# Systematics at the Neutrino Factory ... and the global context

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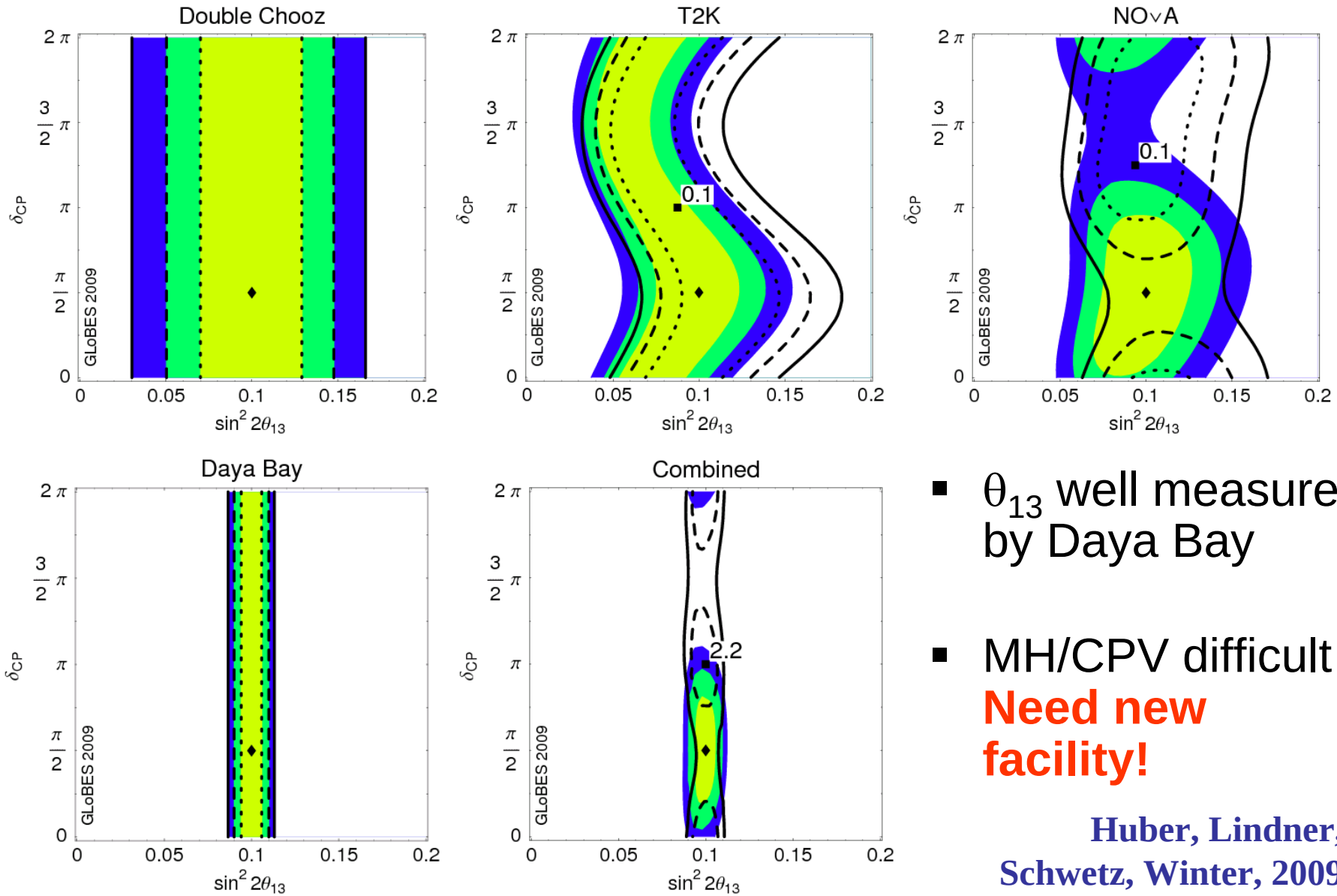
- The setting
- Systematics and its implementation in explicit near-far simulations
- Neutrino Factory performance
- Worldwide comparison
- Main impacts
- Summary

# Consequences of large $\theta_{13}$

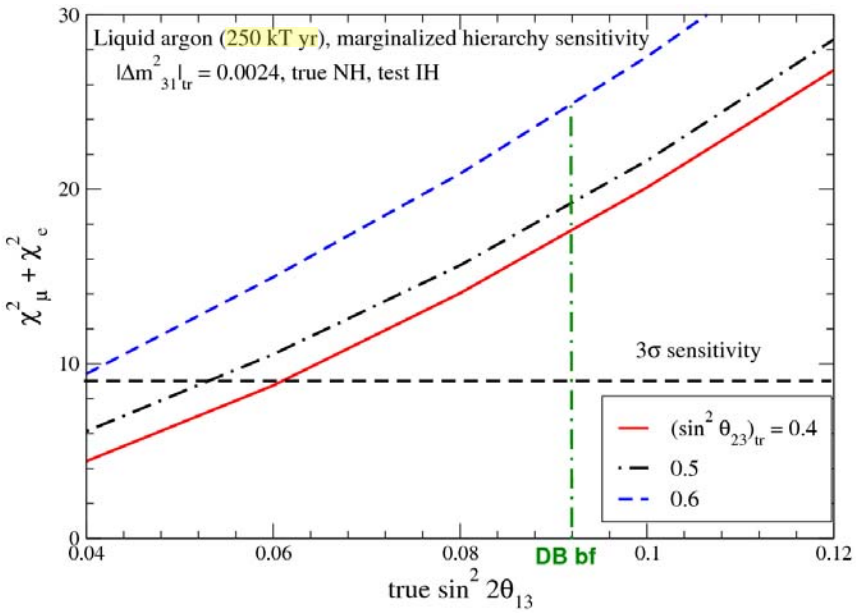



- $\theta_{13}$ well measured by Daya Bay
- MH/CPV difficult **Need new facility!**

**Huber, Lindner, Schwetz, Winter, 2009**

# Mass hierarchy measurement?

- Mass hierarchy [sgn($\Delta m^2$)] discovery possible with atmospheric neutrinos?
  **(liquid argon, HyperK, MEMPHYS, INO, PINGU, LENA, …)**



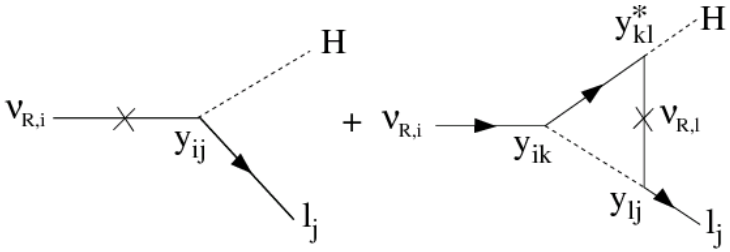

**Barger et al, arXiv:1203.6012;**
**IH more challenging**

Perhaps different facilities for MH and CPV proposed/discussed?

- NB: basically any long-baseline experiment at design luminosity with E > 1 GeV and L >> 600 km can for all $\delta_{CP}$ measure the hierarchy by sufficient Earth matter effects (MSW effect)!

# Why is $\delta_{CP}$ interesting?

- **CP violation** **sinδ**
  Necessary condition for successful baryogenesis
  (dynamical mechanism to create matter-antimatter asymmetry of the universe)
  ⇨ thermal leptogensis by decay of heavy see-saw partner?




