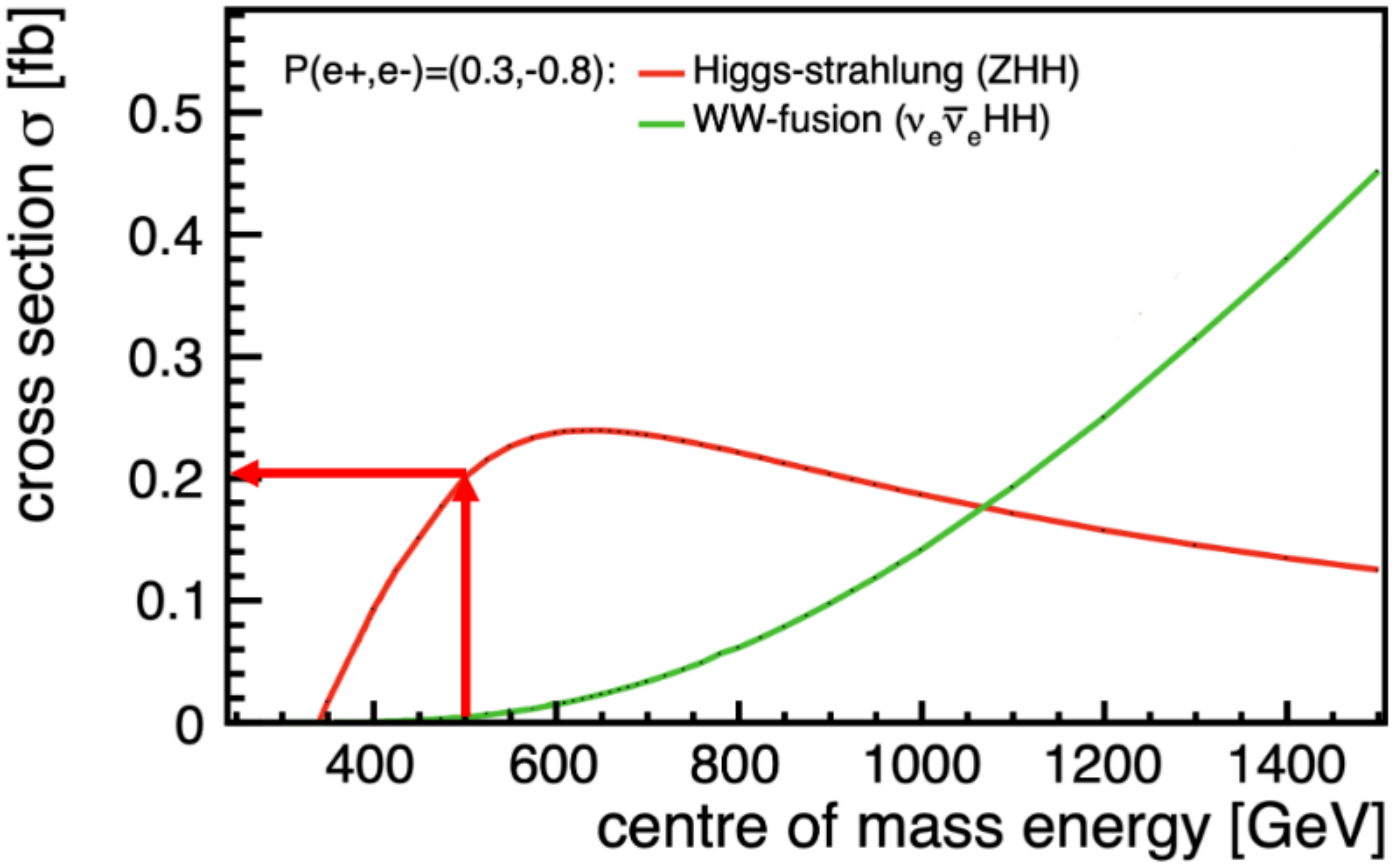
Update on new Higgs self-coupling study

For the ECFA Higgs Factory Report

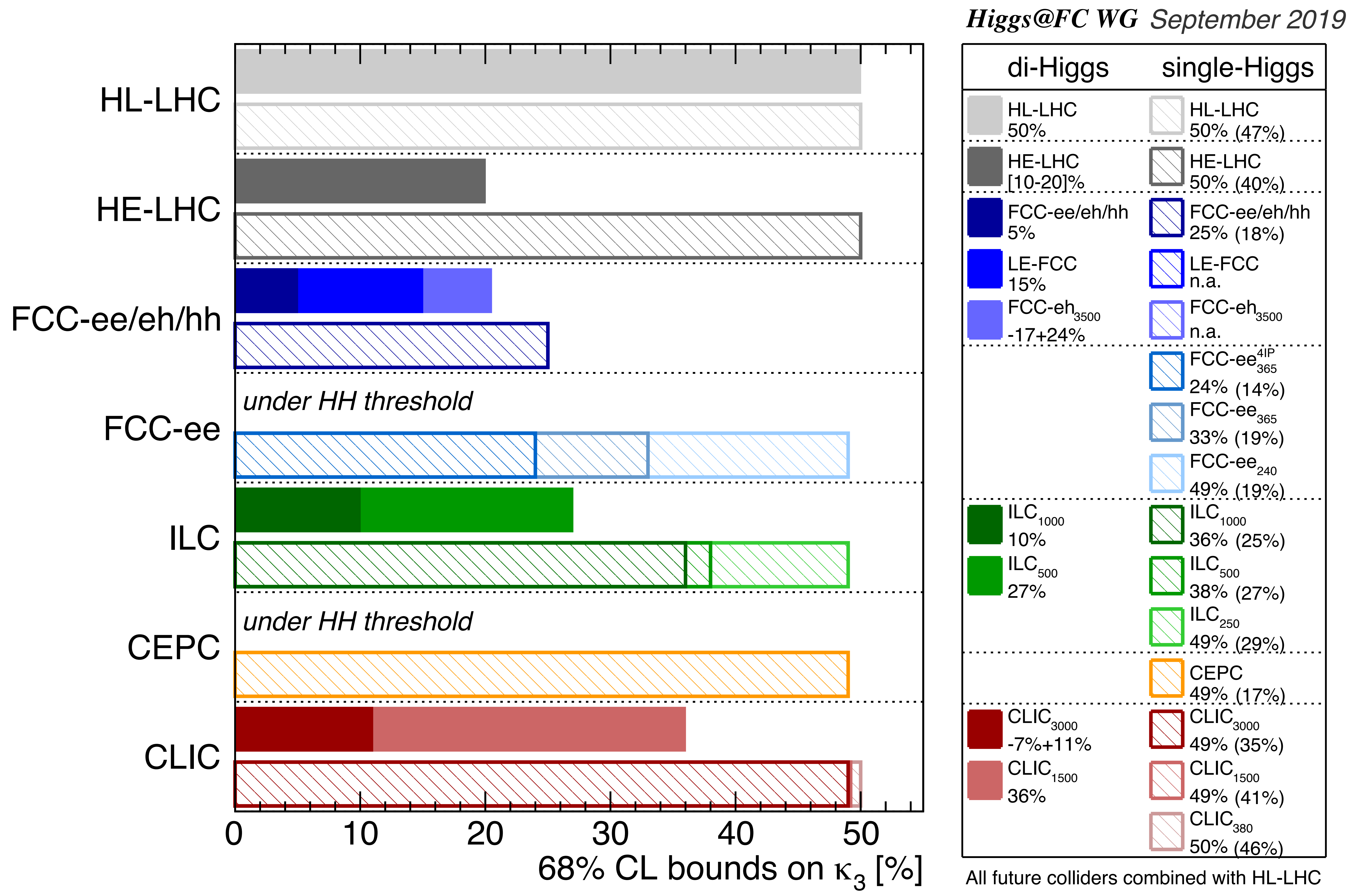
Bryan Bliewert (DESY/UHH), Jenny List (DESY),
Dimitris Ntounis (SLAC), Taikan Suehara (U Tokyo),
Junping Tian (U Tokyo), Julie Torndal (DESY/UHH),
Caterina Vernieri (SLAC)

ILD Software & Analysis Meeting, Jan 21 2025



Motivation I

Higgs self-coupling as key part of physics case for e+e- collisions at >= 500 GeV



Key question of the community in the upcoming EPPSU: **Will a Linear Collider do any better than the HL-LHC ?**

HL-LHC update will only be known from their strategy submission, but we should not be surprised if from the previous 50% -> 25%

— for the SM case!

Apples - Oranges - Pears

A slide from Marcel's talk at the LC Vision Community Event

Top Yukawa coupling comparison

M. L. Mangano et al., *Measuring the Top Yukawa Coupling at 100 TeV*, J. Phys. G **43** (2016) 035001, DOI: 10.1088/0954-3899/43/3/035001, arXiv: 1507.08169 [hep-ph].

Z. Liu et al., *Top Yukawa coupling determination at high energy muon collider*, Phys. Rev. D **109** (2024) 035021, DOI: 10.1103/PhysRevD.109.035021, arXiv: 2308.06323 [hep-ph].

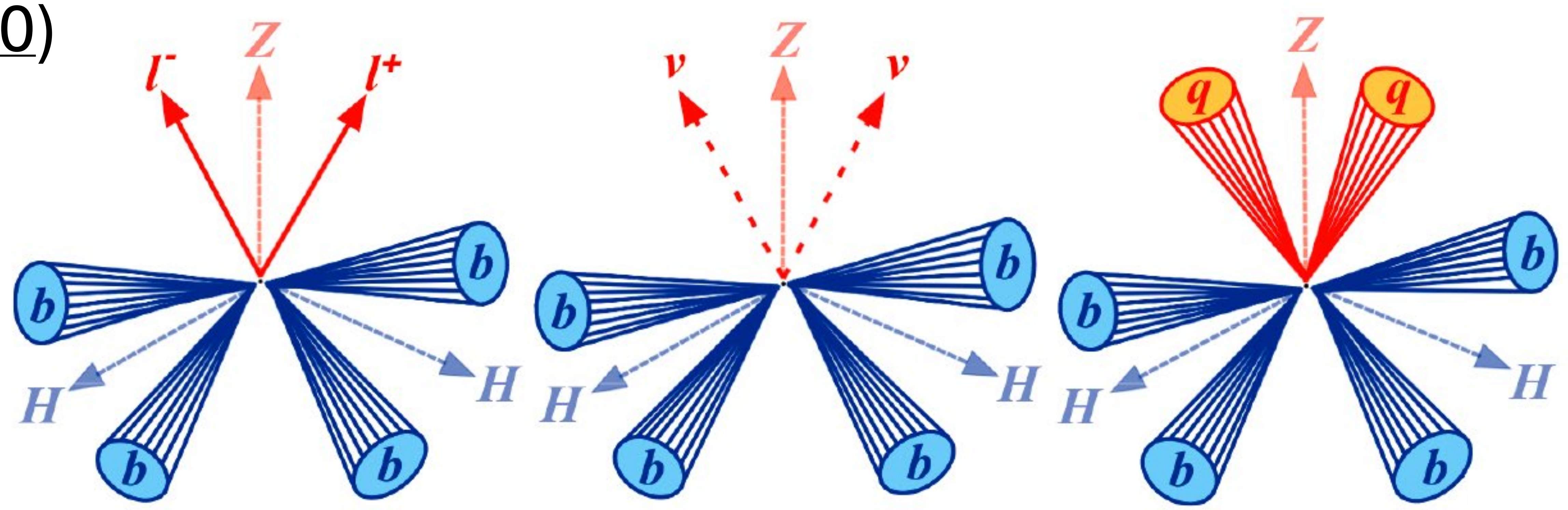
S2 projection: "apples" — LC prospects: "oranges" — Theory studies: "pears"

Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC	FCChh	μ-coll
δy_t	Global fit	12%	5.1%	3.1%	2.6%	1.5%	3.0%	-	-
	Indiv. fit	10%	3.7%	2.8%	2.3%	1.4%	2.5%	1%	1.5%

The previous ZHH Analysis

ILC500 based on ILD DBD2013

- extensive projections at ILC500 (DESY-Thesis-16-027)
  - based on ILD detector concept (DBD2013, IDR2020) and *fully simulated* event samples
  - 17 background and 3 signal channels considered
  - multivariate (MVA) tools for multiple steps
    e.g. lepton and flavor tagging, background rejection etc.
  - event counting weighted by m_{HH}^2
    for further sensitivity enhancement



Lepton, neutrino and hadron channel of the signal process ZHH.
From [Du16]

- precision reach after running $4\mathrm{ab}^{-1}$ at $500\ \mathrm{GeV}$ $\left(\mathrm{HH} \to \mathrm{b\bar{b}b\bar{b}} + \mathrm{HH} \to \mathrm{b\bar{b}W^{\pm}W^{\mp}}\right)$

$$\Delta\sigma_{\mathrm{ZHH}}/\sigma_{\mathrm{ZHH}} = 16.8\%$$

$$\Delta\lambda_{\mathrm{SM}}/\lambda_{\mathrm{SM}} = 26.6\% \quad (10\% \text{ with additional upgrade to } 1\ \mathrm{TeV})$$

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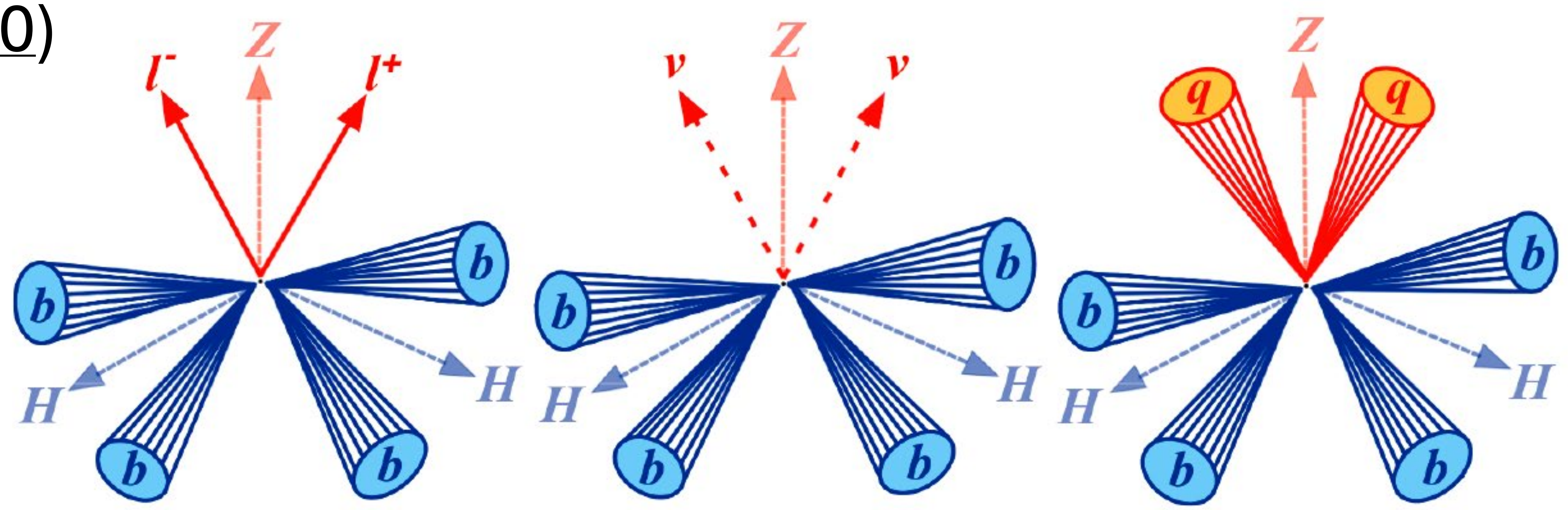

