Neutrino Factories

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Outline

- Physics goals after reactor data
- The Neutrino Factory
- “Low”- vs “high”-energy: the new IDS-NF baseline
- Comparison with other neutrino oscillation facilities
- Conclusions

The PMNS matrix

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix is the leptonic analogous of the CKM matrix

"Atmospheric" oscillation

"Solar" oscillation

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

$\theta_{23} = 39^{\circ}$–48°

$\theta_{13} = 8^{\circ} - 11^{\circ}$

$\theta_{12} = 32^{\circ}$–35°

Majorana phases

Gonzalez-García and Maltoni '07

Global fits

$$\Delta m^2_{21} = 7.59 \pm 0.20 \left({}^{+0.61}_{-0.69}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11\ (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \\ +2.46 \pm 0.12\ (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \end{cases}$$

$$\theta_{12} = 34.4 \pm 1.0 \left({}^{+3.2}_{-2.9}\right)^\circ$$

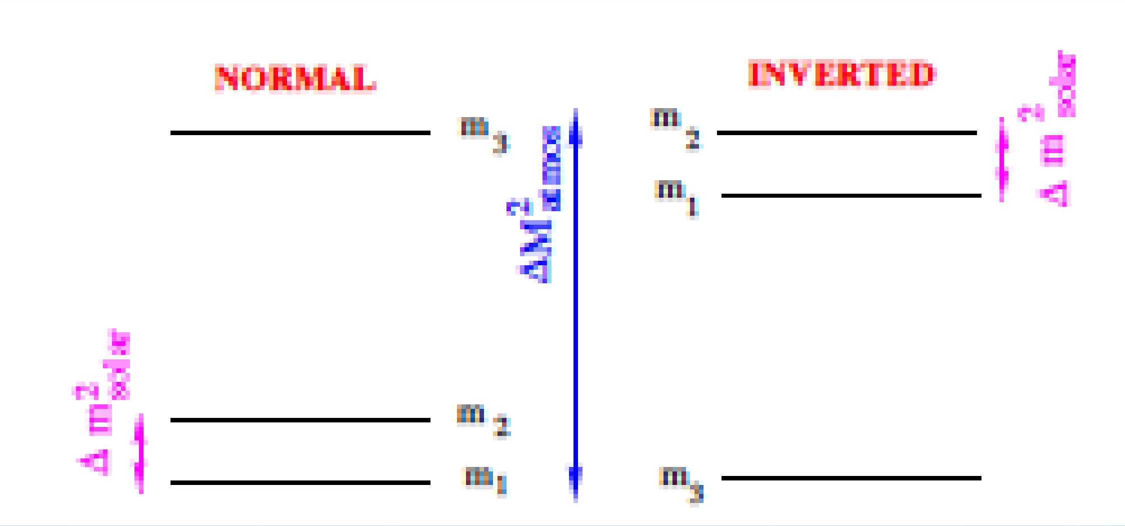
$$\theta_{23} = 42.8\,{}^{+4.7}_{-2.9} \left({}^{+10.7}_{-7.3}\right)^\circ$$

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$$ Daya Bay

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013 \pm 0.019$$ RENO

Missing parameters

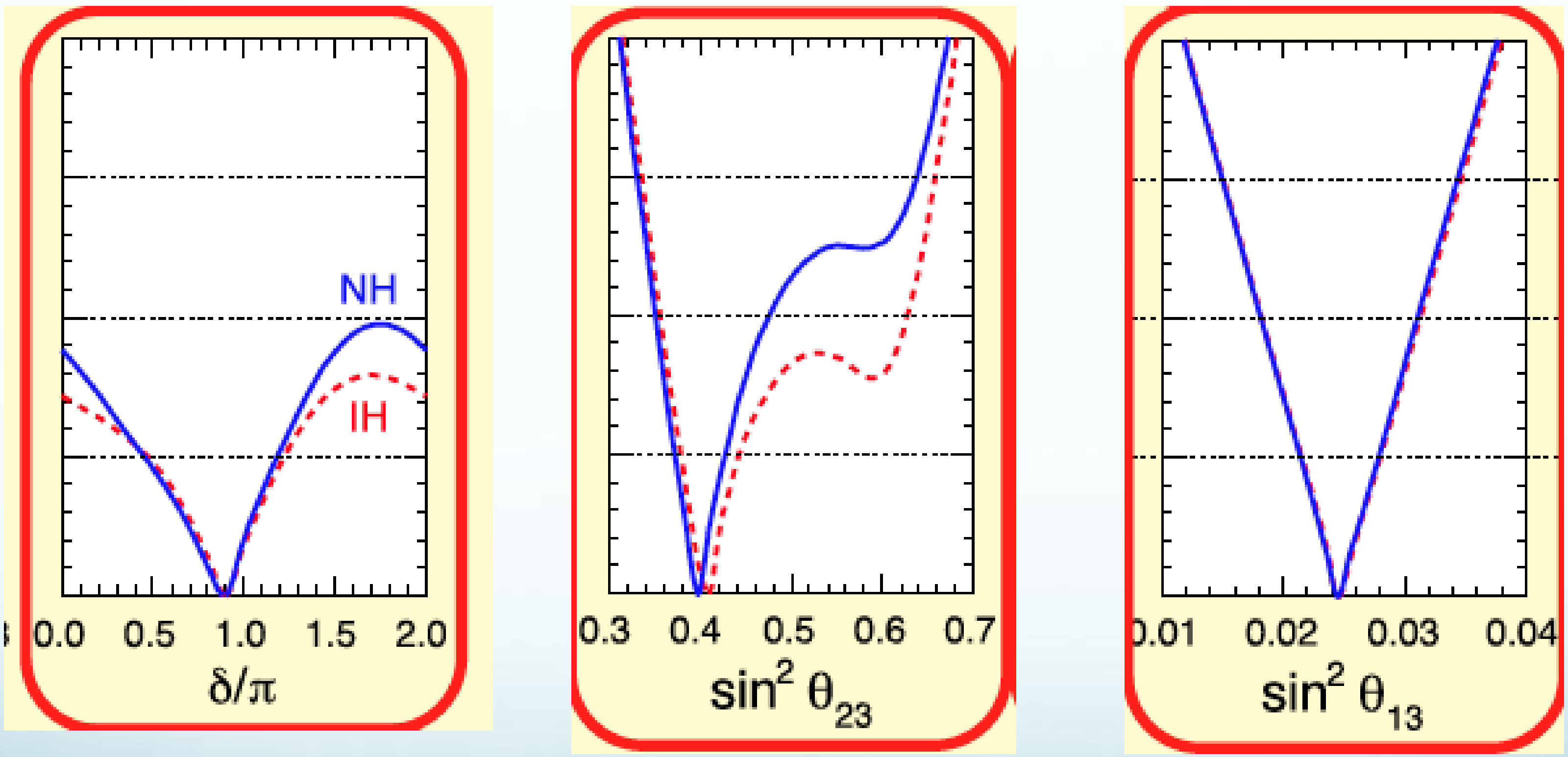
- We must now measure:
  - the CP violating phase δ
  - the neutrino mass hierarchy: is the atmospheric mass difference Δm^2_{13} positive or negative?



  - is the atmospheric mixing angle maximal?

From global fits…

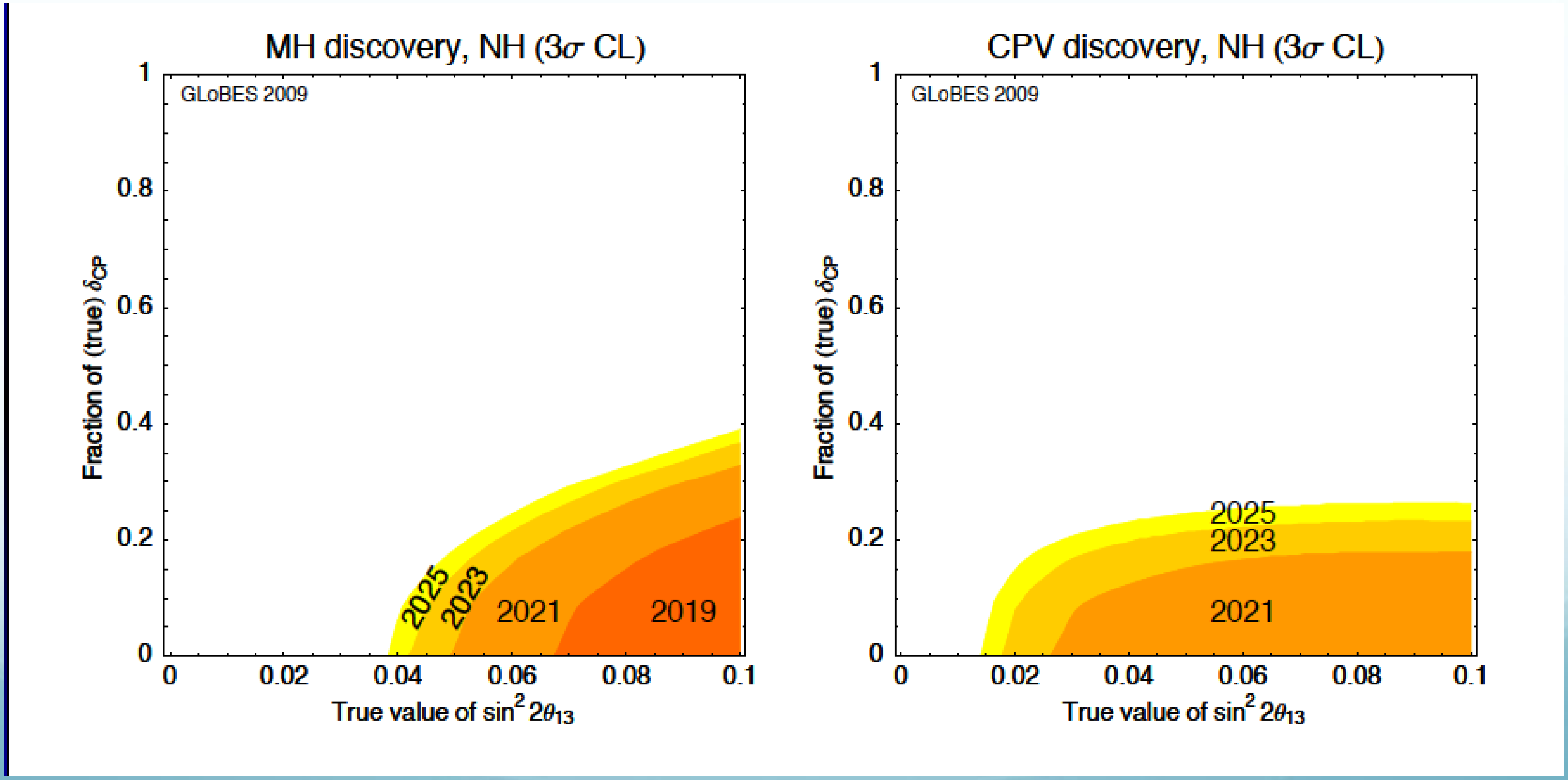
G. Fogli, monday talk



So far, no hints for
NH ⟷ IH

NOνA and T2K

- The combination of NOνA with T2K has some chance to measure the neutrino mass hierarchy and δ