- **Model building** **cosδ**

$$U_{\mathrm{PMNS}} = U_\ell^\dagger U_\nu$$

| Correction leading to non-zero $\theta_{13}$? | Symmetry e.g. TBM, BM, …? |
|---|---|

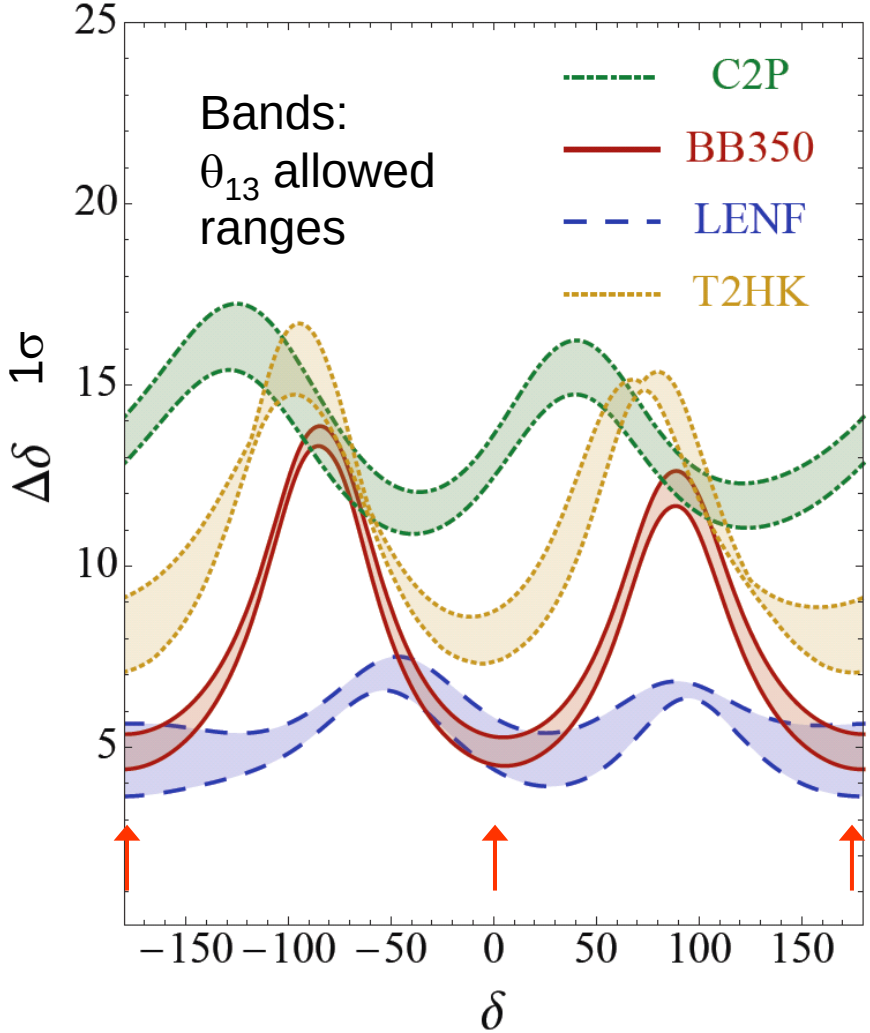
e.g. TBM sum rule: $\theta_{12} = 35° + \theta_{13}$ **cosδ**
**(Antusch, King; Masina)**

➢ Need performance which is equally good for all $\delta_{CP}$

# The new paradigm: Precision?

C2P = LBNO:
CERN-Pyhäsalmi
L~2300 km, 100kt
liquid argon

- CP violation performance represents only two possible values of $\delta_{CP}$ (0 and $\pi$)
  - Need new performance indicators
  - Reveals that some experiments (narrow beam spectra!) strongly optimized for CPV




**(Coloma, Donini, Fernandez-Martinez, Hernandez, 2012;**
**concept: WW, PRD 70 (2004) 033006 )**

# The International Design Study for the Neutrino Factory

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$

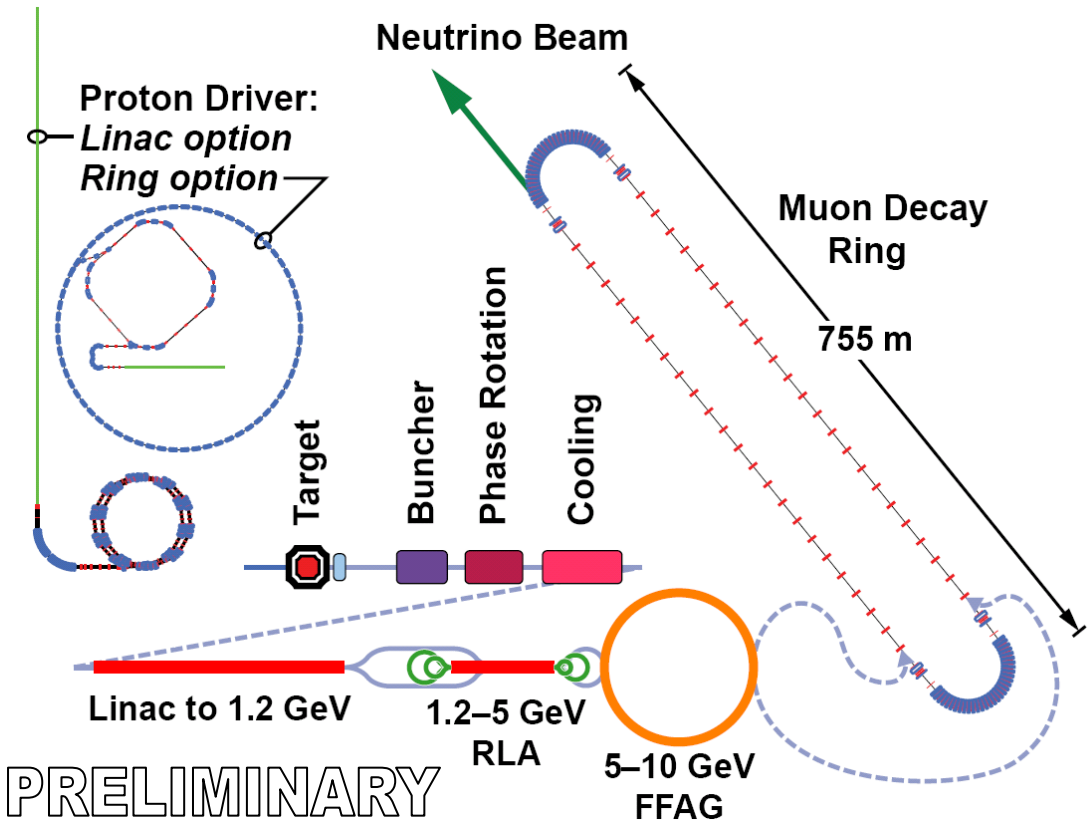
$\nu_\mu \rightarrow \nu_\mu$

(Geer, 1997; de Rujula, Gavela, Hernandez, 1998; Cervera et al, 2000)