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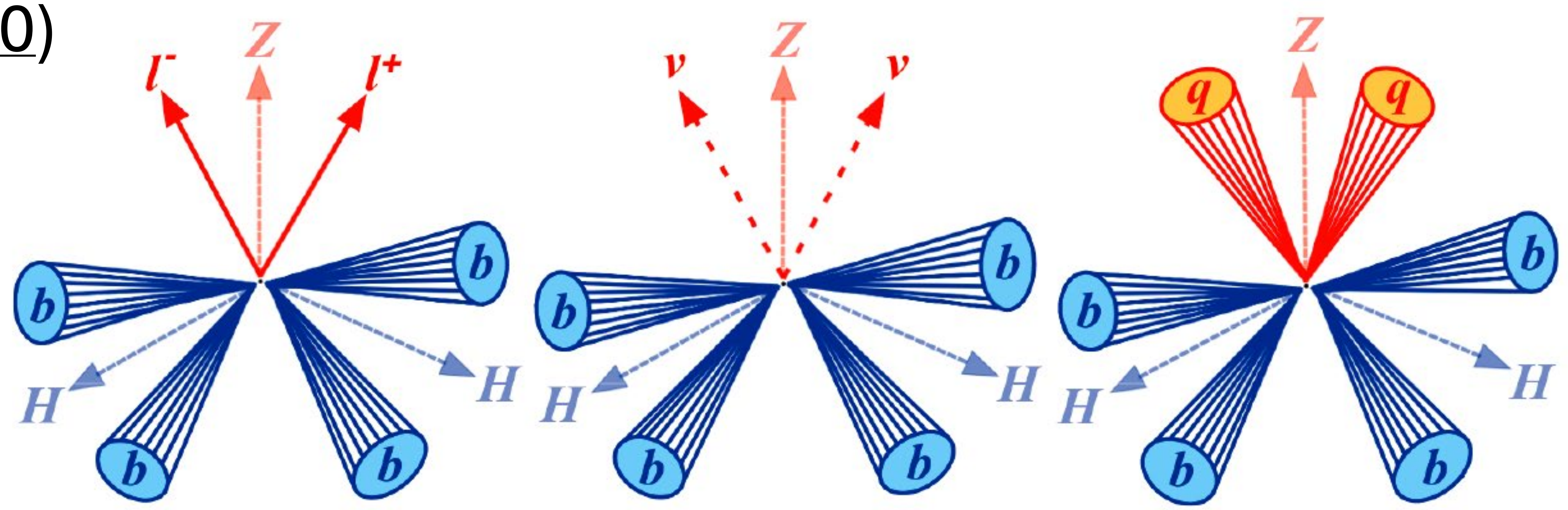

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only 3.x σ observation of λ_{SM}

Bottlenecks of the ZHH analysis

As identified during 2014 analysis and (relative) improvement impact

- jet pairing and jet misclustering: “perfect“ jet clustering $\rightarrow$ 40% improvement
  improve di-jet mass resolution
- removal of $\gamma\gamma$ overlay: 15% improvement expected
  also: improve ISR reconstruction
- flavor tagging: 11% improvement expected from 5% eff. increase with newer LCFIPlus
  important as $H \rightarrow b\bar{b}$ is the dominant Higgs decay channel
- adding $Z \rightarrow \tau\tau$ channel: 8% improvement expected
  include a yet unaccounted decay channel
- more modern ML architectures for signal/background selection
  improvement expected when transitioning from BDTs to (e.g.) transformer-based models etc.
- separation of ZHH diagrams with/without the self-coupling
  would directly improve the sensitivity on λ (lower sensitivity factor)

Expected relative improvements from DESY-Thesis-16-027

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if 25% (rel.) improvement out of (a combination) of these
=> 5 σ discovery of λ_{SM}

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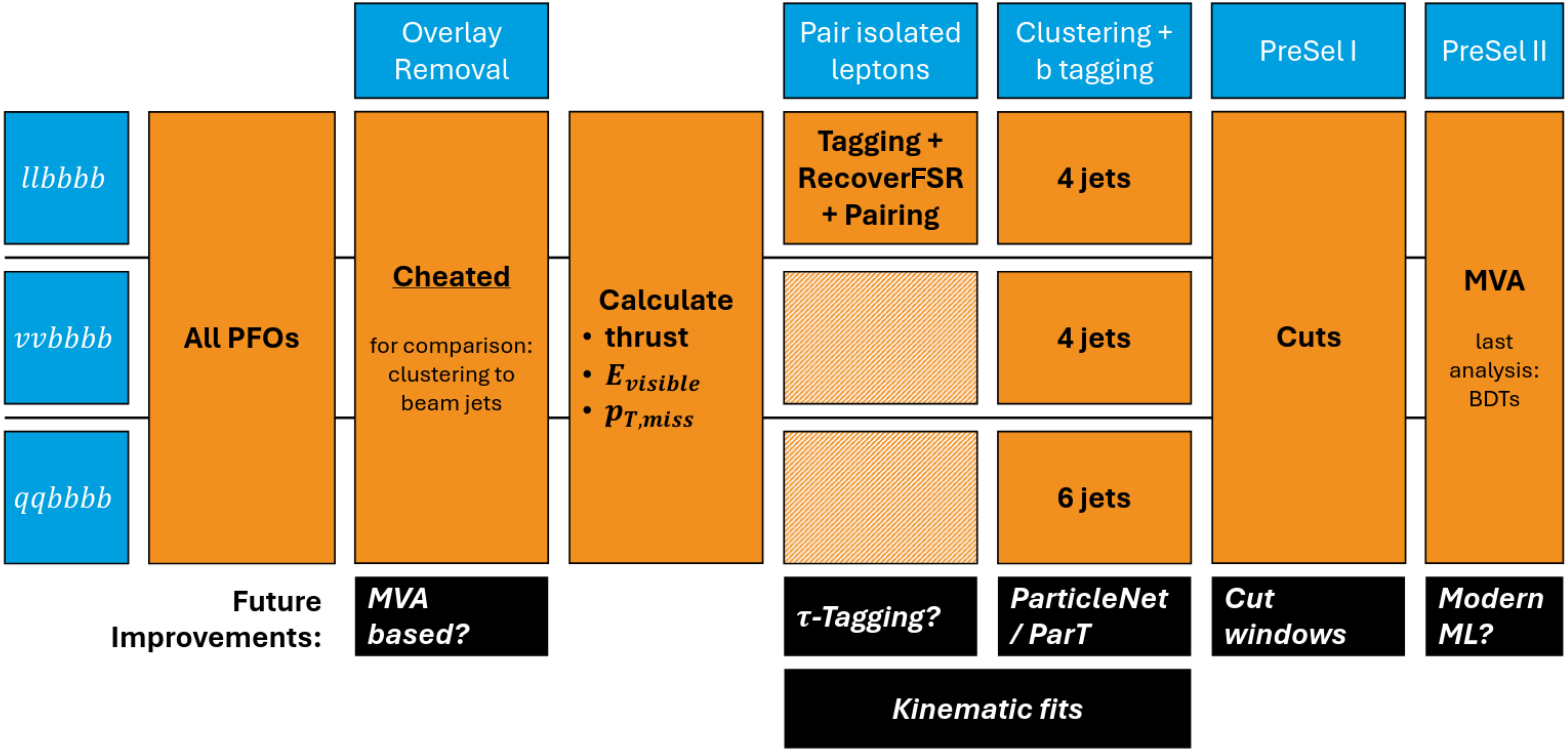
Towards a full update of the di-Higgs analysis

Analysis Flow — set up and working to a large extent



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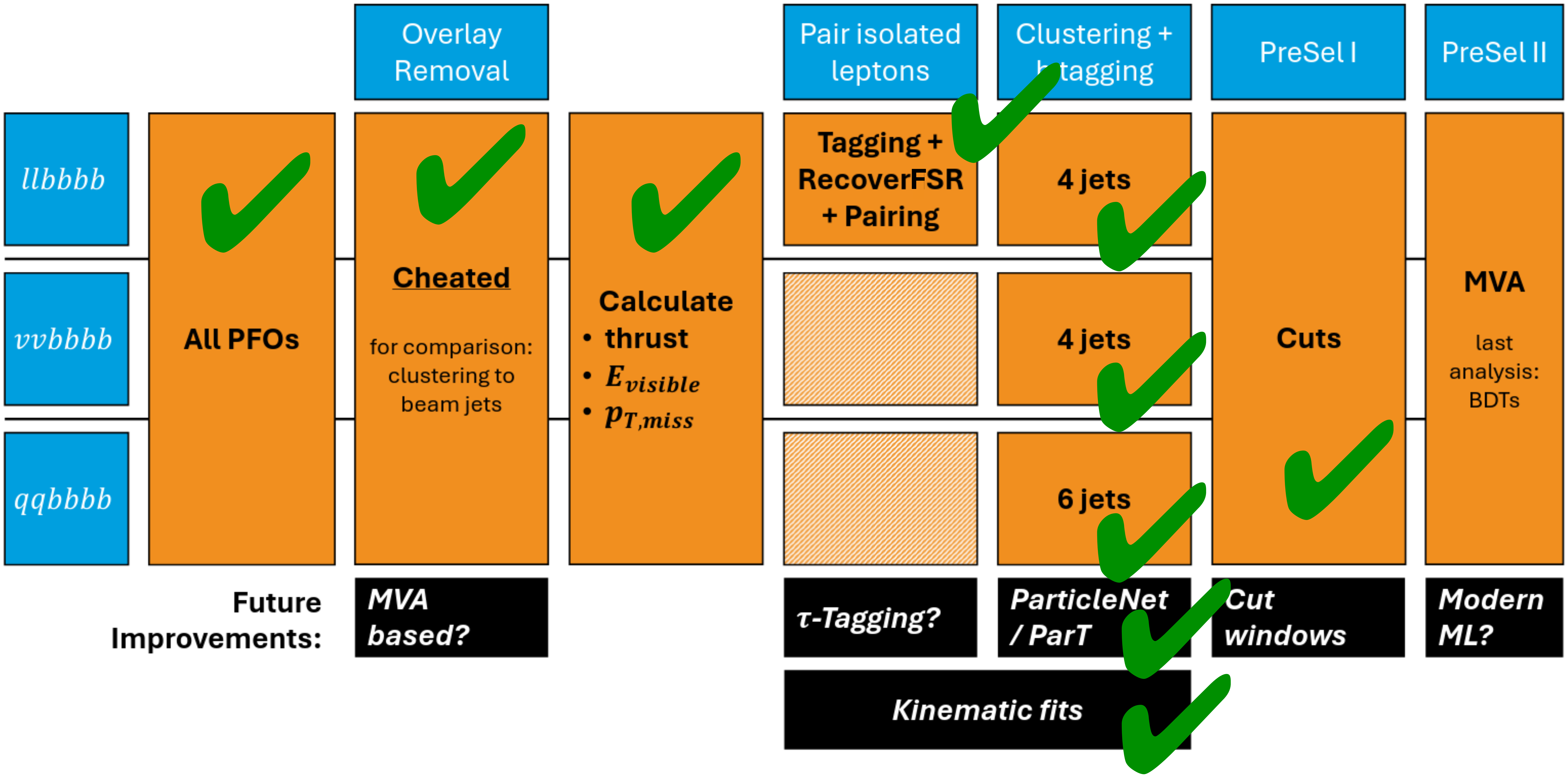

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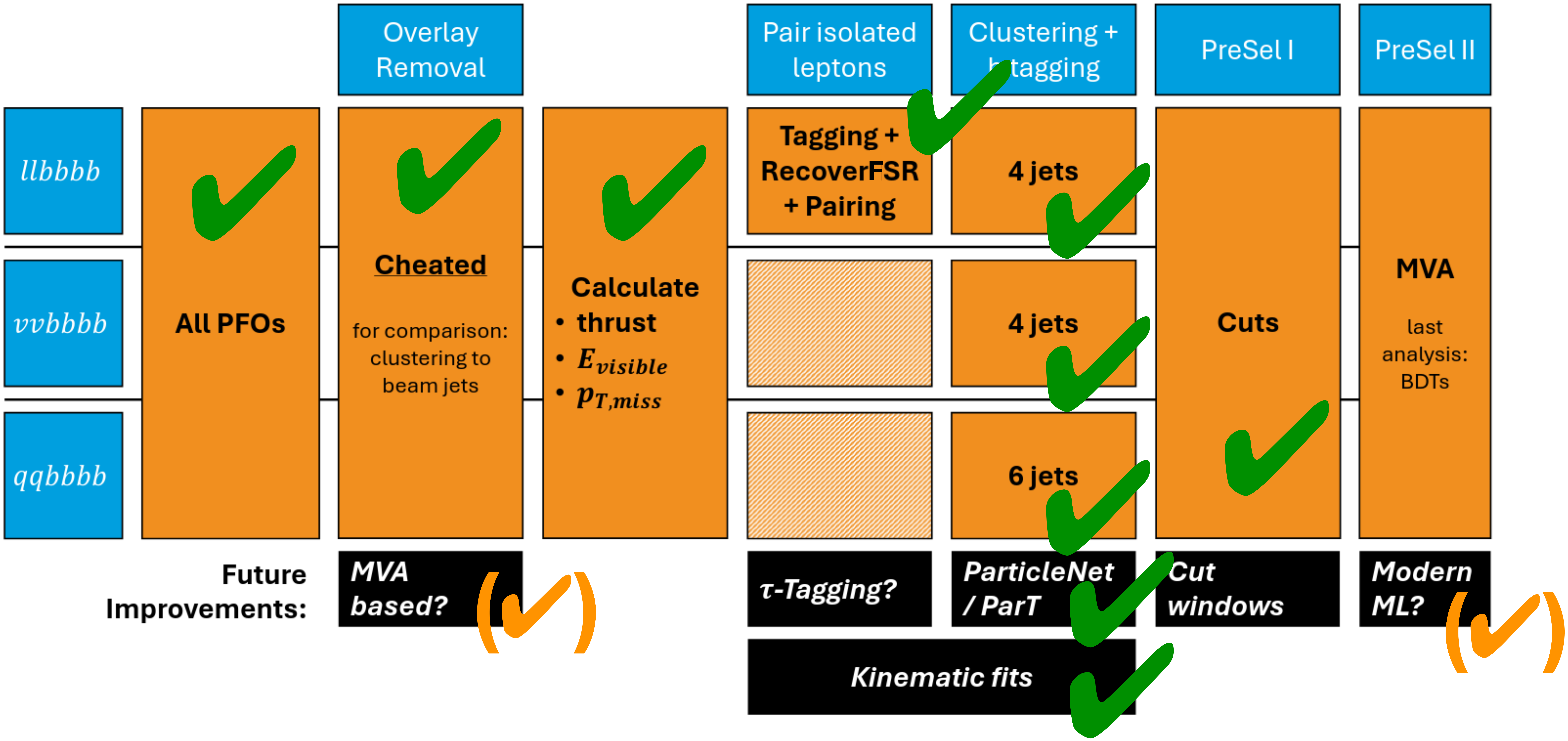

And in addition…

… and some missing things

- **MC samples**
  - “ZHH” and “ZZH” generated, simulated, reconstructed in 2022/23
  - SM backgrounds at 500 GeV from IDR production —- modern PID not available
  - would like to move full analysis to 550 GeV
  - new production at 550 GeV underway, 2f / 4f generated, 6f / 8f wip
  - SGV / full sim comparison very successful => can use SGV for evaluating bulk background rejection
- **Flavour tagging**
  - major progress with actually applying ML in analysis
  - ML tools require huge training samples => SGV, wip
- **kinematic reconstruction and general event selection**
  - major progress in porting semi-leptonic decay correction / kinematic fitting / matrix-elements …
  - even more expected from full ML selection
    c.f. talk by Manqi last week

