How much (joint) Resummation do we need?

[with Gillian Lustermans & Wouter Waalewijn]

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[Parton Showers, Event Generators and Resummation (PSR19),
Erwin Schrödinger International Institute for Mathematics and Physics,
11-13 June 2019]

Why go exclusive?

Precise understanding of **Jets properties** & **substructure:**

➜ confirm SM @ higher accuracy ↔ identify deviations.

➜ **multivariate** analyses,

➜ **correlations.**

Why go exclusive?

Monte Carlos

➜ **"Fully Multi-differential"** predictions of observables. ✓

Analytic Resummation

➜ **Possible** to systematically improve. ✓

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[?]

Difficult to make more differential.

How exclusive is enough?

Analytic Resummation is **hard** to make more differential. **[e.g. Procura, Waalewijn, Zeune, 1806.10622]**

➜ How much effort should we put into trying?

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1\mathrm{d}\mathcal{O}_2\ldots\mathrm{d}\mathcal{O}_N}\right|_{\text{Resummed}} \quad \boldsymbol{\rightarrow} \quad \boldsymbol{N_{\text{optimal}} = ?}$$

How exclusive is enough?

<u>Answer in case study:</u>

1. Start: **“Flat”** phase space **MC**: N observables $\mathcal{O}$. [**PhSp**]

2. **Reweigh** by calculation for N observables $\mathcal{O}$ [**MC** or Resummation].

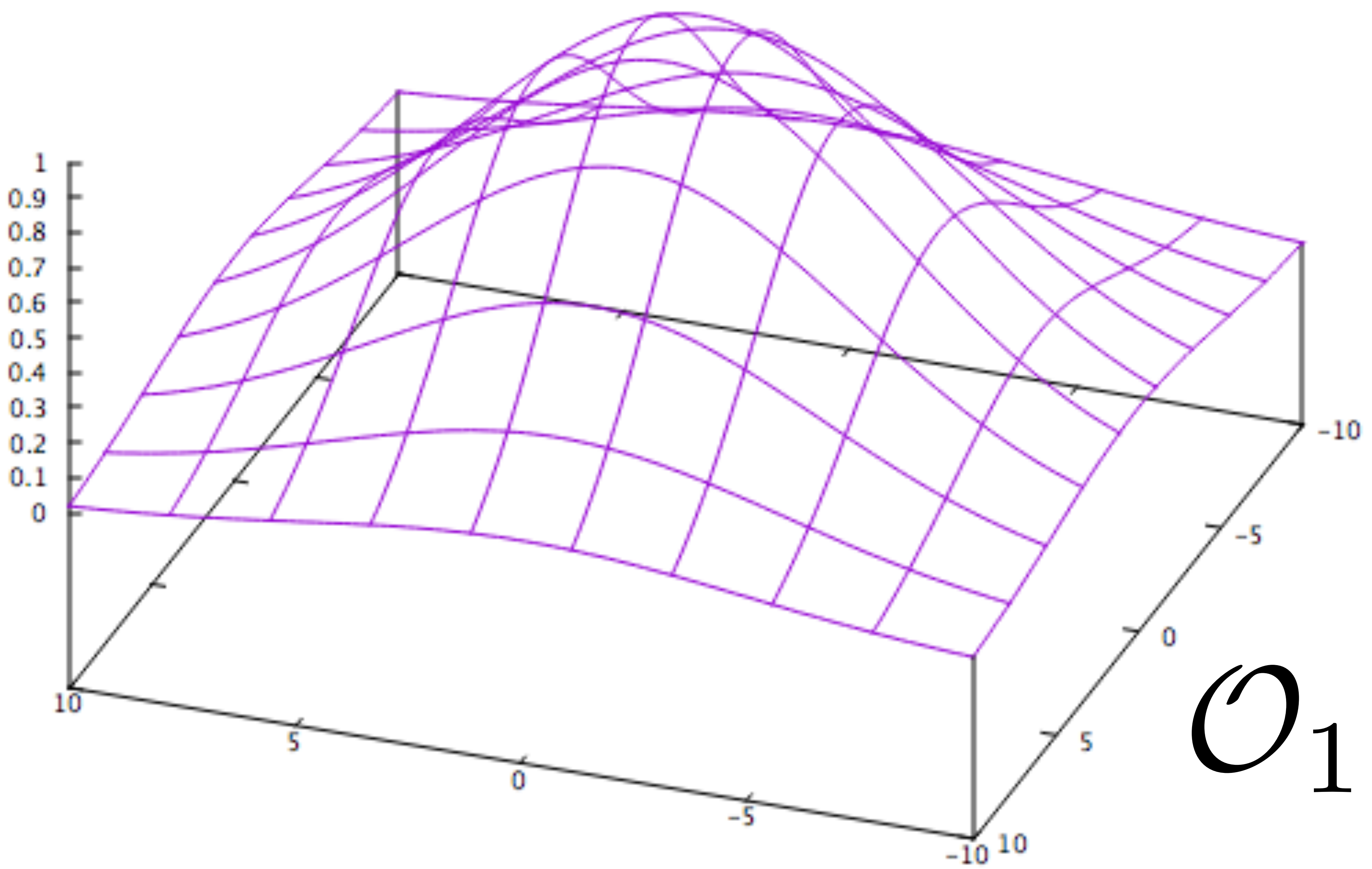
3. **Look** at “other” (**not** Reweighed) observables ,

4. **Compare** Reweighed [**RW**] prediction $\leftrightarrow$ to **MC** or Resummation.

[5. Profit!]

Reweighing

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{PhSp}}$$



$\mathcal{O}_1$

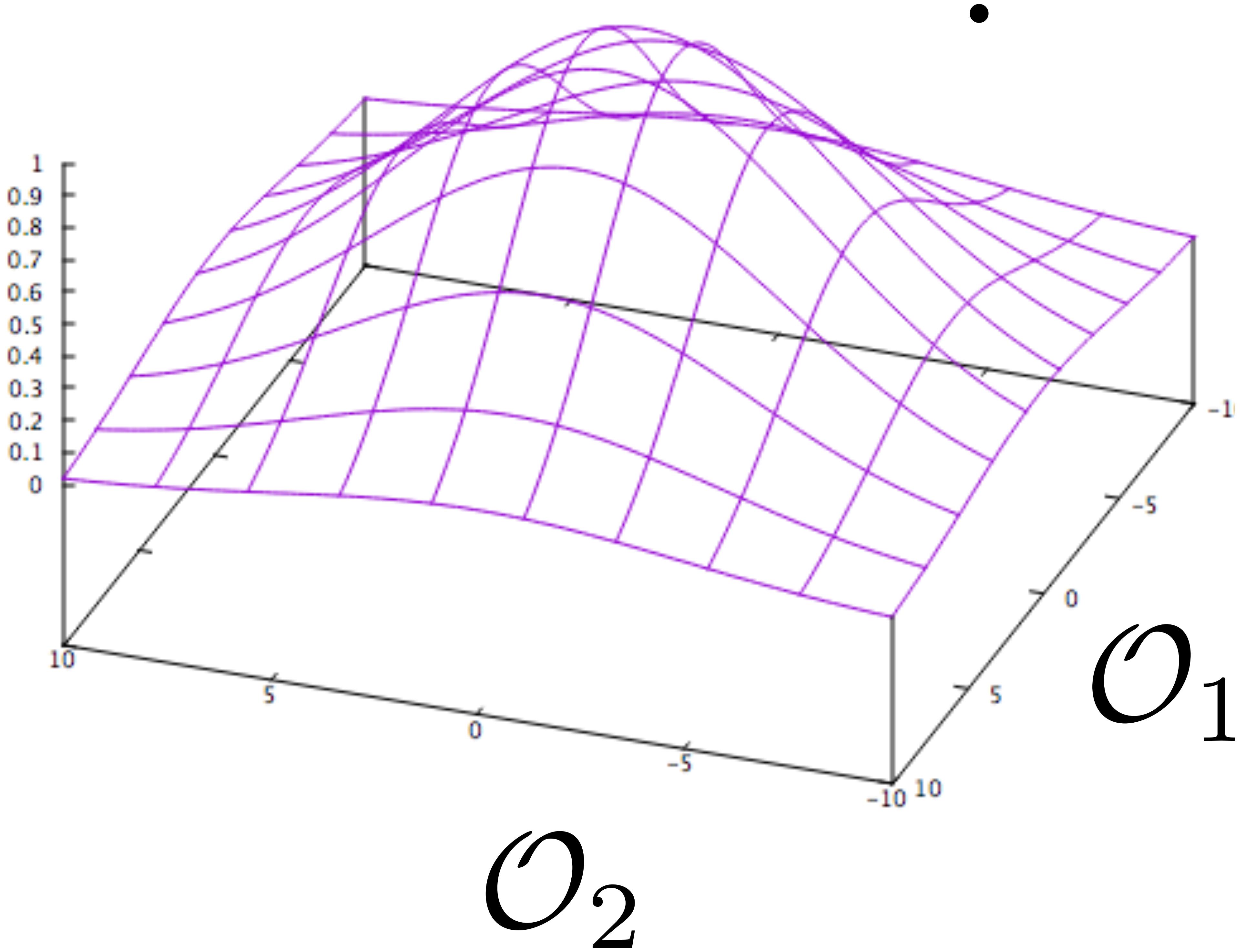
$\mathcal{O}_2$

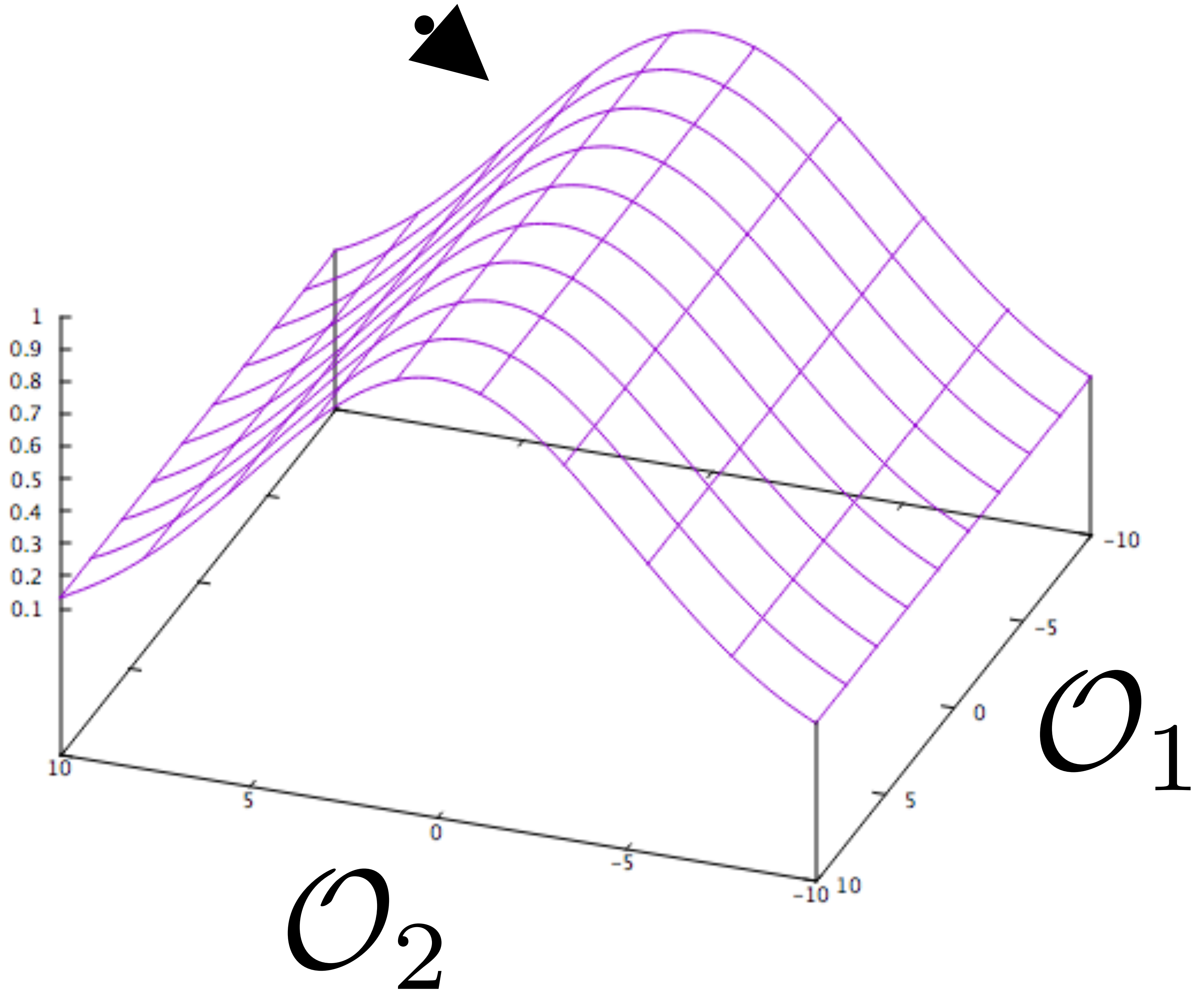
Reweighing

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{PhSp}}$$

Make "Flat" in dimension $\mathcal{O}_1$:

$$\frac{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{PhSp}}}{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1}\right|_{\mathrm{PhSp}}}$$





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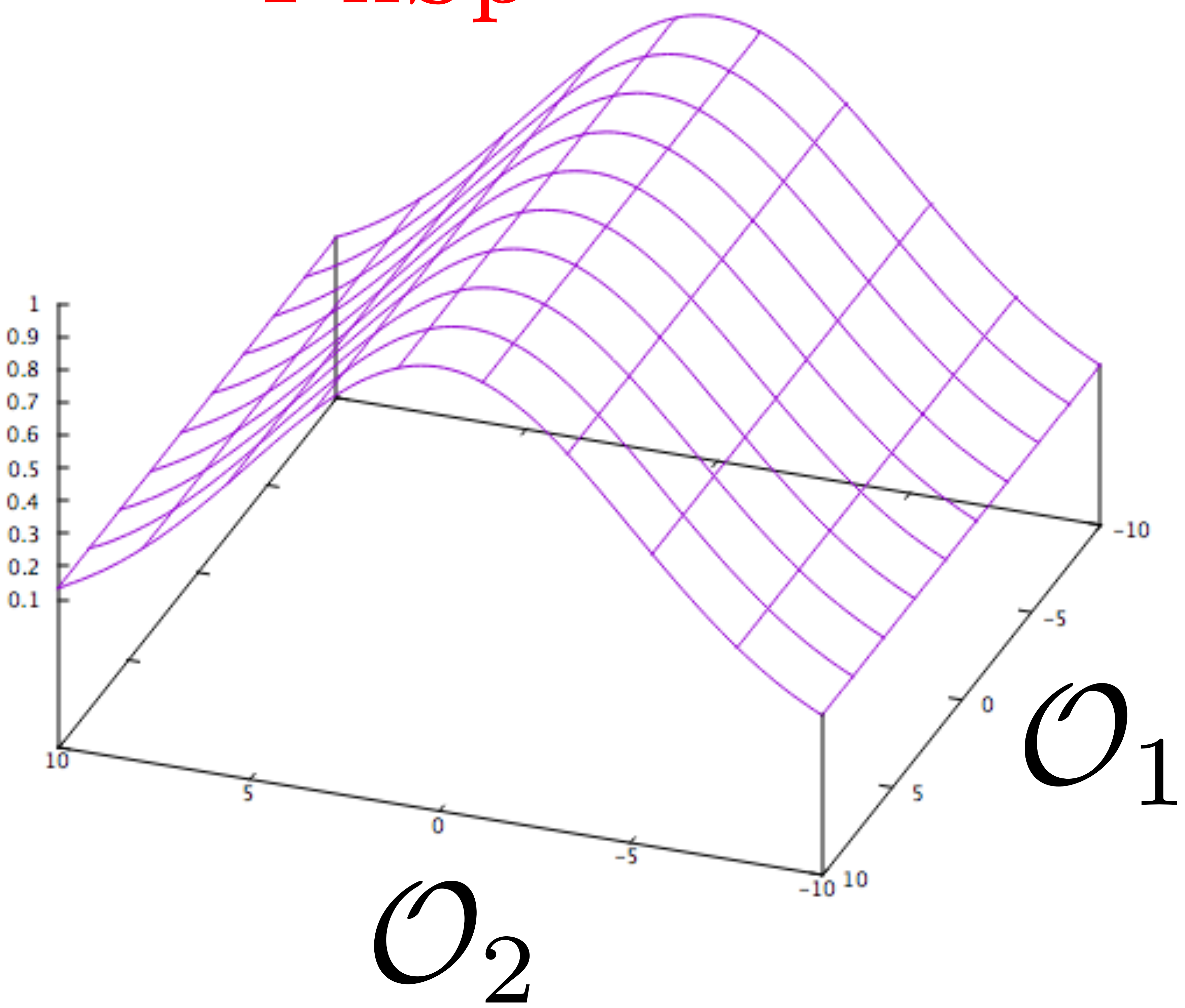
Reweighing

$$\frac{\left.\dfrac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1\,\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{PhSp}}}{\left.\dfrac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1}\right|_{\mathrm{PhSp}}}$$