New facilities

- We (may) need to go beyond existing or under construction experiments
- Proposed strategies are:
  - (Super-)beams: scaling of an existing technology
  - Beta-beams: pure ν_e beam
  - Neutrino Factories: known flux, rich flavour content, the “ultimate” facility….
- Questions for all the proposed strategies:
  - Technical feasibility; achievable luminosity;cost….
- All facilities use $\nu_e \rightarrow \nu_\mu$ or $\nu_\mu \rightarrow \nu_e$

The Golden Channel

$$P_{e\mu}^{\pm} = X_{\mu}^{\pm} \sin^2 2\theta_{13} + \left(Y_c^{\pm}\ cos\delta \mp Y_s^{\pm}\ sin\delta\right) \sin 2\theta_{13} + Z_{\mu}$$

The Golden Channel

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Strong sensitivity to θ_{13}

The Golden Channel

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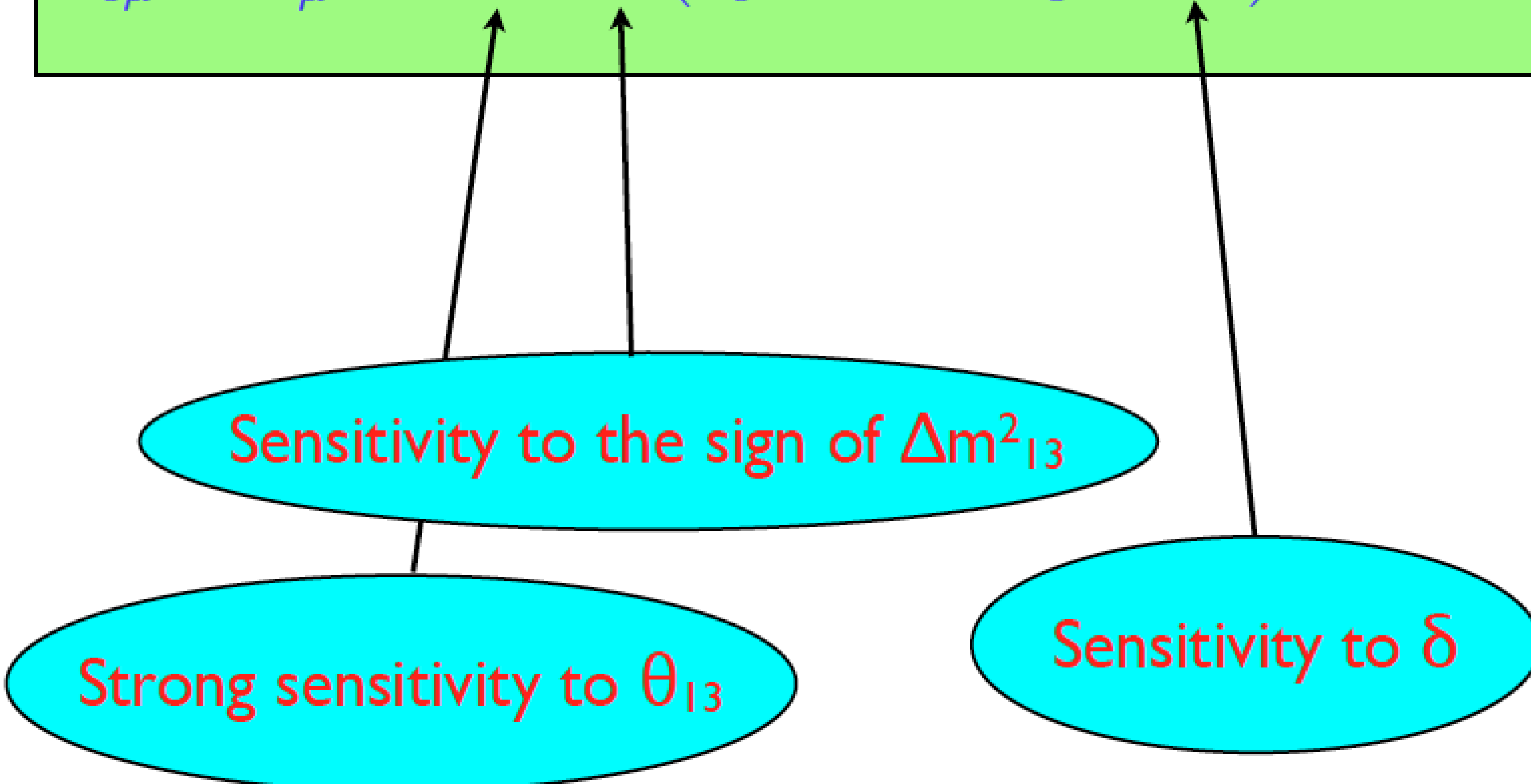

The Golden Channel

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Sensitivity to the θ_{23}-octant

