Searching for New Physics in WW and singleW Events

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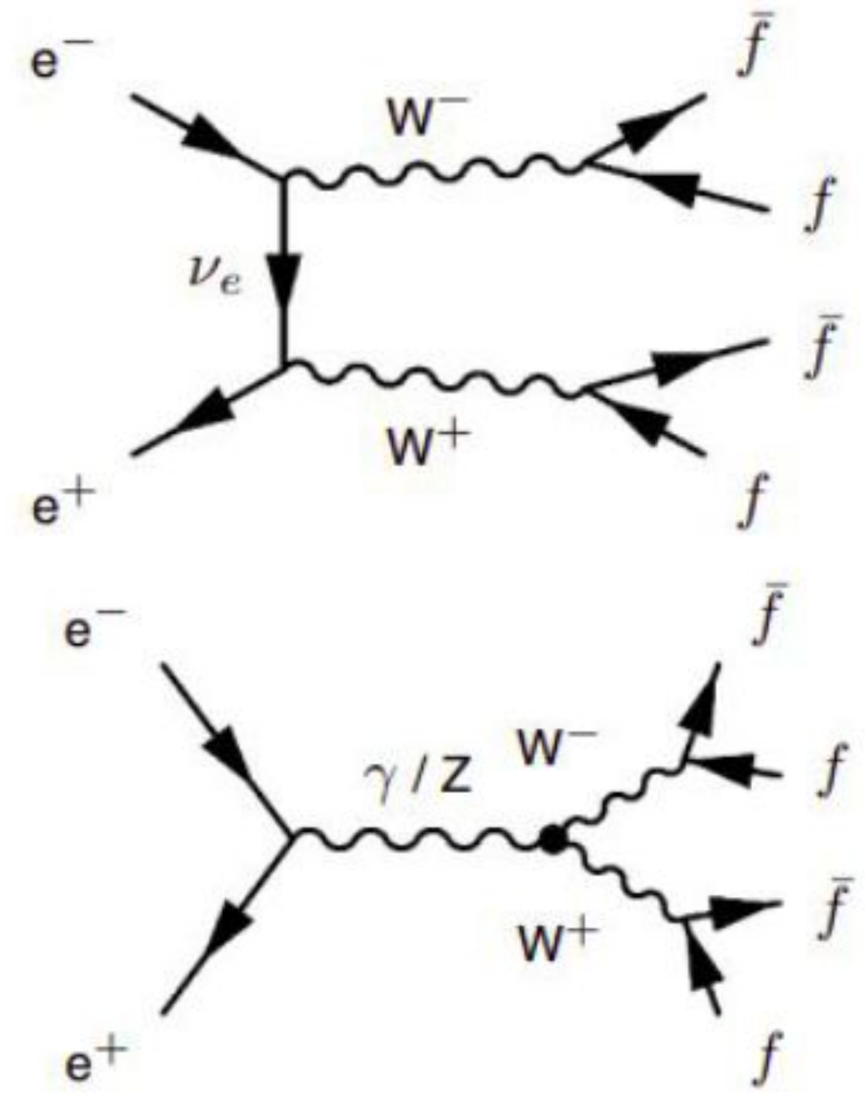
[4] CERN

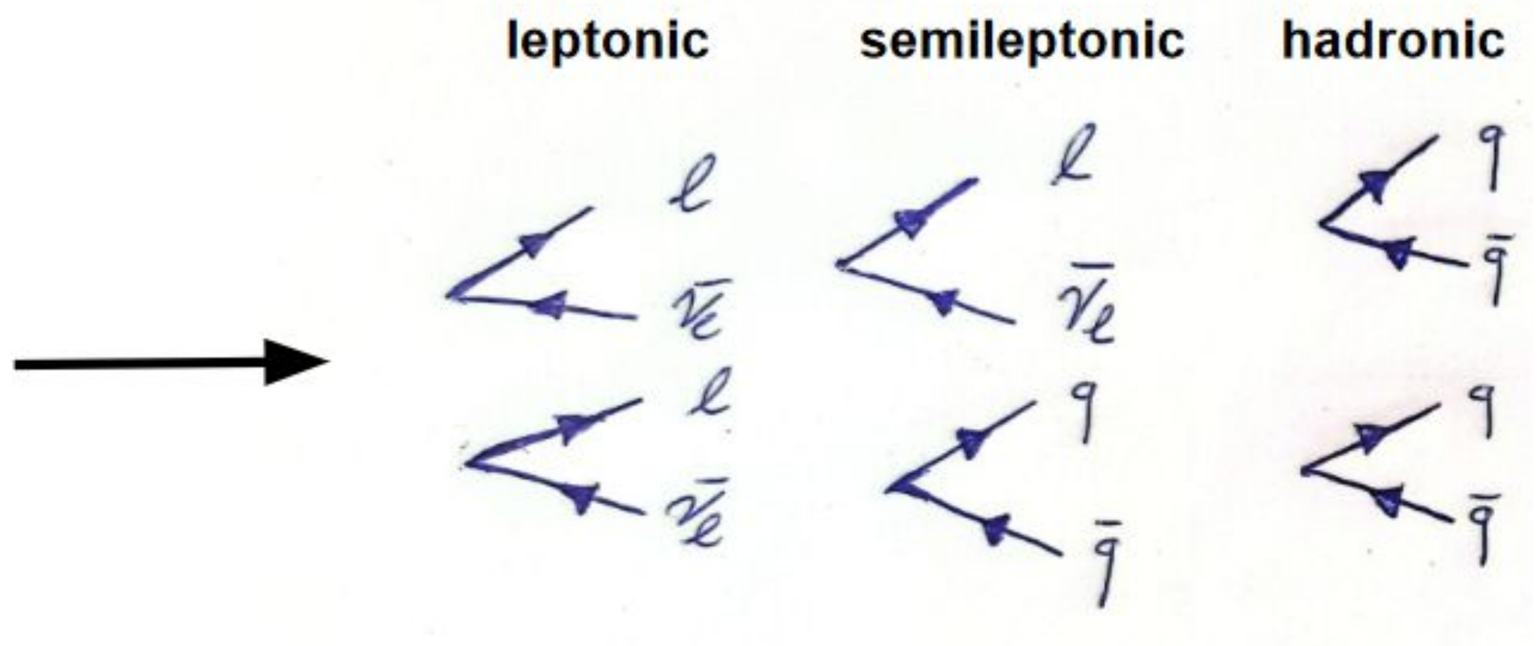
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Introduction

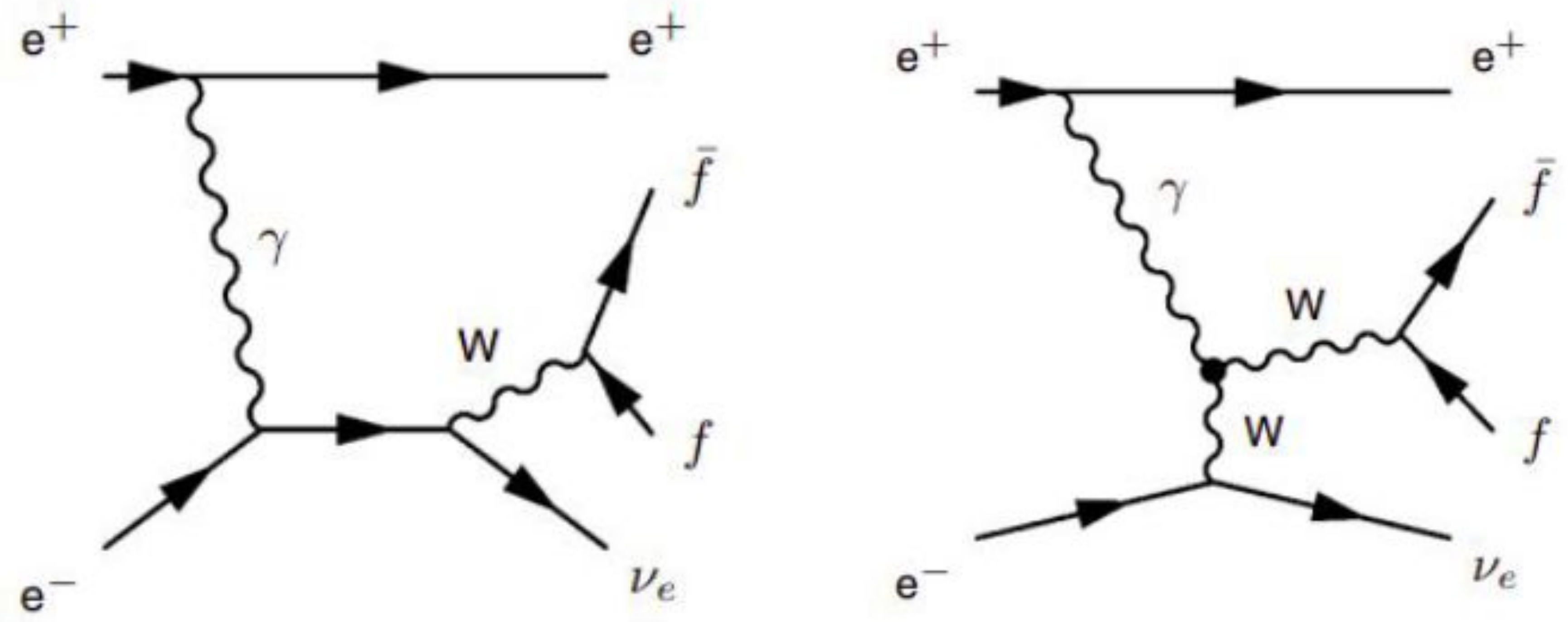
Overview on WW /singleW in e+e-

- single and pairwise production
- total number of W bosons produced in ILC250 + ILC500 running ≈ 1.2E8
- FCCee very similar (1E8)
- This talk:
    - Triple Gauge Couplings
    - Flavour Physics with W's: CKM matrix elements
    - ongoing work, contributing to ECFA focus topics





WW production



single-W production

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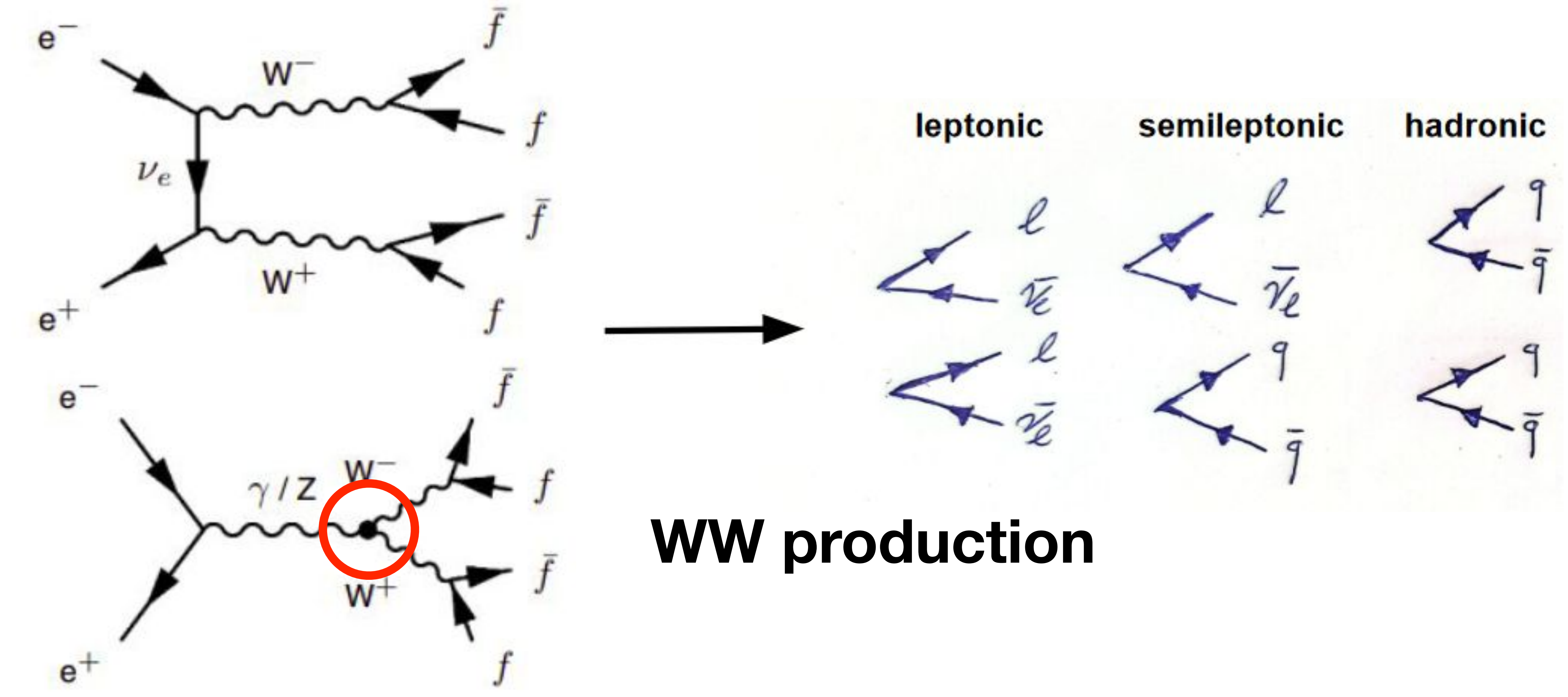

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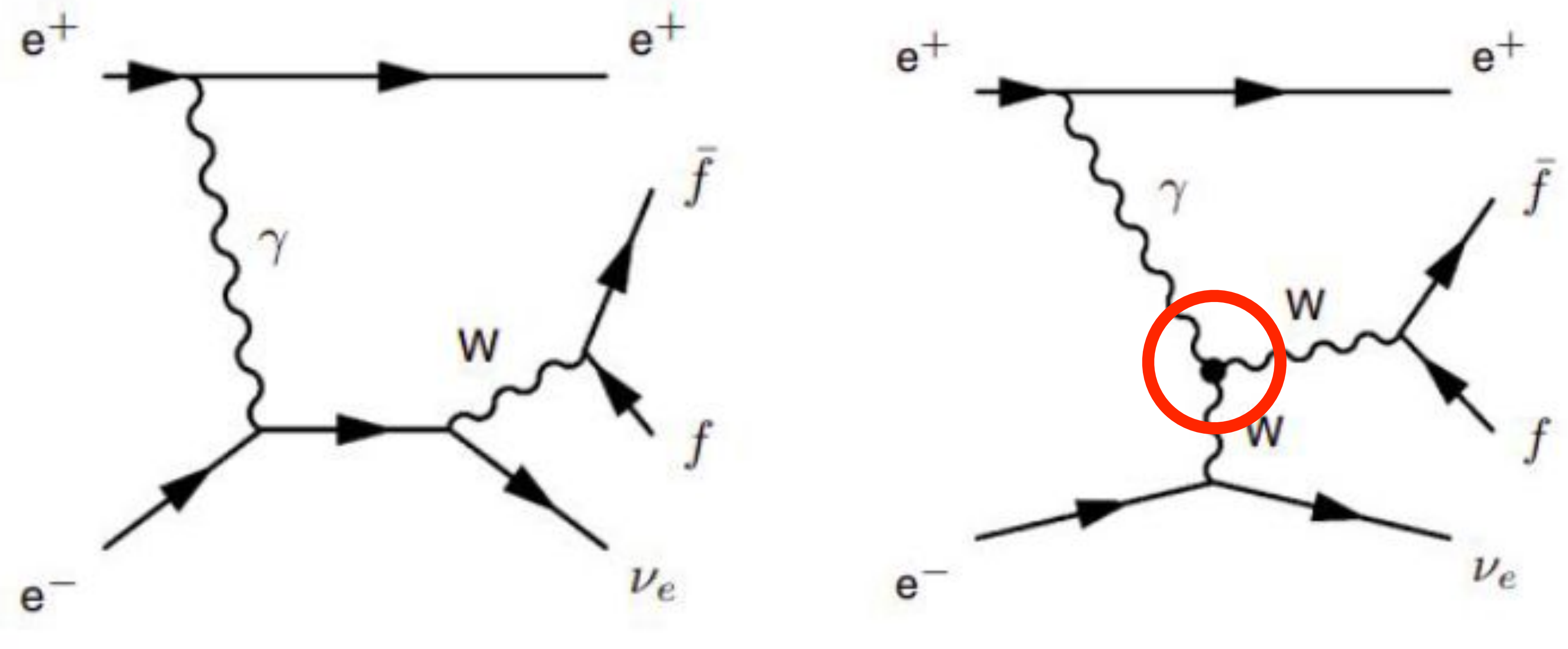

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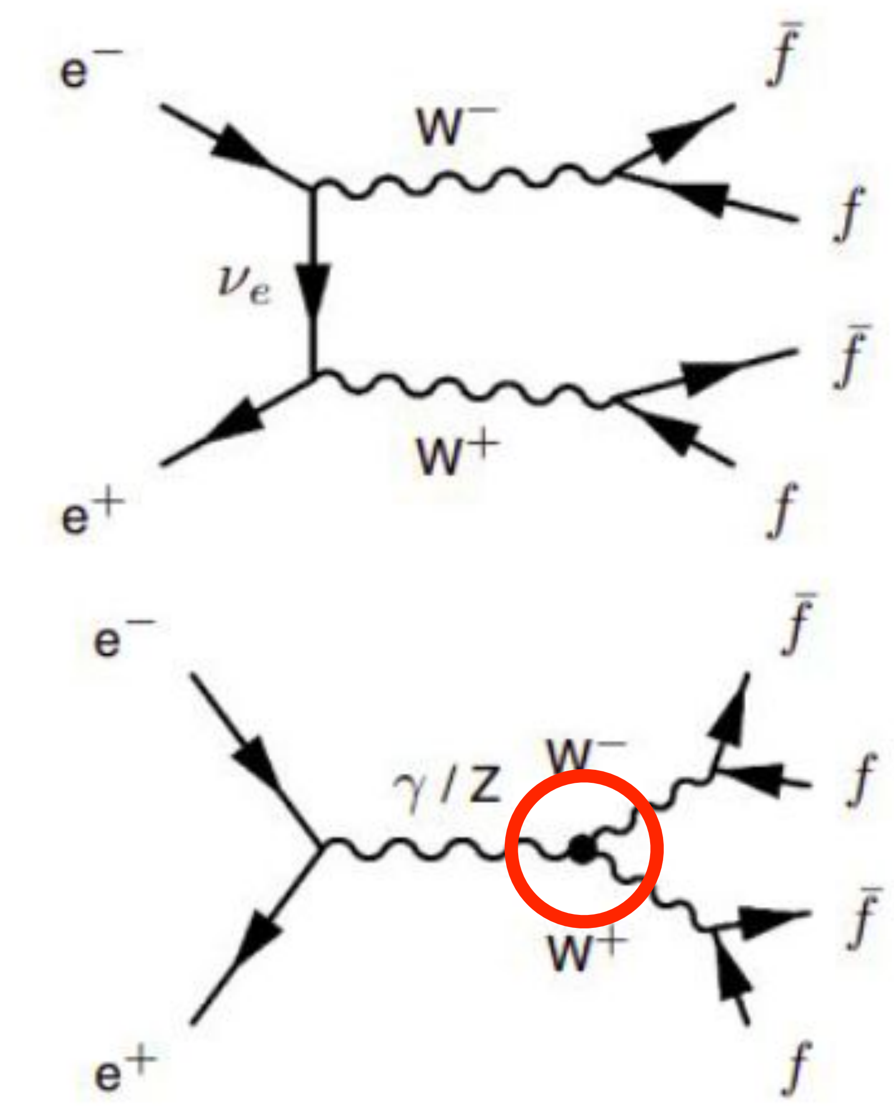

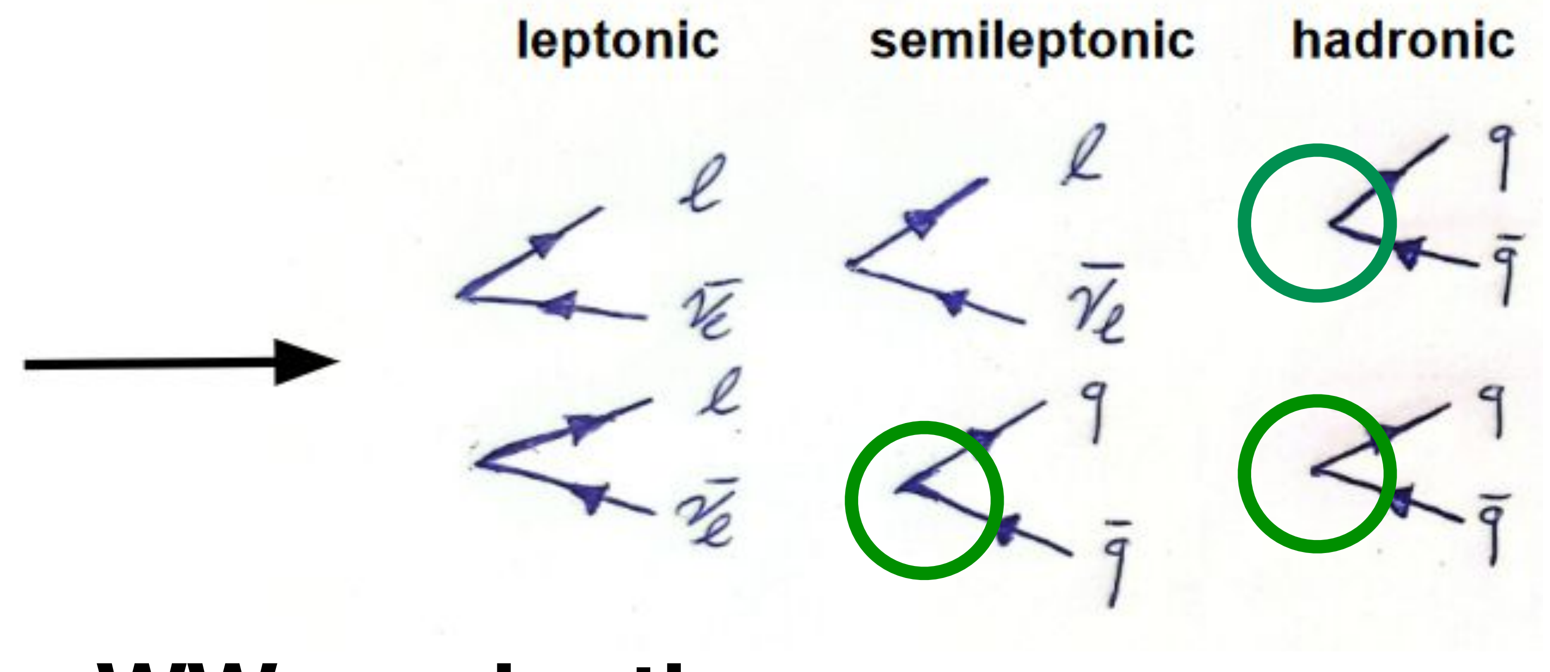

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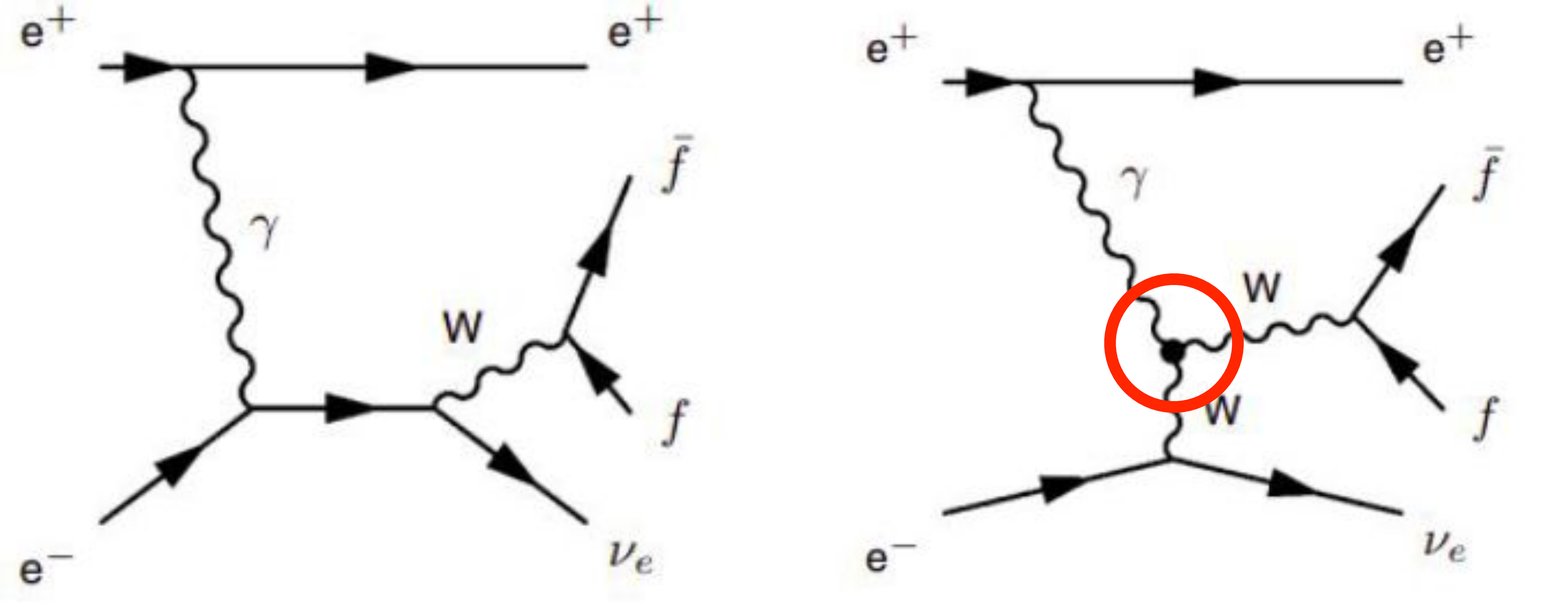


