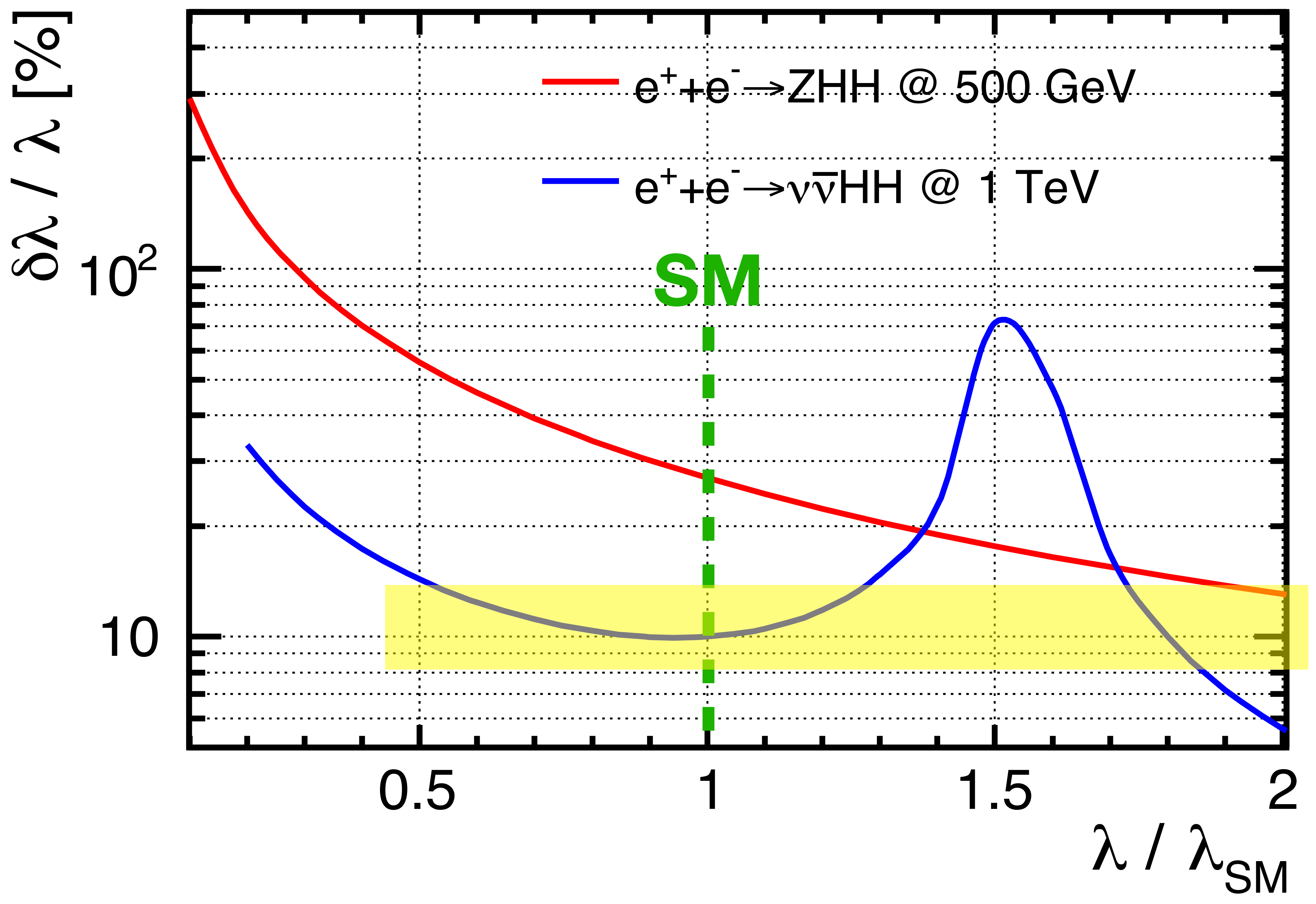
Higgs Self-Coupling at Linear e+e- Colliders



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[4] Tokyo University

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Outline

Today's menu

- Introduction: The tri-linear Higgs coupling is different
- Towards an Update of the ZHH analysis
- Choice of E_{CM} — and interplay with BSM
- Conclusions

Introduction:
The Higgs self-coupling is different…

Deviation of λ from SM prediction can be large

even if all other couplings are SM-like

from dimensional analysis

Self-Coupling Dominance

In other words, no obstruction to having Higgs self-coupling modifications a "loop factor" greater than **all** other couplings. Could have

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \left(\frac{M}{m_h}\right)^2\right]$$

without fine-tuning any parameters, as big as,

$$(4\pi v/m_h)^2 \approx 600$$

which is significant!

Durieux, MM, Salvioni. 2022

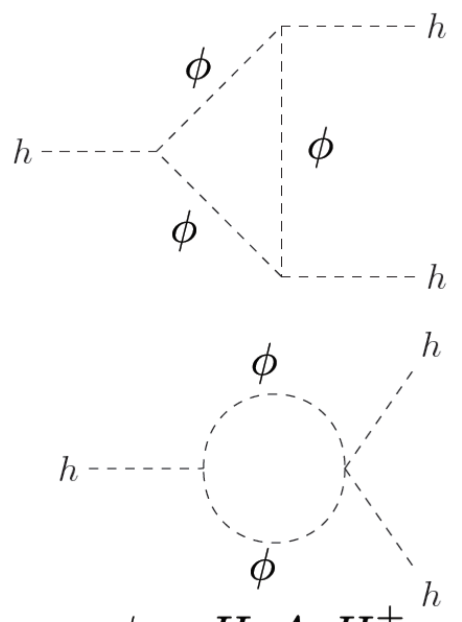
M. McCullough @ LCWS2024

or from UV complete BSM models

Concrete example: 2HDM: [taken from F. Arco '24]

Parameter scan in the 2HDM (all types):

[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]



$\phi = H, A, H^\pm$

Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
I	[-0.2, 1.2]	[0.2, 6.8]	[-1.6, 1.5]	[-2.1, 1.9]
II	[0.6, 1.0]	[0.7, 5.6]	[-1.5, 1.6]	[-1.7, 2.0]
LS	[0.5, 1.0]	[0.6, 5.6]	[-1.7, 1.7]	[-2.0, 2.1]
FL	[0.7, 1.0]	[0.8, 5.6]	[-1.6, 1.3]	[-1.9, 1.5]

(results from the effective potential)

- Very large corrections are possible! $\lambda_{hhh}^{(1)} >> \lambda_{hhh}^{(0)}$
- h couplings to heavy Higgs bosons can be large ($\lambda_{h\phi\phi} \sim 15$)
  - Even at the ***alignment limit*** !!! *(In the SM, top-loops are ~ -8%)*

⇒ effect of the extended BSM Higgs sector!

S.Heinemeyer @ LCWS2024

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Durieux, MM, Salvioni. 2022

Measurement with as little model-assumptions as possible is crucial!

M. McCullough @ LCWS2024

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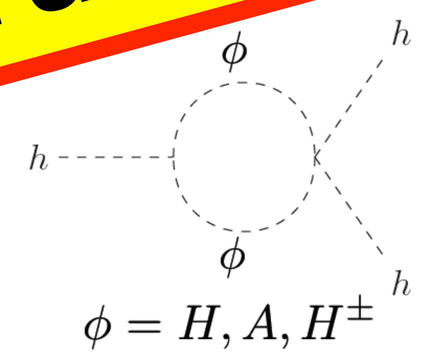
Parameter scan in t…

[F. Arco, S…



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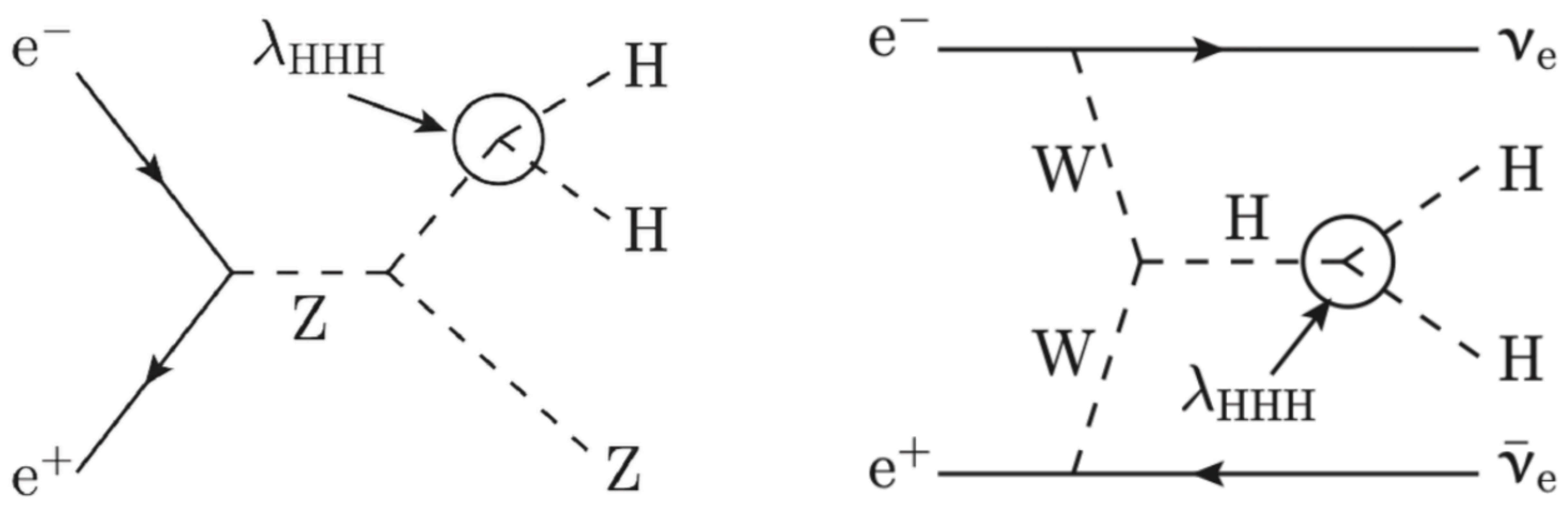
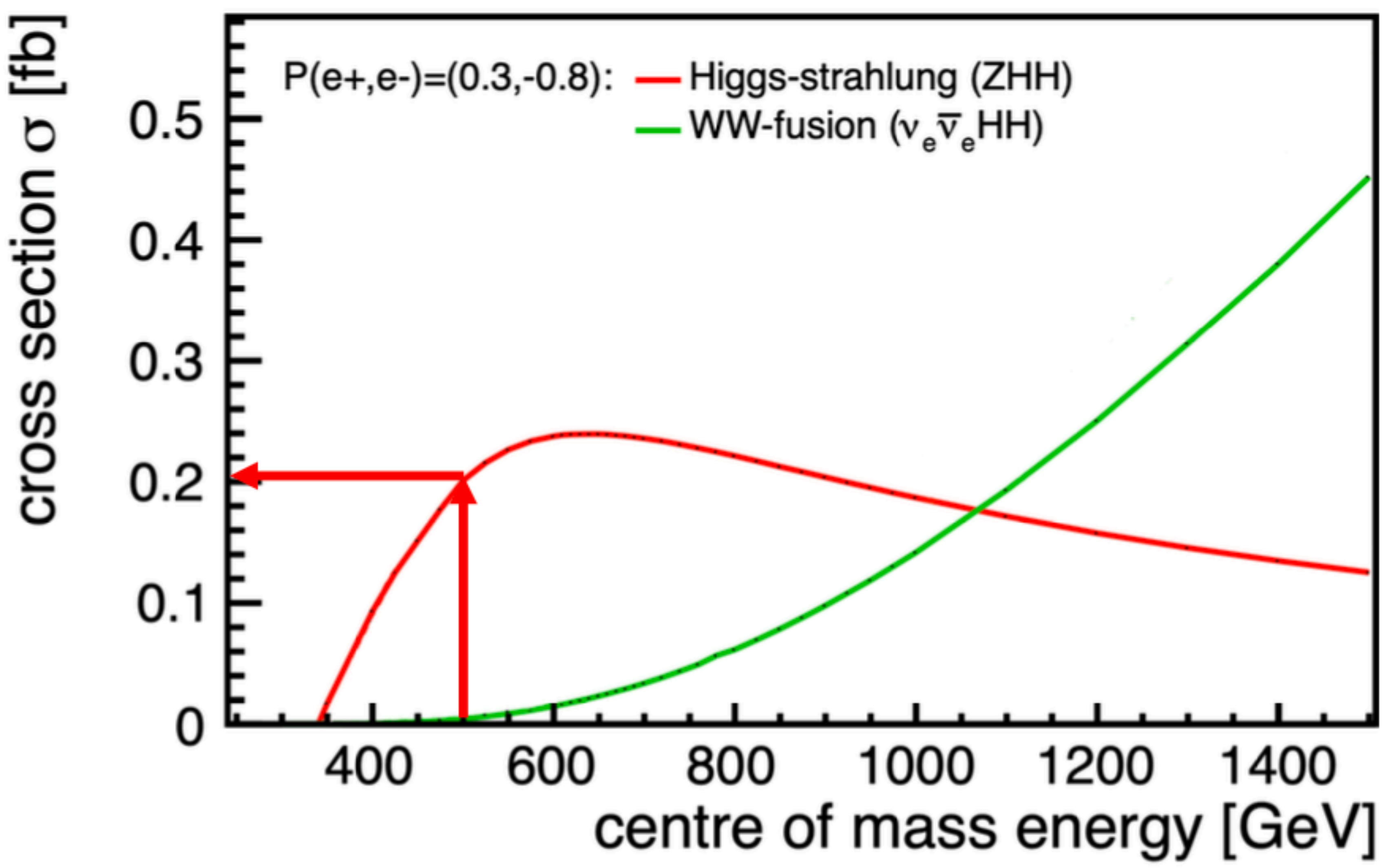
Direct measurement of λ at e+e- colliders

- *direct access* to λ through double-Higgs production
  - Di-Higgs strahlung ($\mathbf{ZHH}$; dominant < 1 TeV)
  - vector boson fusion ($\mathbf{\nu\bar{\nu}HH}$; dominant > 1 TeV)

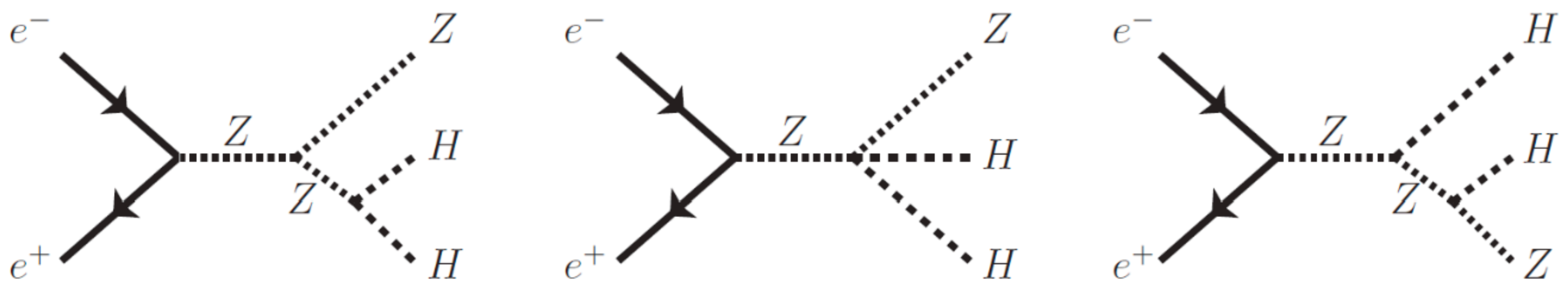




Cross-section of Di-Higgs production processes.

from most detailed ref: PhD Thesis C.Dürig Uni Hamburg, **DESY-THESIS-2016-027**

- degredation of sensitivity in ZHH by diagrams without λ



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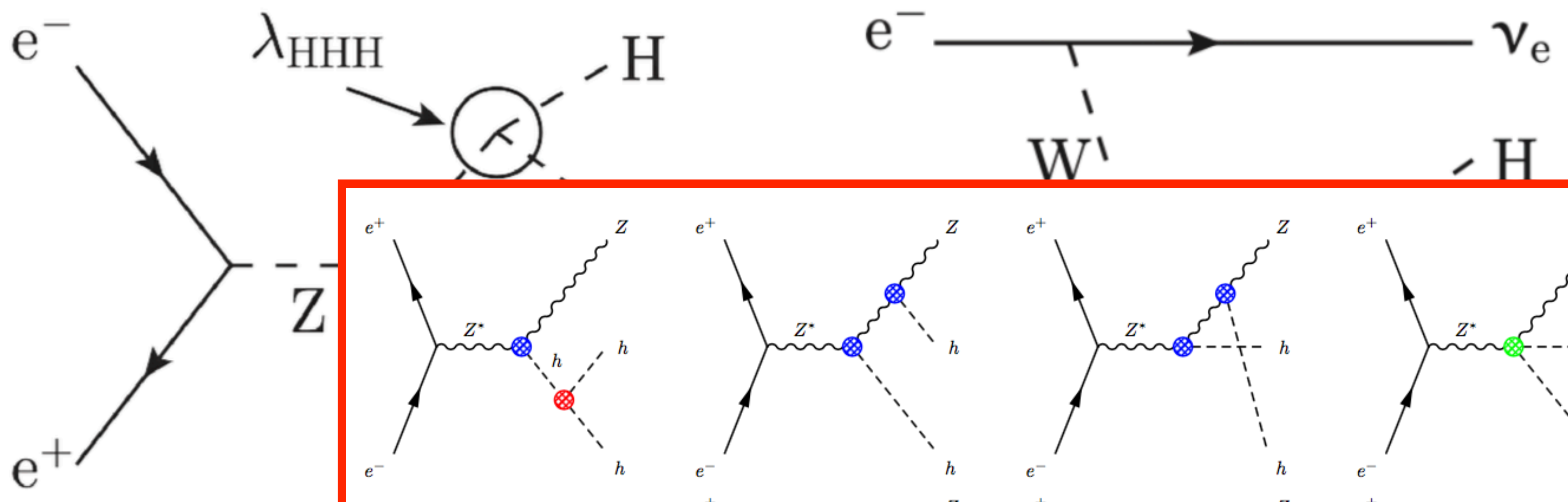

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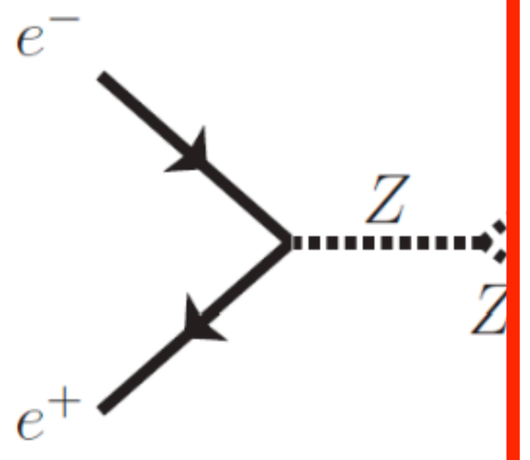
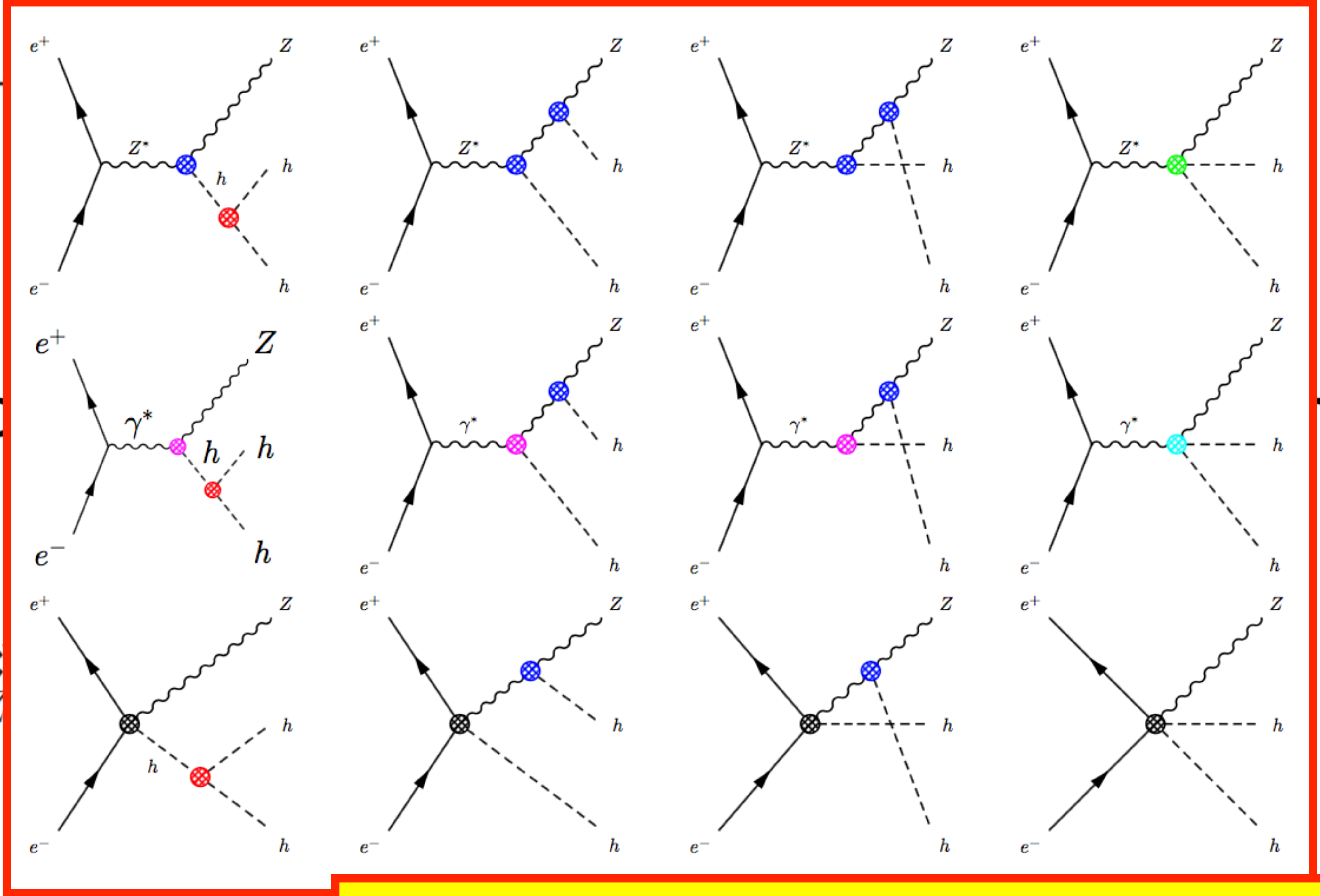
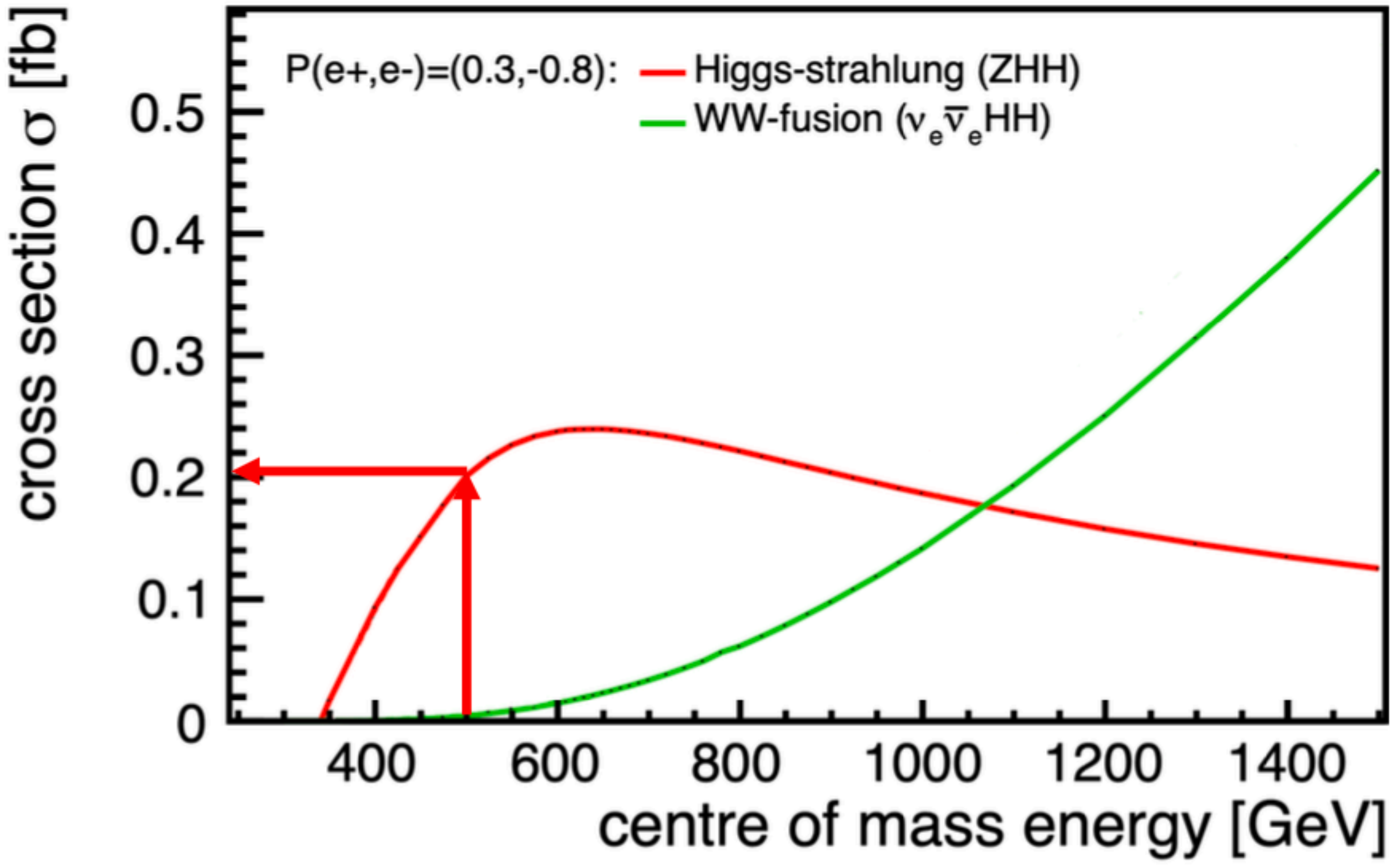




can still extract λ reliably, cf arXiv:1708.09079



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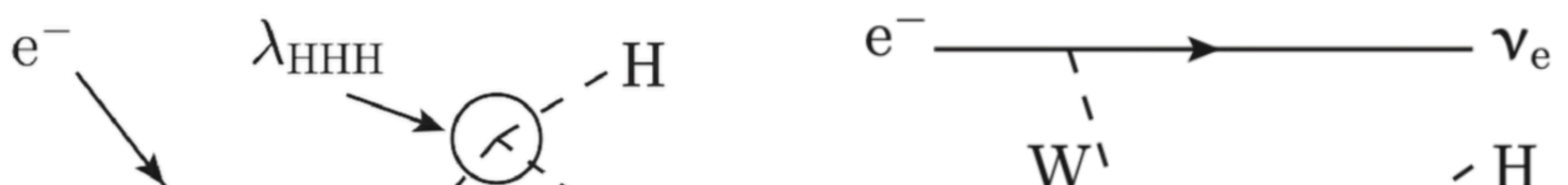

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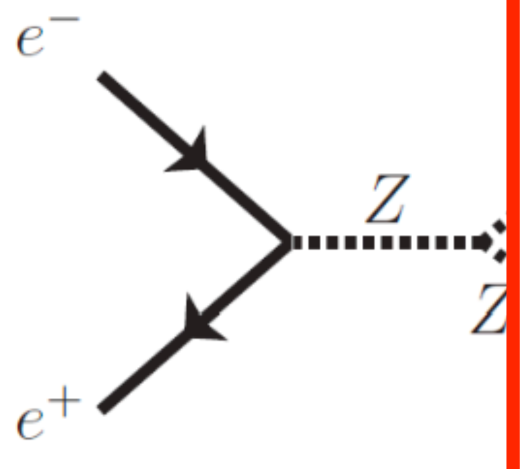

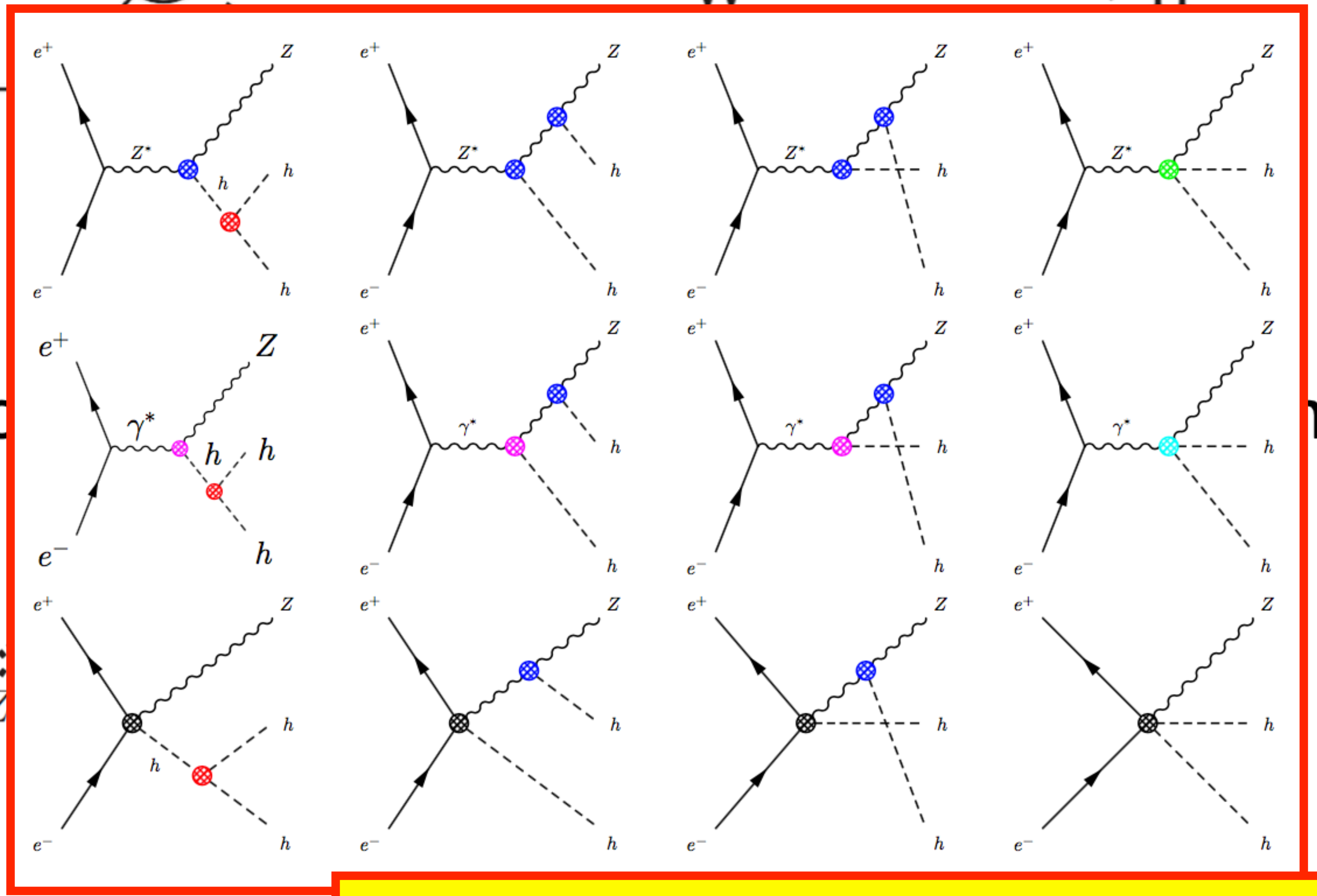

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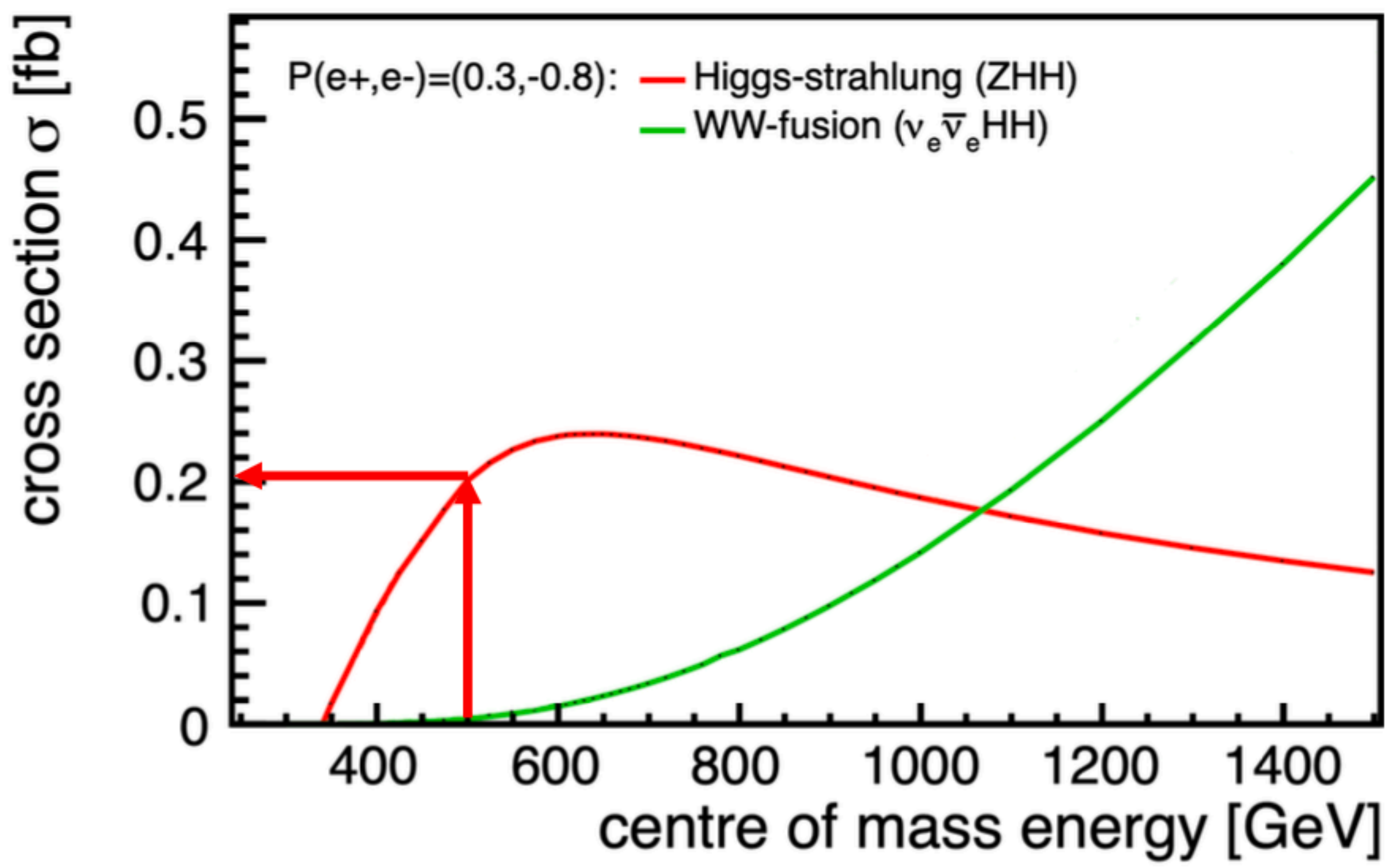