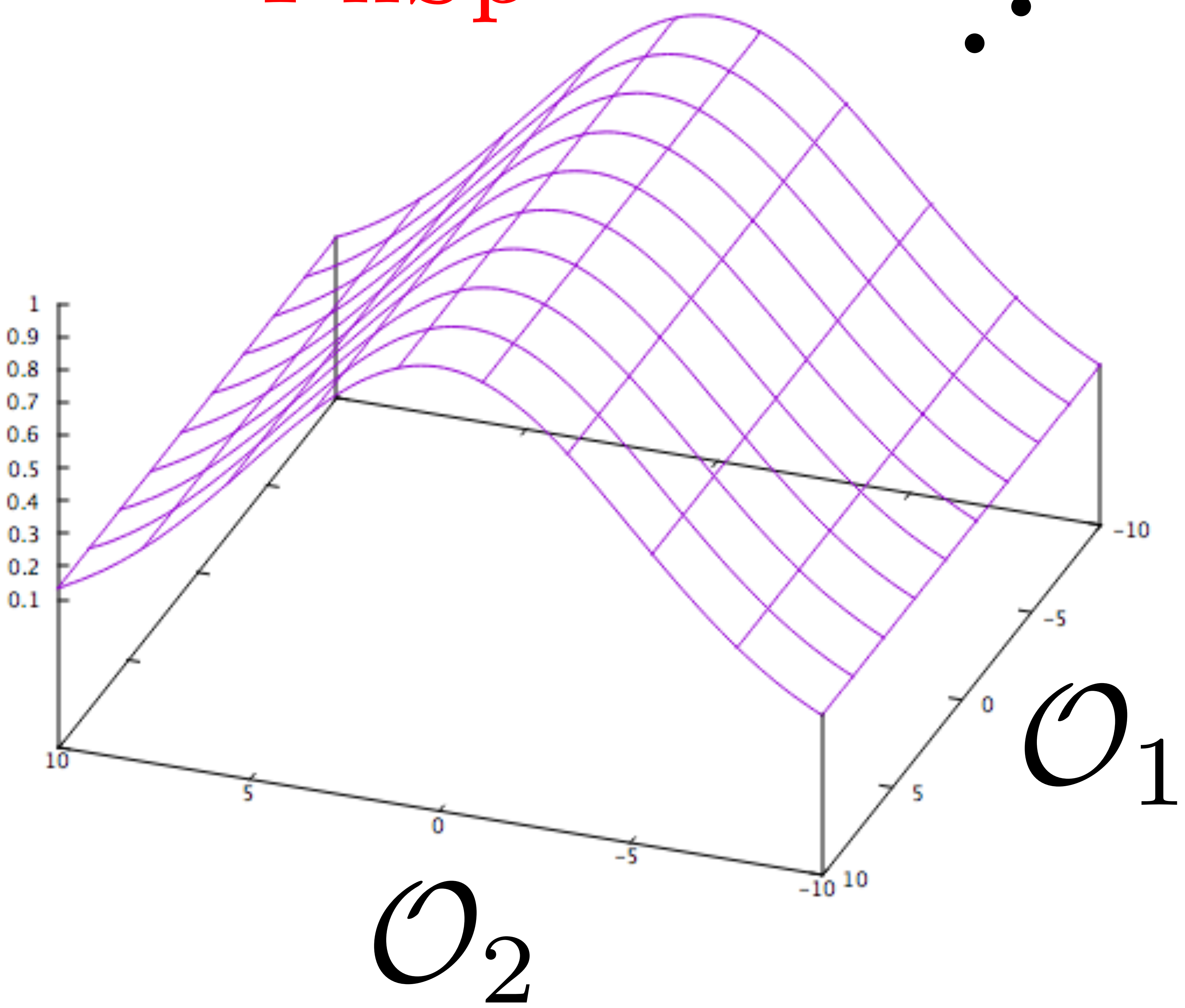


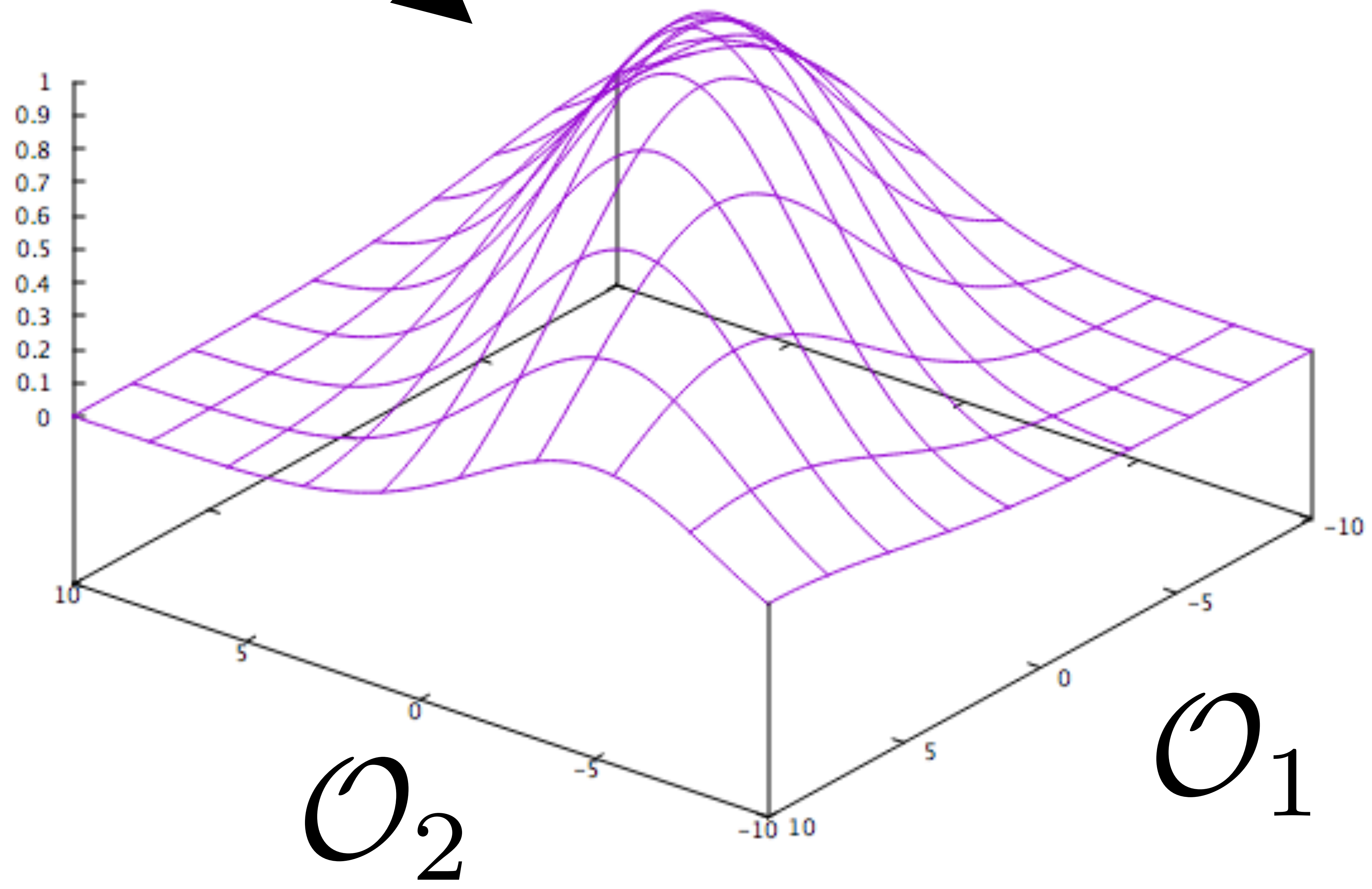
Reweighing

$$\frac{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1\,\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{PhSp}}}{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1}\right|_{\mathrm{PhSp}}}$$

Reweigh by MC $\mathcal{O}_1$ distribution

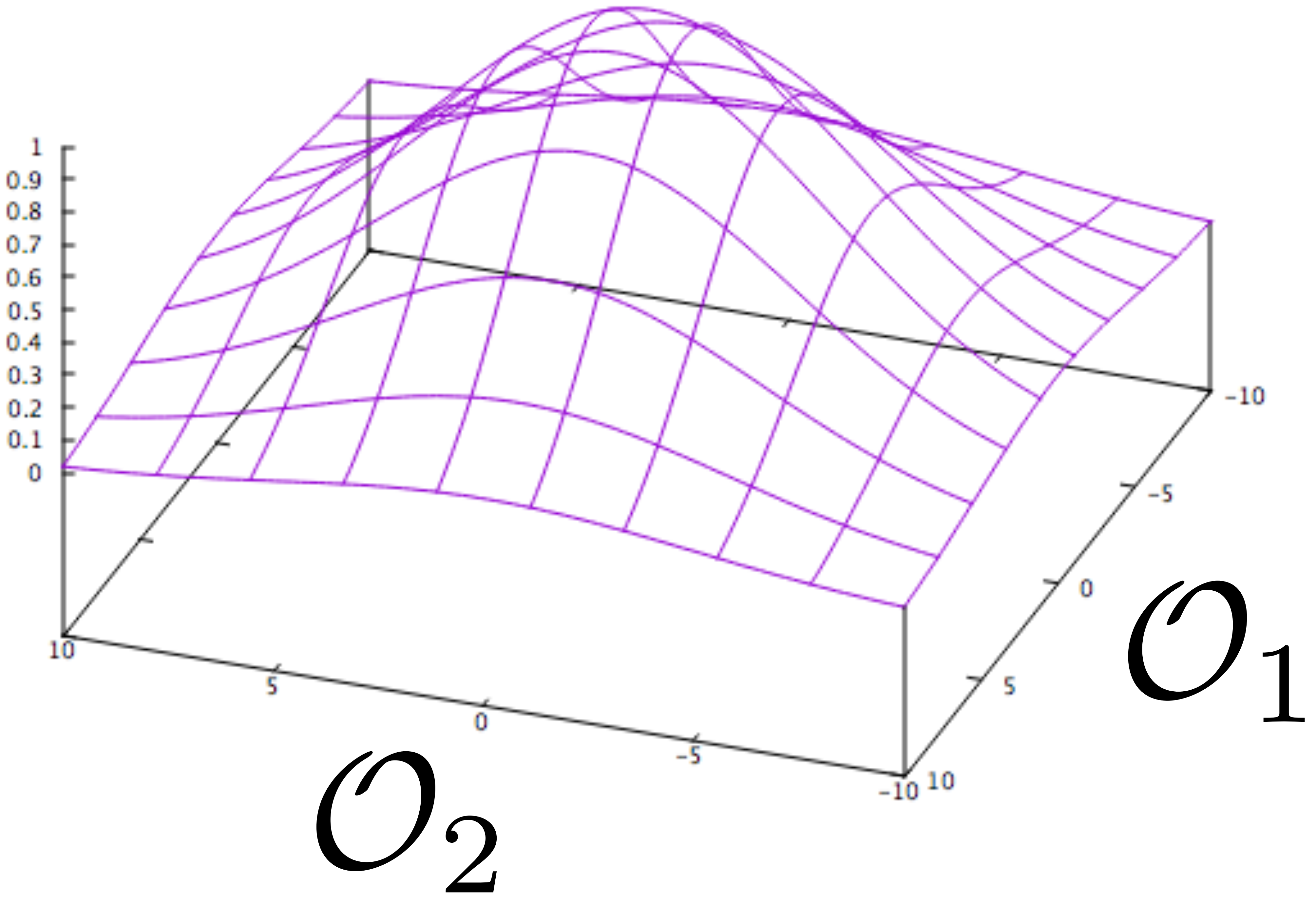
$$\frac{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1\,\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{PhSp}}}{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1}\right|_{\mathrm{PhSp}}} \times \left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1}\right|_{\mathrm{MC}}$$





Drawn for illustrative purposes!

In general, $\mathcal{O}_1$-$\mathcal{O}_2$ are correlated!



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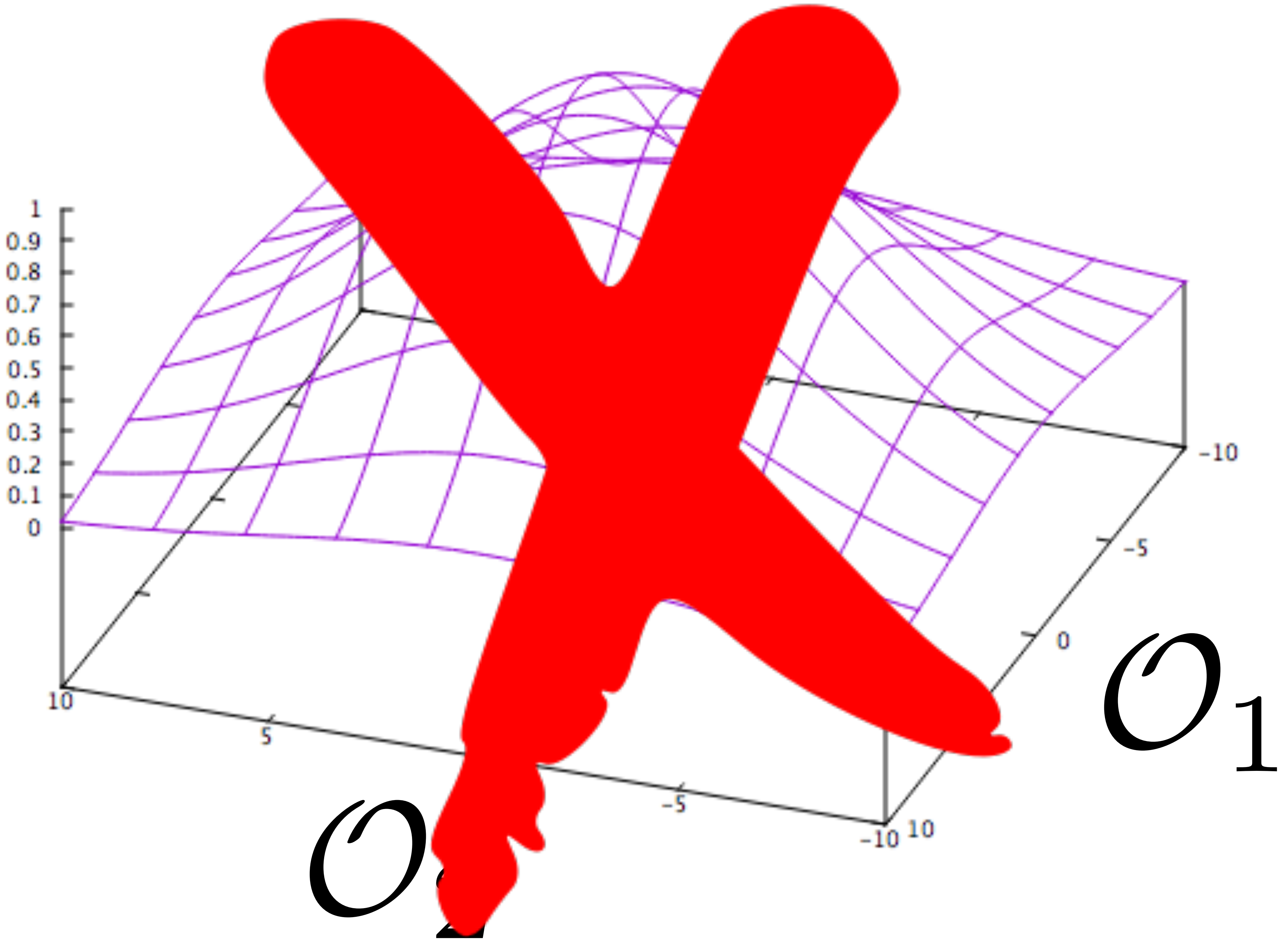