Signal prop. $\sin^2 2\theta_{13}$

Contamination

Muons decay in straight sections of a storage ring

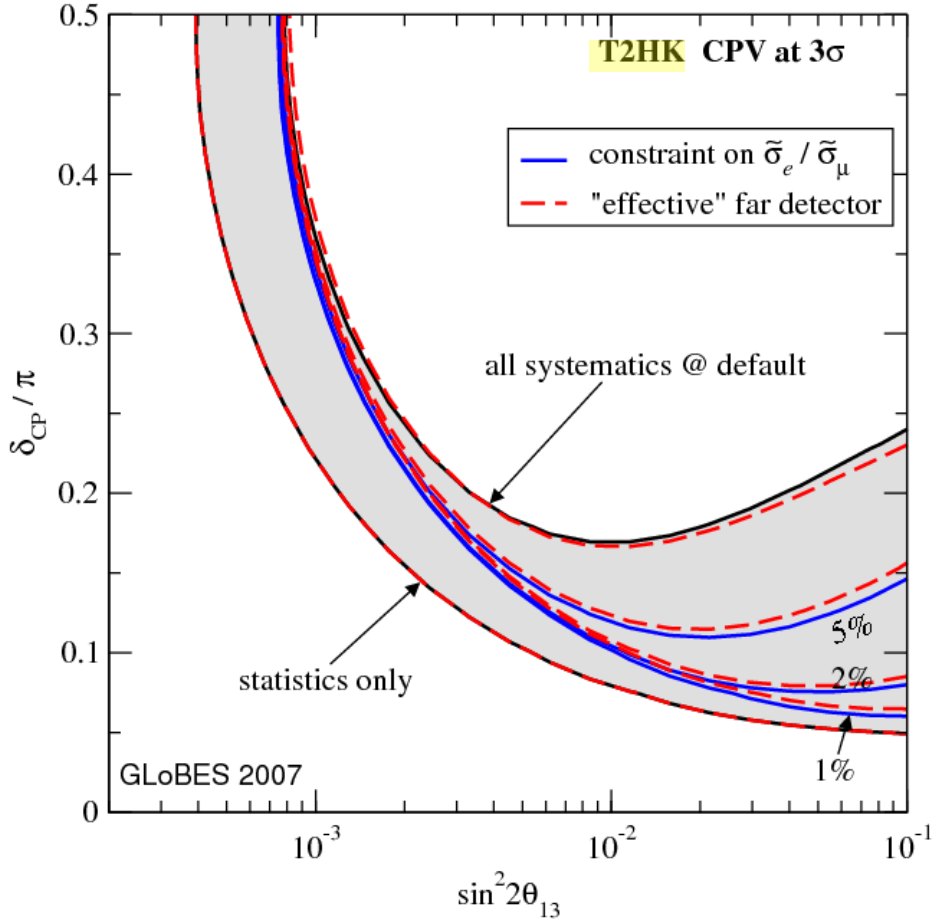



**IDS-NF:**

- Initiative from ~ 2007-2013 to present a design report, schedule, cost estimate, risk assessment for a neutrino factory

# The big unknown: Systematics

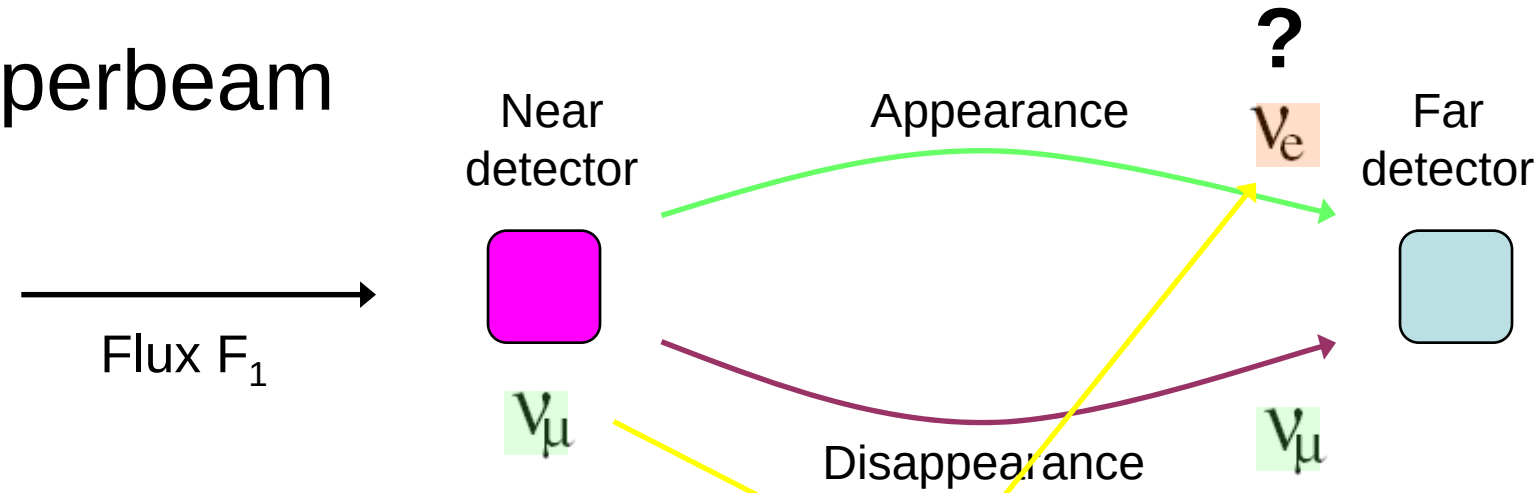
- **Systematics important for large $\theta_{13}$**
- **New treatment needed**
  - Use explicit near-far detector simulations
  - Use same knowledge for cross sections for all experiments
  - Use comparable framework for systematics implementation and correlations!
    (lesson from reactor experiments!)




(Huber, Mezzetto, Schwetz, 2007)

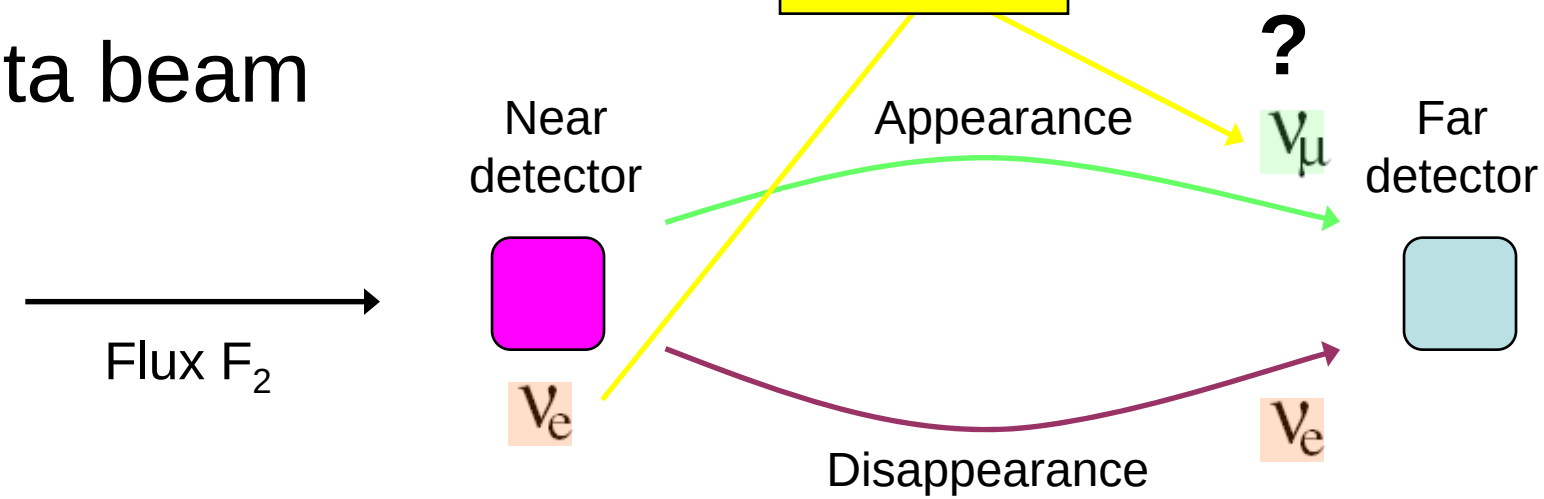
# Fluxes and cross sections:
## Superbeam, beta beam (illustrated)