single-W production

Triple Gauge Couplings

Triple Gauge Couplings

Definitions and LEP / LHC status

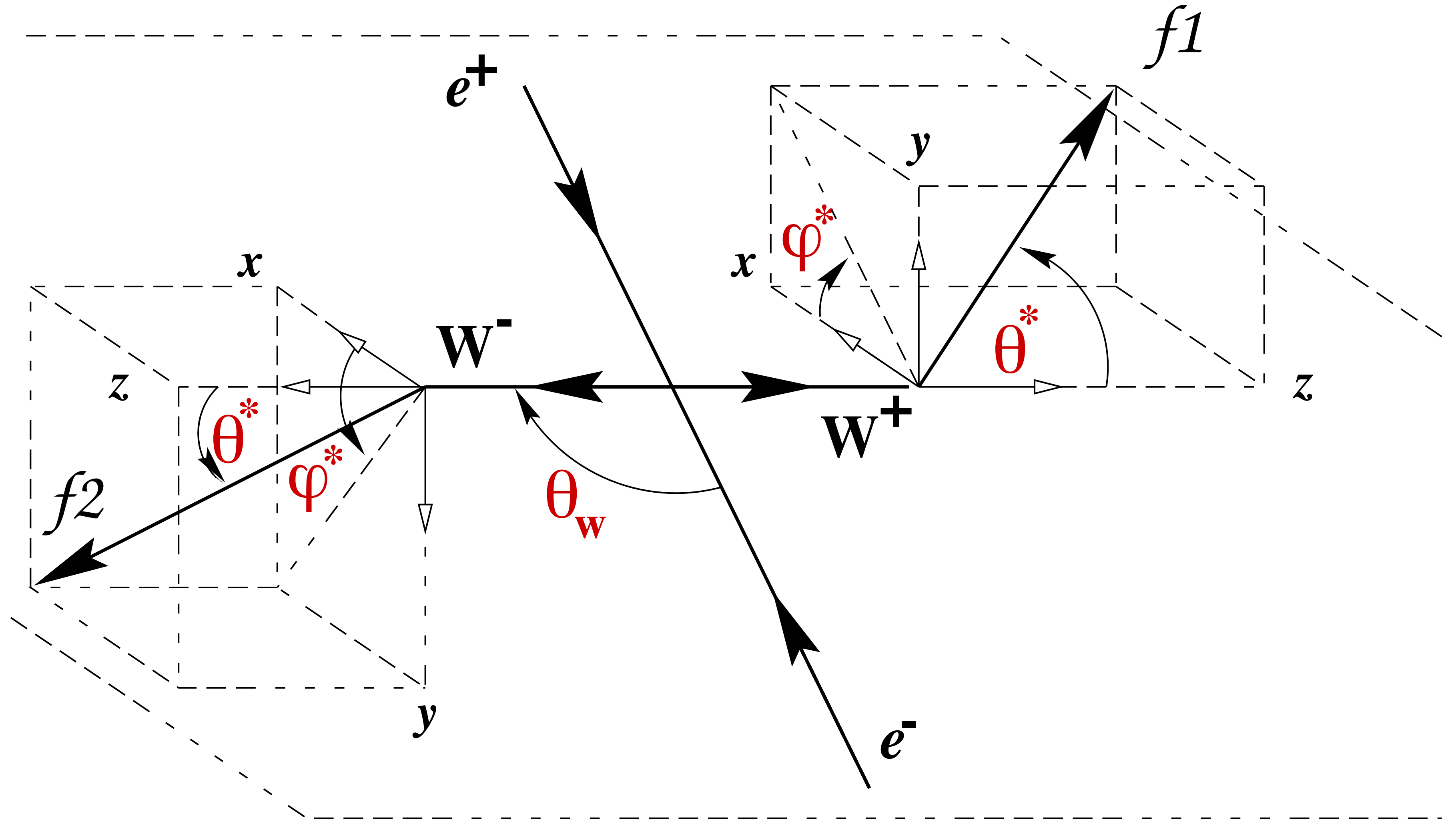
most general WWV (V=Z/γ) Lagrangian: 14 complex couplings (=28 real parameters):

$$\frac{i}{g_{WWV}}\mathcal{L}_{\rm eff}^{WWV} = g_1^V V^\mu\left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}$$
$$+ \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W^-_{\rho\mu} + i g_5^V \varepsilon_{\mu\nu\rho\sigma}\left[\left(\partial^\rho W^{-\mu}\right)W^{+\nu} - W^{-\mu}\left(\partial^\rho W^{+\nu}\right)\right]V^\sigma$$
$$+ i g_4^V W^-_\mu W^+_\nu\left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) - \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma}$$
$$- \frac{\tilde{\lambda}_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}{}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}$$

SM:
g1Z = g1γ = κZ = κγ = 1
all others = 0

often (incl. SMEFT) restricted to
"LEP parametrisation" due to lack of data:
C, P invariance, EM gauge & SU(2)xU(1) invariance
=> g1Z, κγ, λγ

ee->WW: relevant 5 angles



analysis technique plays an important role - watch out whether

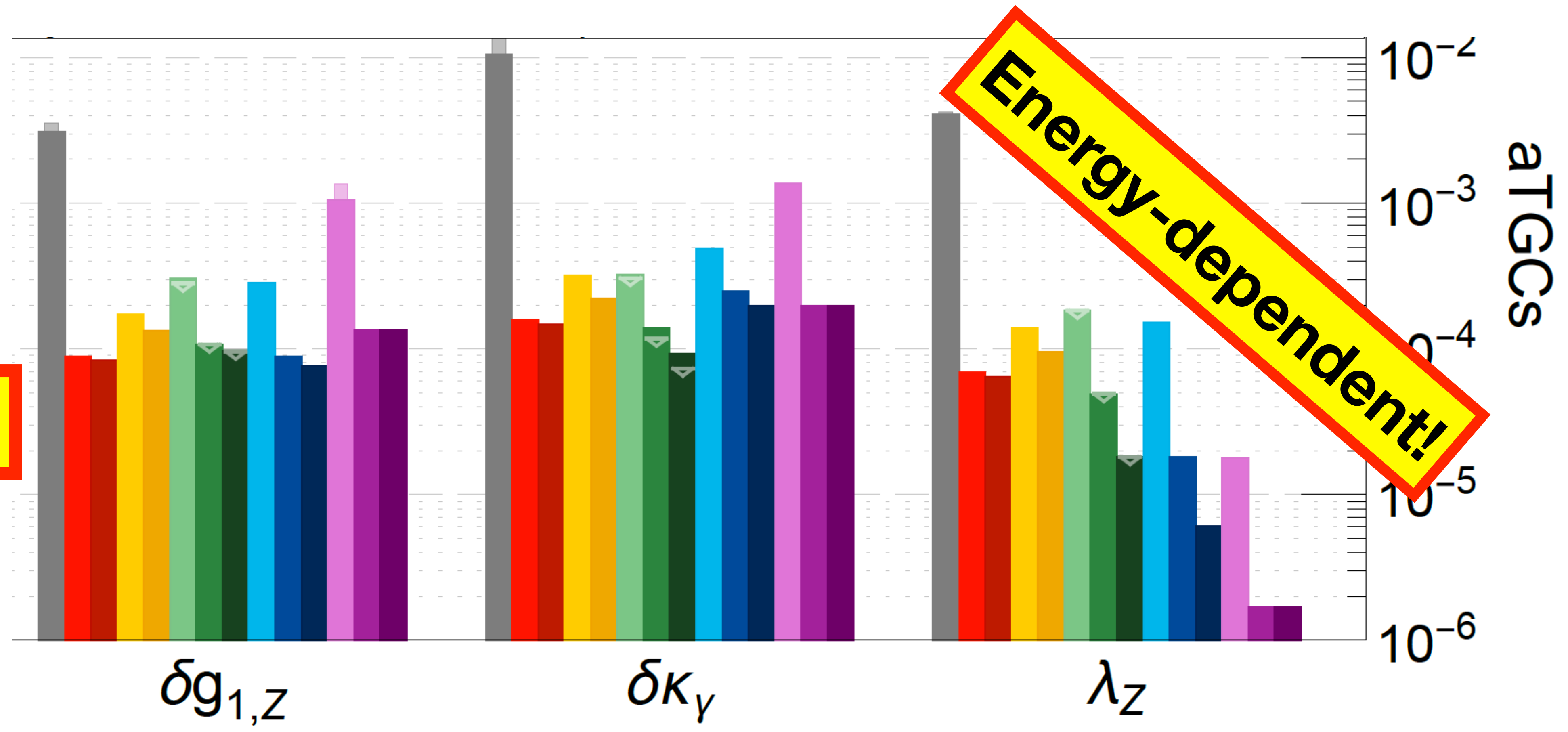
- binned or unbinned analysis
- 5 or 3 angles used
- single- or multi-parameter fits
- treatment of systematics
- …

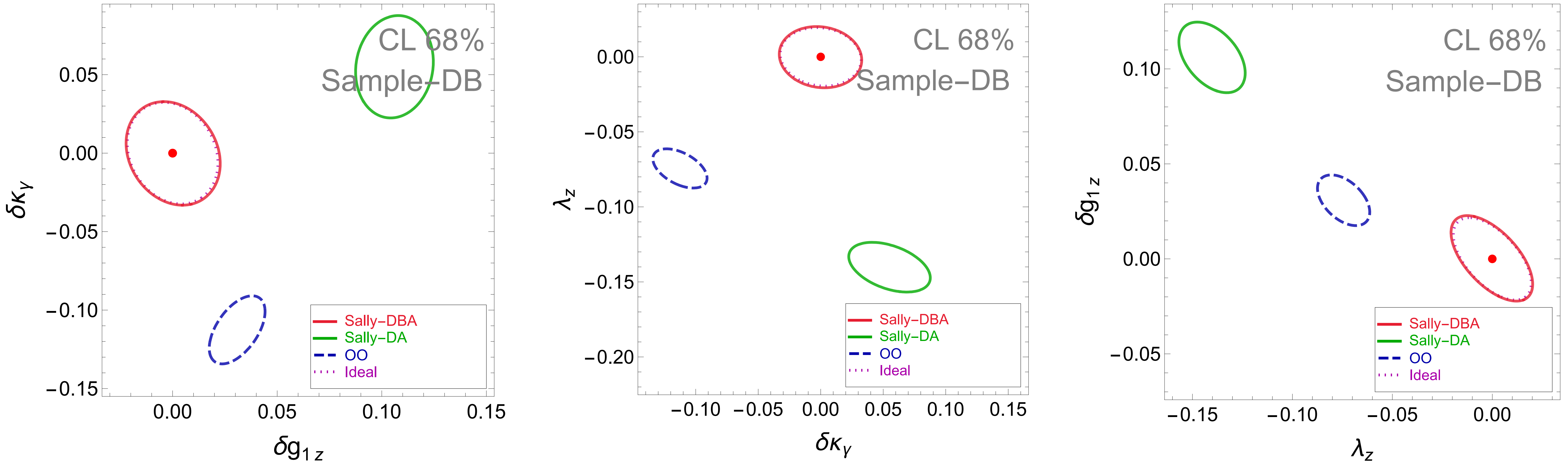
Theory-Level Studies

using optimal observables

- Markus Diehl et al 2003 (!) **Eur.Phys.J.C 27 (2003) 375-397 & Eur.Phys.J.C 32 (2003) 17-27**
  - all 28 real parameters (no detector, no background…)
  - **can disentangle all at 500 GeV with polarised beams**
- For Snowmass SMEFT fits (Jorge de Blas et al): **arXiv:2206.08326**
  - three "LEP" couplings (no detector, no systematics)
  - ~100x gain beyond HL-LHC!
- Jiayin Gu et al: OOs with ML **JHEP 05 (2024) 292**
  - **ILD Delphes card**
  - optionally 10% ZZ background

  => application of theory-level OO to real analysis can lead to huge bias — but when MLing OO on reco data with background, this can be corrected (to be studied further)



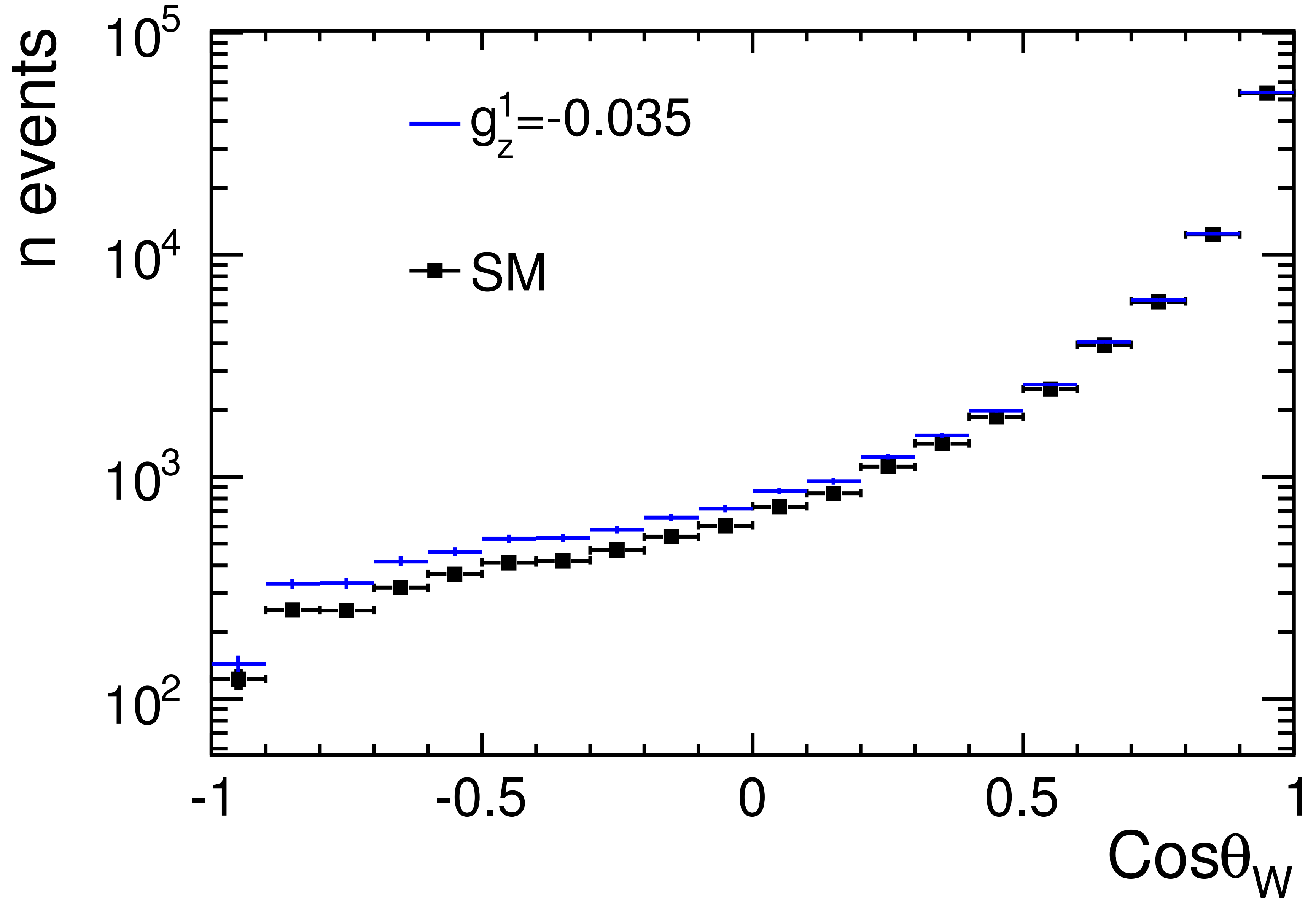


Detector-level Simulations

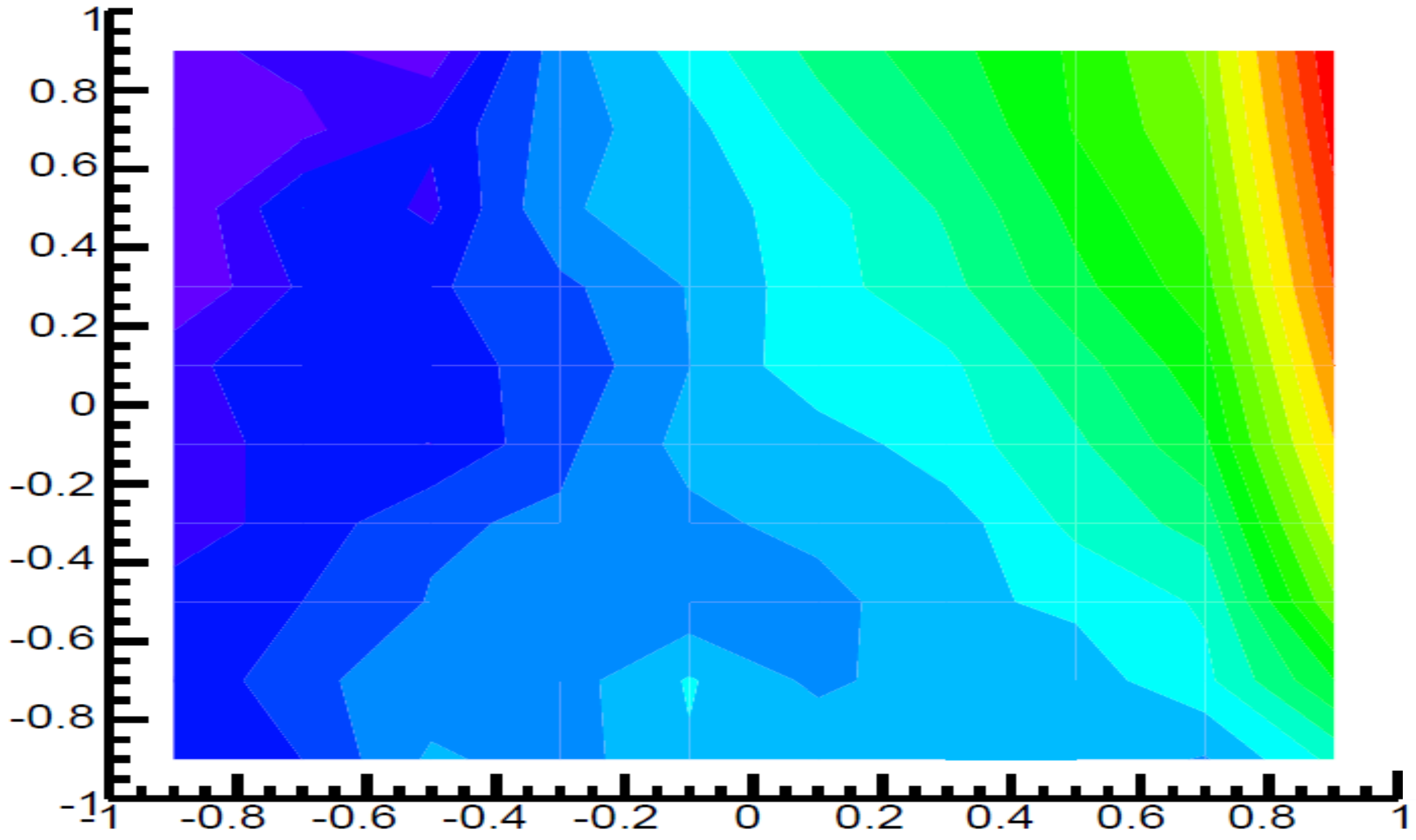
ILD & SiD for ILC TDR (Marchesini, Rosca, Barklow ~2011 ff)

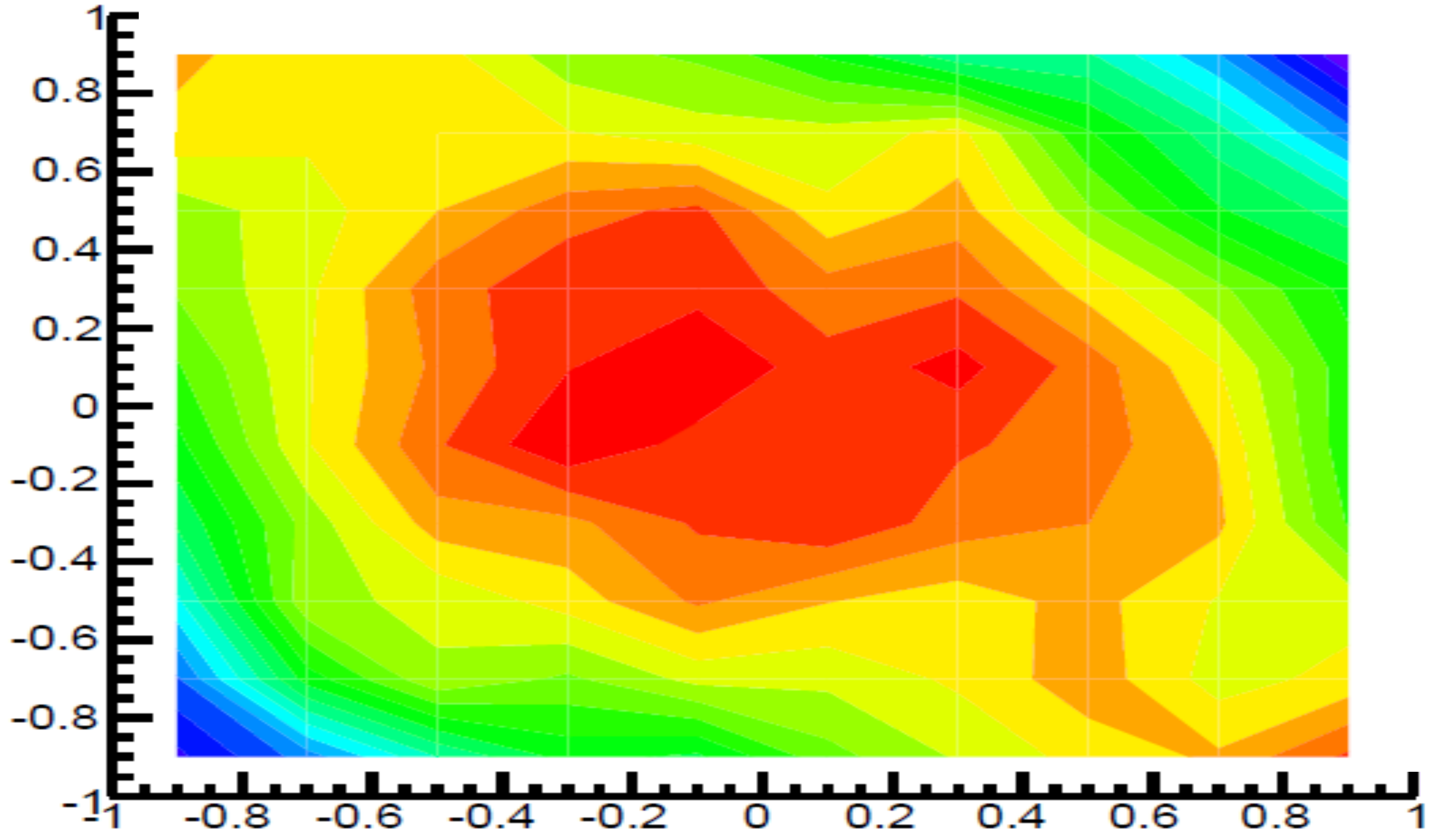
PhD Thesis I. Marchesini

- 500 GeV and 1 TeV
- joint extraction of 3 TGCs (LEP parametrisation) **and beam polarisations** => model impact of all parameters on detector-level
- restricted to WW -> munuqq and WW->enuqq
- 3 TGCs and their covariance matrix passed on to global interpretations, e.g. SMEFT fits