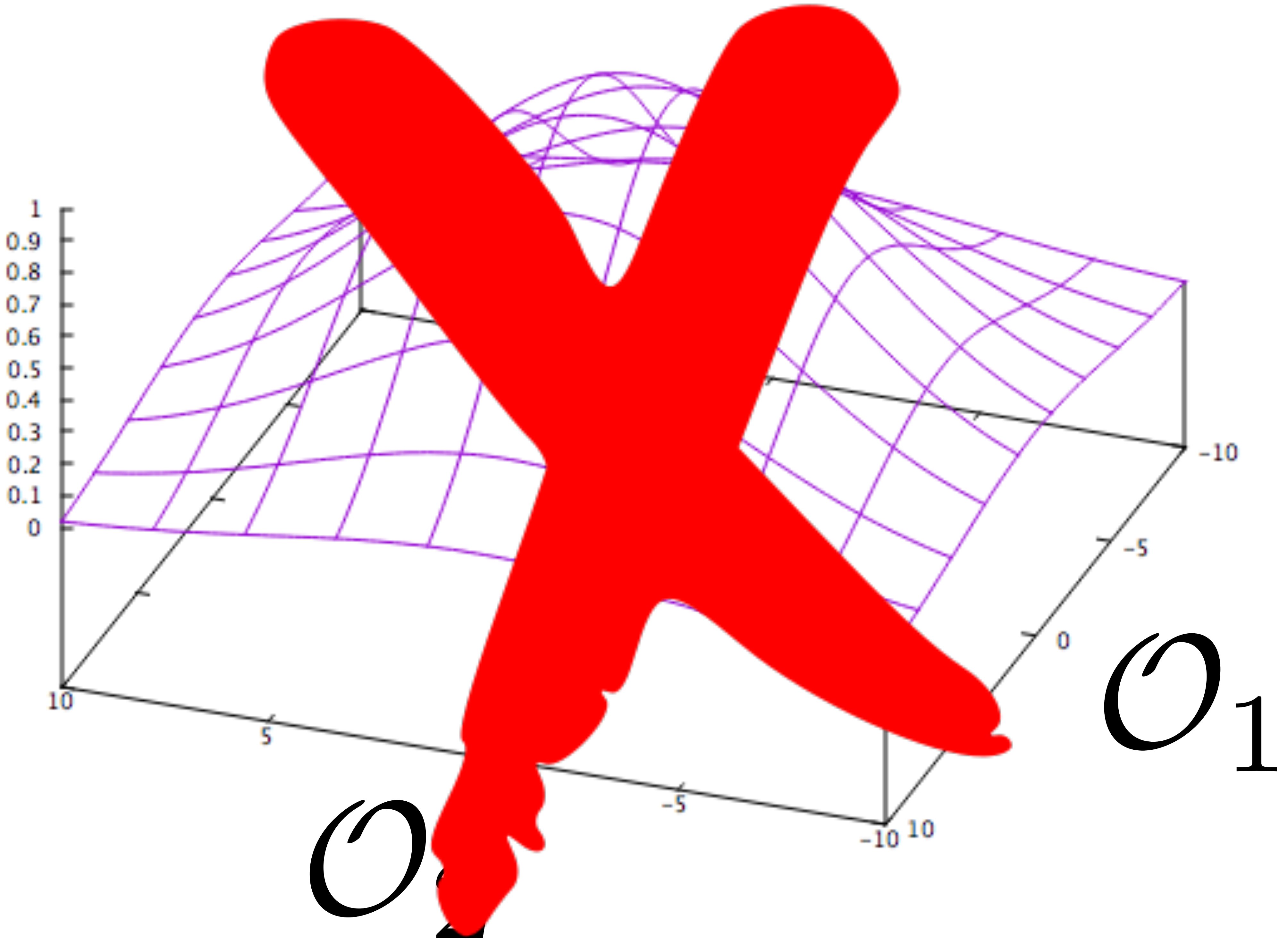

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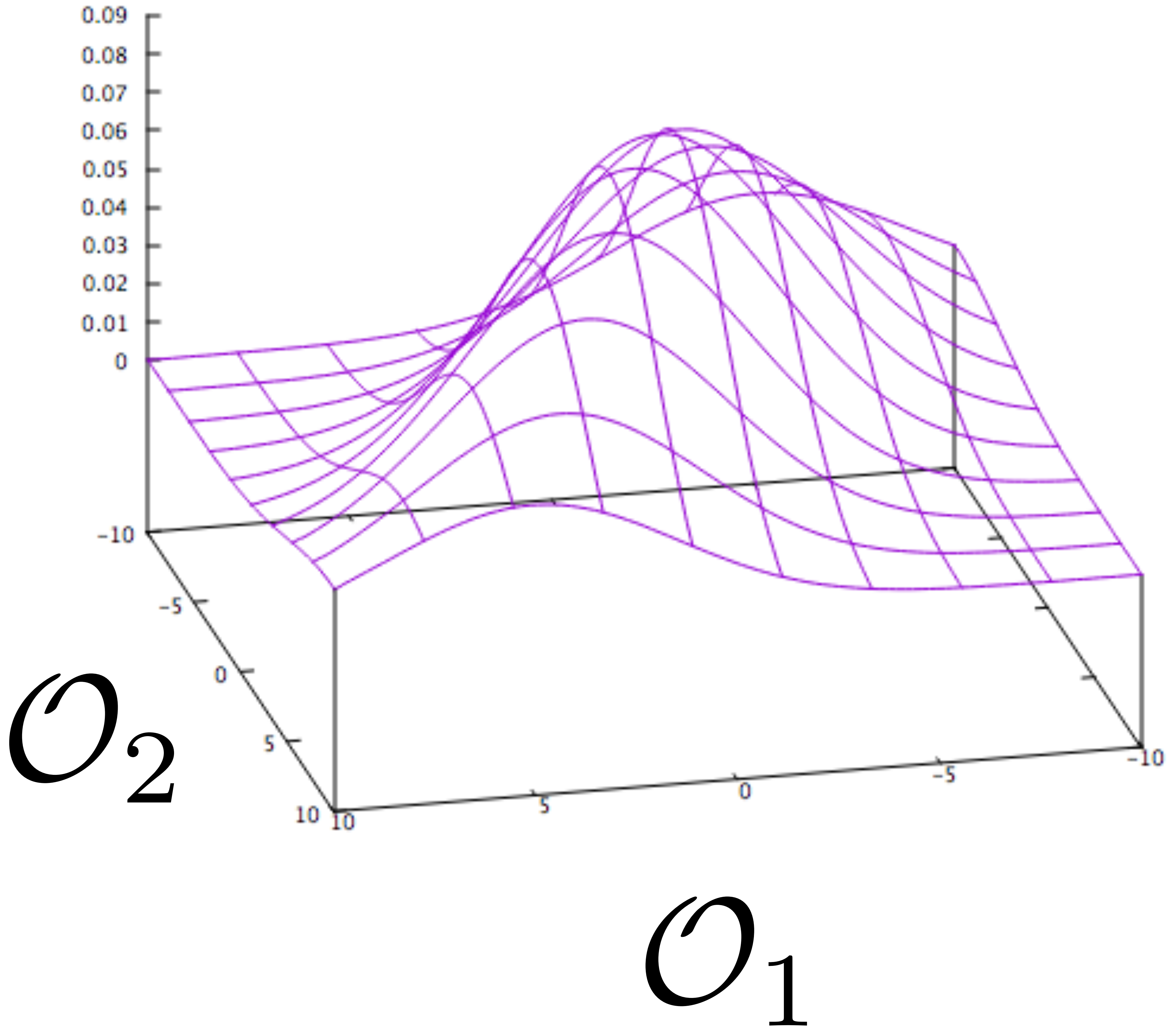

Projecting down

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{RW}} = \int \mathrm{d}\mathcal{O}_1 \frac{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{PhSp}}}{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1}\right|_{\mathrm{PhSp}}} \times \left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1}\right|_{\mathrm{MC}}$$

Compare "other" observable:

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{RW}}$$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{MC}}$$

"prediction" **"truth"**

Projecting down

Compare "other" observable:

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_2}\right|_{\color{red}{\mathrm{RW}}}$$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_2}\right|_{\color{red}{\mathrm{MC}}}$$

via:

$$\chi^2(\mathcal{O}_2) = \sum_{\mathrm{bin}\ i} \left[\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_2}\right|_{\color{red}{\mathrm{RW}},i} - \left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_2}\right|_{\color{red}{\mathrm{MC}},i} \right]^2$$

"goodness of fit"

Flat Phase Space Monte Carlo

$$\mathrm{d}\phi_n(p_i|Q) = \delta(\sum_i p_i - Q) \prod_i \mathrm{d}^4 p_i \delta(p_i^2)\theta(p_i^0)$$

Total momentum conservation

Flat Phase Space Monte Carlo

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→ **Use Simon's "RAMBO on diet" [Thanks!].** **[Plätzer, 1308.2922]**

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Total momentum conservation

→ **Use Simon's "RAMBO on diet" [Thanks!].** **[Plätzer, 1308.2922]**

→ **with a "twist": importance sampling for our observables .**

The setup

Process: $e^+e^- \to jj$ at fixed Q. [MCs: HERWIG 7, Pythia 8]

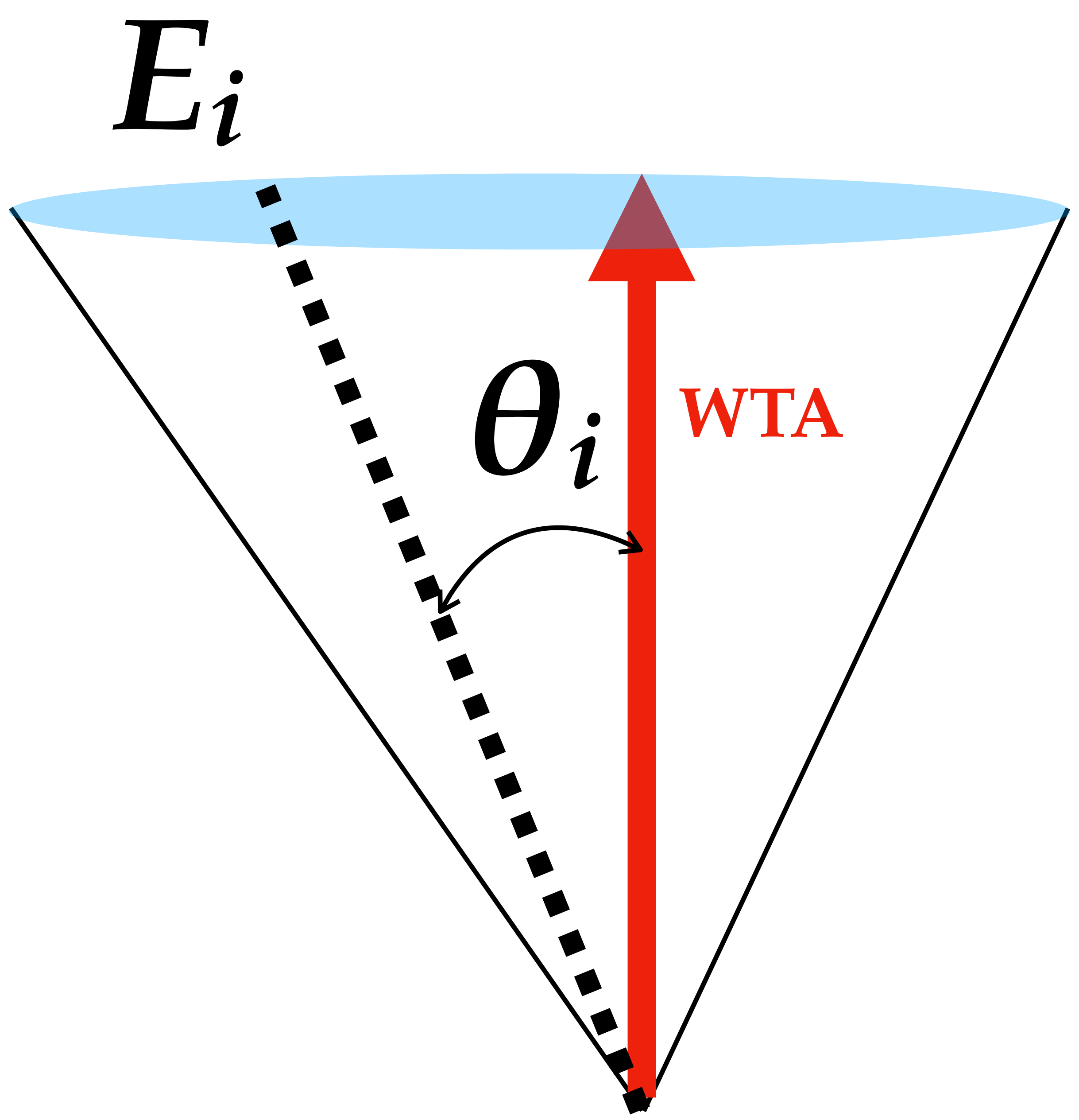
[**no** hadronisation/non-perturbative effects.]

Analysis: Exclusive **k**$_\mathrm{T}$ algorithm ➜ **2** jets,
"Winner-Takes-All" recombination:

$A + B \to (AB):$ $\hat{\vec{p}}_{AB} = \text{hardest of}(\hat{\vec{p}}_A, \hat{\vec{p}}_B)$ [➜ Recoil-insensitive]

The observables

Jet Angularities: $$e_\alpha \sim \frac{1}{Q} \sum_i E_i \theta_i^\alpha$$ **[over both jets]**



$\alpha = 2$ ~ Thrust

$\alpha = 1$ ~ Total broadening

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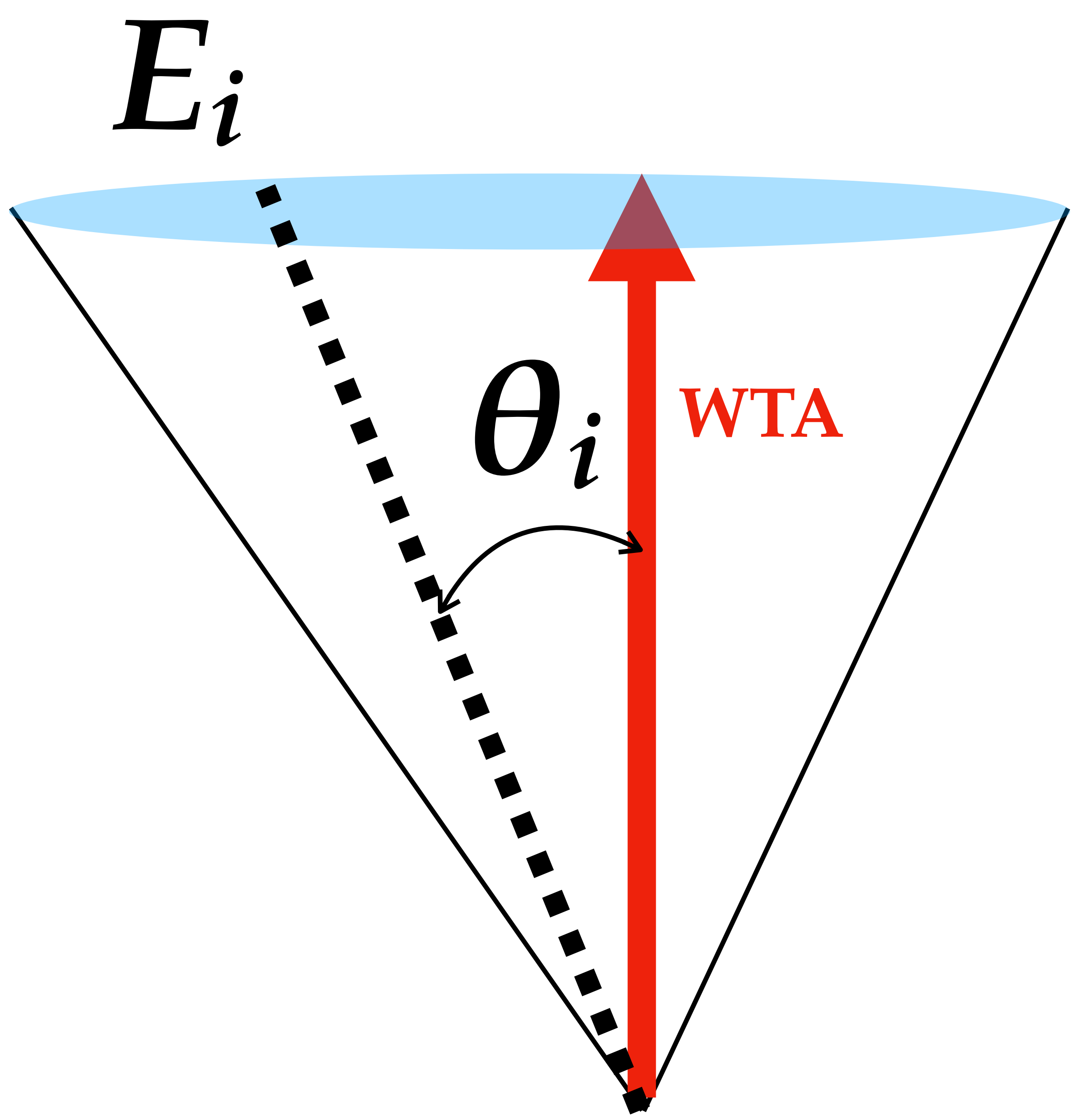
The observables

Jet Angularities: $e_\alpha = \frac{2}{Q} \sum_i E_i \left[\sin\left(\frac{\theta_i}{2}\right) \right]^\alpha$ **[over both jets]**

Actually look at



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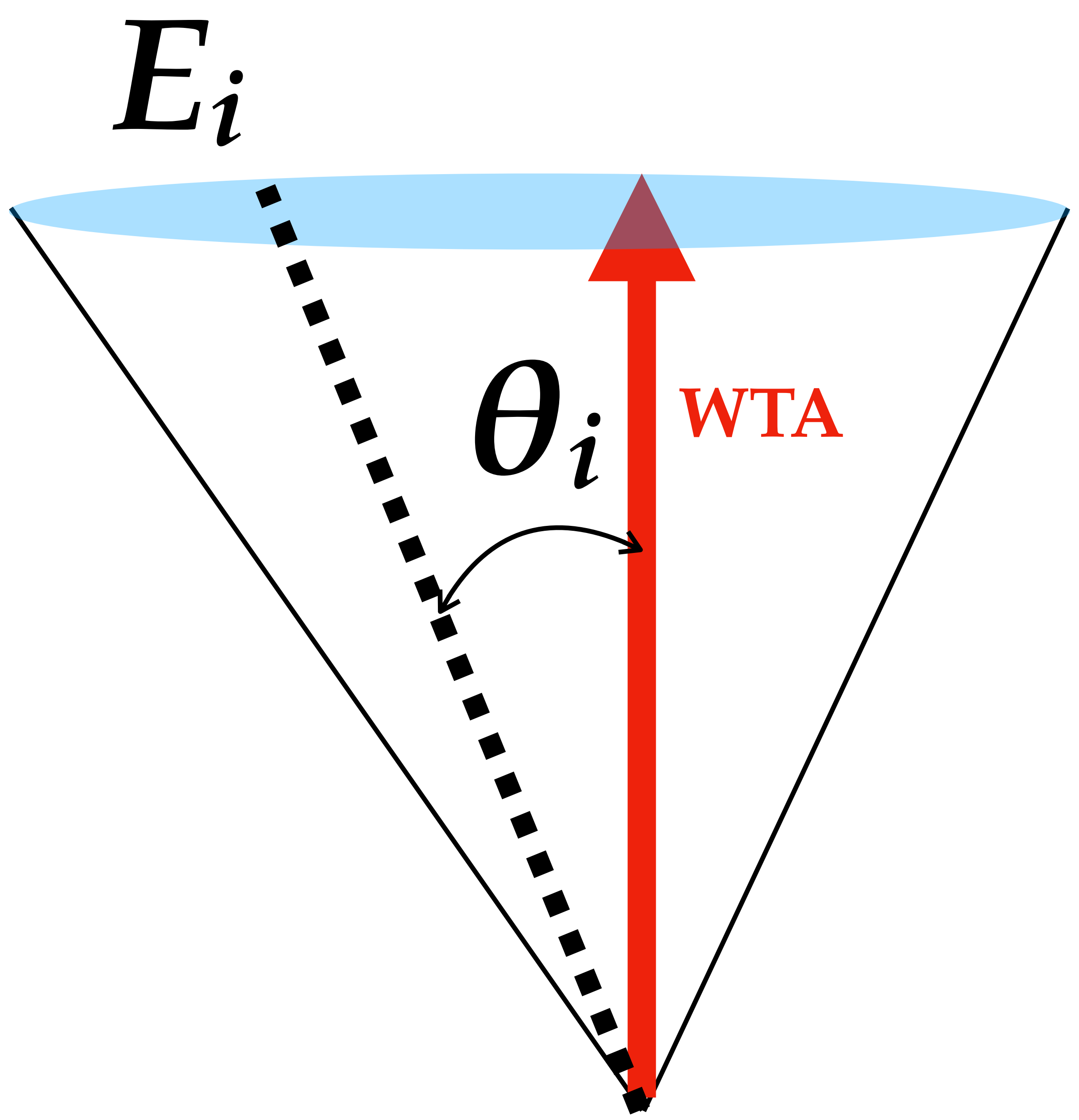