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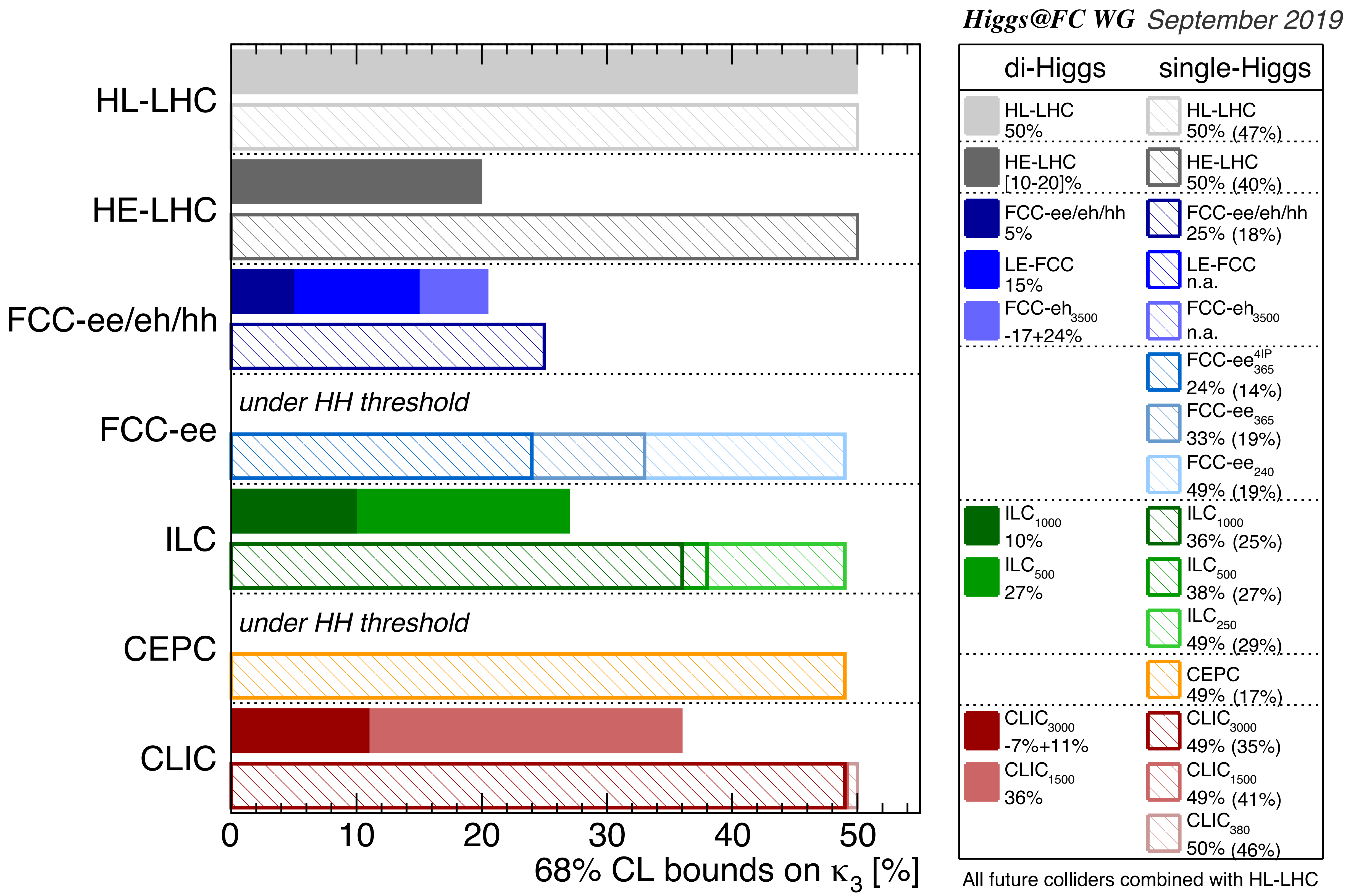
requires at least E_{CM} = 500 GeV

The Higgs self-coupling master plot of the last EPPSU



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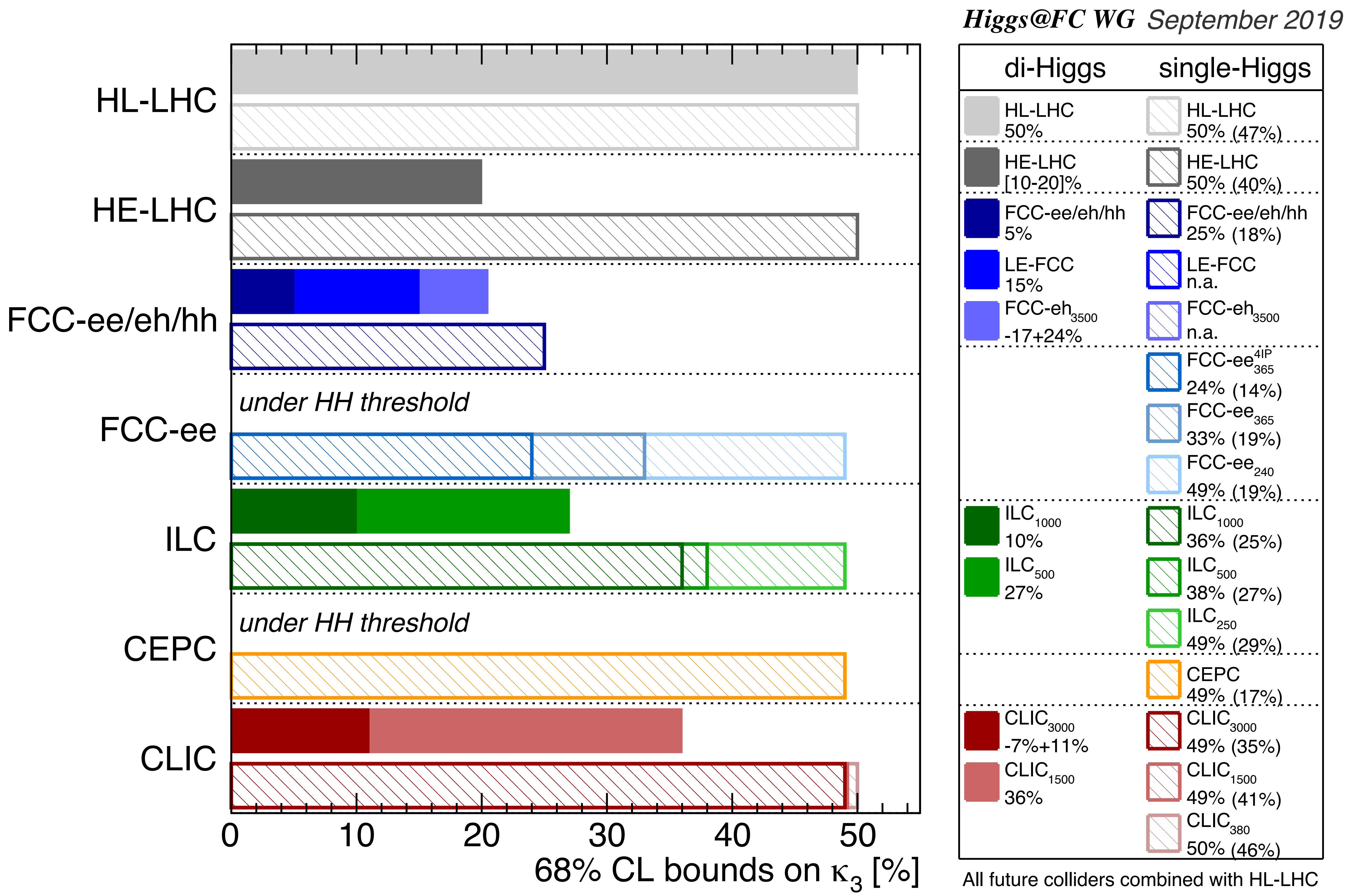

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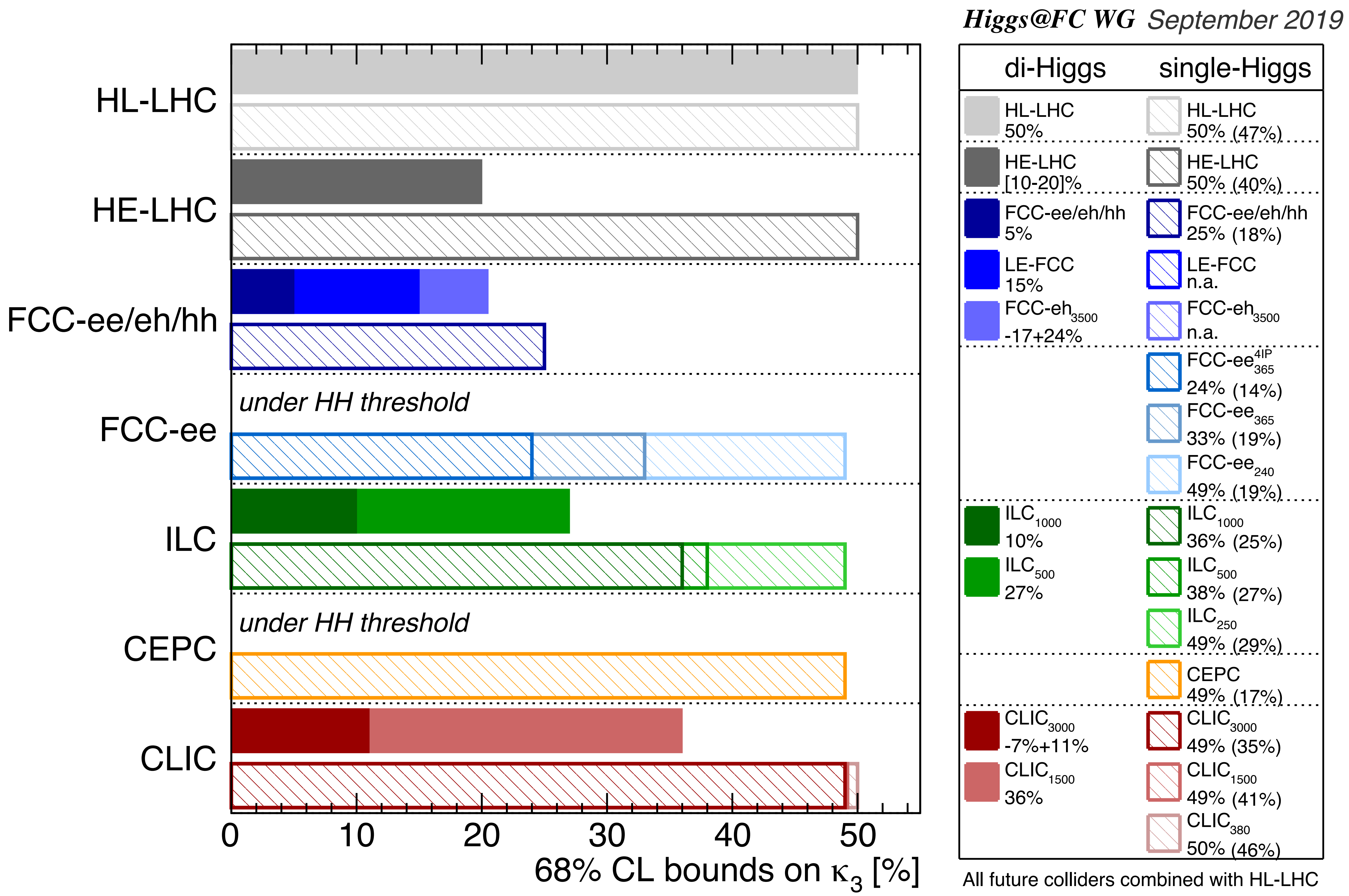

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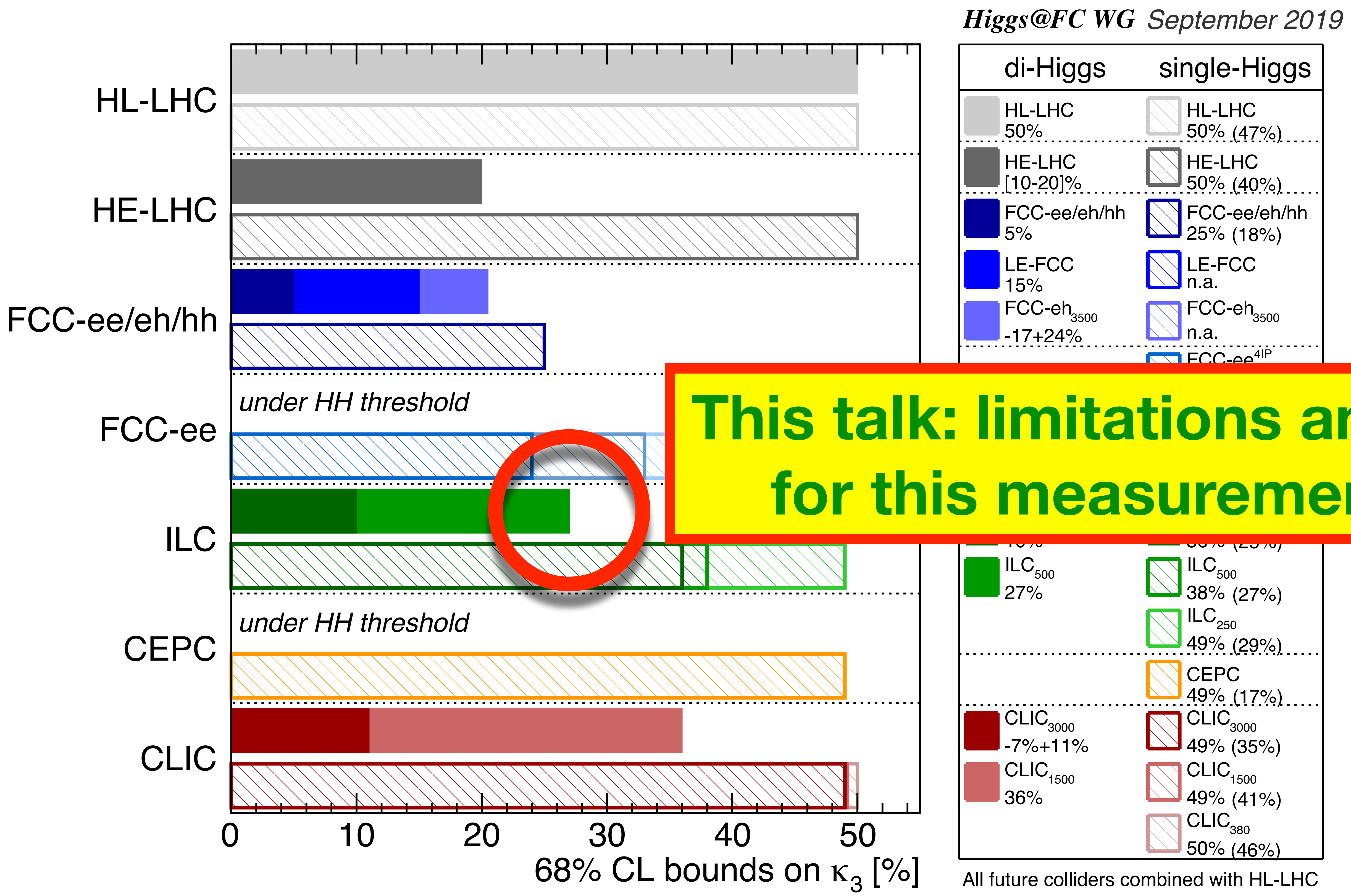

This talk: limitations and prospects for this measurement ("27%")

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Towards an update of the ZHH Analysis

Full Simulation of the ILD Detector Concept

previous analysis & update

Key requirements from Higgs physics:

- **p_t resolution** (total ZH x-section)

  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$

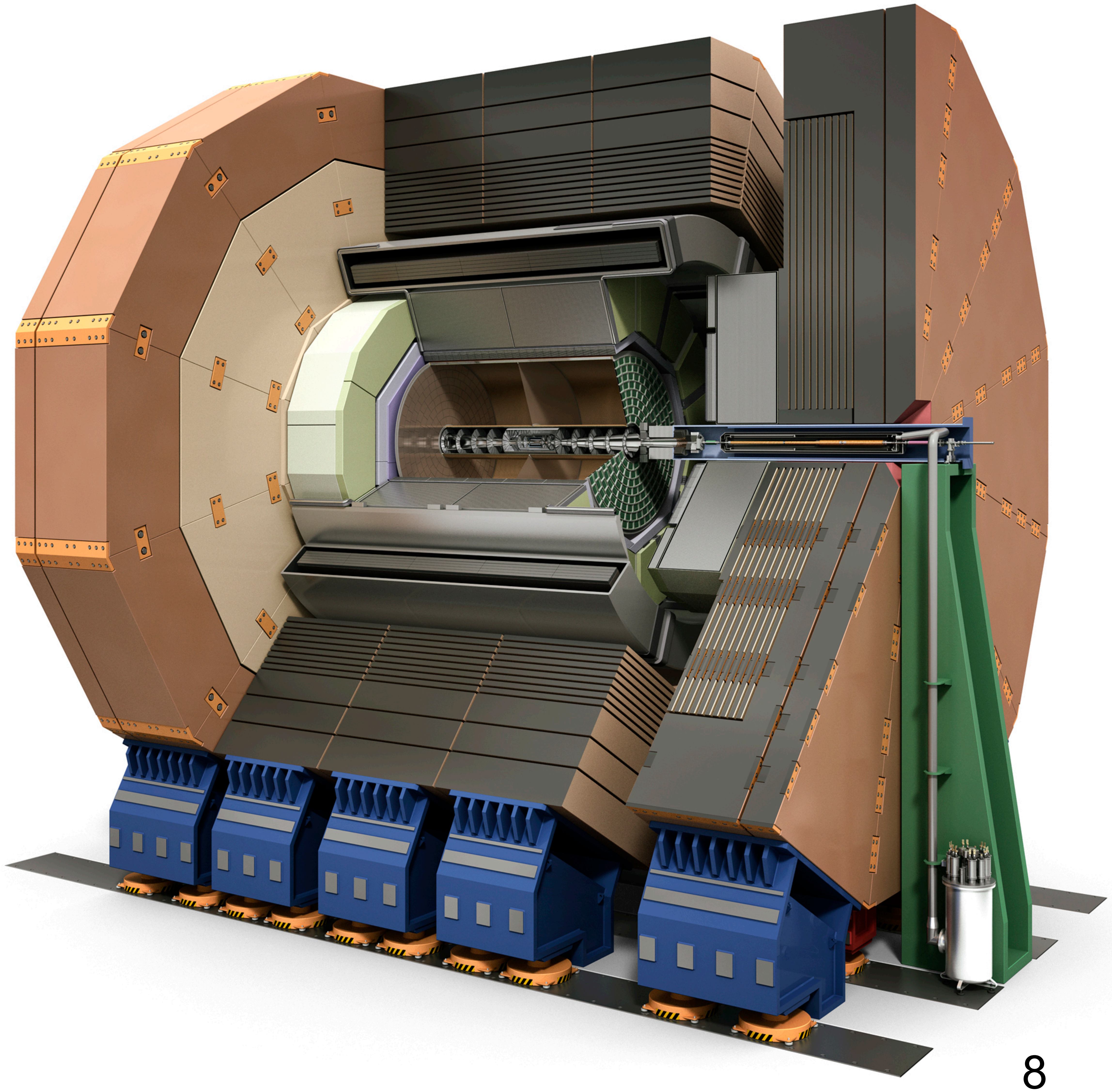
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)

  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$

- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%
- **hermeticity** ($H \rightarrow$ invis, BSM) $\theta_{min} = 5$ mrad

Determine to key features of the detector:

- **low mass tracker:**
  eg VTX: 0.15% rad. length / layer)
- **highly-granular calorimeters,** optimised for
  particle flow
- **3.5-4T** solenoidal **B-field**



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  ≈ CMS / 40

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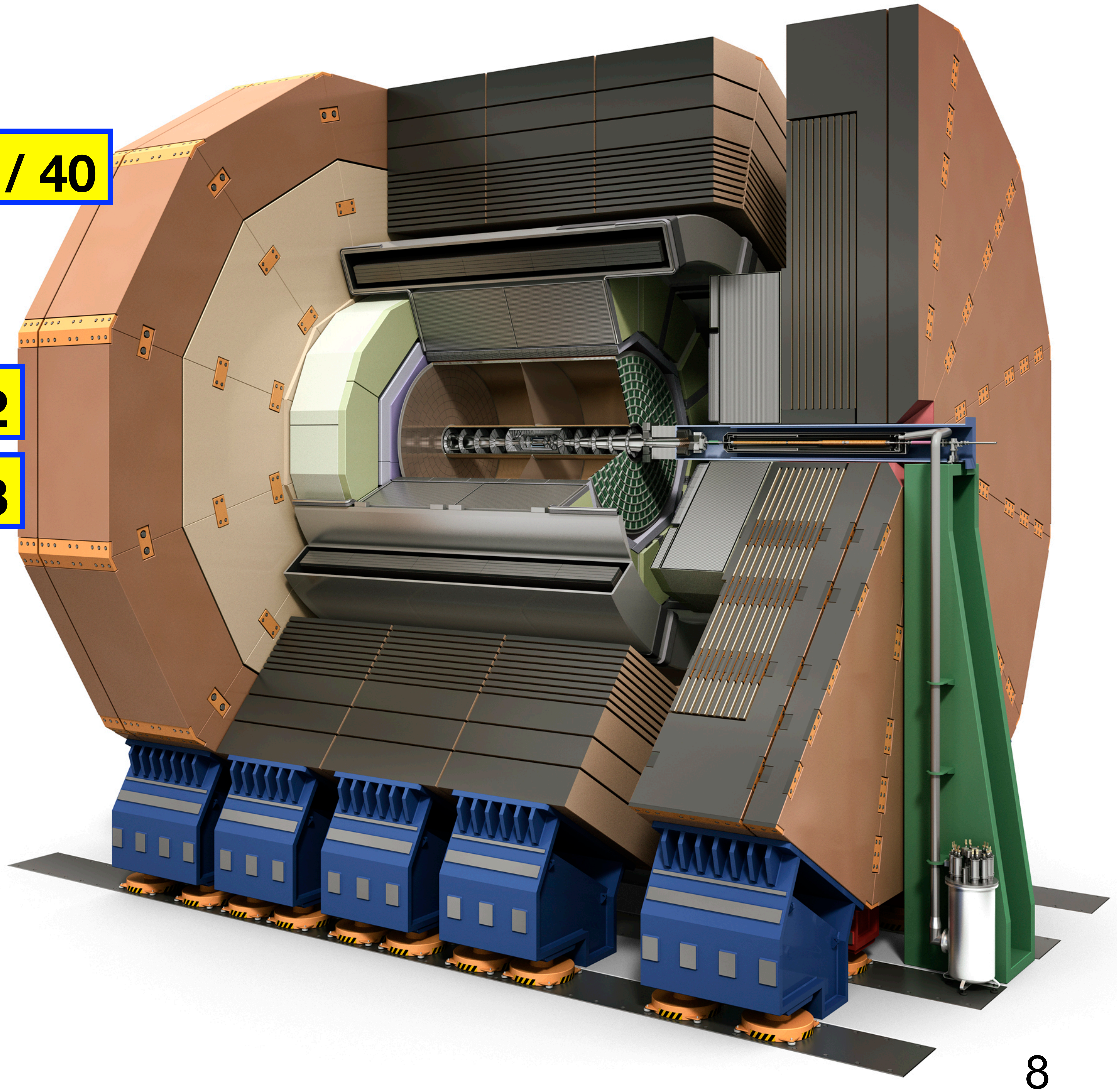

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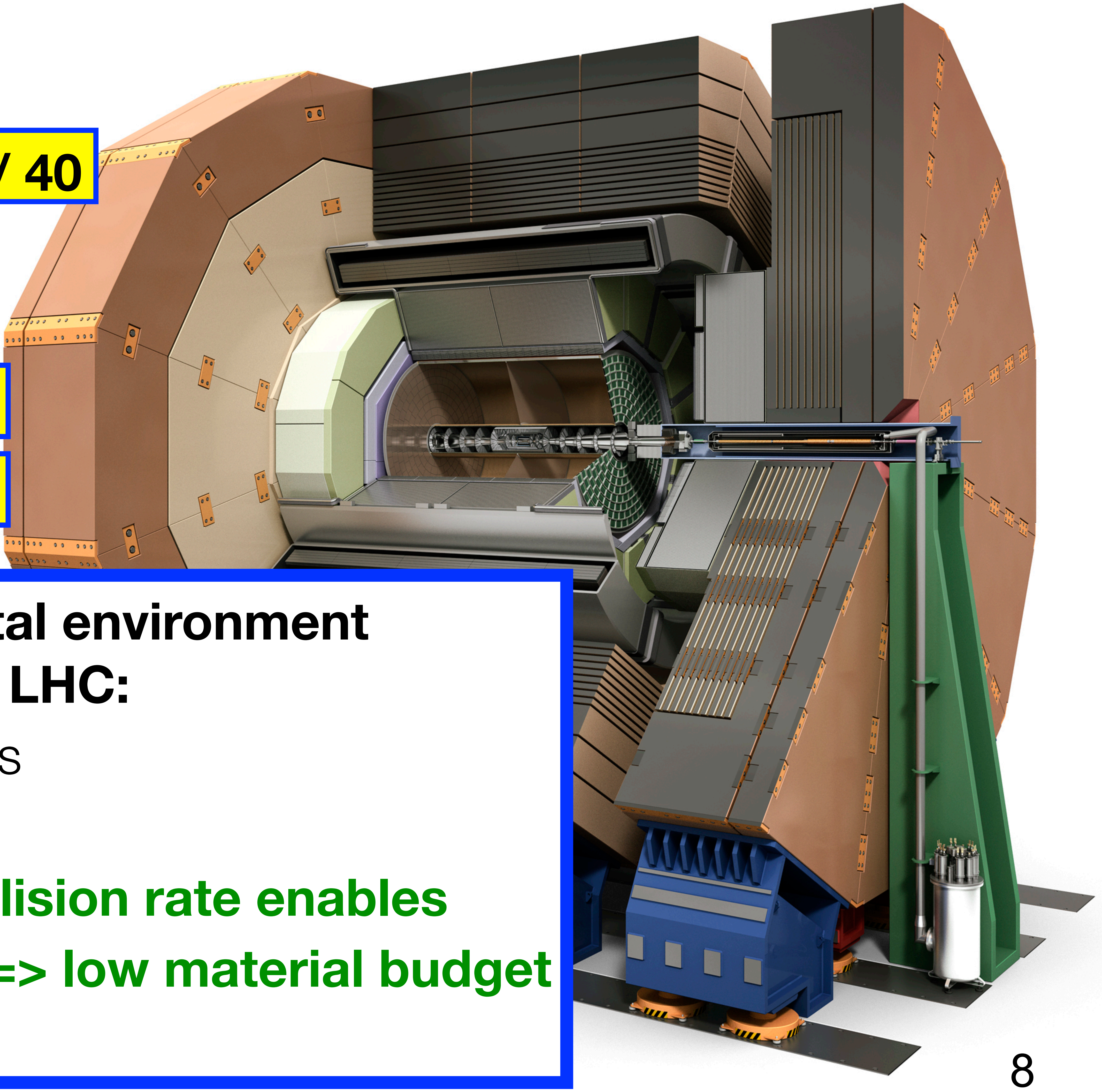


Possible since experimental environment in e+e- very different from LHC:

- much lower backgrounds
- much less radiation

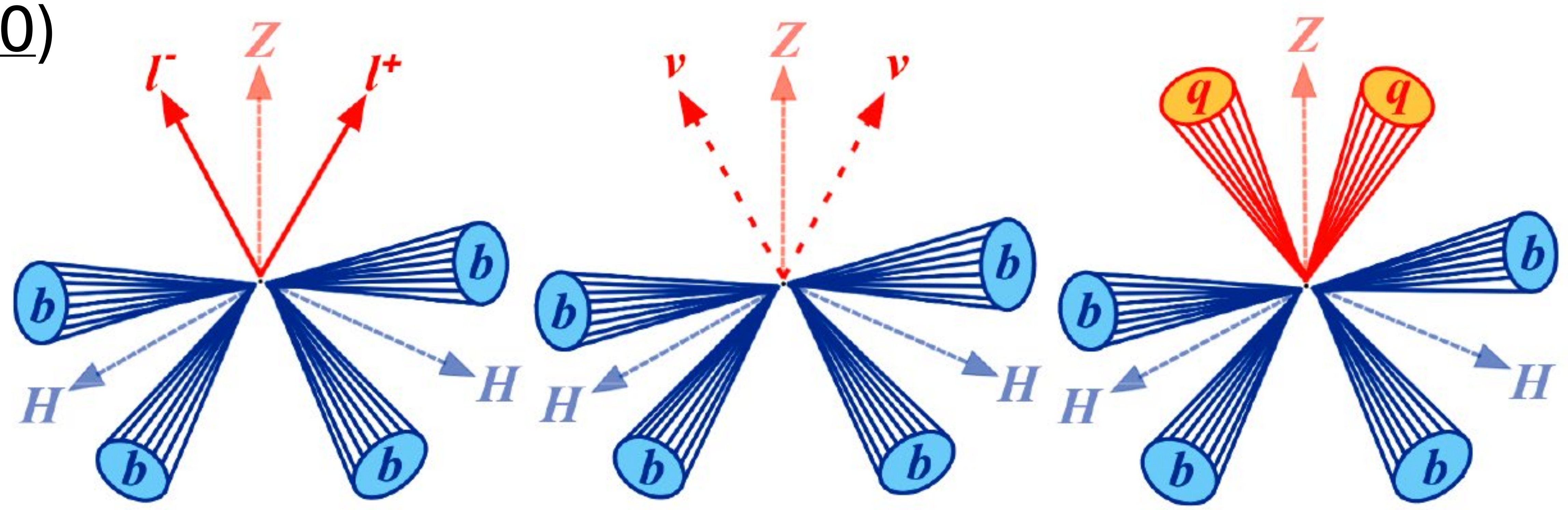
Linear Colliders: lower collision rate enables

- **passive cooling only => low material budget**
- **triggerless operation**

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^2_{HH}
    for further sensitivity enhancement



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

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

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

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

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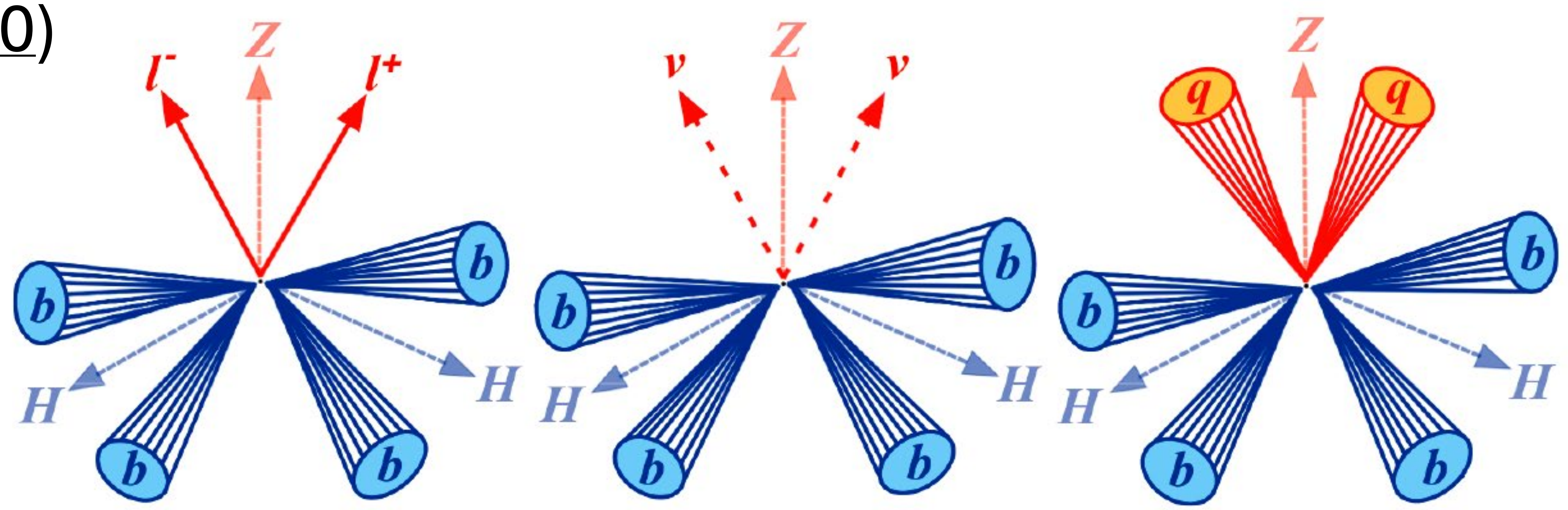

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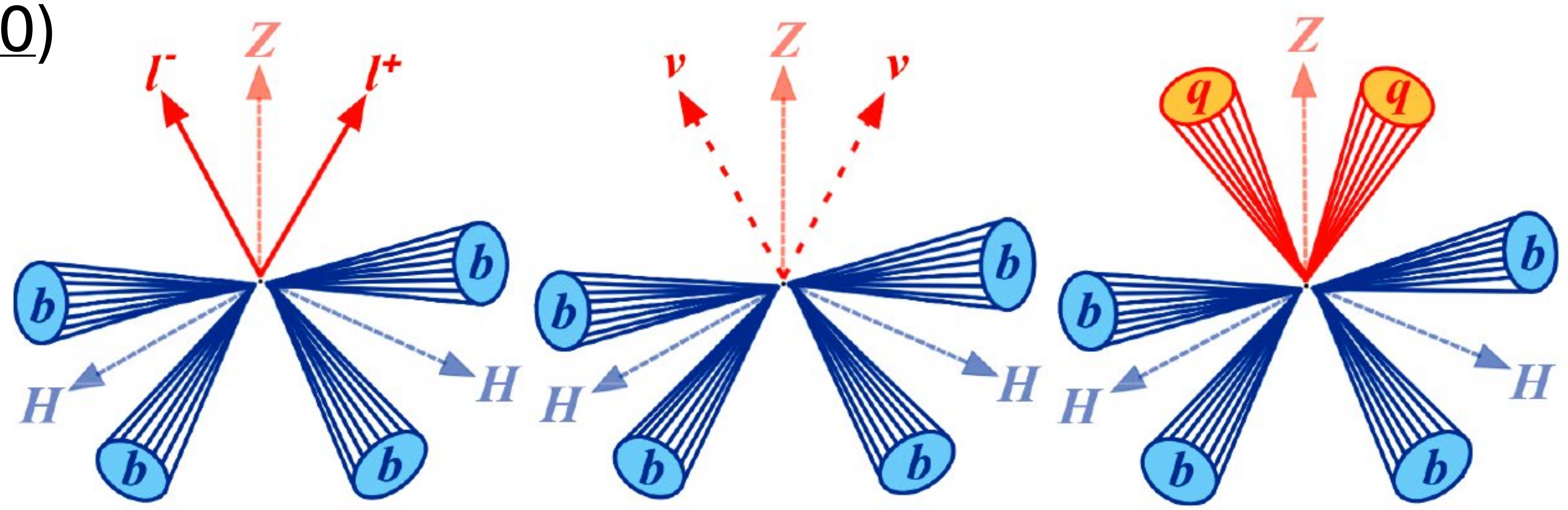

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only 3.x σ observation of λ_{SM}

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}

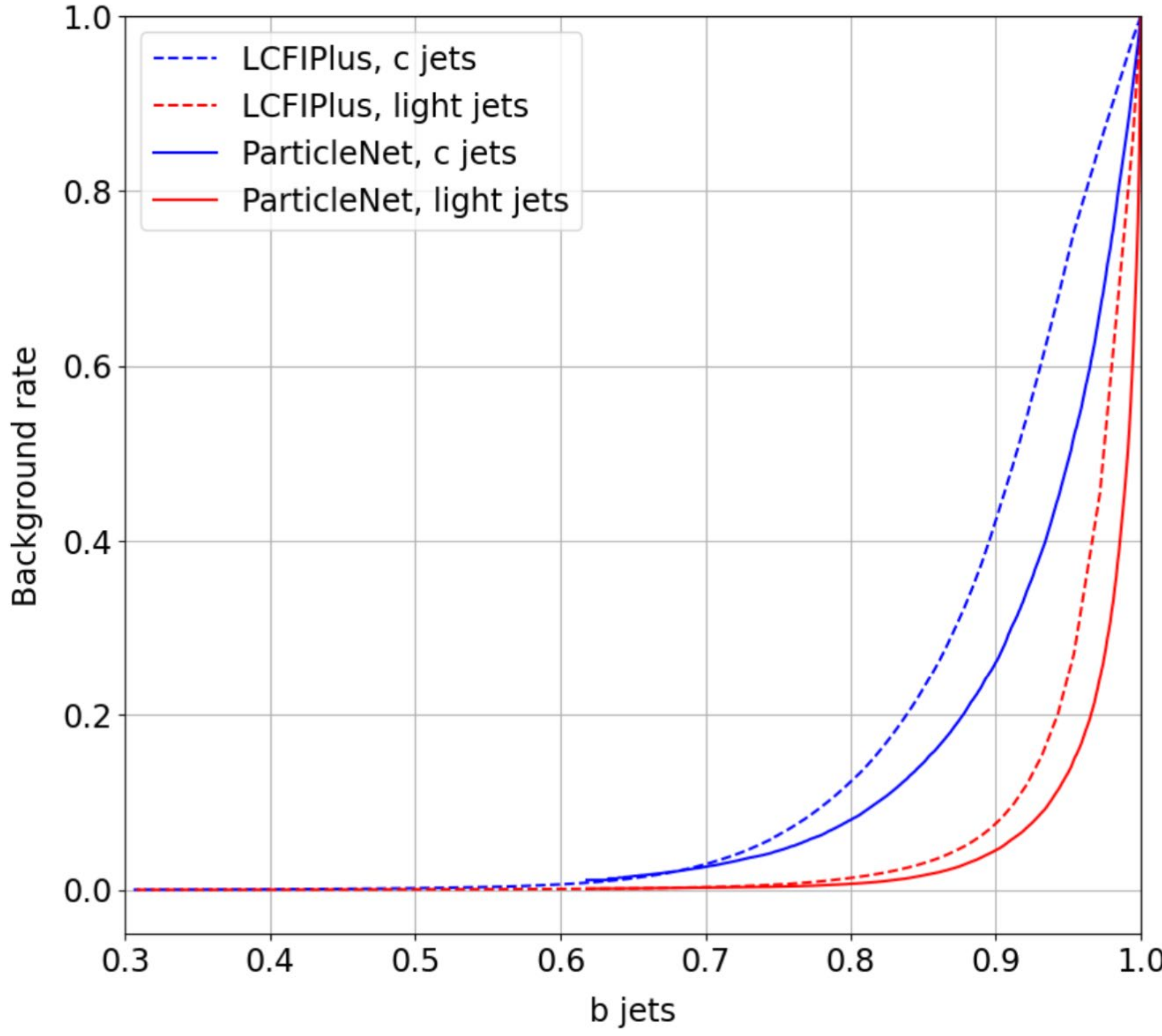
Expected relative improvements from DESY-Thesis-16-027