$P(e^+, e^-) = (+1, -1)$ cos θ_{decay} vs $cos\theta_W$ $P(e^+, e^-) = (-1, +1)$





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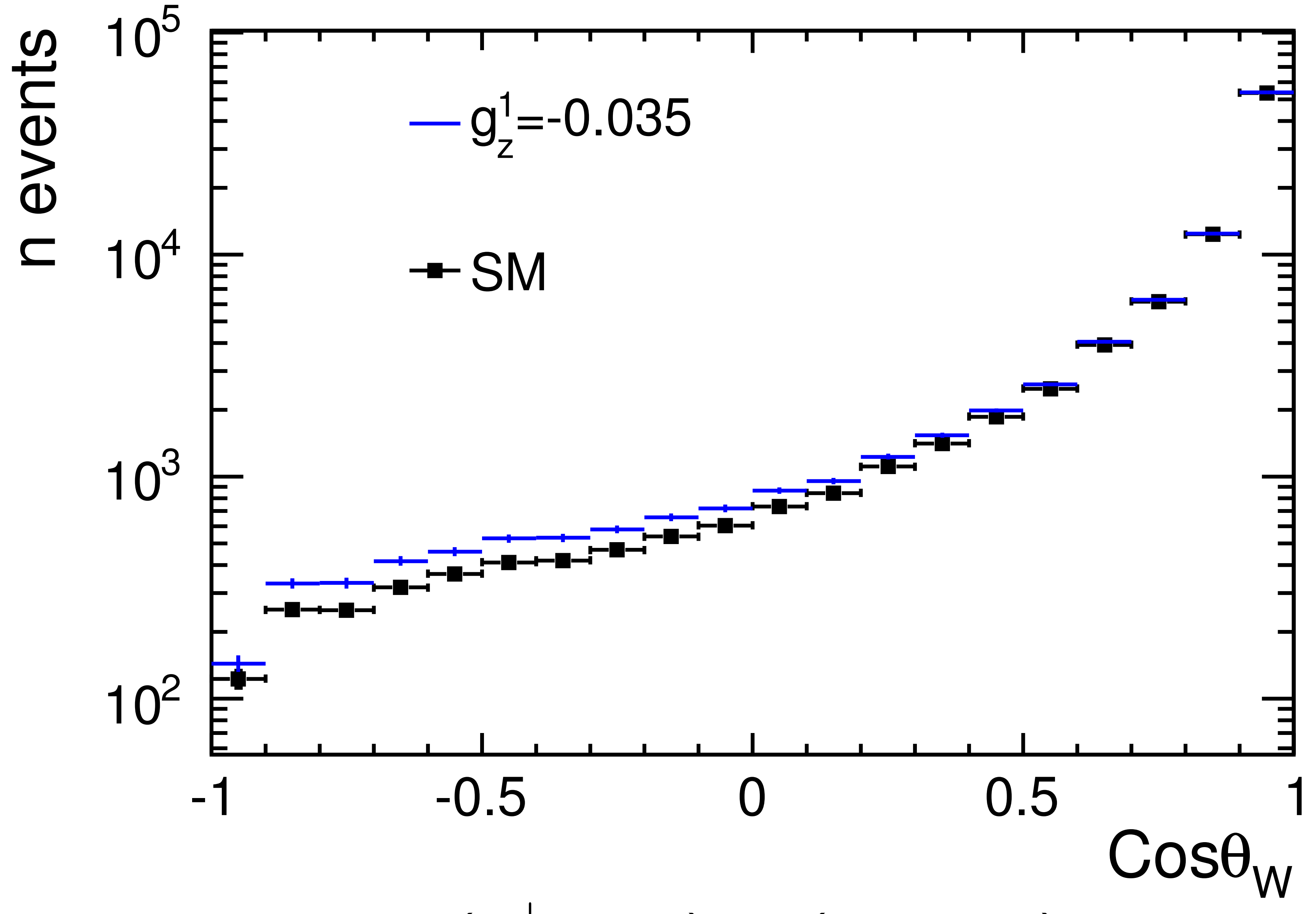
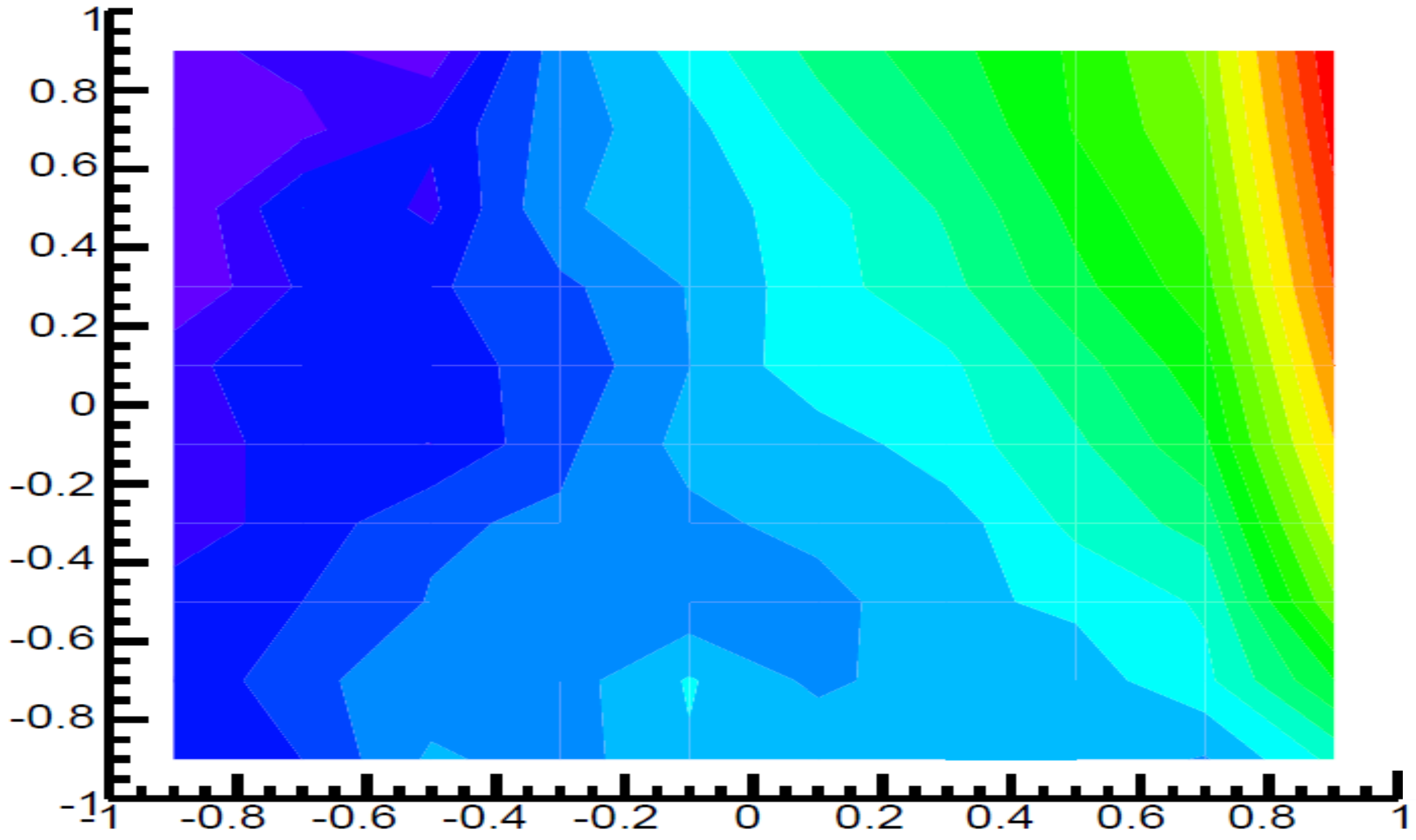
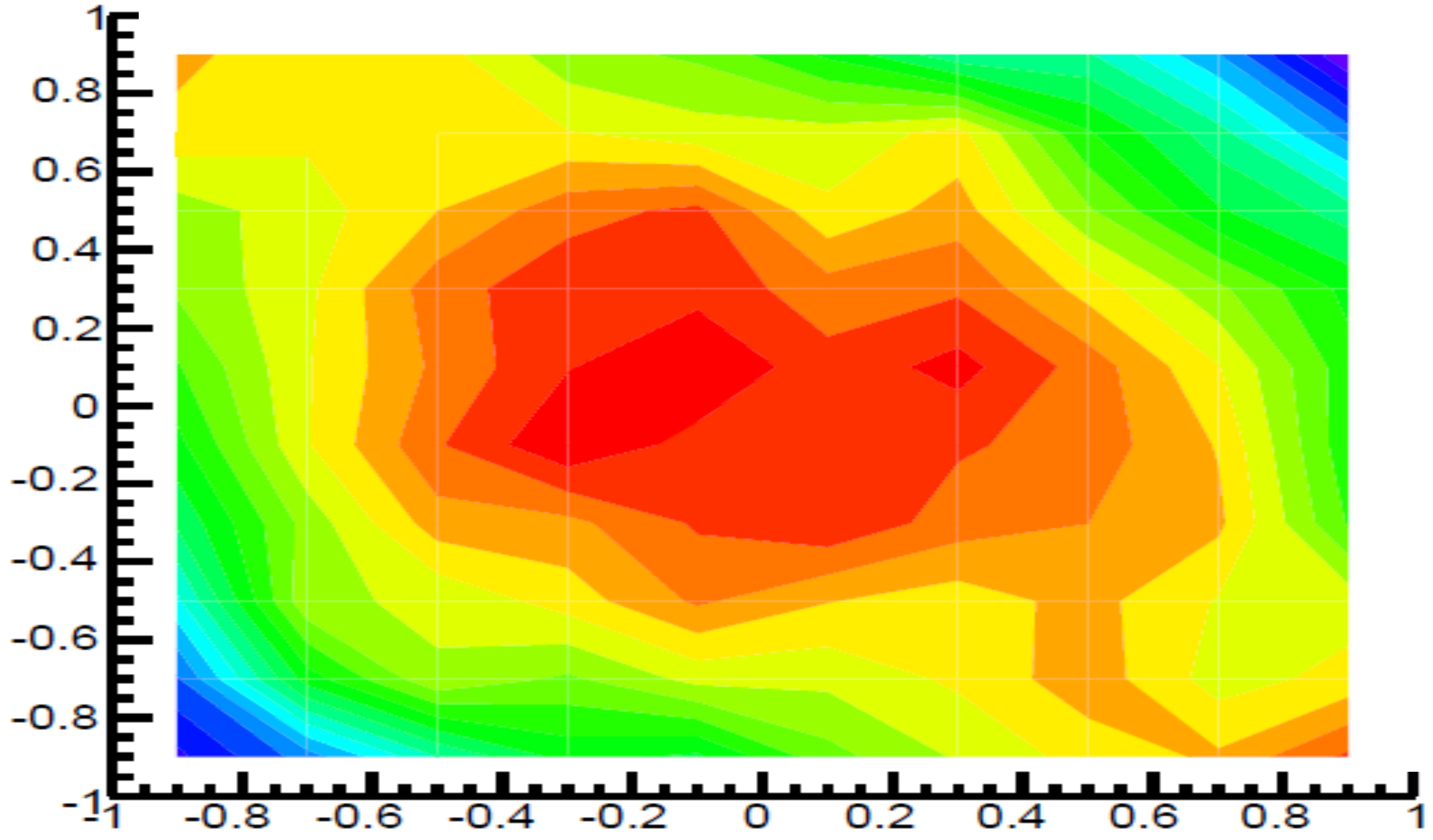


This is not consistent as interplay with other operators and other processes is neglected!

$P(e^+, e^-) = (+1, -1)$ cos θ_{decay} vs $cos\theta_W$ $P(e^+, e^-) = (-1, +1)$



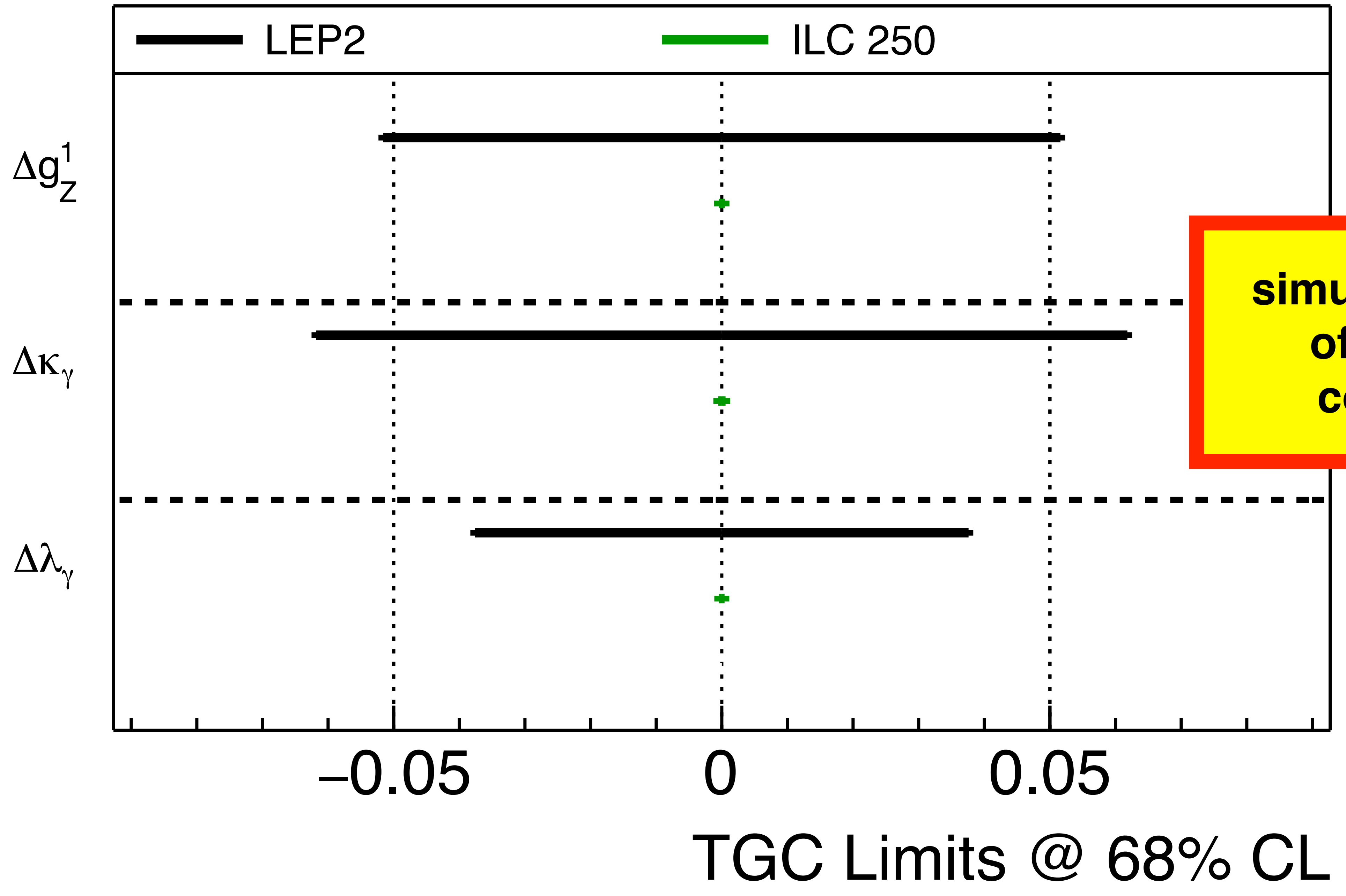


More recently

including 250 GeV (~2017-2018)

PhD Thesis R. Karl

- Extrapolation of 500 GeV / 1 TeV detector-level studies to 250 GeV
- And first look into "single-W" contribution to evqq final-state (detector effects parametrized, but systematics included)
  => single-W important contribution to TGC precicision
  => must be fully included in the future!



simultaneous fit of all three couplings

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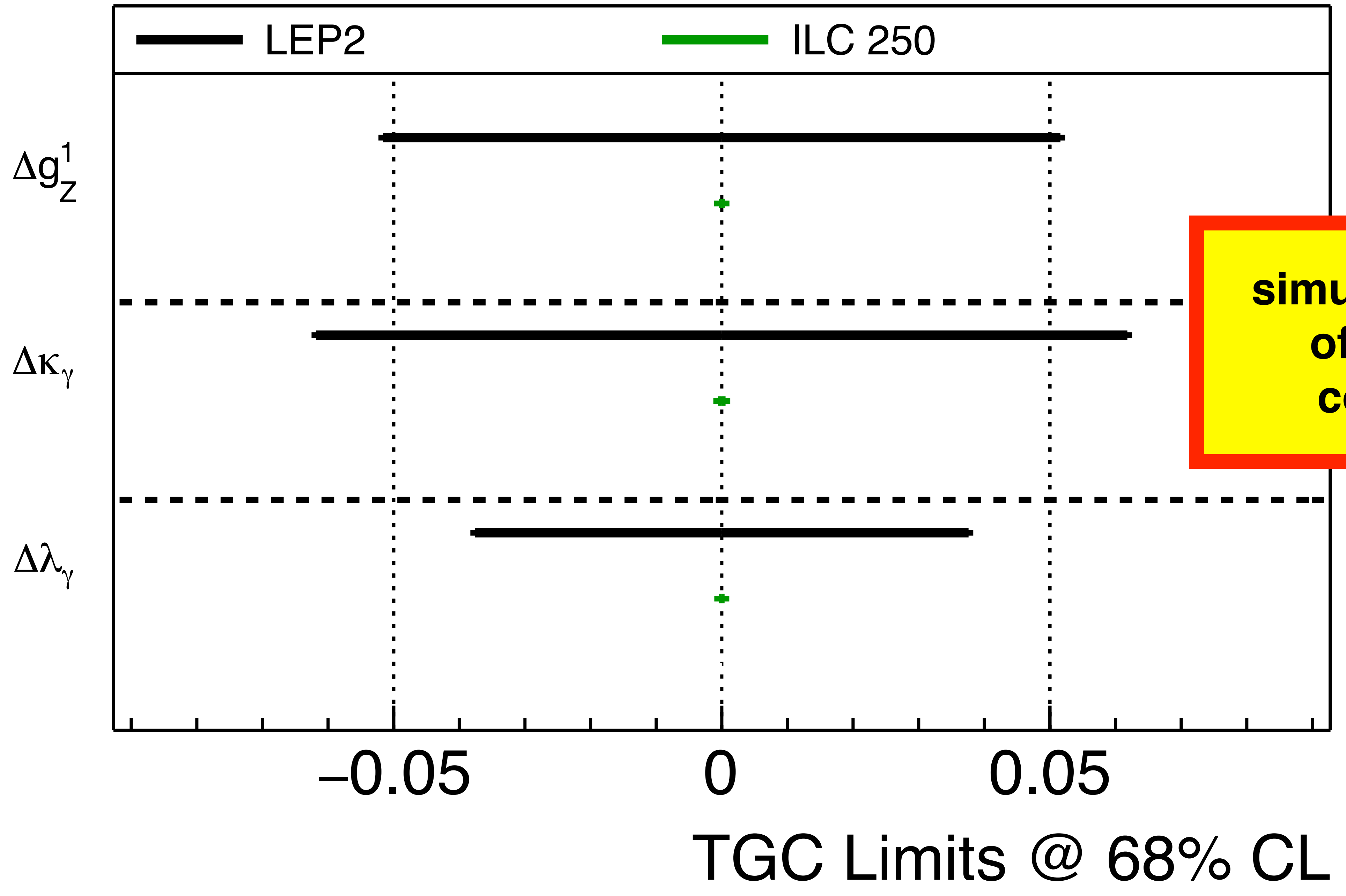

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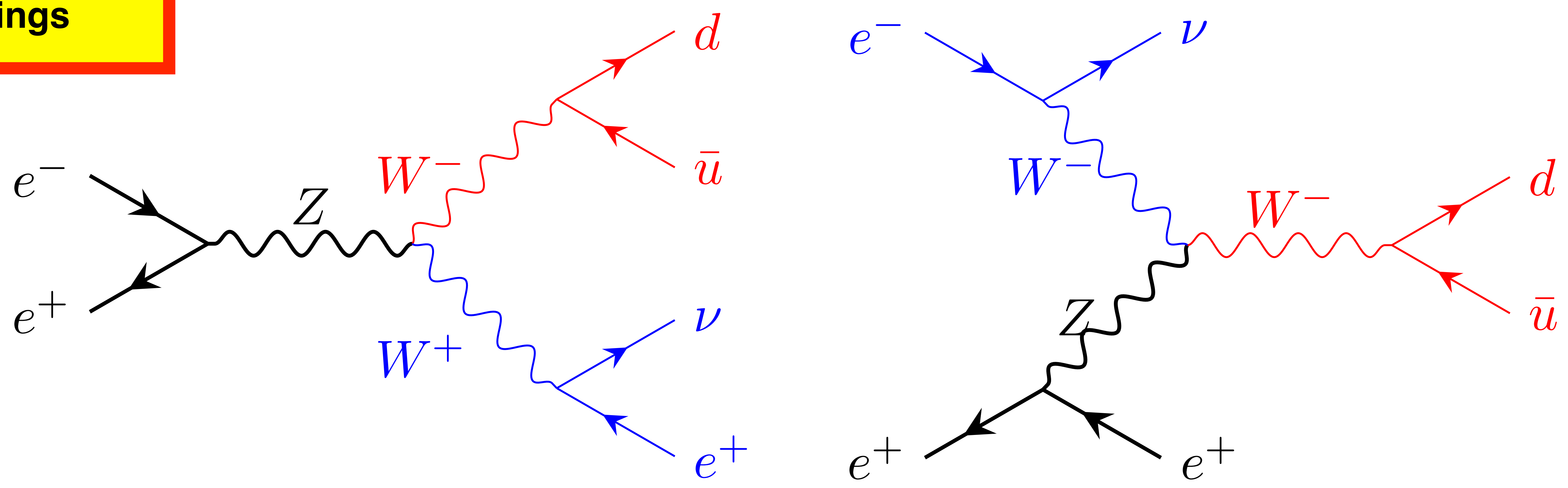

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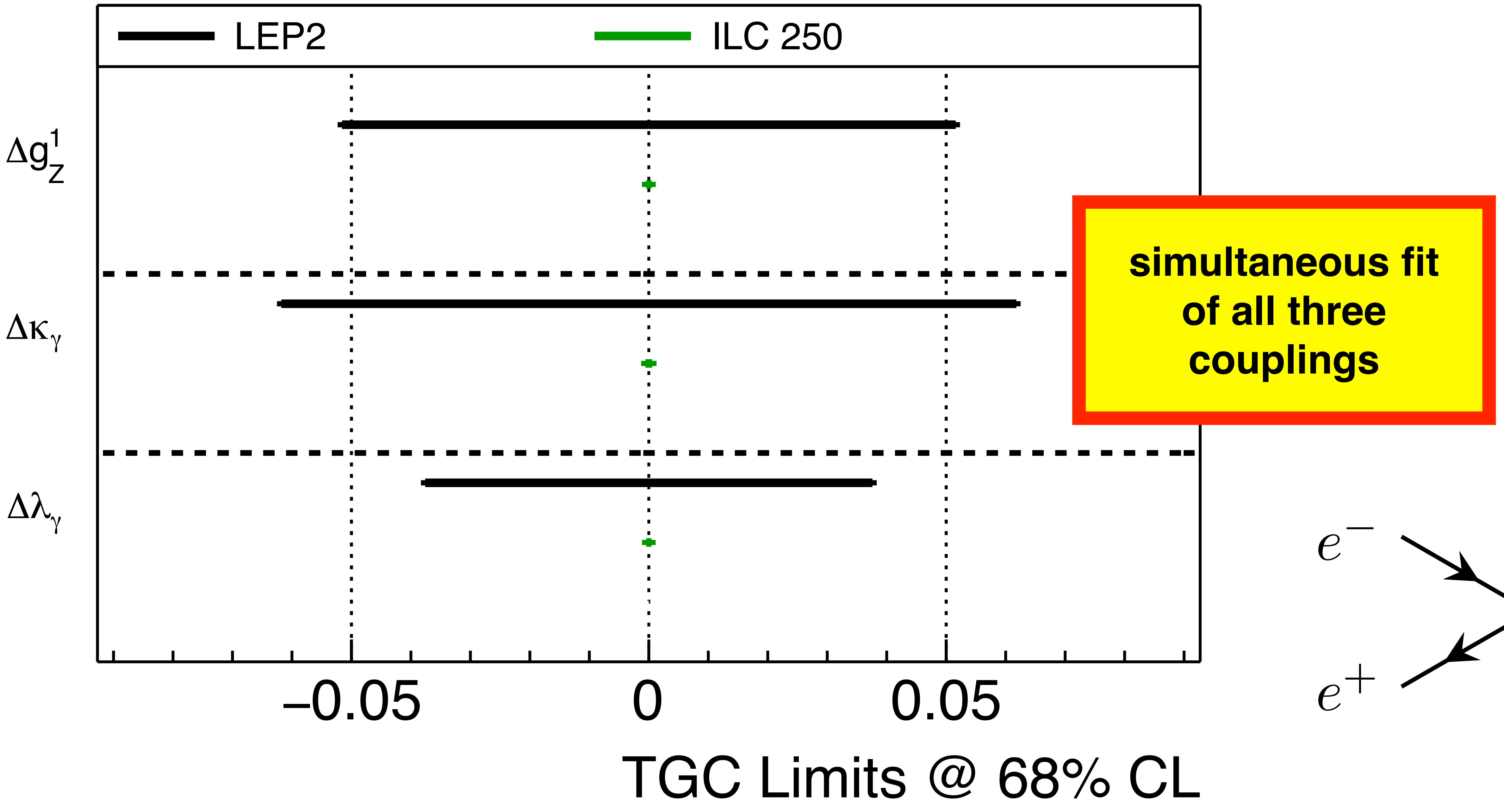