- Superbeam



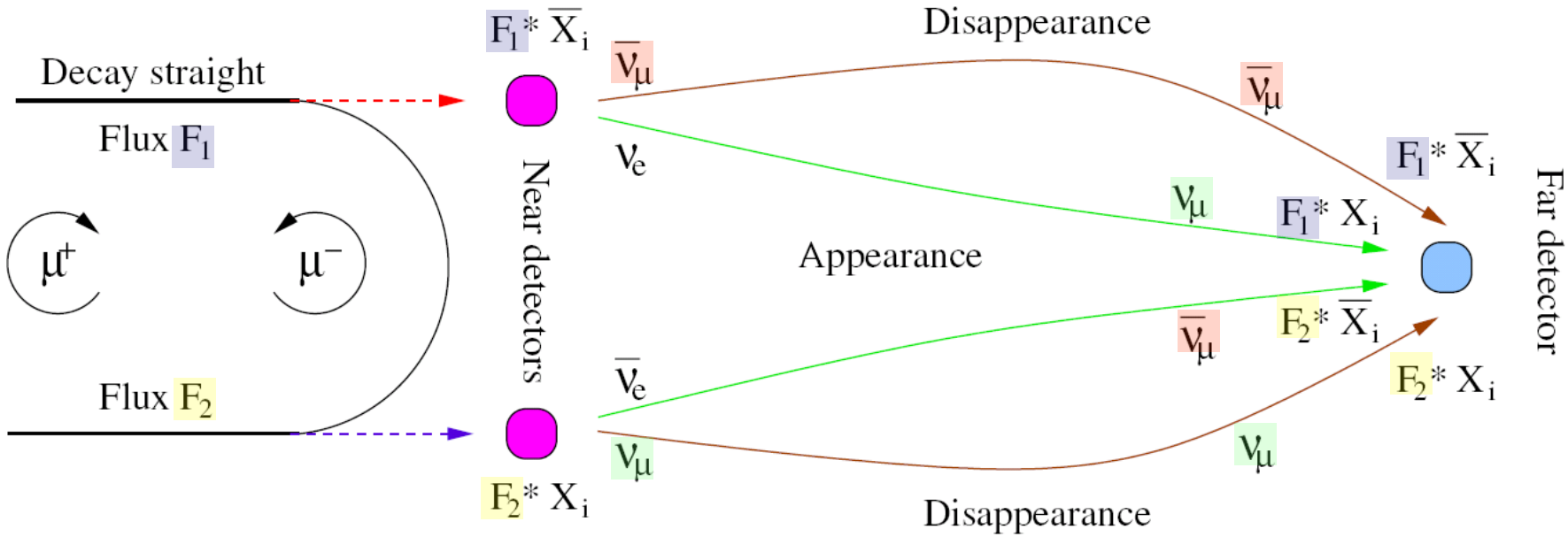

BB+SPL

- Beta beam



# Fluxes and cross sections:
## Neutrino Factory

(Tang, Winter, PRD 80, 053001, 2009)




- Muon (anti)neutrino cross sections measured in self-consistent way
- Fluxes in $\overline{\nu}_\mu$ / $\nu_e$ and $\overline{\nu}_e$ / $\nu_\mu$ fully correlated

# Cross section assumptions

| Systematics | Opt. | Def. | Cons. |
|---|---|---|---|
| Cross secs × eff. QE† | 10% | 15% | 20% |
| Cross secs × eff. RES† | 10% | 15% | 20% |
| Cross secs × eff. DIS† | 5% | 7.5% | 10% |
| Effec. ratio $\nu_e/\nu_\mu$ QE⋆ | 3.5% | 11% | – |
| Effec. ratio $\nu_e/\nu_\mu$ RES⋆ | 2.7% | 5.4% | – |
| Effec. ratio $\nu_e/\nu_\mu$ DIS⋆ | 2.5% | 5.1% | – |

Theoretical constraint (?)

**(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)**

[default values, ratios: efficiency: 5%, X-secs: 10% (QE) - 2% (RES) -1% (DIS) ]

- Universal for all experiments, range optimistic – default – conservative
- Independent errors for QE, RES, DIS
  - Possible shape error implied
- Effective cross section x efficiency errors used
- Independent for $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$ but (theoretical) flavor ratio applied

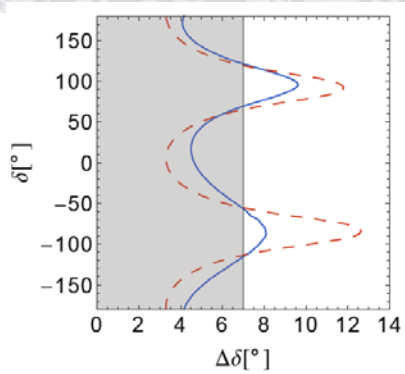
# Other systematics

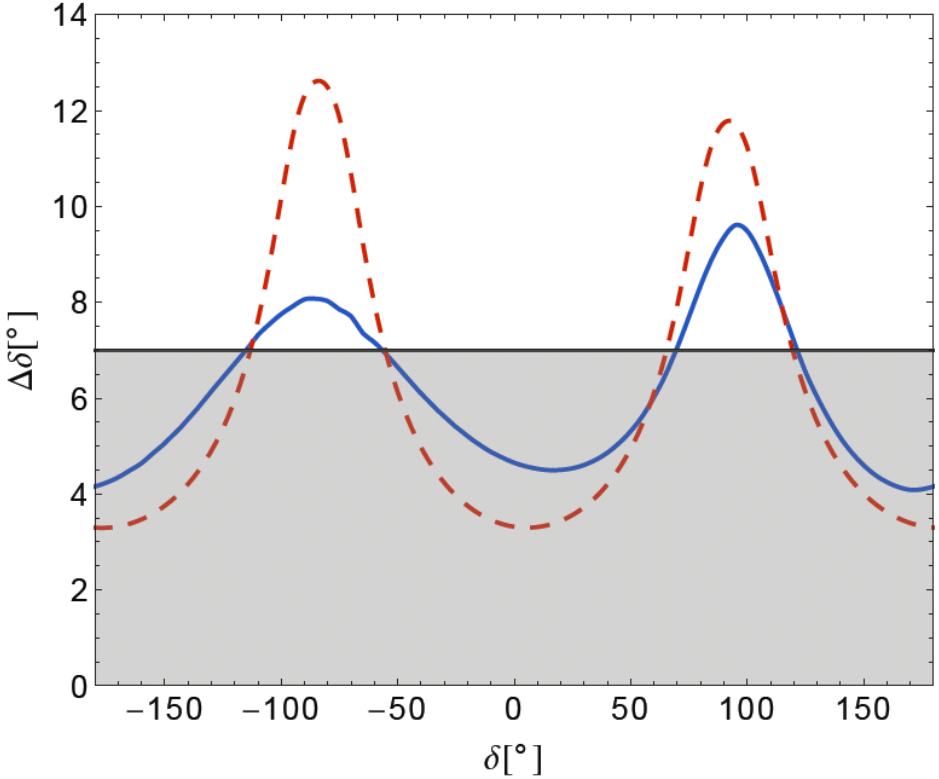
| Systematics | SB Opt. | SB Def. | SB Cons. | BB Opt. | BB Def. | BB Cons. | NF Opt. | NF Def. | NF Cons. |
|---|---|---|---|---|---|---|---|---|---|
| Fiducial volume ND | 0.2% | 0.5% | 1% | 0.2% | 0.5% | 1% | 0.2% | 0.5% | 1% |
| Fiducial volume FD (incl. near-far extrap.) | 1% | 2.5% | 5% | 1% | 2.5% | 5% | 1% | 2.5% | 5% |
| Flux error signal $\nu$ | 5% | 7.5% | 10% | 1% | 2% | 2.5% | 0.1% | 0.5% | 1% |
| Flux error background $\nu$ | 10% | 15% | 20% | correlated | | | correlated | | |
| Flux error signal $\bar{\nu}$ | 10% | 15% | 20% | 1% | 2% | 2.5% | 0.1% | 0.5% | 1% |
| Flux error background $\bar{\nu}$ | 20% | 30% | 40% | correlated | | | correlated | | |
| Background uncertainty | 5% | 7.5% | 10% | 5% | 7.5% | 10% | 10% | 15% | 20% |
| Matter density | 1% | 2% | 5% | 1% | 2% | 5% | 1% | 2% | 5% |