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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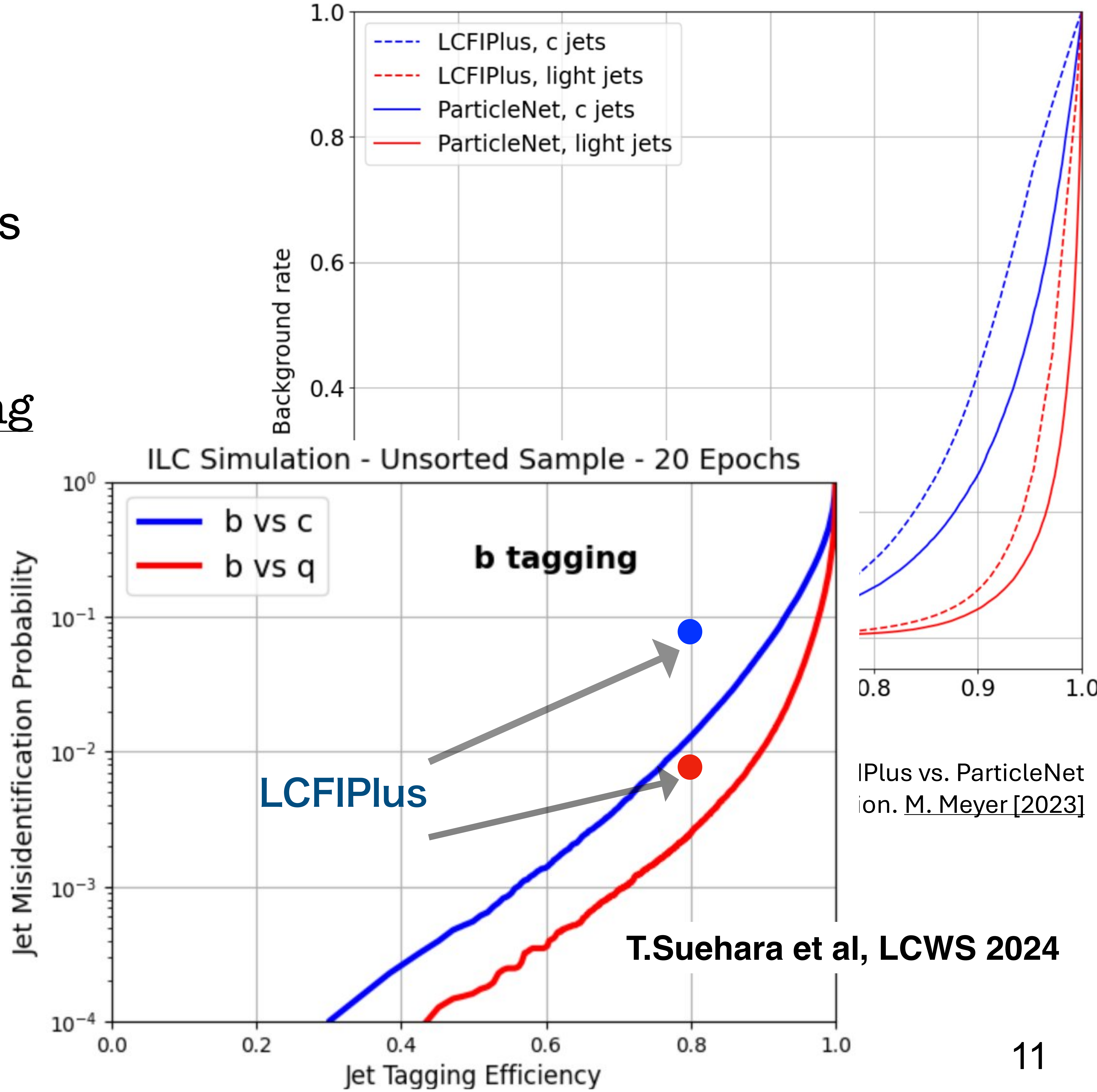

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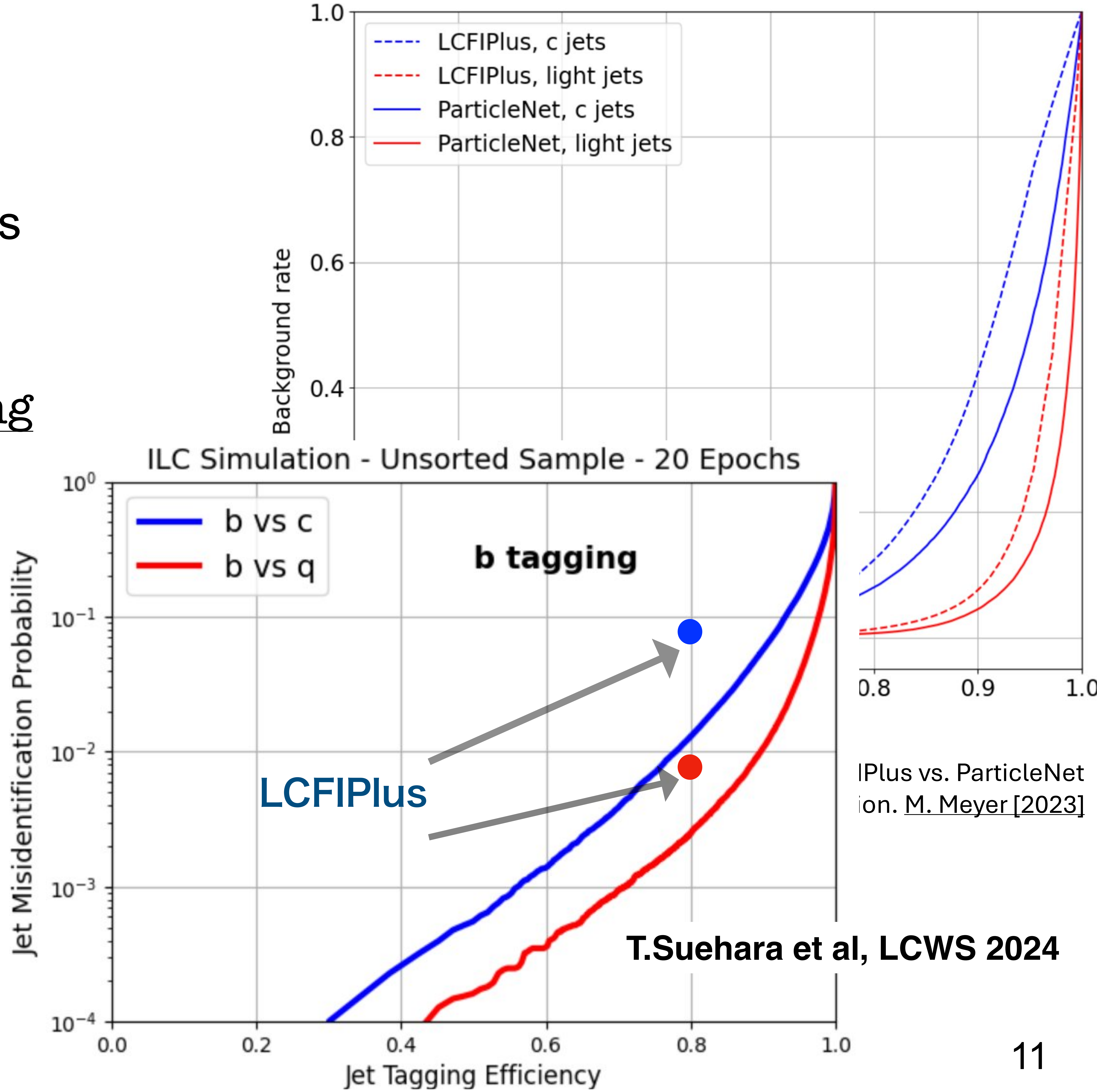
Evaluation of impact in ZHH analysis ongoing, potential improvement even larger than conceivable in 2016…

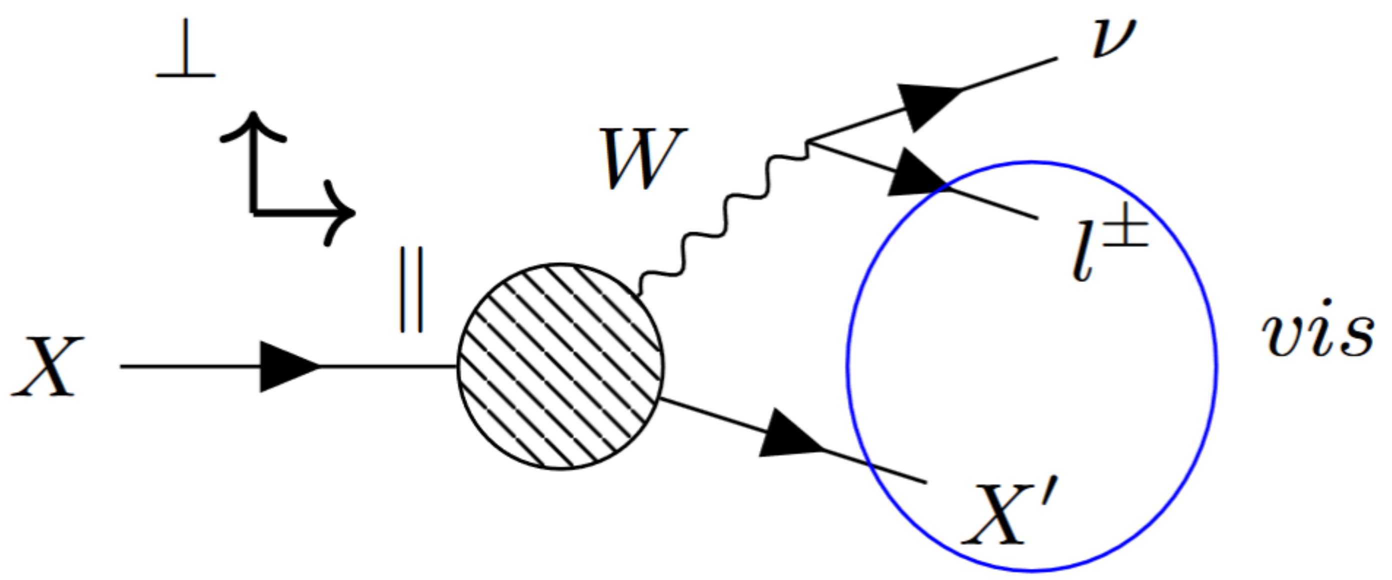


T.Suehara et al, LCWS 2024

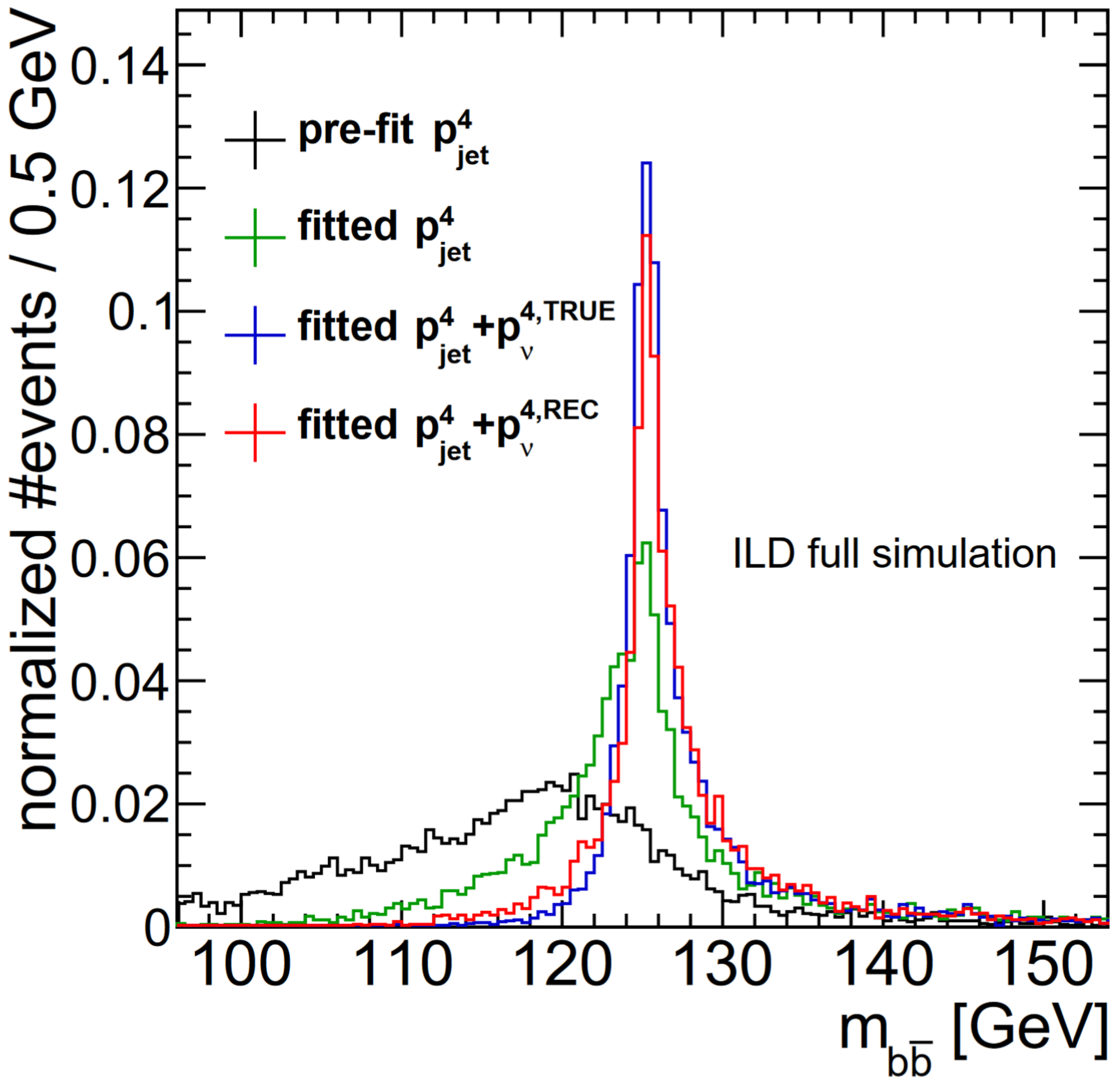
Neutrino Correction with Vertexing, PFlow and Kinematic Fit

Improved m(bb) invariant mass reconstruction

- for semileptonic decay (SLD) processes
  - already in $ZH \rightarrow b\bar{b}/c\bar{c}$, 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]



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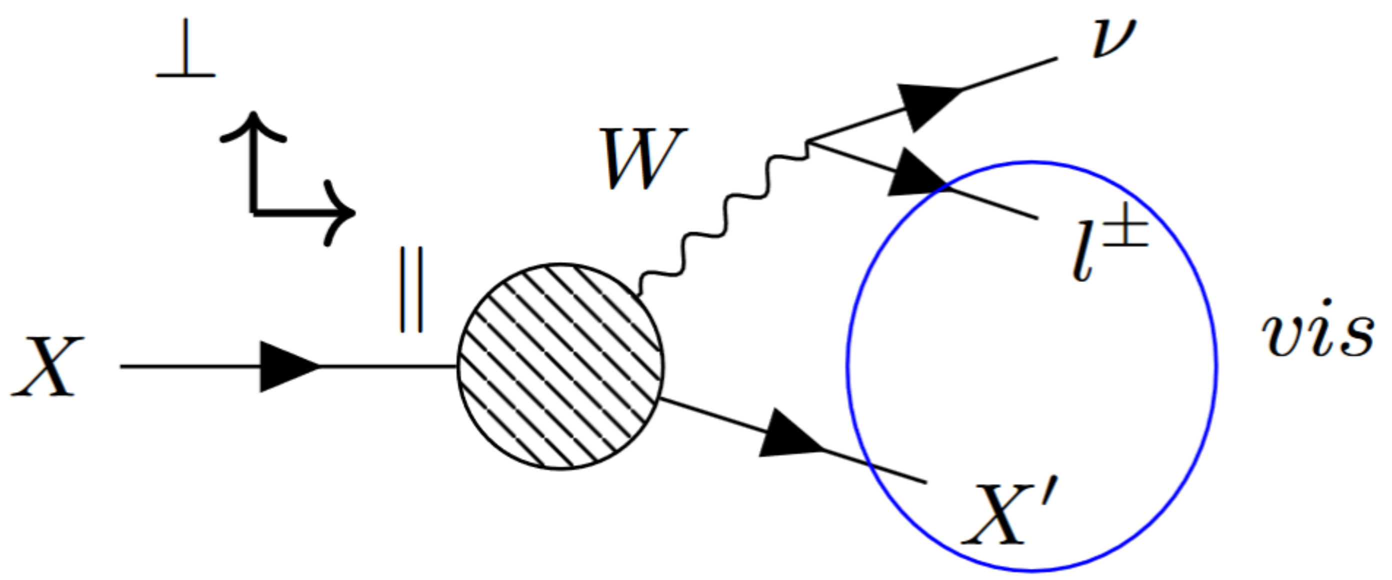
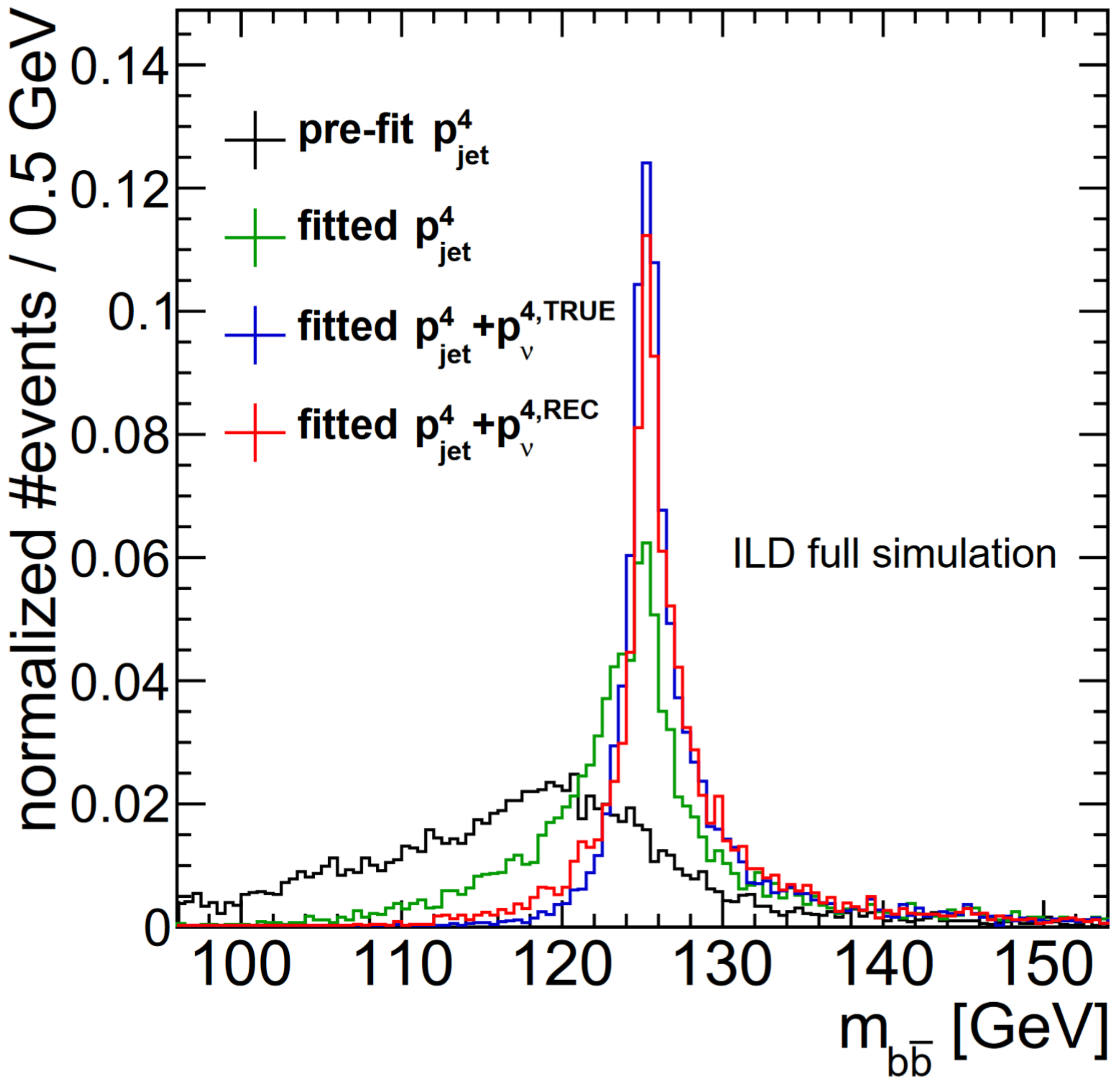
  - identify lepton in jet
  - calculate neutrino four momentum from kinematics with kinematic fitting, the best solution is selected
- status: in production (in MarlinReco)

Evaluation of impact in ZHH analysis ongoing



Recovering the neutrino kinematics. Y. Radkhorrami [2022]



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

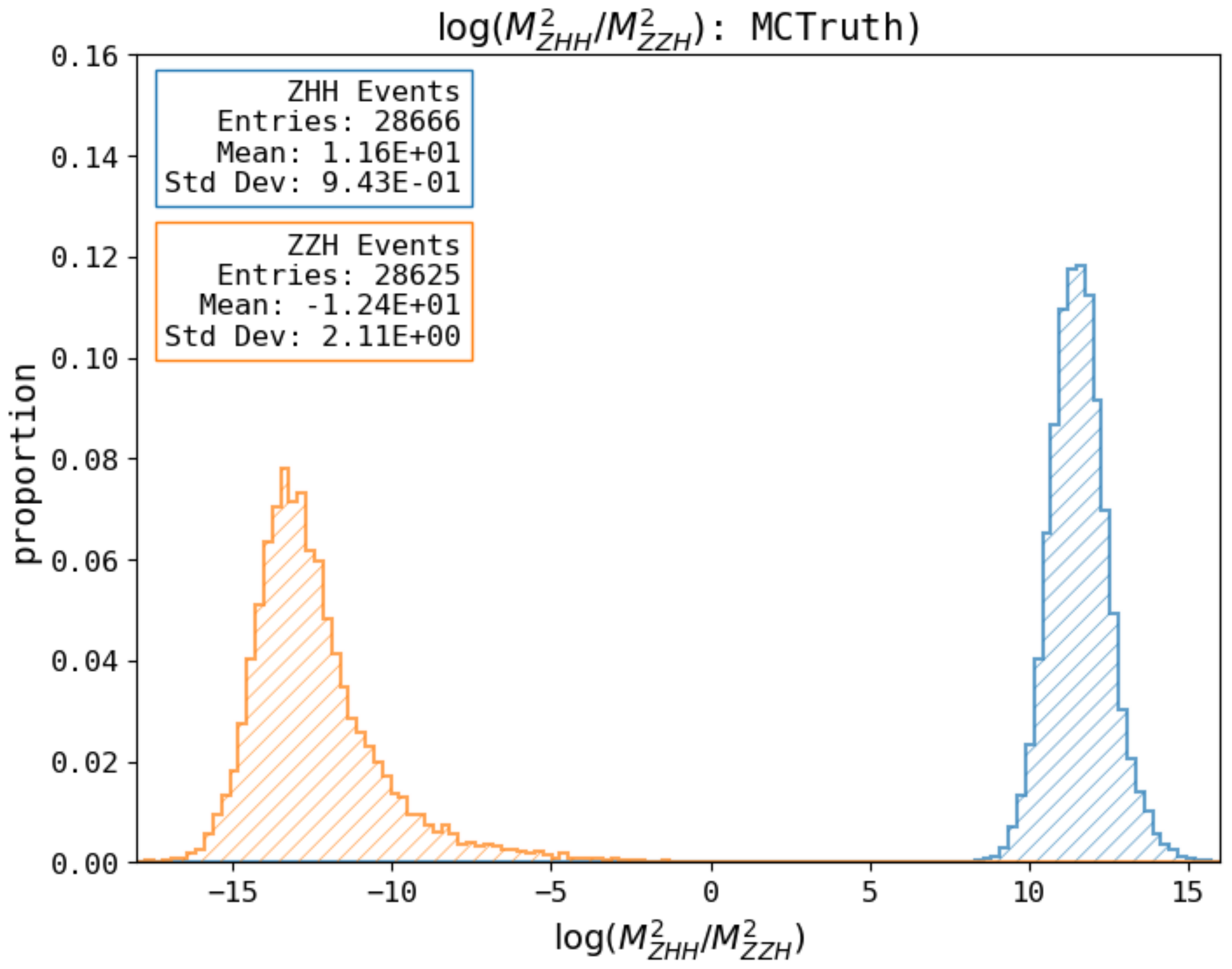
Matrixelements for ZZH / ZHH discrimination

In theory the optimal observable…

generator level check

- excellent separation

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



naive MEM

- separation power lost
  ➔ need to describe smearing with TFs

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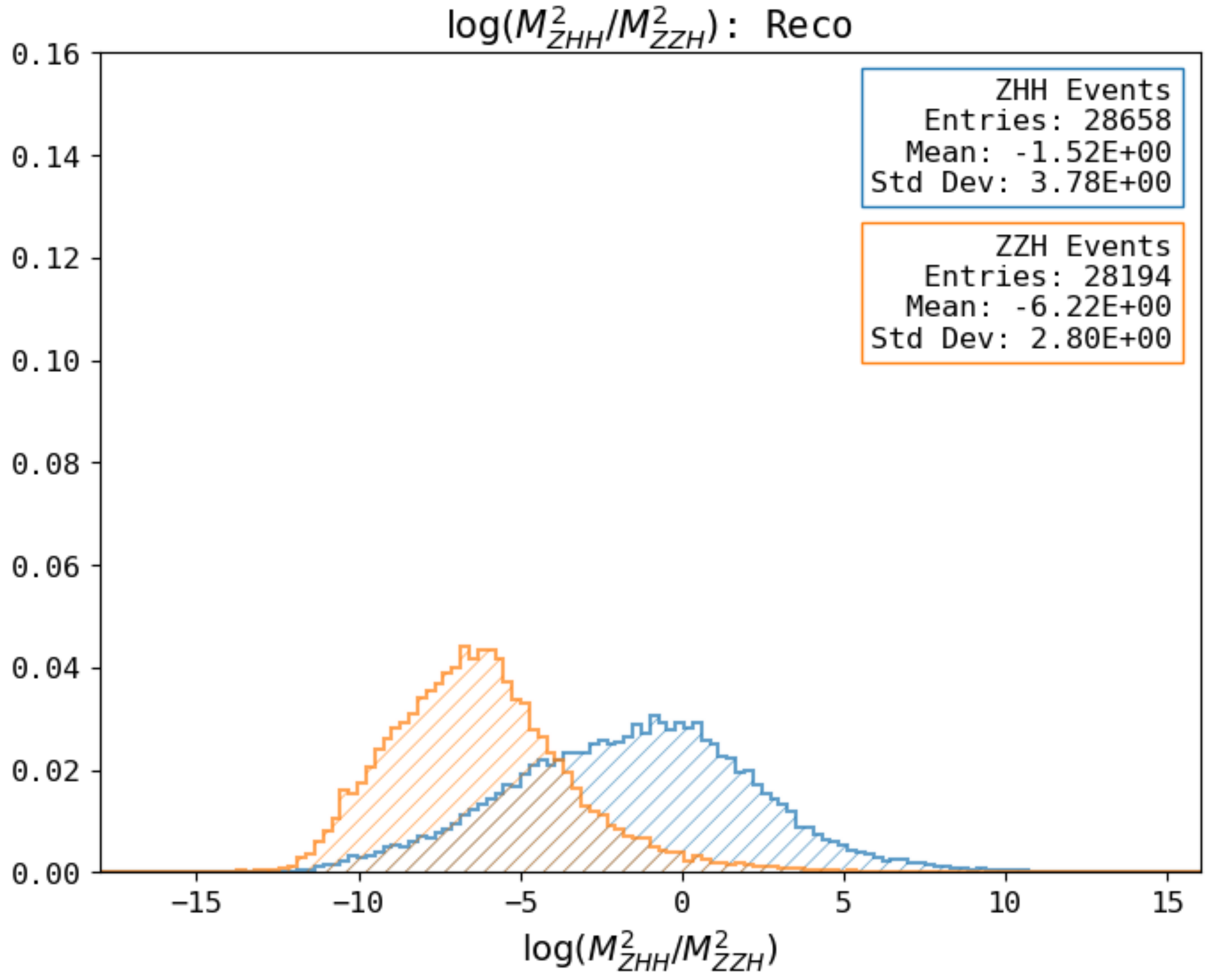

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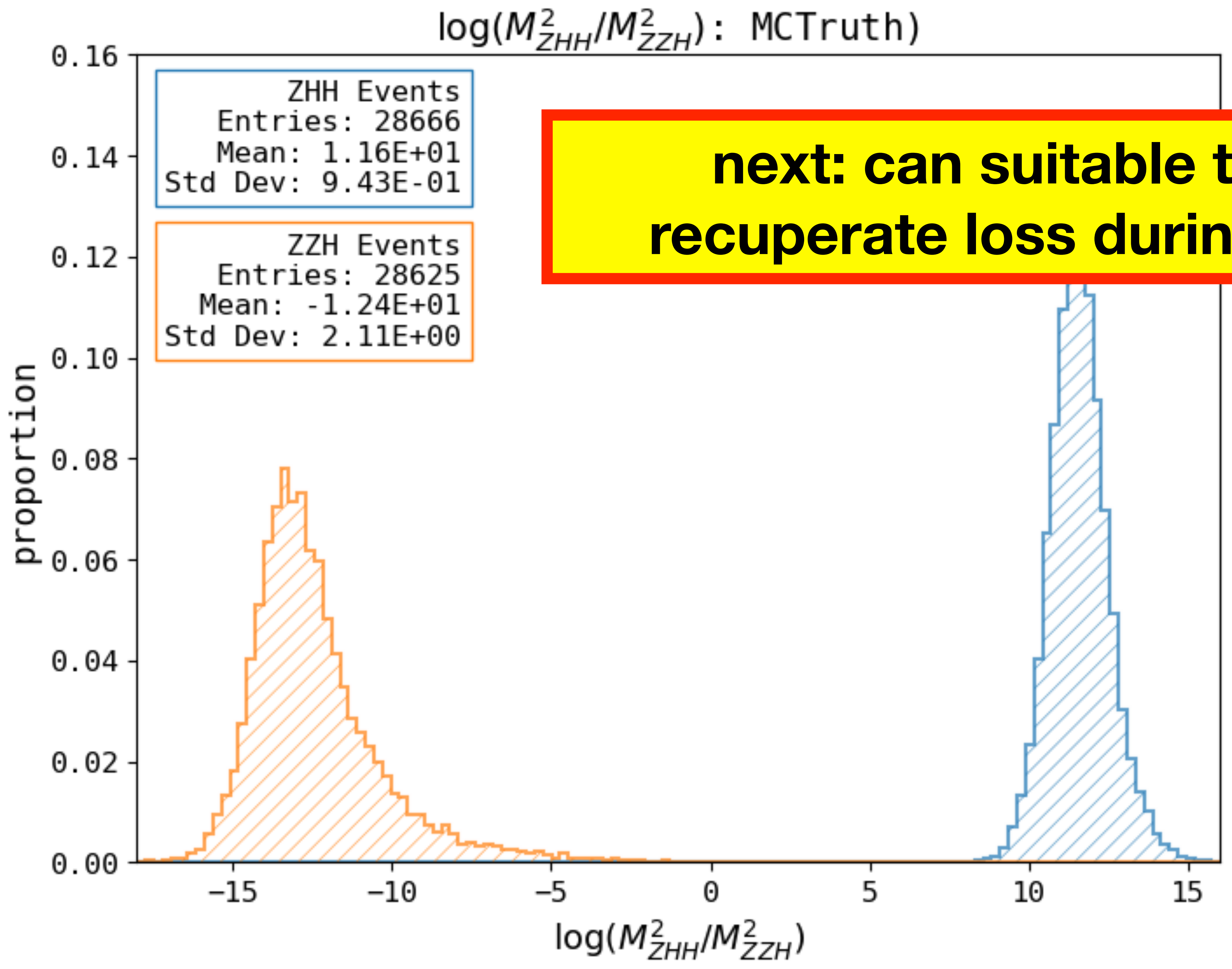
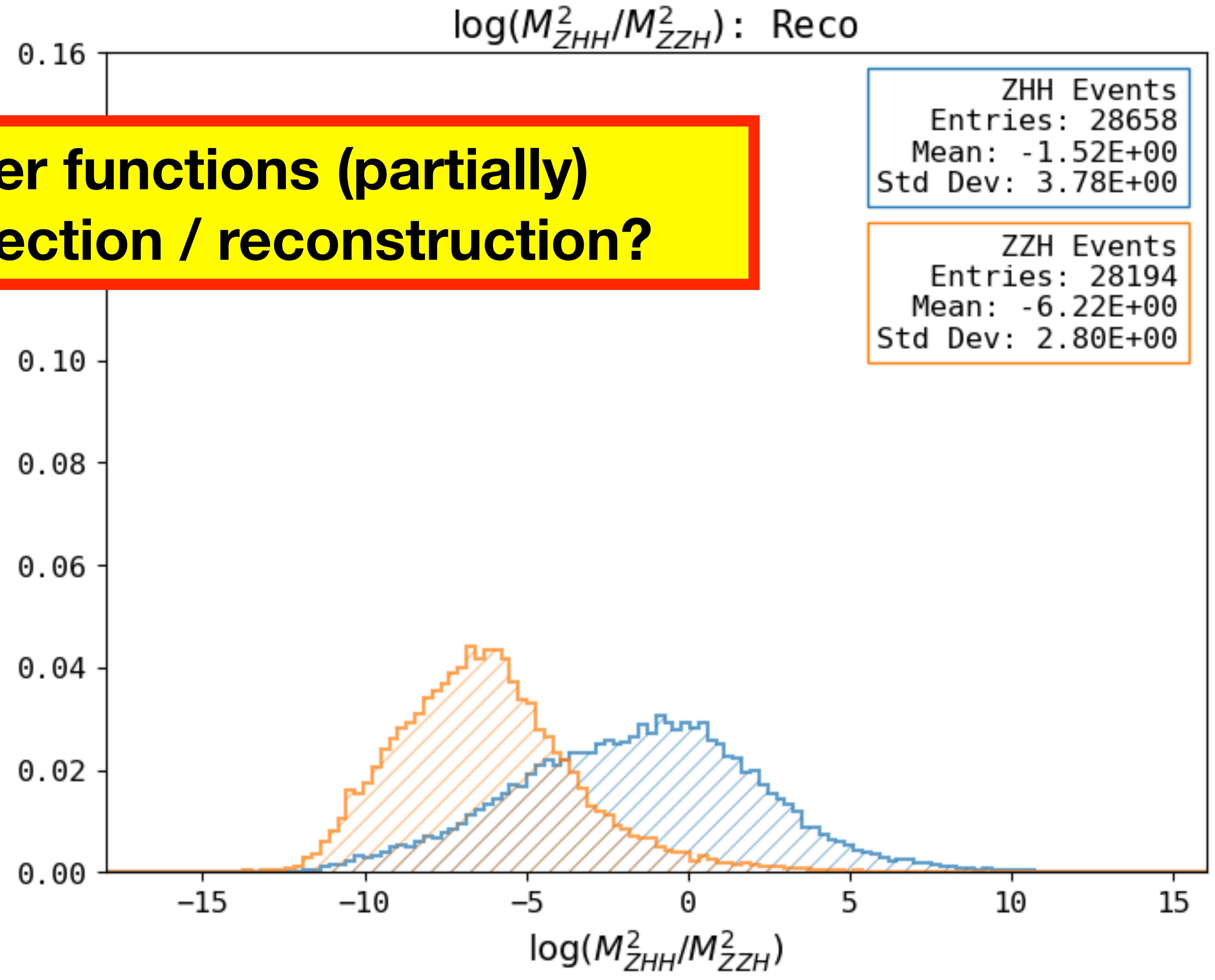


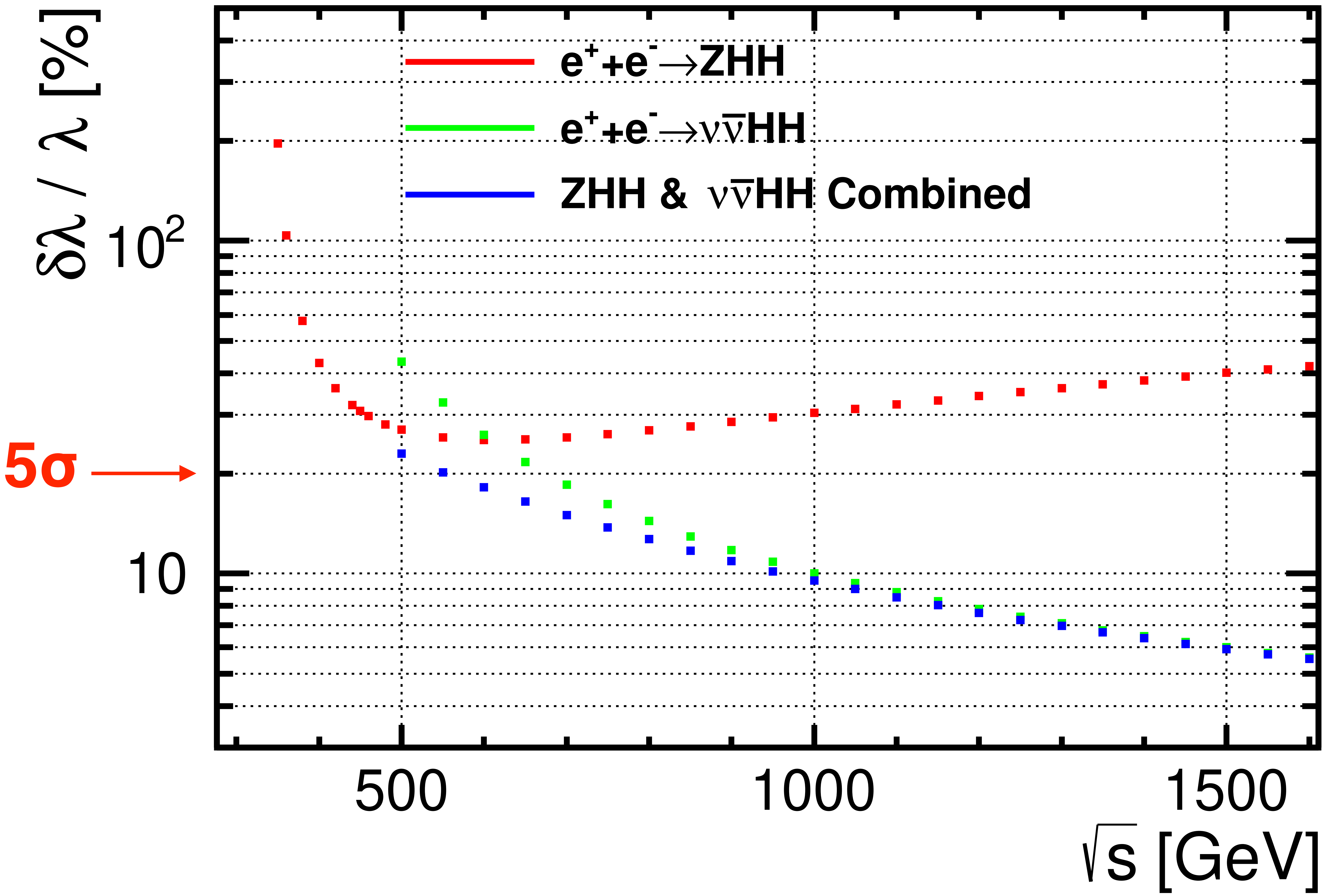


next: can suitable transfer functions (partially) recuperate loss during detection / reconstruction?