Sensitivity to the sign of Δm^2_{13}

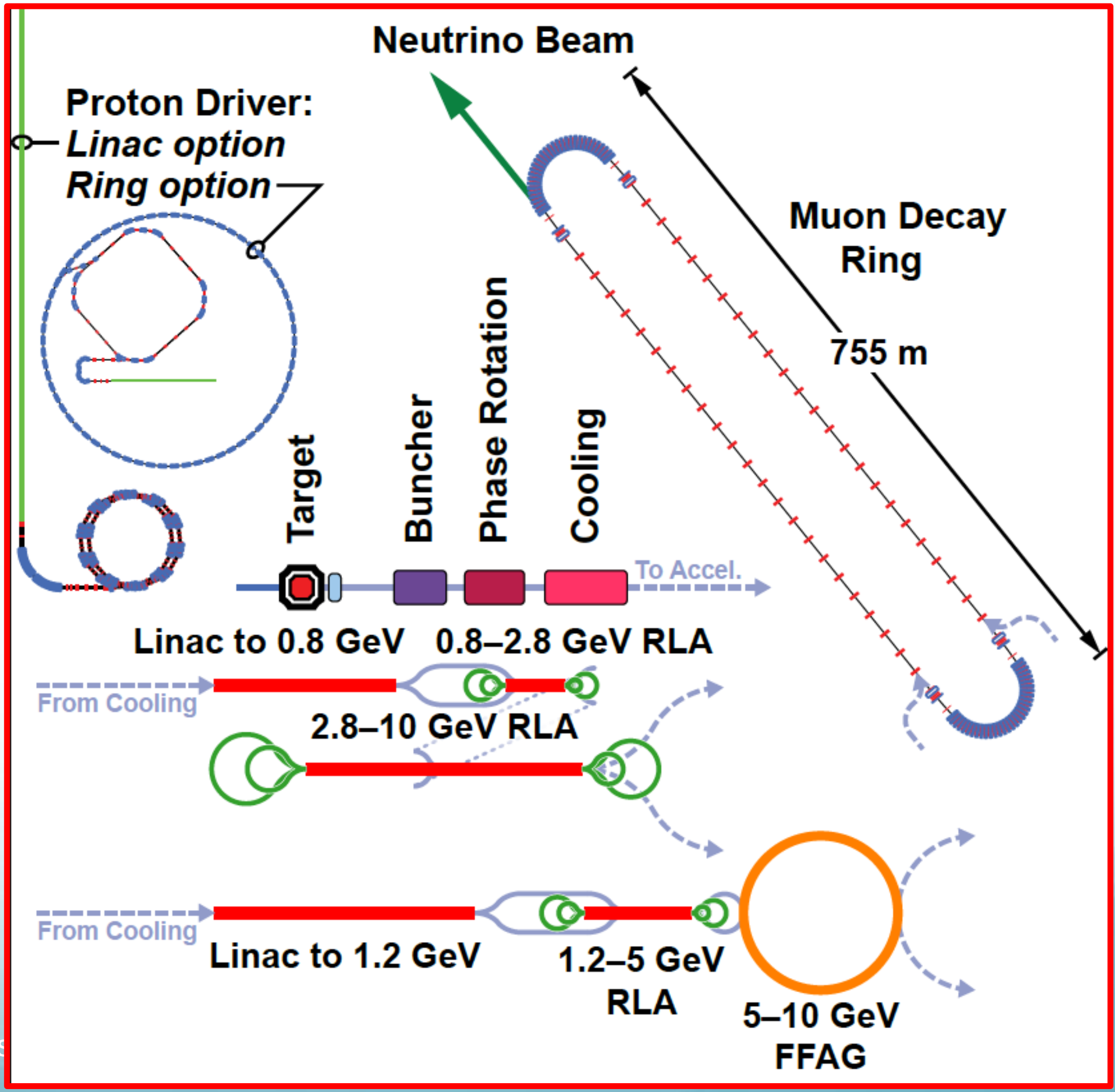
Strong sensitivity to θ_{13}

Sensitivity to δ

The Neutrino Factory

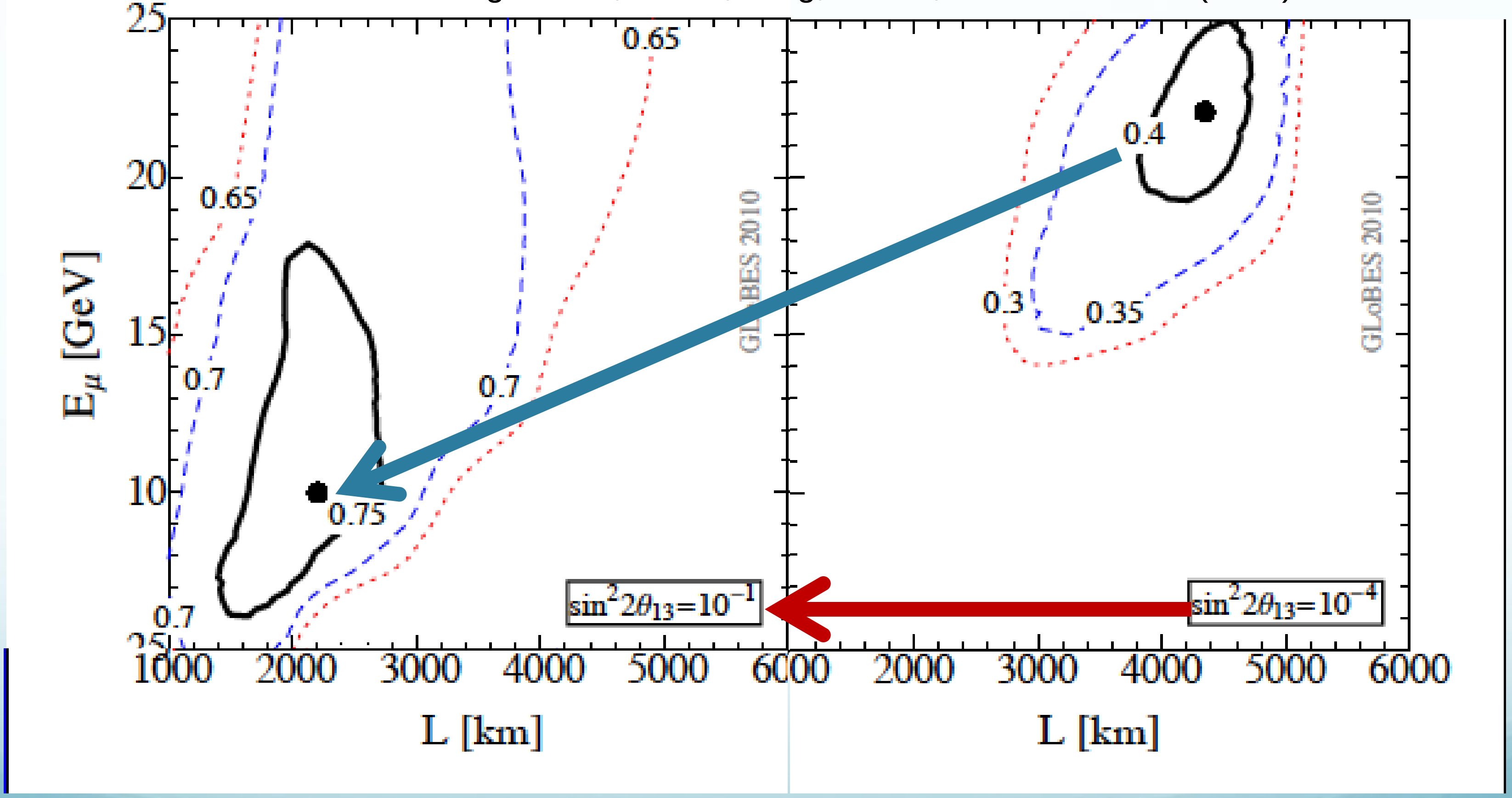
Layout of the present IDS-NF baseline:

10 GeV muons
One storage ring
10^{21} useful decays/year



“Low”- vs “High”-energy

Agarwalla, Huber, Tang, Winter, JHEP 1101 120 (2011)



“Low”- vs “High”-energy

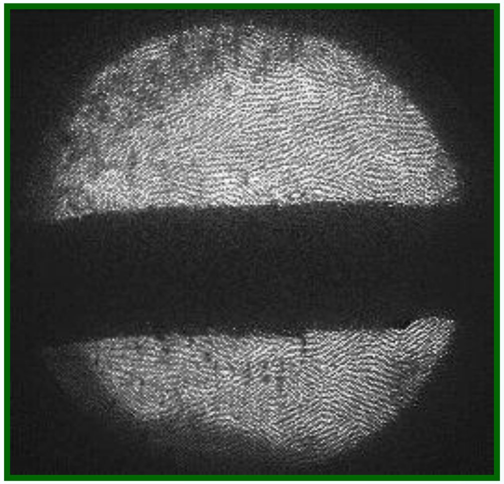
- For large $\theta_{13,}$ using a 100 kton MIND detector and one baseline, the CP discovery potential is maximizal for:
  - L ~ 2000 km; E ~ 10-15 GeV (LENF)
- No Magic Baseline detector is needed any longer! (More than) half of the cost in storage rings is gone, and ALL the muon can be stored in one single ring aiming at one detector

Mature accelerator R&D programme

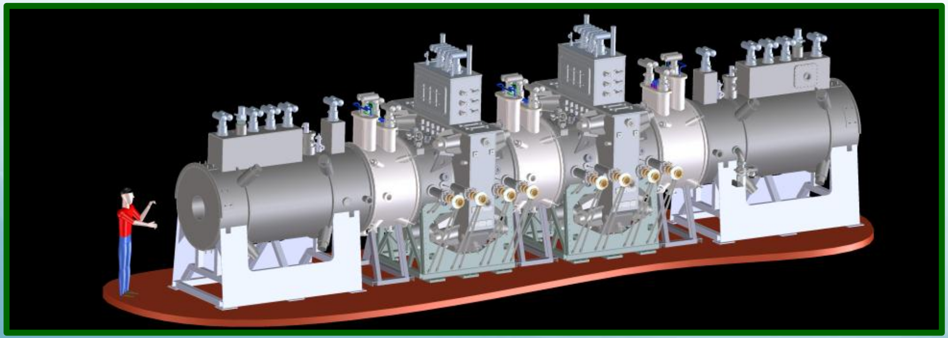
- Proton Driver:
  - LINAC [see, e.g. Garoby's talk]:
    - Possible development option for SPL (CERN) or Project-X (FNAL)
    - Requires accumulator and compressor rings
  - Rings [see Pasternak, Thomason]:
    - Development option for J-PARC or RAL or possible 'green-field' option
    - Requires bunch compression

- **Target:**
  - **Baseline:**
    - **LH2;**

      MERIT @ CERN proof of principle
  - **Options:**
    - **Solid**
    - **Powder jet**



- **Ionization cooling:**
  - **MICE @ Rutherford Appleton Laboratory:**
    - **Proof of principle**

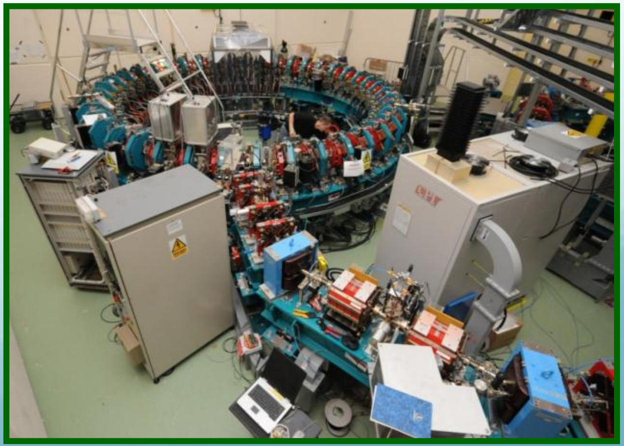


Courtesy of K. Long

- **Muon acceleration**

  EMMA @ Daresbury Laboratory:

  Proof of principle of FFAG



Staging

- First stage: a Very Low-Energy NF (VLENF aka νSTORM)
  - Cross-sections
  - Disappearance parameters
  - Sterile neutrinos

  See talk by A. Bross. LoI may be submitted by end of June at FermiLab PAC and at CERN.

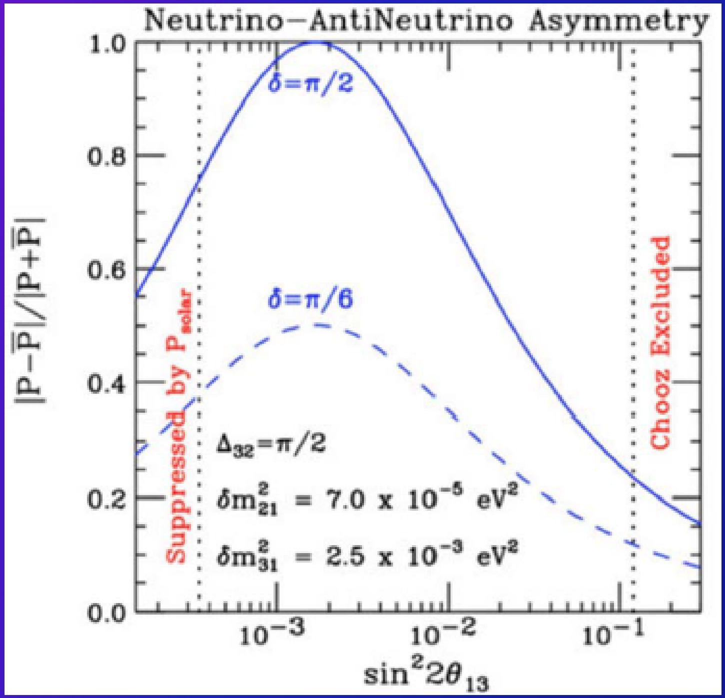
- Second stage: the present IDS-NF baseline, a 10 GeV Neutrino Factory aiming at ~2000 km, 100 Kton MIND + near detector(s)

- A third stage: is it useful to go to 25 GeV?

ν Cross-section measurements

➢ Cross-section measurements

- μ storage ring presents only way to measure ν_μ & ν_e & (ν and $\bar{\nu}$) x-sections in same experiment
  - Supports future long-baseline experiments



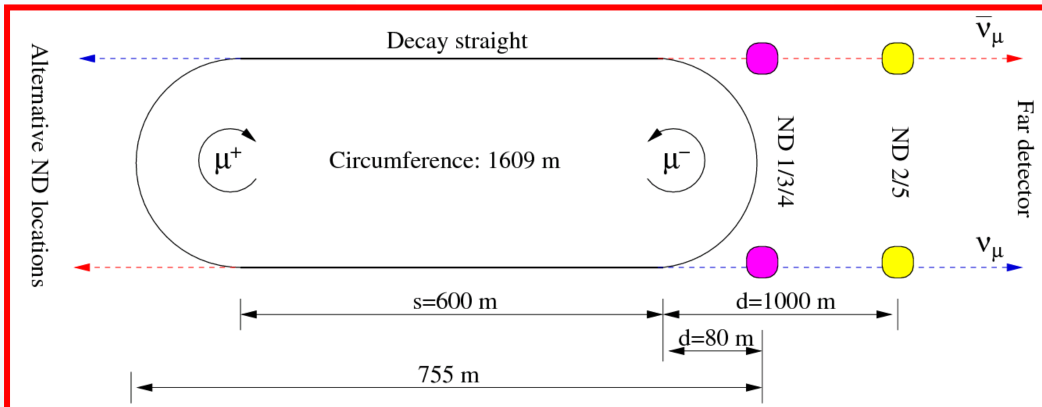
$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