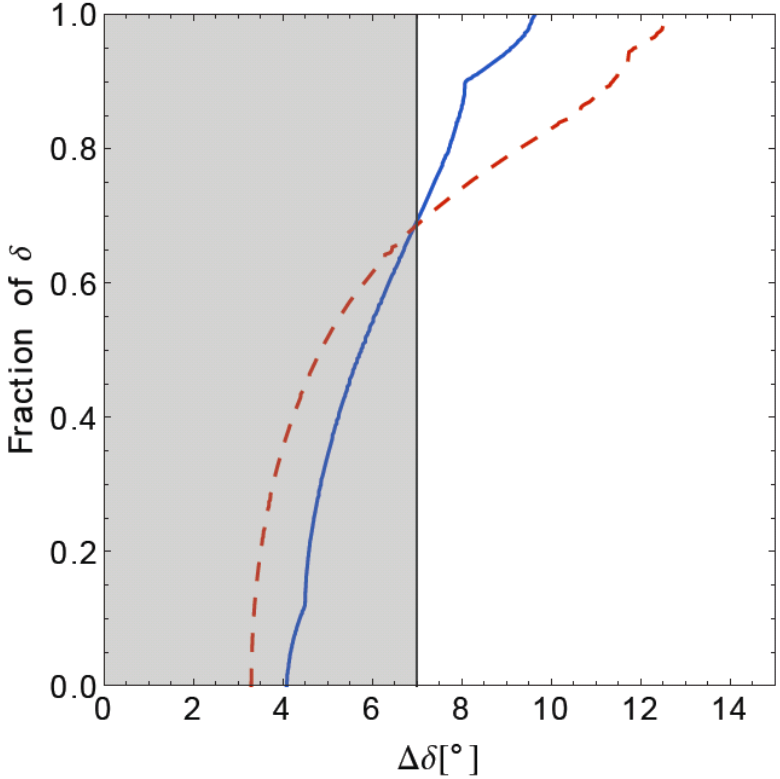
- Background uncertainties uncorrelated
- Superbeam peculiarities:
  - Same parameters for all setups
  - Intrinsic beam backgrounds with separate systematics (near-far correlated) ⇨ “flux error background“
  - Intrinsic beam contamination electron (anti)neutrino disappearance included (without significant effect)

**(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)**

# New performance indicator




(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

# Options

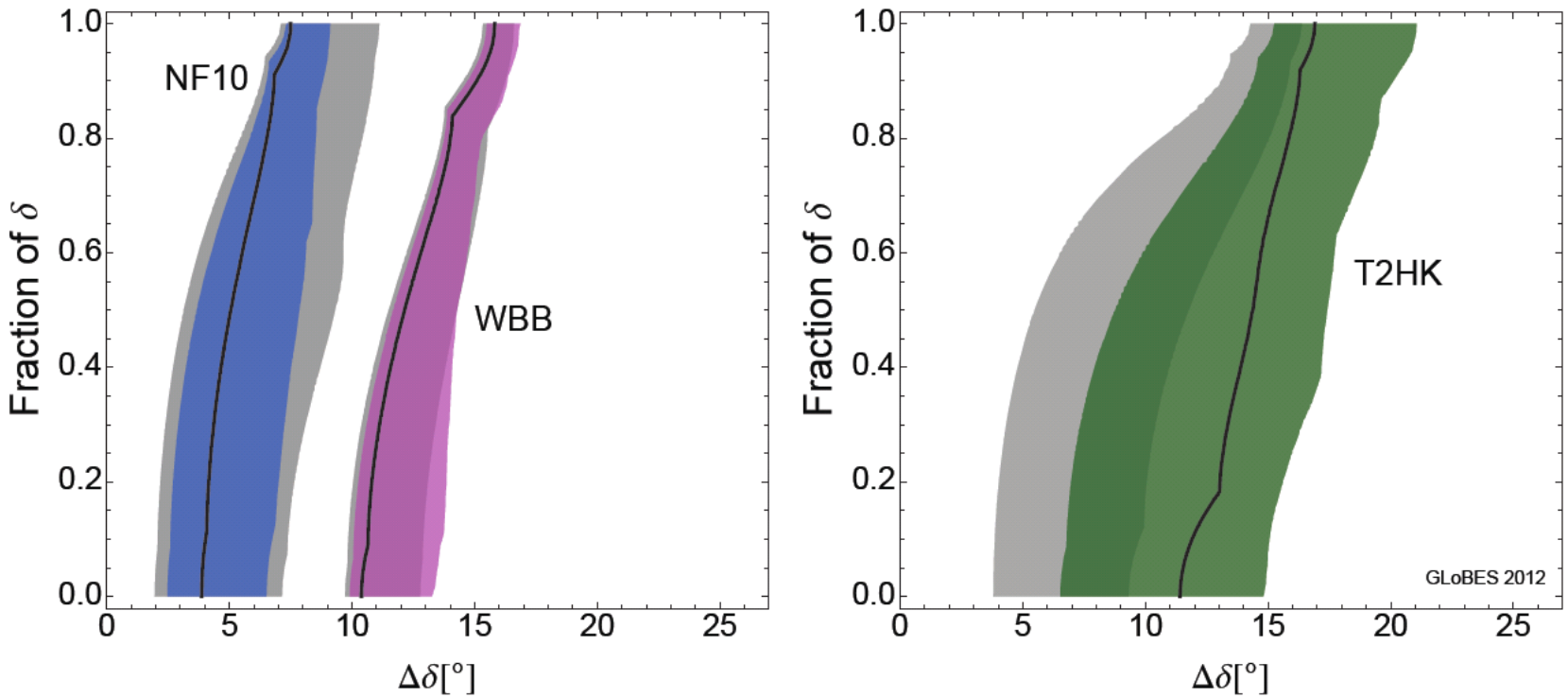
| | Setup | $E_\nu^{\text{peak}}$ | $L$ | OA | Detector | kt | MW | Decays/yr | $(t_\nu, t_{\bar{\nu}})$ |
|---|---|---|---|---|---|---|---|---|---|
| Benchmark | BB350 | 1.2 | 650 | – | WC | 500 | – | $1.1(2.8)\times10^{18}$ | (5,5) |
| | NF10 | 5.0 | 2 000 | – | MIND | 100 | – | $7\times10^{20}$ | (10,10) |
| | WBB | 4.5 | 2 300 | – | LAr | 100 | 0.8 | – | (5,5) |
| | T2HK | 0.6 | 295 | 2.5° | WC | 560 | 1.66 | – | (1.5,3.5) |
| Alternative | BB100 | 0.3 | 130 | – | WC | 500 | – | $1.1(2.8)\times10^{18}$ | (5,5) |
| | + SPL | | | – | | | 4 | – | (2,8) |
| | NF5 | 2.5 | 1 290 | – | MIND | 100 | – | $7\times10^{20}$ | (10,10) |
| | $\text{LBNE}_{\text{mini}}$ | 4.0 | 1 290 | – | LAr | 10 | 0.7 | – | (5,5) |
| | $\text{NO}\nu\text{A}^+$ | 2.0 | 810 | 0.8° | LAr | 30 | 0.7 | – | (5,5) |
| 2020 | T2K | 0.6 | 295 | 2.5° | WC | 22.5 | 0.75 | – | (5,5) |
| | $\text{NO}\nu\text{A}$ | 2.0 | 810 | 0.8° | TASD | 15 | 0.7 | – | (4,4) |