- **we’re not quite there yet to run the whole analysis chain — but not far away either!**

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- **10% rel. efficiency improvement per jet @ same bkg level**
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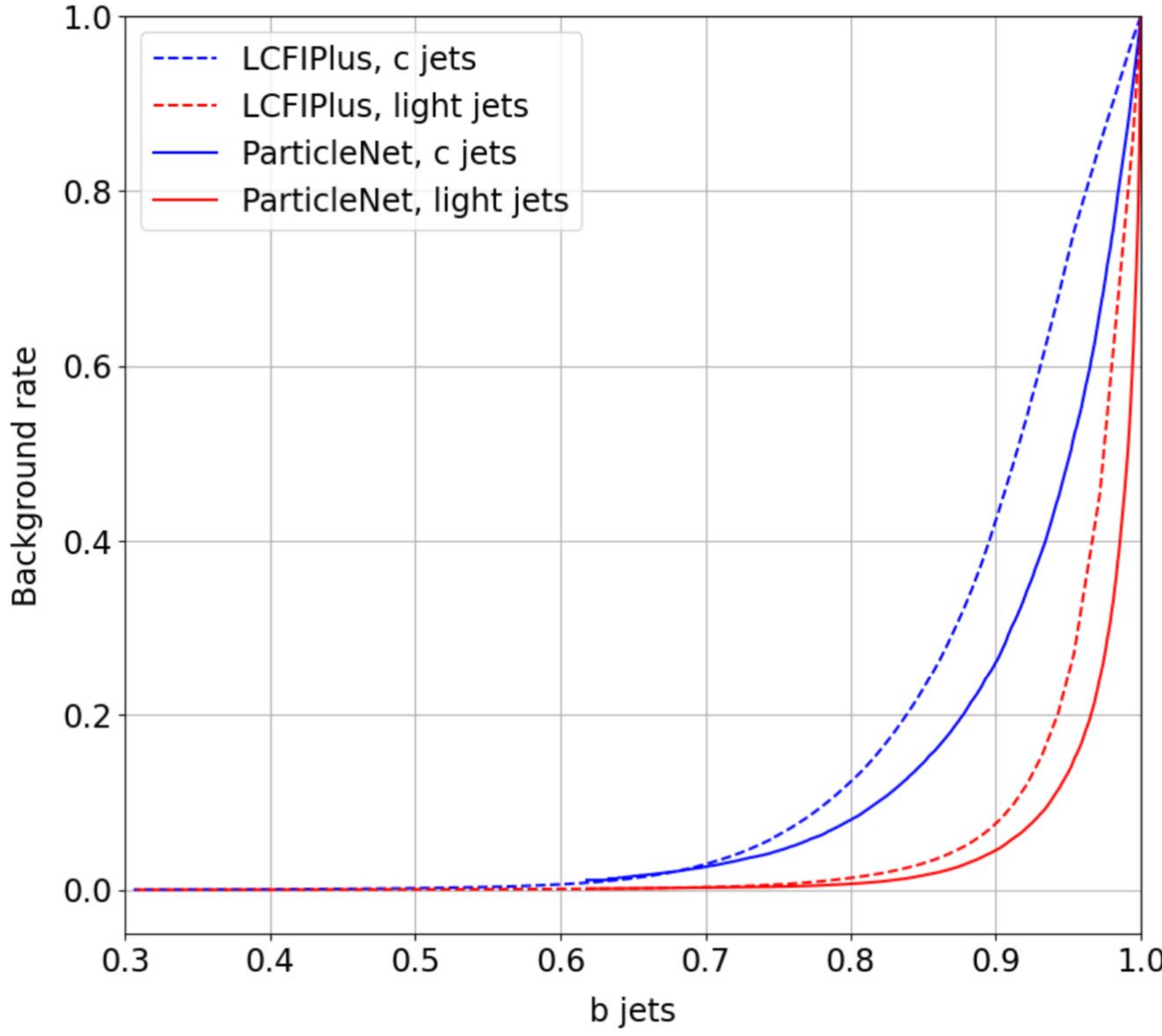
Flavour-Tagging with ML

ParticleNet and ParticleTransformer (ParT)

- significant improvements wrt LCFIPlus achieved
- NEW: receipe to perform inference from Marlin MarlinMLFlavorTagging

  => essential for application in full reconstruction & analysis chain!



Flavor tagging performance of LCFIPlus vs. ParticleNet using ILD full simulation. M. Meyer [2023]

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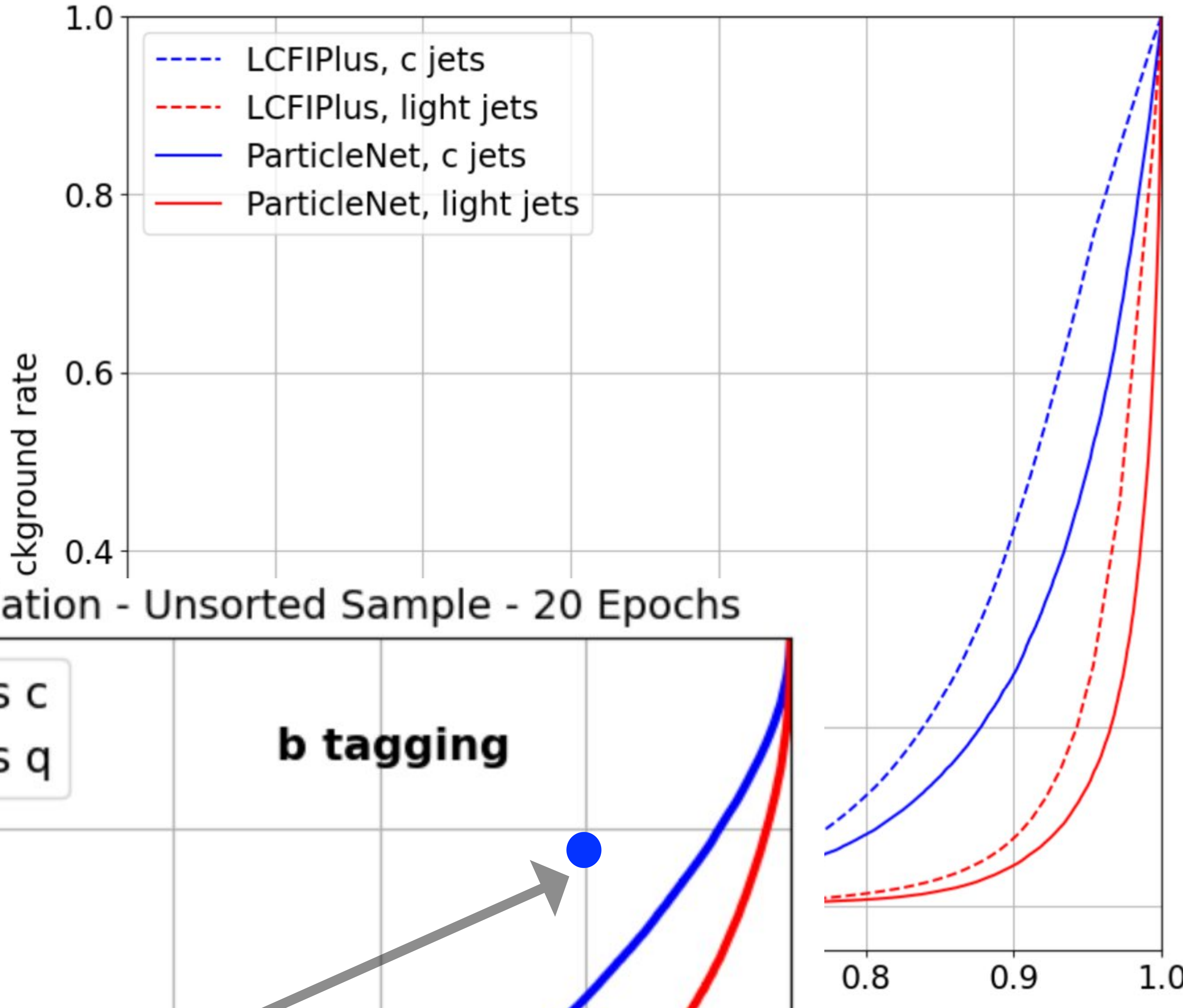

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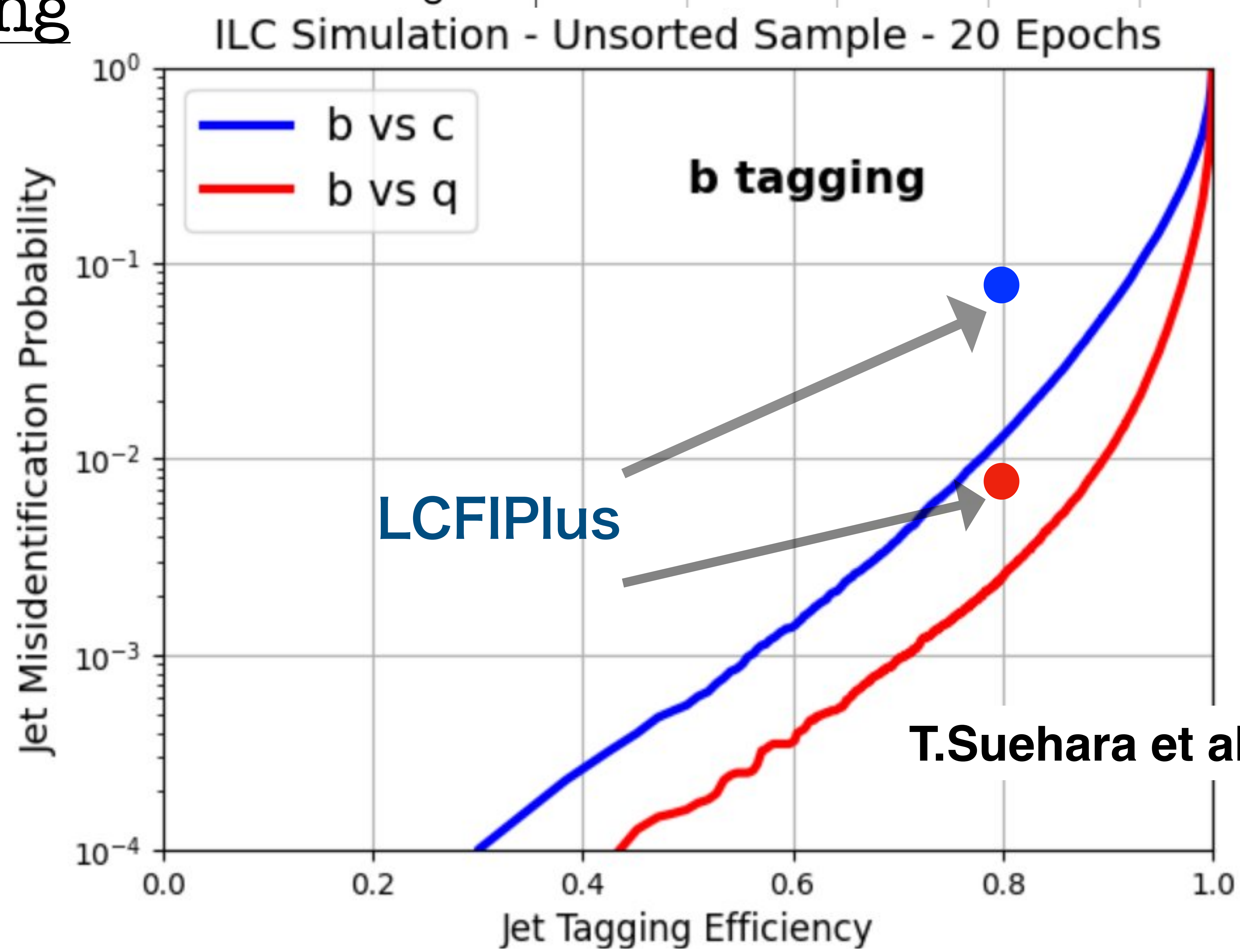

T.Suehara et al, LCWS 2024

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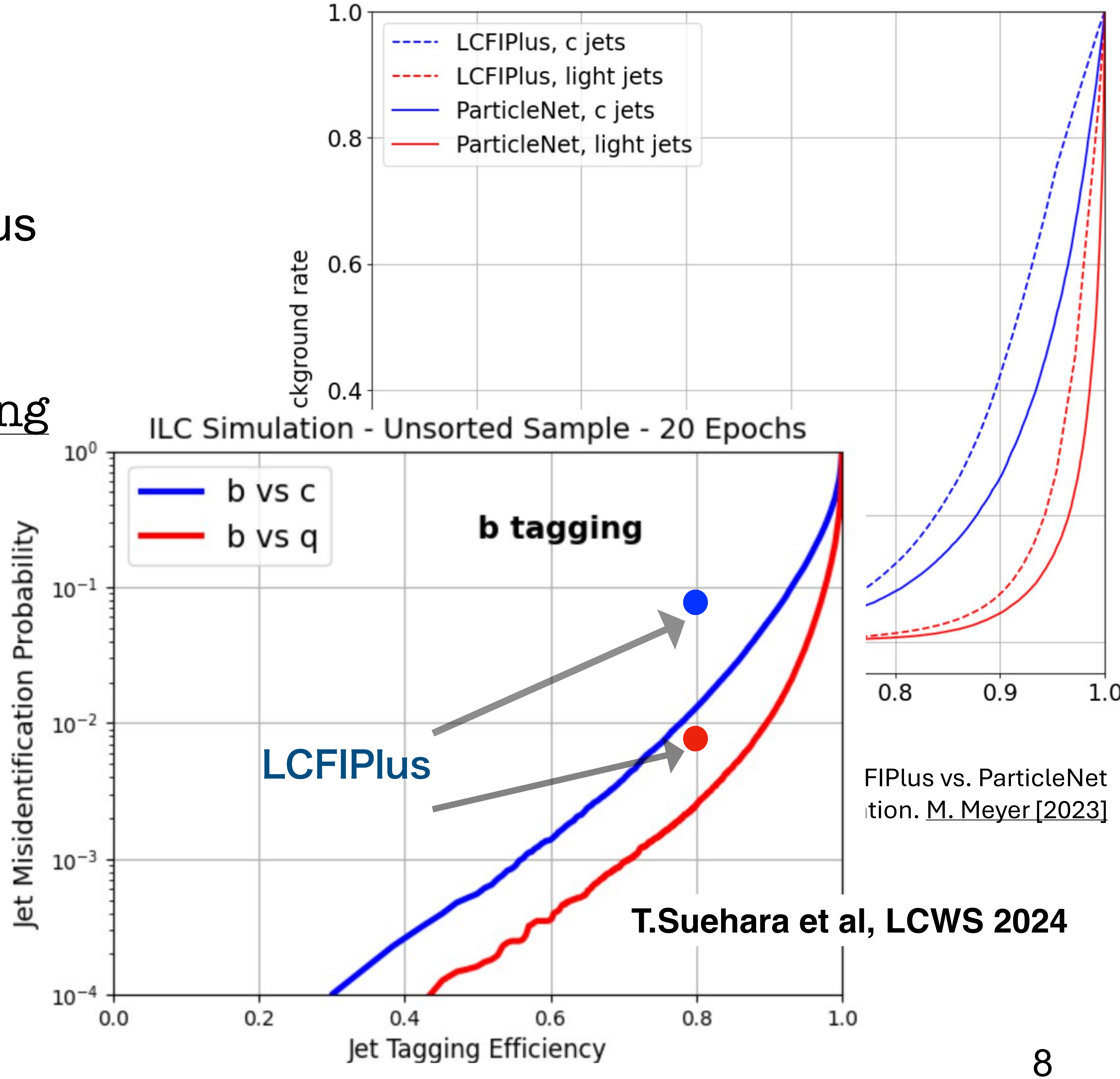
Evaluation of impact in ZHH analysis ongoing, potential improvement even larger than conceivable in 2016…