Choice of E_{CM}
— and interplay with BSM

Combining ZHH & vvHH — as Function of ECM

J.Tian, LCWS2024



Discovery can be guaranteed

ILC500: 23%

ILC550: 20%

ILC600: 18%

note: this is based on old DBD analysis; large room from new analysis

16

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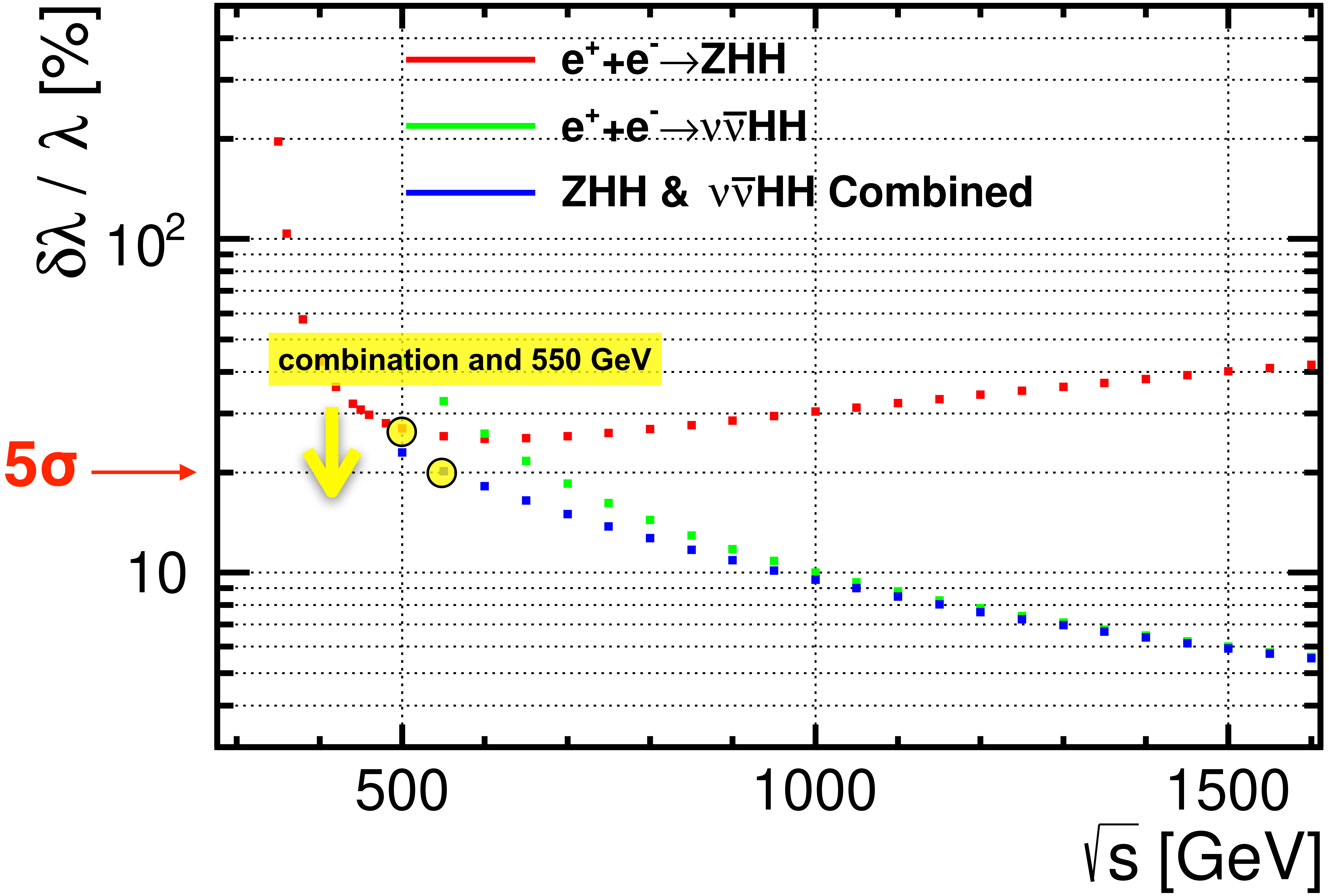

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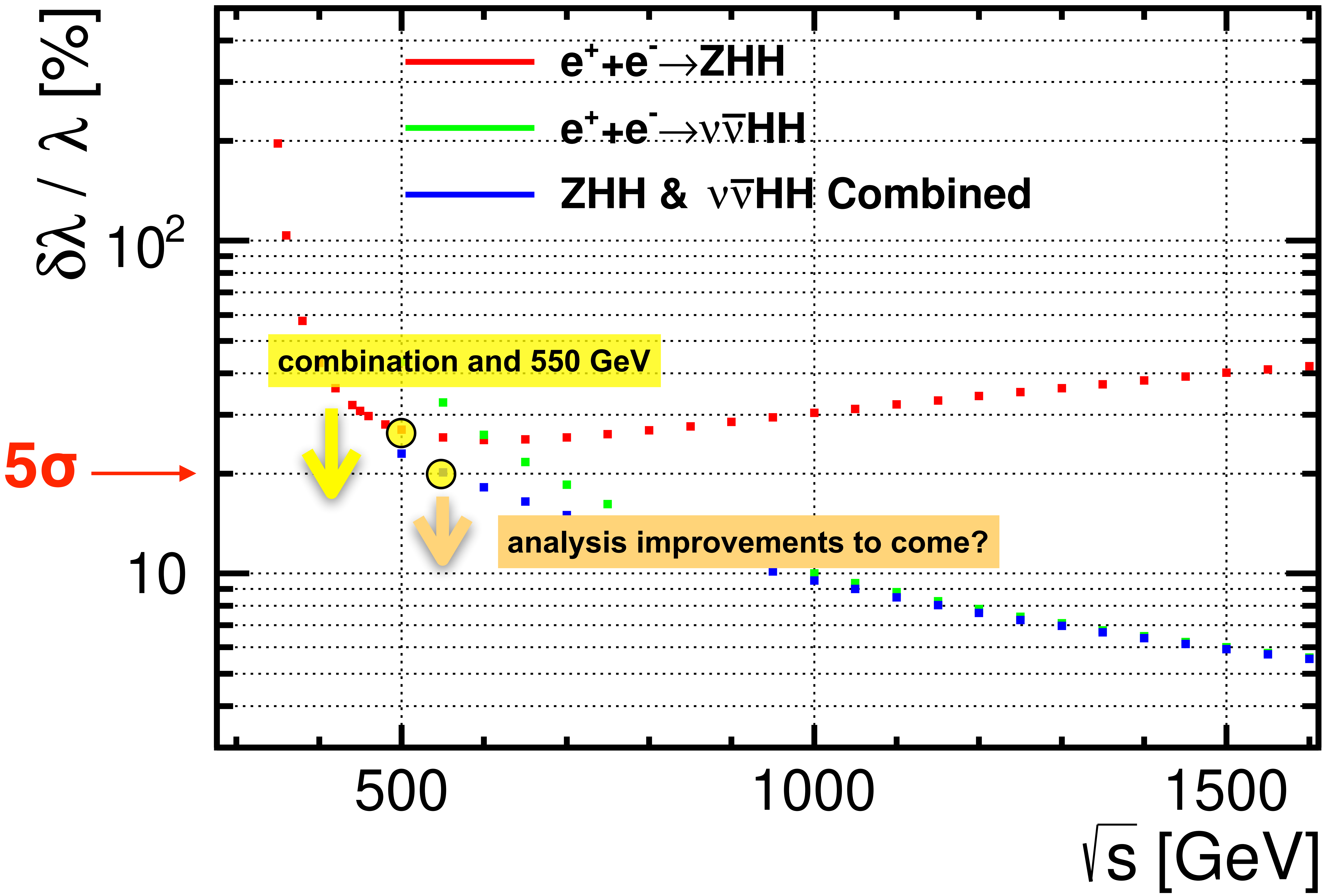

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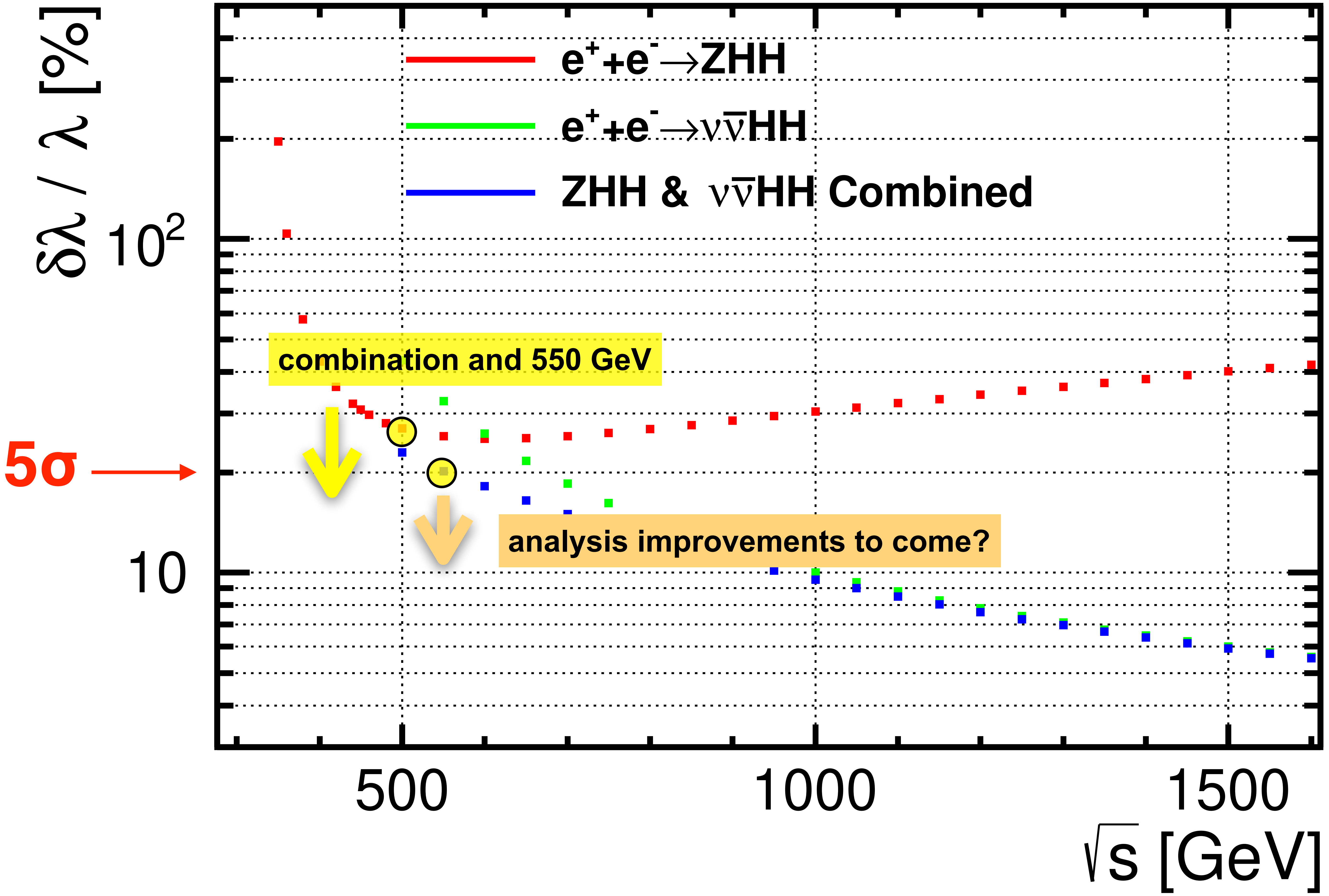

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How far can analysis improvements push this? 15%? => stay tuned…

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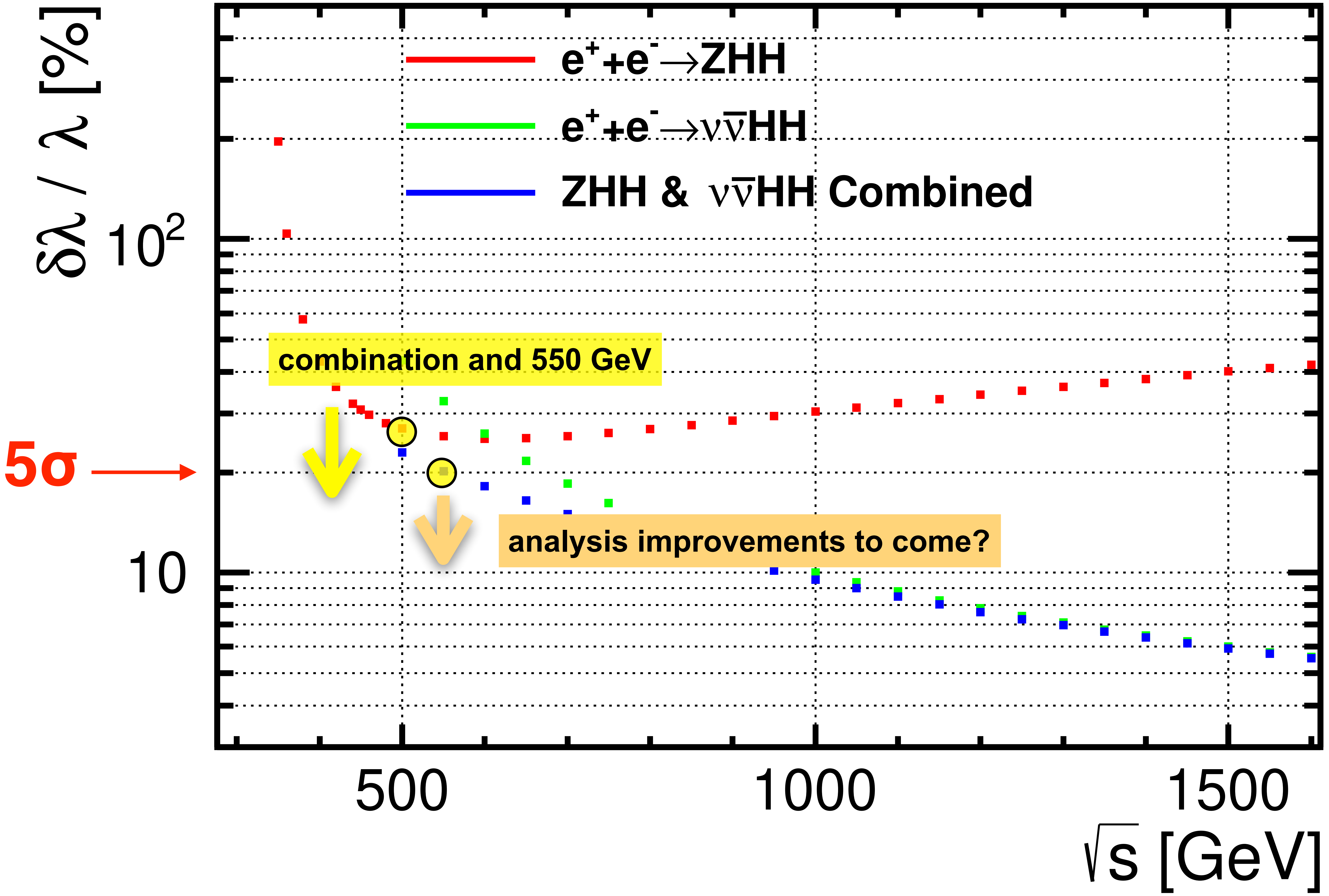

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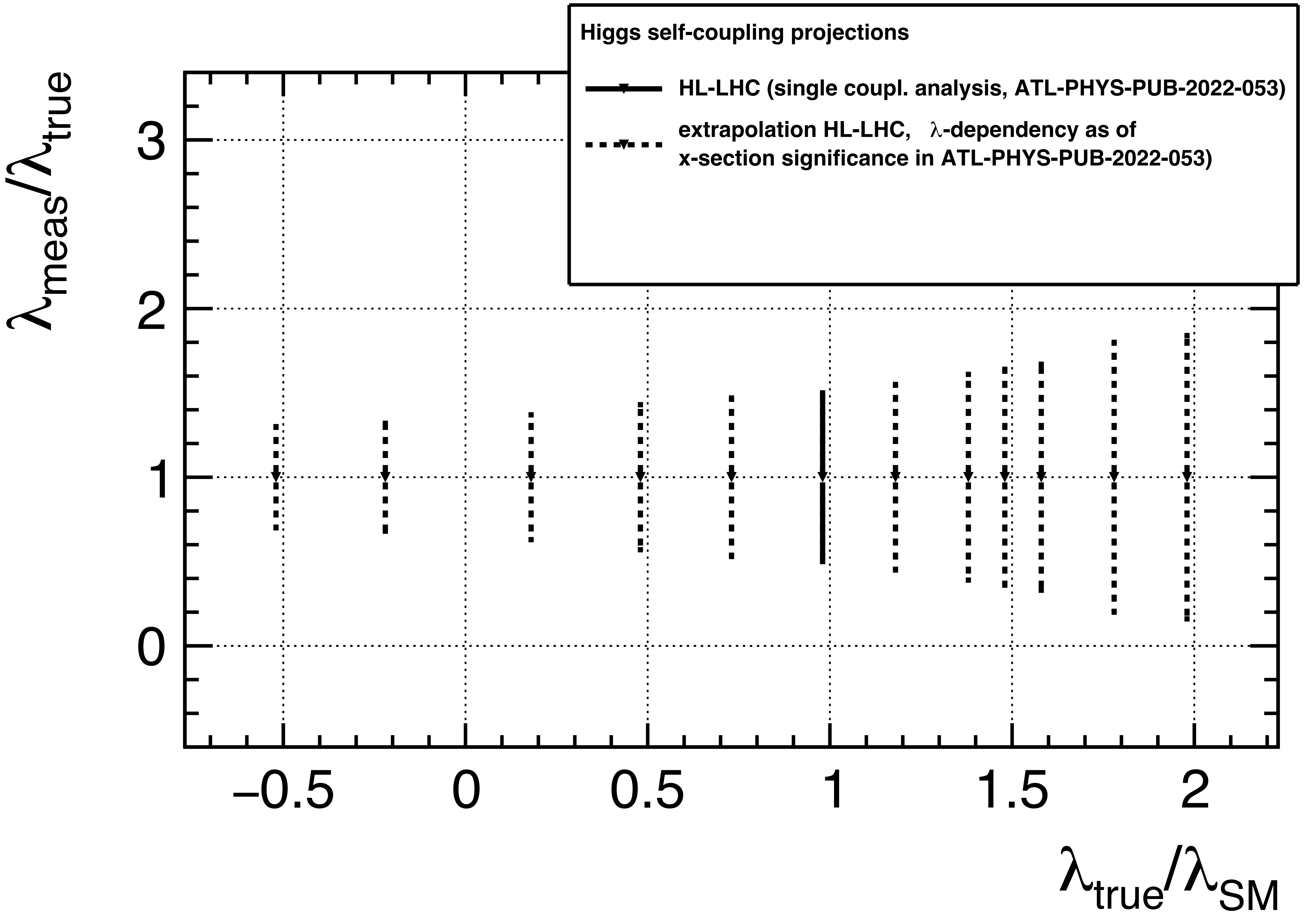
Higgs self-coupling Beyond the SM

Electroweak Baryogenesis?



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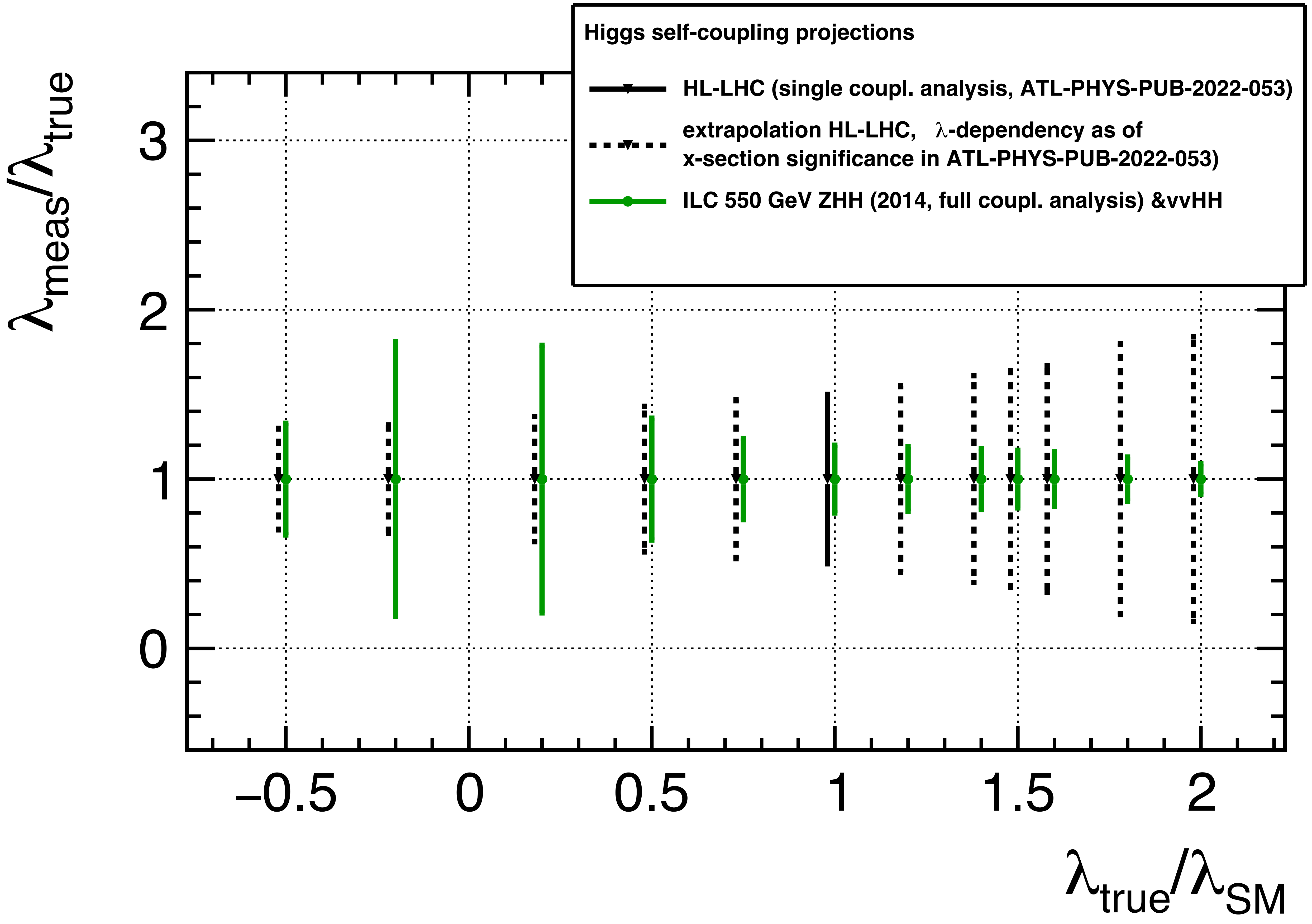

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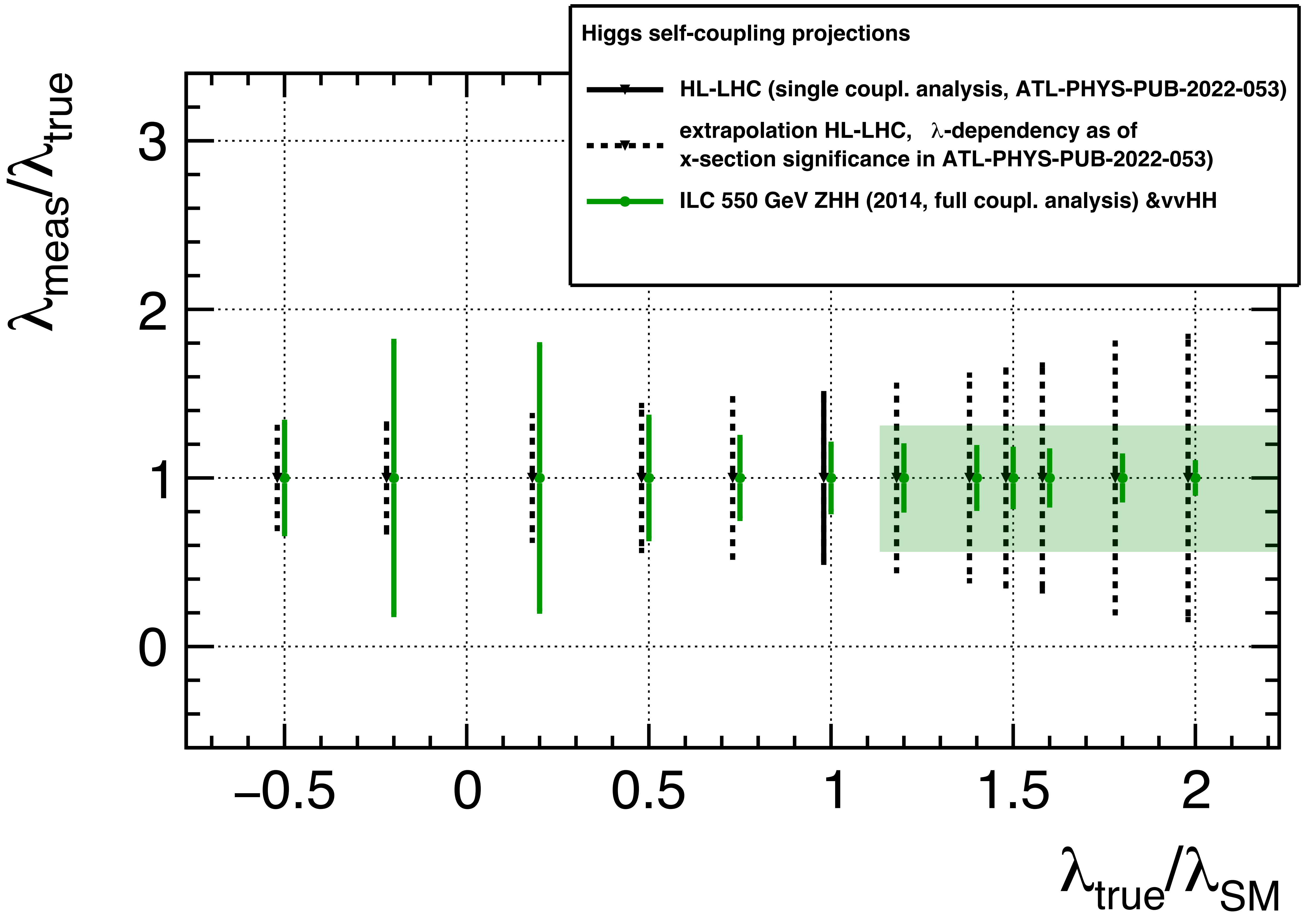
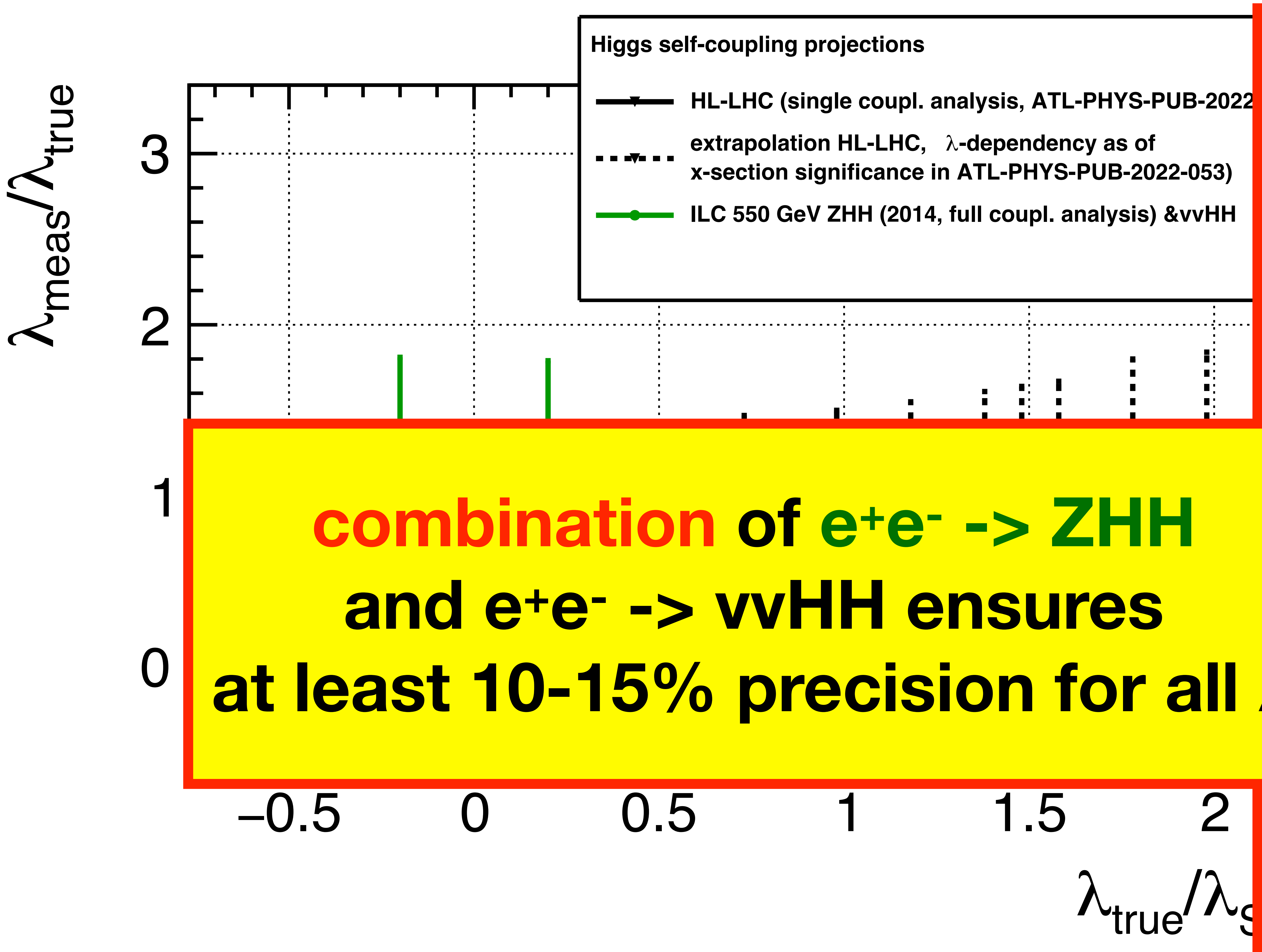


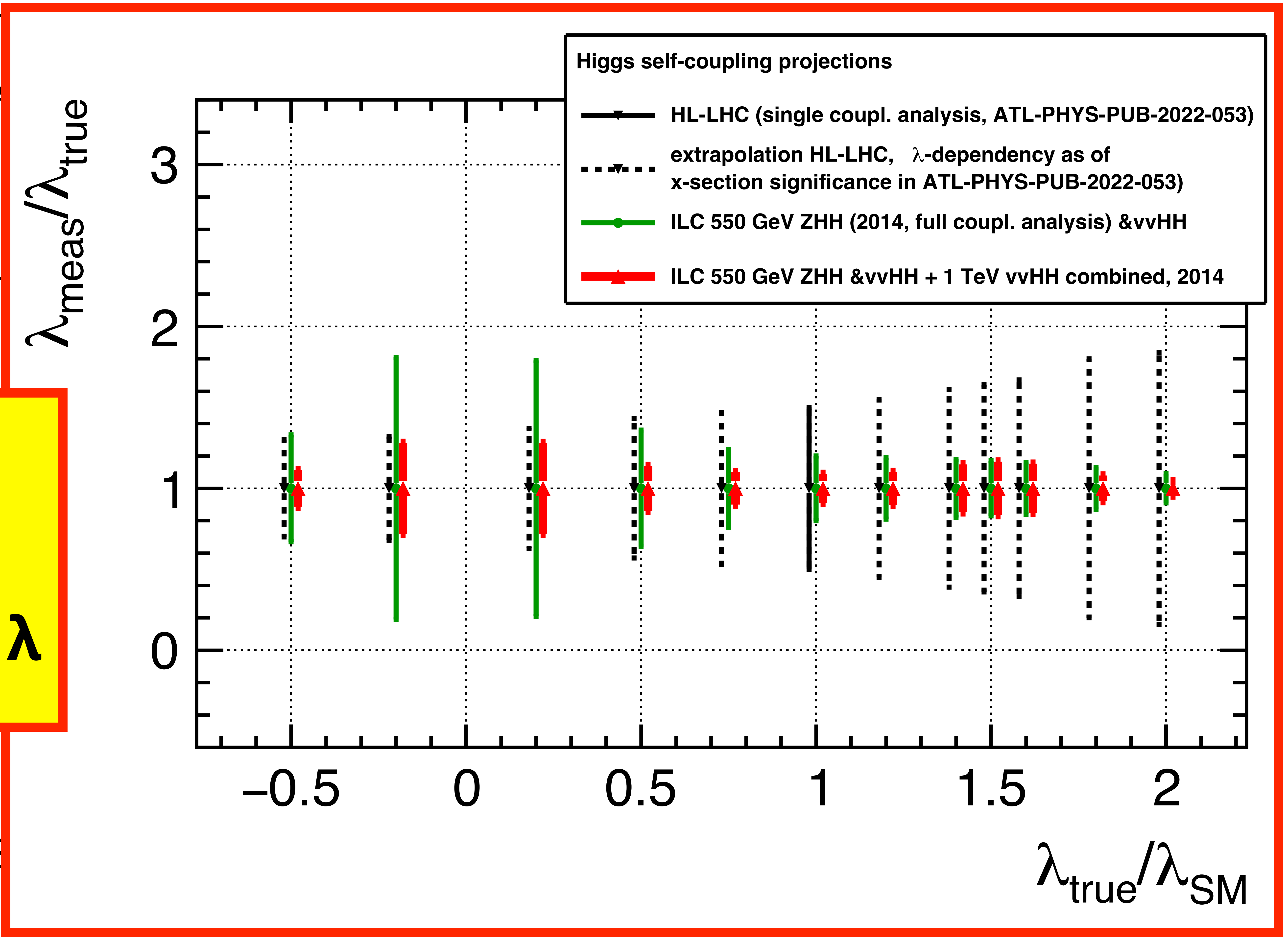
Region of interest for electroweak baryogenesis

Higgs self-coupling Beyond the SM

Electroweak Baryogenesis?



combination of e+e- -> ZHH and e+e- -> vvHH ensures at least 10-15% precision for all λ



Conclusions

And Outlook

- The Higgs self-coupling can have large deviations from SM (even if others don't!)
- Direct tree-level access to tri-linear Higgs coupling in e+e- collisions at ≥ 500 GeV
- The previous ILC500 projection, from 2014, based on full detector simulation, gave 27% for the SM case, but eg 18% for $\kappa_\lambda = 1.5$
- **A lot of room for improvement has been identified**
  - **at slightly higher ECM, eg 550 GeV, di-Higgs production from WW-fusion starts to contribute => eg 27% → 20% for SM case**
  - **progress in flavour tag, jet reco, kinematic fitting, MEMs, … 20% → x% for SM case**

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≥ 5σ dicovery of λ should be possible at 550 GeV for $\lambda \geq \lambda_{SM}$

in combination with 1 TeV: 10-15% for any value of λ

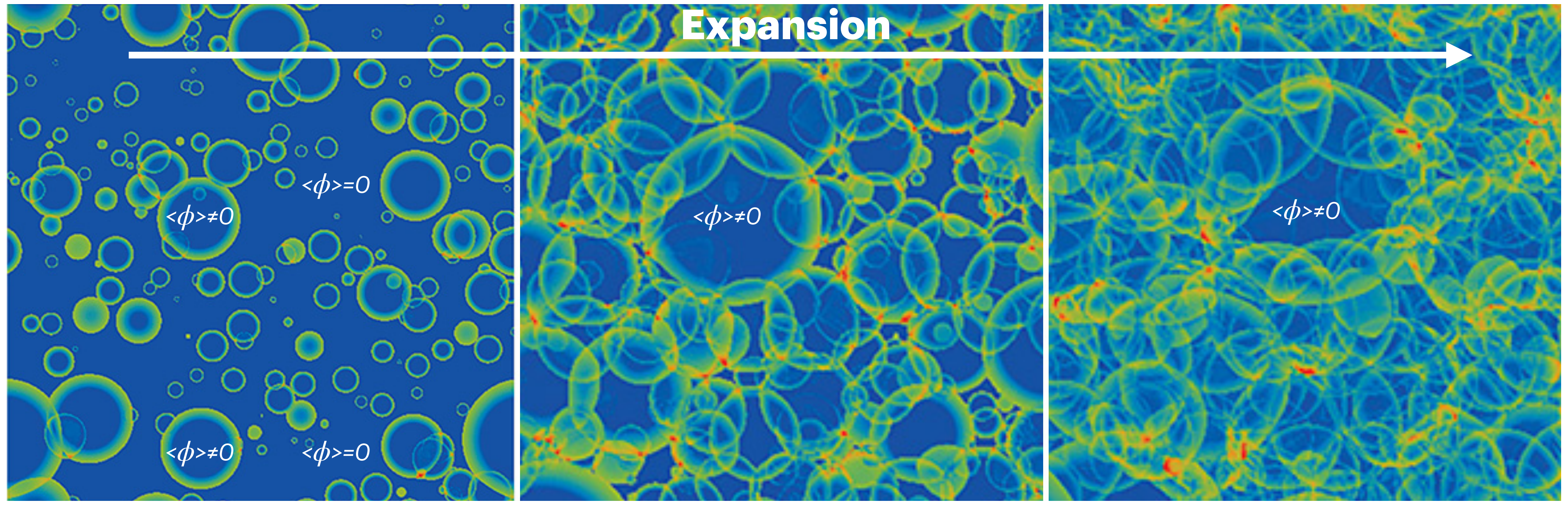
Stay tuned for a full update!