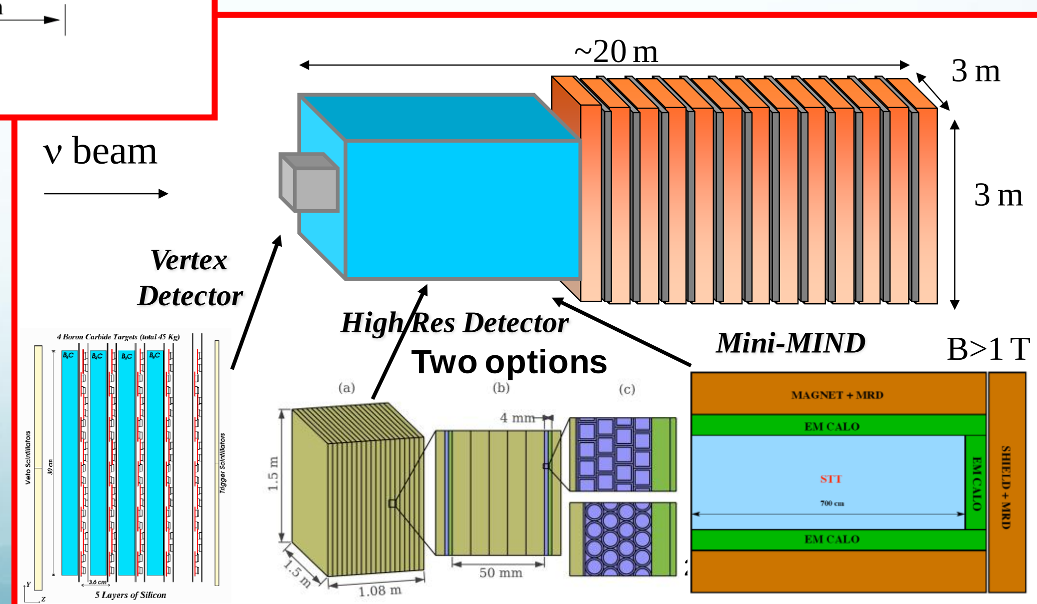
- Important to note that with θ_{13} large, the asymmetry you're trying to measure is small, so:
  - Need to know underlying ν/vbar flux & σ more precisely
  - Bkg content & uncertainties start to become more important

Morfin, Tsenov

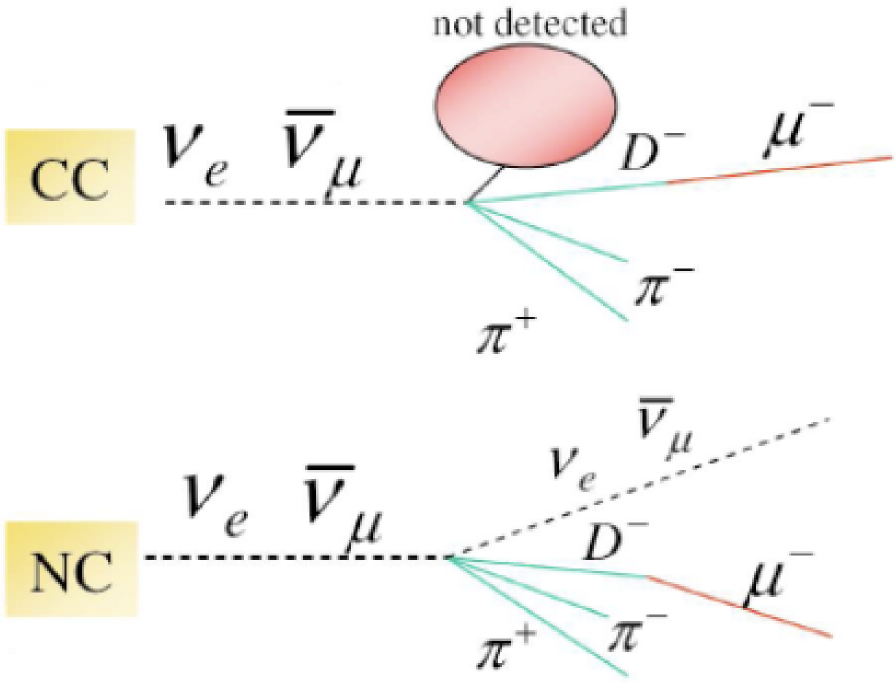
Near detector for LENF

- Neutrino flux (<1%) and extrapolation to far detector
- Charm production (main background) and taus for Non Standard Interactions (NSI) searches
- Cross-sections and other measurements (ie PDFs, $\sin^2\theta_W$)





Charm production



This is the main source of background for the golden channel searches

Errors on this cross-section are huge, and enter in the final systematic error of the measurement. They must be reduced at an acceptable level

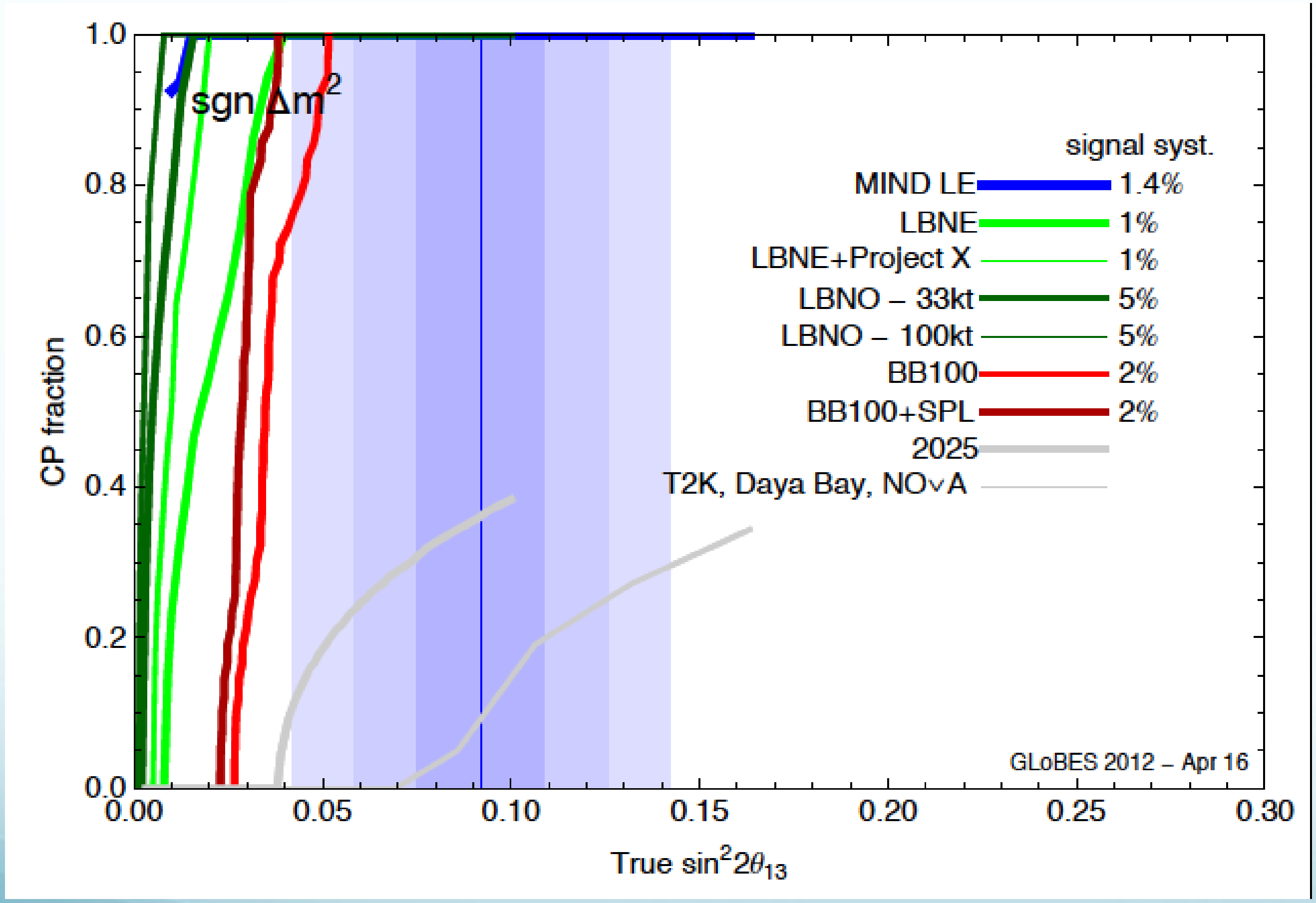
A. Laing, PhD thesis

The NuFact is a charm factory: a dedicated near detector could study CKM matrix elements, D-D mixing and search for New Physics through rare processes

Comparison with others…

- We compare the NuFact performance with other facilities on the basis of the following observables:
  - Sensitivity to the mass hierarchy
  - CP discovery potential
  - Deviations from maximality of θ_{23}
  - Sensitivity to the θ_{23}–octant
  - Precision on θ_{13} and δ

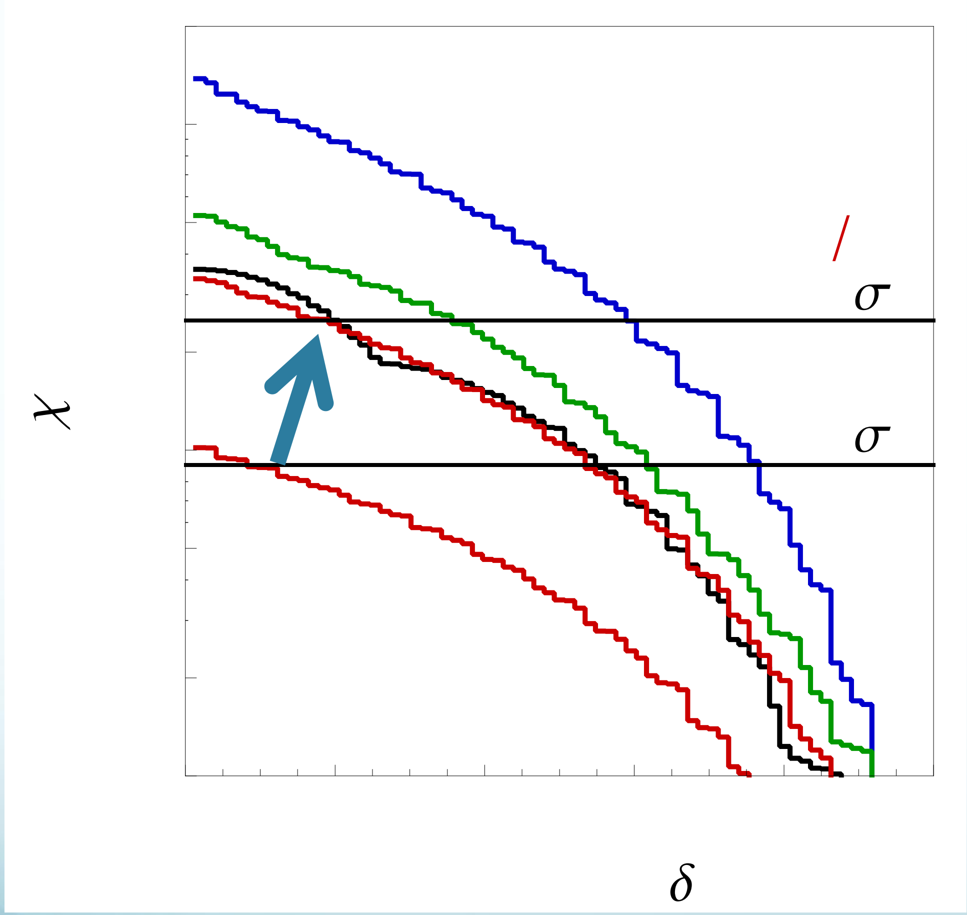
The mass hierarchy



P. Huber, previous talk

Everybody can do it!