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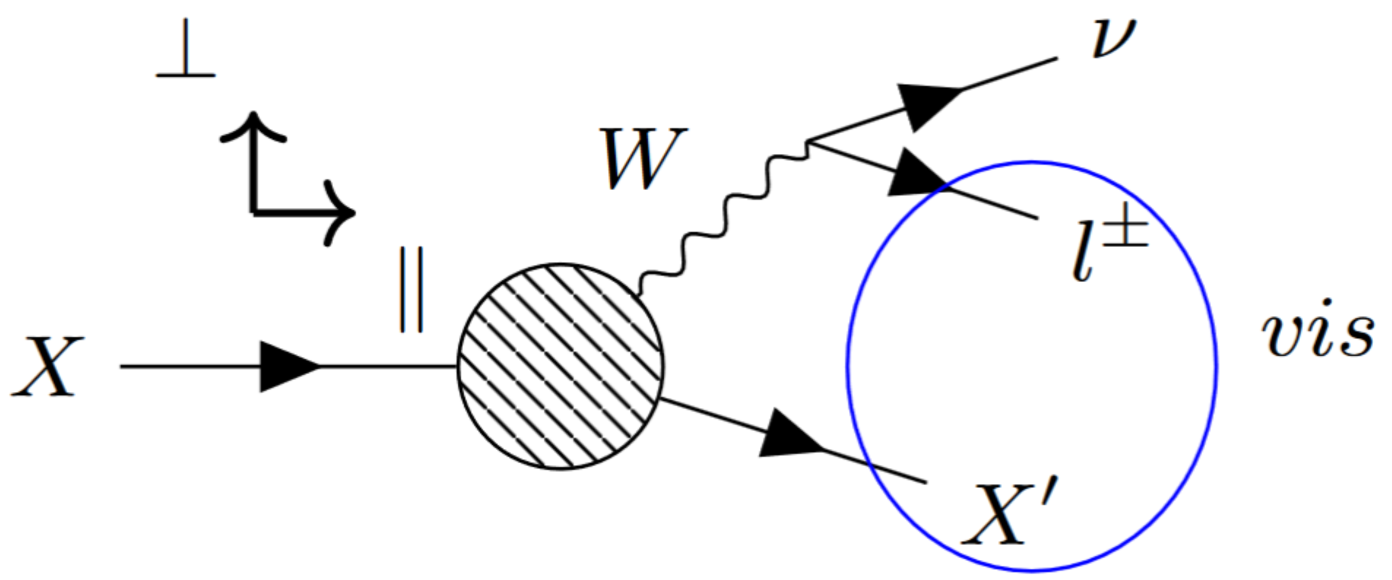
Flavour Tagging with ML

Final status for now, motivate ~10% higher efficiency at same background level

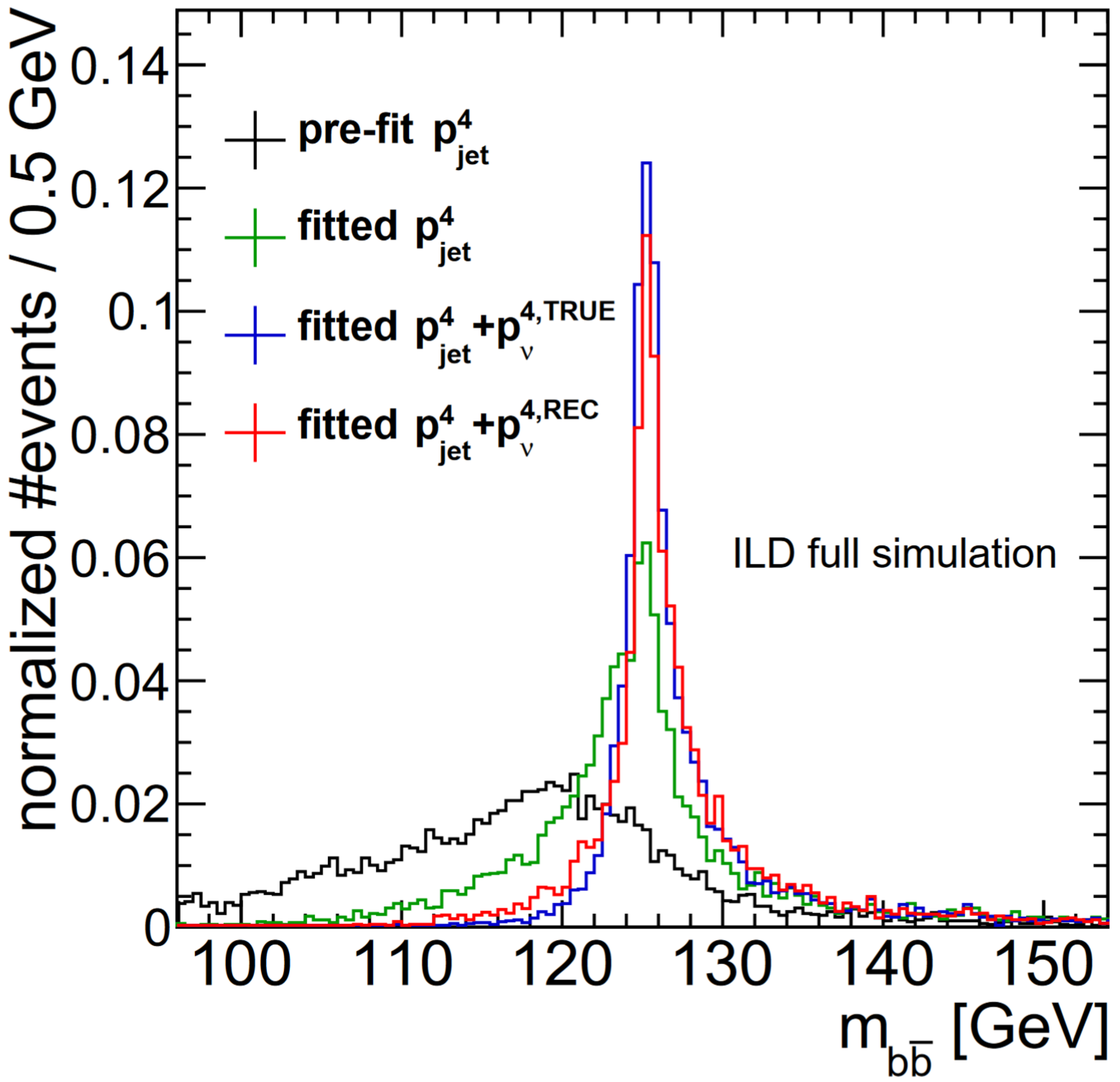
Neutrino Correction with Vertexing, PFlow and Kinematic Fit

Improved m(bb) invariant mass reconstruction

- for semileptonic decay (SLD) processes
  - already in $\mathrm{ZH} \to b\bar{b}/c\bar{c}$, 66% of events include at least one SLD
- procedure:
  - identify/tag heavy quark jet
  - identify lepton in jet
  - calculate neutrino four momentum from kinematics with kinematic fitting, the best solution is selected
- status: in production (in MarlinReco)



Recovering the neutrino kinematics. Y. Radkhorrami [2022]



Improved di-jet mass reconstruction. Y. Radkhorrami [2022]

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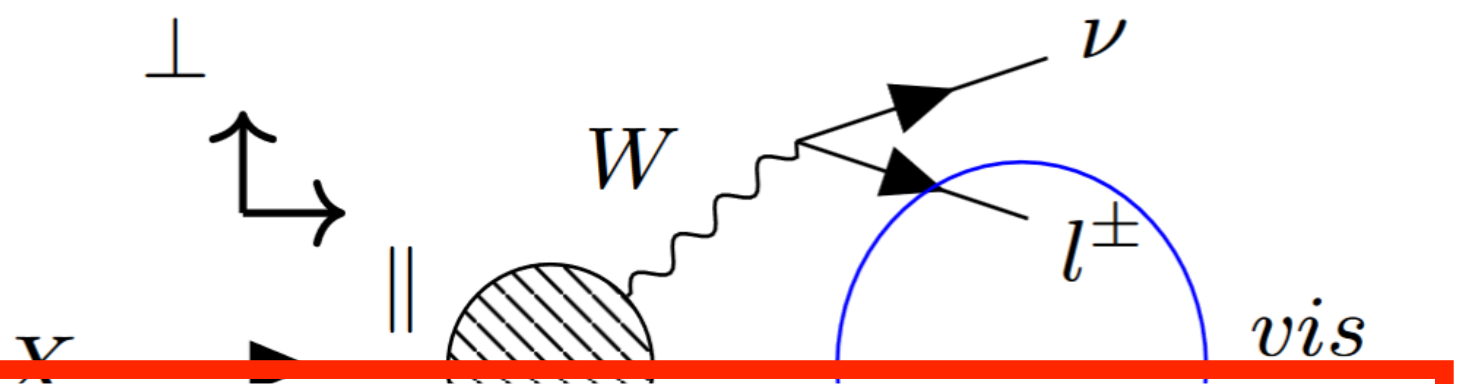
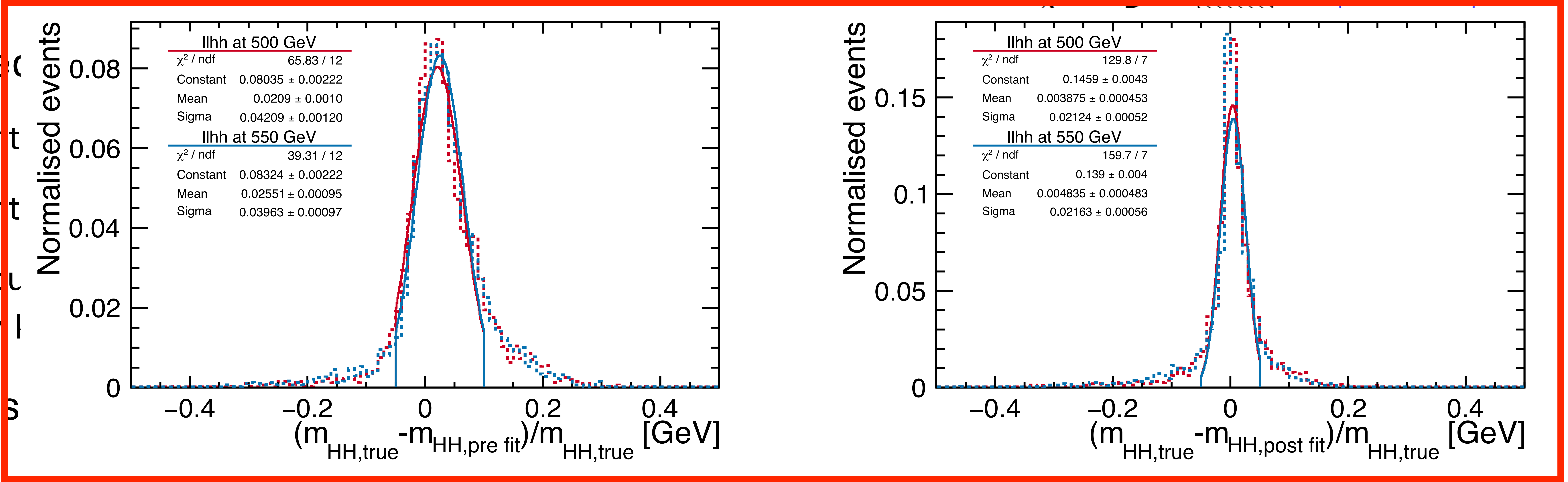
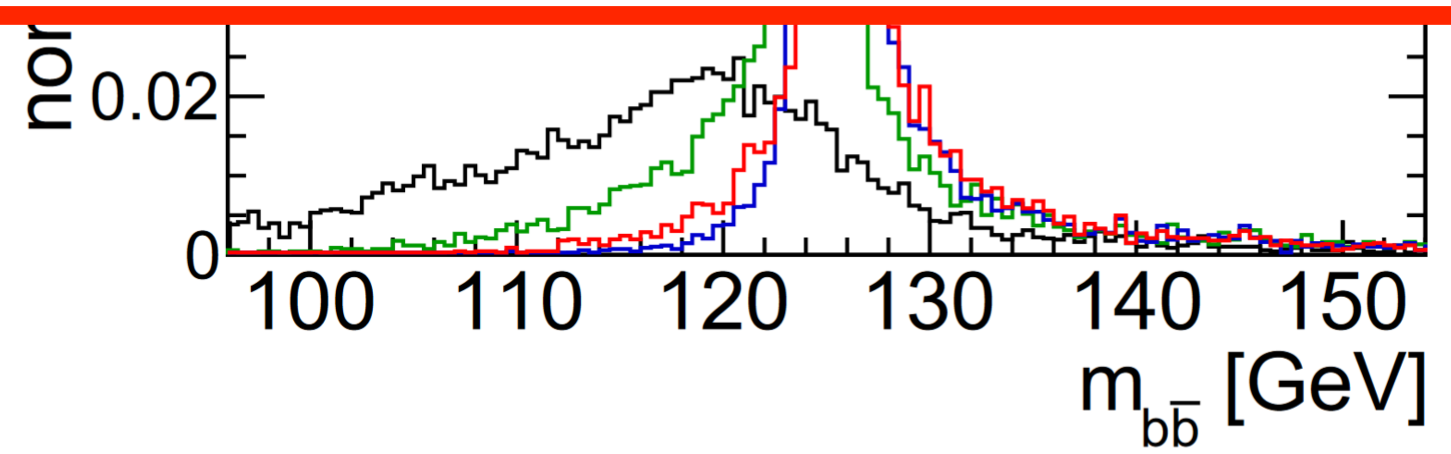