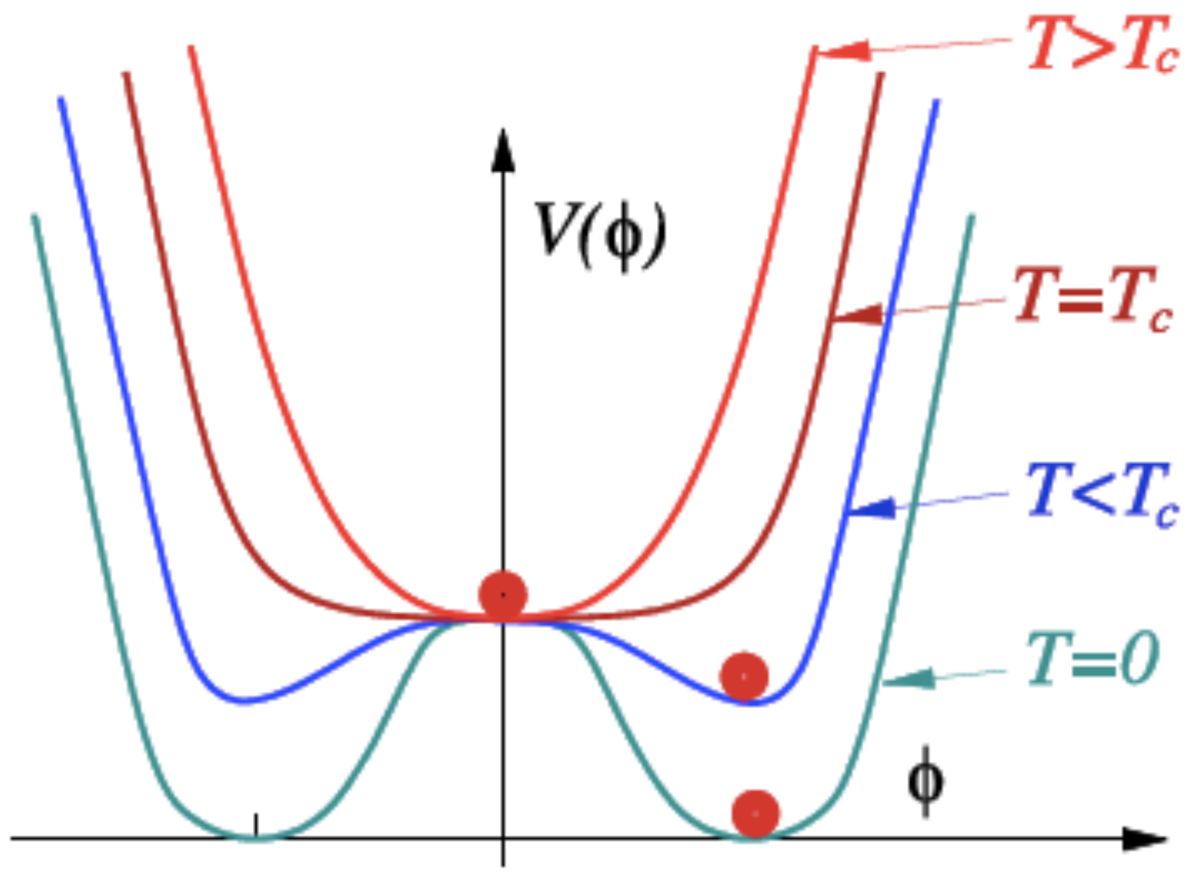
Backup

The Higgs potential, the Higgs self-coupling and Baryogenesis

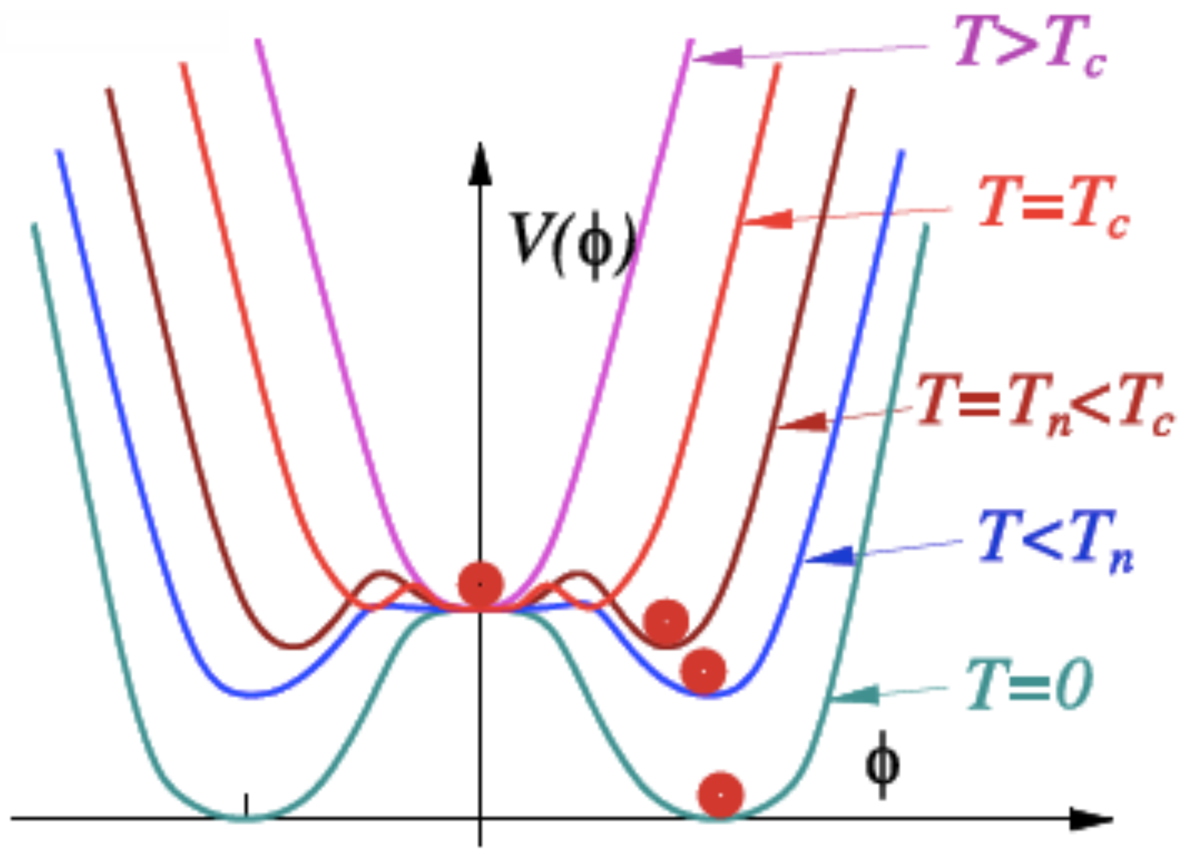
1st vs 2nd order phase transition

- origin of matter-antimatter asymmetry: universe must have been out of thermal equilibrium => 1.order phase transition
- **Electroweak phase transition?**





2nd order



1st order, requirement for EW baryogenesis

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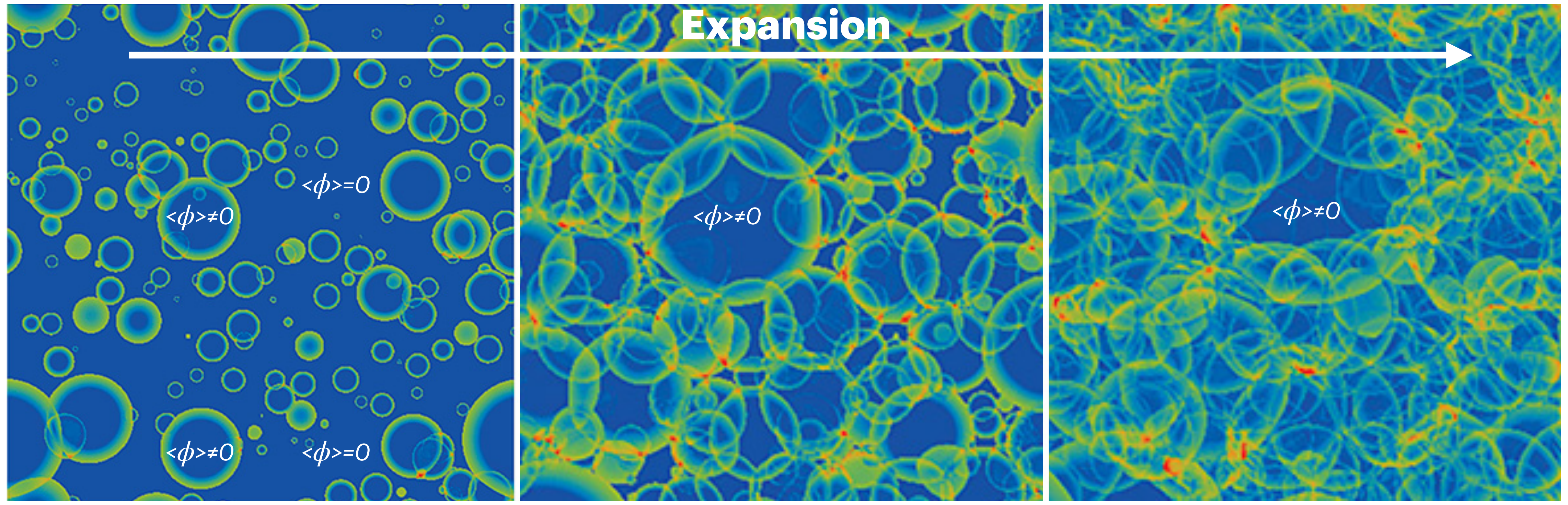

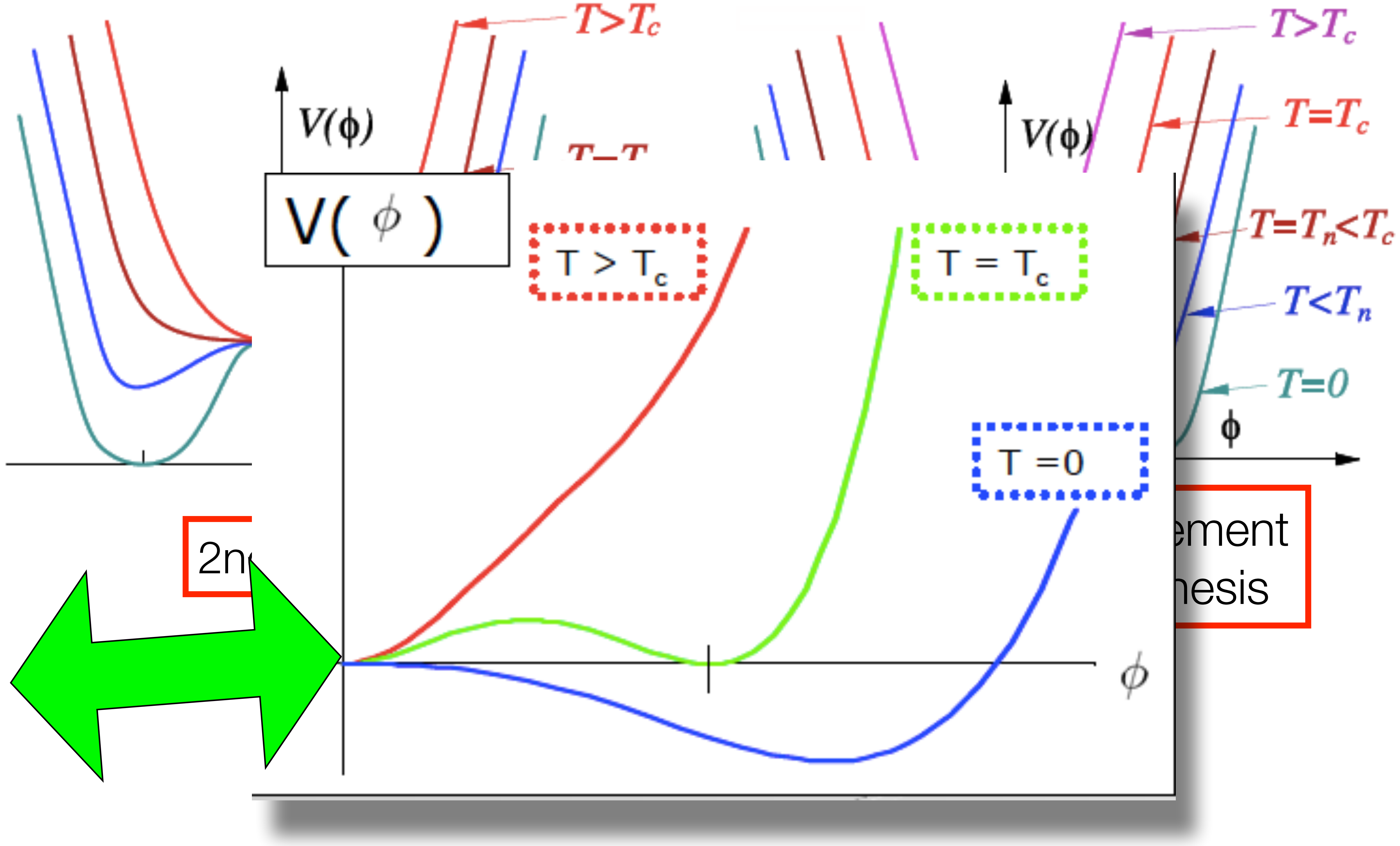

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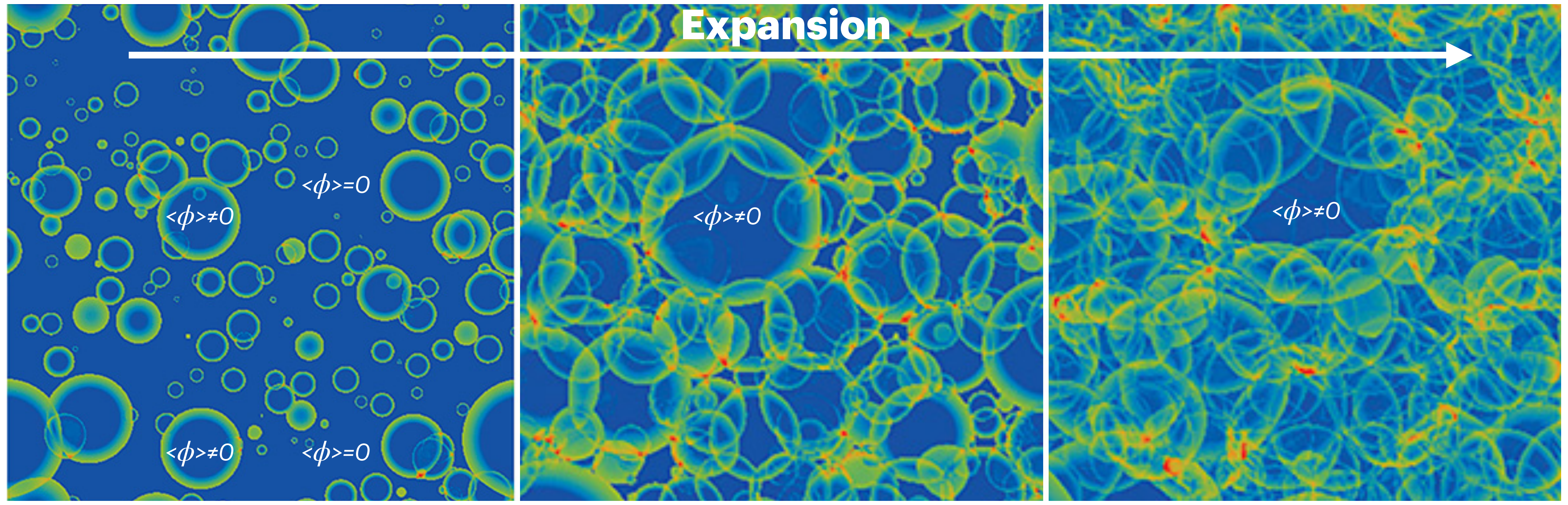

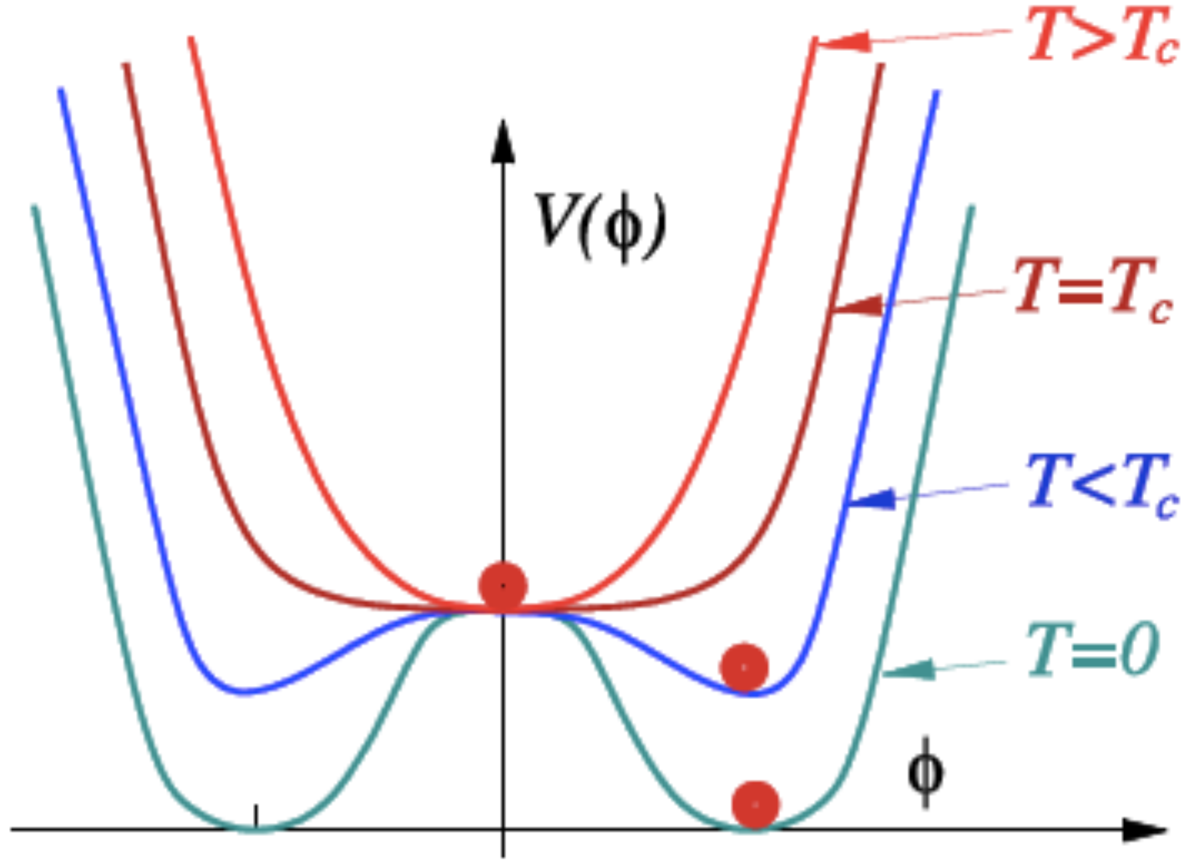

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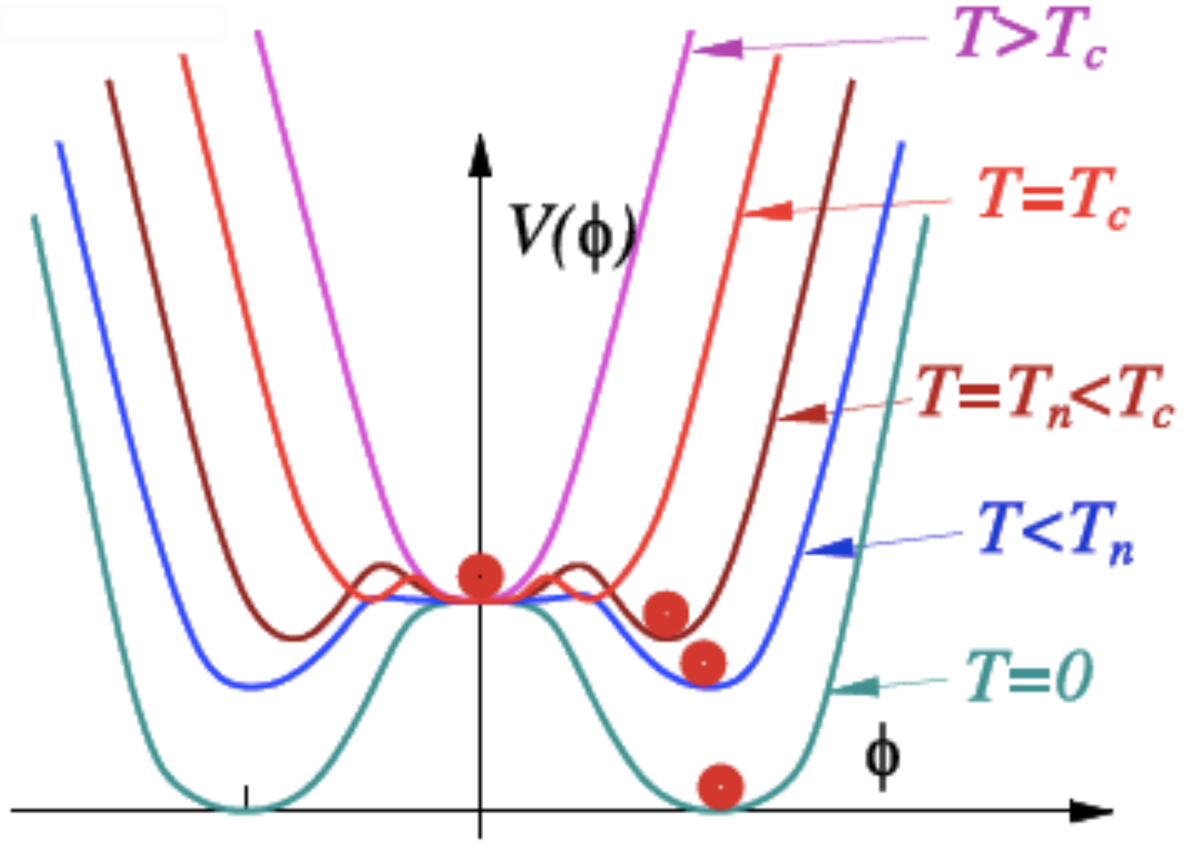

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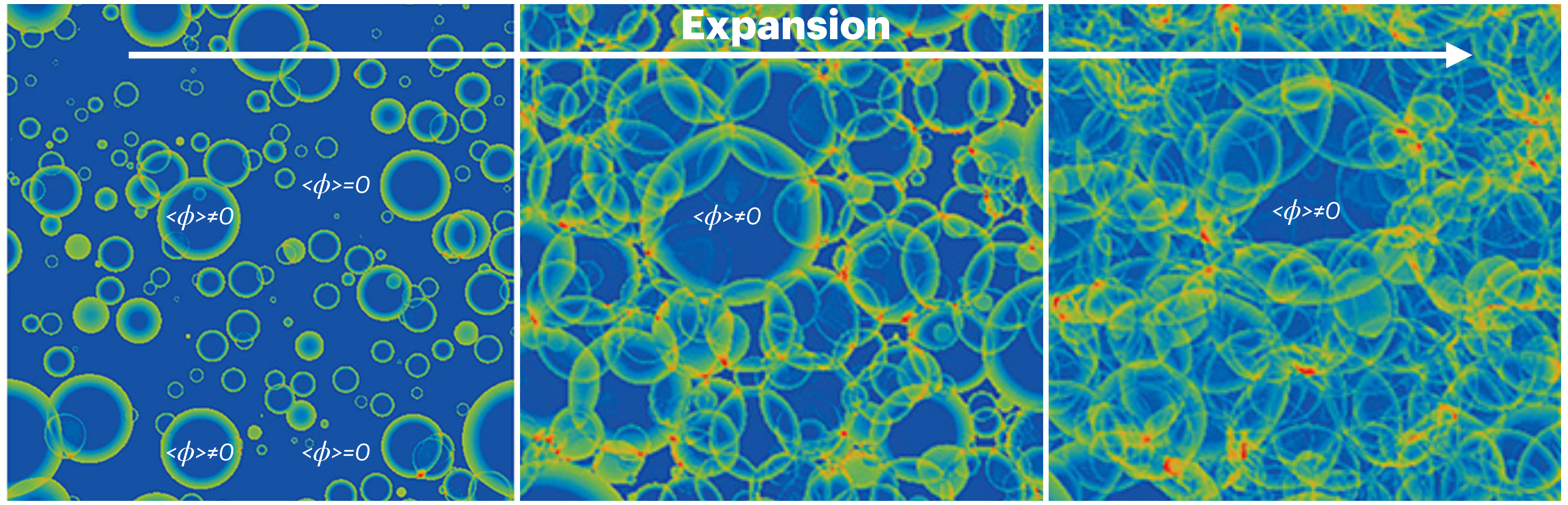

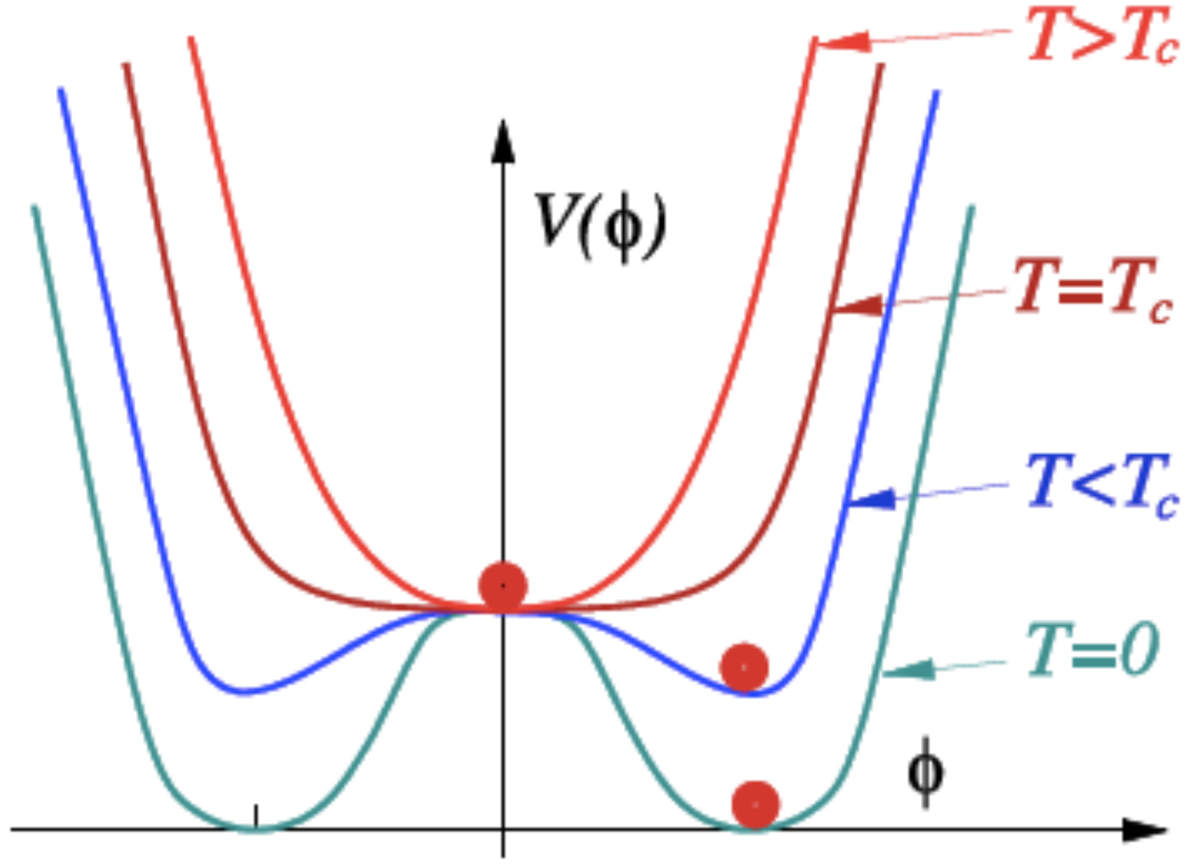

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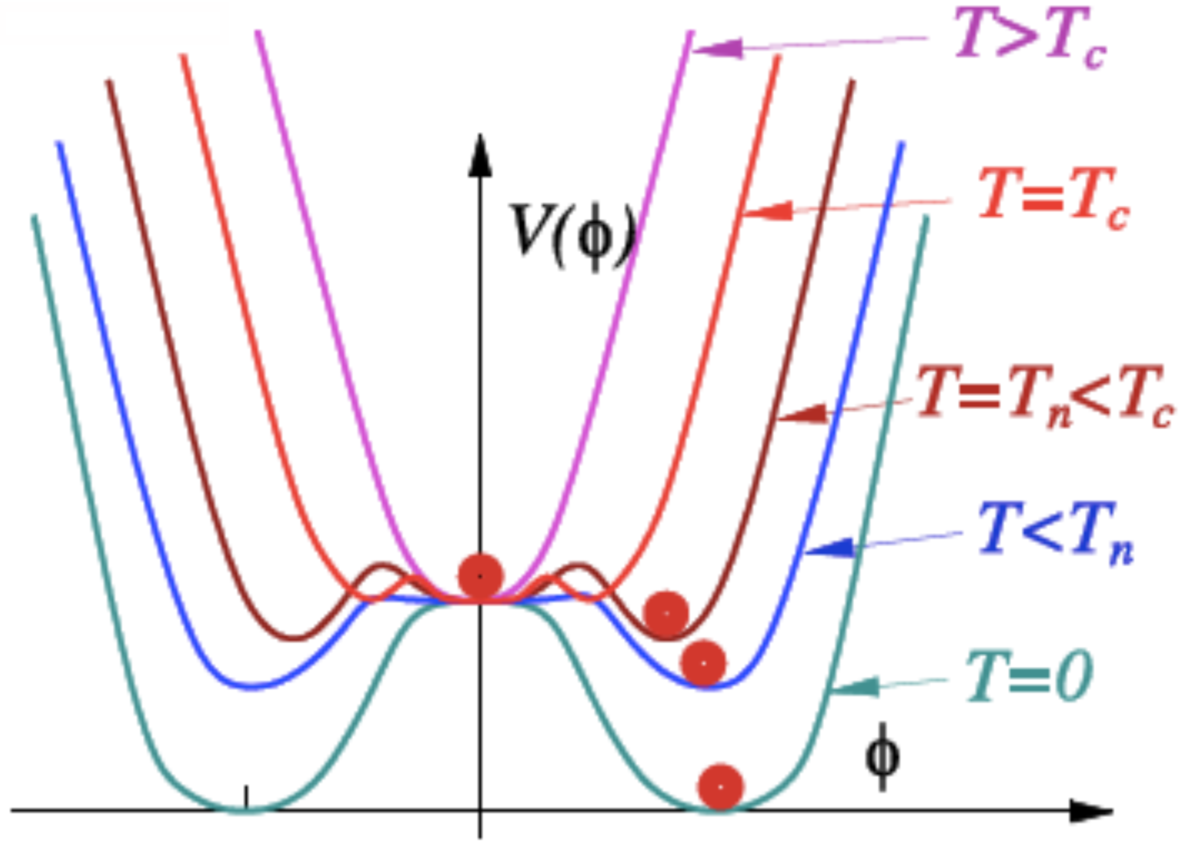