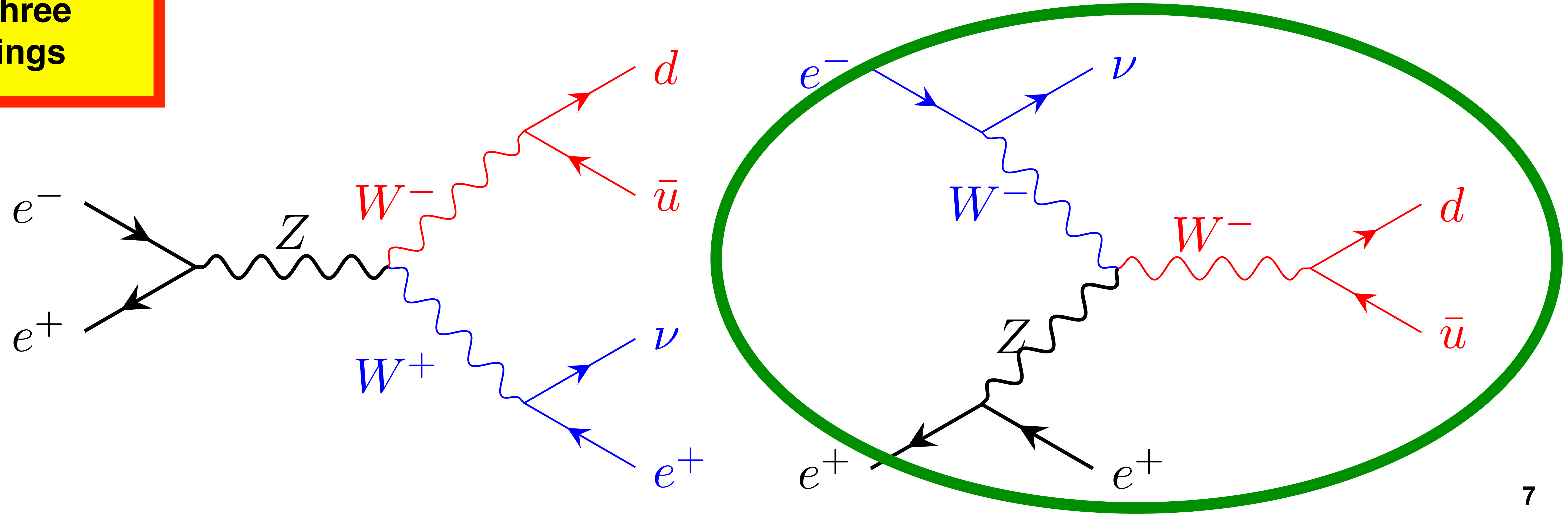

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$\Delta g\ [10^{-4}]$	250	45.8	15.8	13.9
	500	8.46	4.14	3.52
$\Delta\kappa\ [10^{-4}]$	250	54.9	19	16.5
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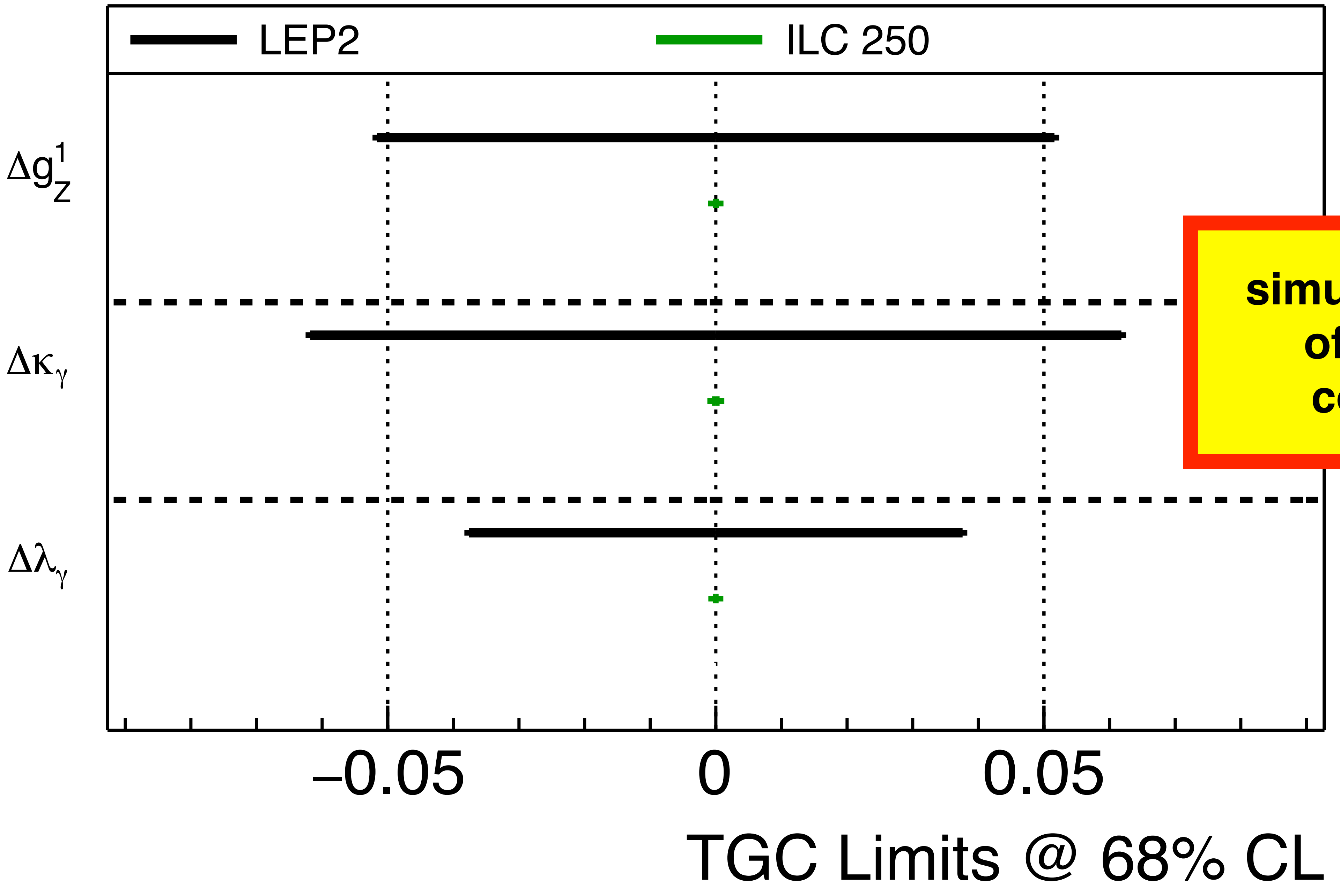

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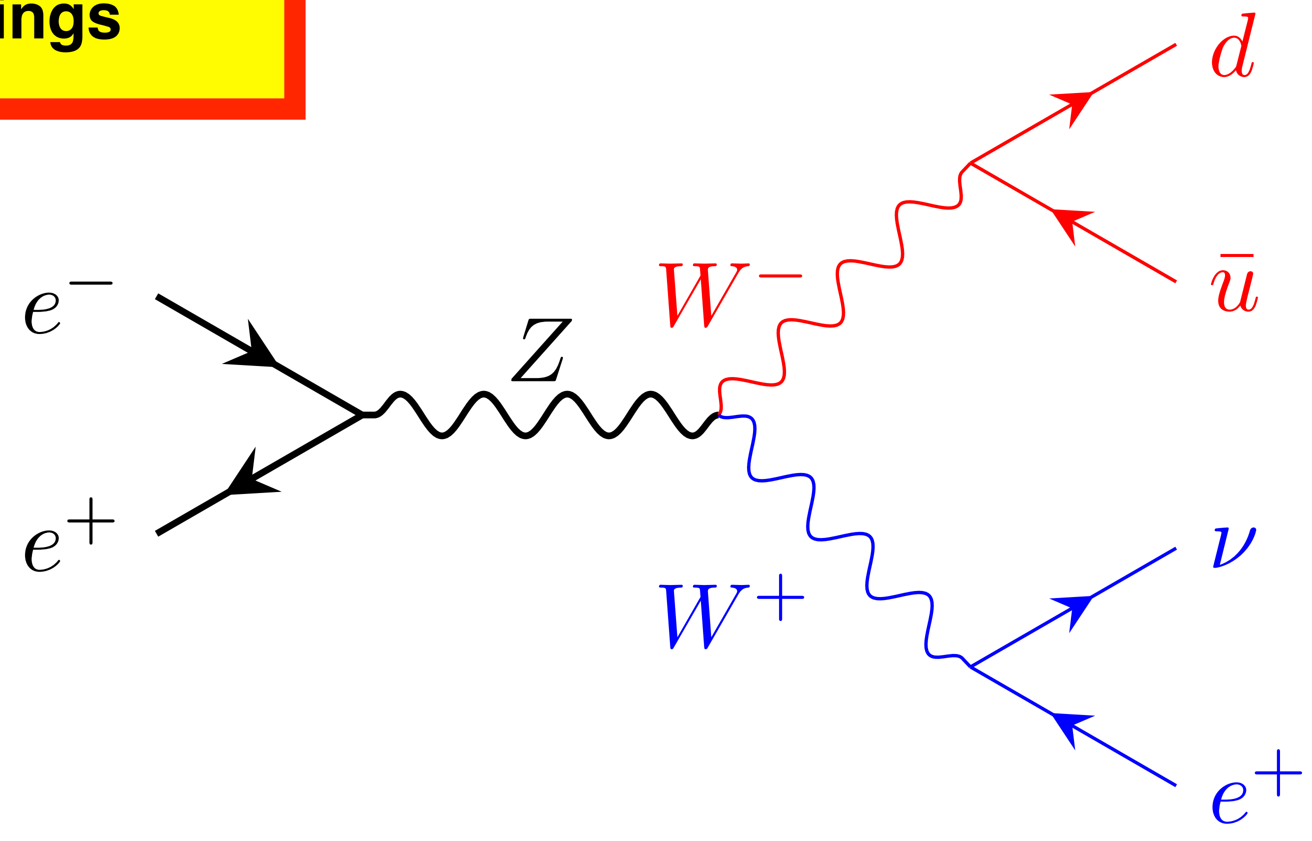

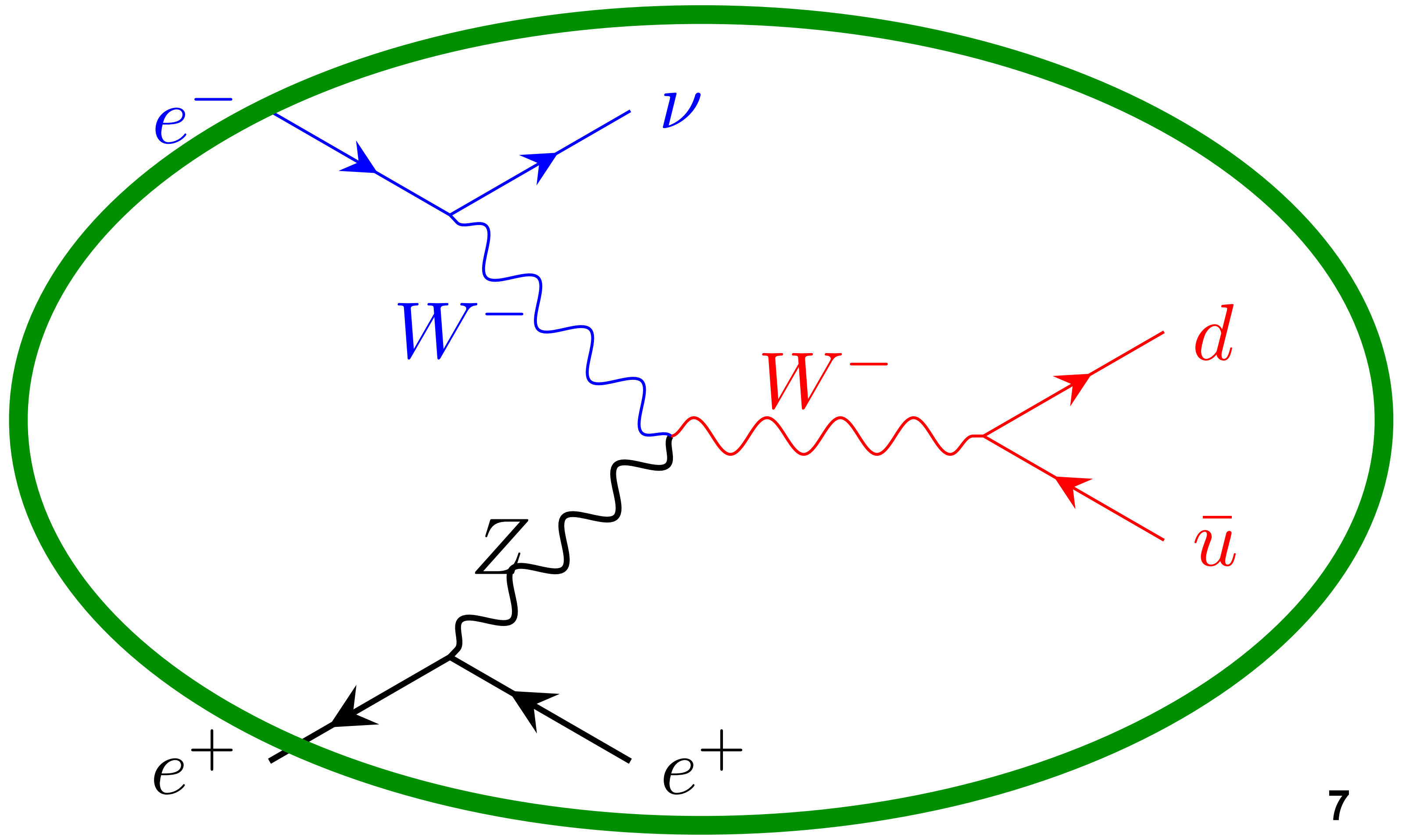

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+single-W

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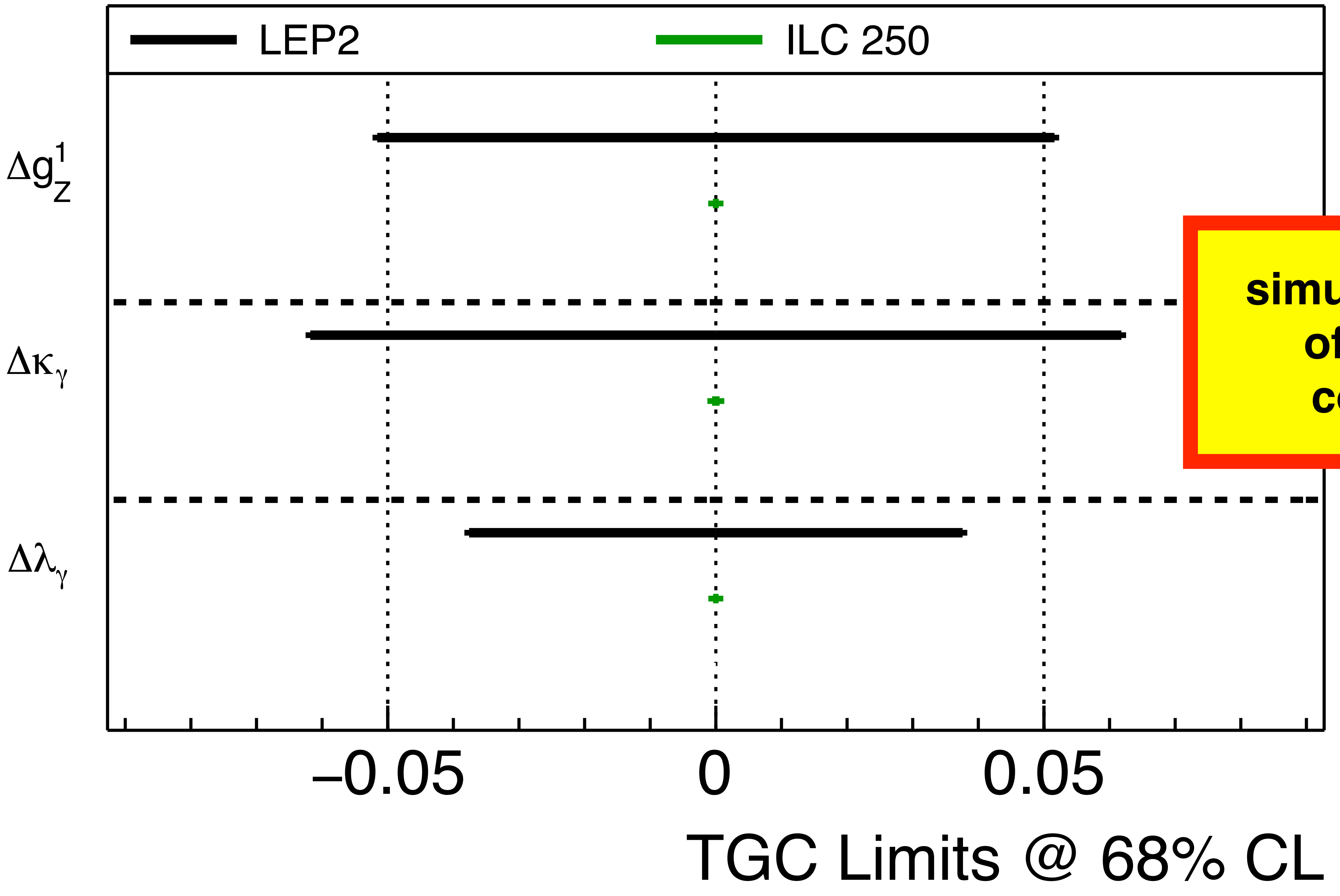

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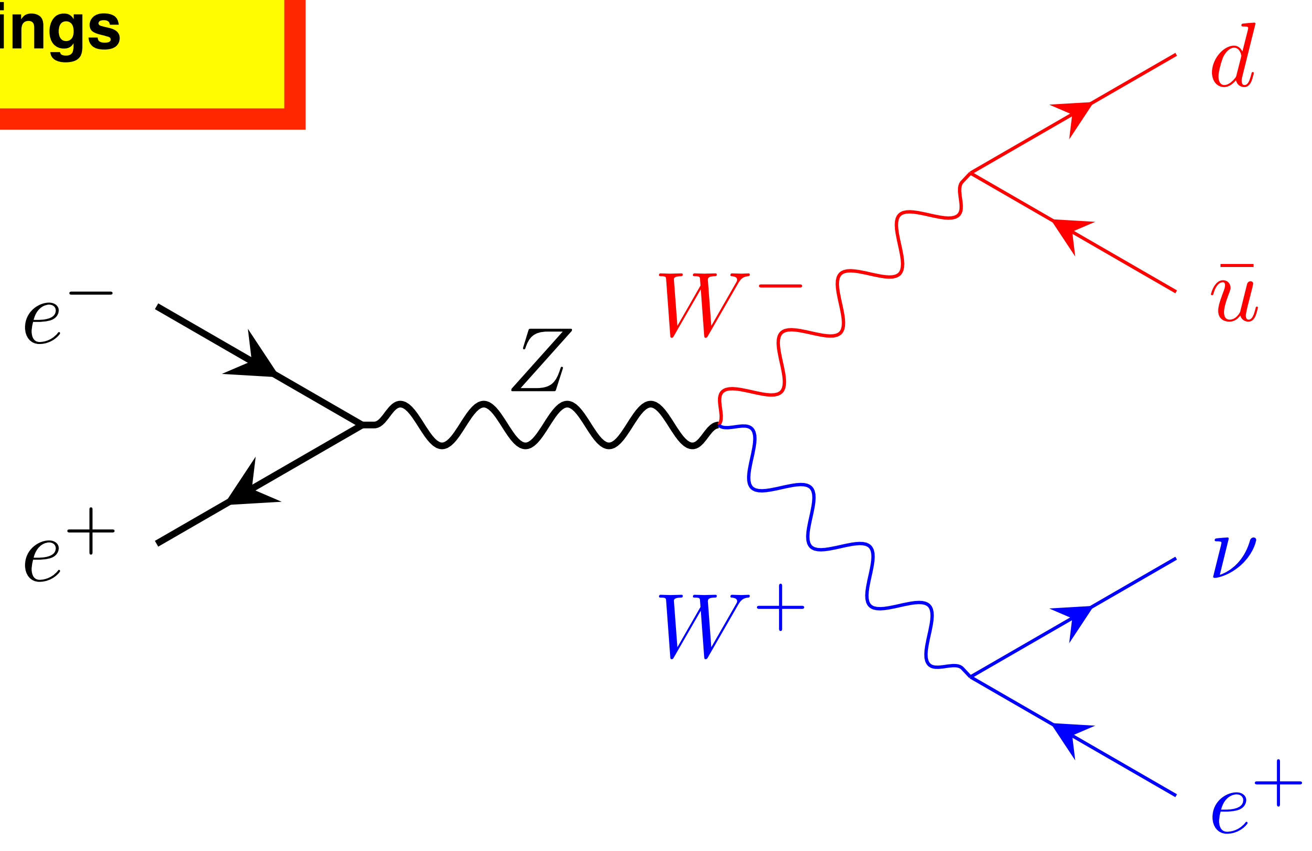
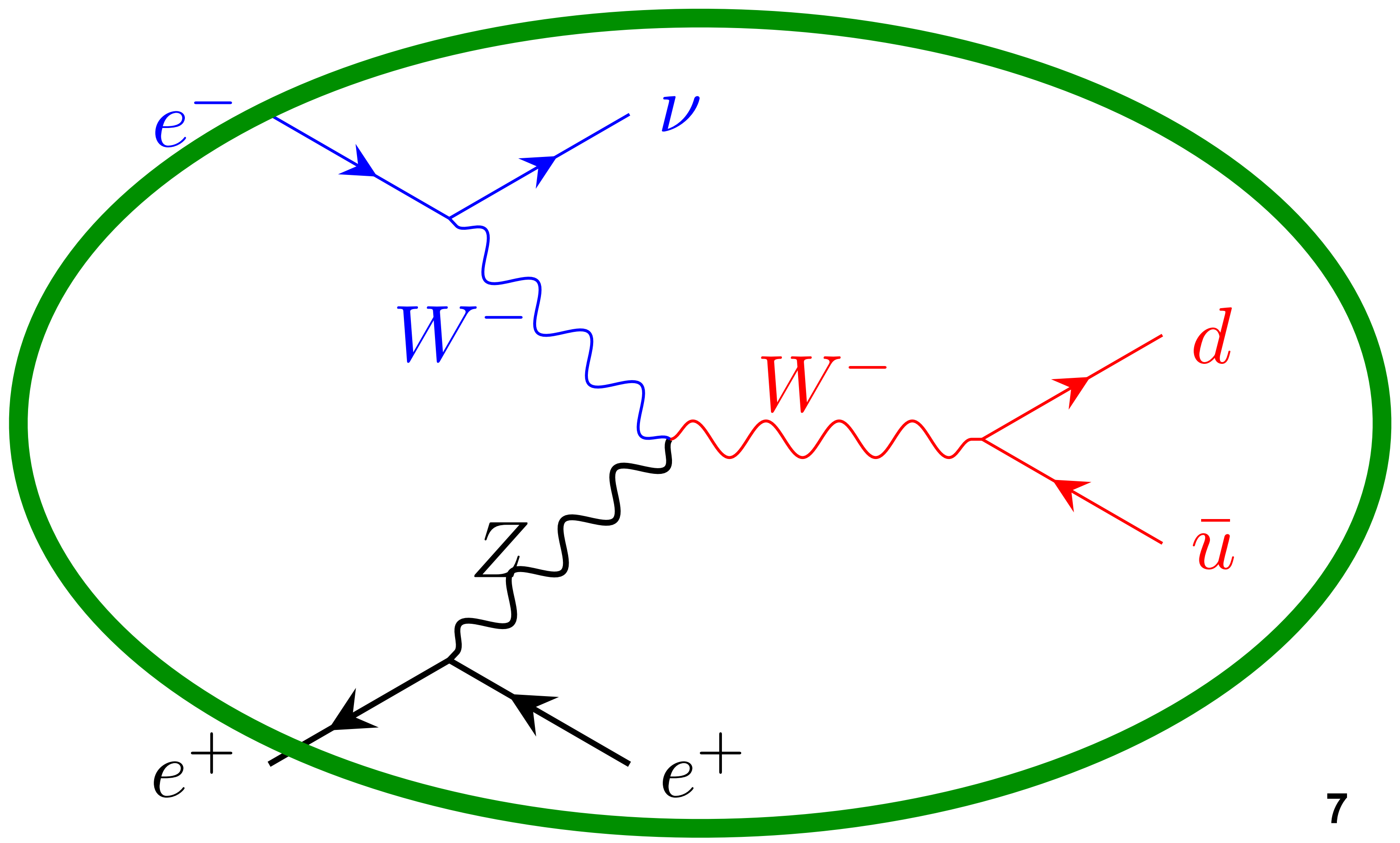