CP discovery potential



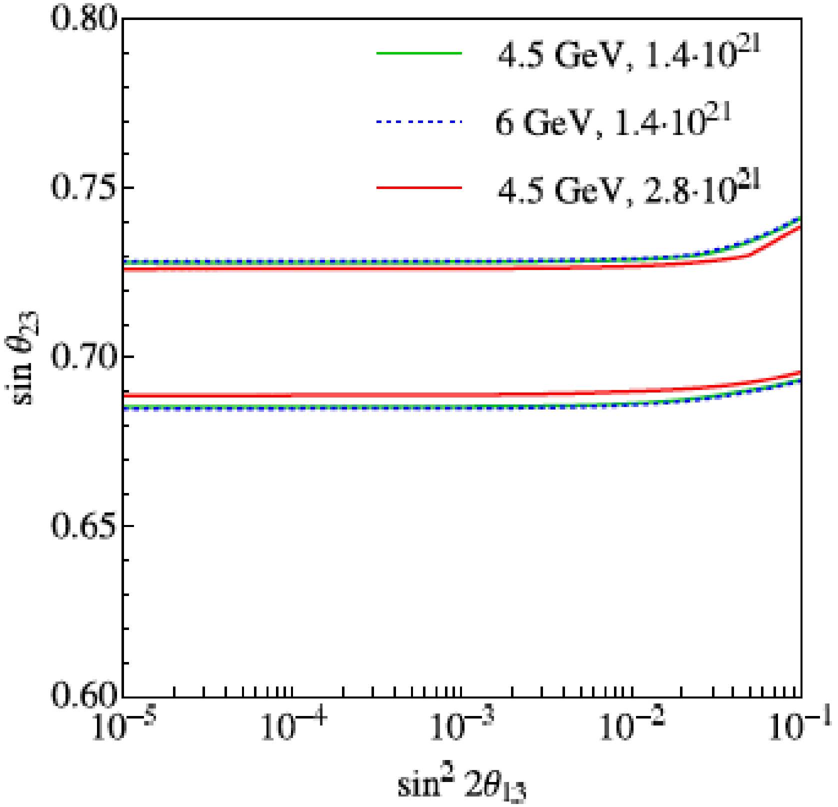
Comparison between setups must be done with EXTREME care!

Syst: 5% / 10% all fac.
$\Delta A = 2\%$ all fac.
10 years all fac.

Luminosity differs!
Detector size differs!