1st order, requirement for EW baryogenesis

- SM with M_H = 125 GeV: 2nd order :(
- value of self-coupling λ determines shape of Higgs potential
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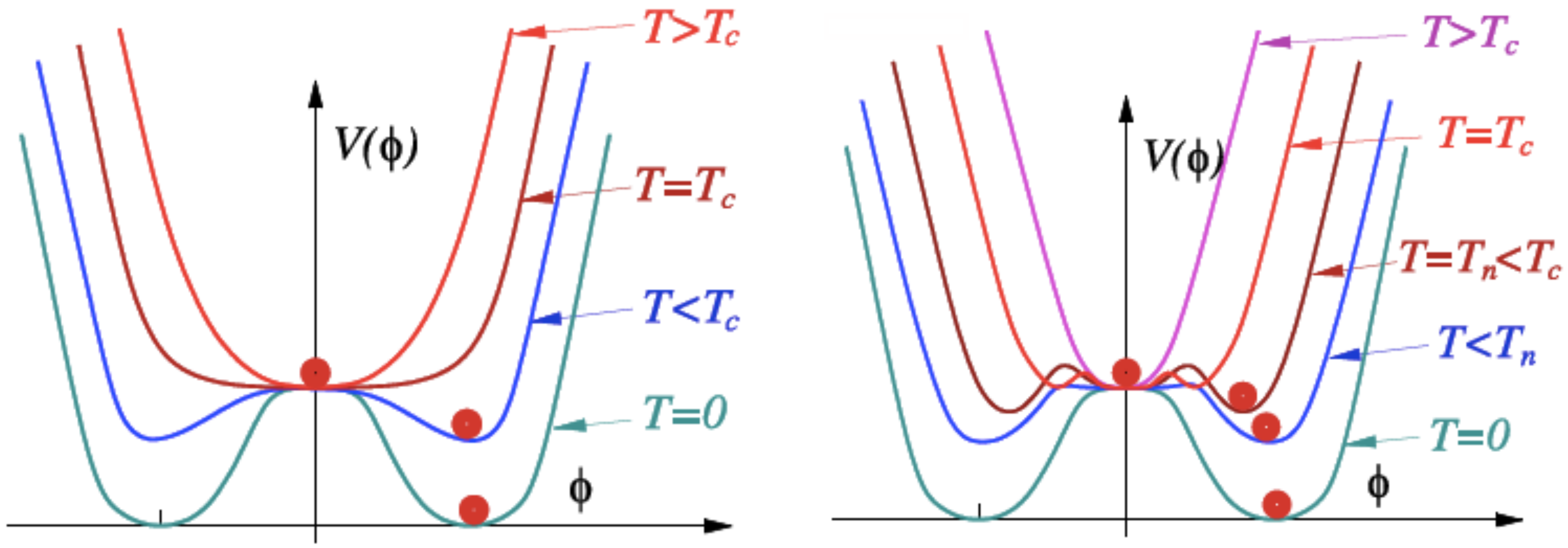

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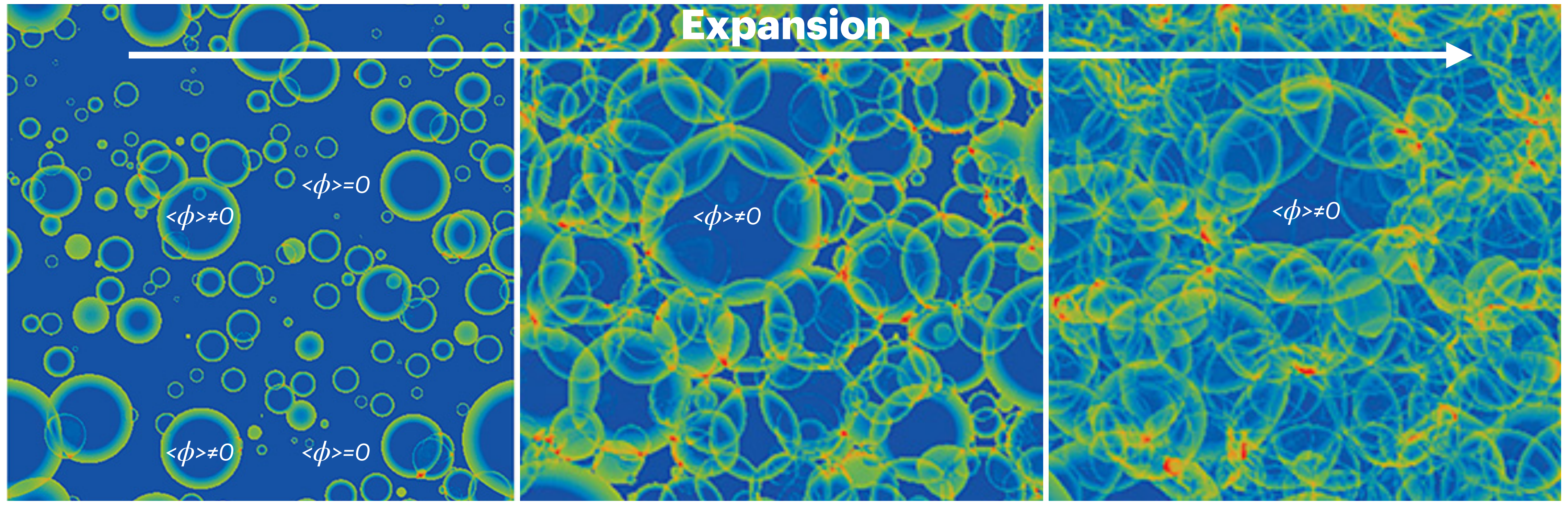

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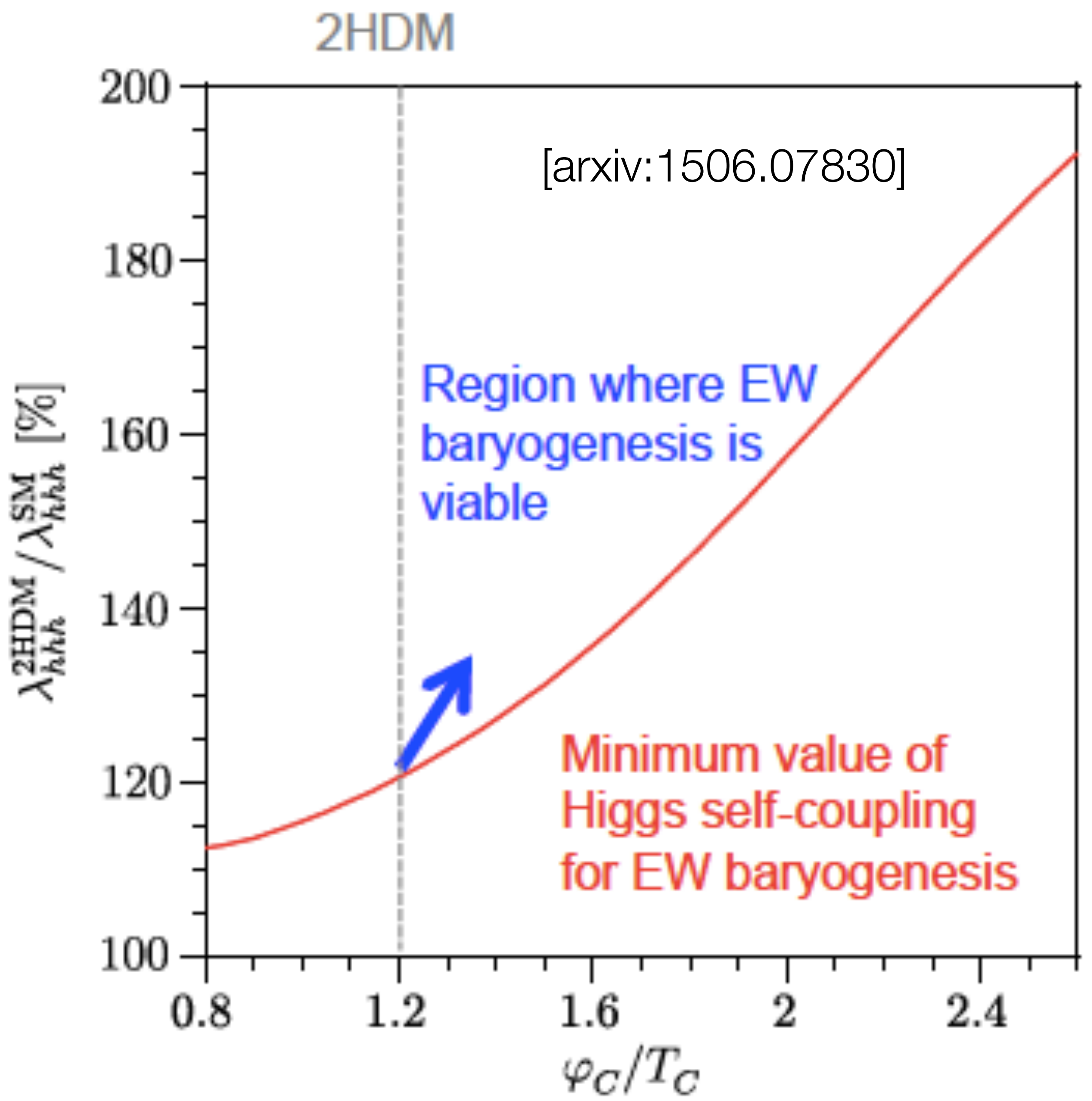

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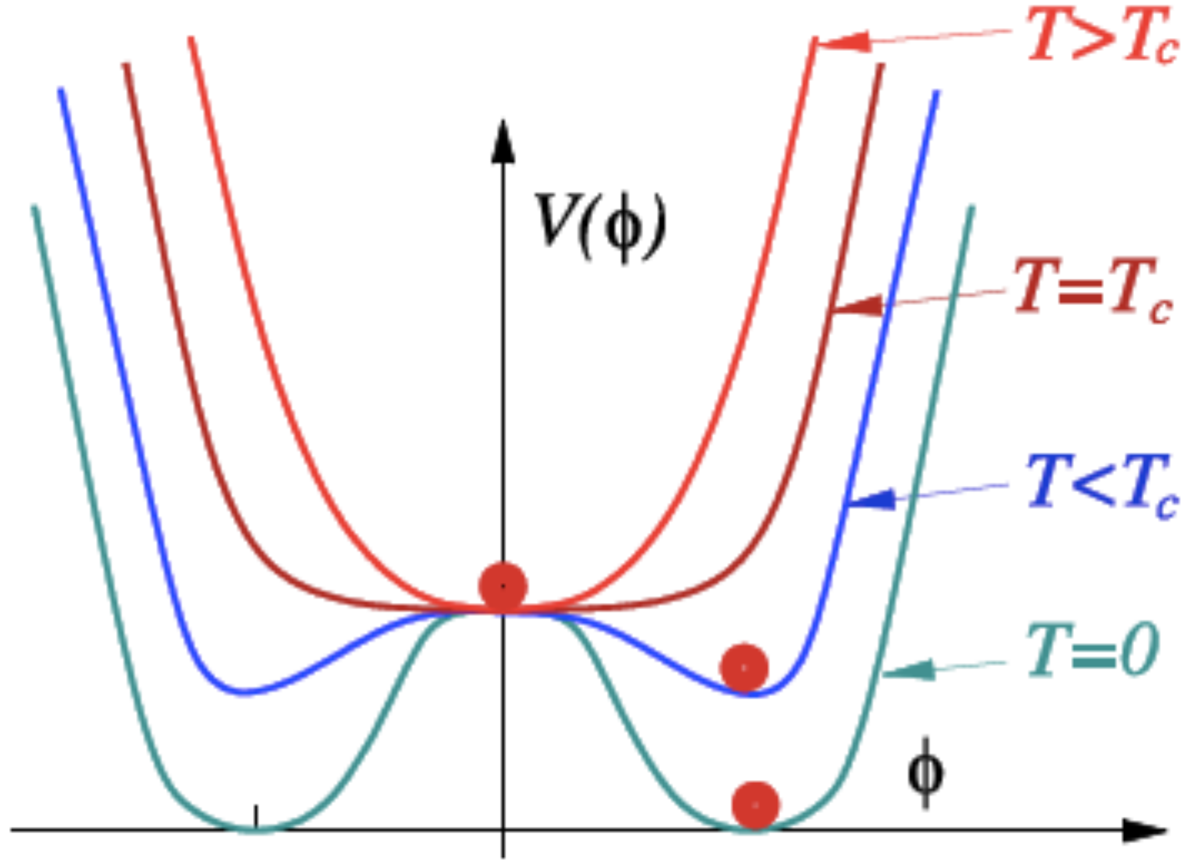

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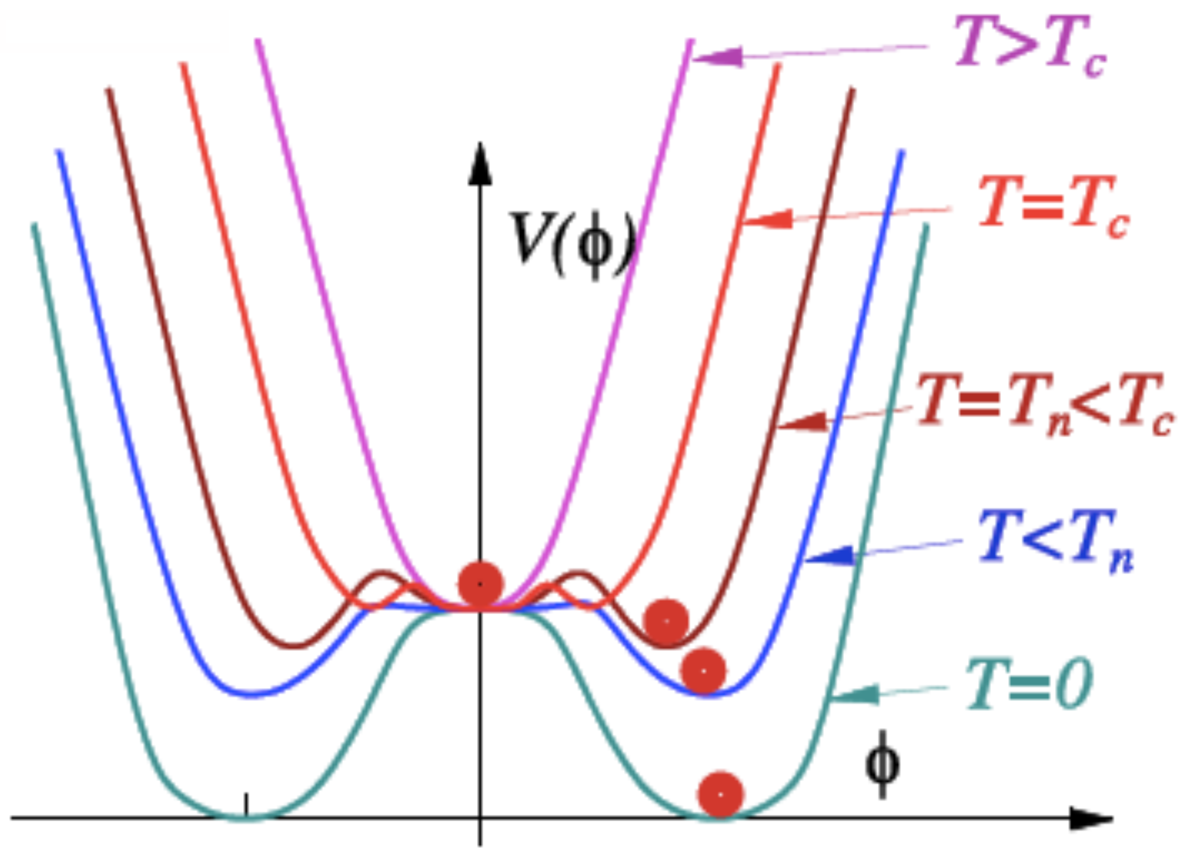

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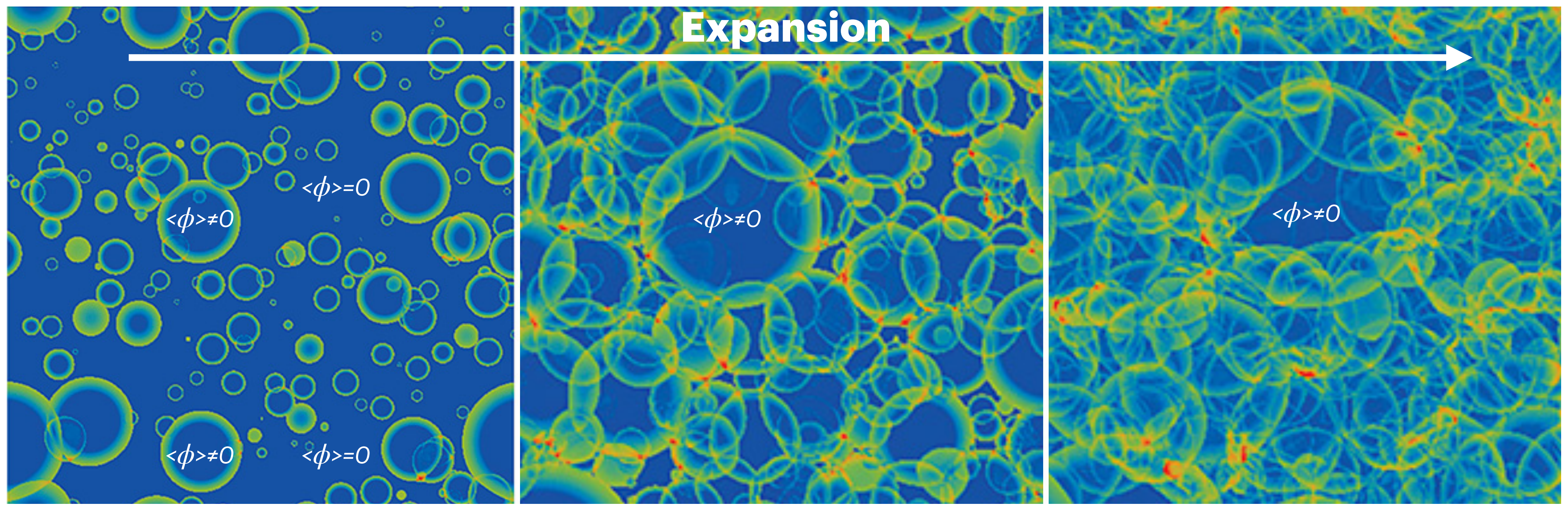

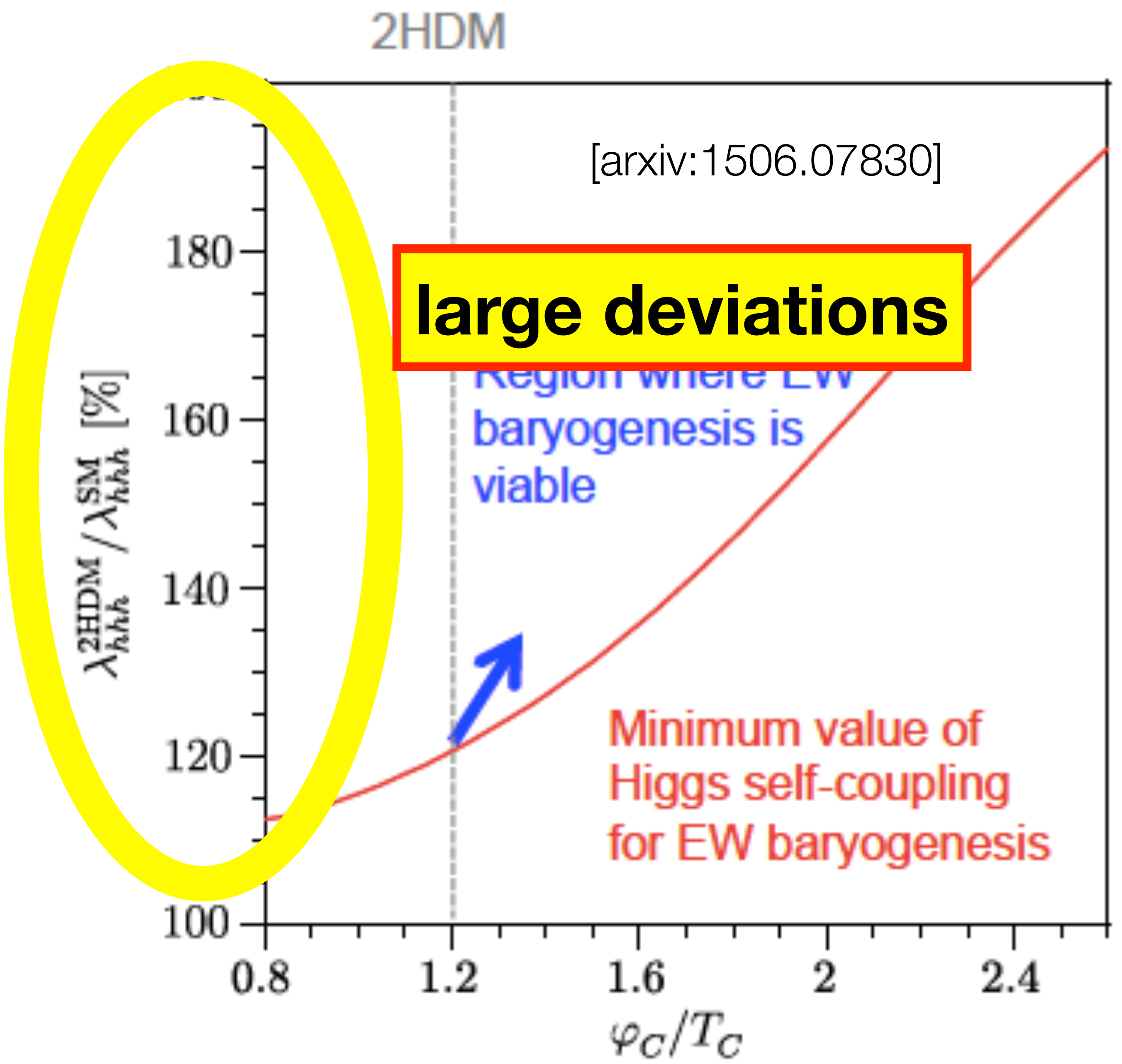

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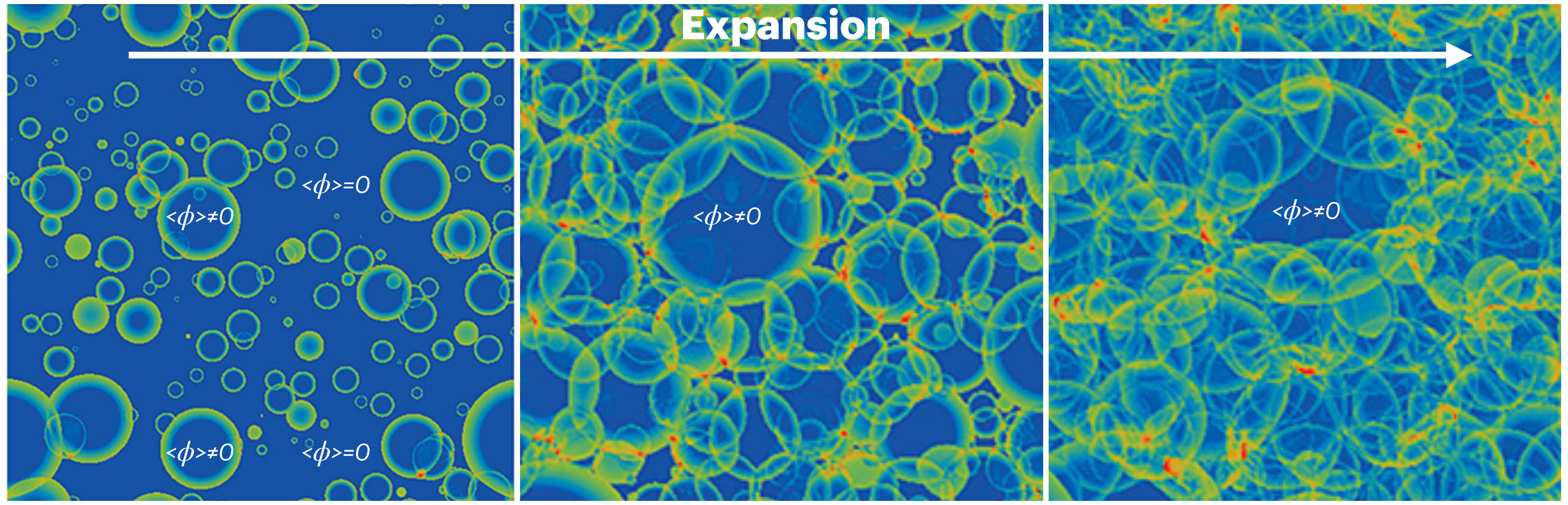

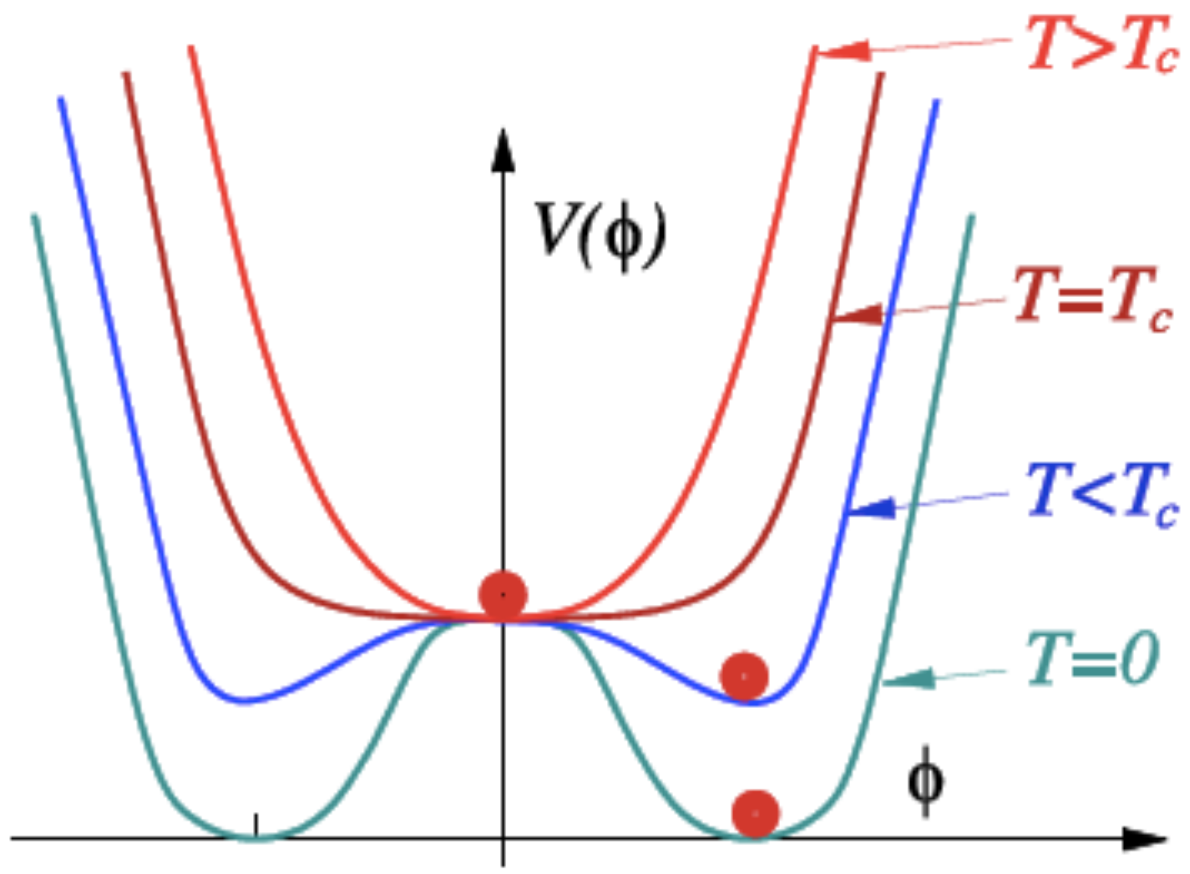

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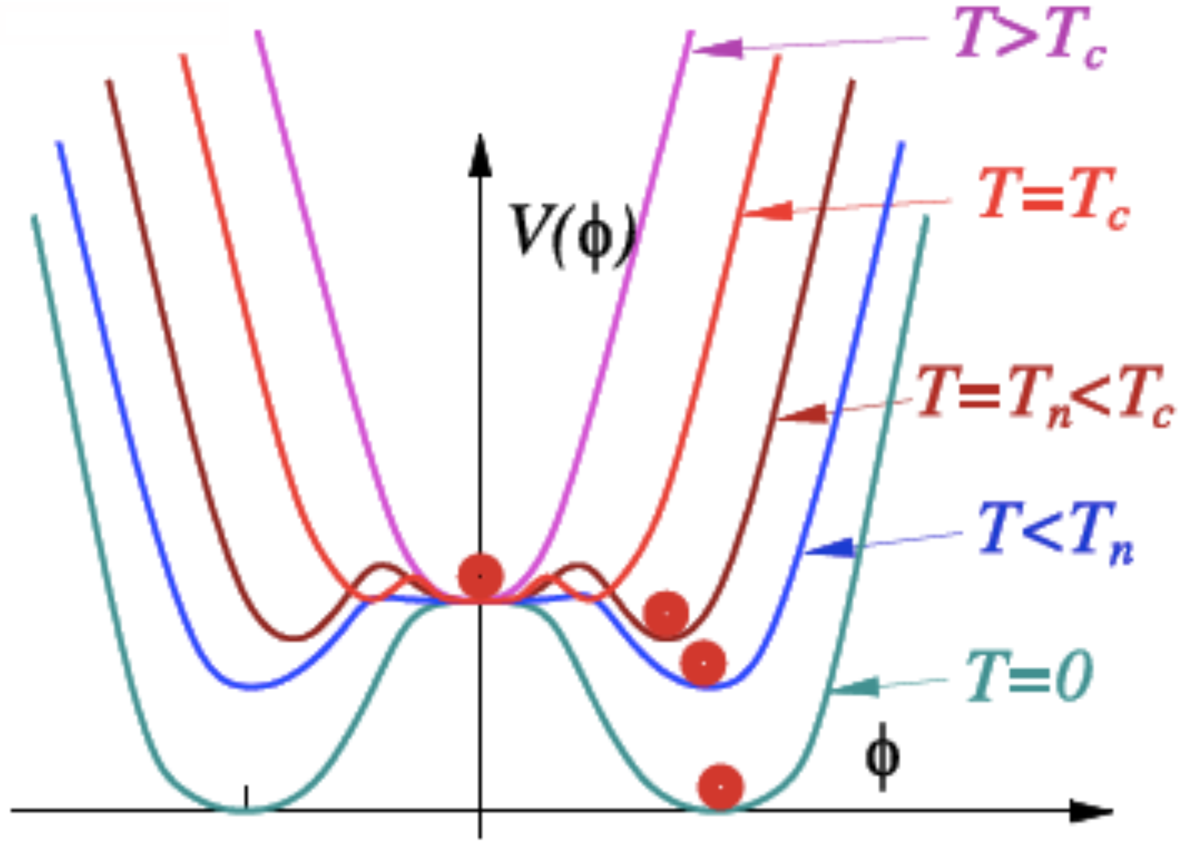

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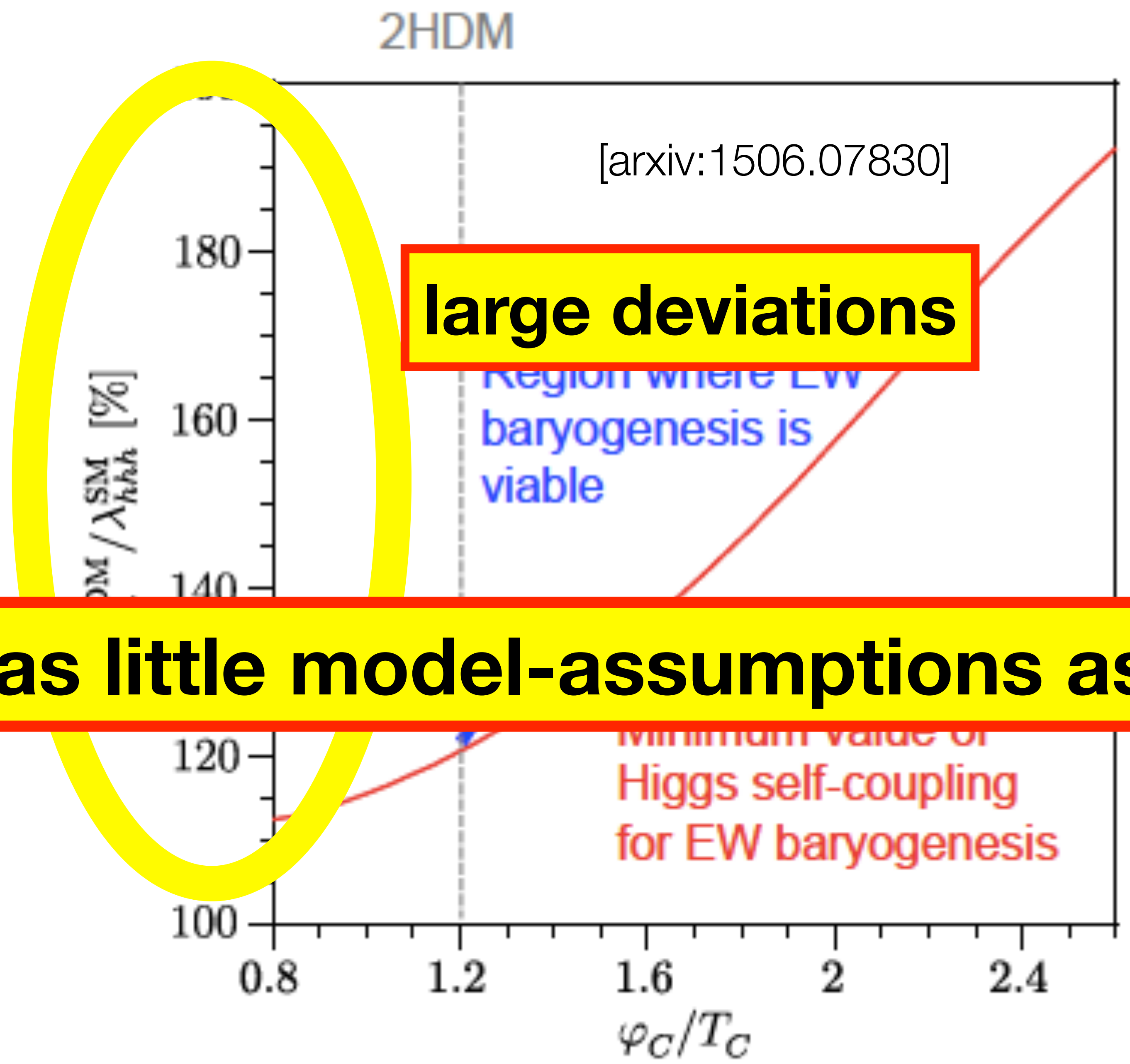
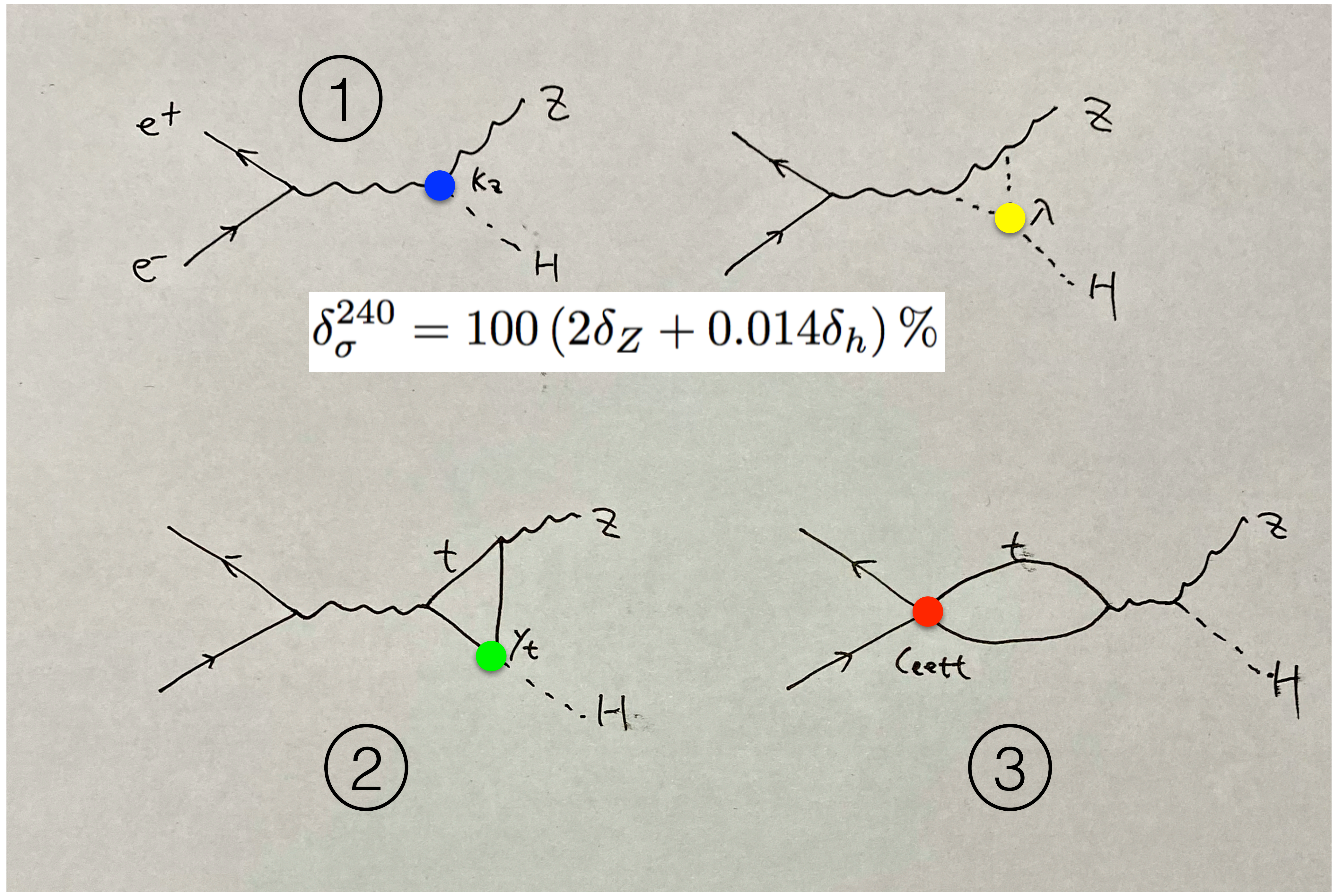


large deviations

=> measure λ, with as little model-assumptions as possible!