+ Daya Bay

**(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)**

# Impact of implementation

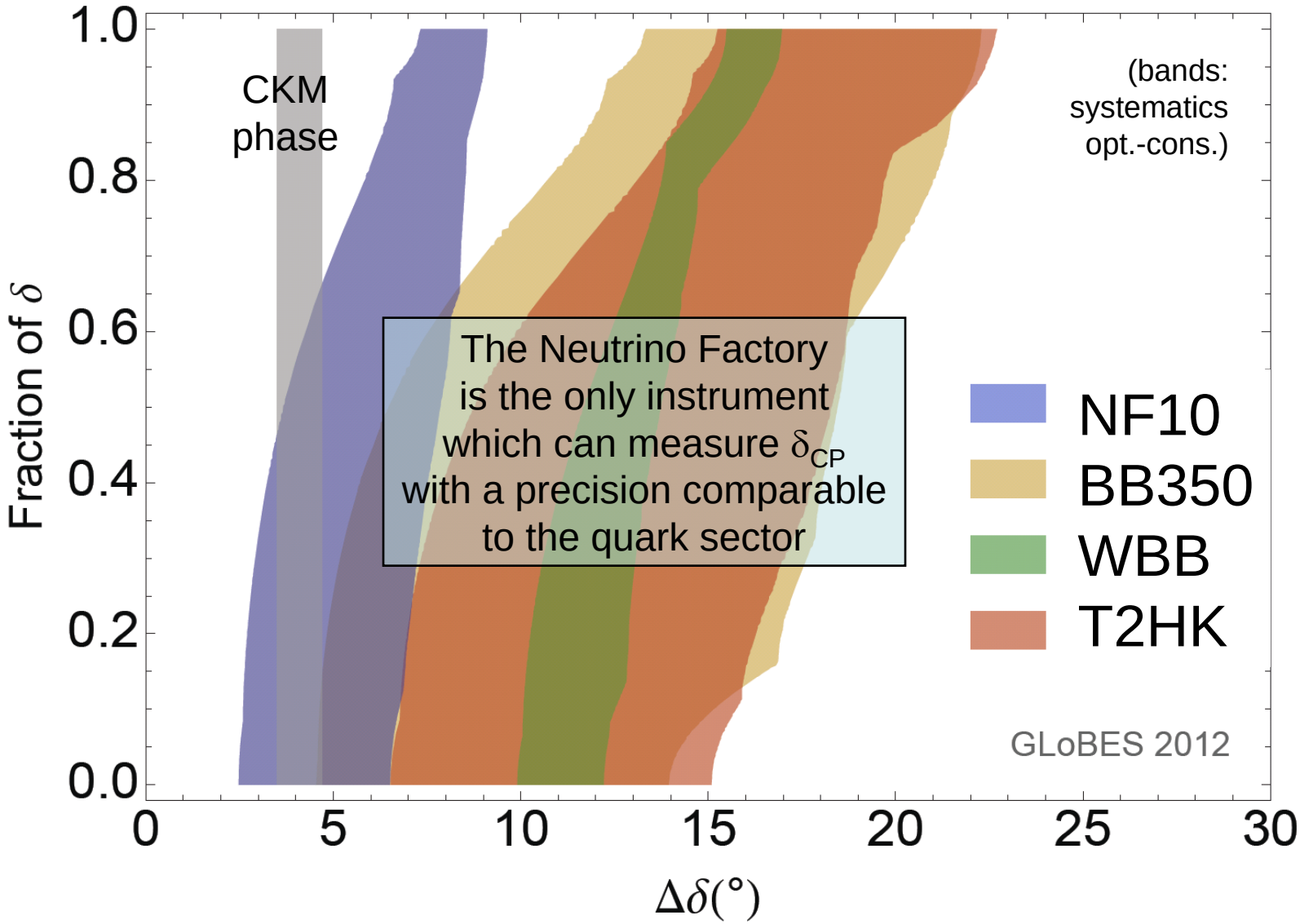
- Gray (eff. systematics, 0-10%) versus color (new):




- ➢ More precise predictions for Neutrino Factory (bands: conservative – optimtistic, curves: default)
- ➢ Systematic offset for T2HK, BB350 (QE $\nu_e$ cross sec. issue)

**(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)**

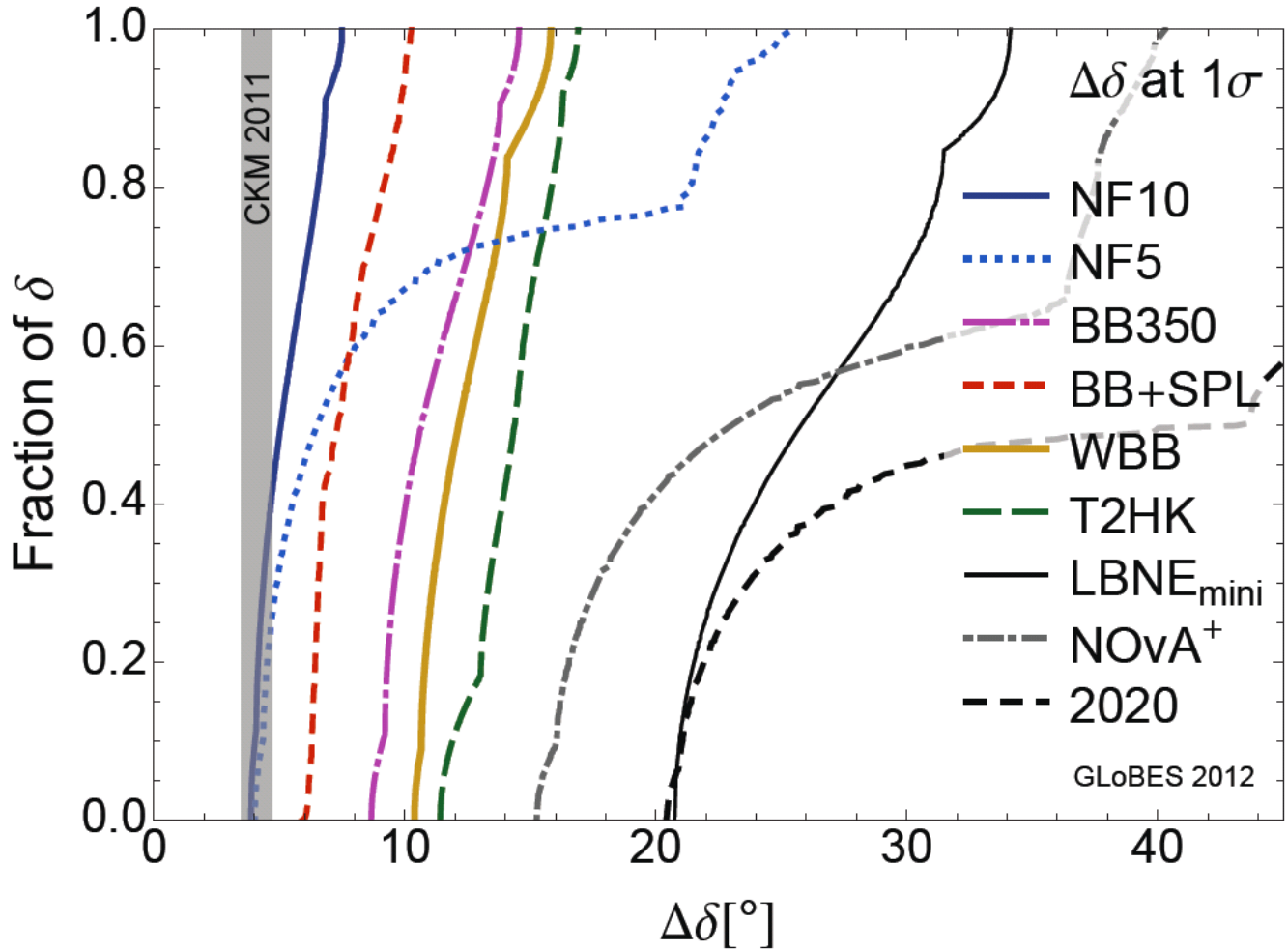
# Precision: Worldwide comparison




(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

# Interesting alternatives

- Comparison at default systematics:

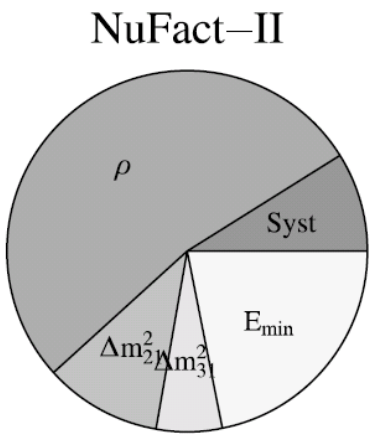



NF5 exhibits strong dependence on $\delta_{CP}$ (some dependence on binning!)