Shown to work on ZHH, twice better resolution of m(HH) cf talk by Julie Dec 4



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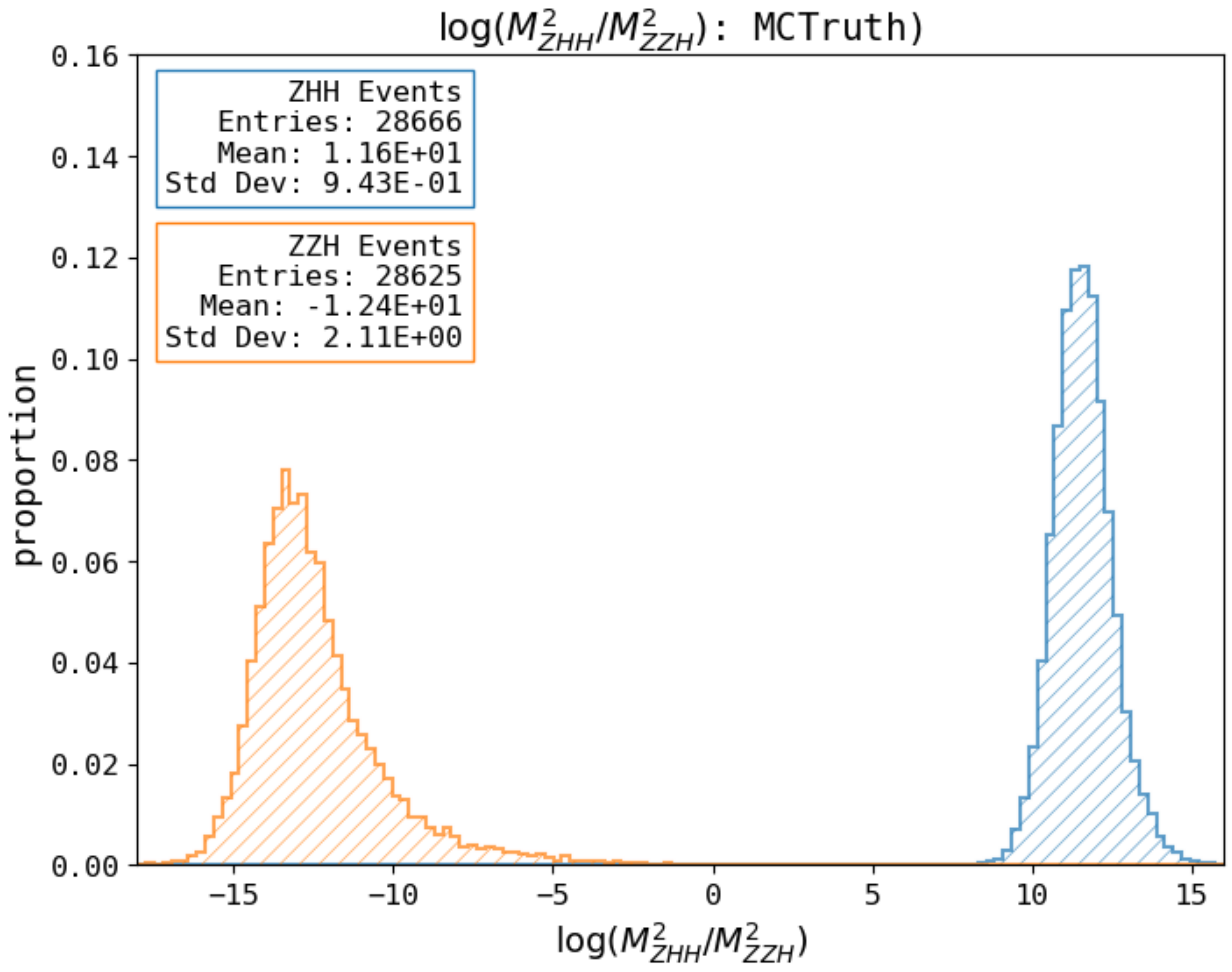
Matrixelements for ZZH / ZHH discrimination

In theory the optimal observable…

generator level check

- excellent separation

MEM type \ Event data	MC truth	Reco
ME only		
ME+DTF	-	



naive MEM

- separation power lost
  ➔ need to describe smearing with TFs

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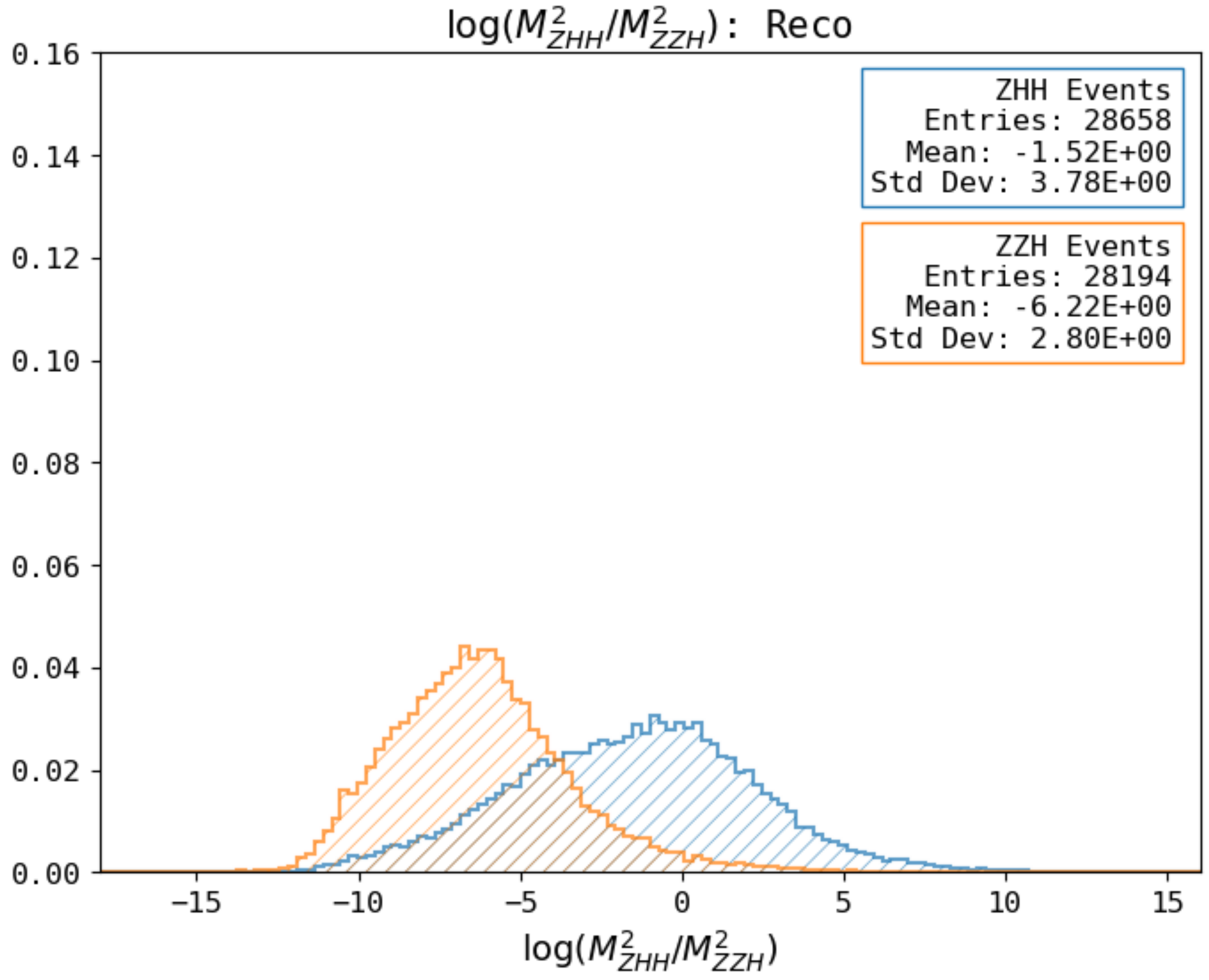

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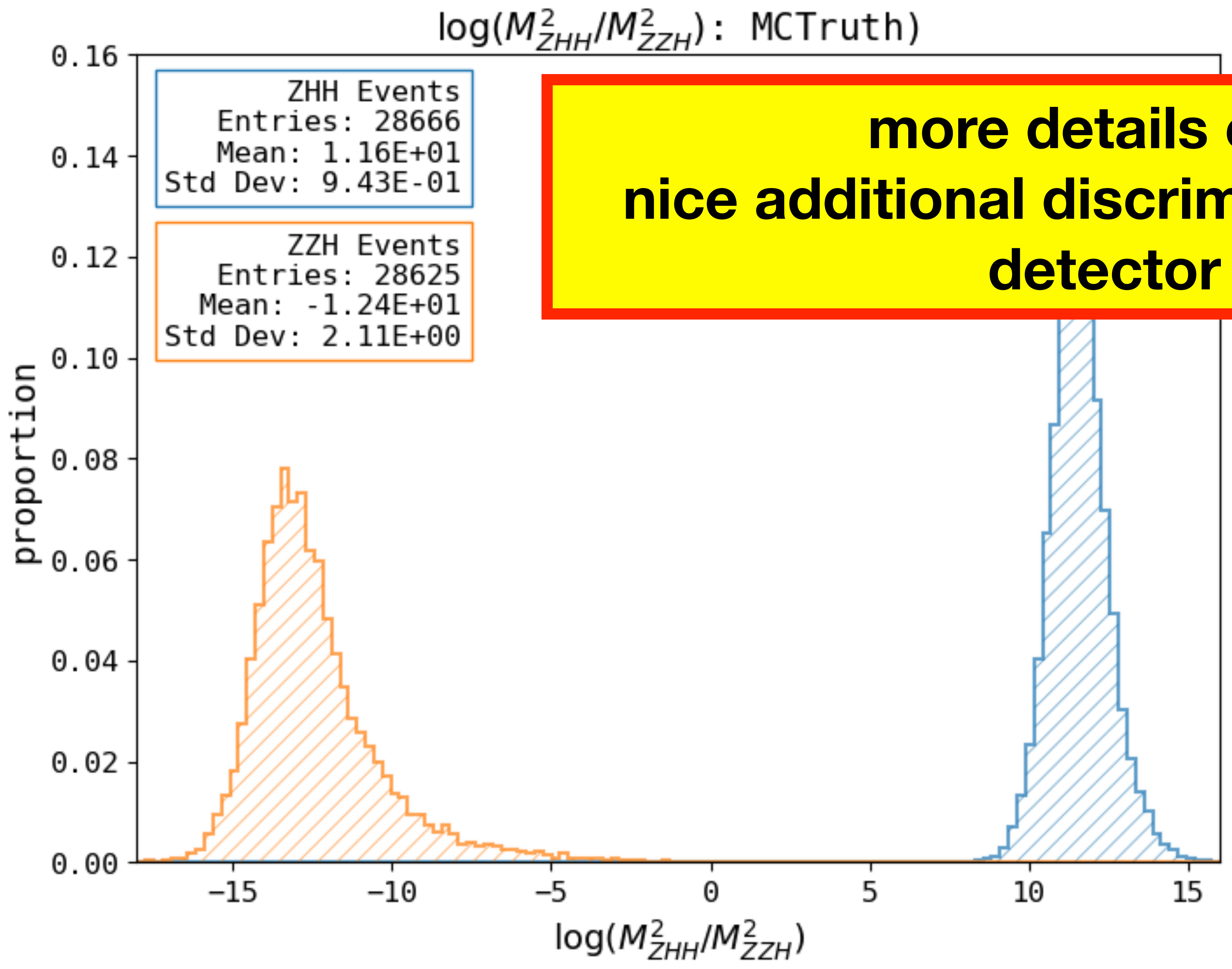
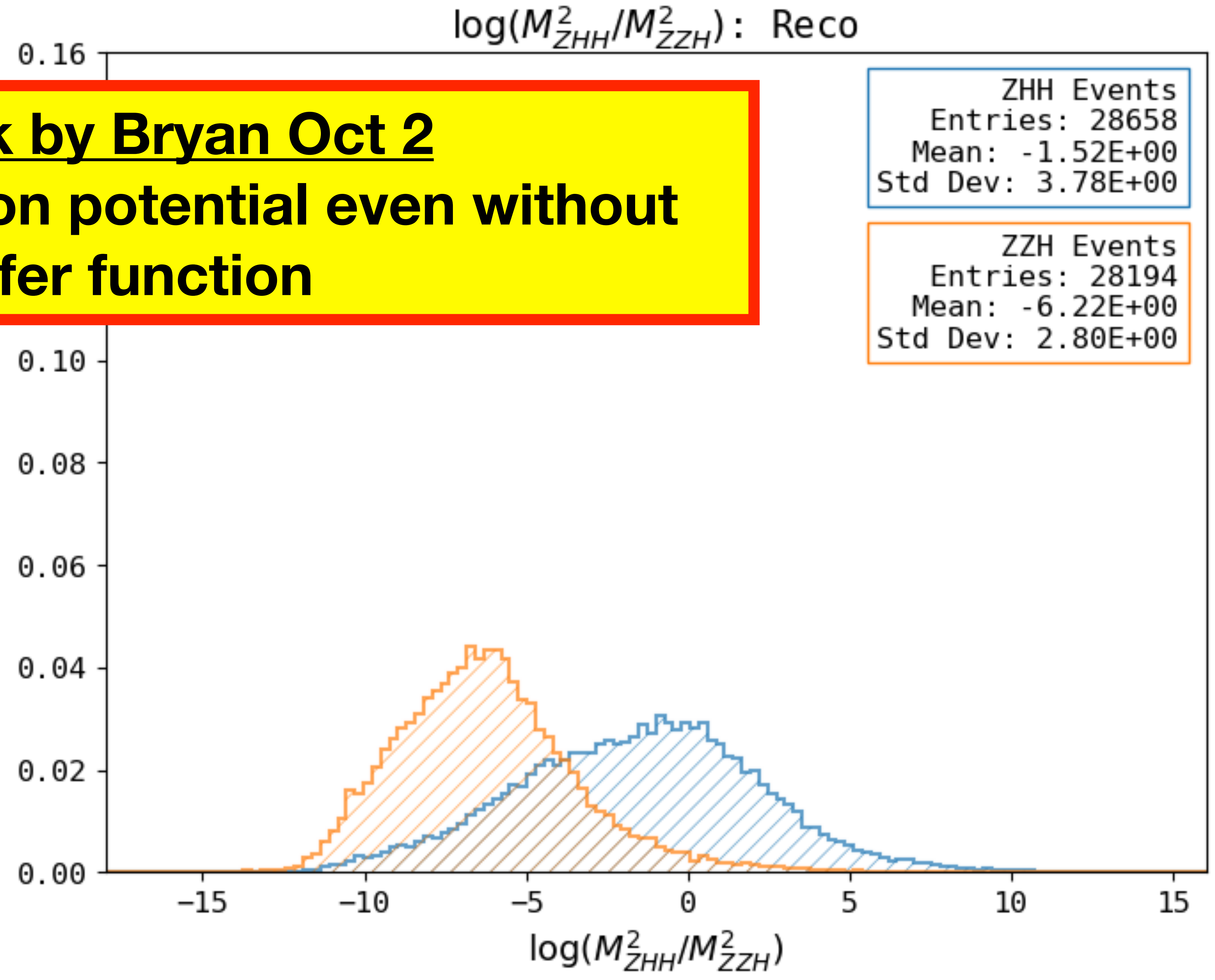


more details cf talk by Bryan Oct 2
nice additional discrimination potential even without detector transfer function



Extrapolation scheme

Incorporating the shown flavour tag and kinematic reconstruction/selection improvements

- **starting point: Table 9.1 Thesis Claude Dürig with S, B and significances for both polarisations**

	eebbbb		mumubbbb		nunubbbb		bbbbbb		qqbbbb		comb sig	comb. X-sec. uncert
Pol	-80,+30	+80,-30	-80,+30	+80,-30	-80,+30	+80,-30	-80,+30	+80,-30	-80,+30	+80,-30		
Significance (meas.) Claude	1.07	0.92	1.26	1.1	1.5	1.54	1.57	1.58	1.55	1.64	4.41	**0.227**
x^2	1.14	0.85	1.59	1.21	2.25	2.37	2.46	2.50	2.40	2.69	19.46	
s Claude (Tab 9.1)	**3.9**	**2.9**	**5.1**	**3.8**	**5.6**	**3.6**	**8.5**	**5.9**	**12.6**	**8.3**		
b Claude (Tab 9.1)	**7**	**4.2**	**8.9**	**5.3**	**6.9**	**1.1**	**21.9**	**7**	**55**	**16**		
s/sqrt(s+b)	1.18	1.09	1.36	1.26	1.58	1.66	1.54	1.64	1.53	1.68	4.39	**0.228**
x^2	1.40	1.18	1.86	1.59	2.51	2.76	2.38	2.70	2.35	2.83	19.29	

