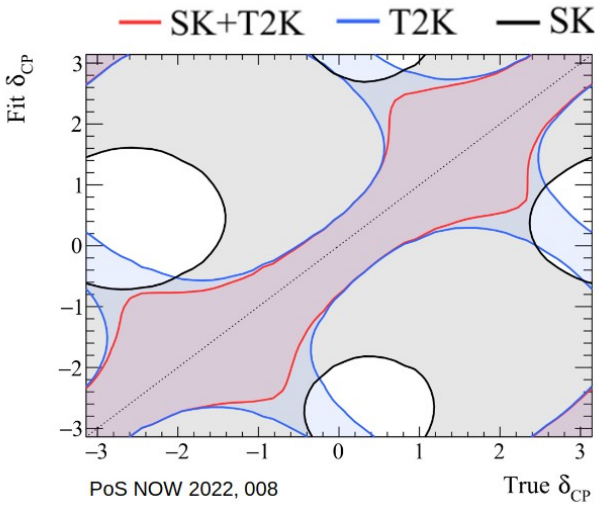
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



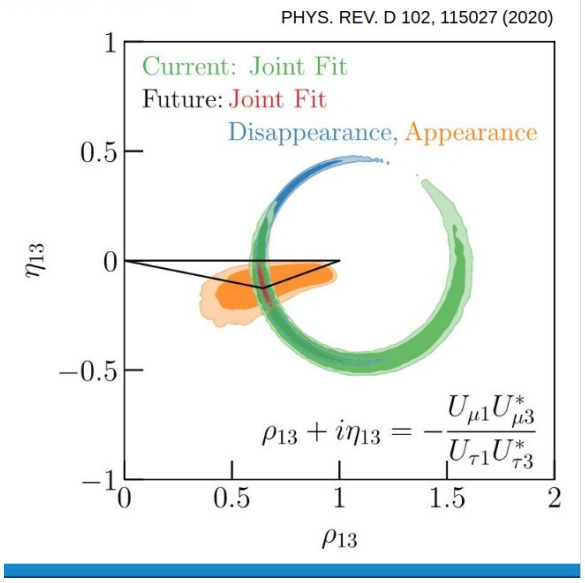


Why combining?

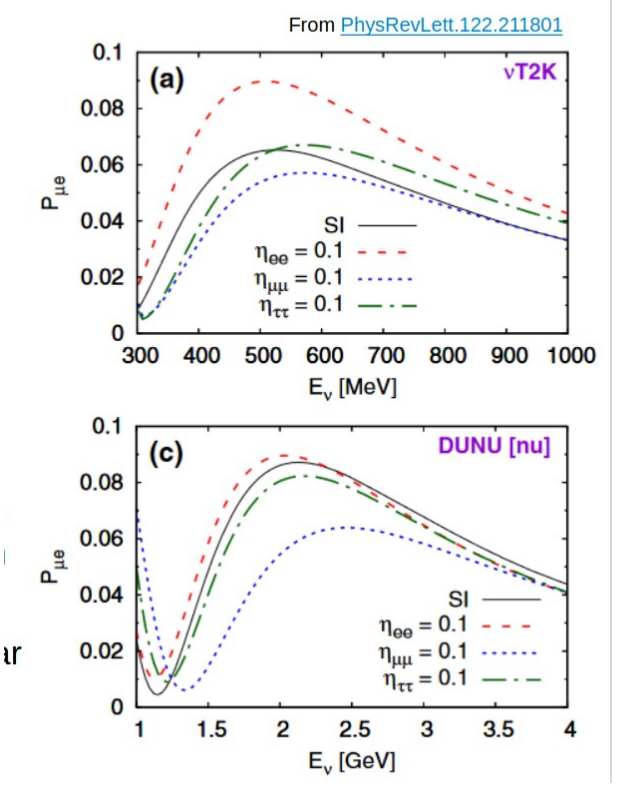
- **Breaking degeneracies** in the PMNS parameter space



- **Overconstraining** the PMNS parameter space: eg, unitarity



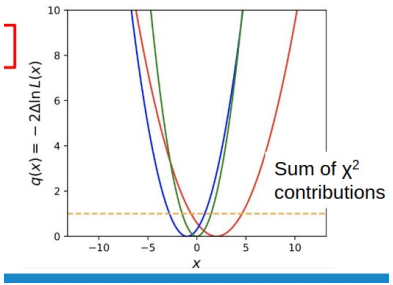
- **Distinguish New Physics** scenarios: eg, NSI



How combining?