Courtesy of E. Fernández-Martínez

Deviations from maximality

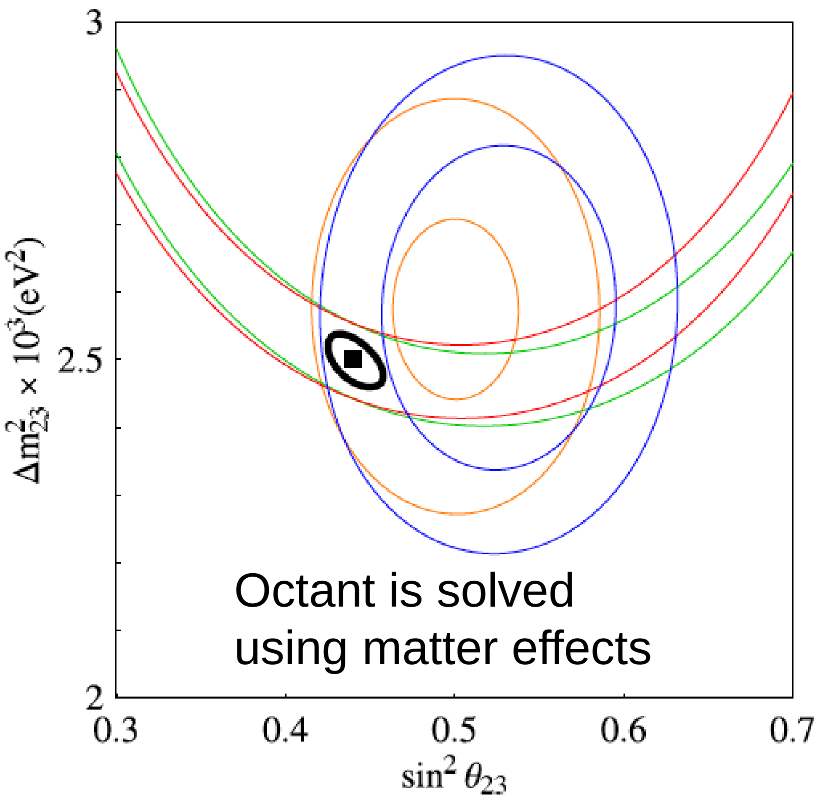


(a) Sensitivity to $\theta_{23} \neq 45°$

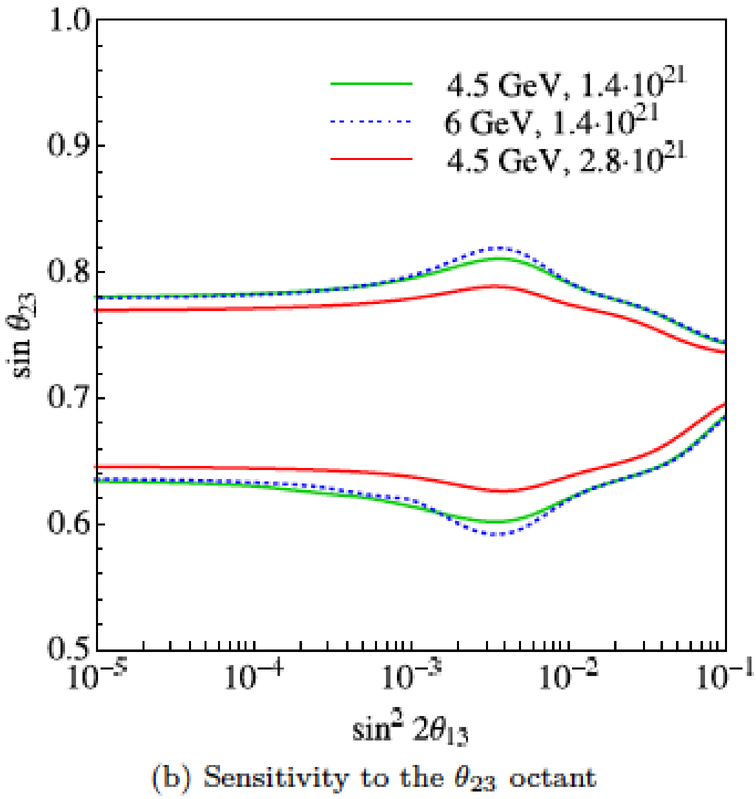
Must be updated
to the 10 GeV LENF

A. Bross et al., arXiv:0911.3776

Octant measurement



A. Donini et al., hep-ph/0512038

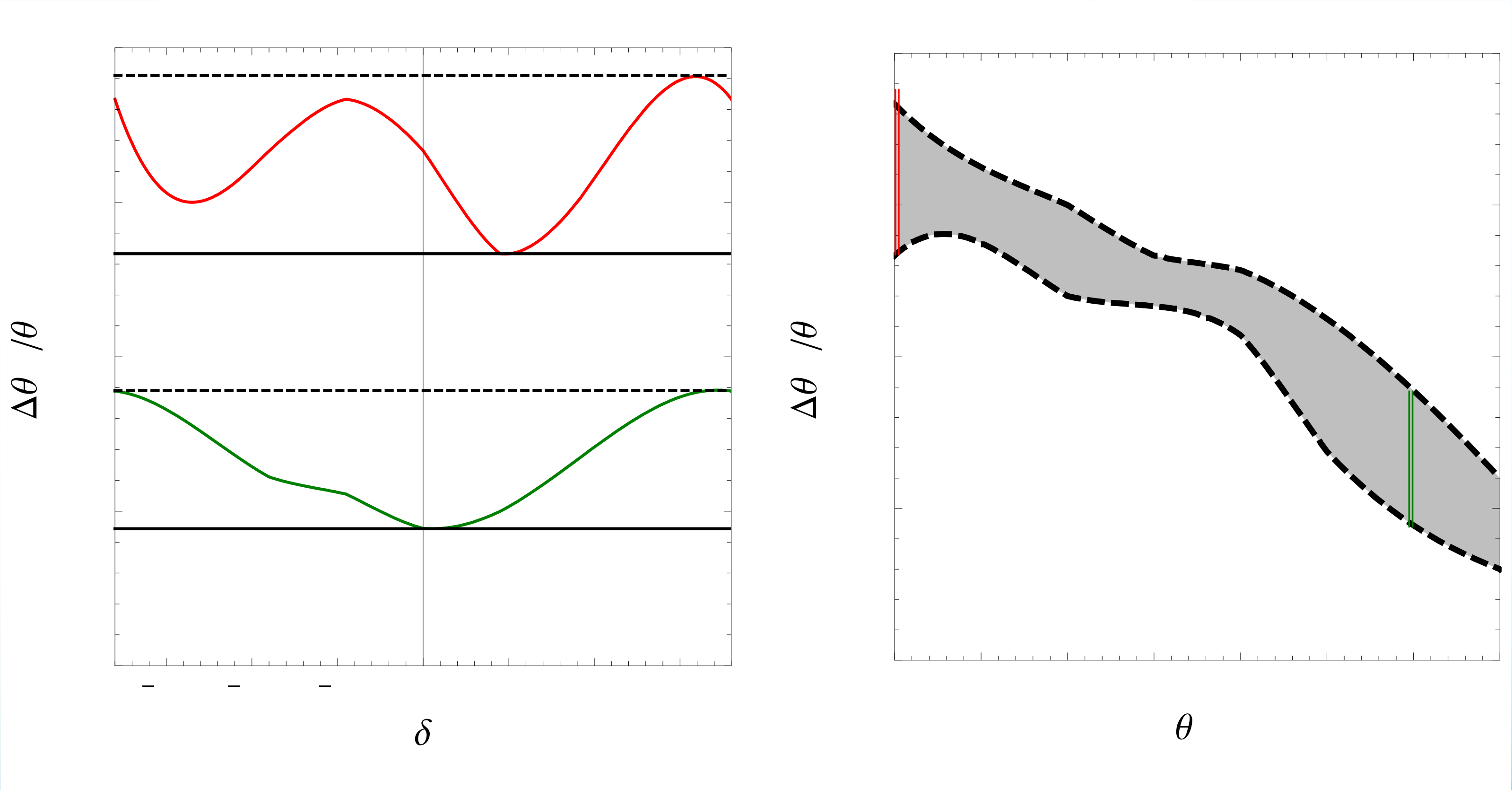


A. Bross et al., arXiv:0911.3776

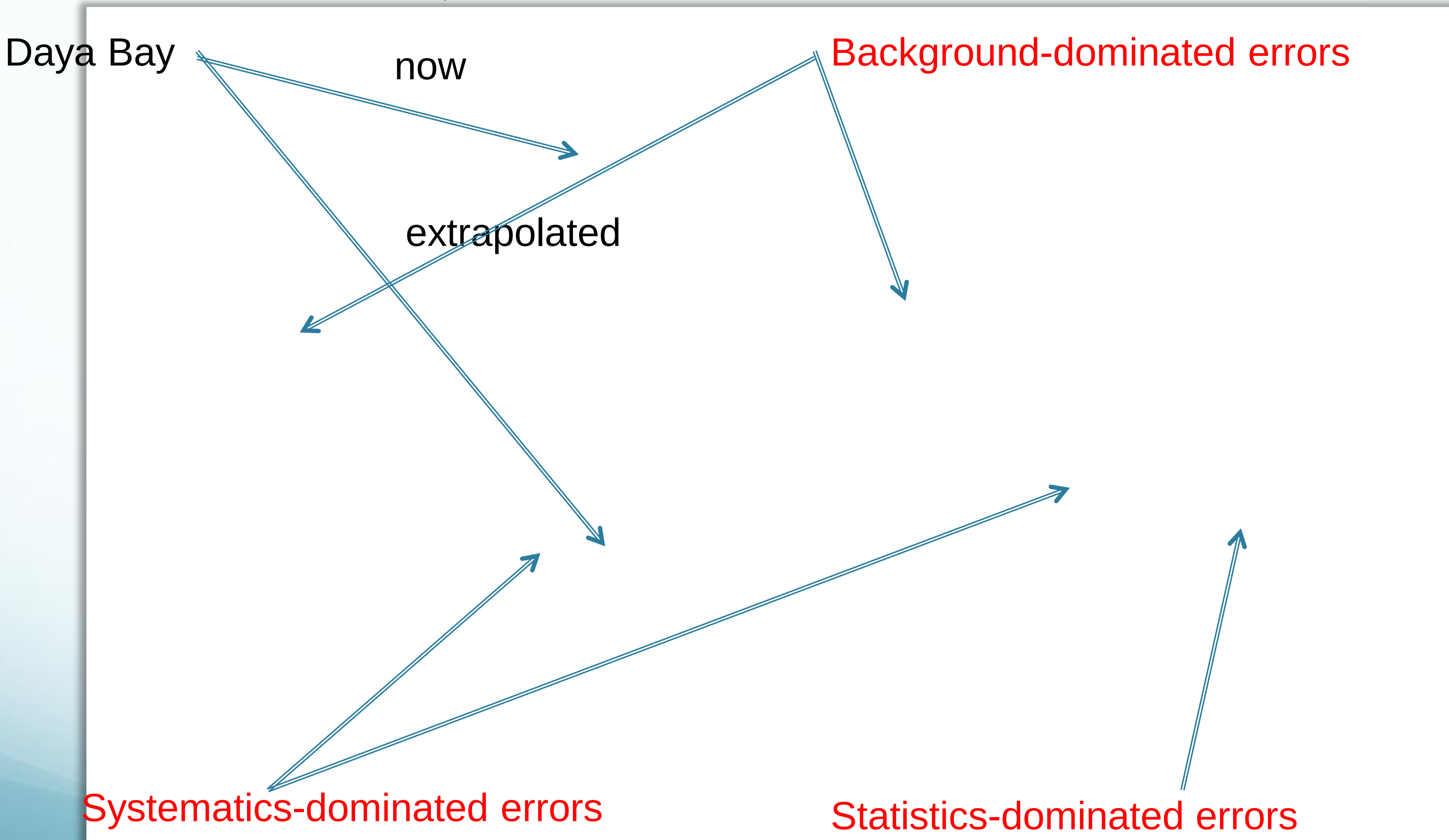
Is precision an issue?

- Question first asked during the last stages of ISS
- In the hadronic sector, precision on the CKM matrix elements is a requirement for:
  - model building
  - new physics searches
- Precision on θ_{13} will play the same role
- Precision on δ is a different issue: the CP discovery potential is strongly affected by the true δ value