- **apply changes to signal s per channel and polarisation, re-calculate combined cross-section significance**
  - flavour tag improvement: 22.8% -> 17.2%
  - kin. sel. improvement: 17.2% -> 16%
- **include additional channels (also done for the good old 26.6% ~=27%): 16% -> 11.2%**
  - Z-> tautau
  - HH->bbWW
  - HH->bb tautau and "other"
- **convert to dlamba/lambda with sensitivity factor incl. mHH weighting (1.62):**

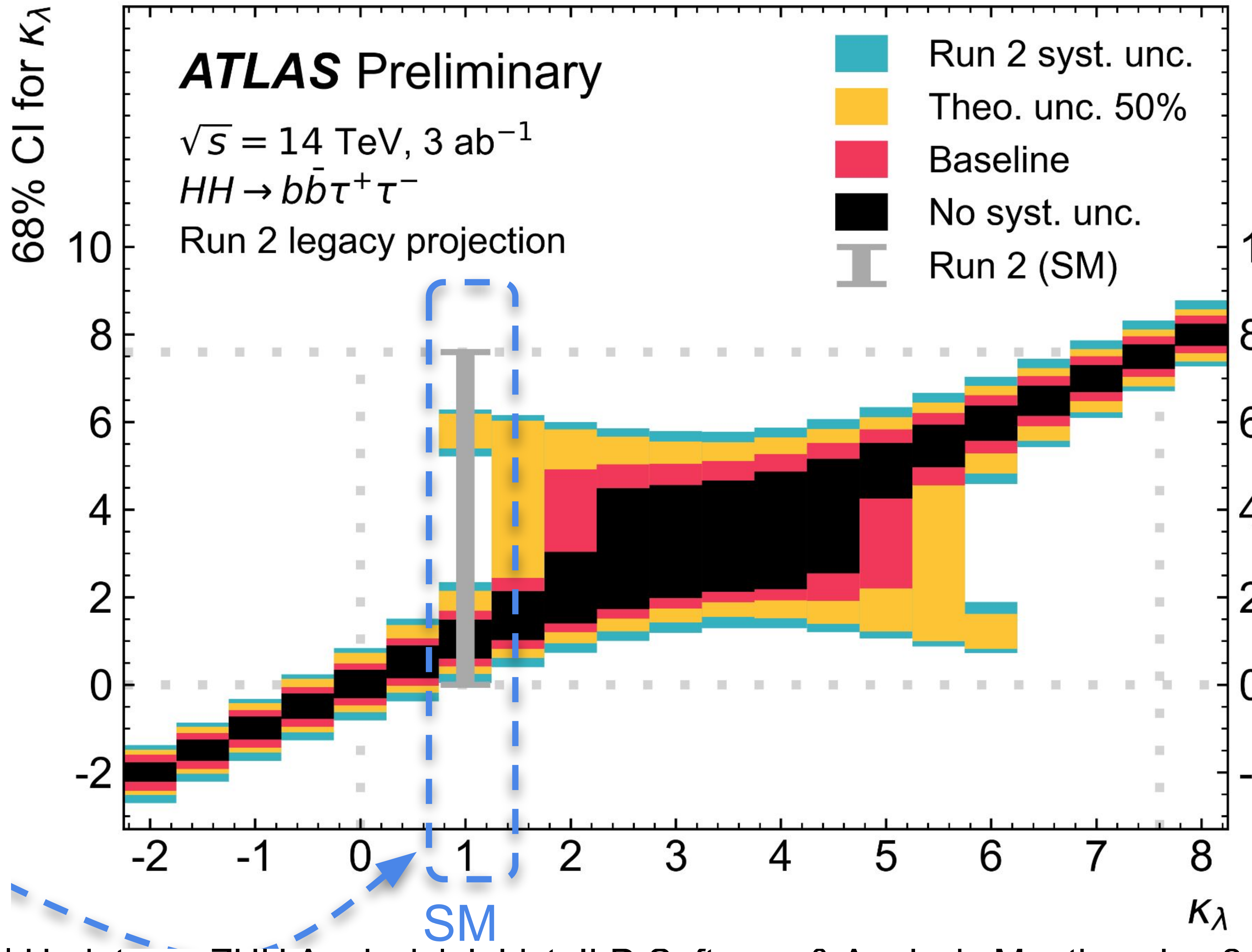
$d\lambda/\lambda$ (SM) = 18 %

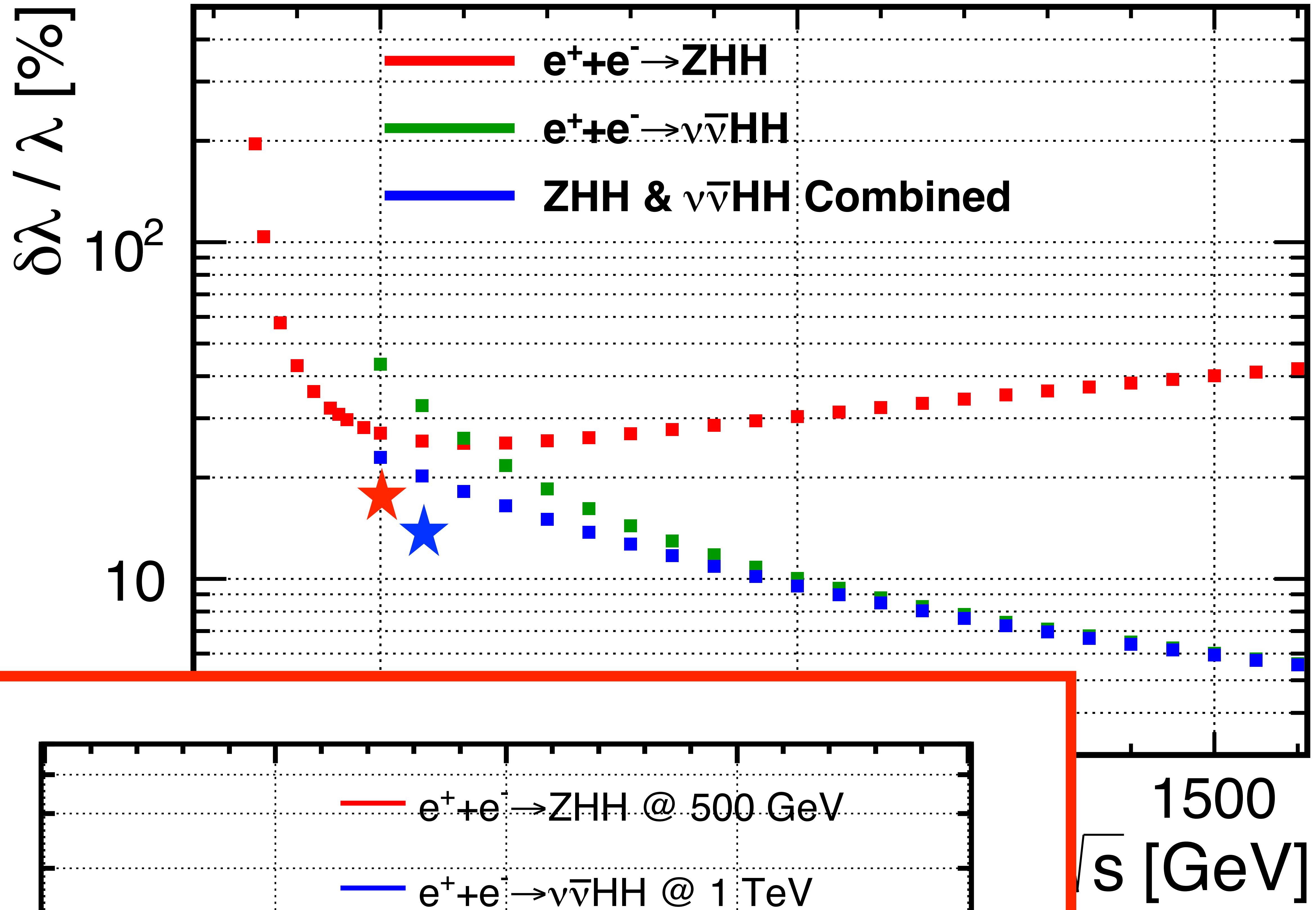
"flavour tag and kinematic reconstruction improvements demonstrated in detailed simulations of the ILD detector concept, propagated to the ZHH analysis based on [cite PhD Claude Dürig]"

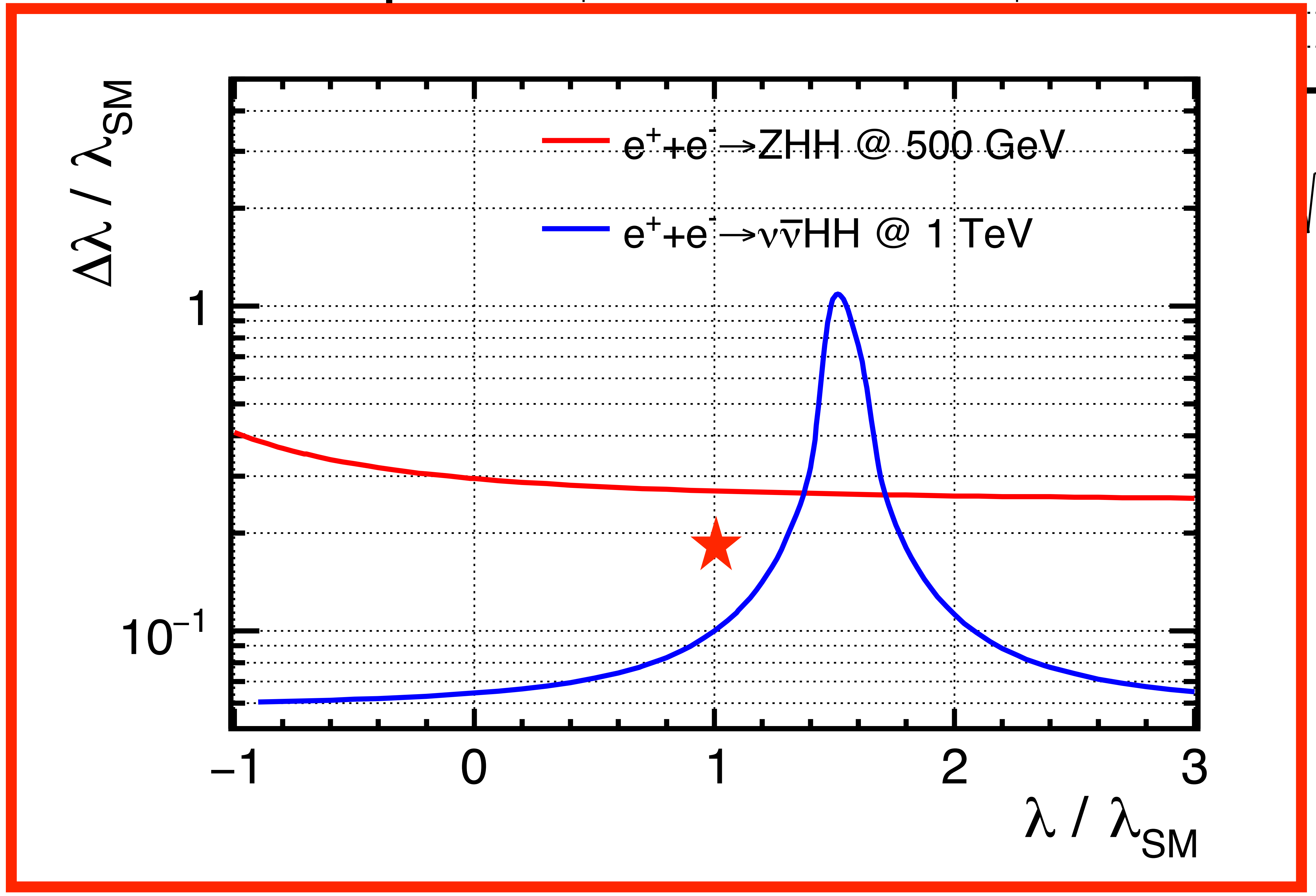
BSM / ECM dependency

as before….

- **use the "usual" cross-section-level extrapolation to project the dependency on**
  - **ECM: 550 GeV incl vvHH -> 13%**
  - **value of λ**
- **draw in style / scale comparable to ATLAS HH->bbtautau projection**







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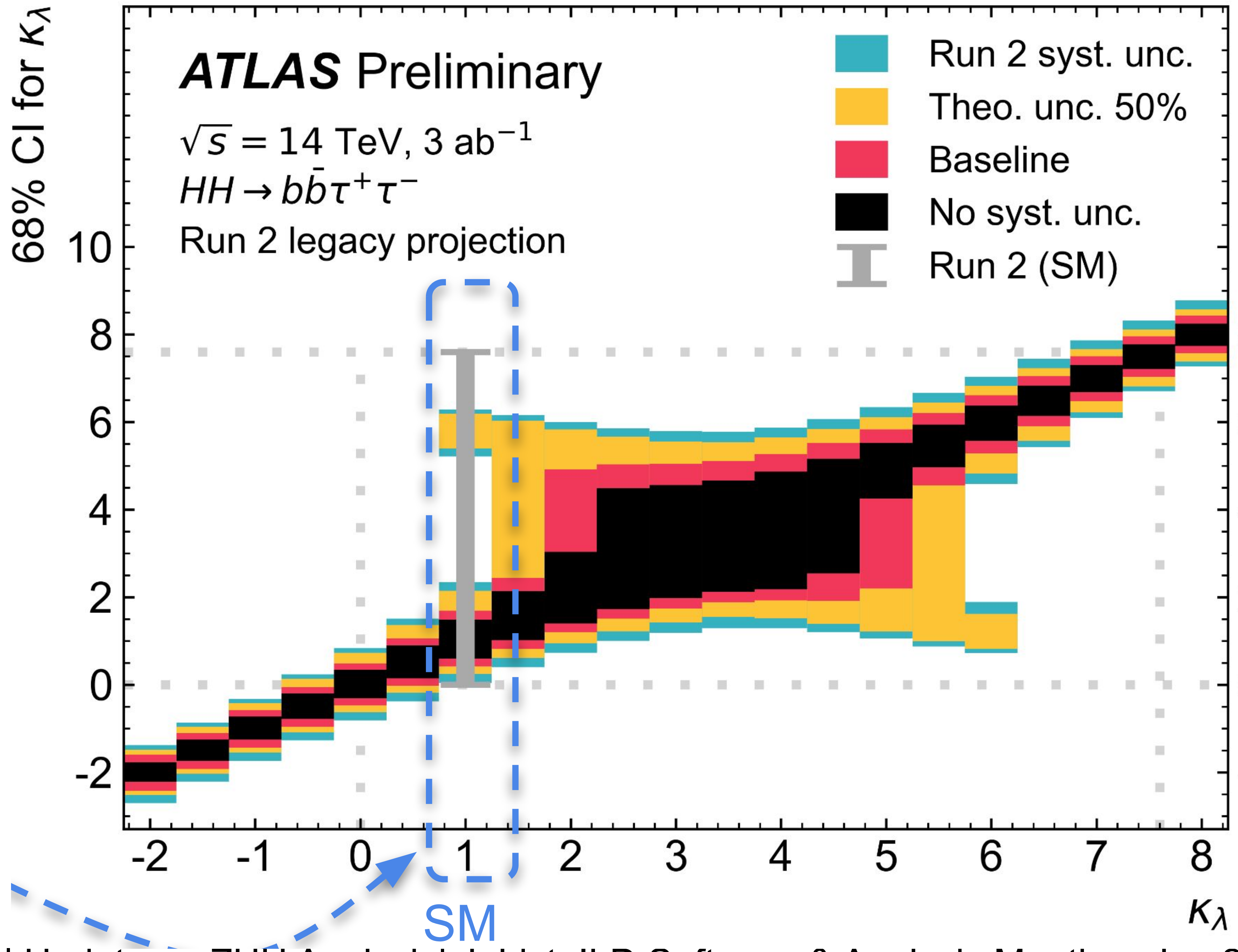