Actually look at

$$\log_{10} e_\alpha$$

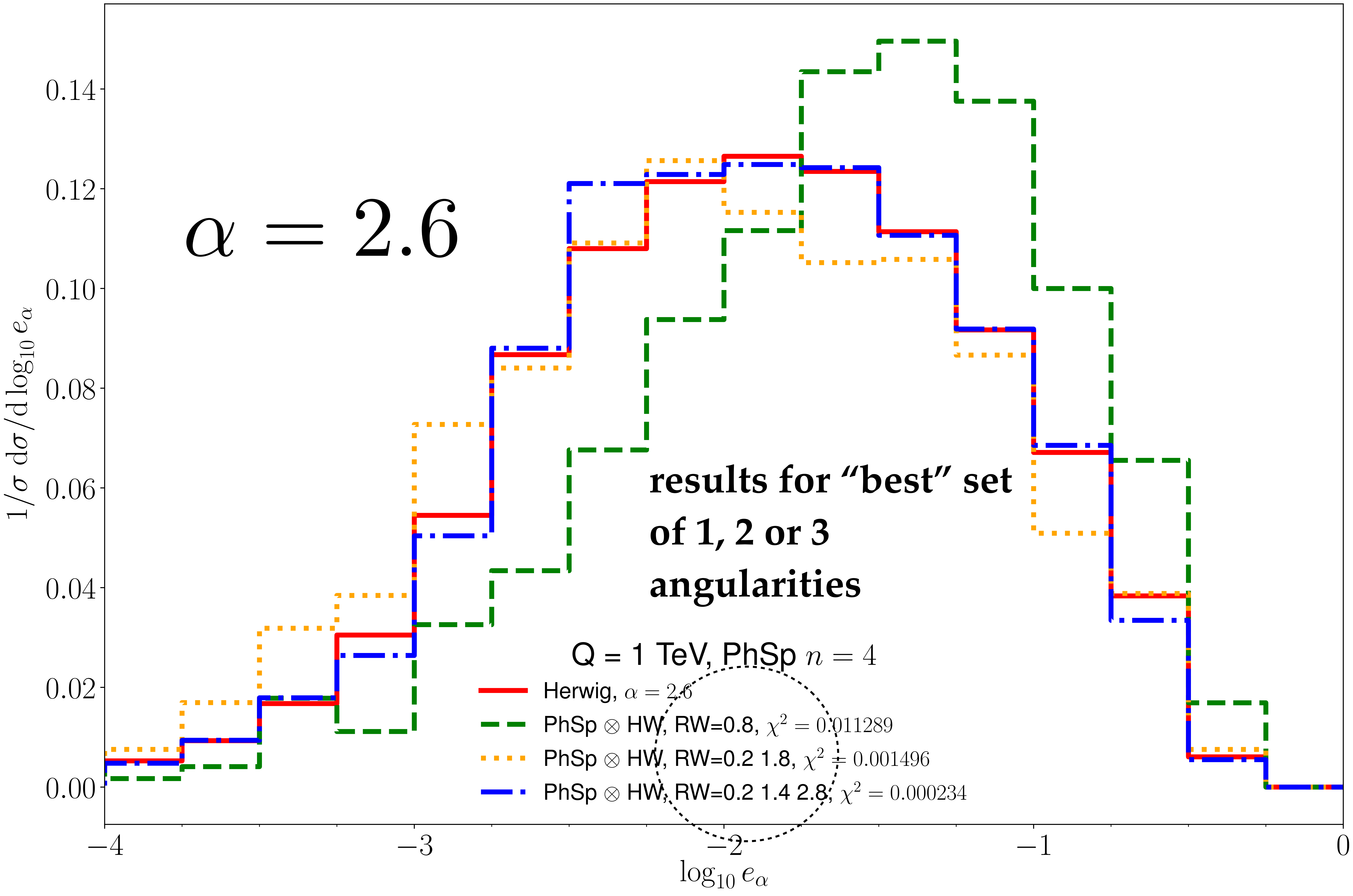
The "best" Angularity set

➜ **Reweigh by: [1, 2, 3, 4, 5] angularities.** $\left\{ \begin{array}{l} \alpha \in [0.2, 3.0] \\ \textbf{in steps of 0.2} \end{array} \right.$

➜ **Get "best" RW angularity set ➜ by minimising sum of the χ^2 over all "other" angularities:**

$$\min \sum_{\alpha} \chi^2(\alpha)$$

$Q = 1$ TeV $\quad n = 4$



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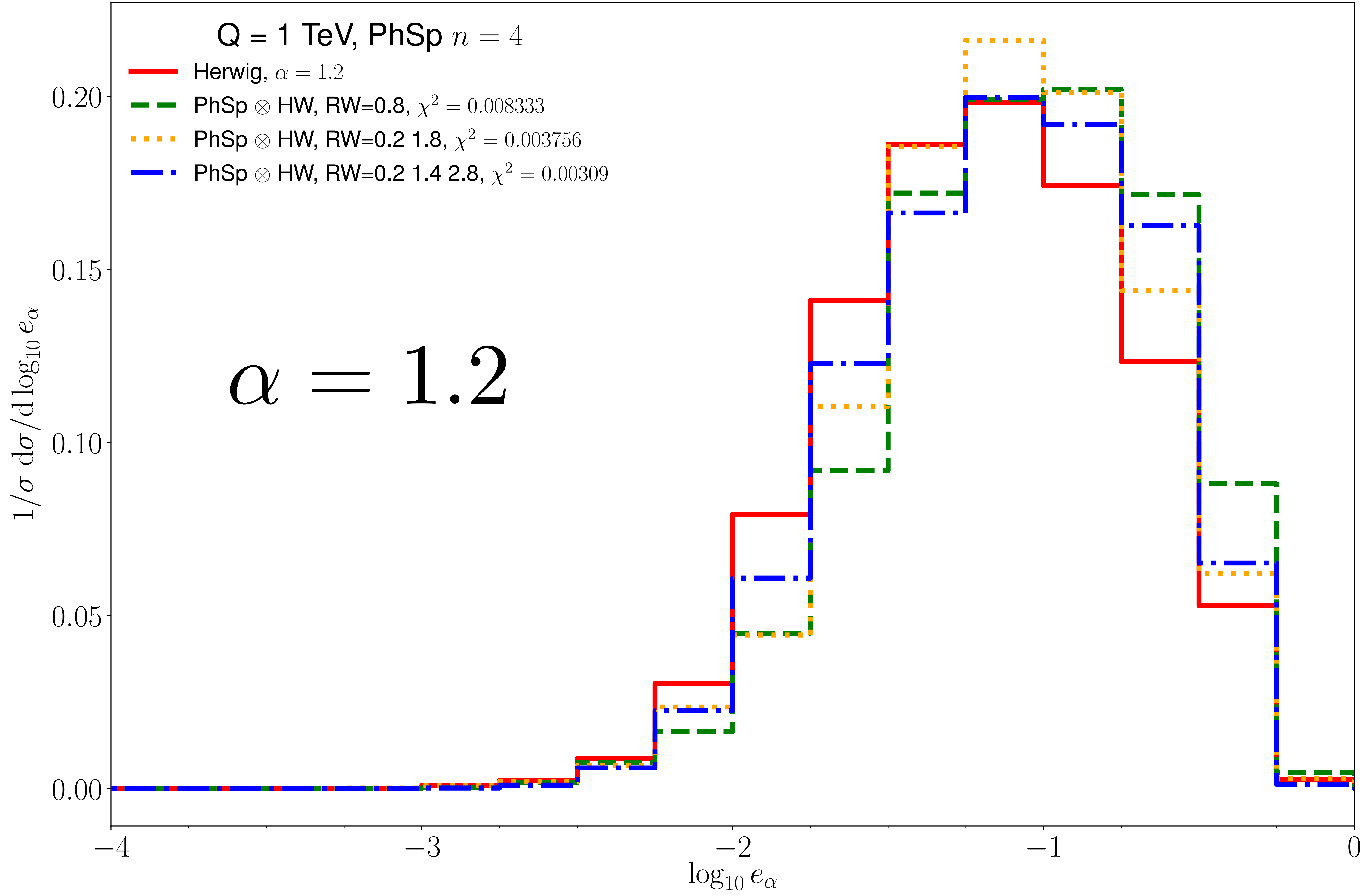
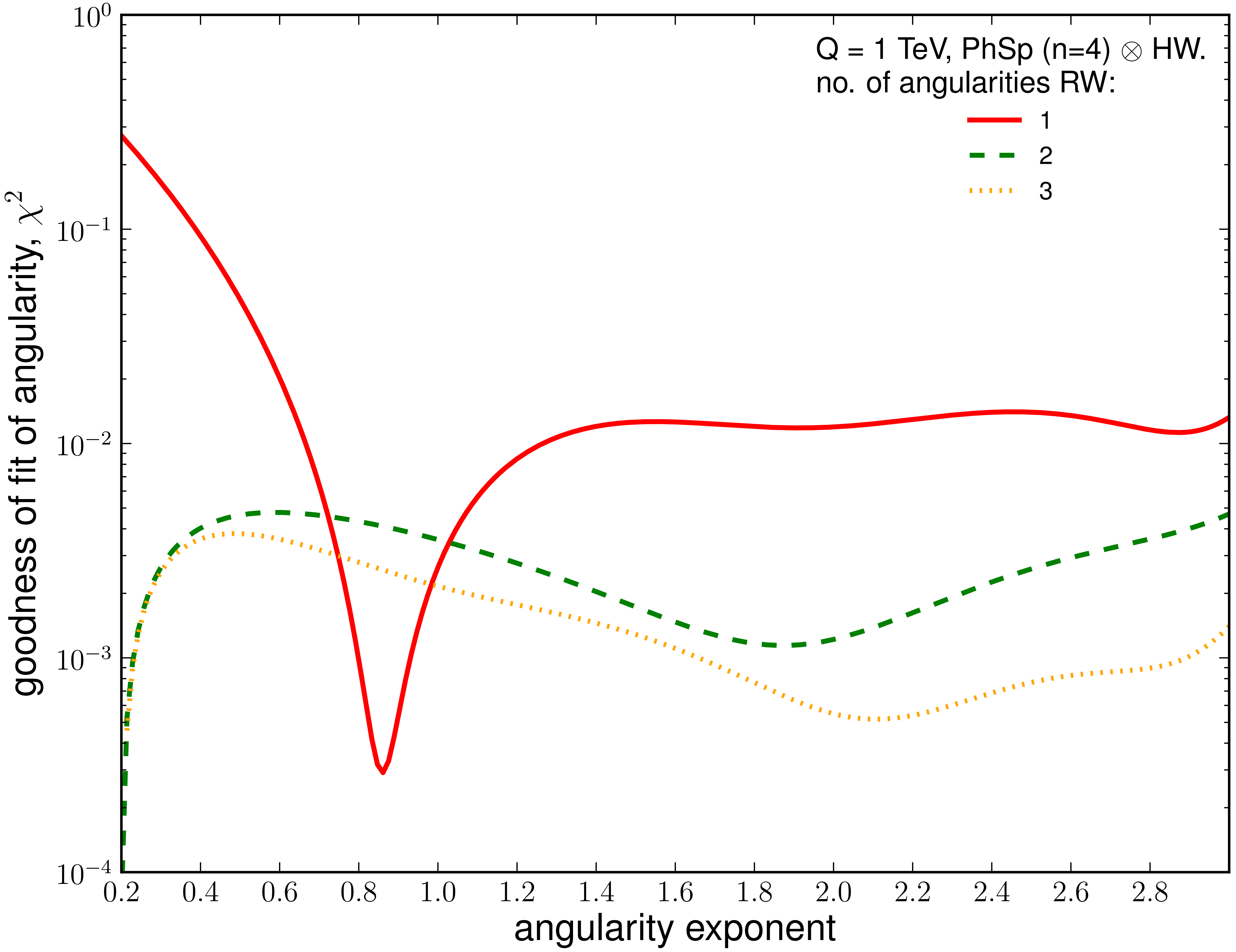
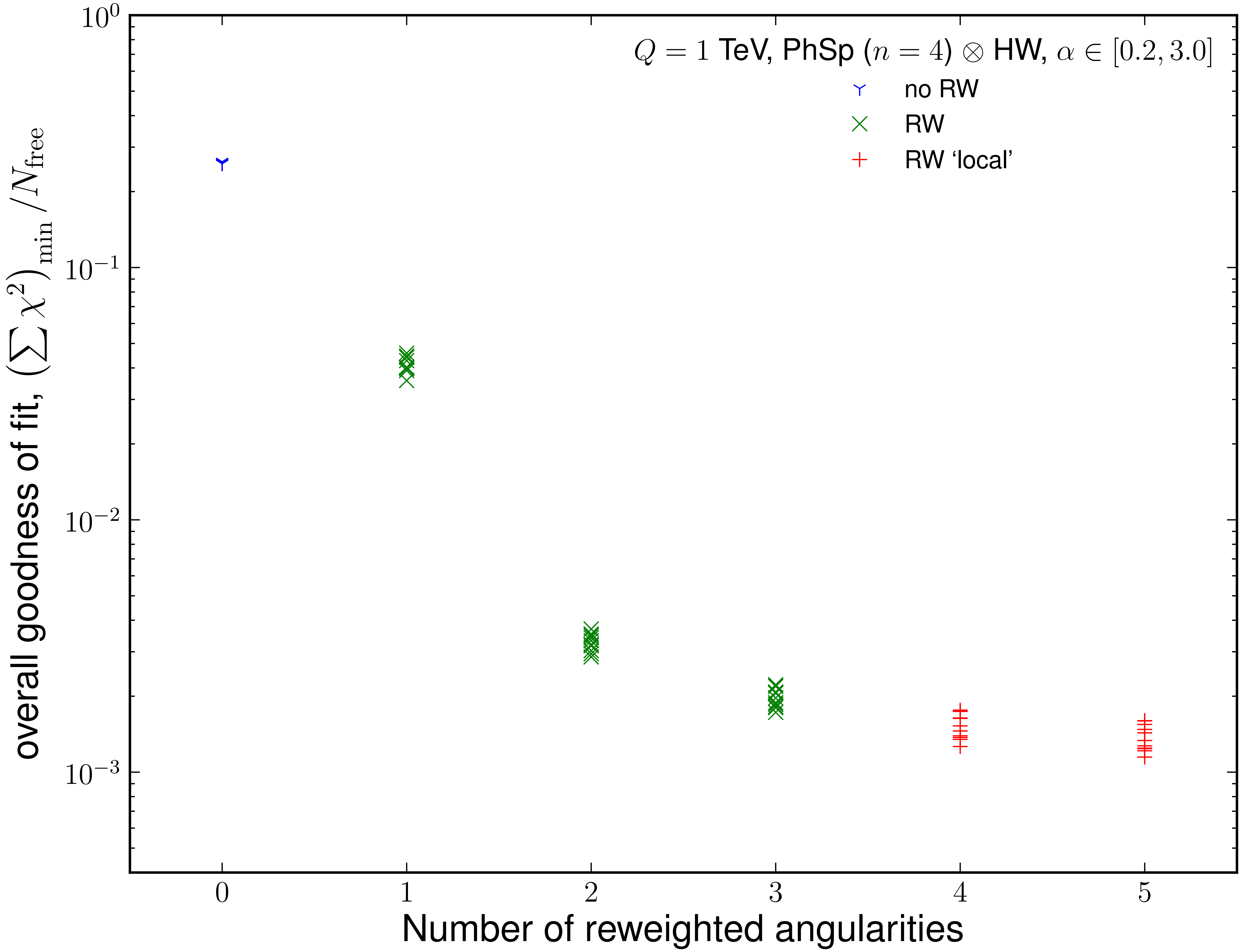


How good is “best” set do for angularity α?



Lines: the median [over 11 “pseudo-experiments”].

What is the overall improvement?



Estimate uncertainty:

11 "pseudo-experiments" ➜ Get Median & uncertainty.