Precision bands



$\Delta\theta_{13}/\theta_{13}$: Super-Beams



Coloma et al., arXiv:1203.5651

β-beams and ν-factories

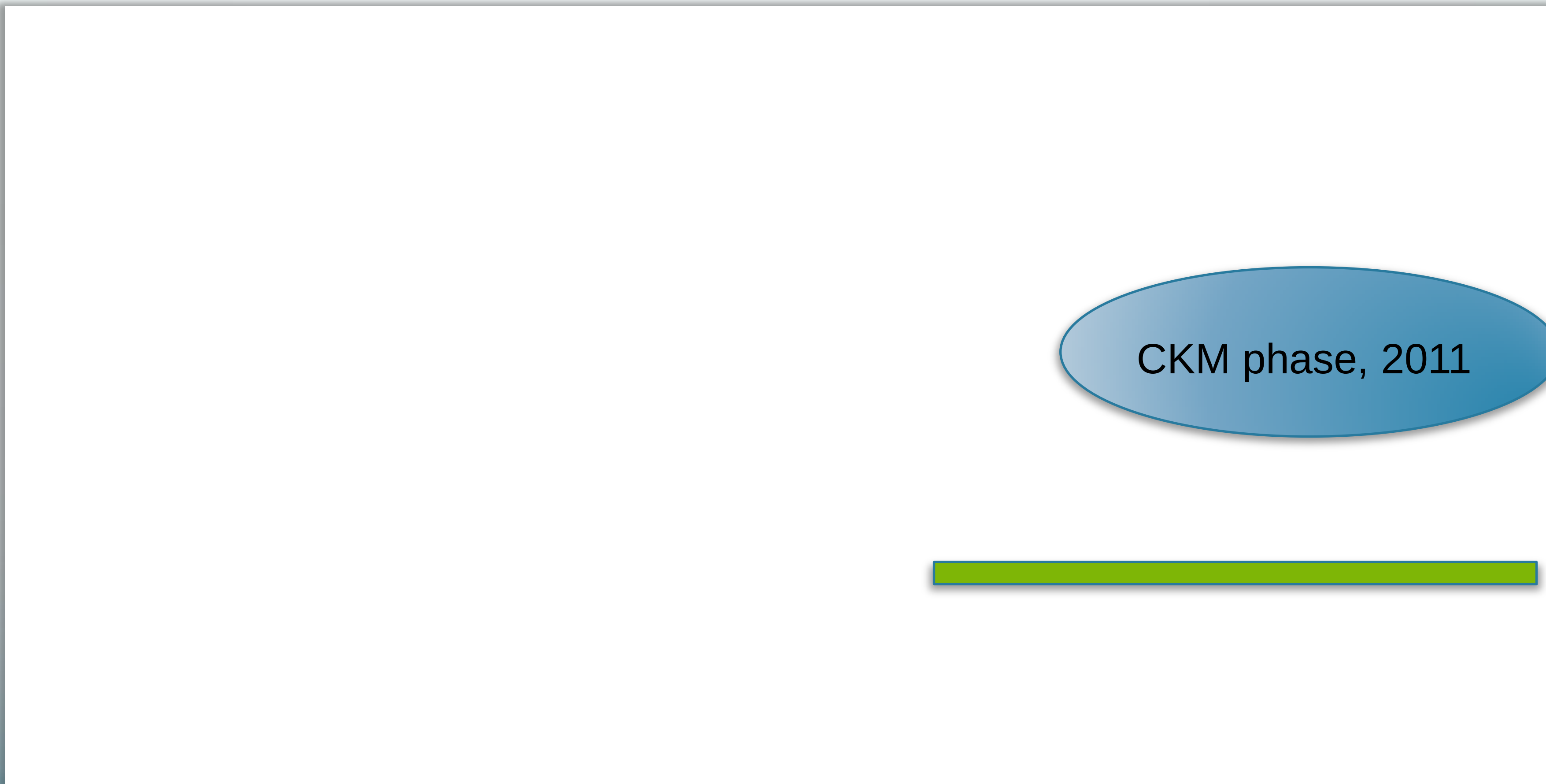
All setups: statistics-dominated errors

Coloma et al., arXiv:1203.5651

Precision in δ: (Super-)Beams

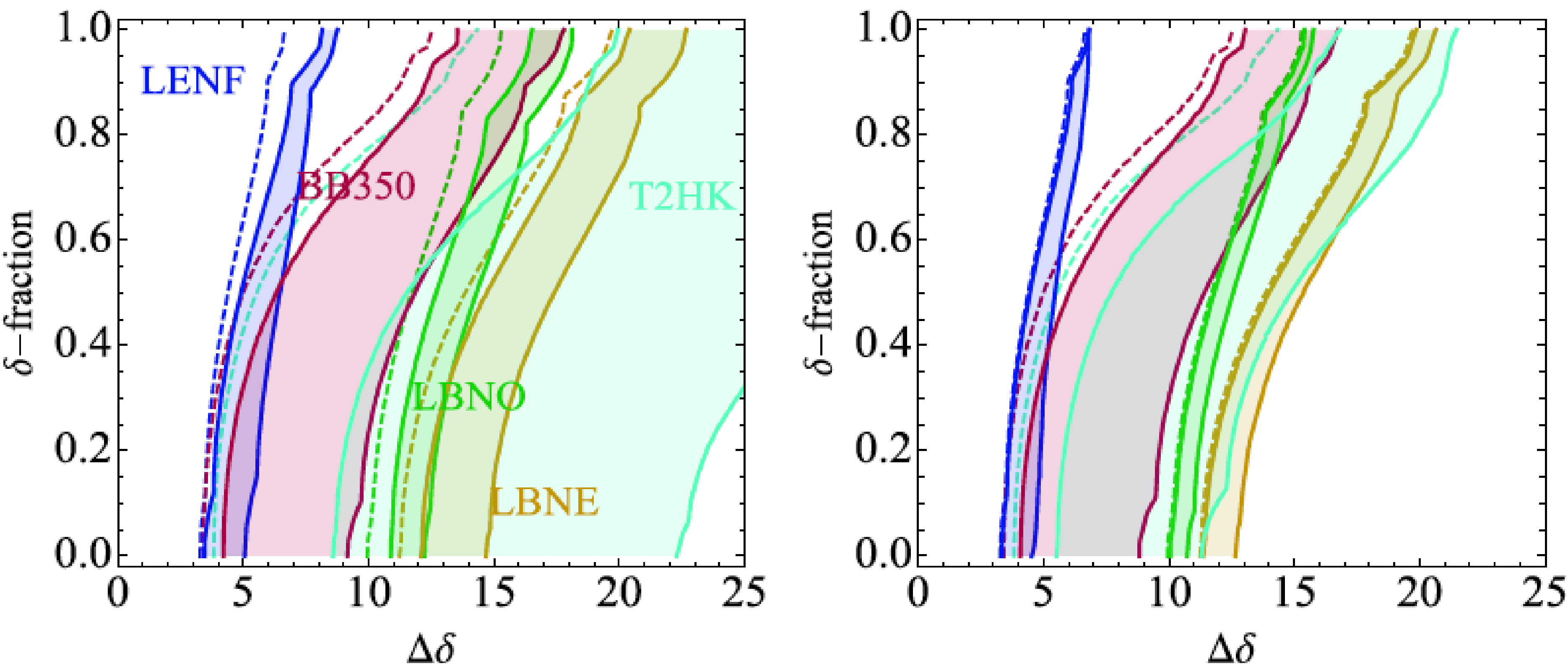
Coloma, Donini, Fernández-Martínez, Hernández, arXiv:1203.5651

β-beams and ν-facts



Coloma, Donini, Fernández-Martínez, Hernández, arXiv:1203.5651

Systematics impact on precision



Coloma, Huber, Kopp, Winter, in preparation

New physics

- Beyond the shopping list related to three-family oscillations (δ, mass hierarchy, θ_{23} deviations from maximality and θ_{23}–octant), a new facility should be able at least to make a try for new physics:
  - Most important of all: origin of neutrino masses!
  - Possible singlet fermion states (“sterile neutrinos”)
  - Non-Standard Interactions in production/detection (violation of unitarity of the PMNS matrix) or in propagation

Sterile neutrinos

- The relevant question is if a new facility such as the neutrino factory can be an interesting place to look for eV sterile neutrinos
- If you put a near detector, the answer is yes:
  - you have access to a huge flux
  - flavour content is richer than at a typical SBL experiment: both ν_e and ν_μ
  - If the energy is large enough, at the far detector you can exploit $\nu_\mu \rightarrow \nu_\tau$: this channel is very sensitive to the less constrained active-sterile mixing angles

NSI's in prod/det

Near Detectors:
S. Antusch *et al*,
arXiv:1005.0756 [hep-ph]
MINSIS workshop report,
arXiv:1009.0476 [hep-ph]

NSI@production

$$\mu^- \to e^- \nu_\mu \bar{\nu}_\alpha$$

NSI@detection

$$\nu_\alpha N \to \mu^- N'$$

NSI@propagation

$$\nu_\alpha f \to \nu_\beta f$$

A very good control over the flux is needed (this is why NF or BB are preferred over SB)

NSI's in propagation

- Sensitivity to NSI parameters at 25 GeV Nufact
  - sensitivity to $|\varepsilon_{\mu\tau}|, |\varepsilon_{e\mu}|, |\varepsilon_{e\tau}| \leq 10^{-3}$ (correlations are not very important)
  - sensitivity to $\varepsilon_{ee}-\varepsilon_{\tau\tau} \leq 10^{-1}$ (limited: matter uncertainty) sensitivity to $\varepsilon_{\mu\mu}-\varepsilon_{\tau\tau} \leq 10^{-2}$ (θ_{23} and $\delta\theta_{23}$ dependent)
  - sensitivity to θ_{13} worsens due to $\varepsilon_{\alpha\alpha}$, $|\varepsilon_{e\mu}|, |\varepsilon_{e\tau}|$

Coloma, Donini, López-Pavón, Minakata, arXiv:1105.5936

Conclusions

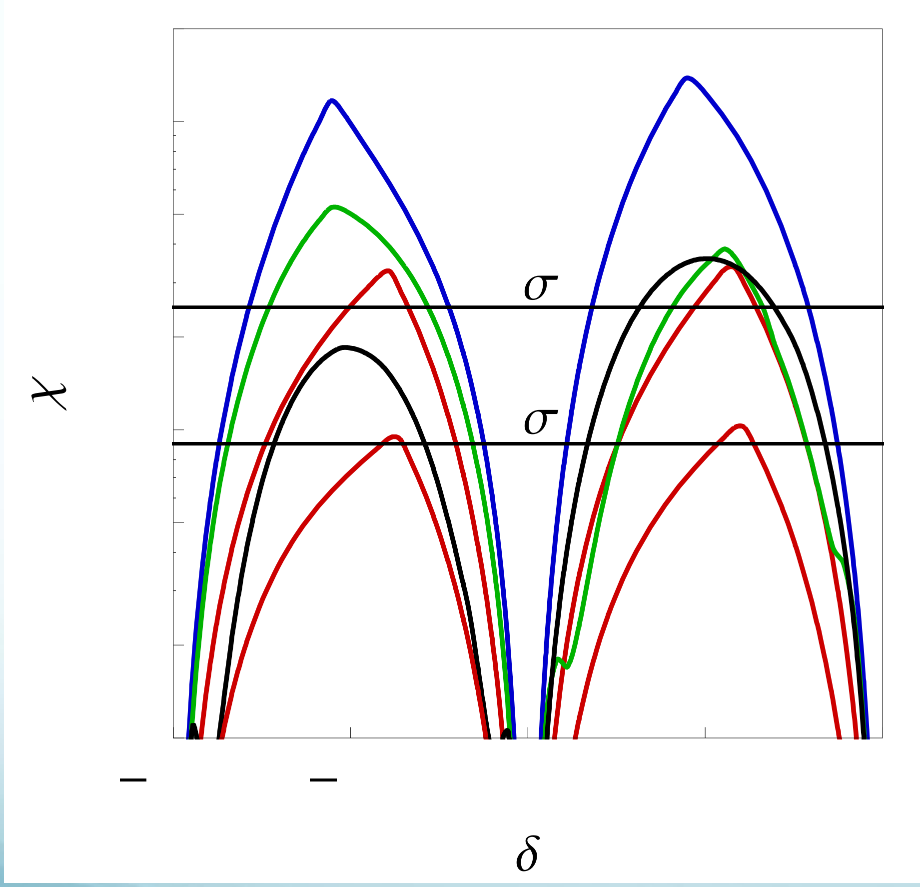
- Large θ_{13} requires to master systematic uncertainties
- Neutrino Factory, the staged approach:
  - Outstanding opportunity to contribute in the short term: νSTORM
    - Essential cross section measurements; the only way to measure electron (and muon) neutrino and anti-neutrino cross-sections
    - Sterile-neutrino search
  - Medium term:
    - Initial Neutrino Factory, perhaps starting at lower proton-driver power and without cooling, competitive with medium-term super-beam alternatives;
  - Long-term:
    - IDS-NF baseline, 10 GeV/2000 km with multi-MW proton driver and cooling, out-performs realistic alternatives;
- The first steps on this road
  - MICE
  - Cross section measurement [sterile neutrino search] (νSTORM?)

- A long list of measurements at the far detector…
  - 5σsensitivity to mass hierarchy;
  - 5σCP discovery potential with ~ 70% CP-fraction;
  - Precision on oscillations parameters: $\Delta\theta_{13}/\theta_{13}$ ~1.5%; $\Delta\delta \sim 5°$
  - Deviation from θ_{23} maximal mixing; sensitivity to θ_{23} - octant
  - NSI in propagation
- … and at the near detector:
  - Sterile neutrinos
  - NSI in production/detection; violation of unitarity in the PMNS
  - Charm production; PDF's; $\sin^2\theta_W$
- The Neutrino Factory is:
  - Unique; meeting the "5σ" sensitivity for MH and CPV with good precision;
  - Mature:
    - Key hardware issues addressed, or being addressed by R&D programmes;
    - Conceptual design documented in IDS-NF IDR
    - Costing in preparation for EUROnu final report and IDS-NF RDR
  - Incremental approach to full Neutrino Factory conceivable

Altogether, an exciting programme!