BB100+SPL is the only setup comparable with NuFact

(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

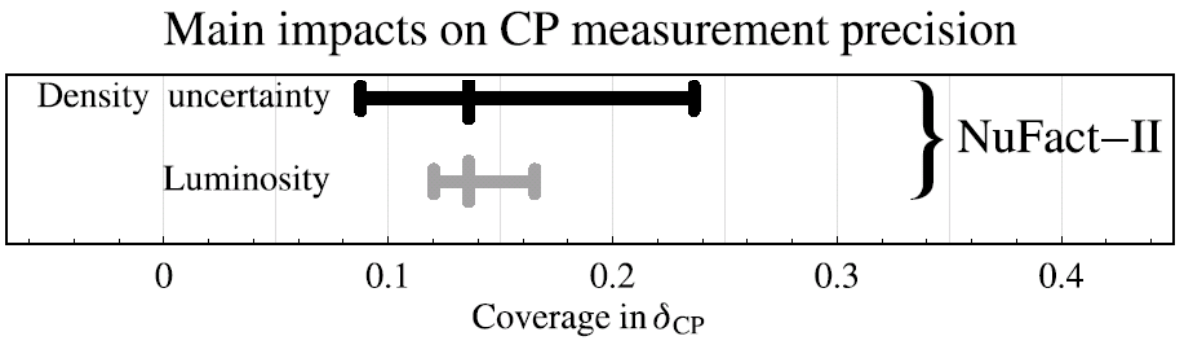
# Main impacts: Neutrino Factory




(Huber, Lindner, Winter, hep-ph/0204352)

## 2002

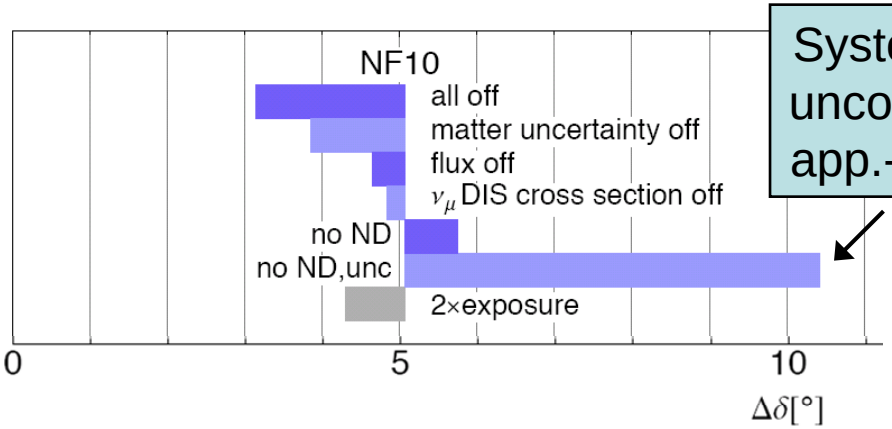
- Matter density uncertainty (ρ)
  **(detailed analysis: Ohlsson, Winter, PRD 68, 073007, 2003)**
- Det. performance at energy threshold ($E_{min}$)
- Exposure/luminosity




## 2012

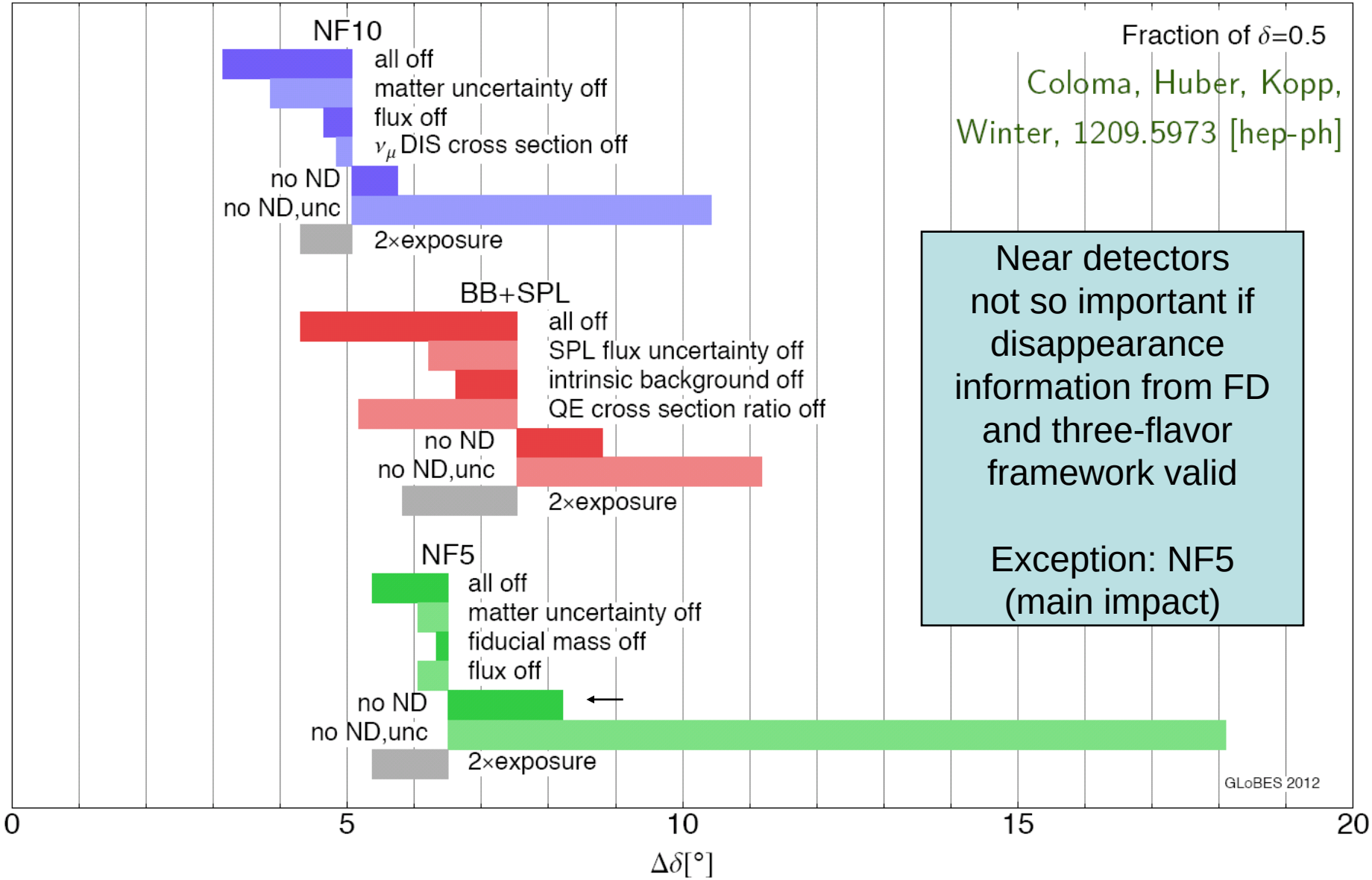
- Matter density unceraintiy
- Exposure

(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)




Systematics uncorrelated app.-disapp.