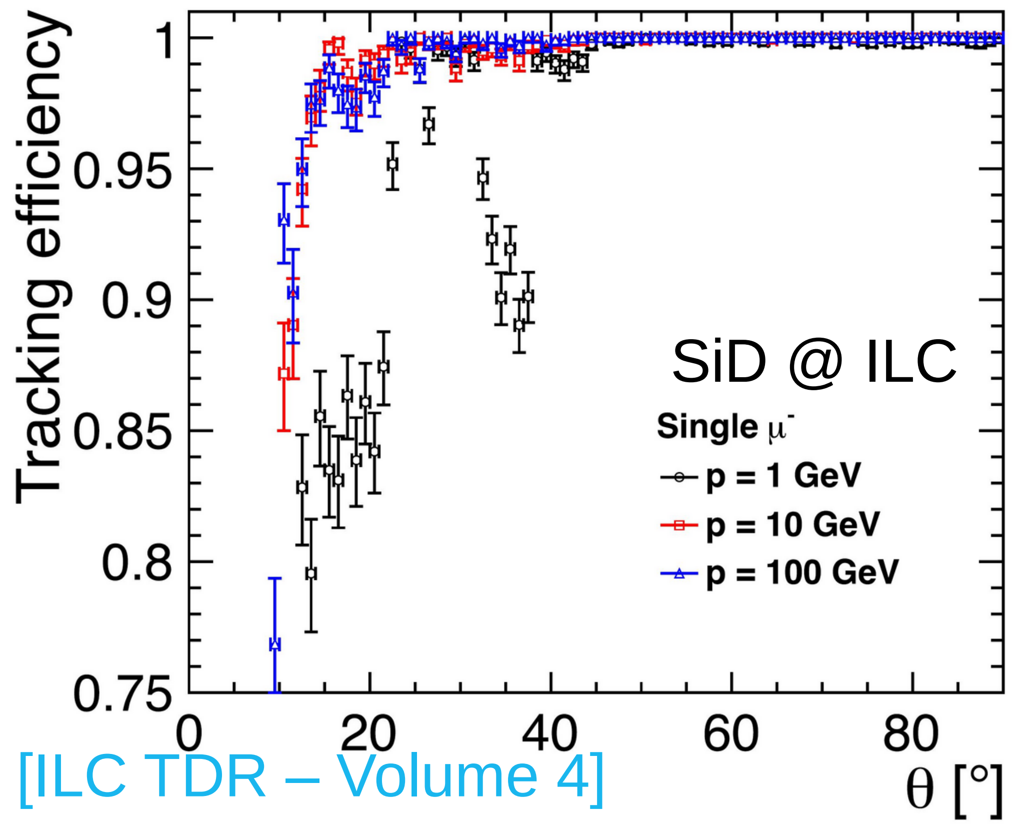


Even more recently

PhD Thesis J. Beyer

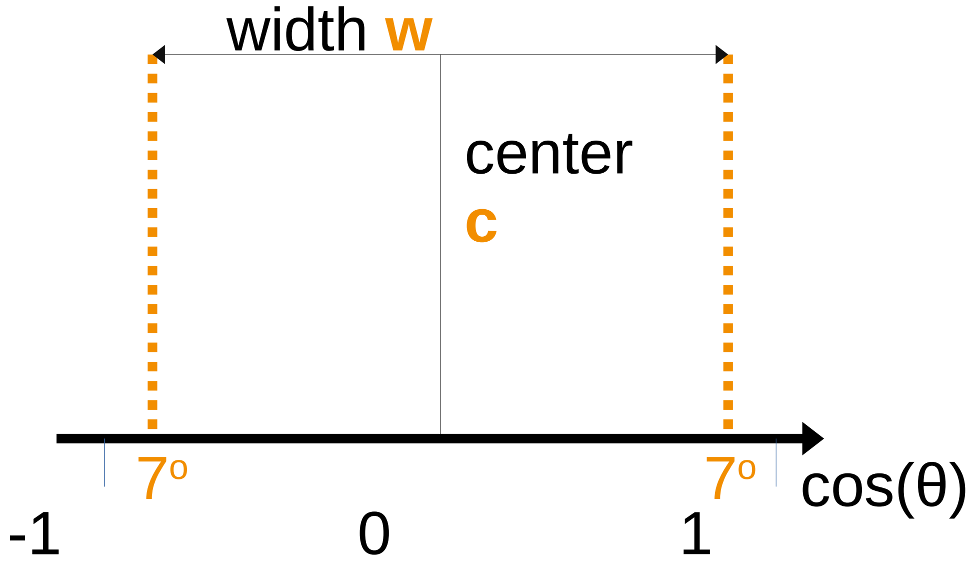
4f and 2f final state combination with detector effects eg acceptance

- detector acceptance in forward region was a leading systematic in ee->$\mu\mu$ at LEP
- future colliders aims for much higher precision
  => can we eliminate this source of uncertainty by extracting the acceptance directly together with physics parameters?
- **detailed study of ability to reduce impact systematics by combined fits to differential cross sections of 2f and 4f processes including many nuisance parameters at 250 GeV using LEP parametrisation**



[ILC TDR – Volume 4]

Simplified picture:
Event passes if all μ's inside box



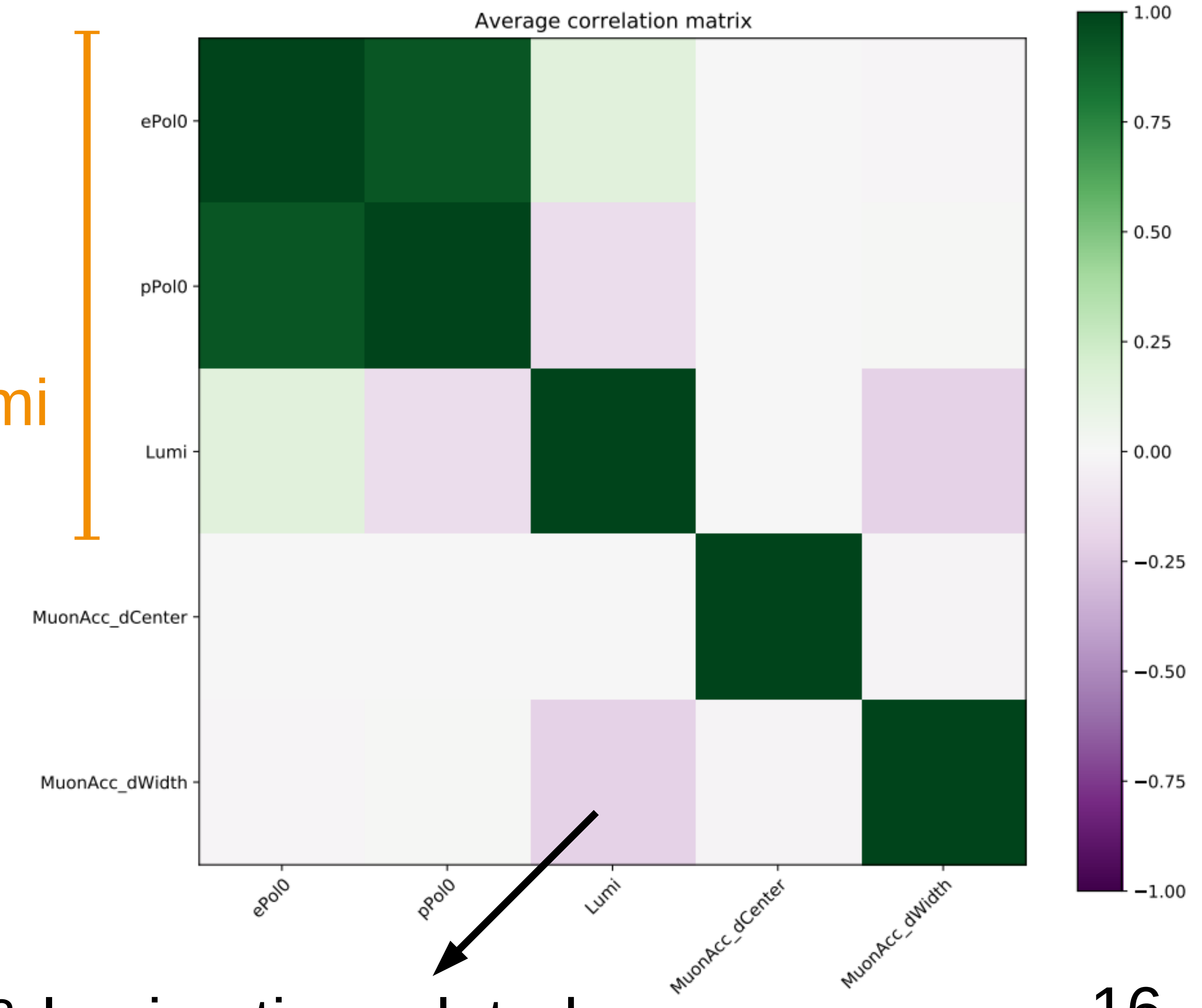
Fit parameters: Δc, Δw

Example:
2ab^{-1} unpolarised

Free parameters:

Polarisations & Lumi
(w/ constraints)

μ acceptance parameters



accept. width & lumi anticorrelated

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CKM Matrix elements

The Motivation

Complementarity to B decays

- main motivation:
  - persistent 3σ-level discrepancy in |Vcb| from B decays:

    $|V_{cb}|$ from inclusive B decays $(42.19 \pm 0.78) \times 10^{-3}$

    $|V_{cb}|$ from exclusive B, B_s and Λ_b decays $(39.10 \pm 0.50) \times 10^{-3}$
  - difficult to solve in B decays due to inherent hadronic uncertainties — absent in (real) W decays!
  - LHC prospects: ~10%
  - Higgs Factories offer O(10^8) W bosons in clean e+e- environment, theory uncertainties estimated to be at the 10^{-4} level
- but also all other CKM MEs!
- Naive number of event level of sensitivity (100%, no background):

$W^- \to$	$\bar{u}d$	$\bar{u}s$	$\bar{u}b$	$\bar{c}d$	$\bar{c}s$	$\bar{c}b$
BR	31.8%	1.7%	4.5×10^{-6}	1.7%	31.7%	5.9×10^{-4}
N_{ev}	64×10^6	3.4×10^6	900	3.4×10^6	63×10^6	118×10^3
$\delta^{th}_{V_{ij}}$	0.0063 %	0.027 %	1.7 %	0.027 %	0.0063 %	0.15 %

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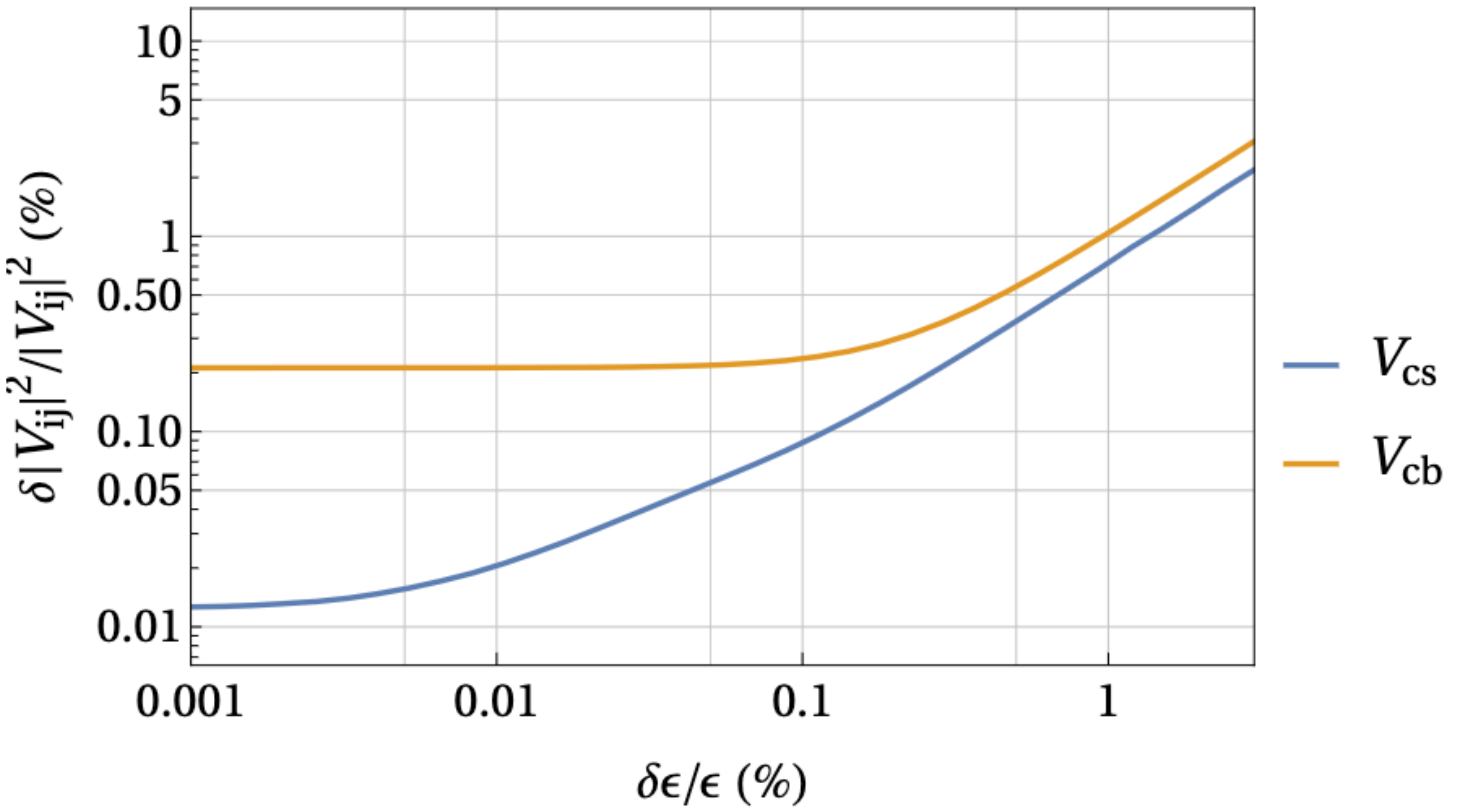
How close can we get in real-life? Implications for detector design?

State-of-the-Art

Higgs Factory Projections

- M. Tammaro et al:
  - parametrised flavour tagging as developed for IDEA@FCCee
  - 2f ("QCD") background only
  - dependence on syst. uncertainty on tagging efficiencies
- brand-new CEPC-240 study arXiv:2406.01675
  - ILD@CEPC in full simulation (MokkaPlus + Marlin)
  - 2f, 4f and Higgs backgrounds
    => considering only 2f is too optimistic…
  - dominant systematics: tagging efficiency and background, assume convervative (~LEP) and optimistic (4-8 x better than LEP) scenario
  - extrapolation to ILC250 conditions



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Unpolarized, Baseline (5 ab^{-1})	0.72%	1.5%	0.20%
Unpolarized, Extended (20 ab^{-1})	0.36%	1.5%	0.20%
WW Threshold (5×10^7 WW)	0.95%	1.5%	0.20%
Unpolarized, Baseline + WW	0.58%	1.1%	0.15%
Unpolarized, Extended + WW	0.34%	1.1%	0.18%
Polarized, Baseline (0.5 ab^{-1})	1.5%	1.5%	0.20%
Polarized, Extended (2 ab^{-1})	0.75%	1.5%	0.20%

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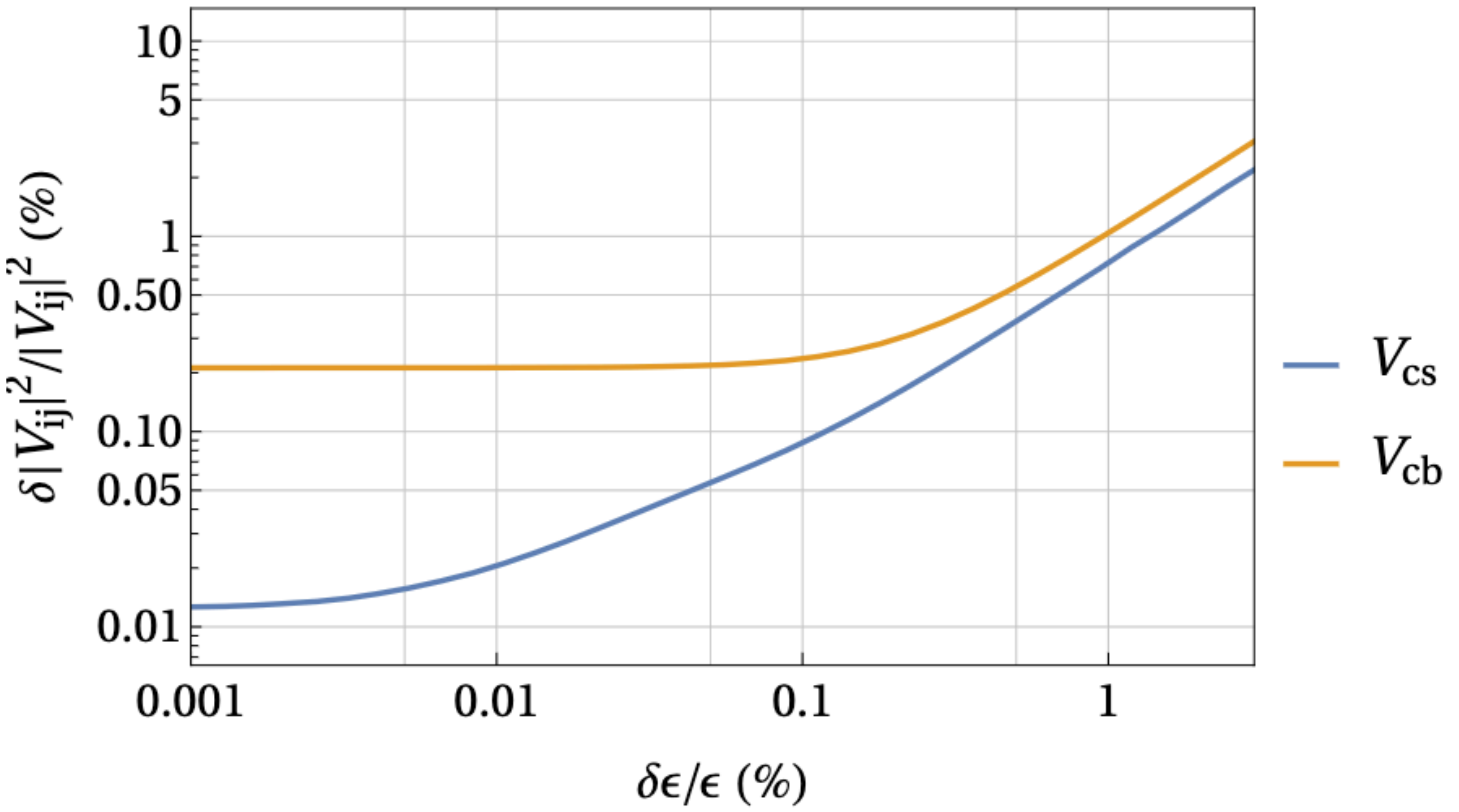

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Polarized, Extended (2 ab^{-1})	0.75%	1.5%	0.20%

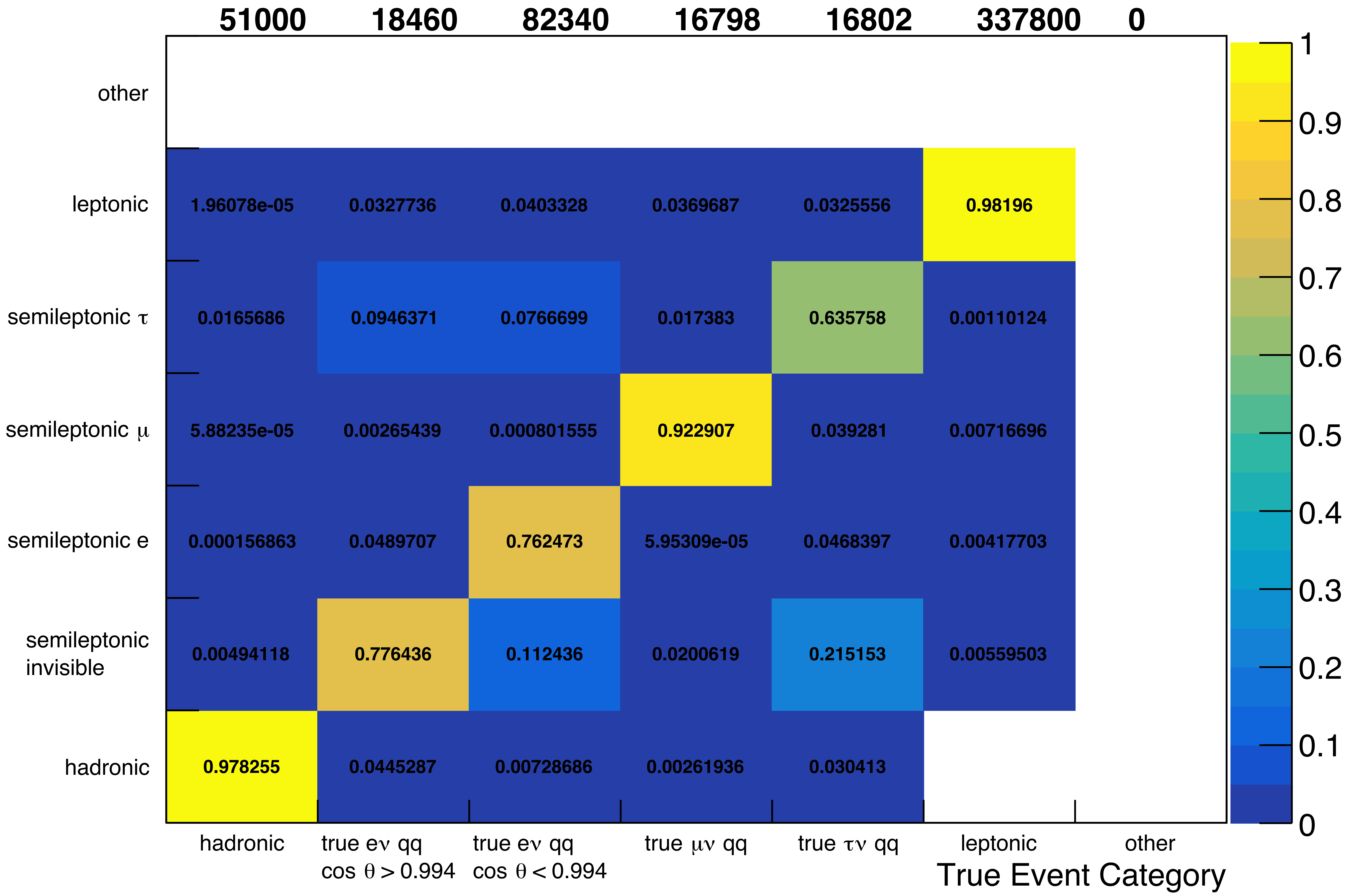
Planned: Confirm with ILD@ILC, include single W, look at hadronic channel, add 500 GeV (~doubles #Ws)

Ongoing Work ILD/CLD

WW / single W channel separation

Define uniquely & overlap free in order to allow easy combination afterwards

- based on MiniDST
- IsolatedLeptonTagging & TauFinder
- cut-based overlay rejection
- reshuffle events according to N_{PFO}, pt_{miss}, M_{miss}
- forward acceptance important for eνqq due to single-W
- qqqq, **μν**qq => ready for analysis
- **eν**qq, **τν**qq would profit from reconstruction improvements



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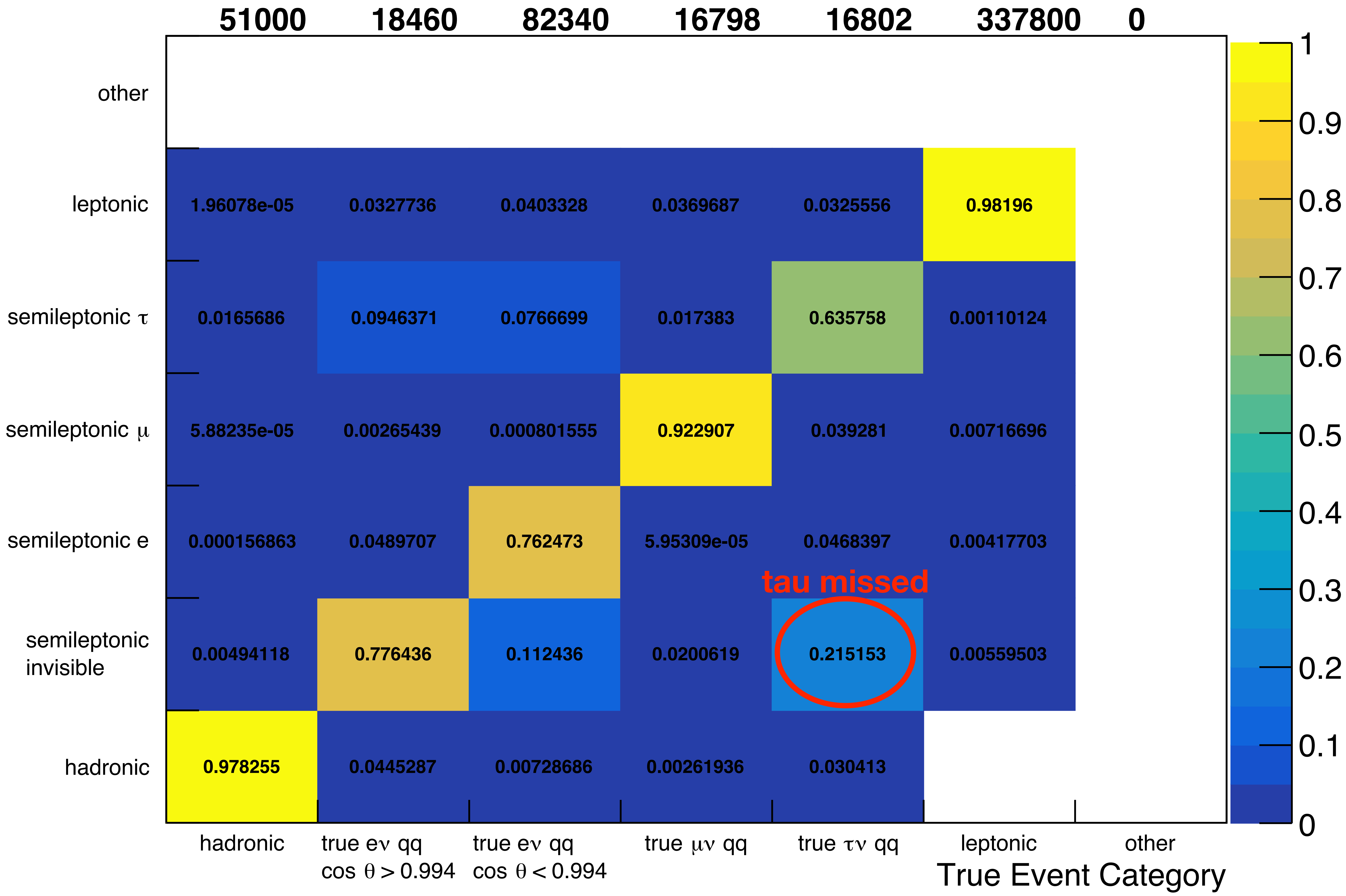