Backup slides

CP discovery potential



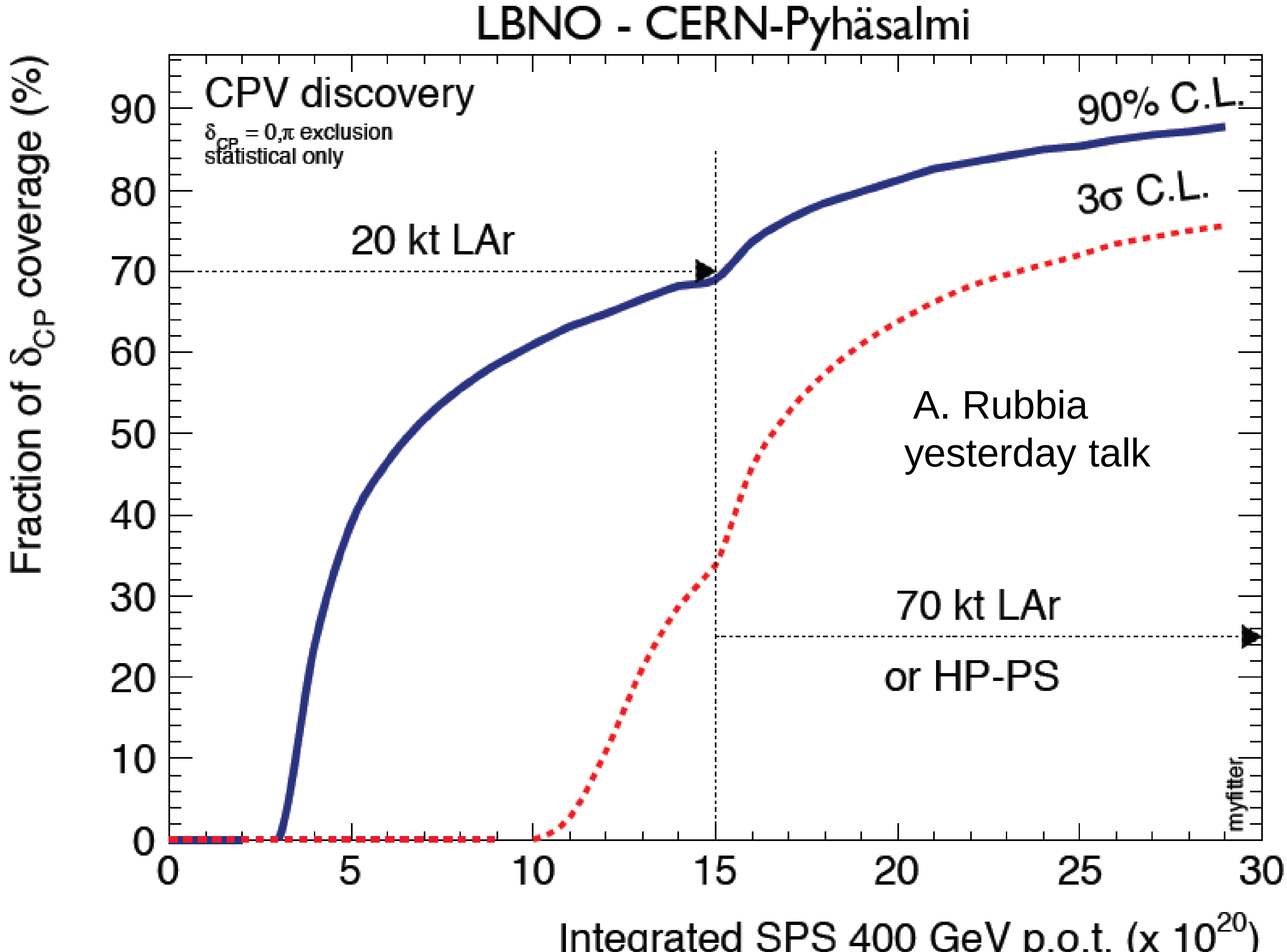
Under the following assumptions:

Syst: 5% / 10% all fac.
$\Delta A = 2\%$ all fac.
10 years all fac.

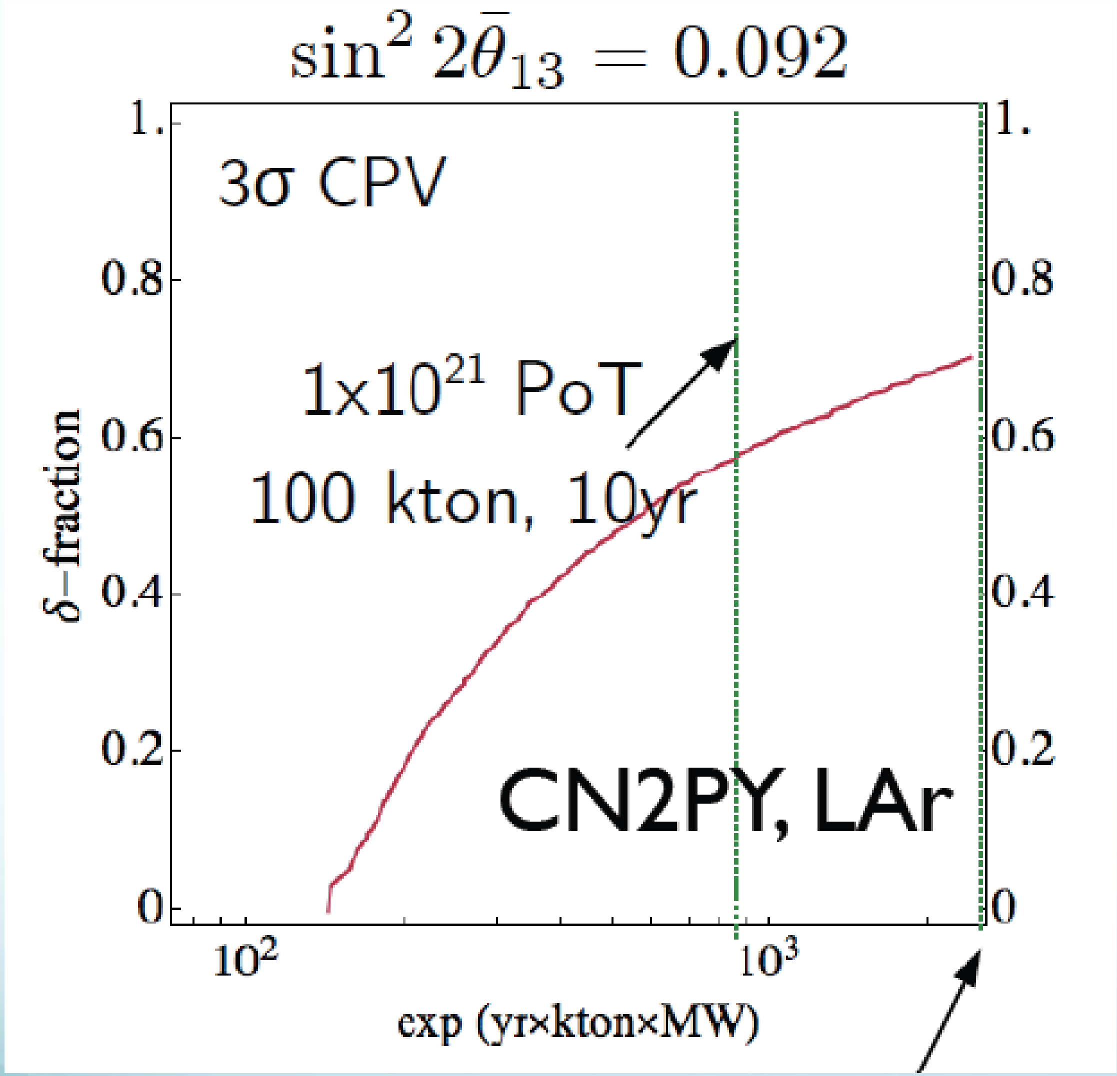
the C2PY super-beam
and the BB100 beta-beam
CP discovery potential
deteriorates sharply going from
3 to 5σ

Courtesy of E. Fernández-Martínez

CPV discovery as function of p.o.t.

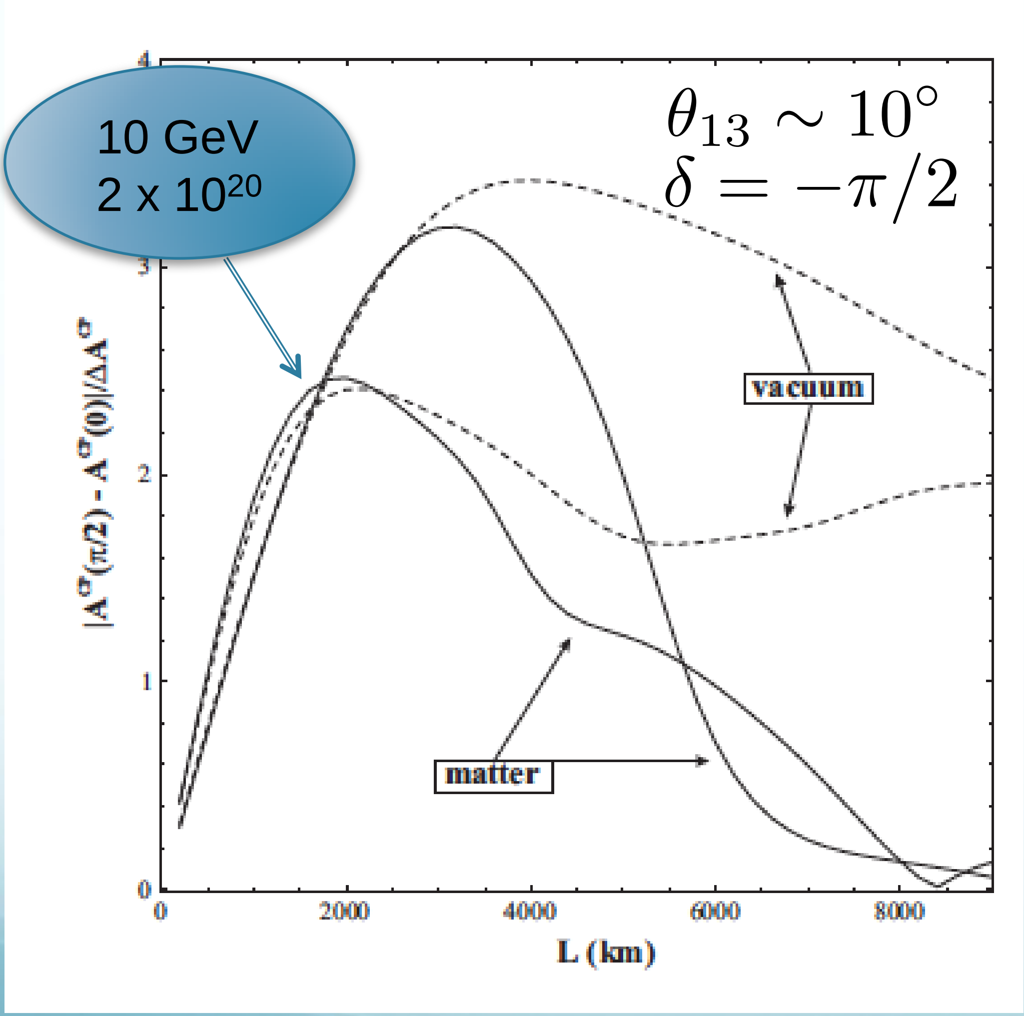


- PRELIMINARY



Coloma, Li, Pascoli,
In preparation

From ancient past….



Scaling with distance
of the statistical significance
of the CP-asymmetry

Scaling with θ_{13}:

$$\frac{A}{\Delta A} \propto \frac{1/\sin\theta_{13}}{1/\sqrt{\sin^2\theta_{13}}} \sim \text{const.}$$

Donini et al., hep-ph/9909254