EASY

DIFFICULT



Sum of final Gaussian errors on single parameter:
- non-gaussian effects?
- correlations?

APPROXIMATED

PRECISE

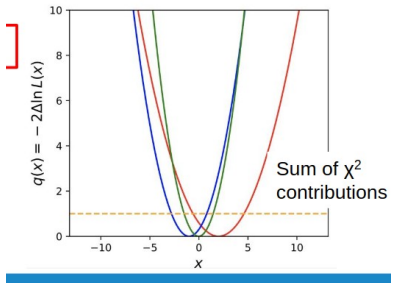
How combining?

EASY

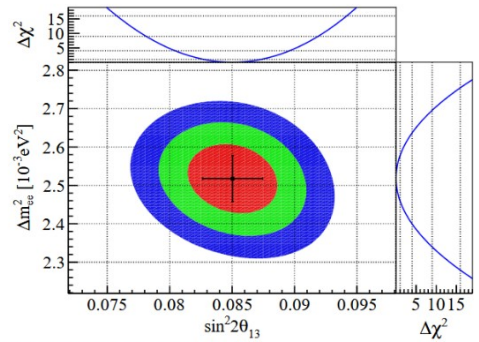
DIFFICULT

APPROXIMATED

PRECISE



Sum of final Gaussian errors on single parameter:
- non-gaussian effects?
- correlations?



https://arxiv.org/abs/2309.05989

Sum of multidimensional likelihood
- handle large dimensionality, especially for systematic uncertainties
- if partial likelihood: marginalization/profile could hide correlations and/or New Physics effects

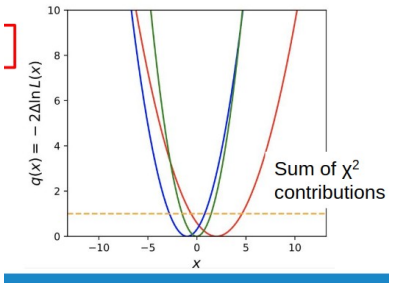
How combining?

EASY

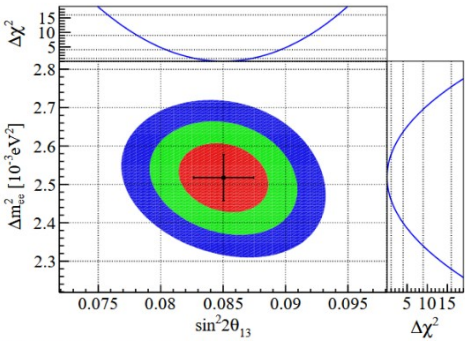
DIFFICULT

APPROXIMATED

PRECISE



Sum of final Gaussian errors on single parameter:
- non-gaussian effects?
- correlations?



https://arxiv.org/abs/2309.05989

Sum of multidimensional likelihood
- handle large dimensionality, especially for systematic uncertainties
- if partial likelihood: marginalization/profile could hide correlations and/or New Physics effects

→ **Full joint data fits between experiments!**
(and even in that case, what about different models?)