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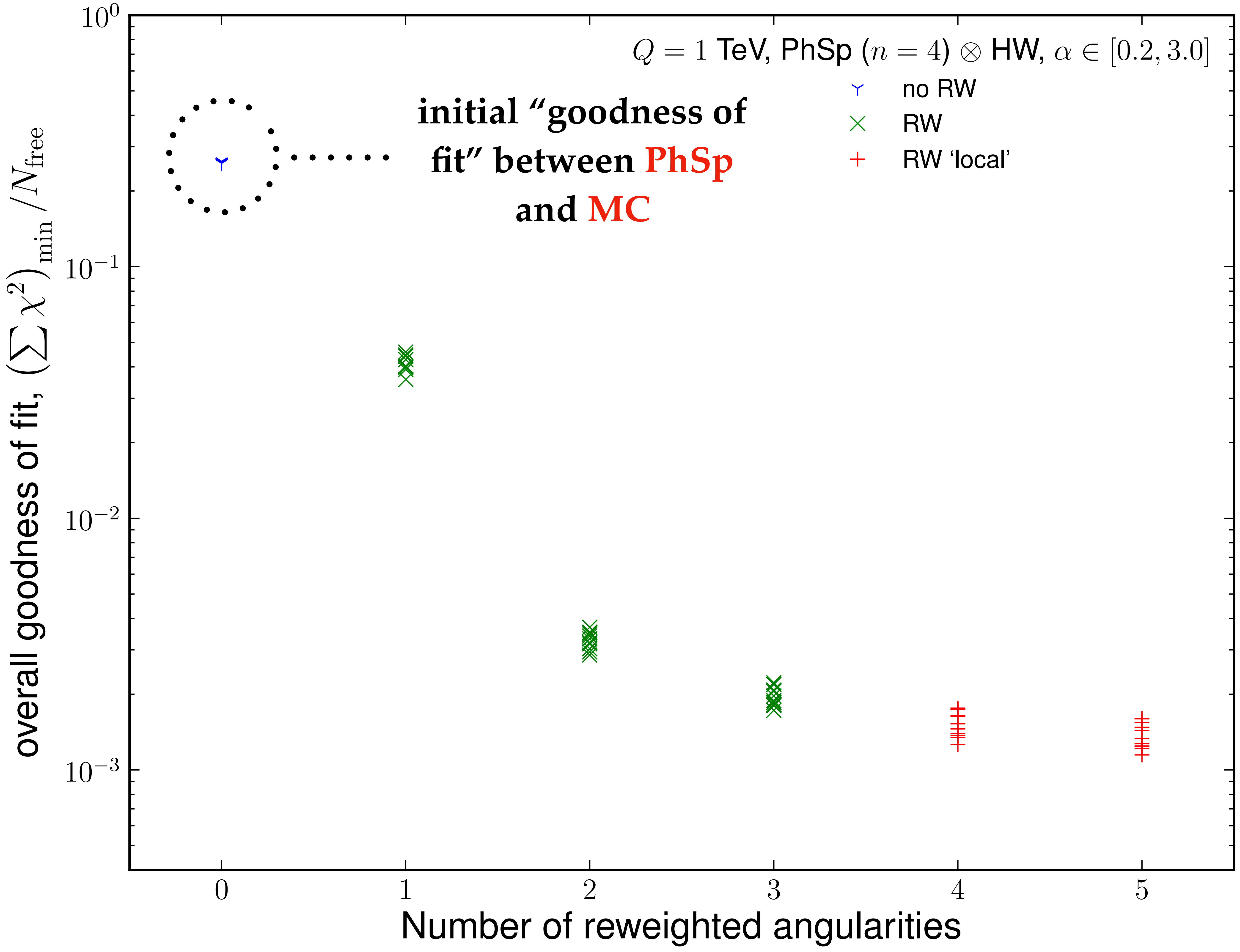

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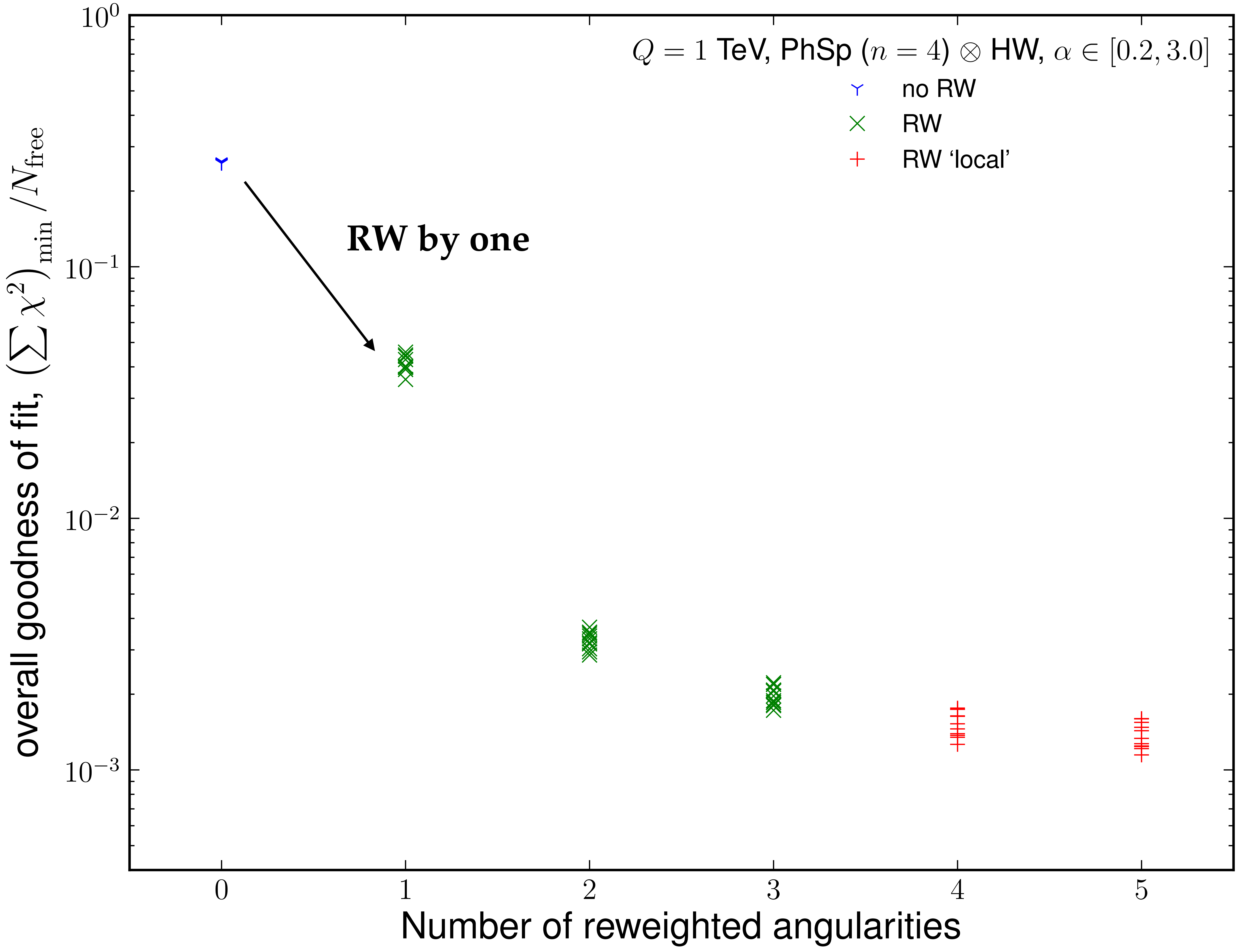

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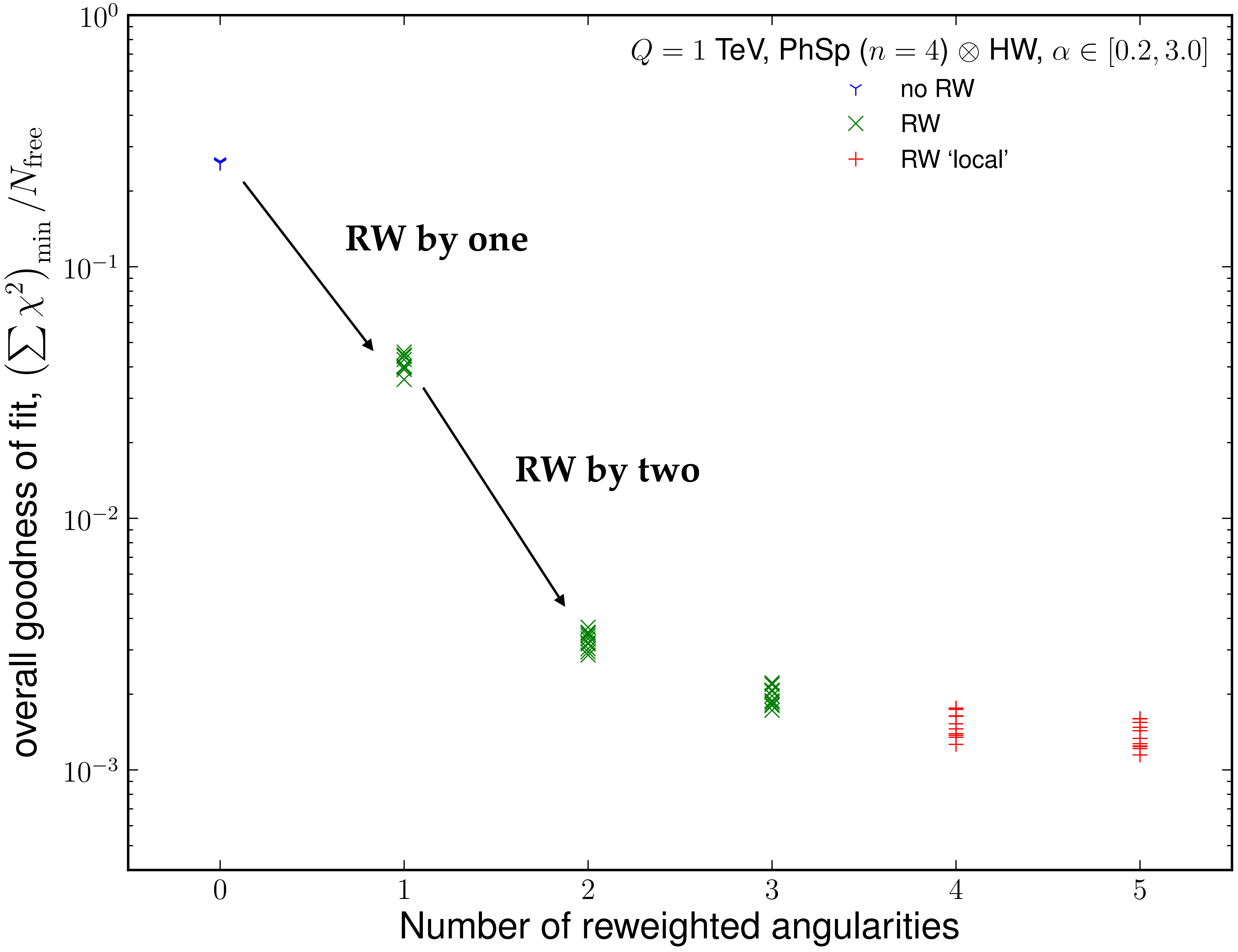

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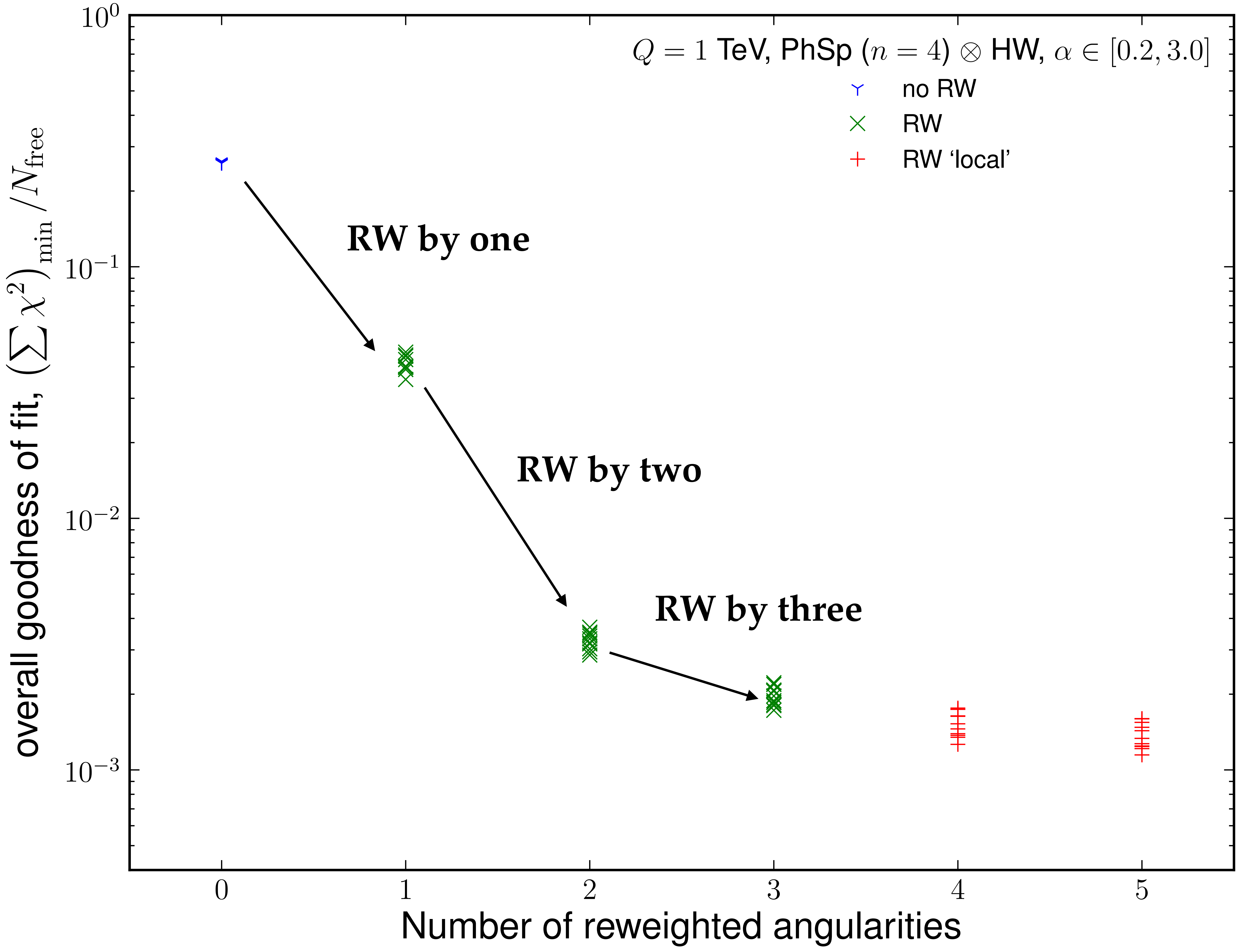

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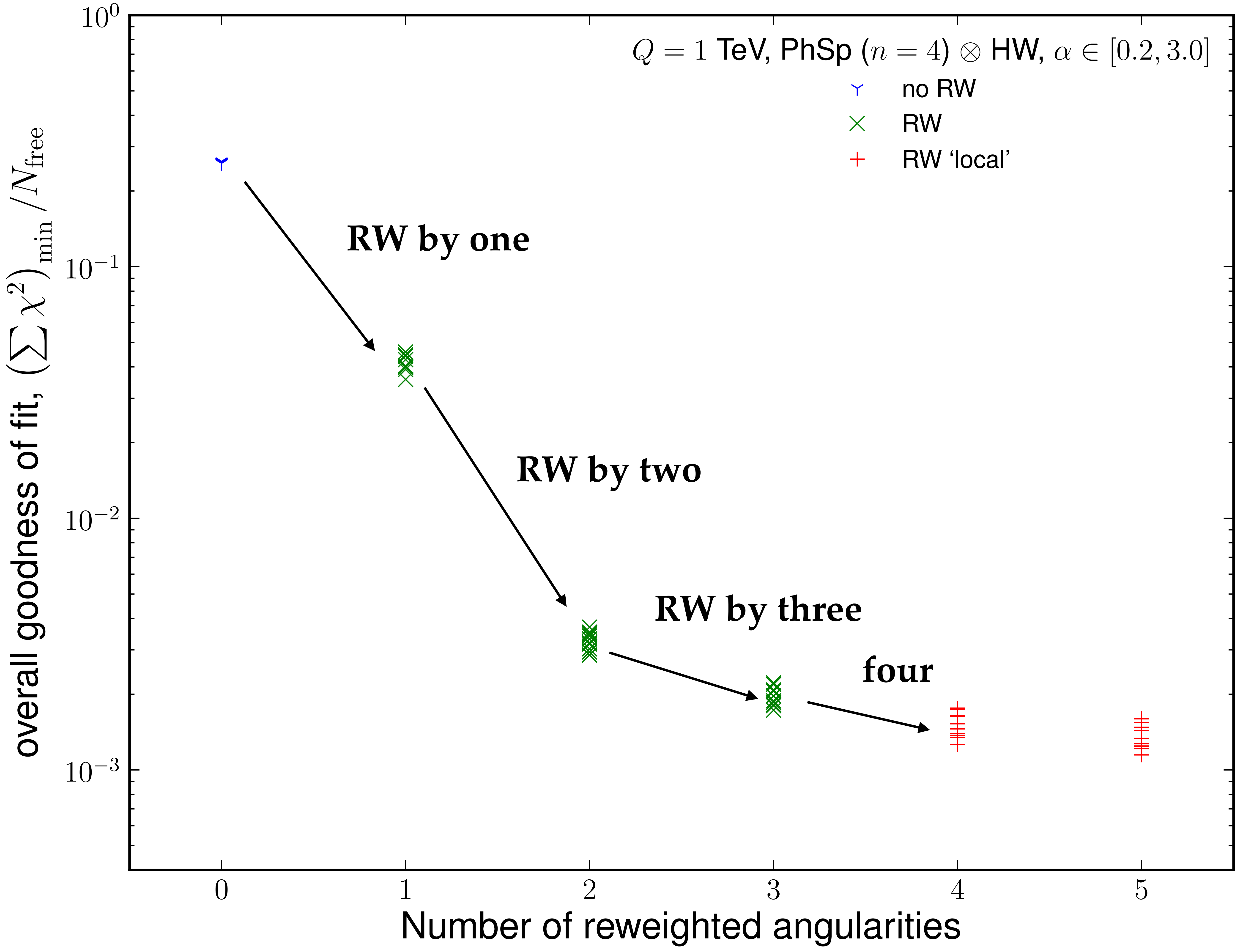