WW / single W channel separation

Define uniquely & overlap free in order to allow easy combination afterwards

- based on MiniDST
- IsolatedLeptonTagging & TauFinder
- cut-based overlay rejection
- reshuffle events according to N_{PFO}, pt_{miss}, M_{miss}
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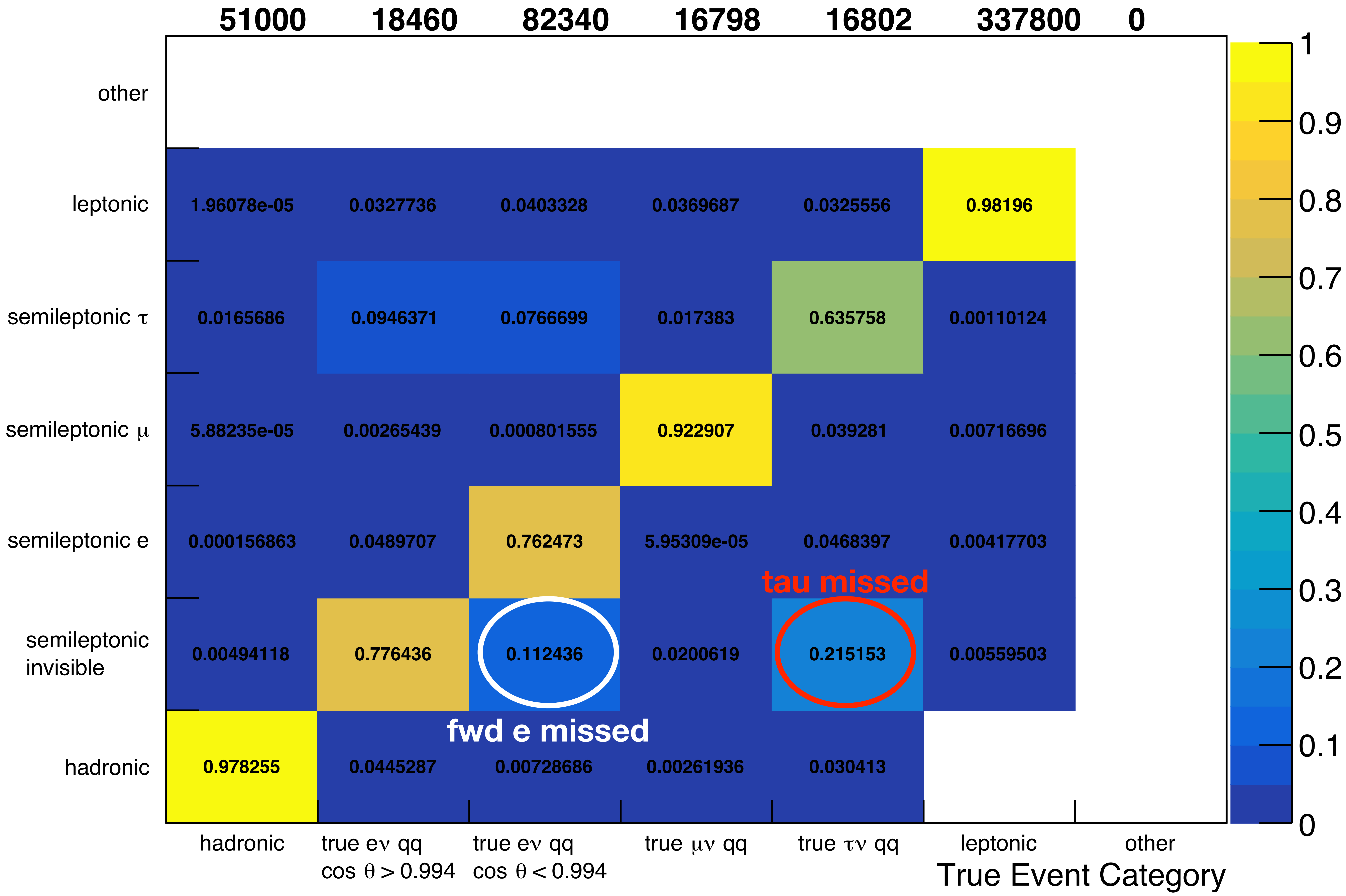

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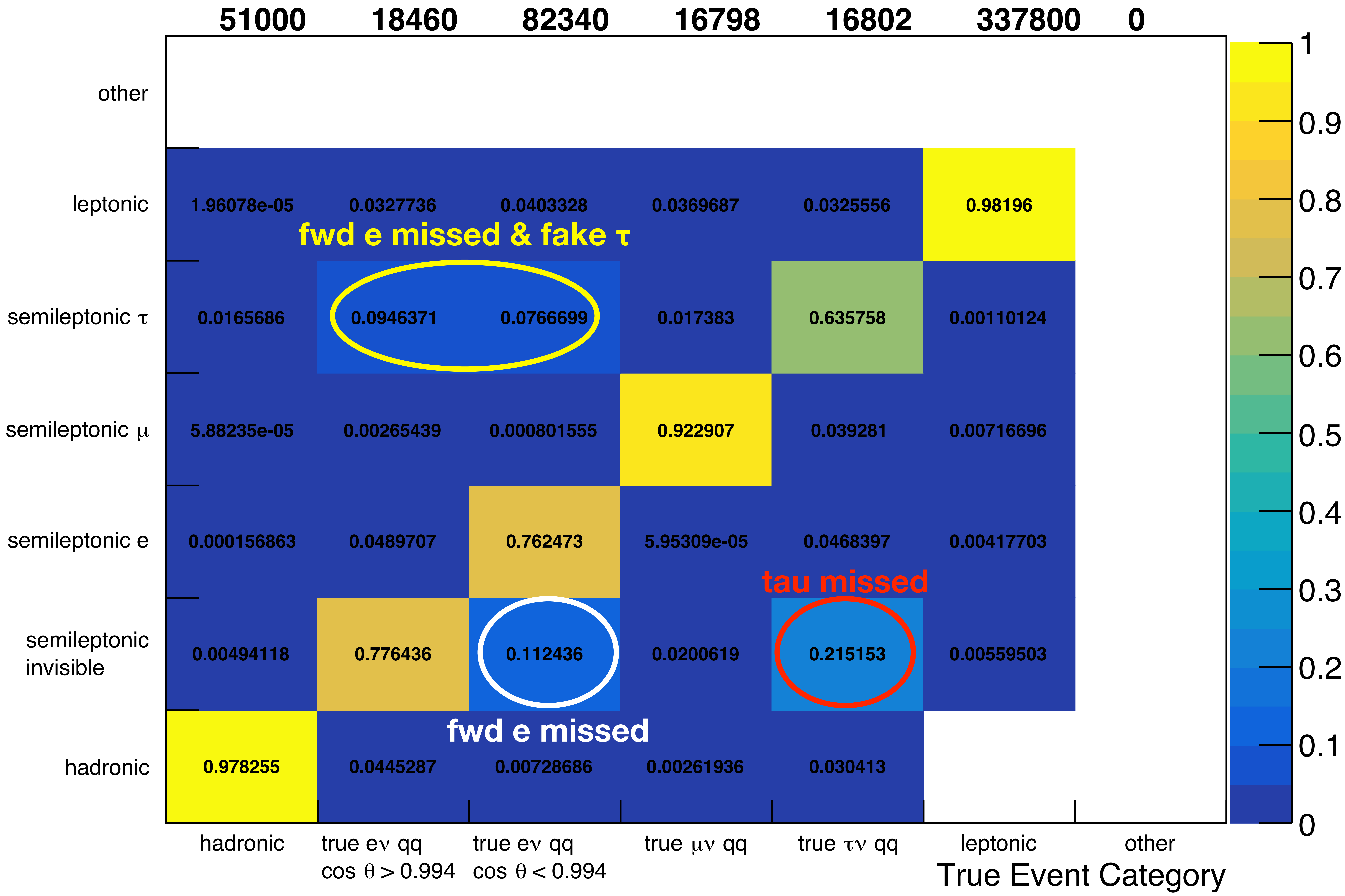
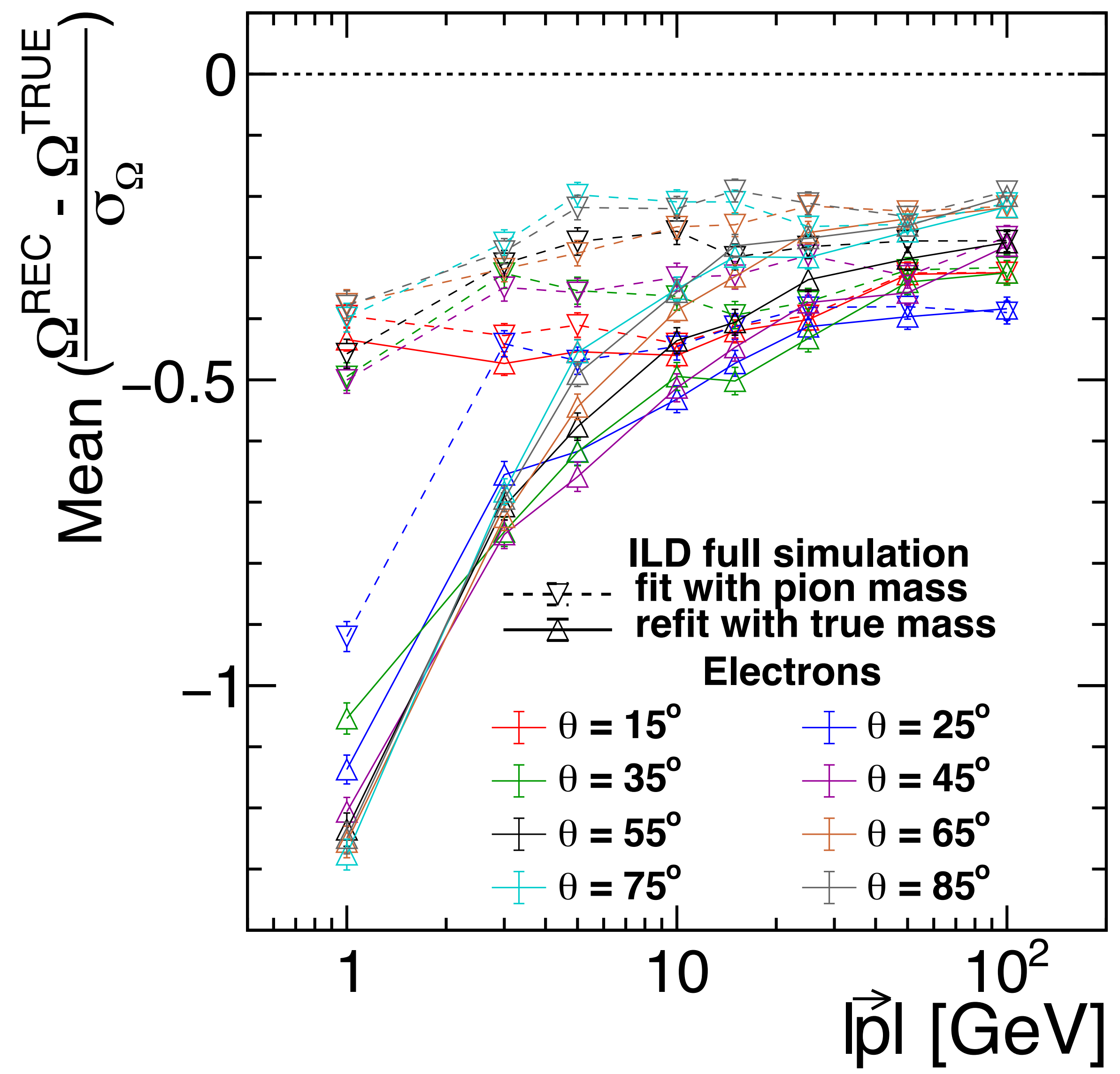


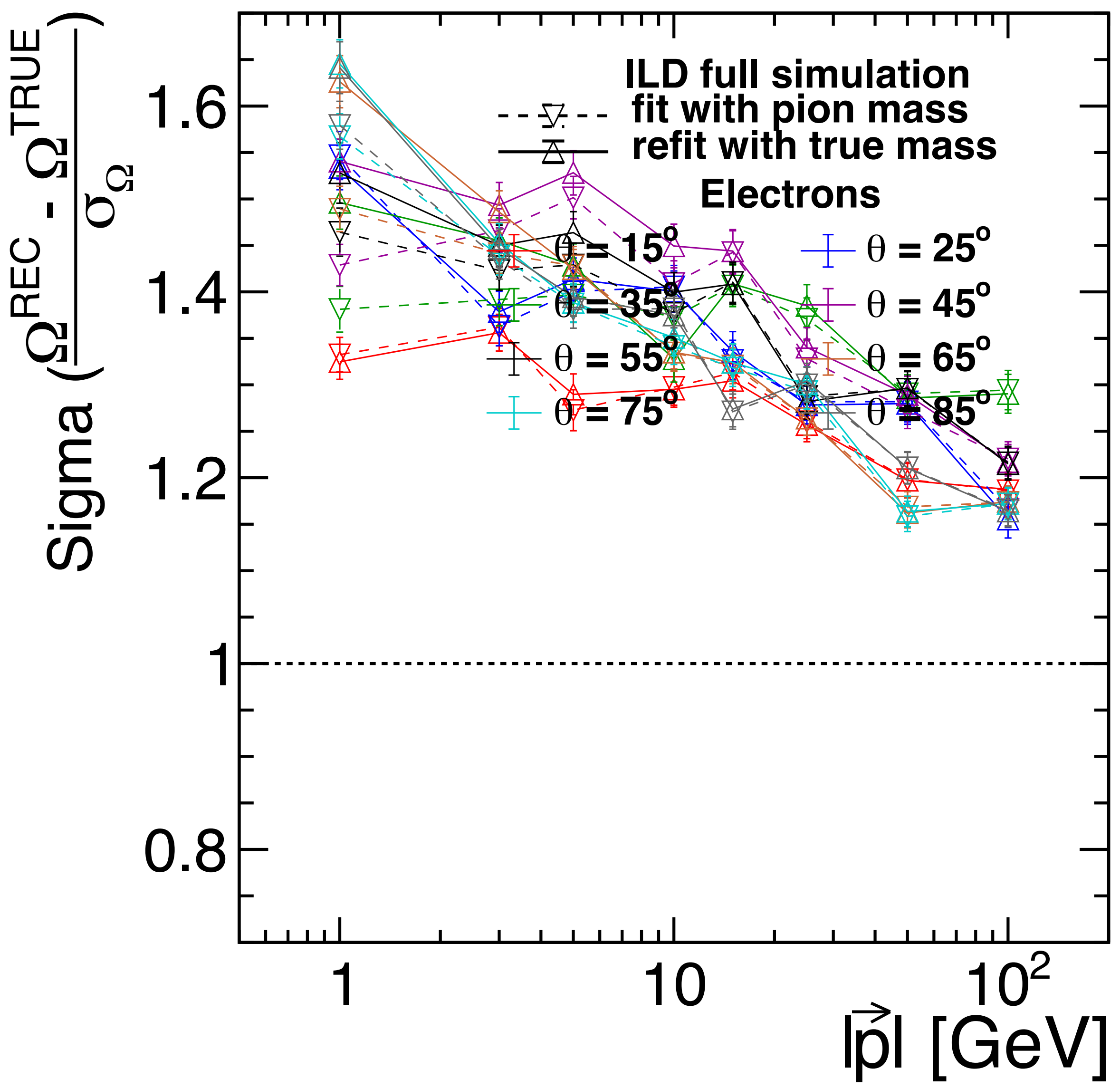
Single W: forward tracking for electrons

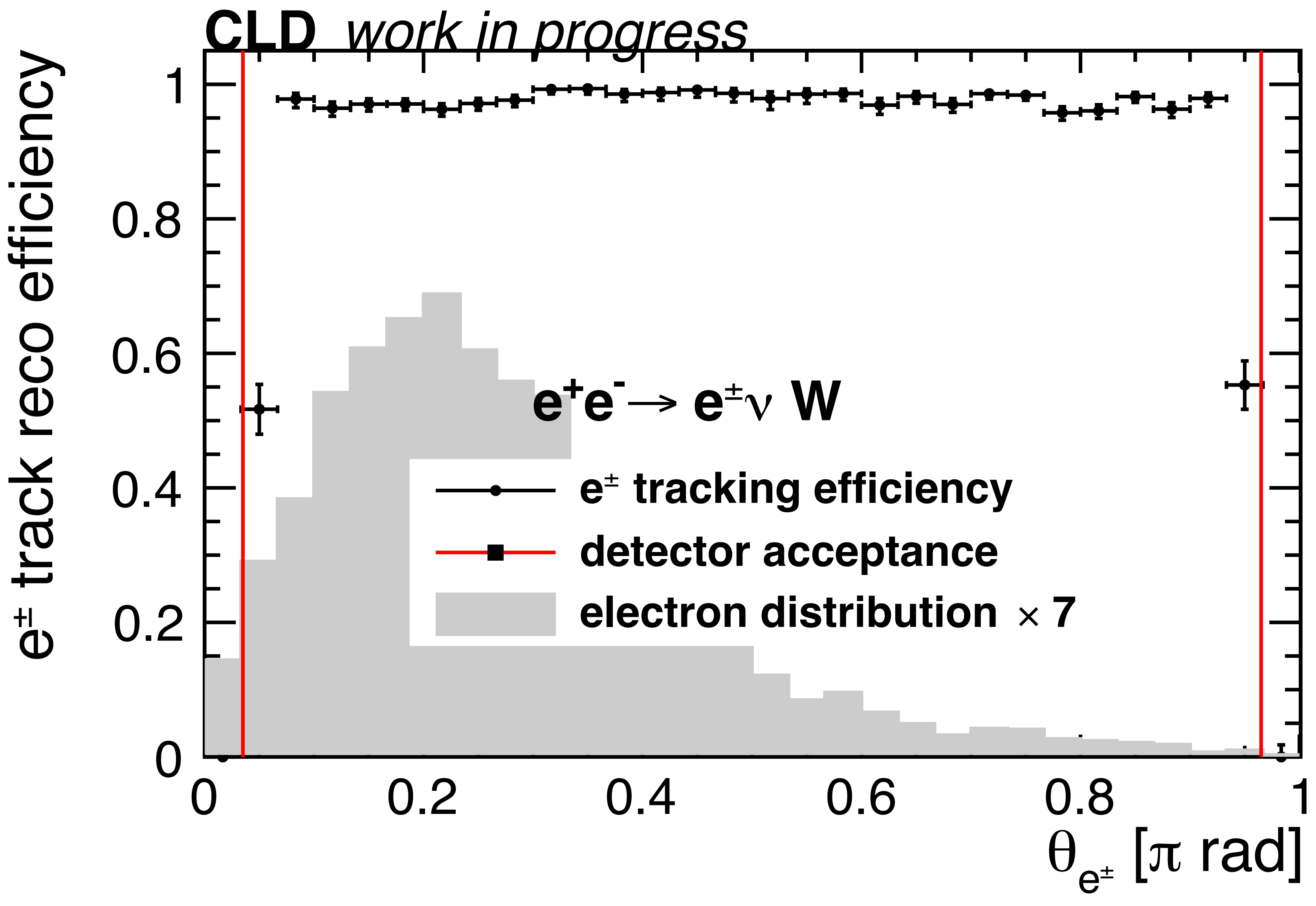
Y.Radkhorrami

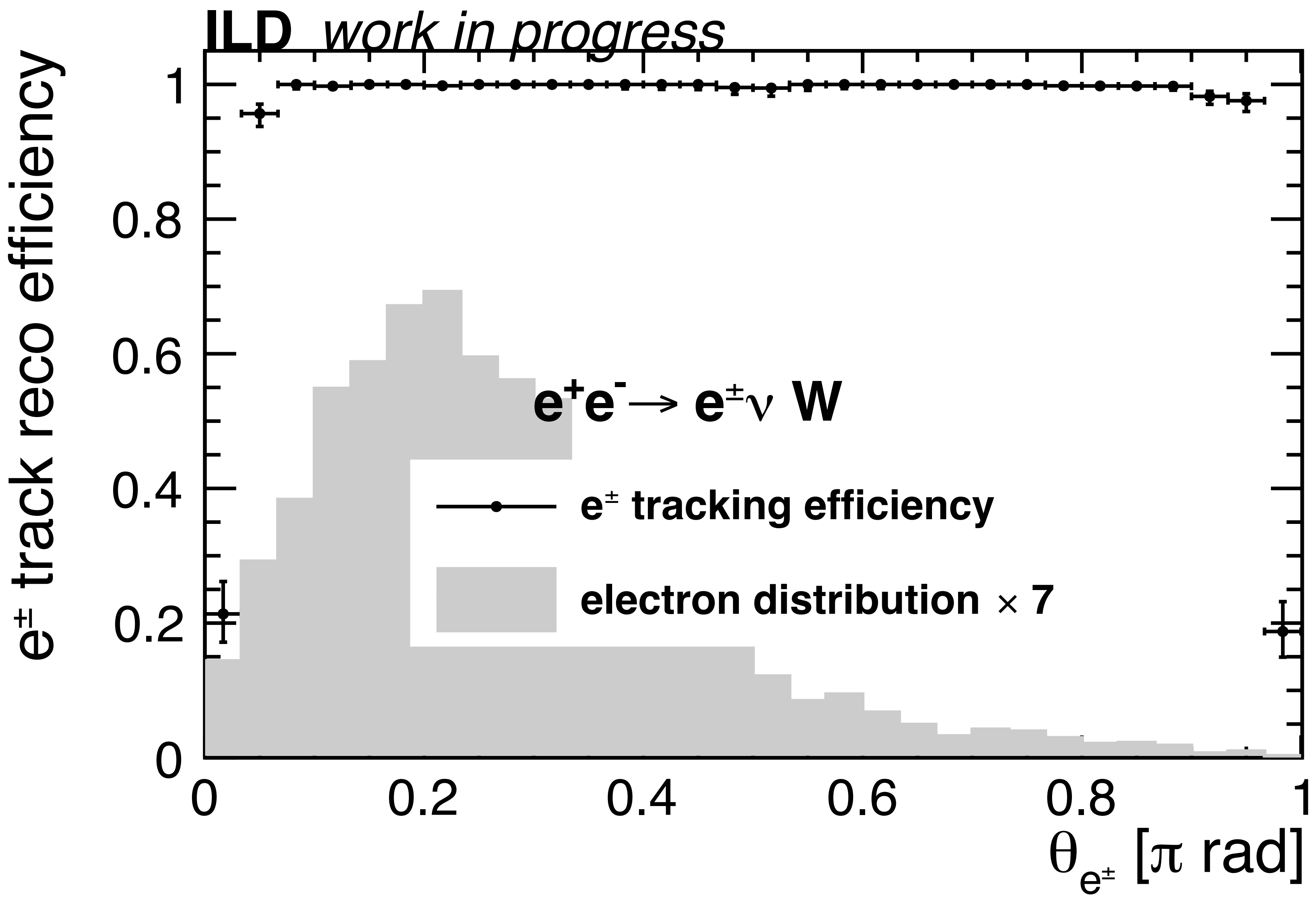
Double challenge due to forward and bremsstrahlung

- electron reconstruction and its systematic uncertainties crucial for singleW analysis
- central values and pulls of track parameters biased
- no improvement when using correct mass in track fit
- large bremsstrahlung => Gaussian Sum Filter?
- goal: use ACTS in key4hep, do this for all Higgs Factory concepts providing full detector simulation