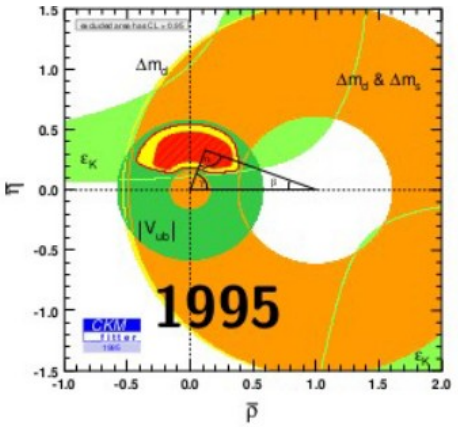
Main message for the future

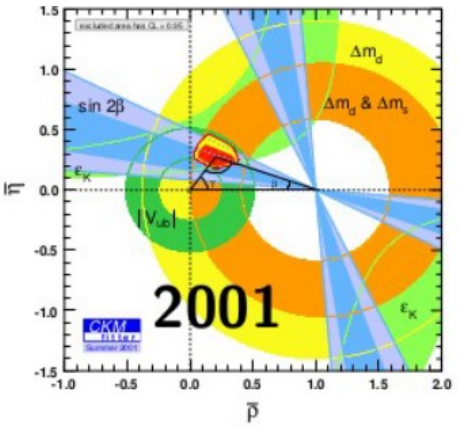
Imperial College London

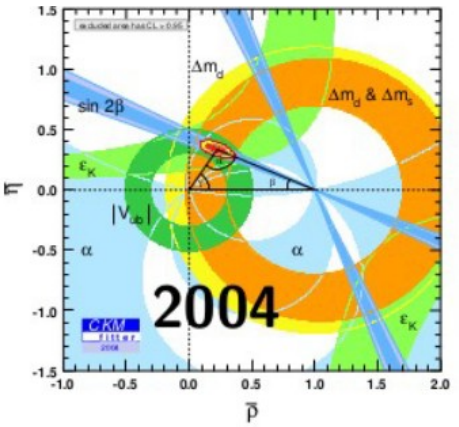
Overcoming difficulties

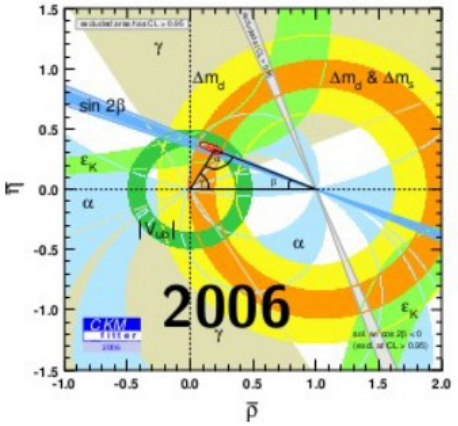
- Start talking about them!
  - Help experiments develop analyses with ease of combination in mind
  - Help with sociological side of combined analyses
  - Support development of common formats (NuHEPMC etc.)
- Start doing it now!
  - T2K + NOvA and T2K + SK demonstrate how to do this
  - Discover (and address) potential issues for future experiments
- Potential to have joint facilities in future!
  - NA61/SHINE for next gen experiments
  - Neutrino beamline at CERN (NuSTORM, EnuBET etc.) with argon, scintillator, water Cherenkov detectors

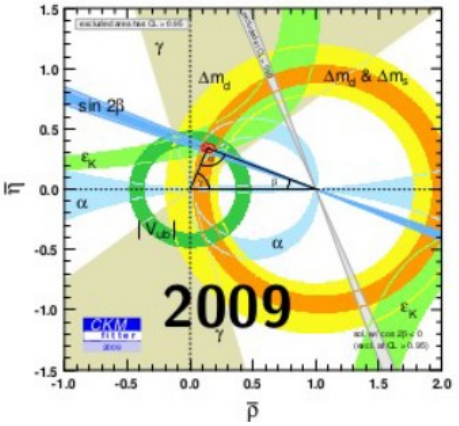
Flavour joint fits: CKMFit

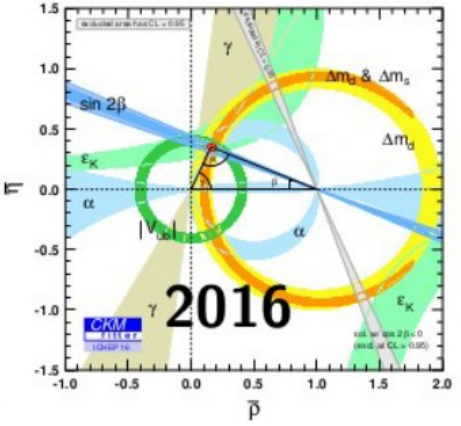












How to treat theoretical systematics?