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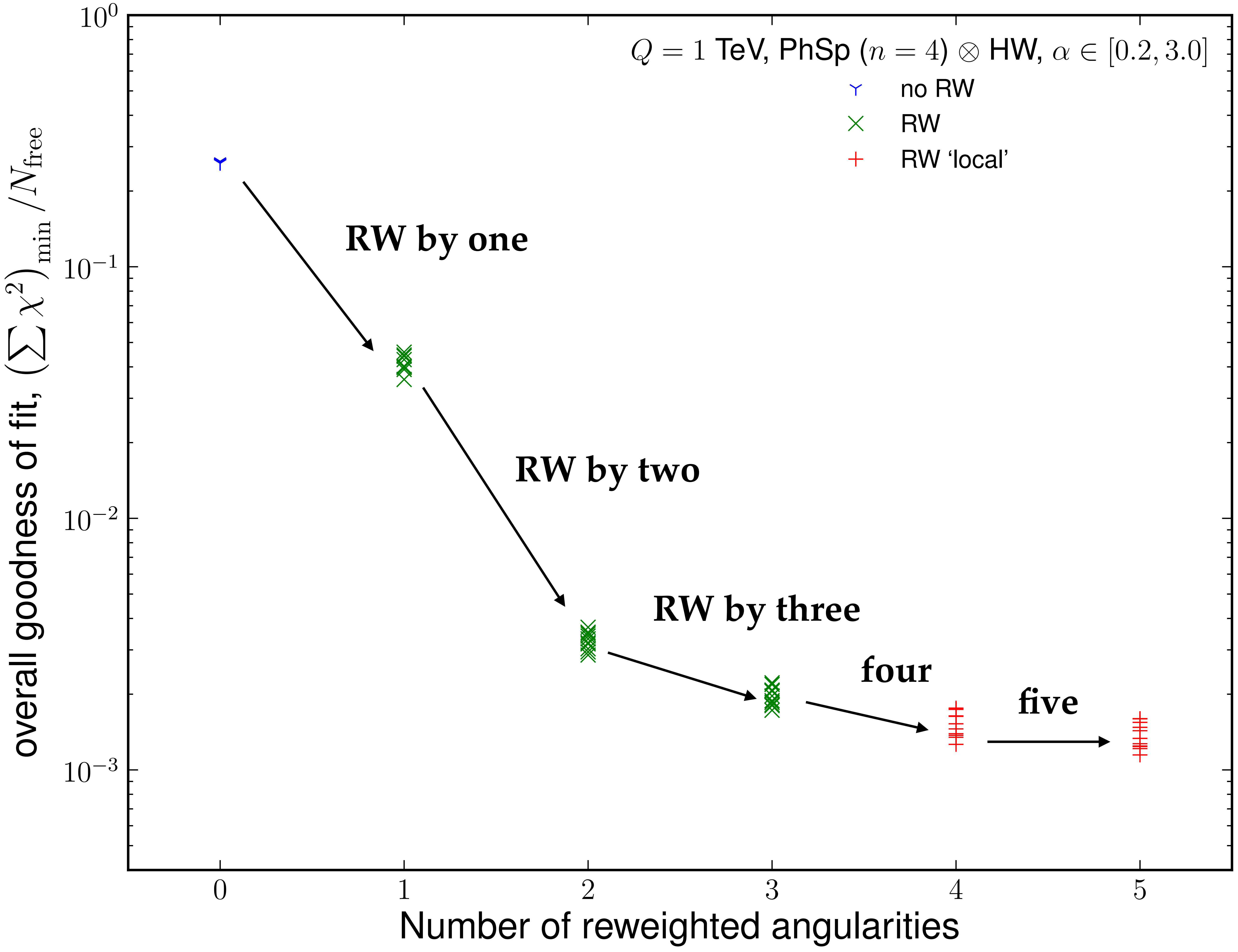


Estimate uncertainty:

11 "pseudo-experiments" ➜ Get Median & uncertainty.

Conclusions & Outlook

- Reweighing **flat phase space** by **MC** ➜ Get **predictions** of **other** angularities.
- Investigate "**How much angularity resummation required**":

$$2 > 1$$

$$3 \gtrsim 2$$

$$4 \sim 3$$

[...]

Conclusions & Outlook

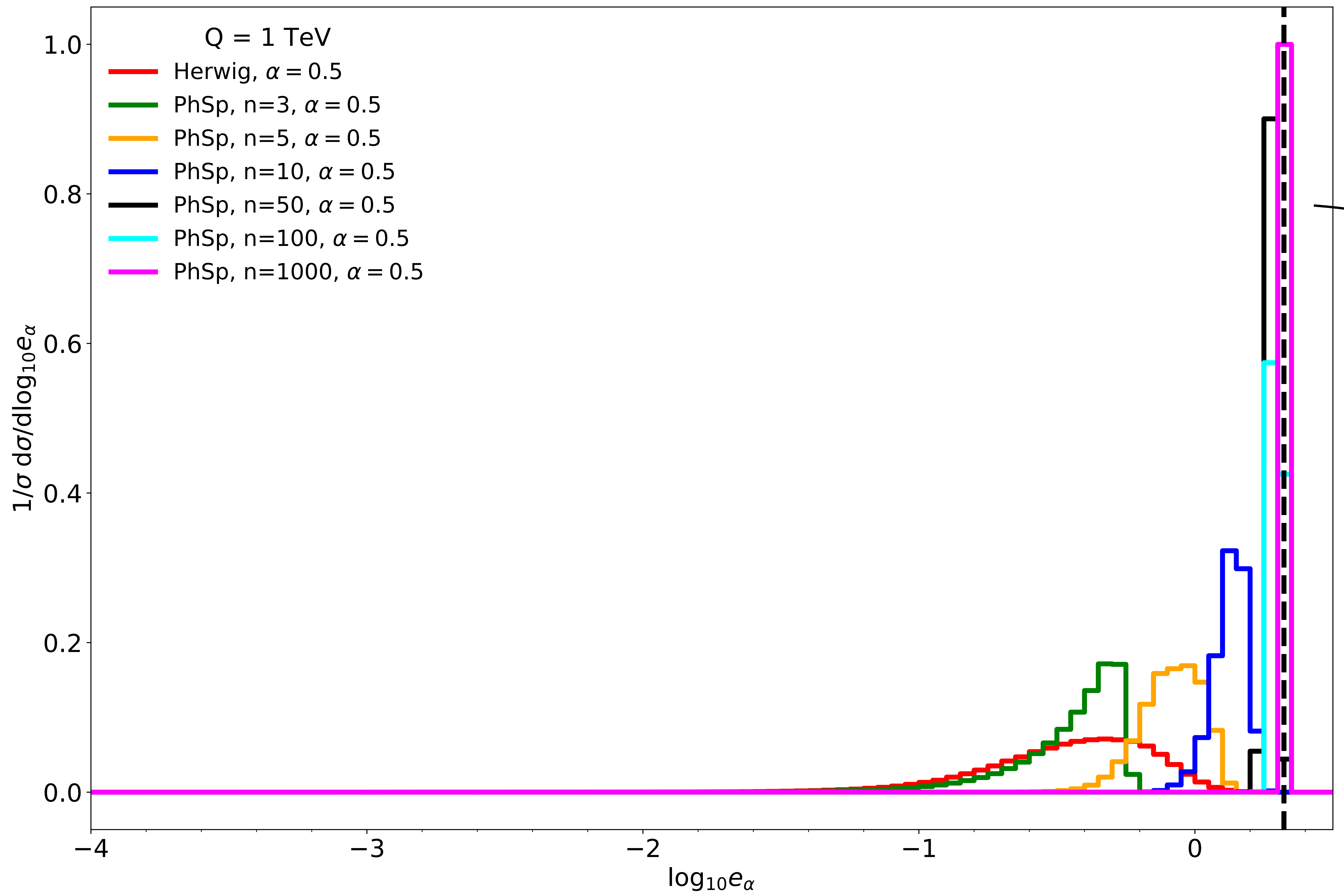
- Conclusions **robust** under:
  - Number of phase space particles,
  - MC dependence [HERWIG 7, Pythia 8],
  - COM Energy Q,
  - Binning,
  - Set of angularities.
- Multi-differential resummation: **any number of angularities at NLL**, via **SCET**.

[with Gillian Lustermans & Wouter Waalewijn]

Thanks!

APPENDIX

Flat phase space



n: number of particles in flat phase space

dashed line: prediction from 2 hemisphere "jets" of uniform energy density.

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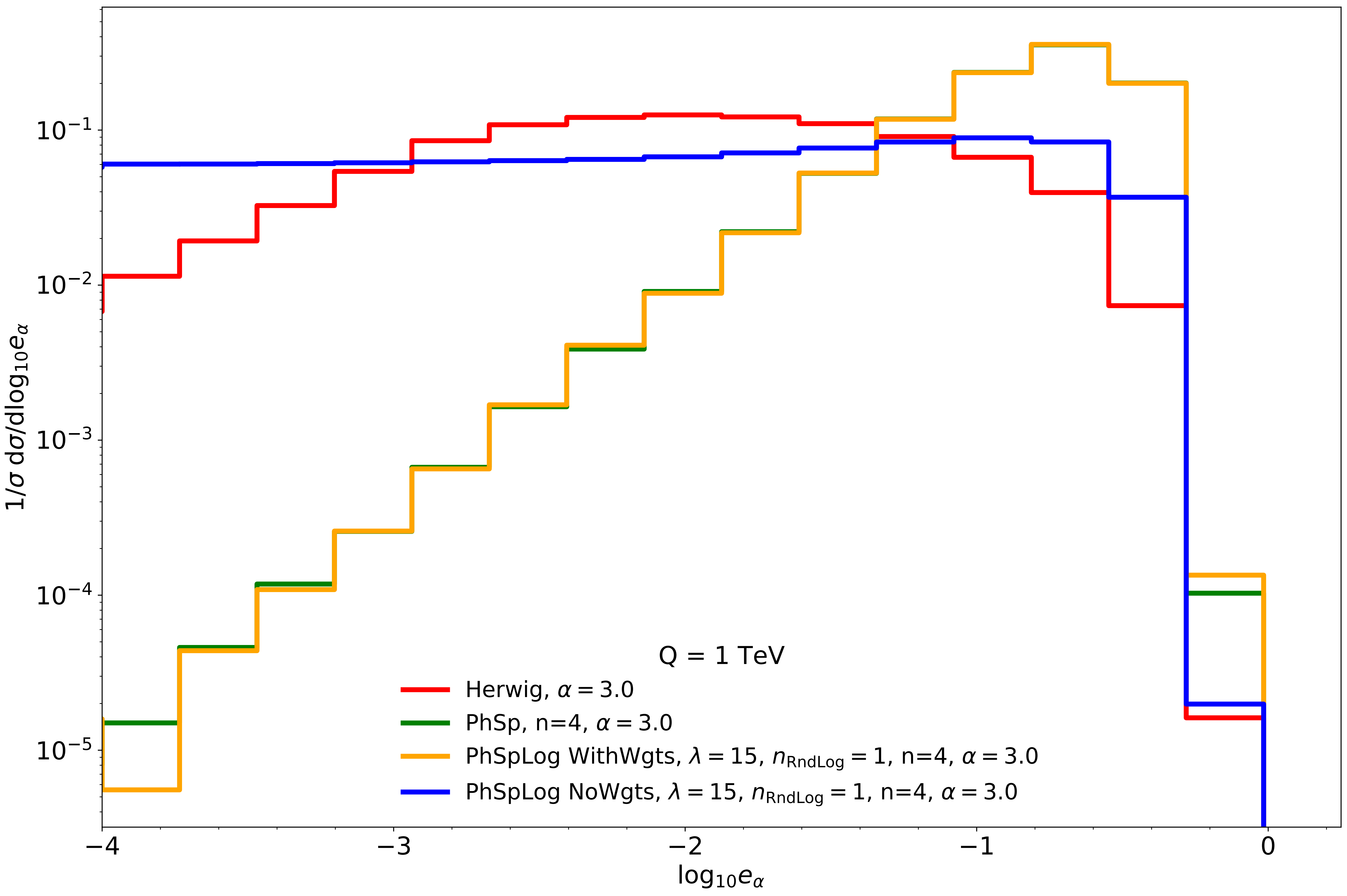
PhSp with "importance sampling"



n: number of particles in flat phase space

λ: parameter that determines range of distribution of random numbers in RAMBO-on-diet method.

n_{RndLog}: number of random numbers distributed logarithmically.

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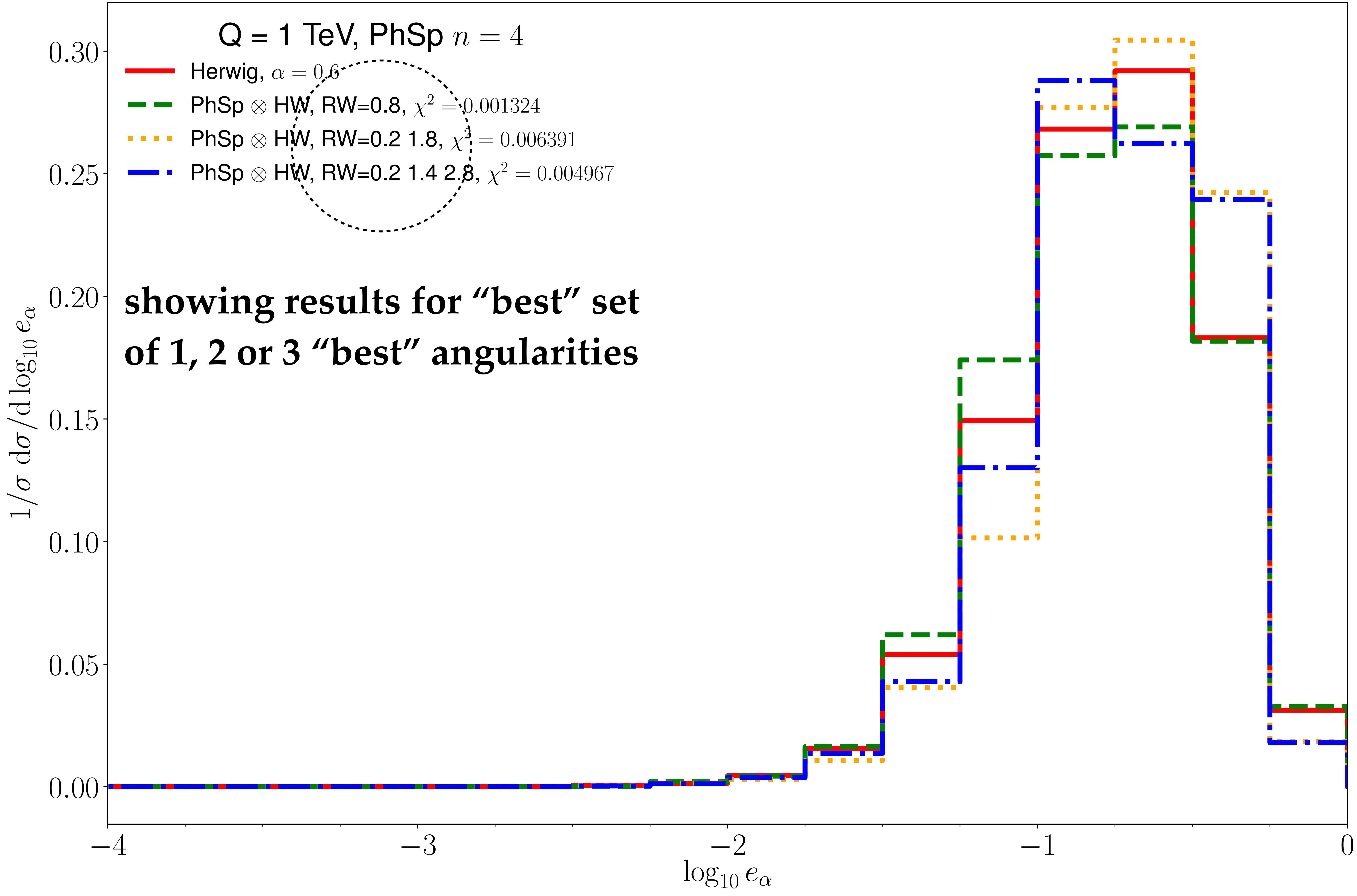
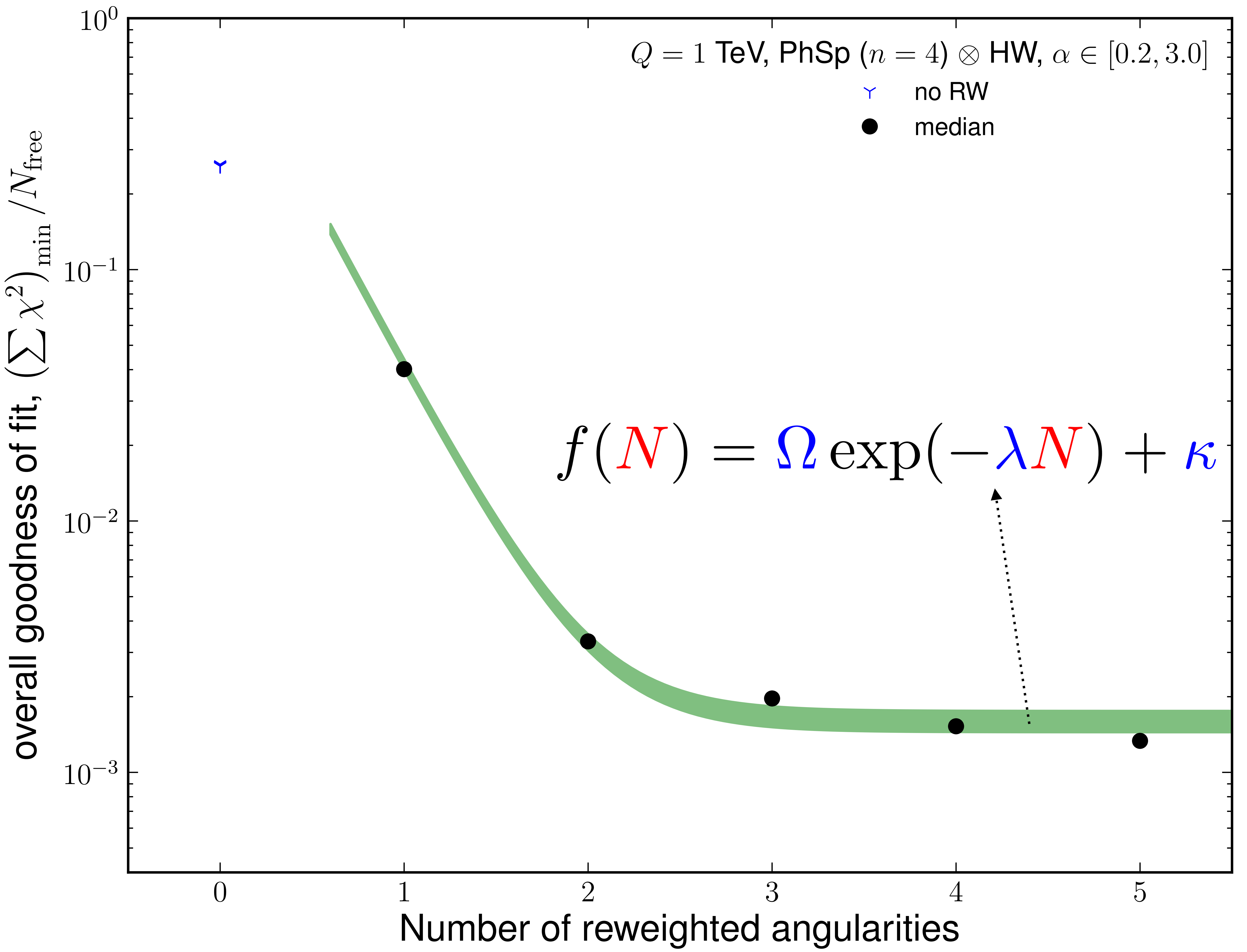


showing results for “best” set of 1, 2 or 3 “best” angularities

What is the overall improvement?