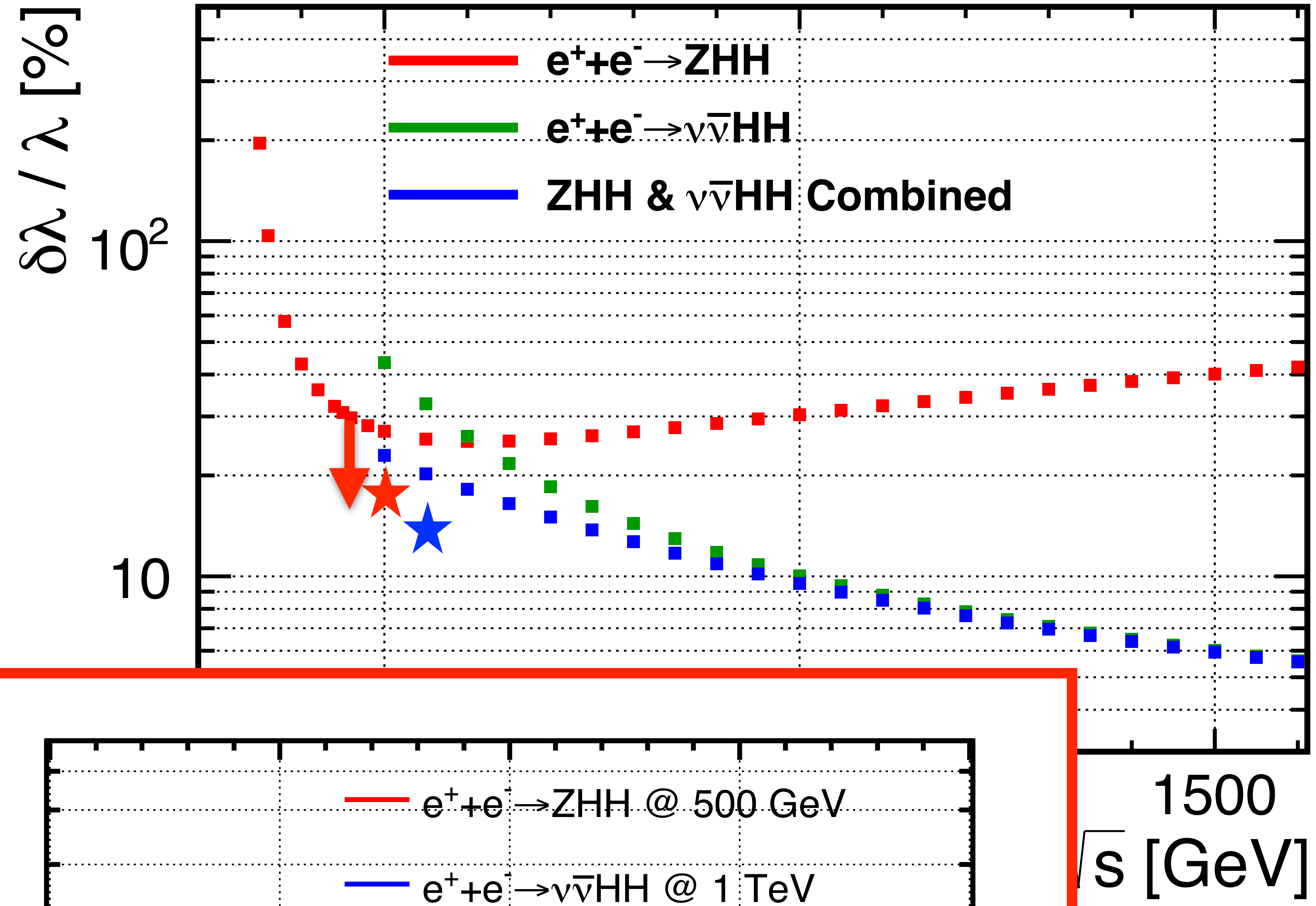

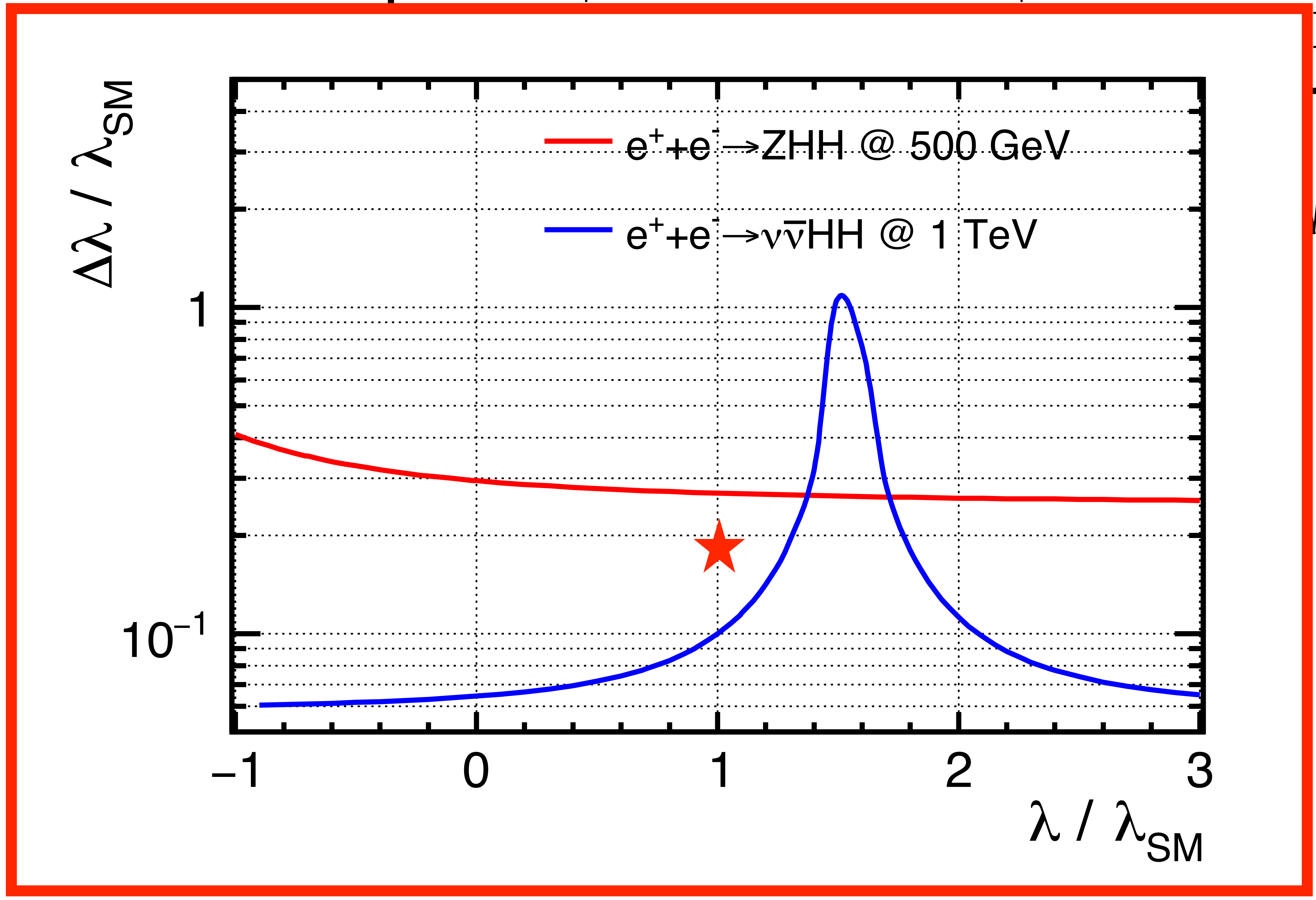

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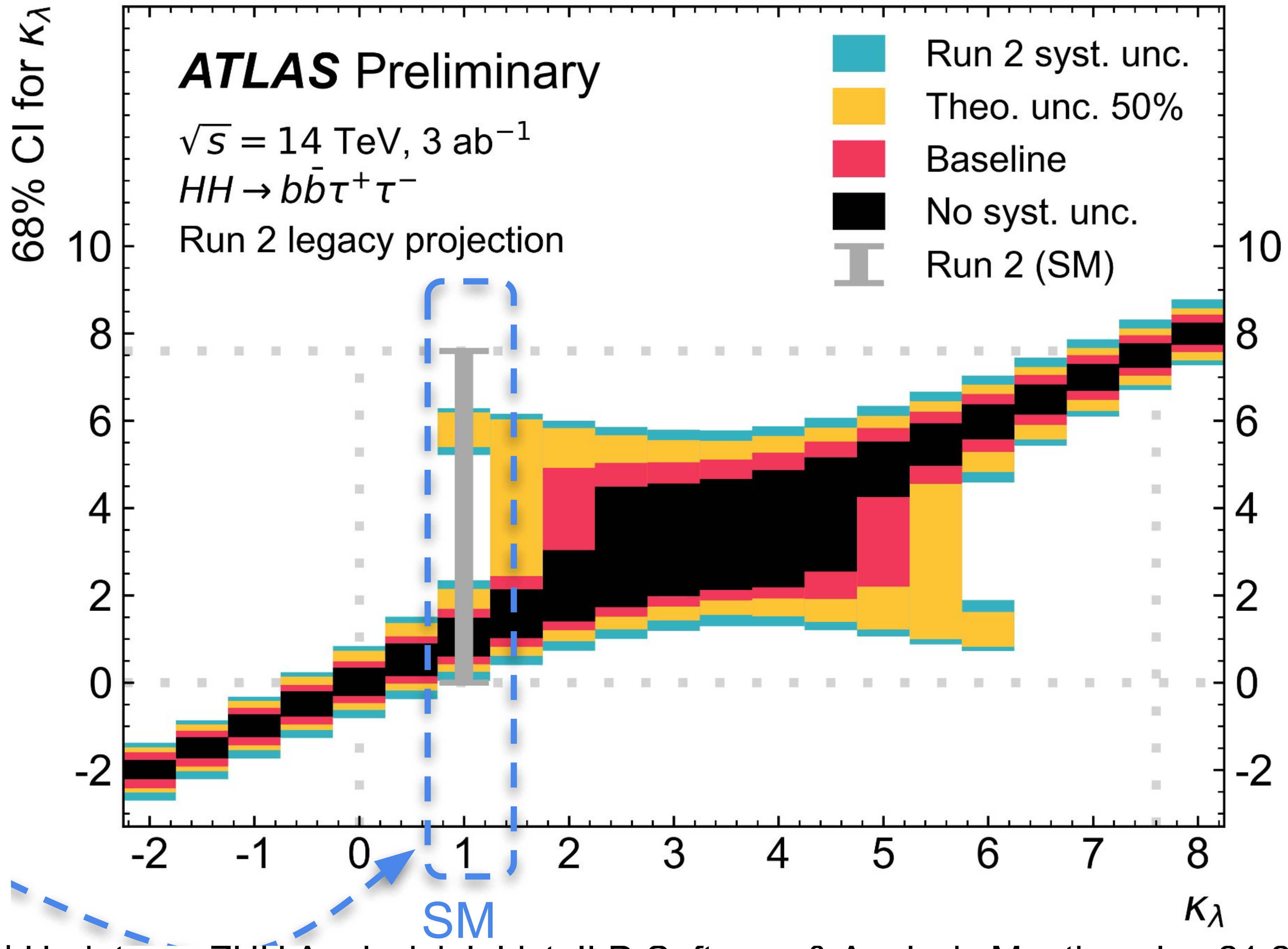