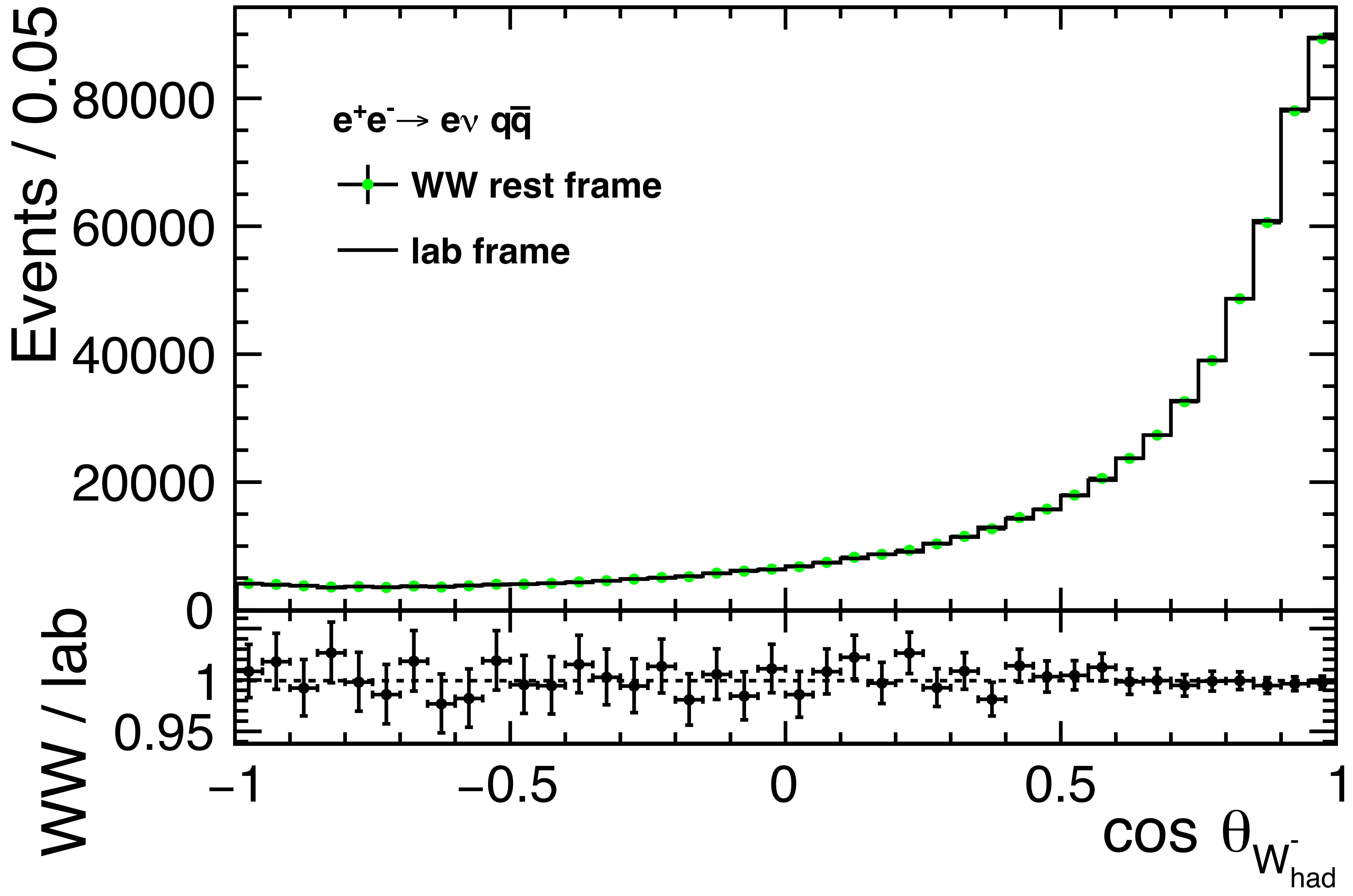


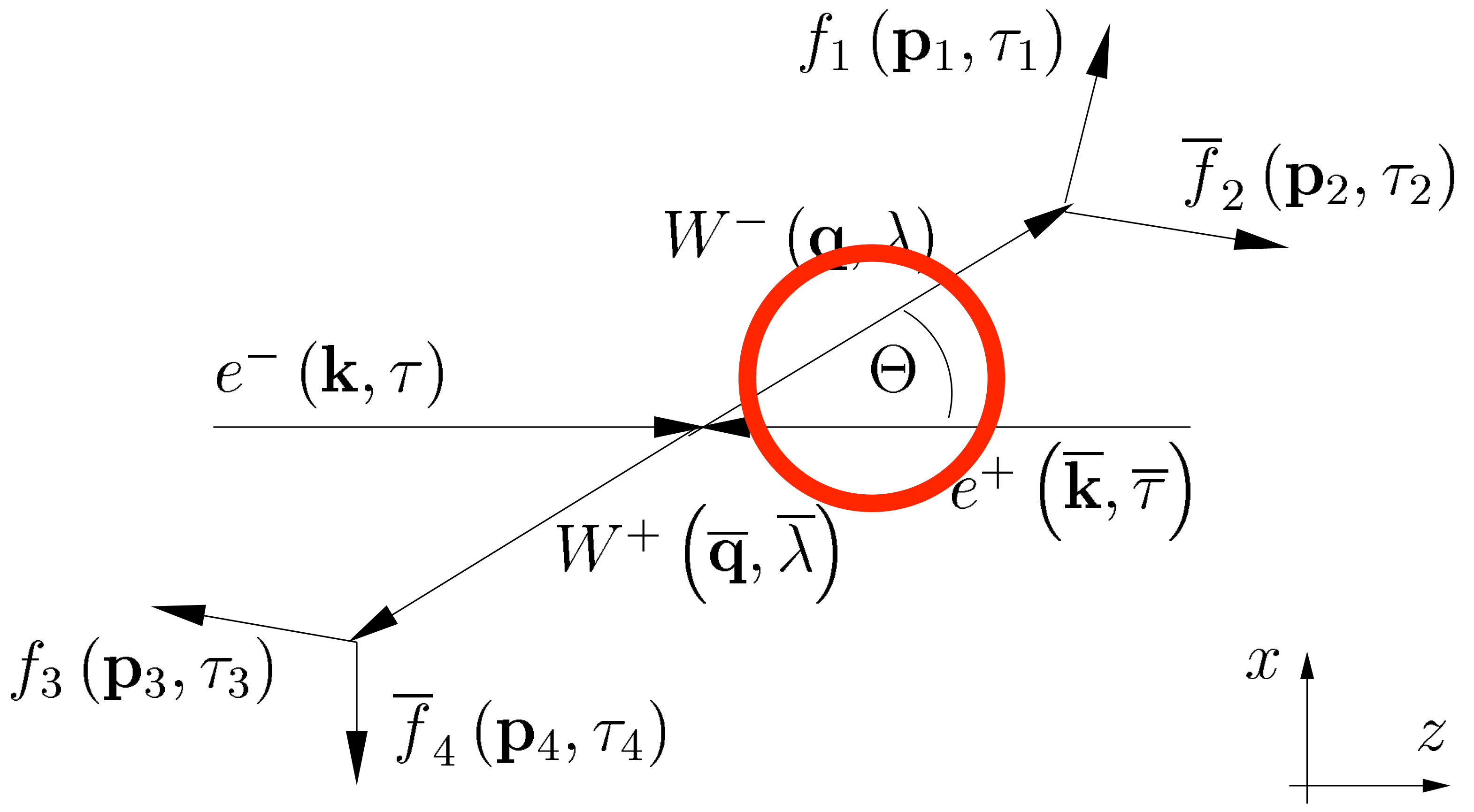


intermediate success: run same performance evaluation in key4hep on CLD and ILD data

WW: production angle

verifying effects of ISR on generator level



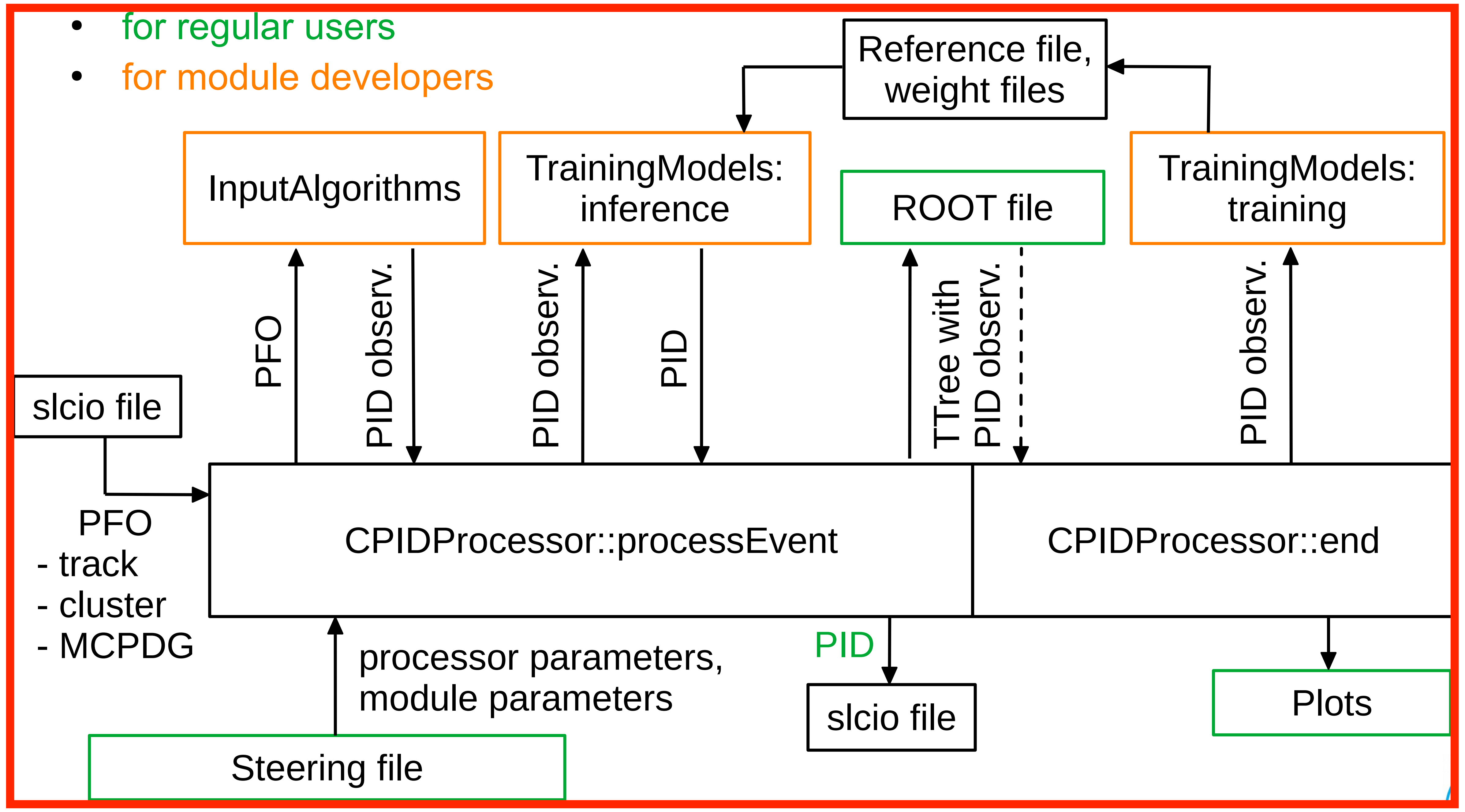


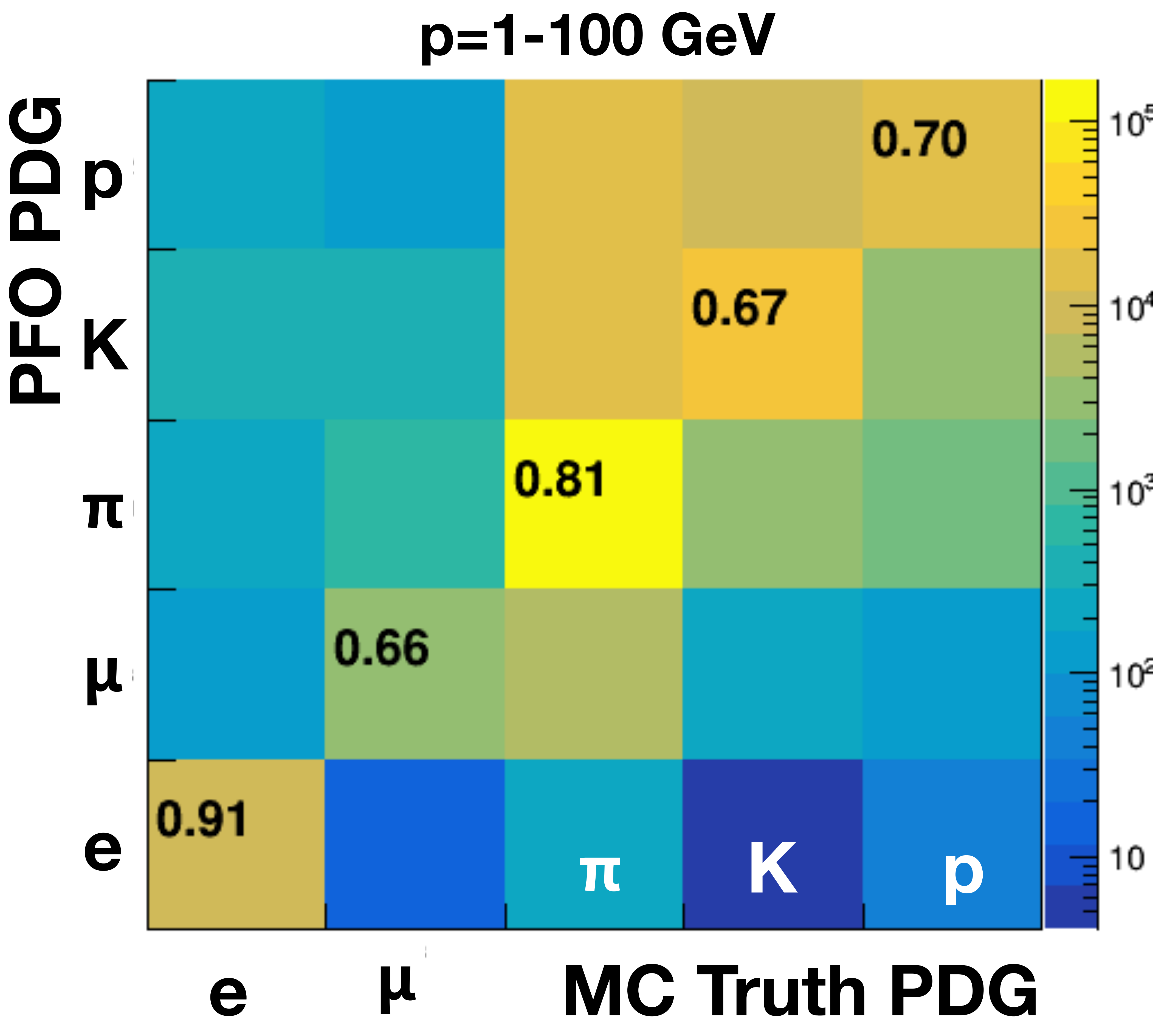
at 250 GeV, rather small ISR effects

decay angles & reco-level = work in progress

Particle ID for FlavourTag

towards CKM matrix elements

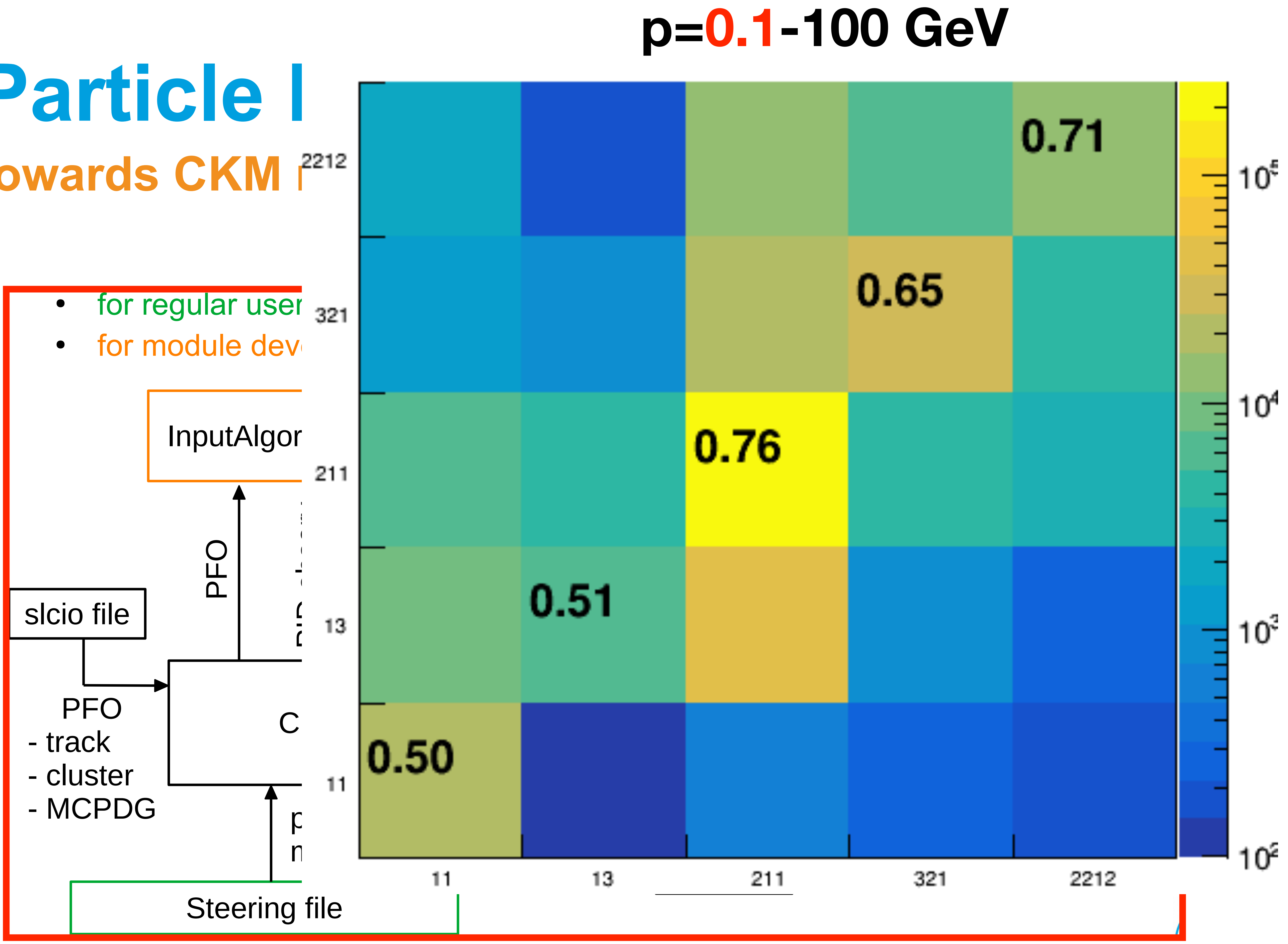


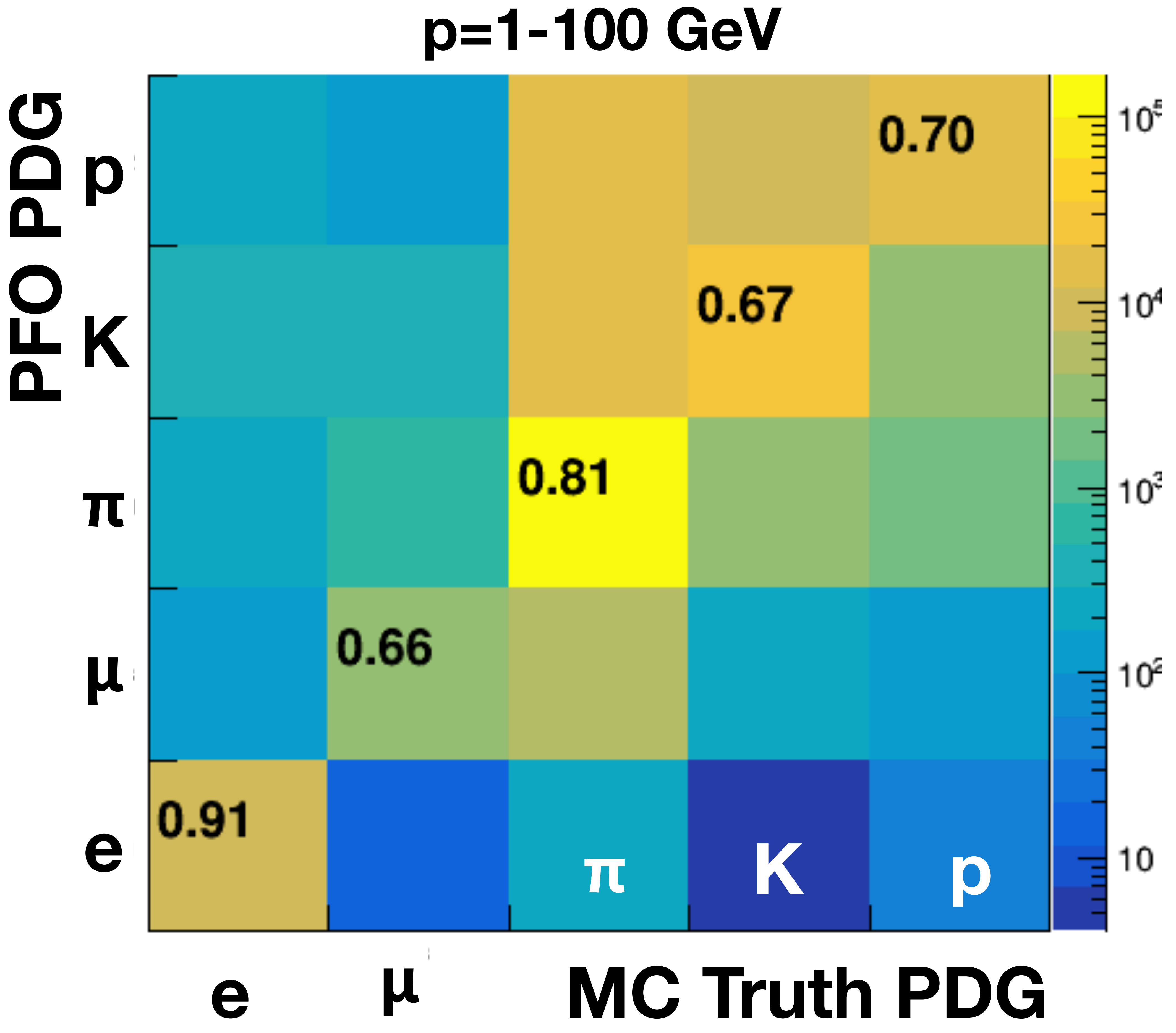


- recent addition to MarlinReco: Comprehensive PID (CPID)
- new: trainings for single particles, ee->qq and ee-> qqqq
- use as imput for ML flavourtag

Particle I

towards CKM r





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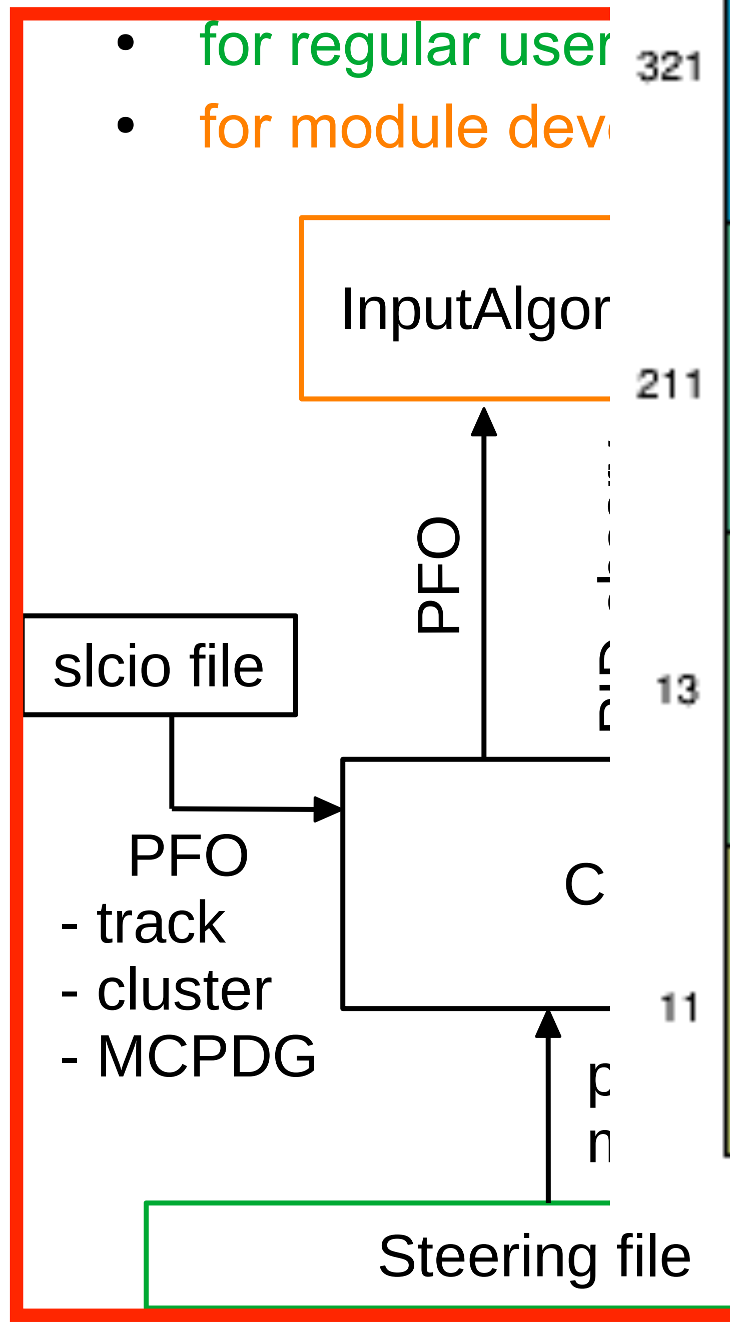