green band: exp. fit of "upper" and "lower" 68% interval over 11 MC replicas

black dots: median

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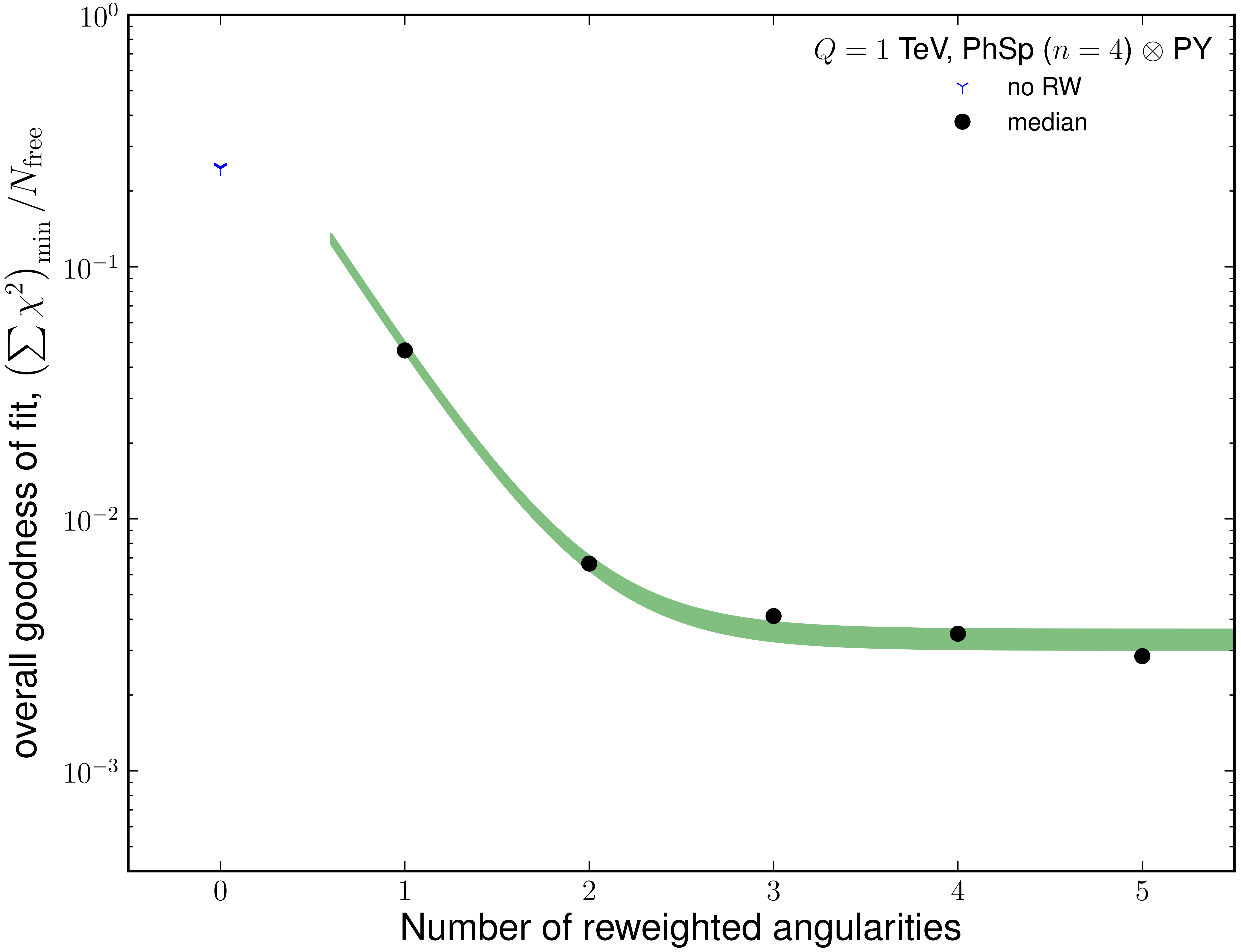
MC dependence



same as previous but with Pythia 8

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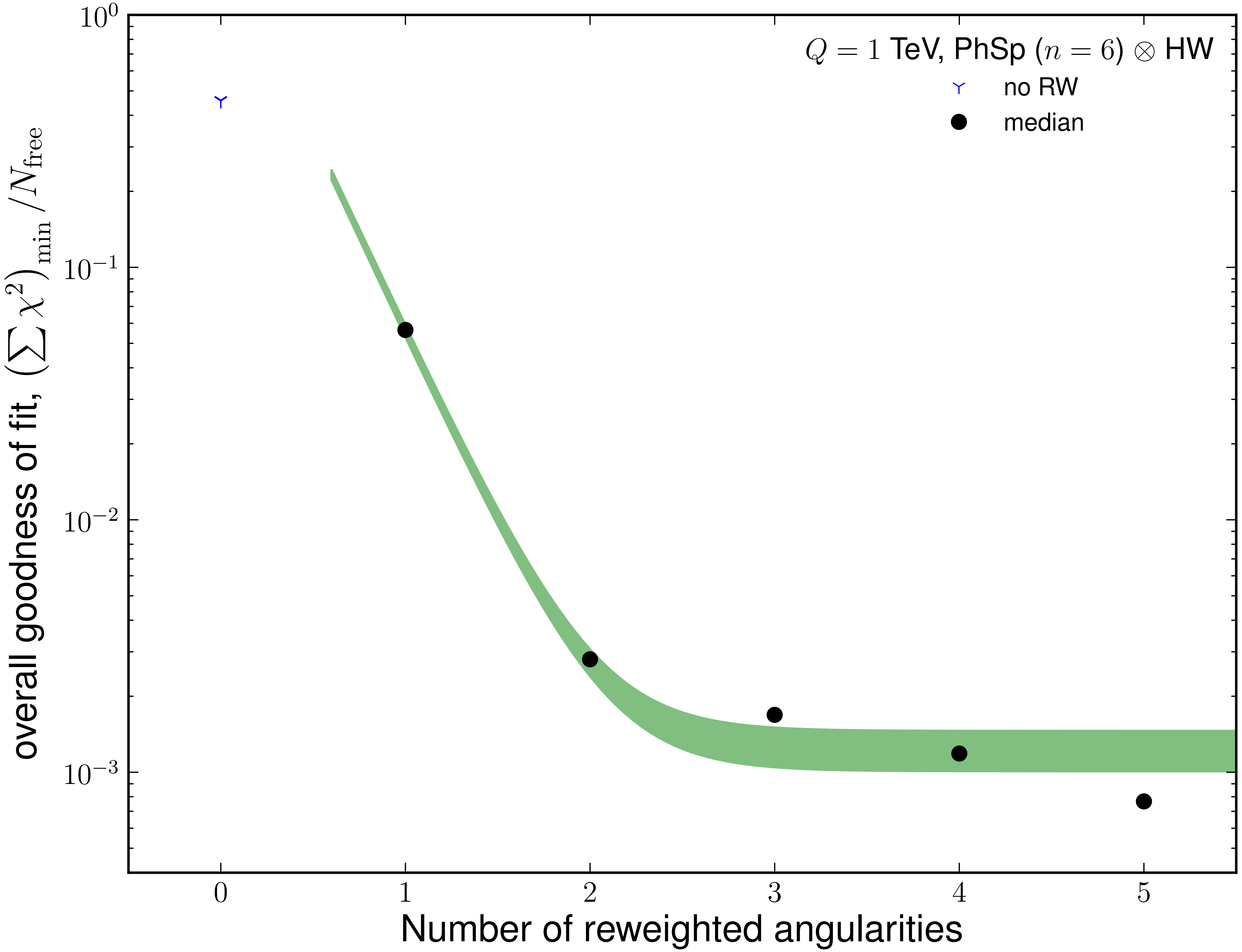
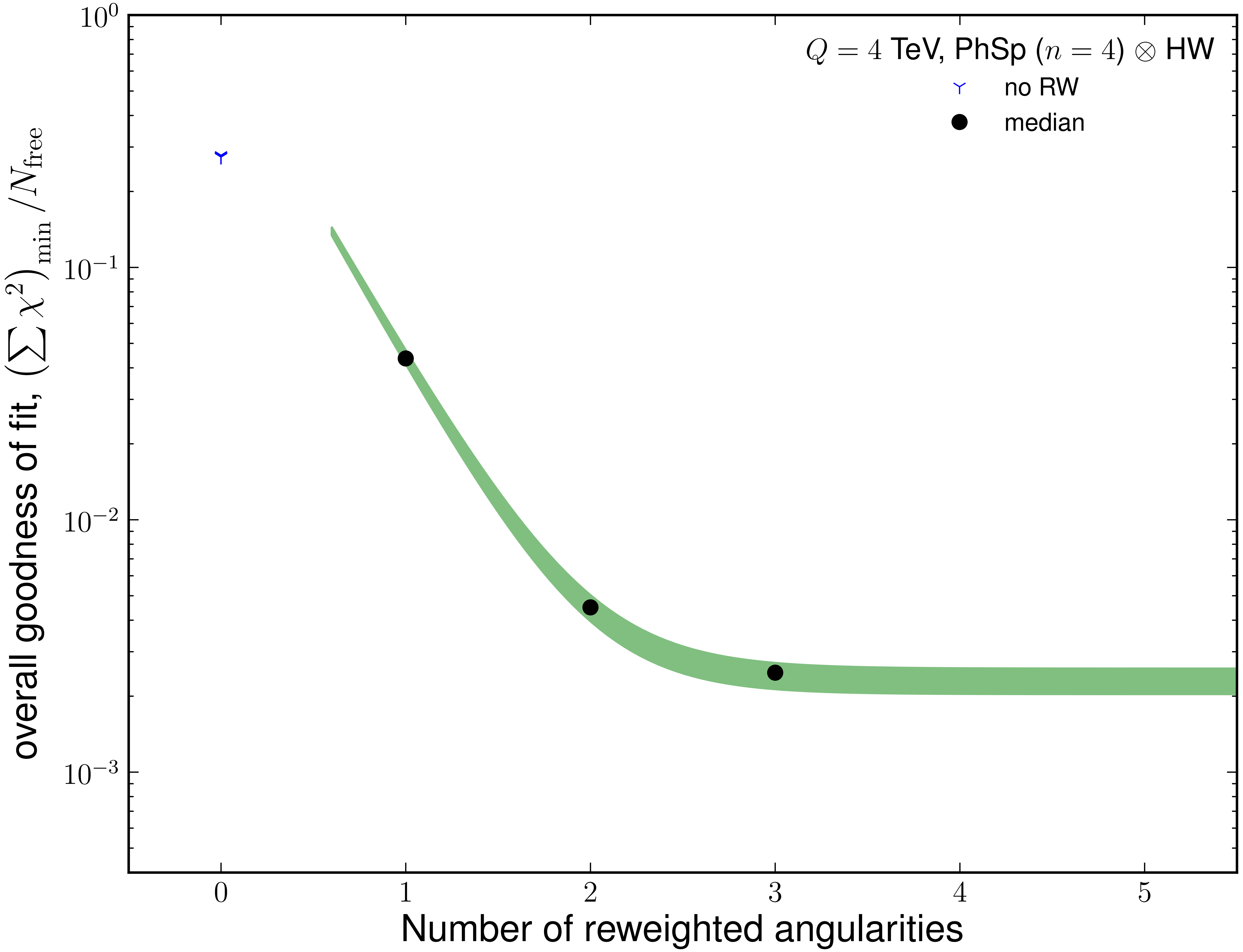
phase space dependence



phase space with *n*=6 particles

COM energy dependence



$$Q = 4 \text{ TeV}$$

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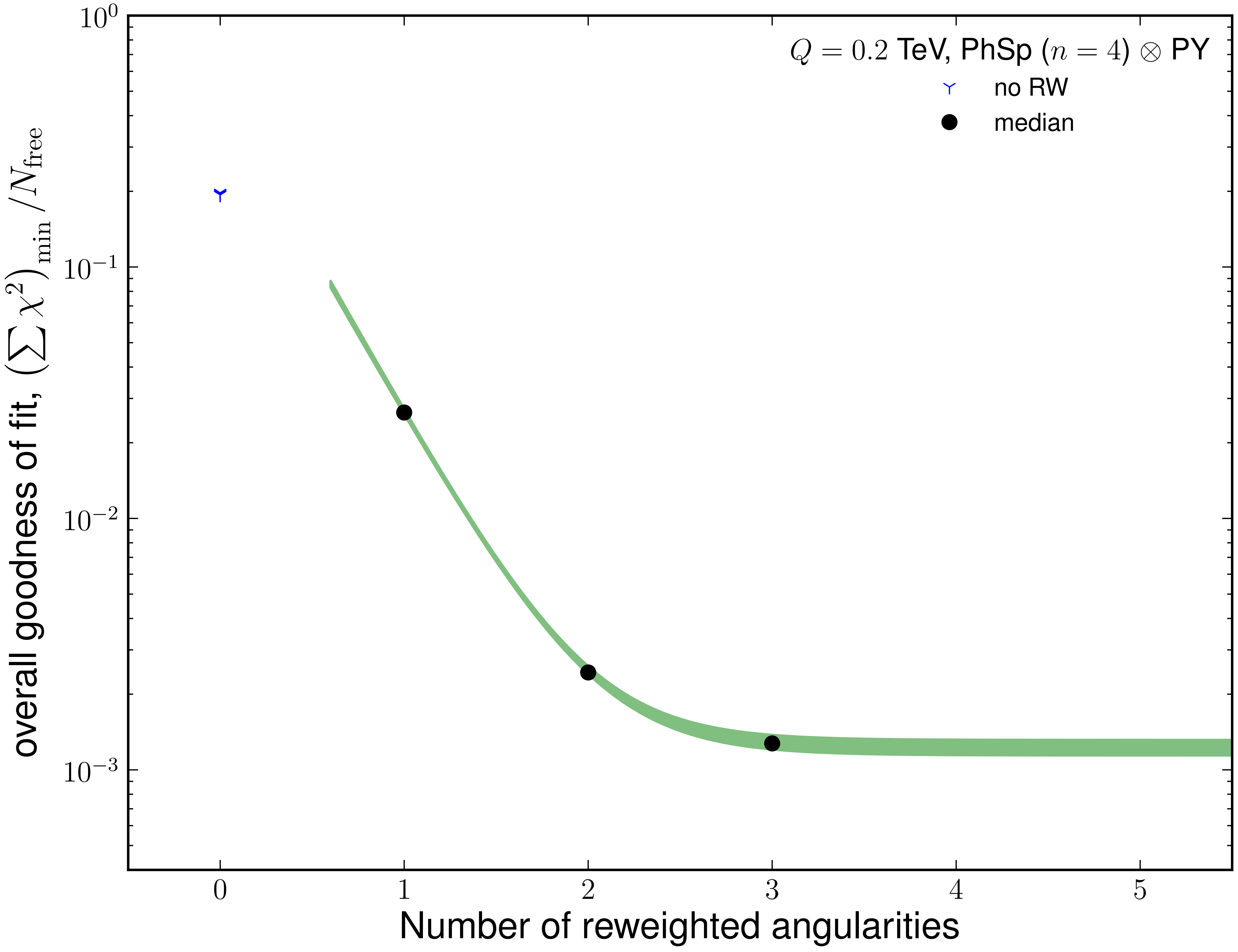
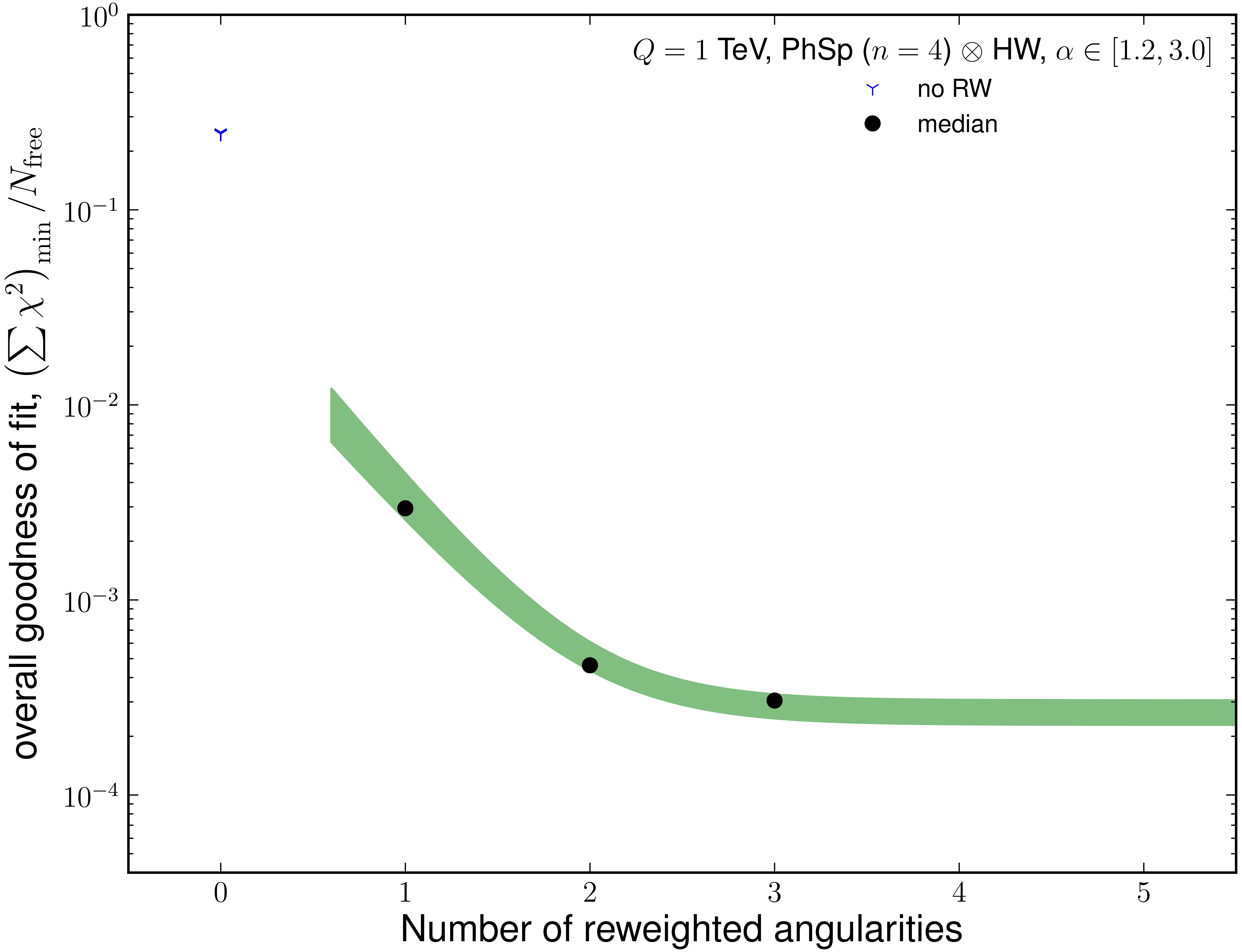
COM energy dependence