At “Higgs Factory” energies

- can gain some information from loop corrections to single Higgs production, however need
  - better than 1% measurement of σ(ZH)
  - at 2 E_{CM} to distinguish from change in κ_Z
  - y_t from HL-LHC
  - C_{eett} 4-fermion operators
    - very challenging at HL-LHC
    - limited information from ee at 365 GeV
    - full information at ≥ 500 GeV with polarised beams!



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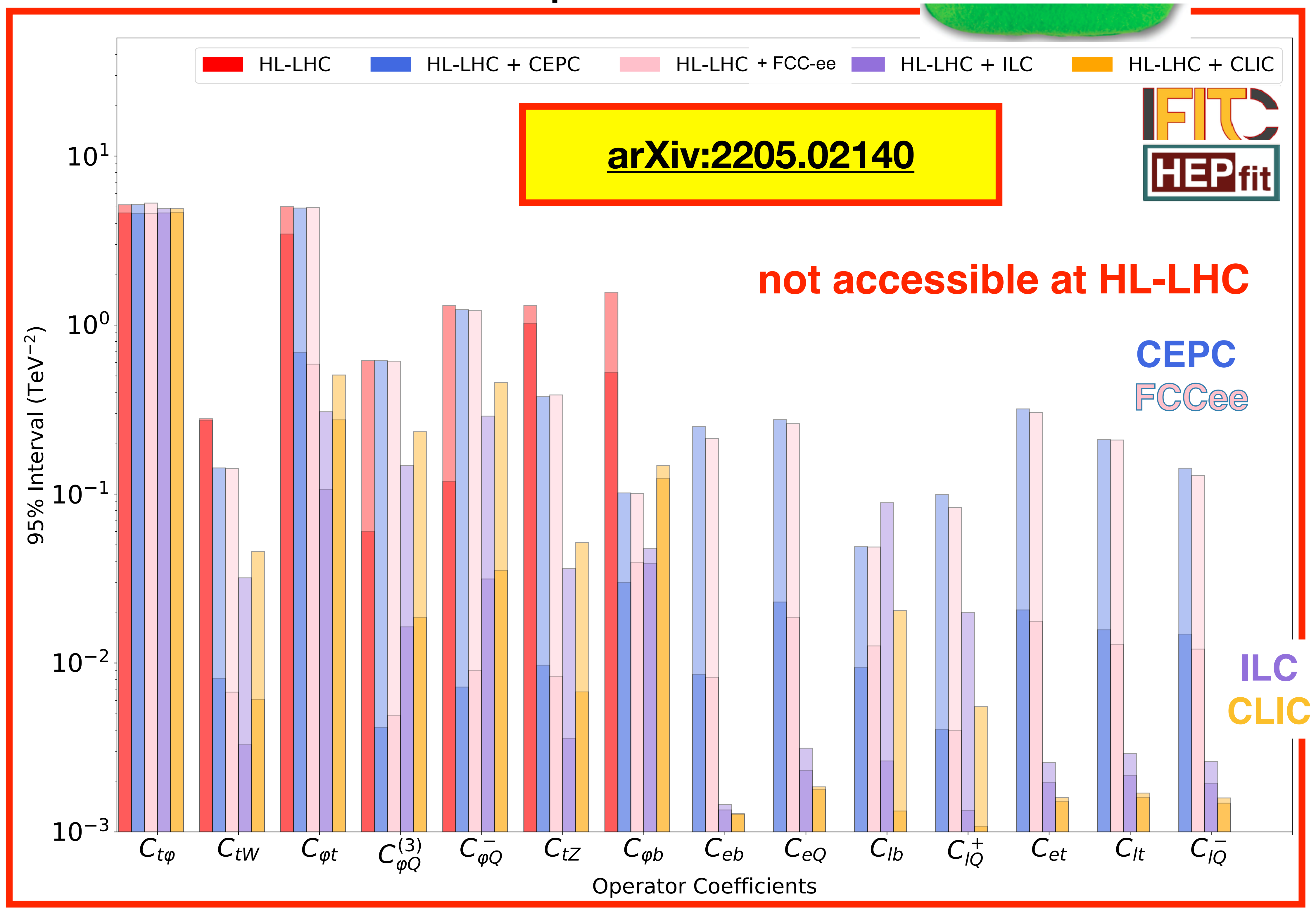

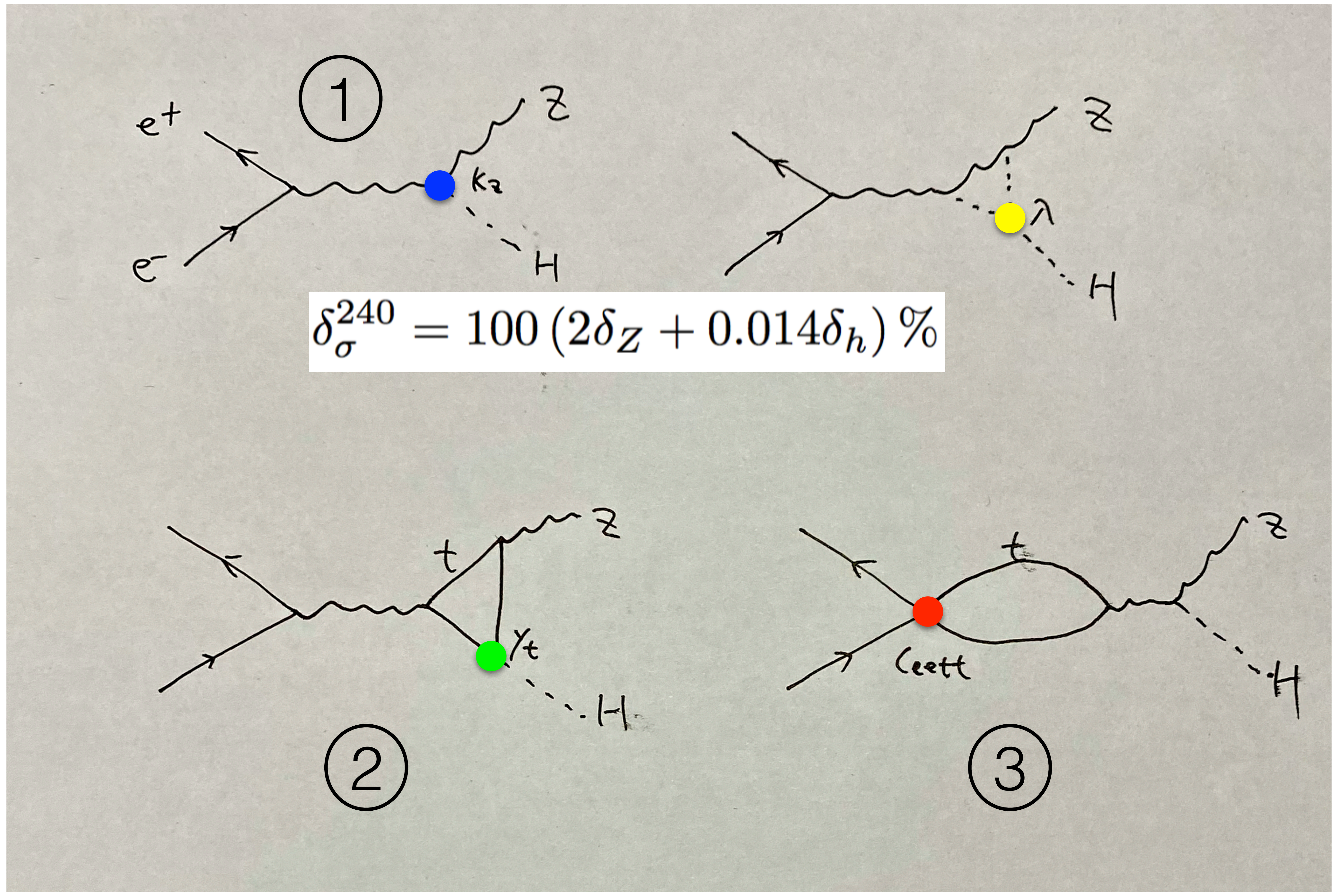

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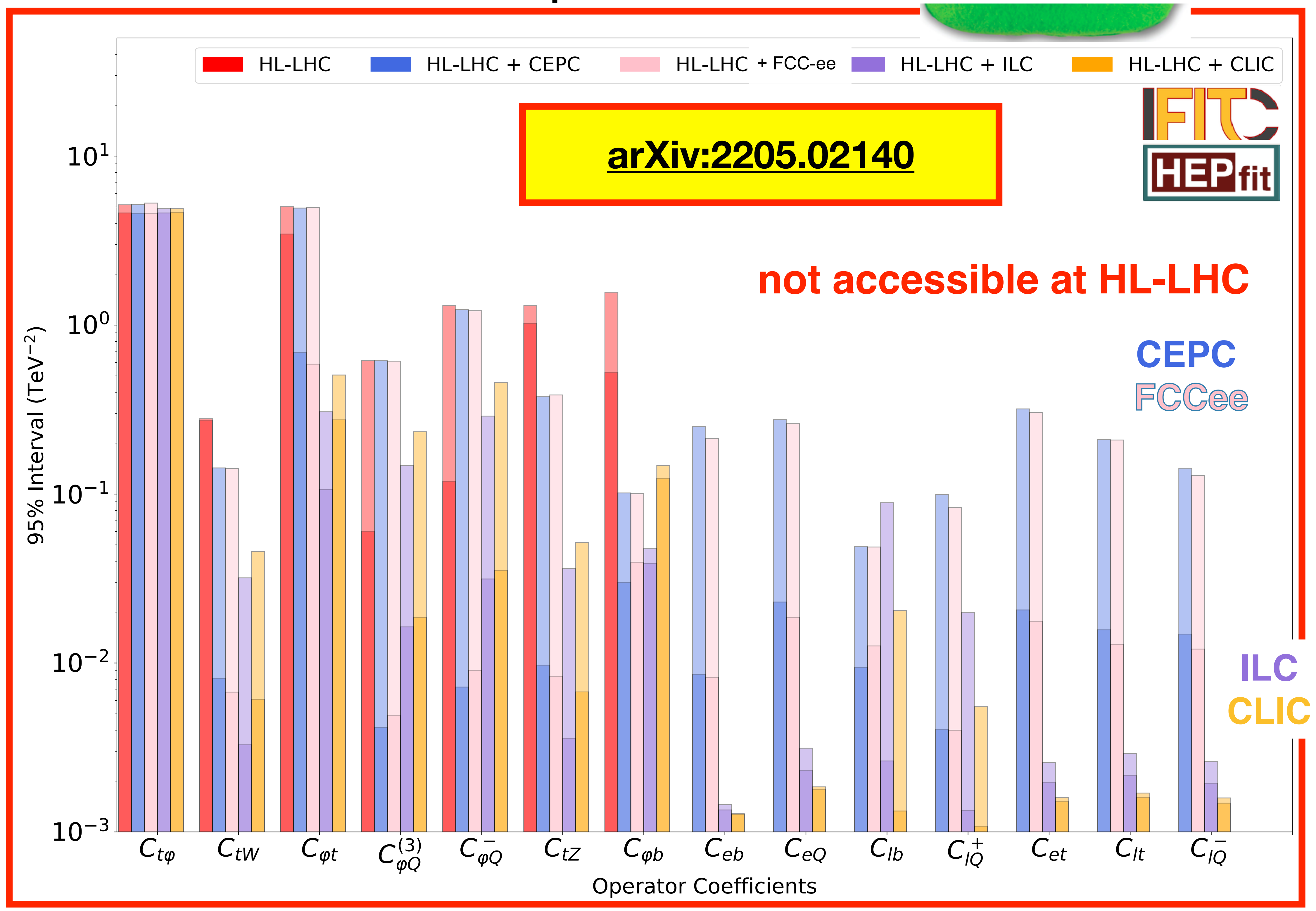
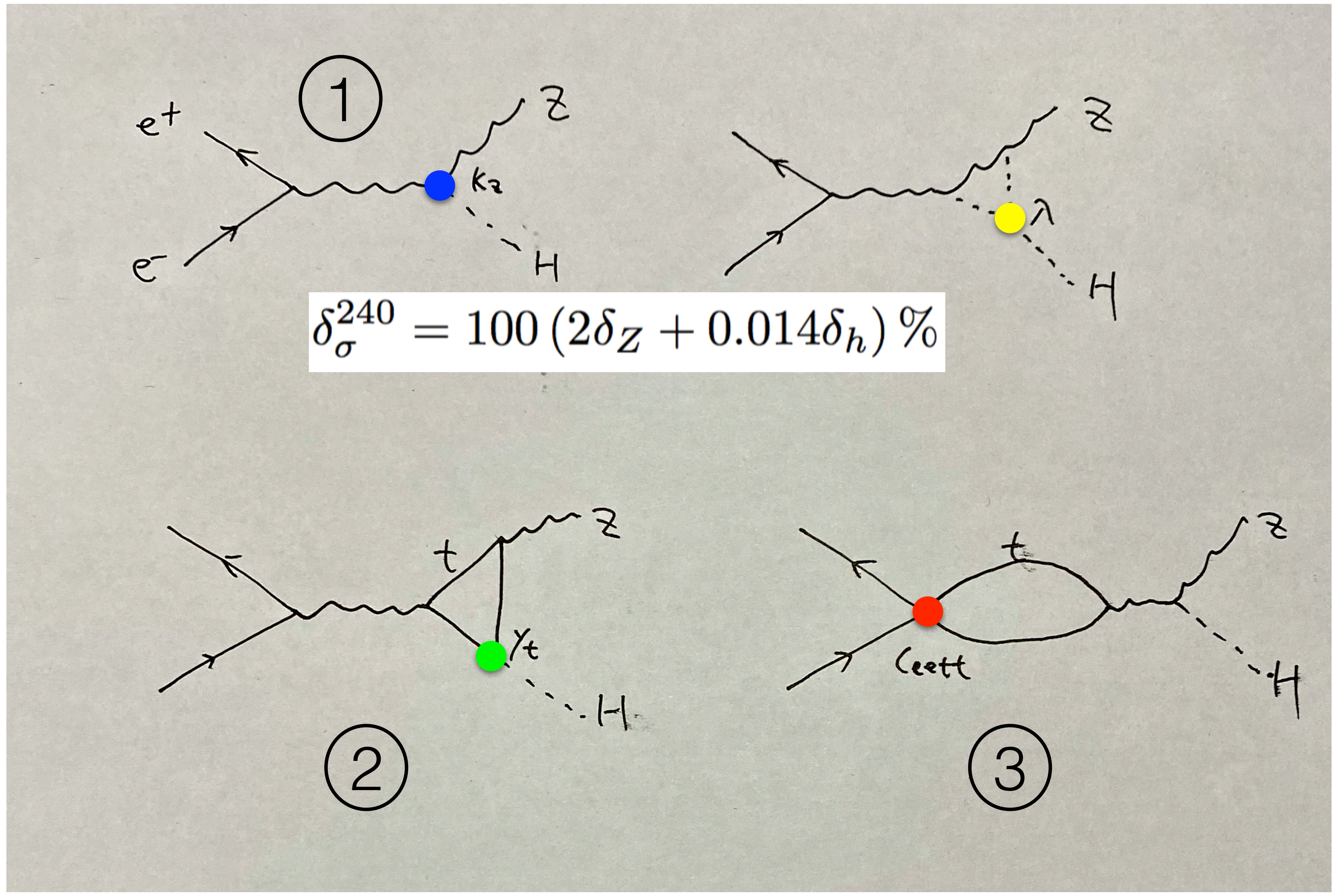




Top and Higgs physics are intertwined!

The Higgs Potential and the Self-Coupling

in the SM $\lambda_3 = \lambda_4$:

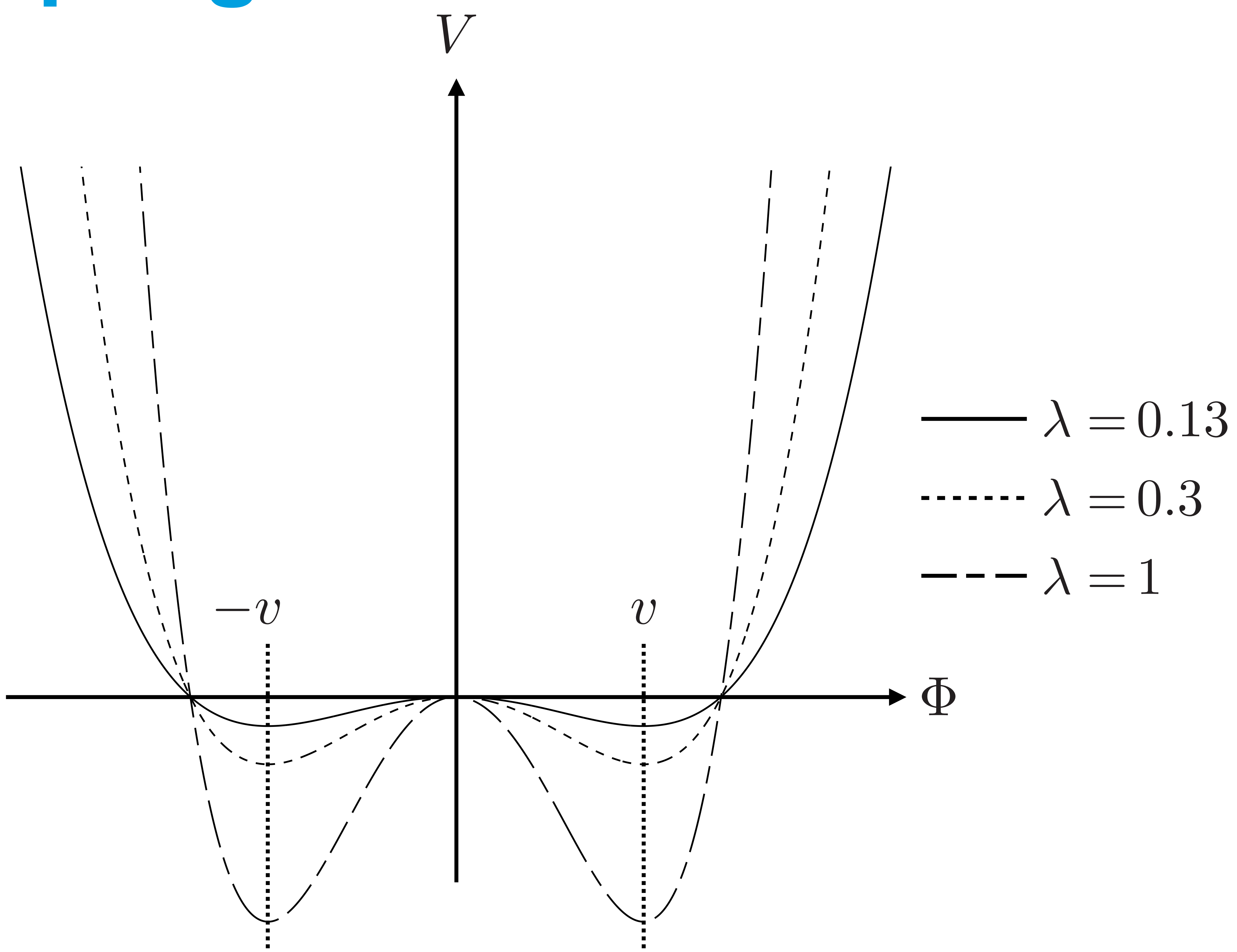
$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

v = VEV (246 GeV)

λ = coupling parameter

η_H = physical Higgs field

SM prediction: $\lambda \pm \delta\lambda = \frac{m_H{}^2}{2v^2} \pm \frac{\delta m_H}{v^2} m_H \sim 0.130 \pm 0.001$



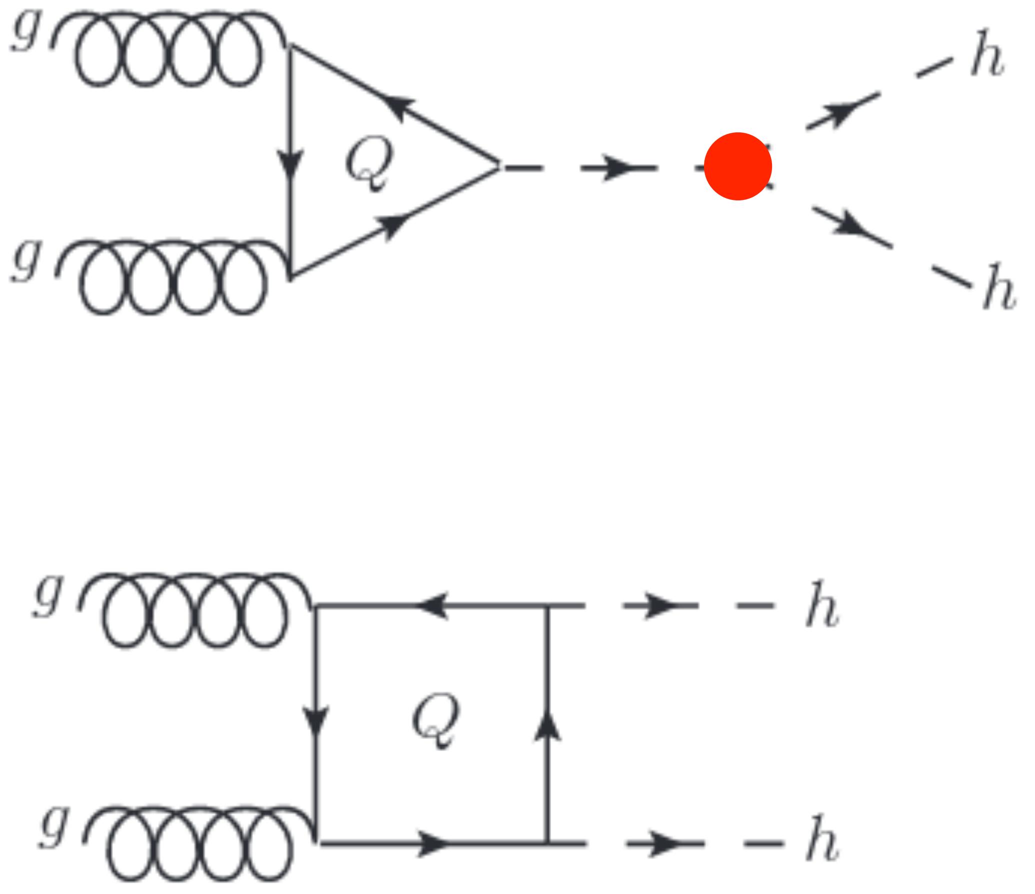
The Higgs self-coupling determines the shape — and evolution — of the Higgs potential
=> the key to understand EWSB and its role in the evolution of the universe!

From di-Higgs production to λ

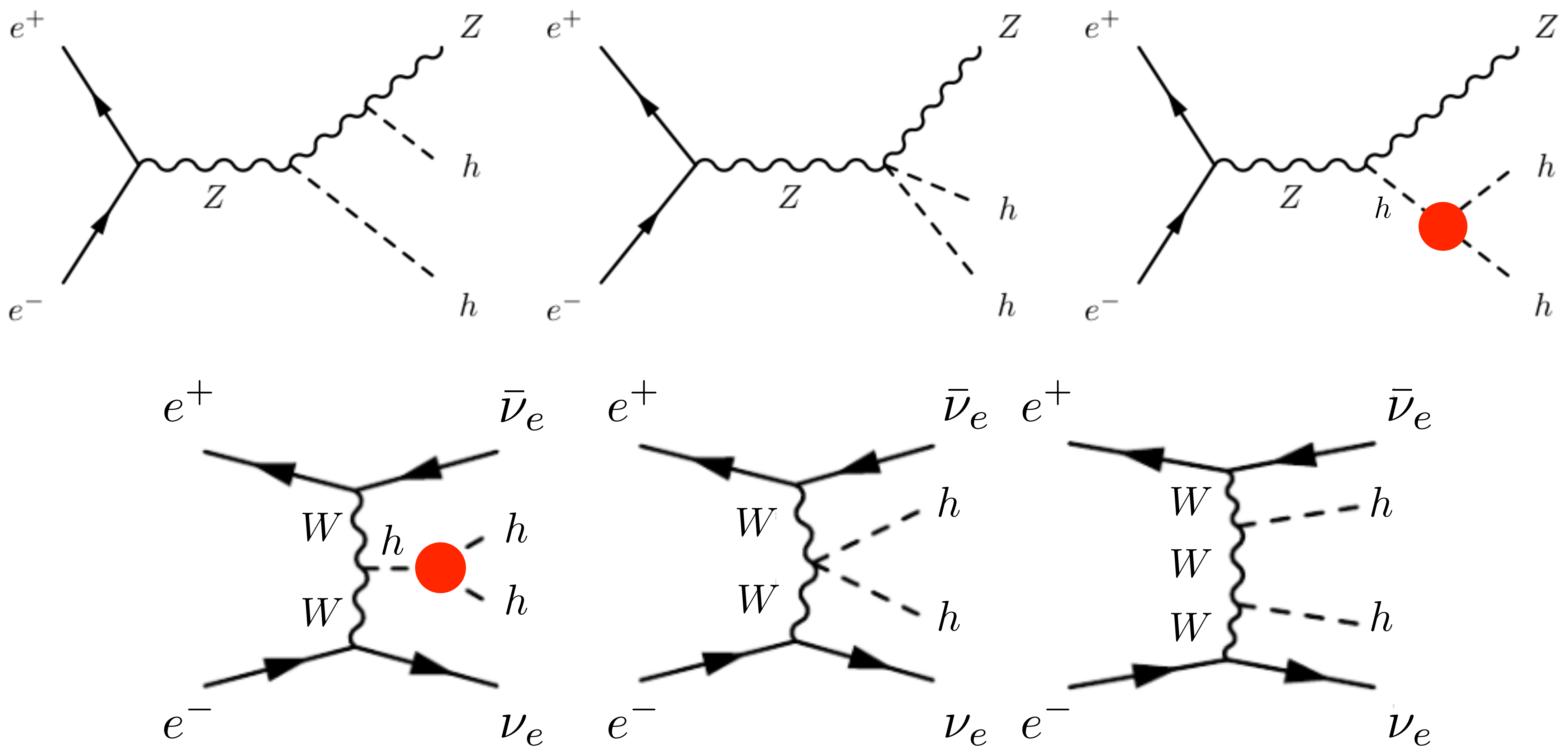
1. Discover di-Higgs production
2. Measure cross section (total and differential!)
3. Extract λ

- Interference of diagrams with / without triple Higgs vertex ●
  => **k:= (δλ/λ)/(δσ/σ) > 1/2**
- k can be "improved" by using *differential* information
- **k depends on: process, *value of λ* and *E*$_{CM}$**

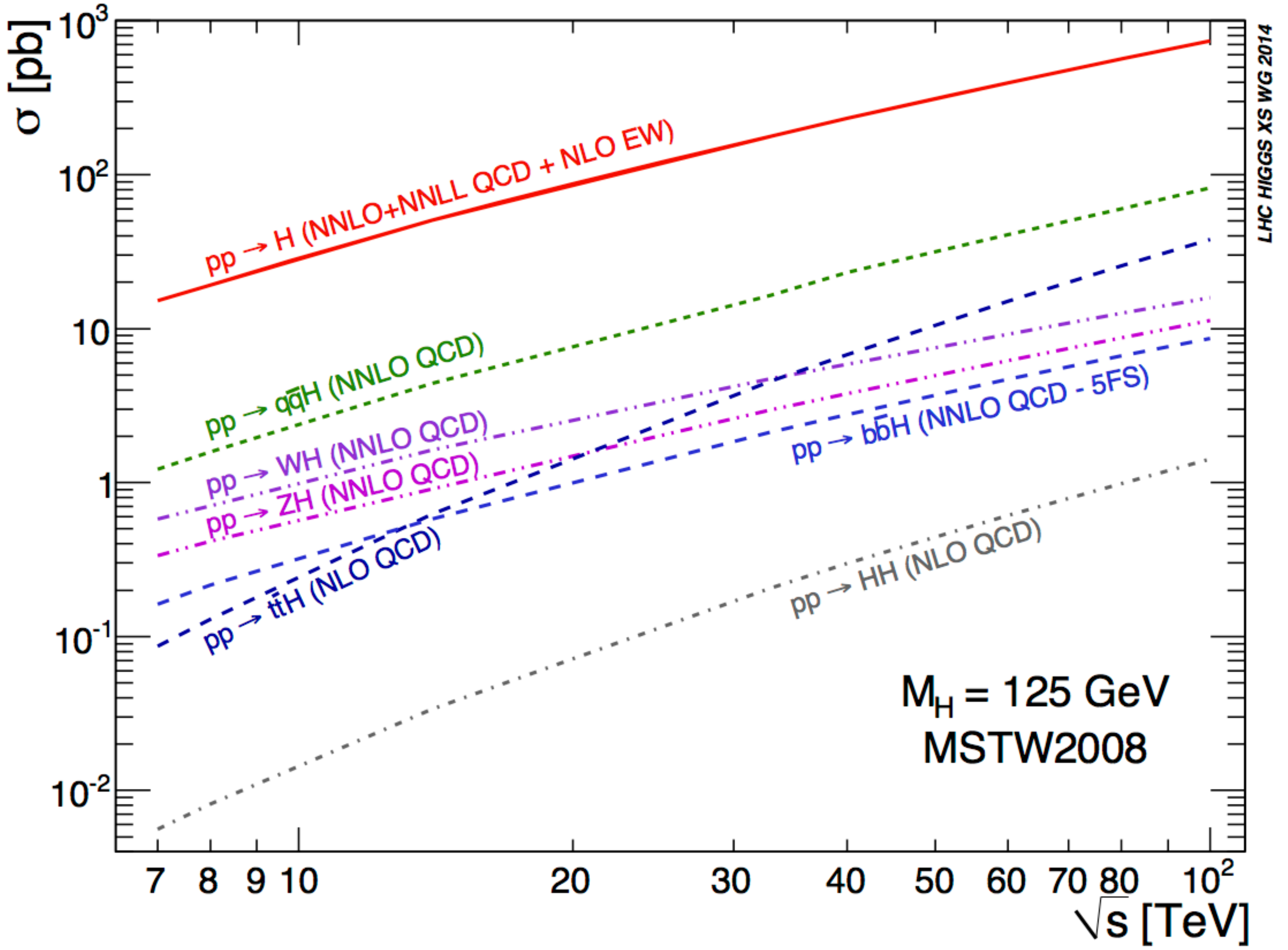
Hadron collider



Lepton collider



Di-Higgs Production Cross sections - pp



dependence on ECM:
14 TeV -> 100 TeV : ~40 x larger cross section
14 TeV -> 38 TeV: ~8 x larger cross section

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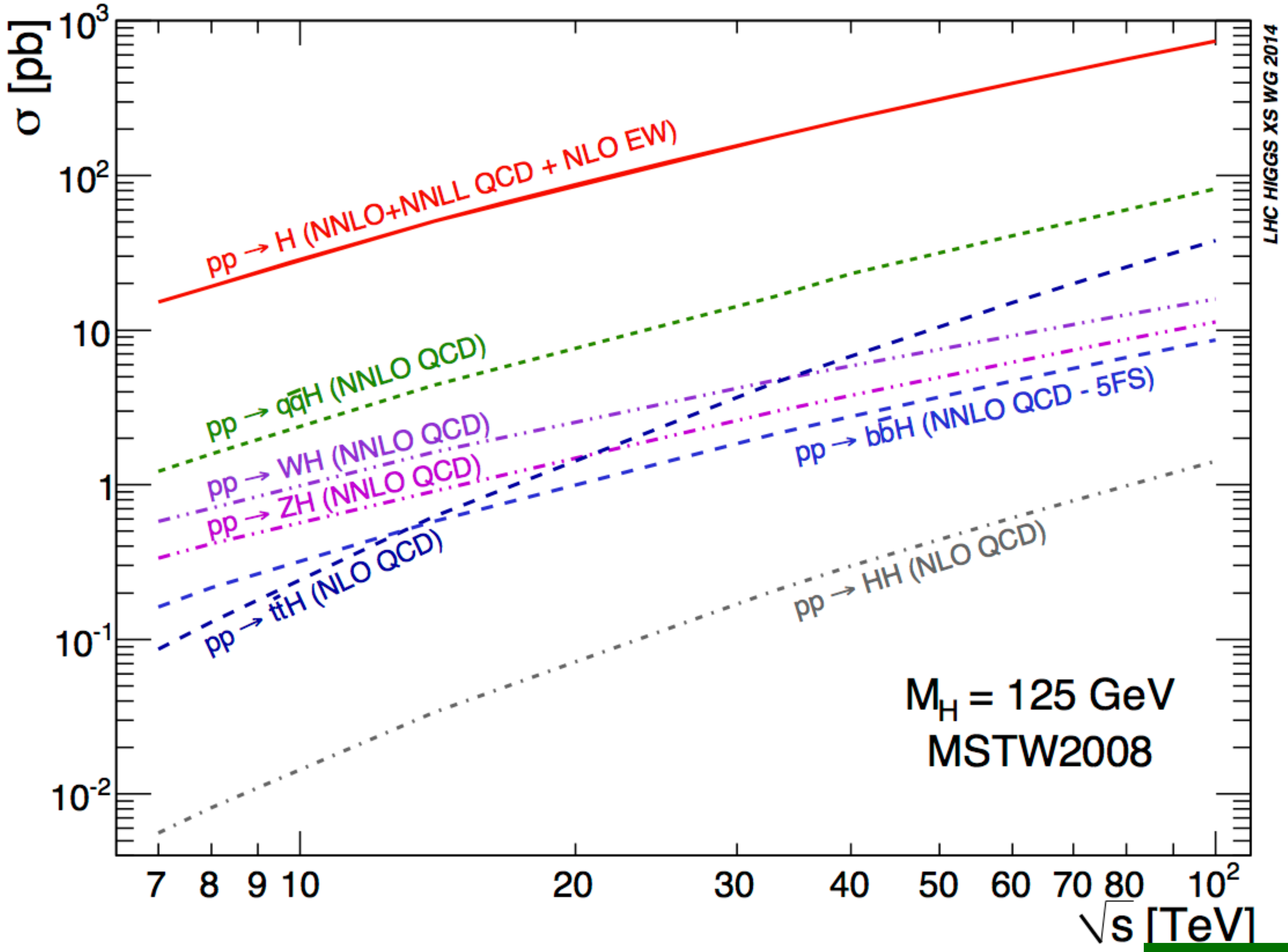