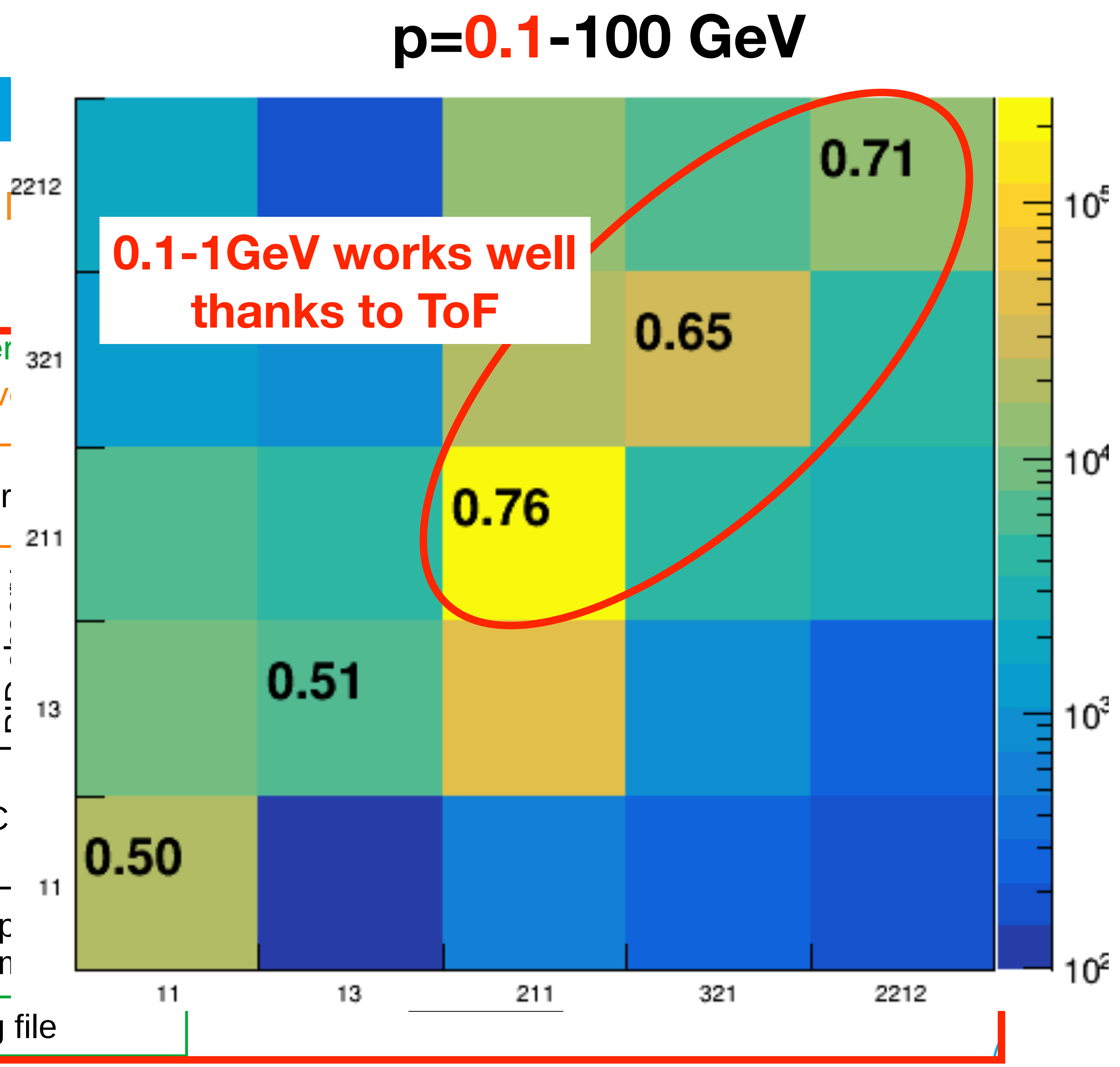

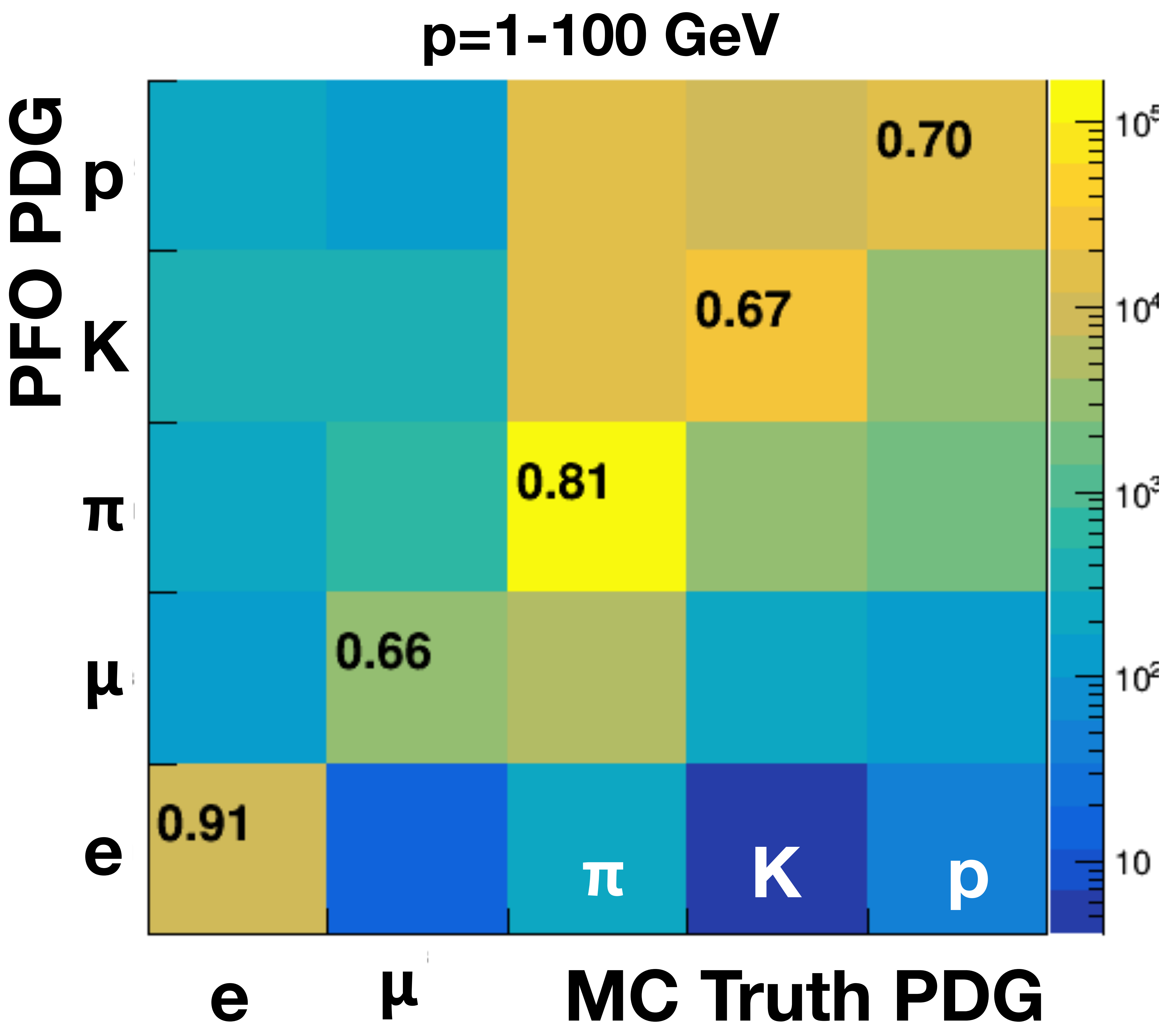

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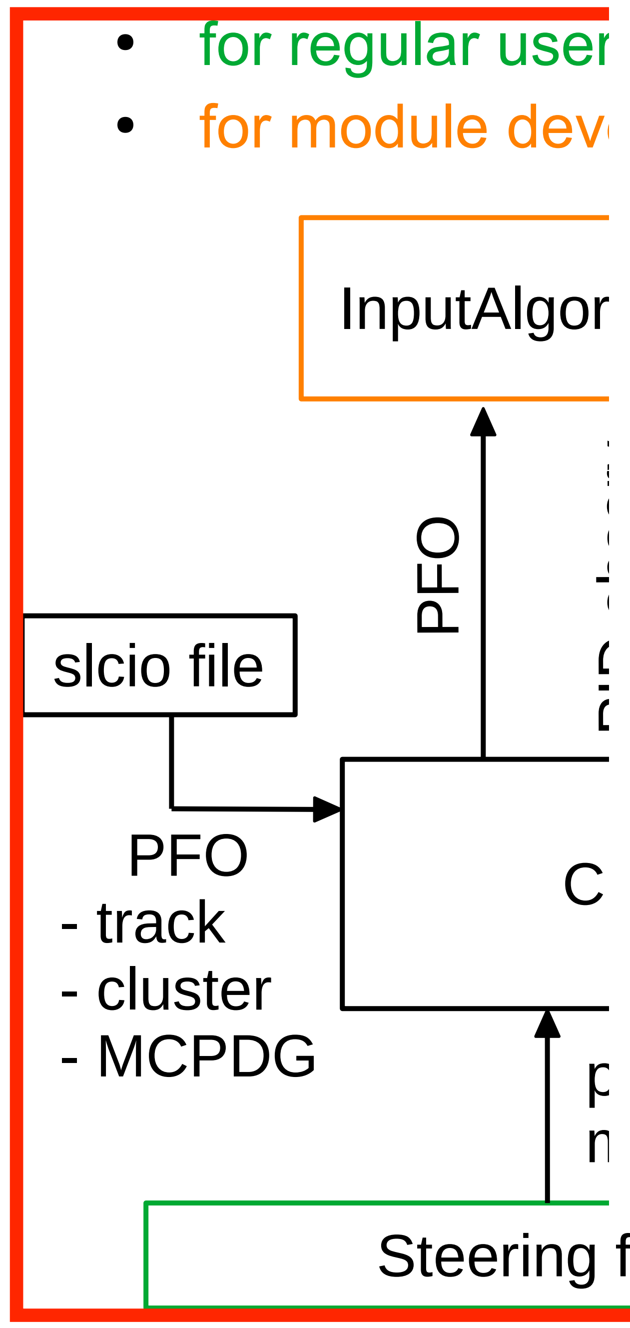

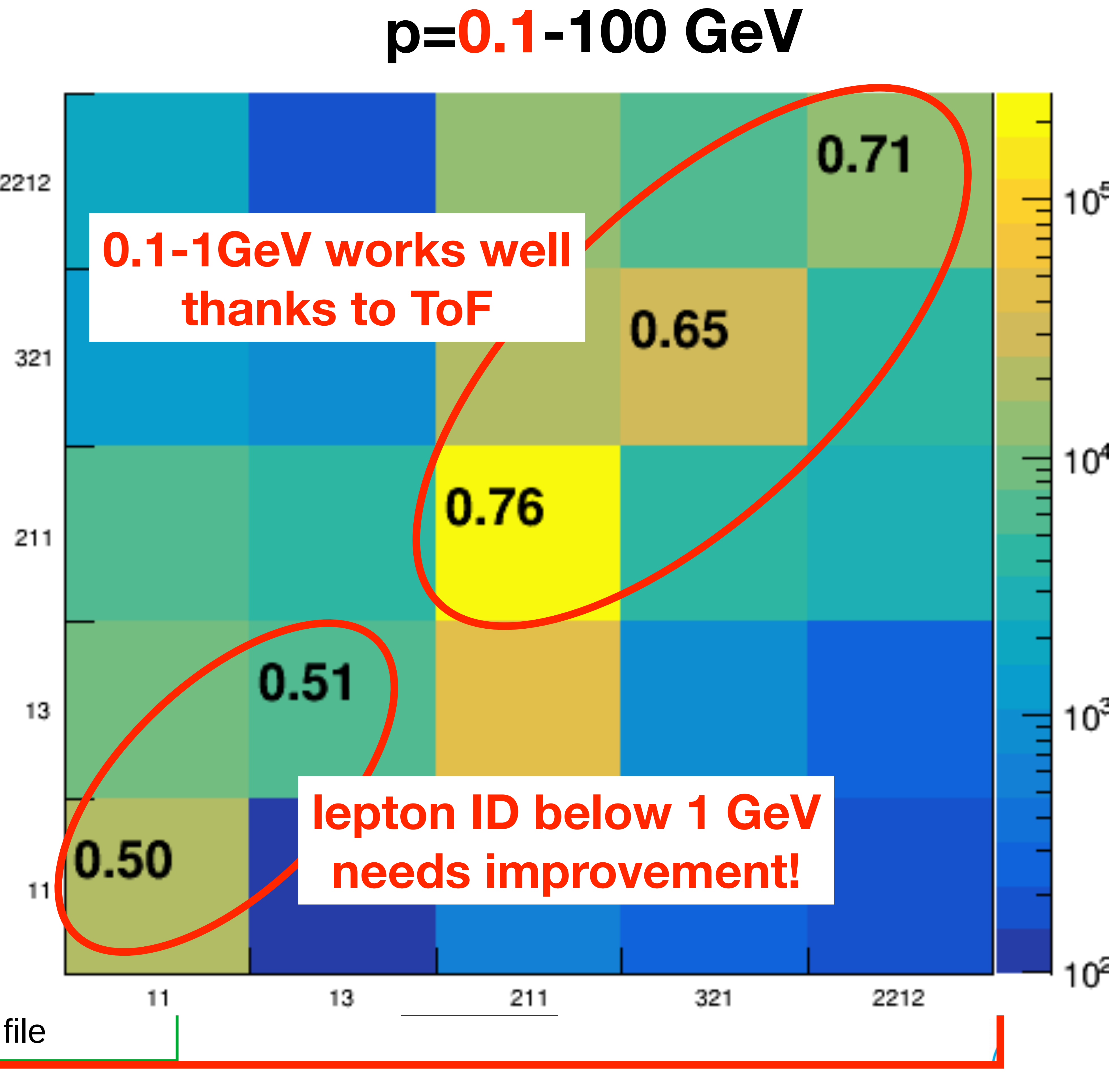

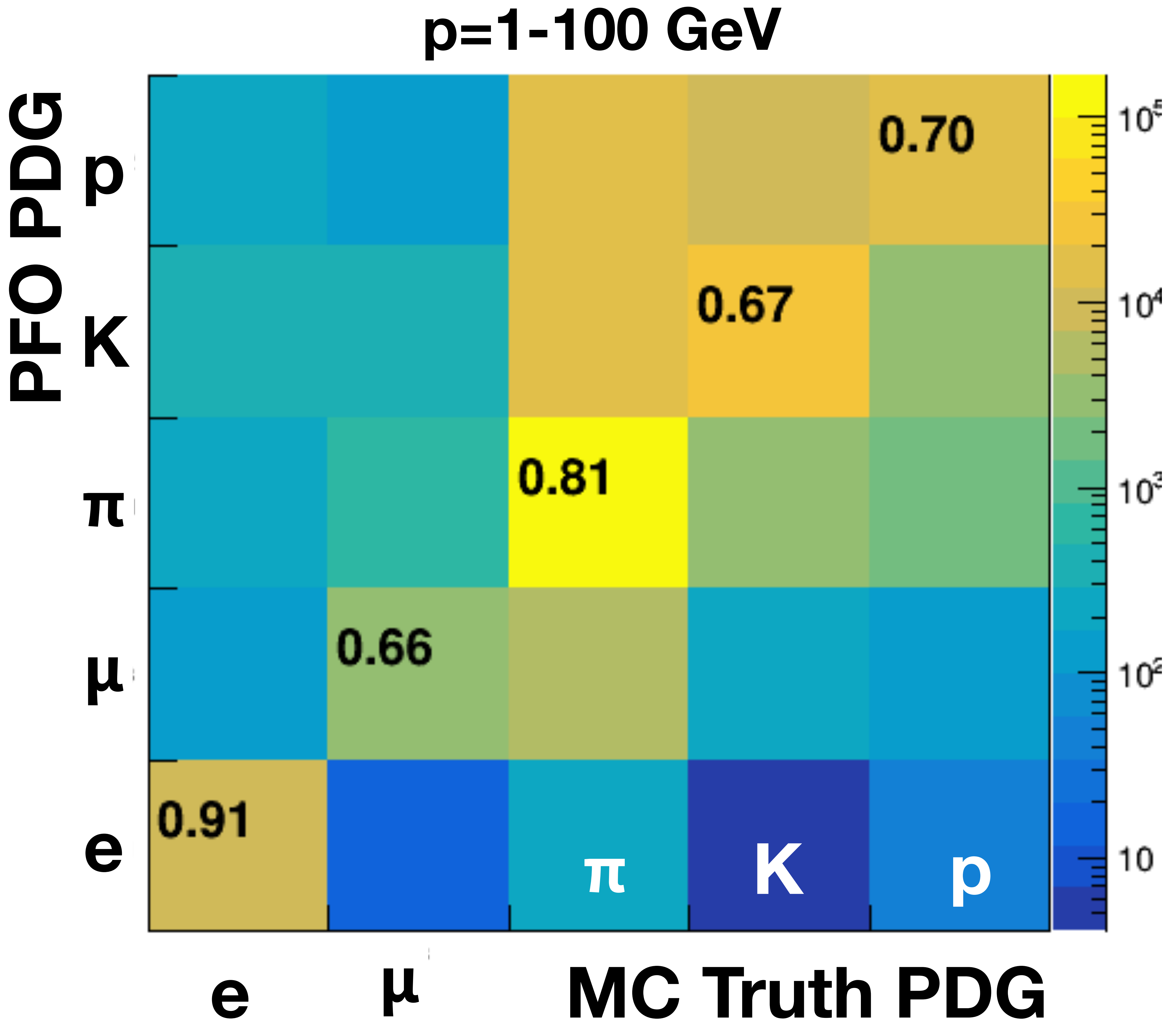

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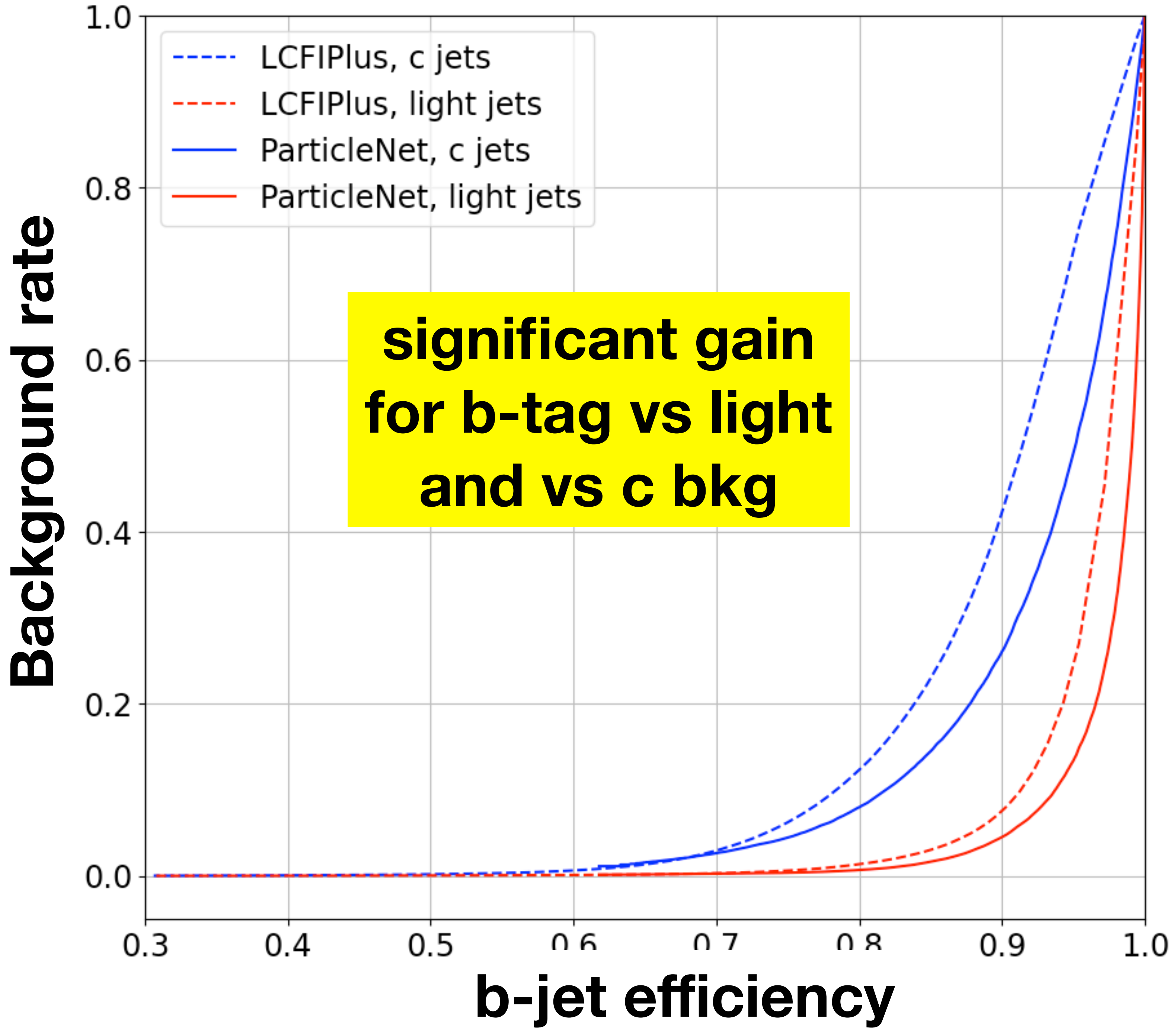
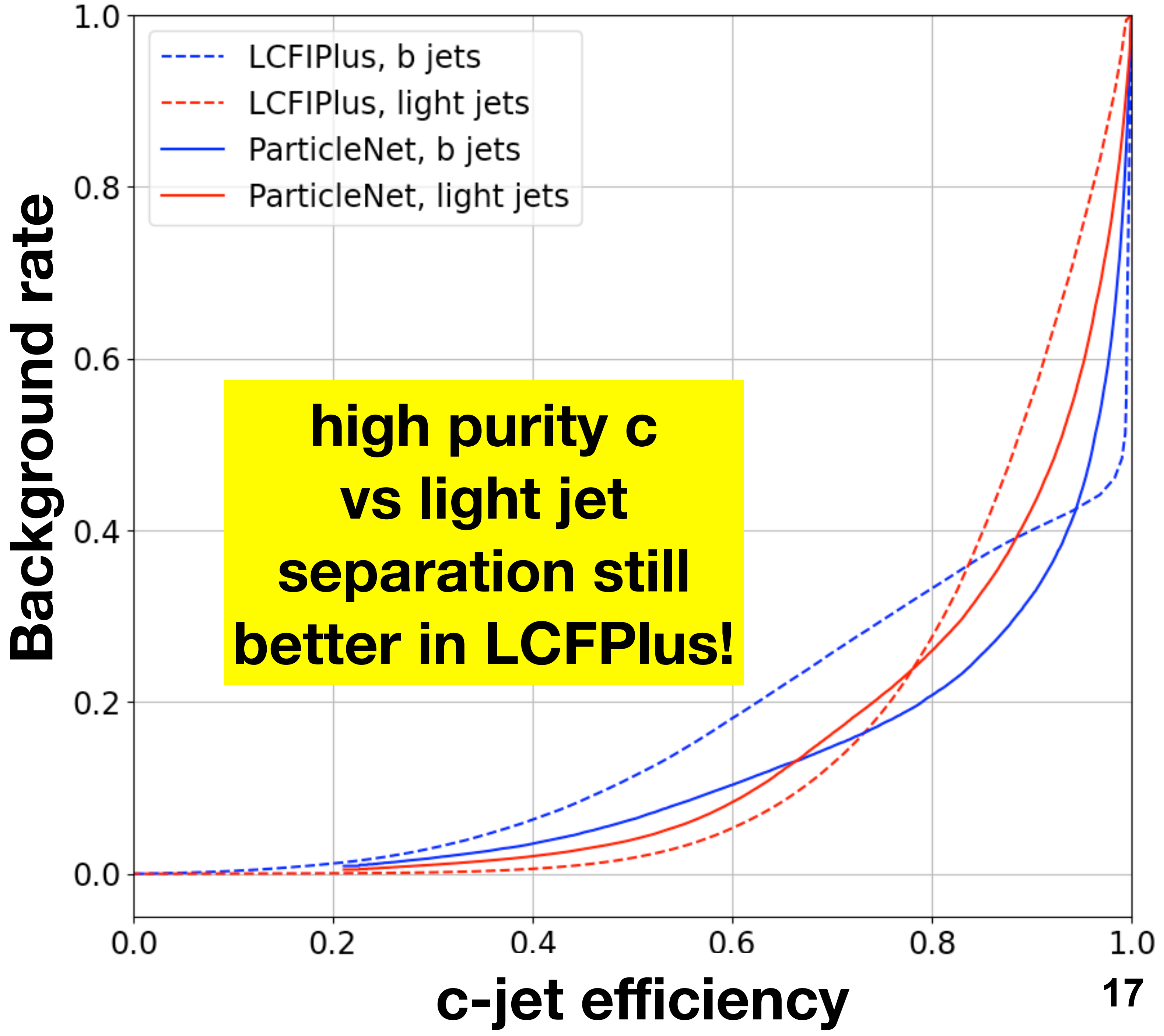
FlavourTag beyond LCFIPlus

towards CKM matrix elements

- Flavour Tagging being revolutionized by ML
  - Example here: **`FlavorTaggingML`** — ParticleNet adapted to ILD (M. Meyer / F. Gaede)
  - many others (M. Selvaggi, T. Suehara, M. Ruan…) even better, e.g. Transformer based
- **Application in physics analysis requires more than a nice ROC curve => need inference from Marlin / Gaudi!**
- for **`FlavorTaggingML`** training and inference now available from Marlin, via **`MarlinMLFlavorTagging`**
- **brand-new: integration of inference into ILD-MiniDST**
- **upcoming: new training including full CPID and s-tagging**





Conclusions

and Outlook

- W's are an integral part of the physics program of future e+e- colliders
- most W physics is above threshold
- **several new results / analyses contributing to ECFA Higgs Factory study**
- TGCs
  - great place to look for new physics
  - beam polarisation and high energy boost sensitivity
  - **how to best interface full experimental studies with global interpretations?**
  - **extension to more general WWV vertex (incl. CPV etc)?**
- CKM MEs
  - complementary to B-decays, independent theory uncertainties
  - competitive measurents possible for Vcb and others
  - great impact from new ML-based flavour taggers
  - likely limited by experimental systematics (tagging efficiencies, background,…)
- **ongoing ILD/CLD:**
  - inclusion of single-W processes => improvement of forward electron reconstruction
  - coherent approach to include all WW / single-W channels
  - application of new PID and flavour tagging tools