$$Q = 0.2\ \mathrm{TeV}$$

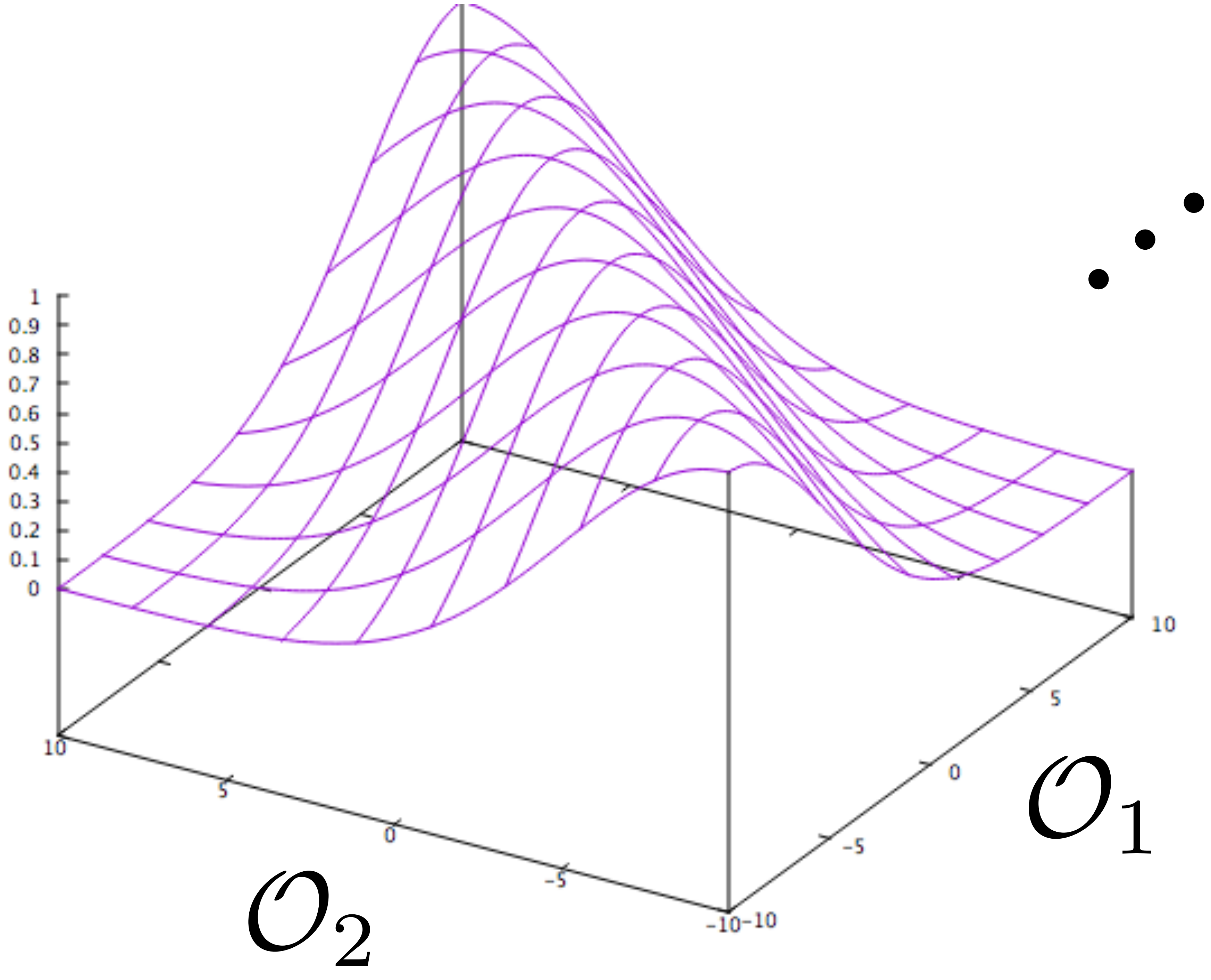
set of angularities dependence



$$\alpha \in [1.2, 3.0]$$

Reweighing

$$\left.\frac{d\sigma}{d\mathcal{O}_1 d\mathcal{O}_2}\right|_{\text{PhSp}}$$



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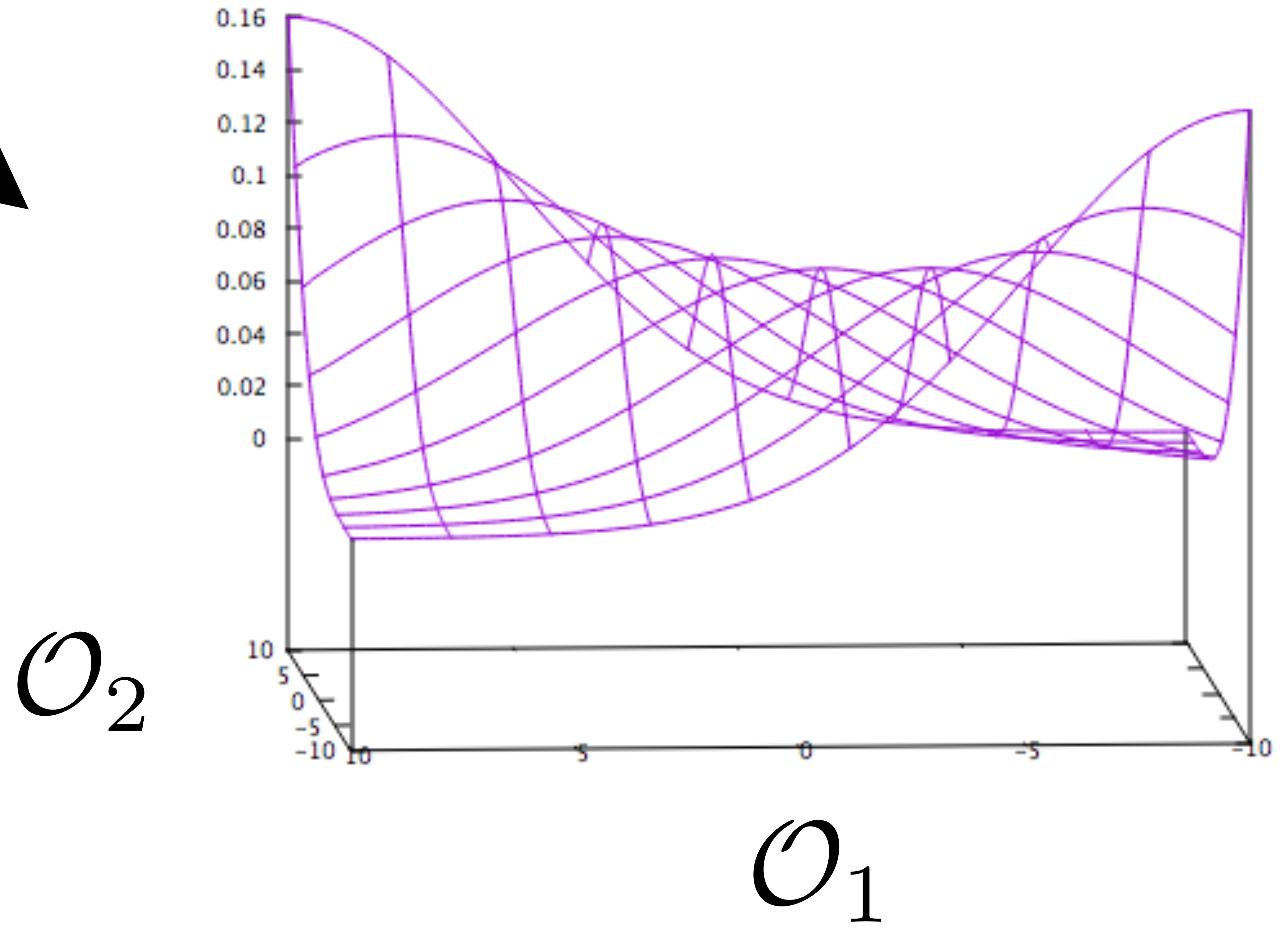
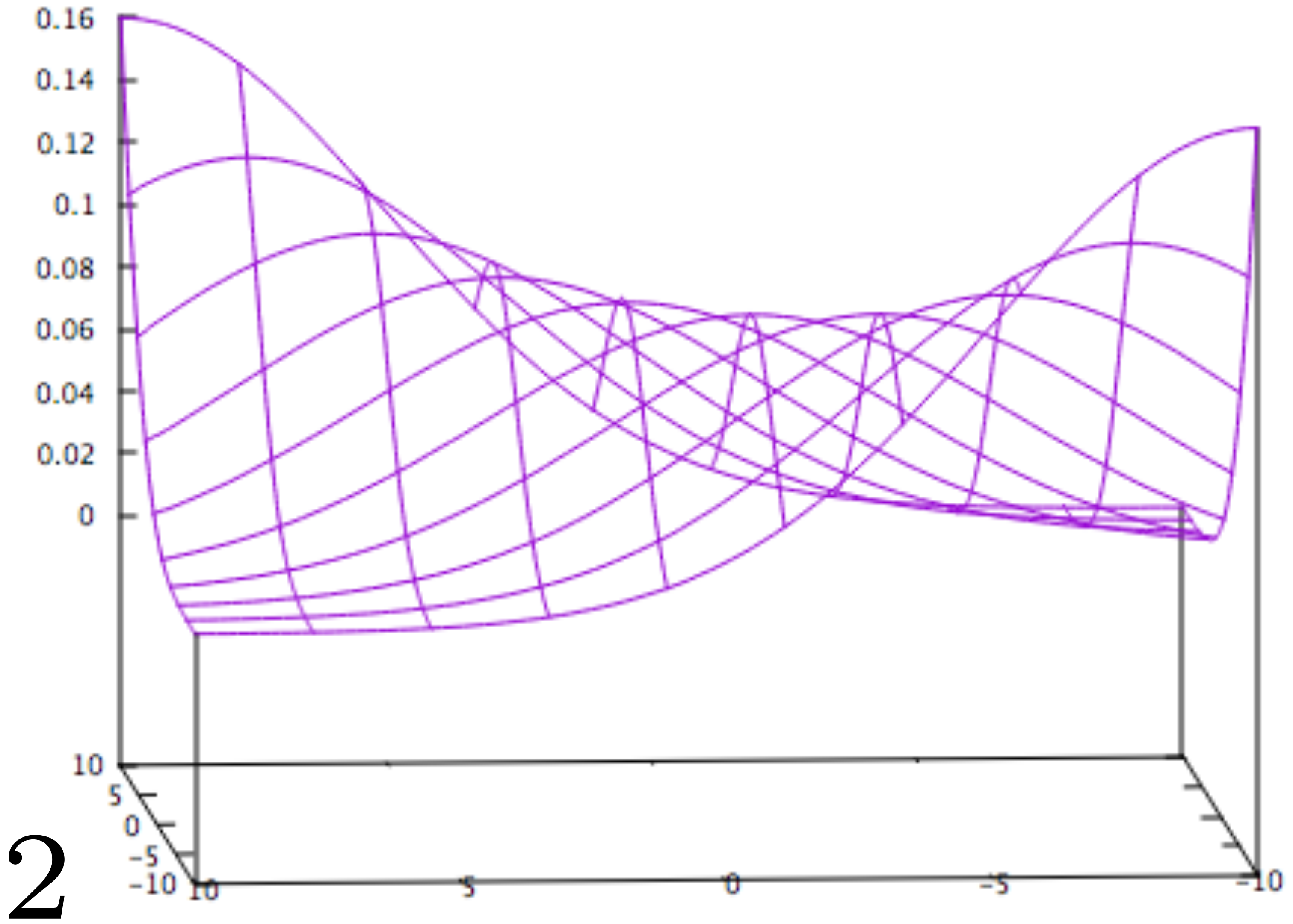


Reweighing

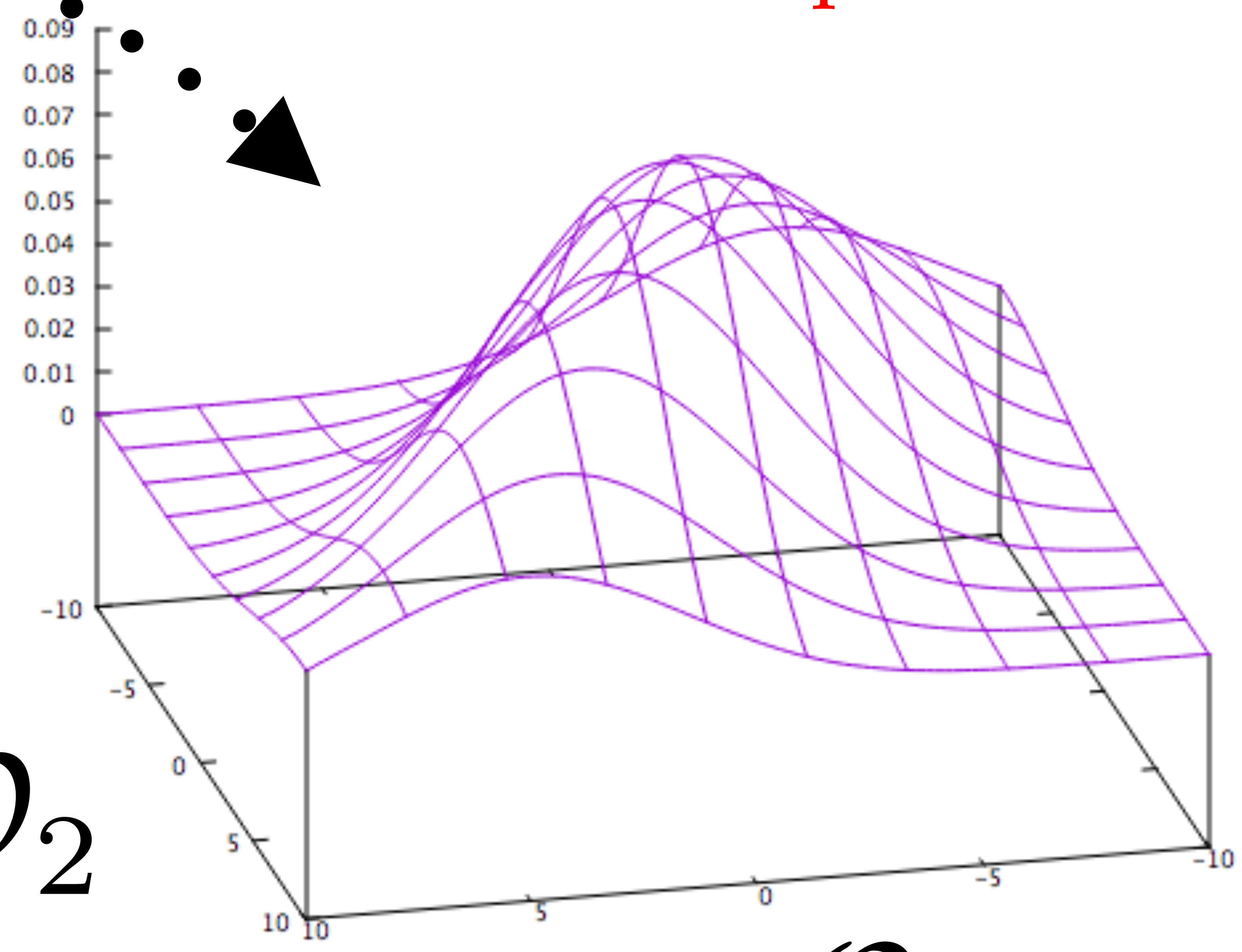
$$\frac{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1\,\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{PhSp}}}{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1}\right|_{\mathrm{PhSp}}}$$



$\mathcal{O}_2$ $\mathcal{O}_1$

Reweigh by MC $\mathcal{O}_1$ distribution

$$\frac{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1\,\mathrm{d}\mathcal{O}_2}\right|_{\mathrm{PhSp}}}{\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1}\right|_{\mathrm{PhSp}}} \times \left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_1}\right|_{\mathrm{MC}}$$



$\mathcal{O}_2$ $\mathcal{O}_1$

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