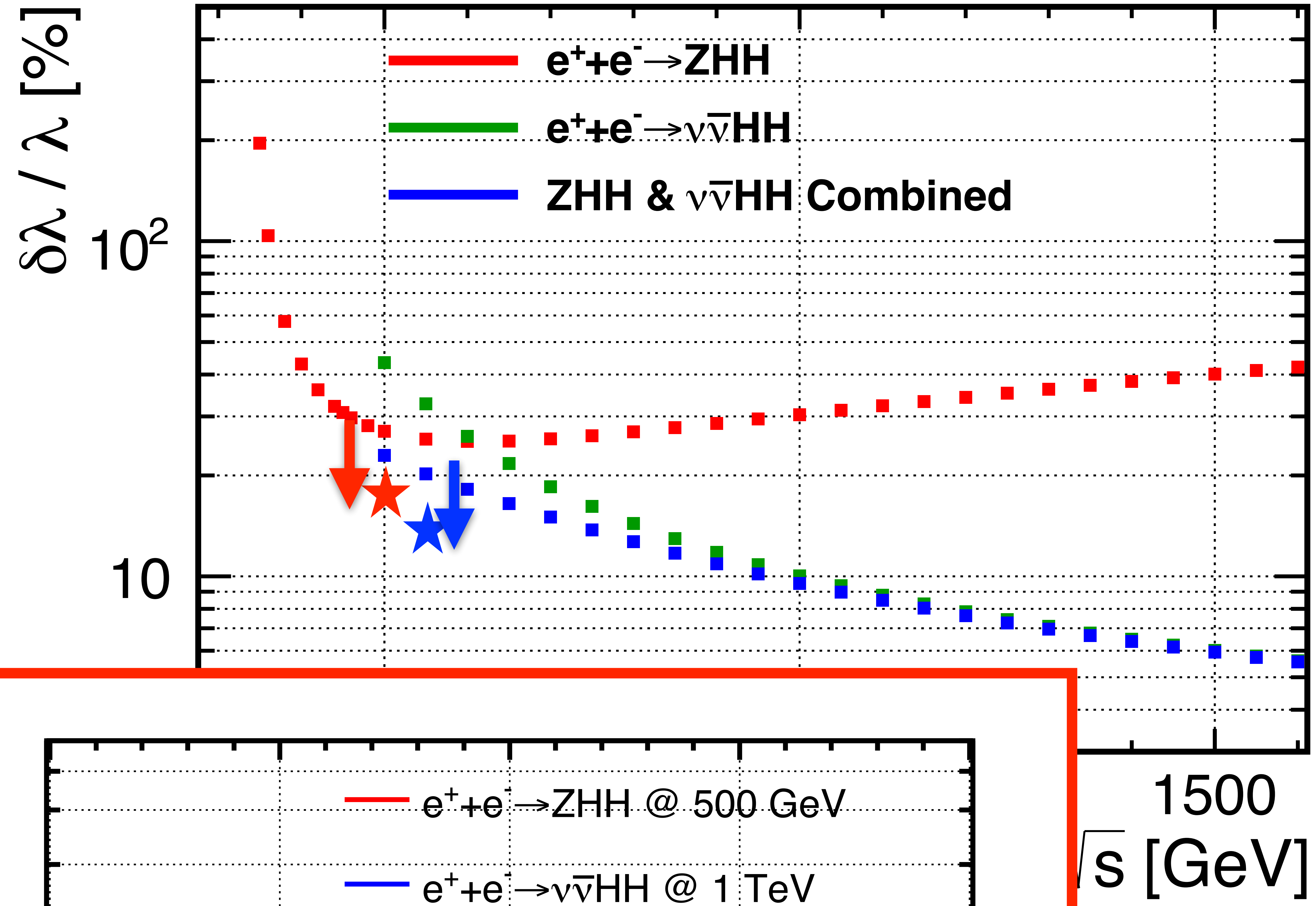

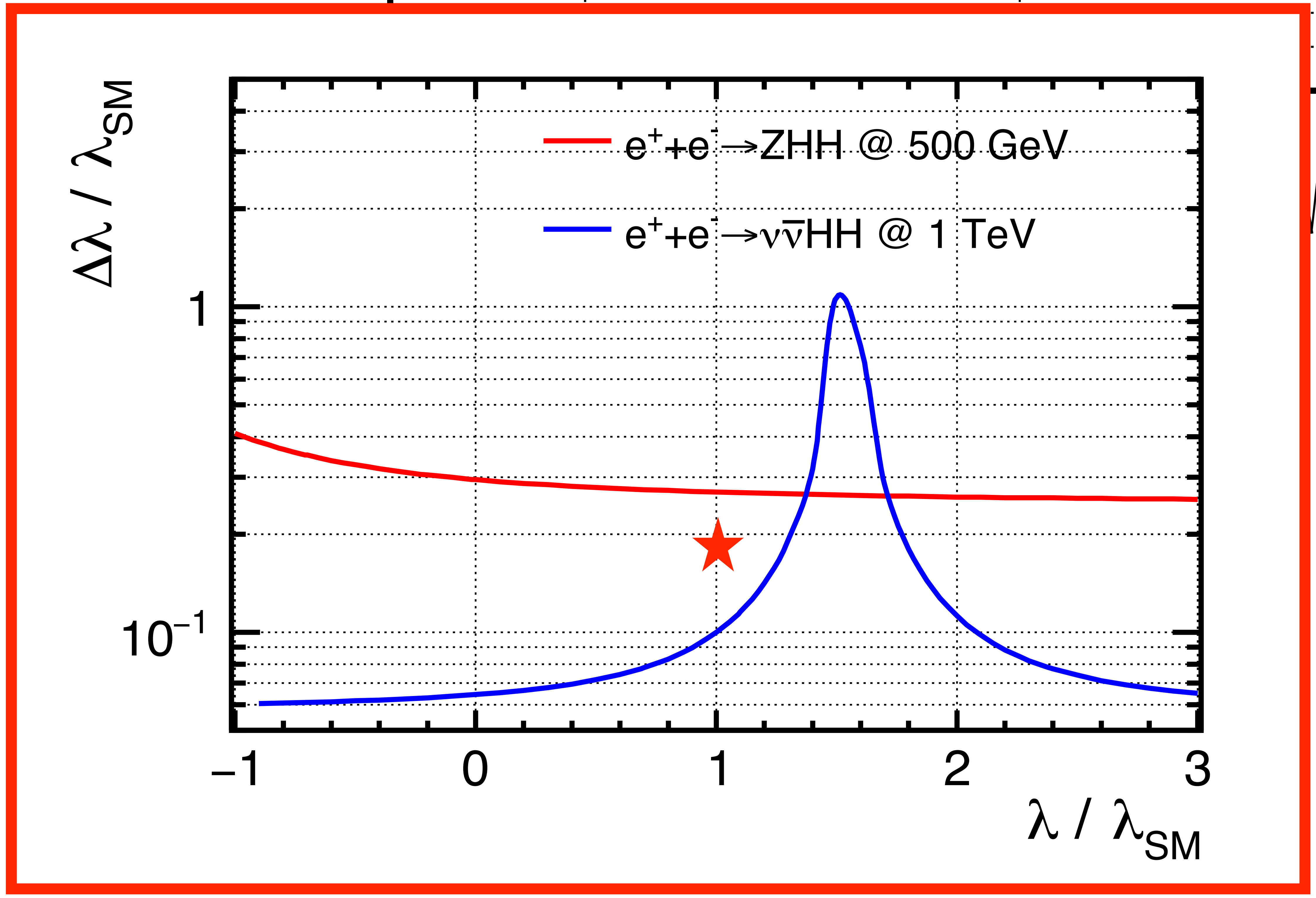

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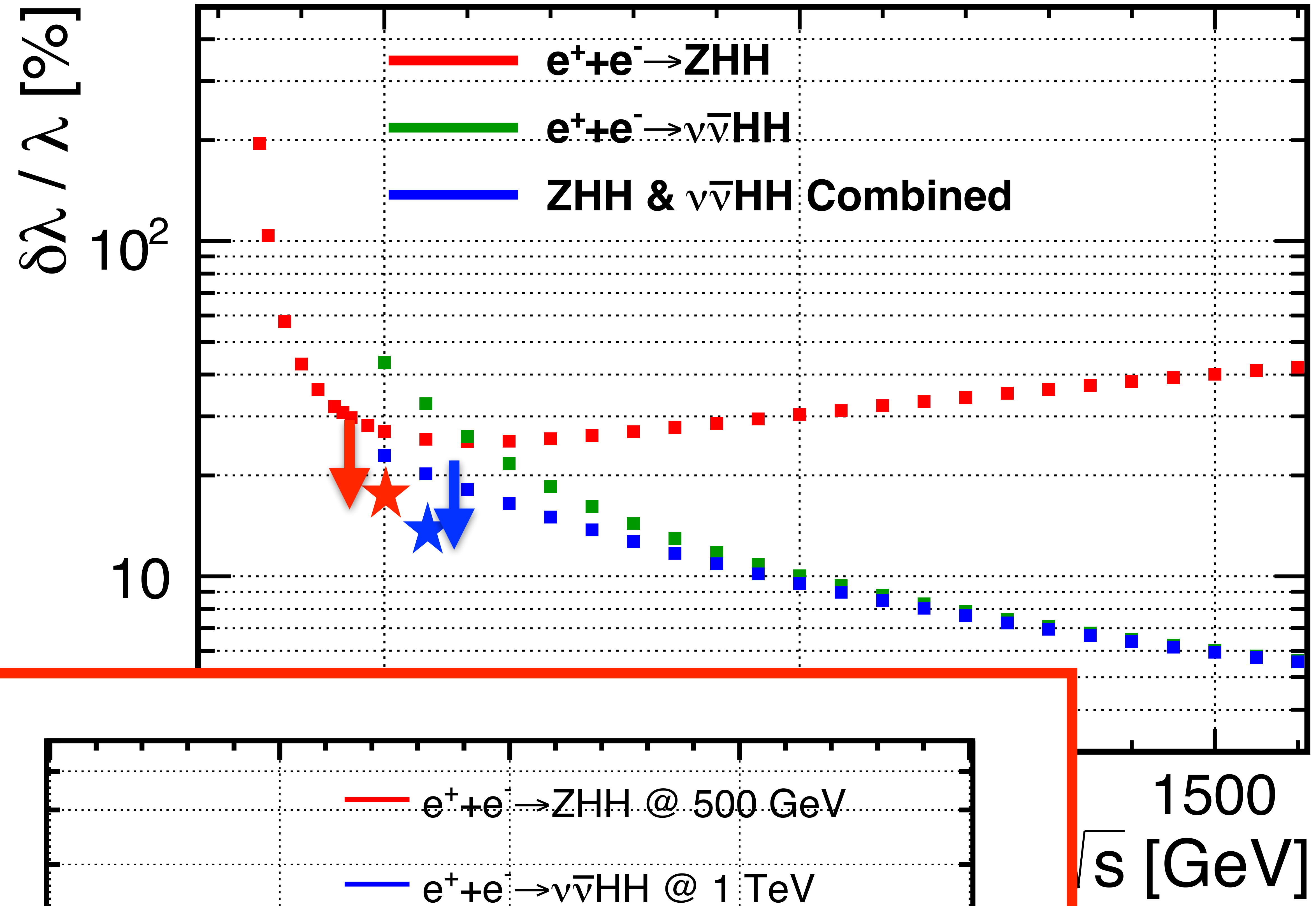

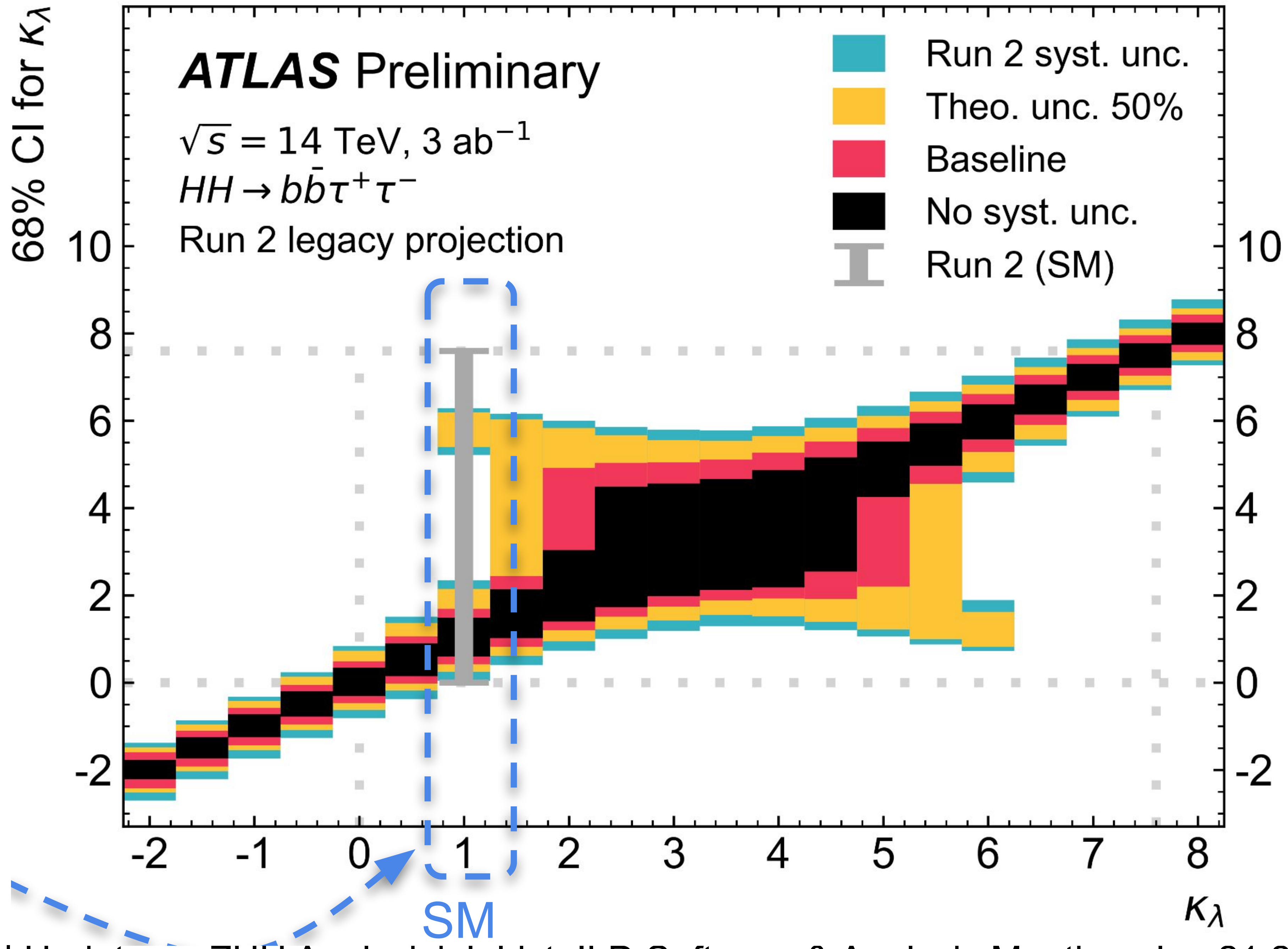

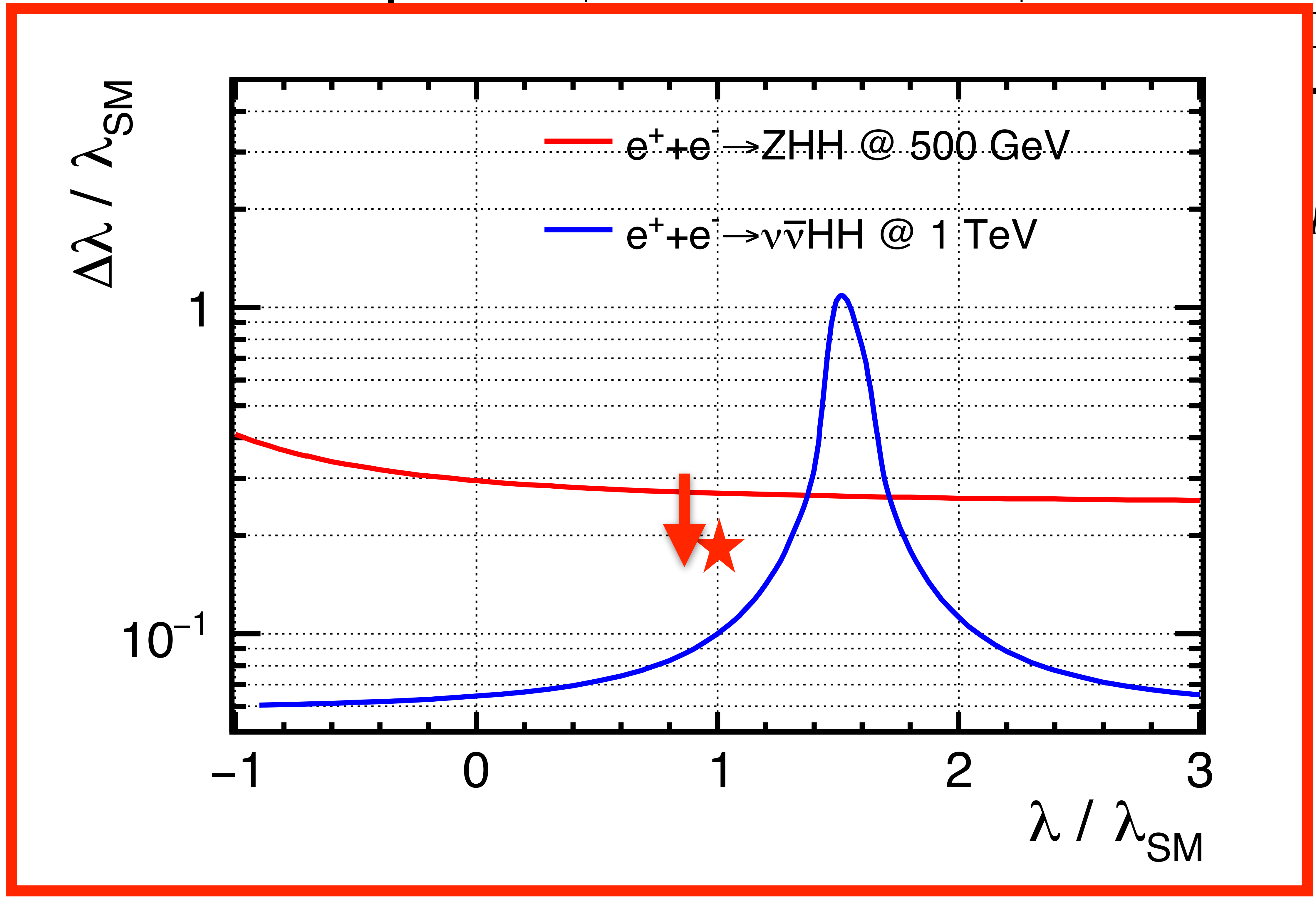

Conclusions / Next steps

Overview

Conclusions / Next steps

Overview

Outlook on mid-term schedule

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