Standard approach:

product of likelihoods

$$\mathcal{L} \overset{Rfit}{=} \mathcal{L}_{stat} \times \mathcal{L}_{theo},$$

$$\chi^2 = -2\,\ell\mathrm{n}\,\mathcal{L}$$

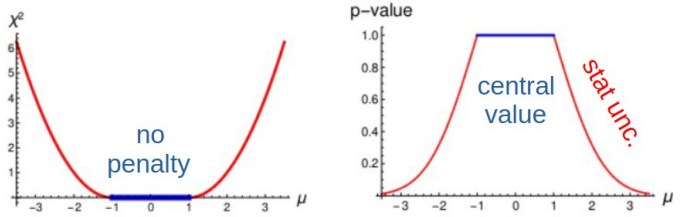
$\mathcal{L}_{stat}$: exp. data

$\mathcal{L}_{theo}$: had. inputs

[cf. Charles, Descotes-G., Niess, LVS '17]

[Hoecker et al. '01, Charles et al. '04]

Example in 1D, $0 \pm 1_{stat} \pm 1_{theo}$ ($N_{dof} = 1$)



χ^2: flat bottom, quadratic walls

How to treat theoretical systematics?

Standard approach:

product of likelihoods

$$\mathcal{L} \overset{Rfit}{=} \mathcal{L}_{stat} \times \mathcal{L}_{theo},$$

$$\chi^2 = -2\,\ell n\,\mathcal{L}$$

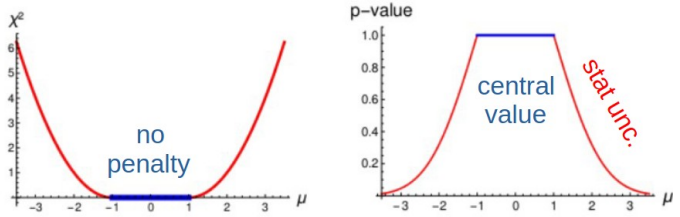
$\mathcal{L}_{stat}$: exp. data

$\mathcal{L}_{theo}$: had. inputs

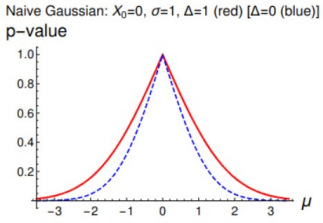
[cf. Charles, Descotes-G., Niess, LVS '17]

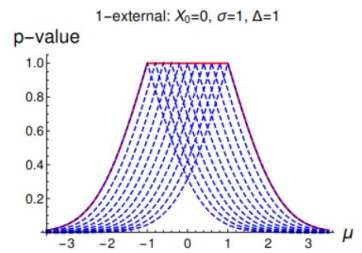
[Hoecker et al. '01, Charles et al. '04]

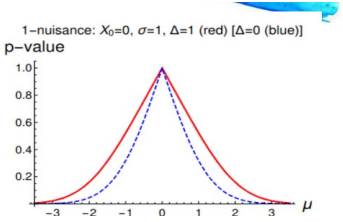
Example in 1D, $0 \pm 1_{stat} \pm 1_{theo}$ $(N_{dof} = 1)$

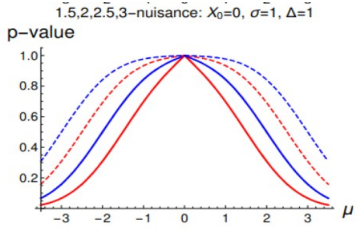


χ^2: flat bottom, quadratic walls

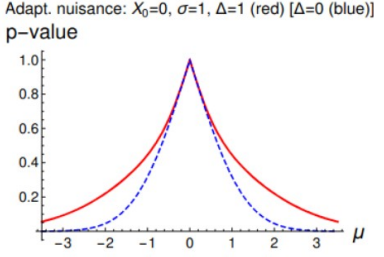








Many other possibilities ...



How to treat theoretical systematics?

Standard approach:

product of likelihoods

$$\mathcal{L} \overset{Rfit}{=} \mathcal{L}_{stat} \times \mathcal{L}_{theo},$$

$$\chi^2 = -2\,\ell n\,\mathcal{L}$$

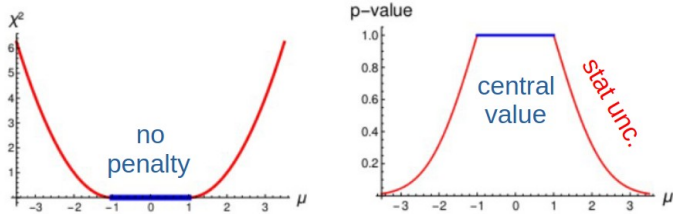
$\mathcal{L}_{stat}$: exp. data

$\mathcal{L}_{theo}$: had. inputs

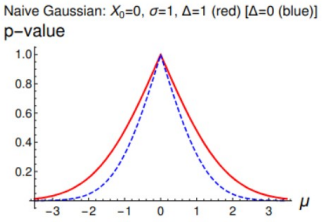
[cf. Charles, Descotes-G., Niess, LVS '17]