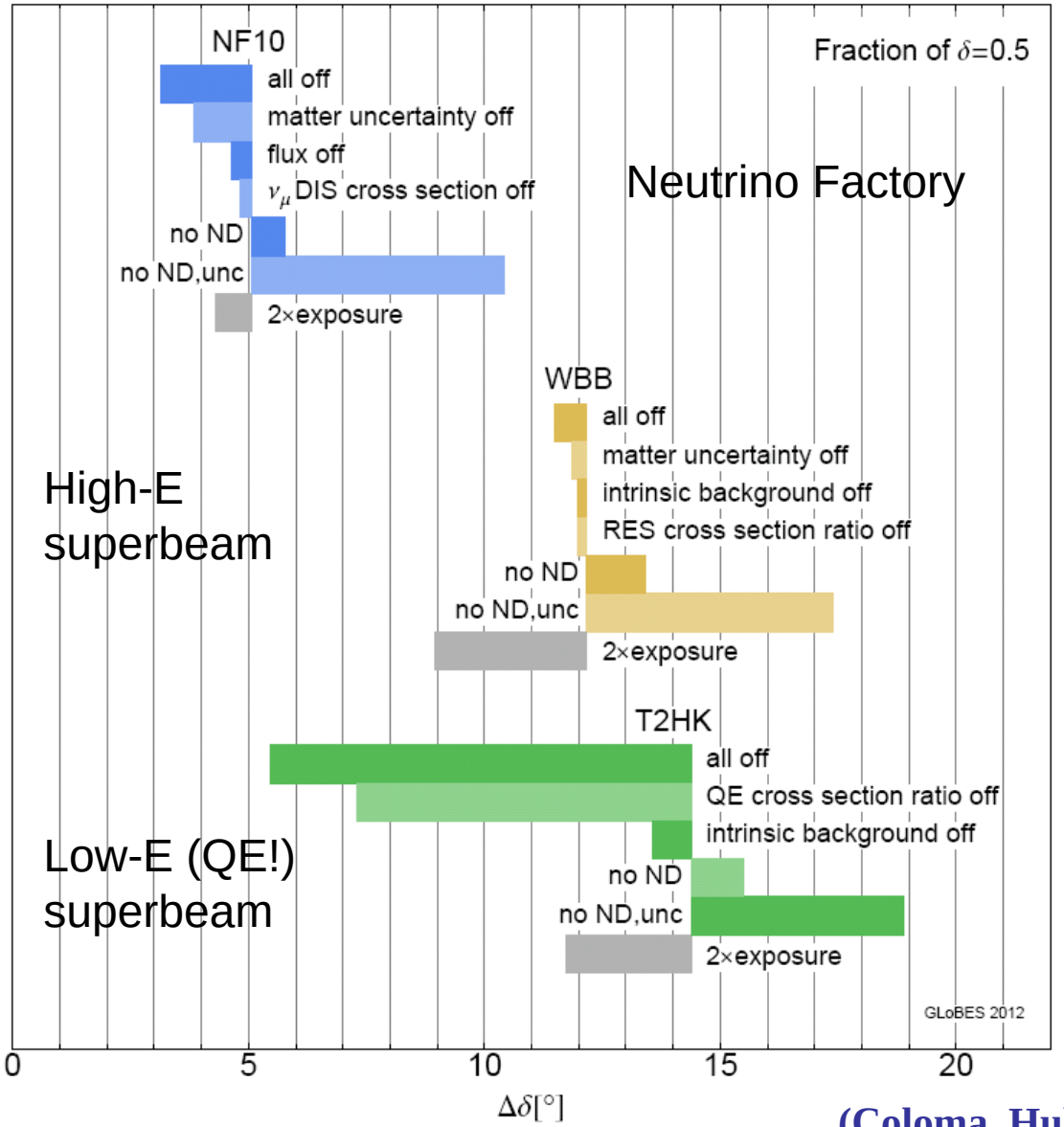
# Main impacts




Near detectors not so important if disappearance information from FD and three-flavor framework valid

Exception: NF5 (main impact)

# Comparison to superbeams




Robust wrt systematics

Main impact:
Matter density uncertainty

Operate in statistics-limited regime

Exposure more important than near detector

QE $\nu_e$ X-sec critical:
no self-consistent measurement

Theory: $\nu_e/\nu_\mu$ ratio?
Experiment: $\nu$STORM?

(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

# Summary

- The Neutrino Factory is the only experiment which can measure the CP phase with CKM-like precision
- Main impacts (NF):
  - Matter density uncertainty
  - Exposure
  - Near detector (low-E NuFact). In no other experiment the near detector has found to be the dominant impact factor!
  - ➢ Can control systematics in self-consistent way!

- Comparsion to alternatives:
  - BB+SPL: Best alternative performance, better than $\gamma$=350 beta beam. Self-consistent cross-section measurements
  - Low-E superbeams (T2HK): QE cross section ratio critical
    - ➢ Theoretical: Better predictions/models especially for this ratio?
    - ➢ Experimental: Measure $\nu_e$ cross sections? **$\nu$STORM? Systematics *from* Neutrino Factory?**
  - High-E superbeams (such as LBNE): Exposure seems more important than the near detector …

# CAPES-AvH fellowships

- Brazilian researcher ⇨ German host institute
  [Application by researcher, with host institute]

- **Postdocs** (Ph.D. < 4 years ago)
  for a period of 6-24 months

- **Experienced researcher** (Ph.D. < 12 years ago)
  for a period of 6-18 months in max. three blocks

- Next application deadline: **~January 2013**

- More information
  **http://www.capes.gov.br/cooperacao-internacional/alemanha/capes-humboldt**
  **http://www.humboldt-foundation.de/web/capes-humboldt-fellowship.html**

[or ask me, if you have questions …]

# BACKUP

# A technical note

GLoBES, CPC 167 (2005) 195

$$\frac{dn_\beta^{\rm IT}}{dE'} = N \int_0^\infty \int_0^\infty dE\, d\hat{E} \quad \underbrace{\Phi_\alpha(E)}_{\text{Production}} \times$$
$$\underbrace{\frac{1}{L^2} P_{(\alpha\to\beta)}(E, L, \rho; \theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{31}, \Delta m^2_{21}, \delta_{\rm CP})}_{\text{Propagation}} \times$$
$$\underbrace{\sigma_f^{\rm IT}(E) k_f^{\rm IT}(E-\hat{E})}_{\text{Interaction}} \times$$
$$\underbrace{T_f(\hat{E}) V_f(\hat{E}-E')}_{\text{Detection}},$$

$E$ : true energy

$E'$ : reconstructed energy

$\hat{E}$ : interaction partner

X-sec

$$n_i^c = N/L^2 \int_{E_i-\Delta E_i/2}^{E_i+\Delta E_i/2} dE' \int_0^\infty dE\; \Phi^c(E)\, P^c(E)\, \underbrace{\sigma^c(E)\, R^c(E,E')\, \epsilon^c(E')}_{\text{X-sec x det. response needed for osc. analysis}}$$

$$R_\beta^{\rm IT}(E,E')\, \epsilon_\beta^{\rm IT}(E') \equiv \int_0^\infty d\hat{E} \quad T_\beta(\hat{E})\, k_\beta^{\rm IT}(E-\hat{E})\, V_\beta(\hat{E}-E')$$

Do issues present in the extraction of cross sections arise in an oscillation analysis, which does (in principle) not need these explicitely?
[however, this object is experiment-dependent …]