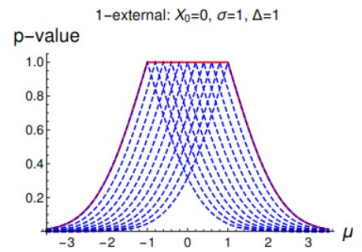
[Hoecker et al. '01, Charles et al. '04]

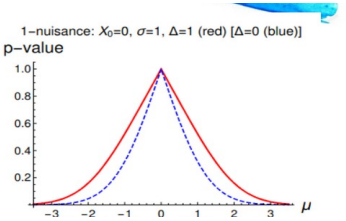
Example in 1D, $0 \pm 1_{stat} \pm 1_{theo}$ $(N_{dof} = 1)$

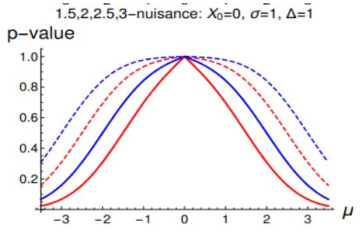


χ^2: flat bottom, quadratic walls

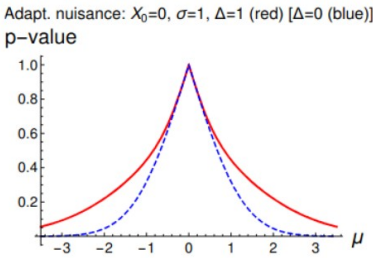








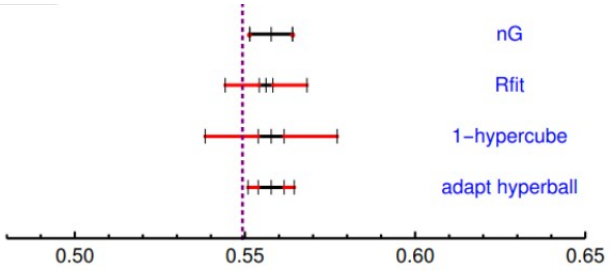
Many other possibilities ...



And it does matter!!

Example: combination of different extractions of $B_K^{\overline{\rm MS}}\,(2\ {\rm GeV})$

nG	0.5577	(63)	-
*R*fit	0.556	(02)	(10)
1-hypercube	0.558	(04)	(18)
adapt hyperball	0.5577	(38)	(50)



[further examples: Charles, Descotes-G., Niess, LVS '17]

HFLAV: averaging physics variables

Heavy Flavor Averaging Group
https://hflav.web.cern.ch

"The Heavy Flavor Averaging Group (HFLAV) was established at the May 2002 Flavor Physics and CP Violation Conference (Philadelphia) and continues the LEP Heavy Flavor Steering Group's tradition of providing regular updates to the world averages of heavy flavor quantities."

Requests and recommendations

- When publishing limits, also publish the central value and uncertainty
  - Well-known rule, but you'd be surprised how often it's not followed…
- When possible, provide the likelihood function of your measurement with respect to all the parameters considered.
  - This will enable the most accurate calculation of averages while updating nuisance parameters
- In any case, provide the values and systematics associated with nuisance parameters to enable executing the y_i-update procedure
  - E.g., $Br(\Upsilon(4S) \to B^0\bar{B}^0)$
- Publish measurements of BR ratios (more precise than measurements of BRs)!
  - LHCb does this regularly since they can't measure the number of b hadrons produced.
  - e^+e^- experiments utilize their ability to measure N_B and $Br(\Upsilon(4S) \to B^0\bar{B}^0)$, so usually quote absolute BRs, which are less precise.
    Therefore, averaging requires accounting for correlations, which can be difficult (different samples taken at slightly different energies by same/different experiments)

Conclusions (?)

- **Combination of experiments** is more important than ever in neutrino and quark flavour sector.

- Basic procedures and main challenges have been identified → **major results published!**

- The best way to address them **remains a challenge** for the years to come!