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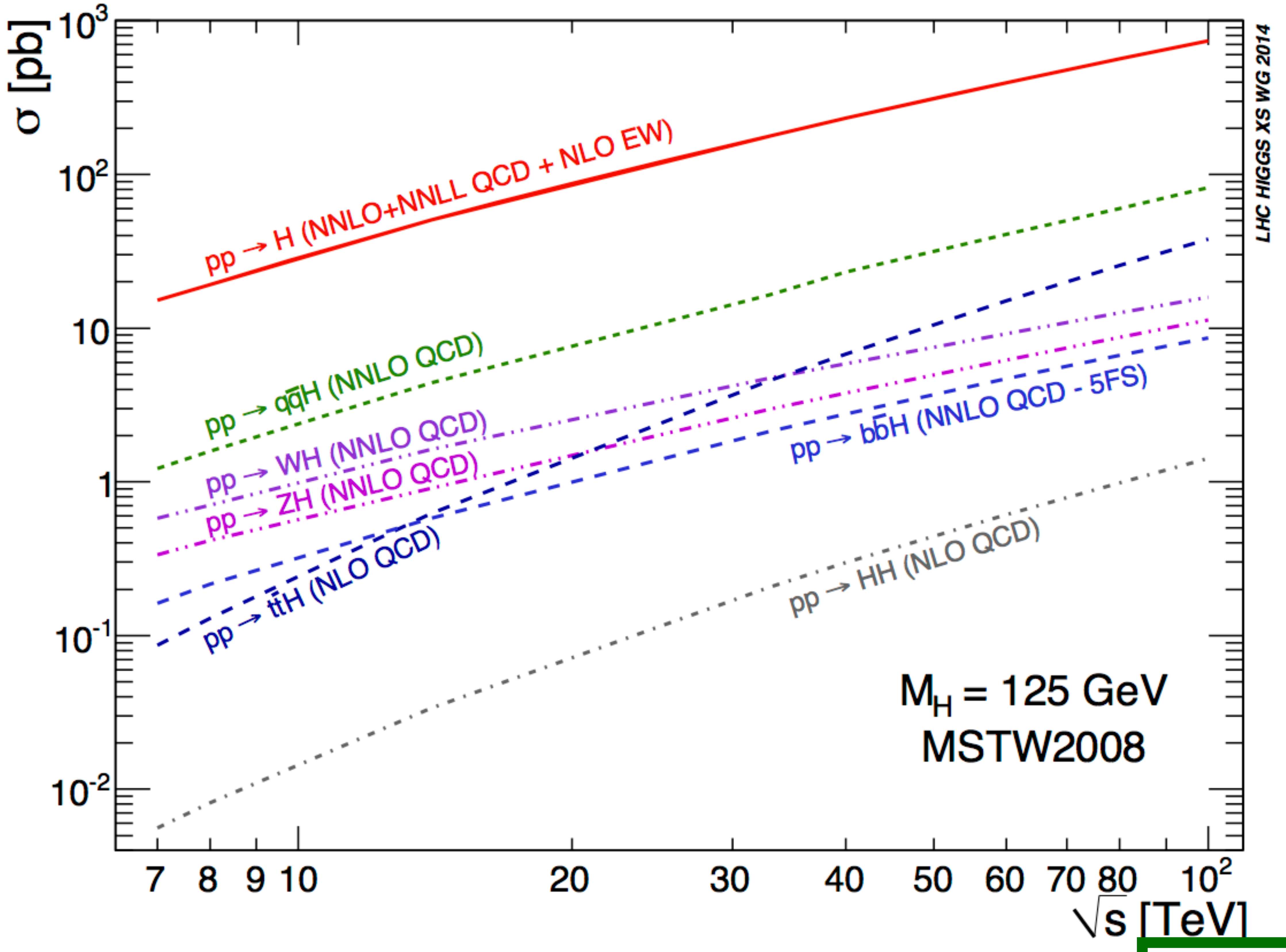

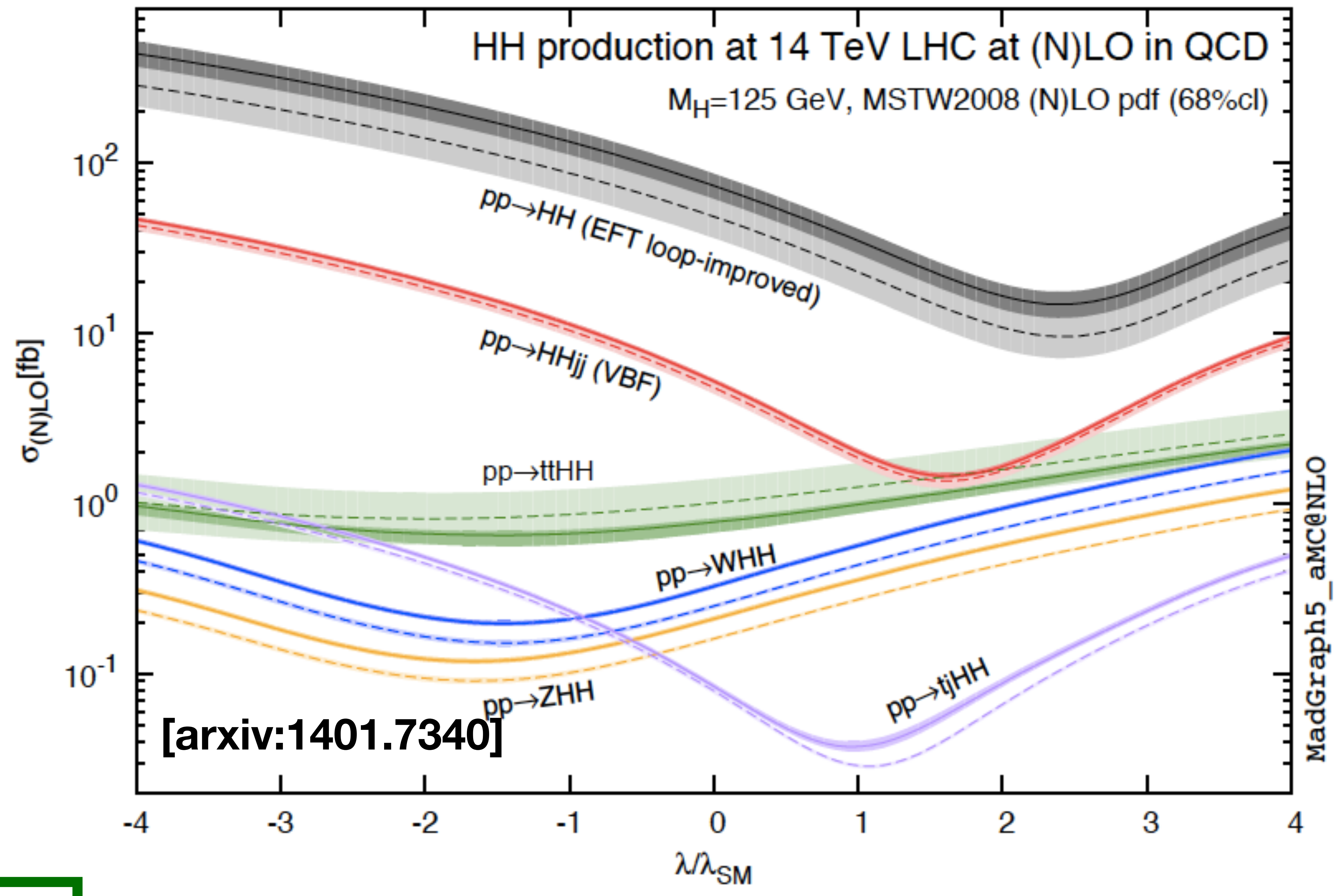

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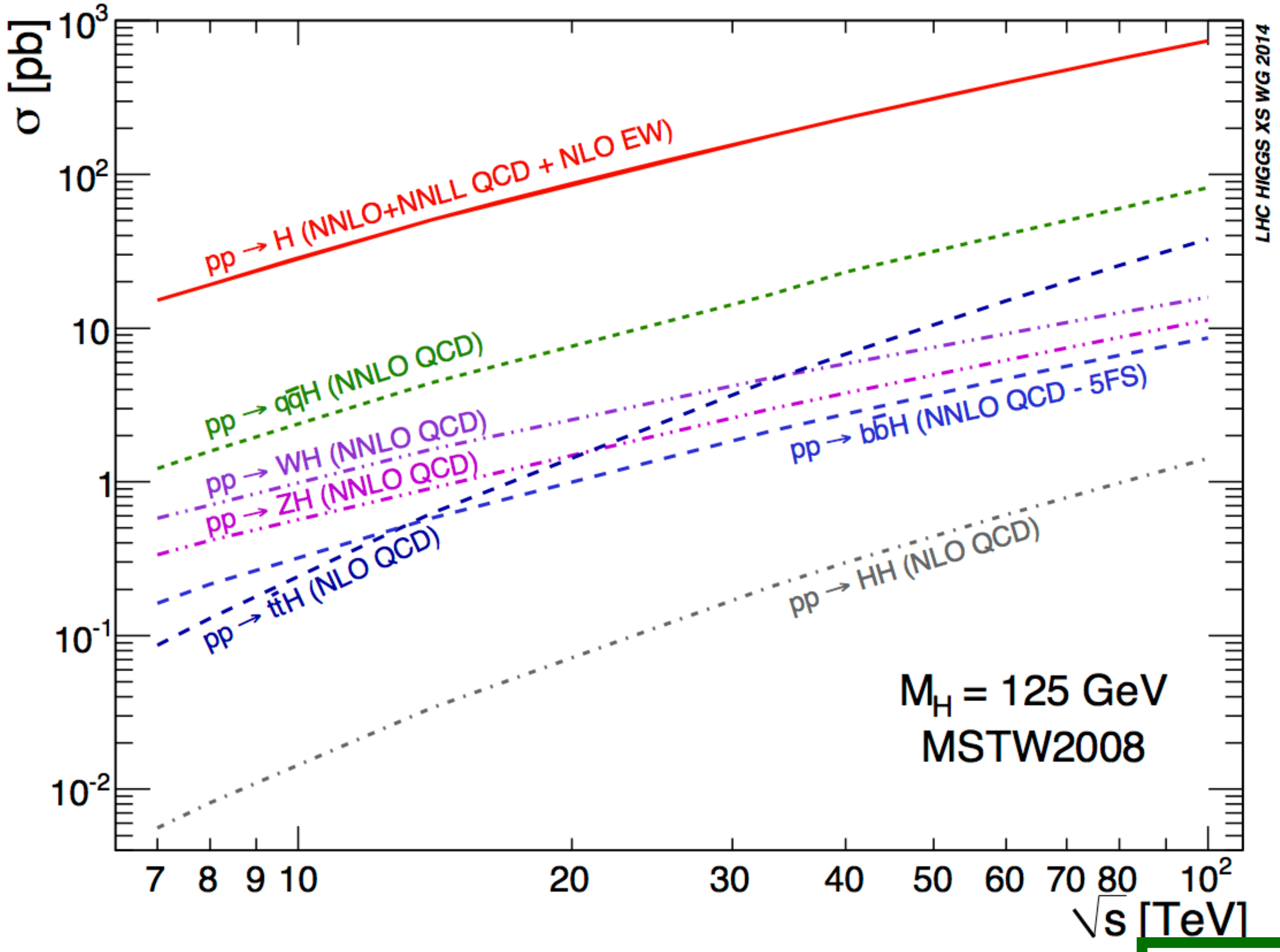

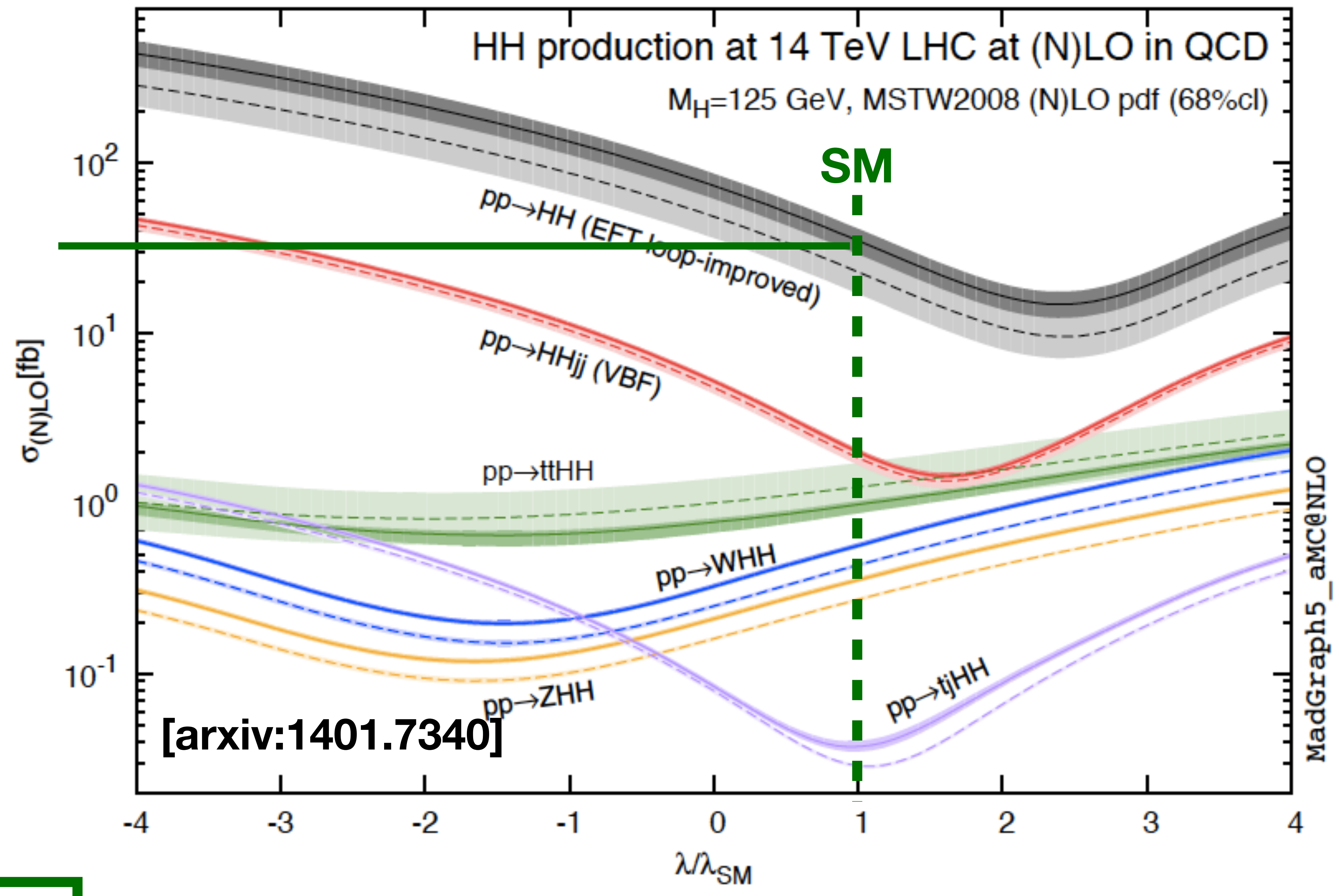

differential distributions!

dependence on ECM:
14 TeV -> 100 TeV : ~40 x larger cross section
14 TeV -> 38 TeV: ~8 x larger cross section

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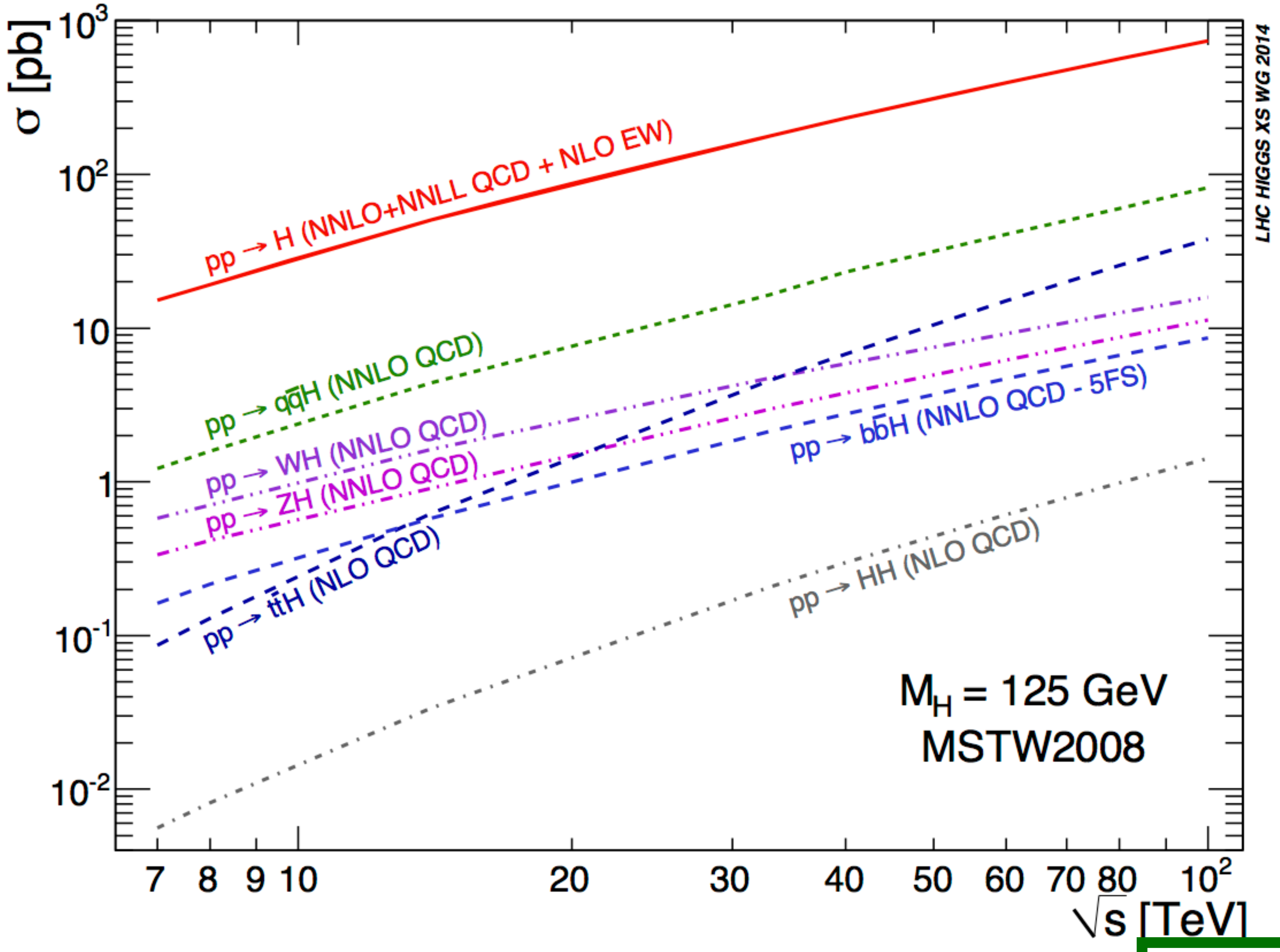

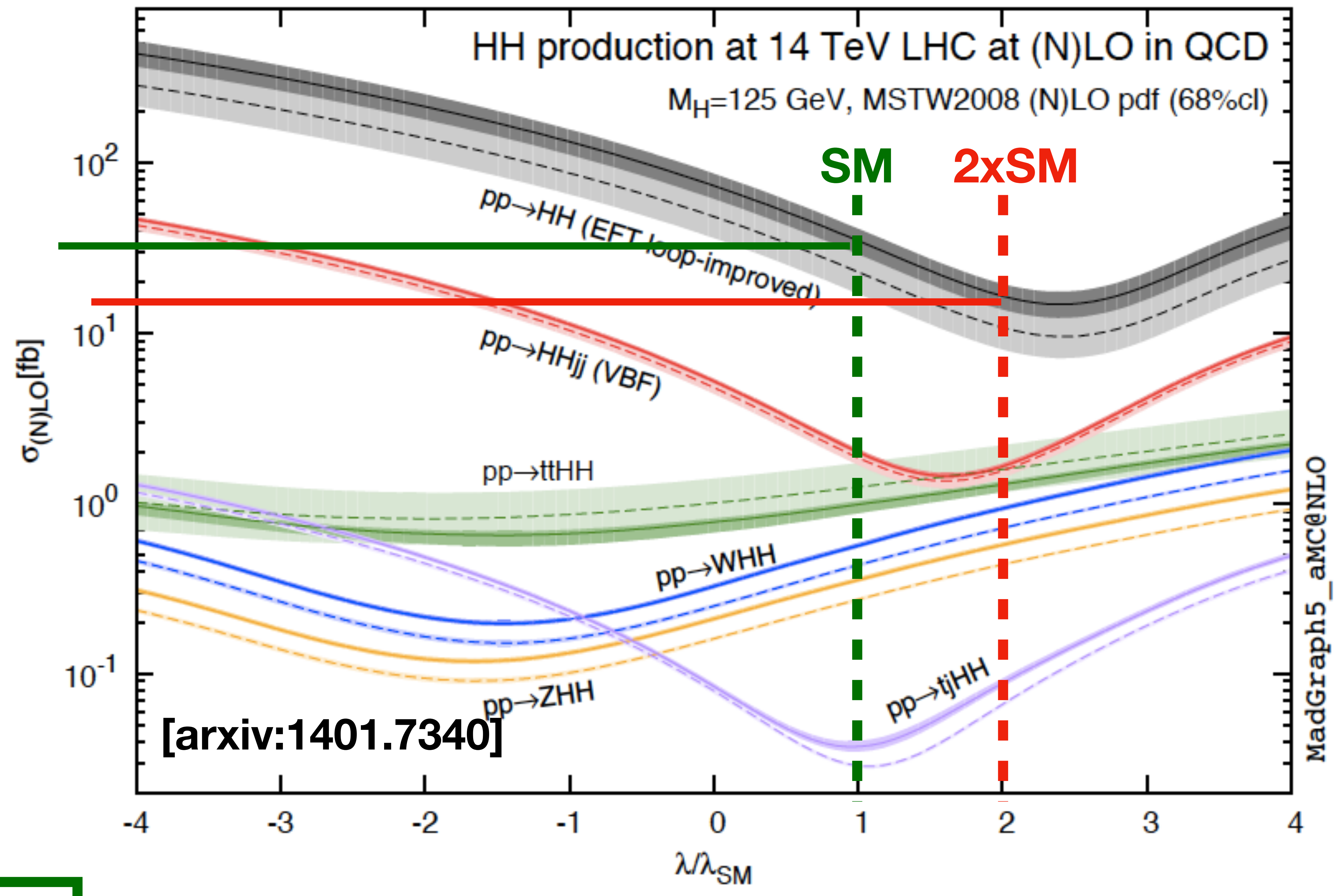

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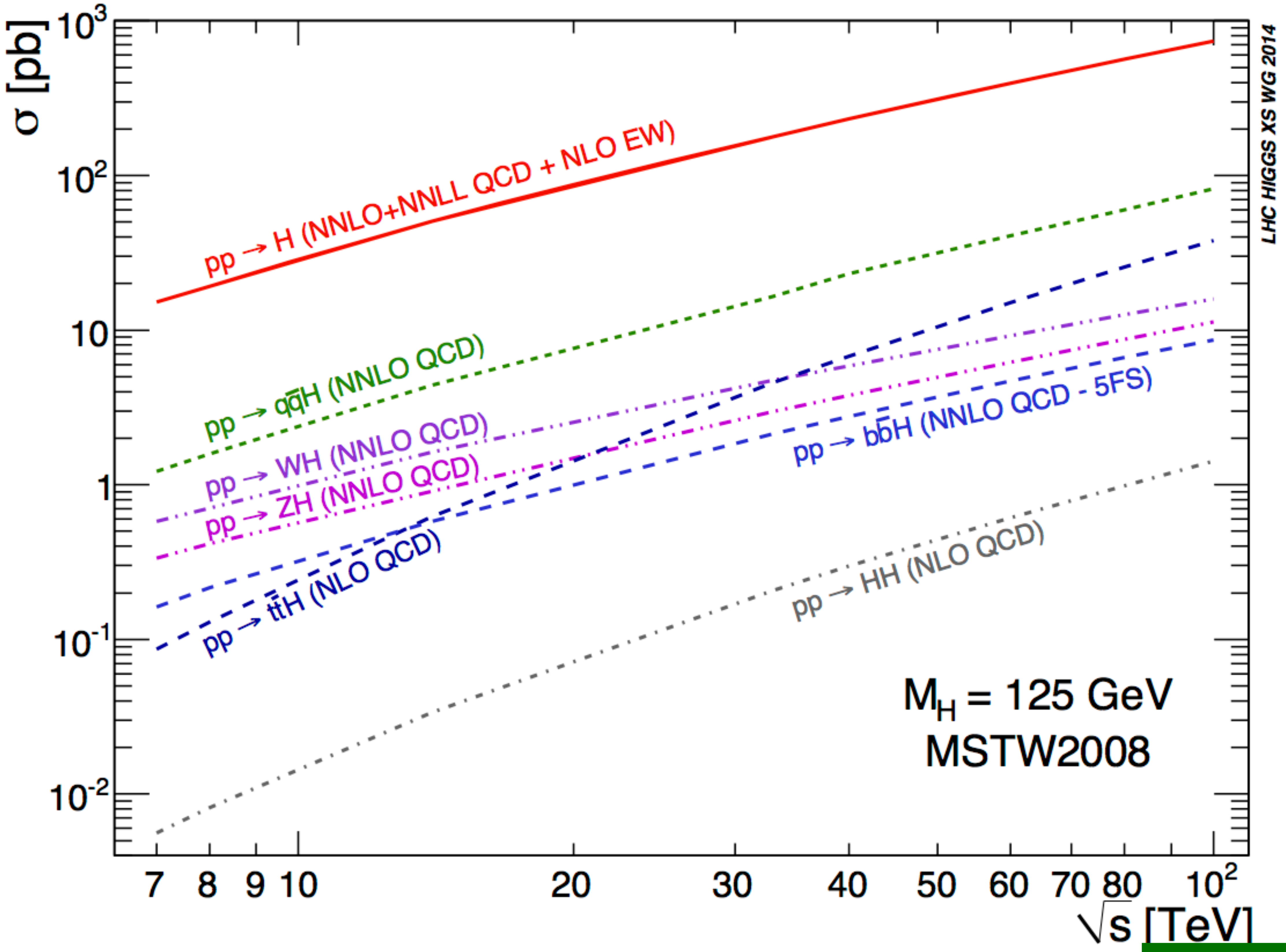

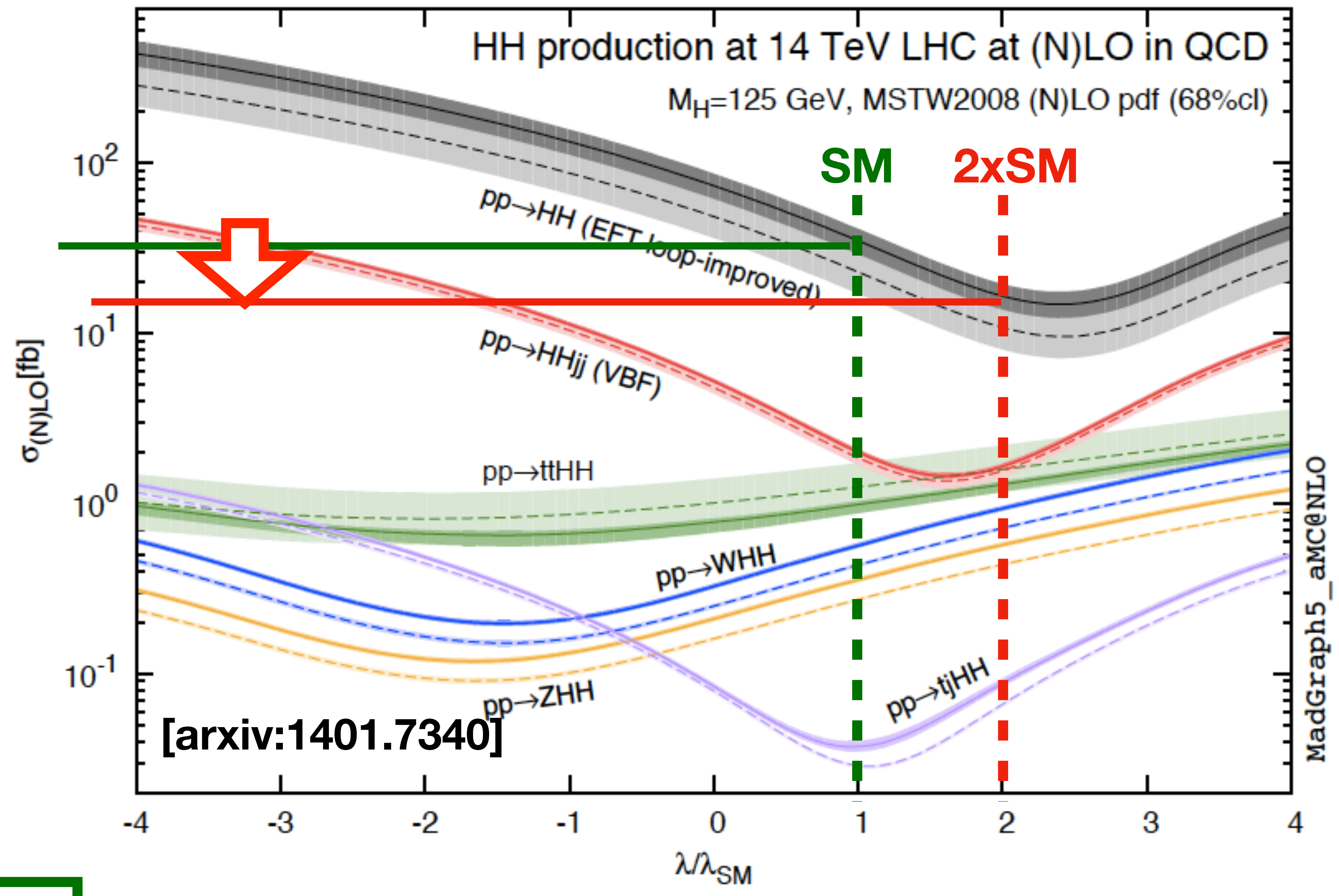

differential distributions!

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14 TeV -> 100 TeV : ~40 x larger cross section
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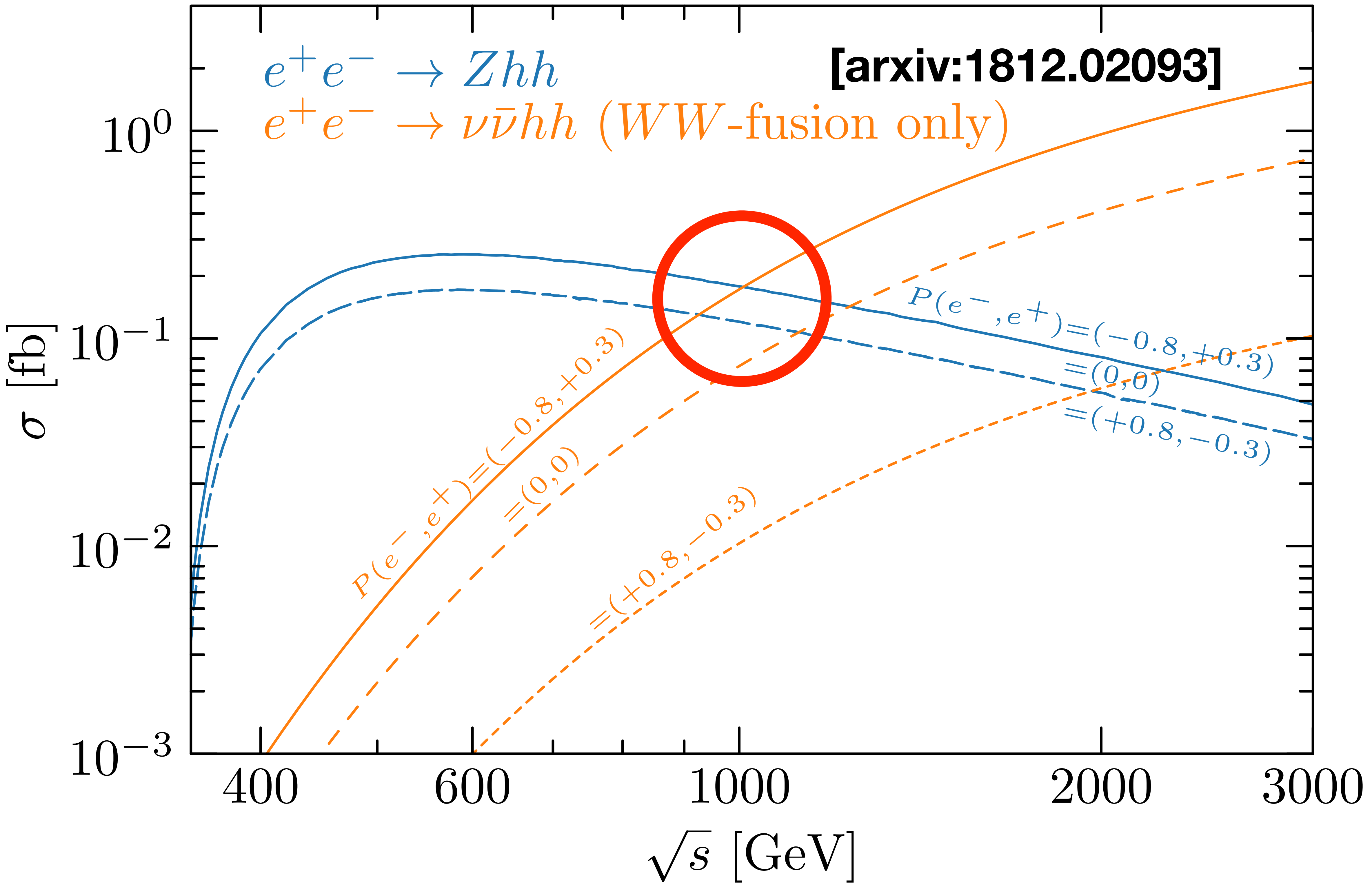
dependence on λ:
$\lambda > \lambda_{SM}$: cross section drops,
i.e. by factor ~2 for $\lambda = 2\,\lambda_{SM}$

Di-Higgs Production Cross sections - ee



ZHH: P(-80%,+30%) and P(+80%,-30%) give about equal sensitivity

vvHH (fusion): effectively only P(-80%) counts

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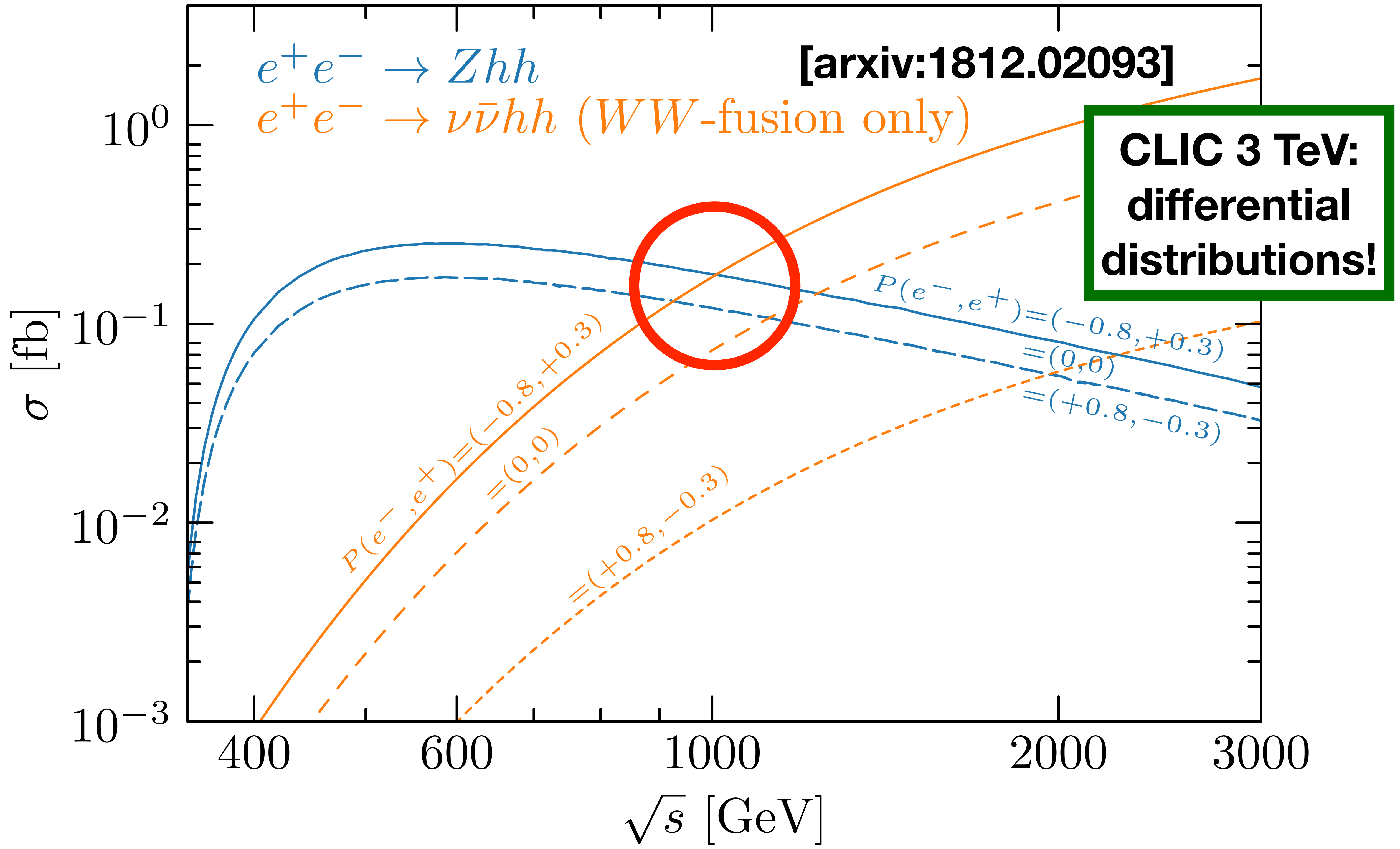

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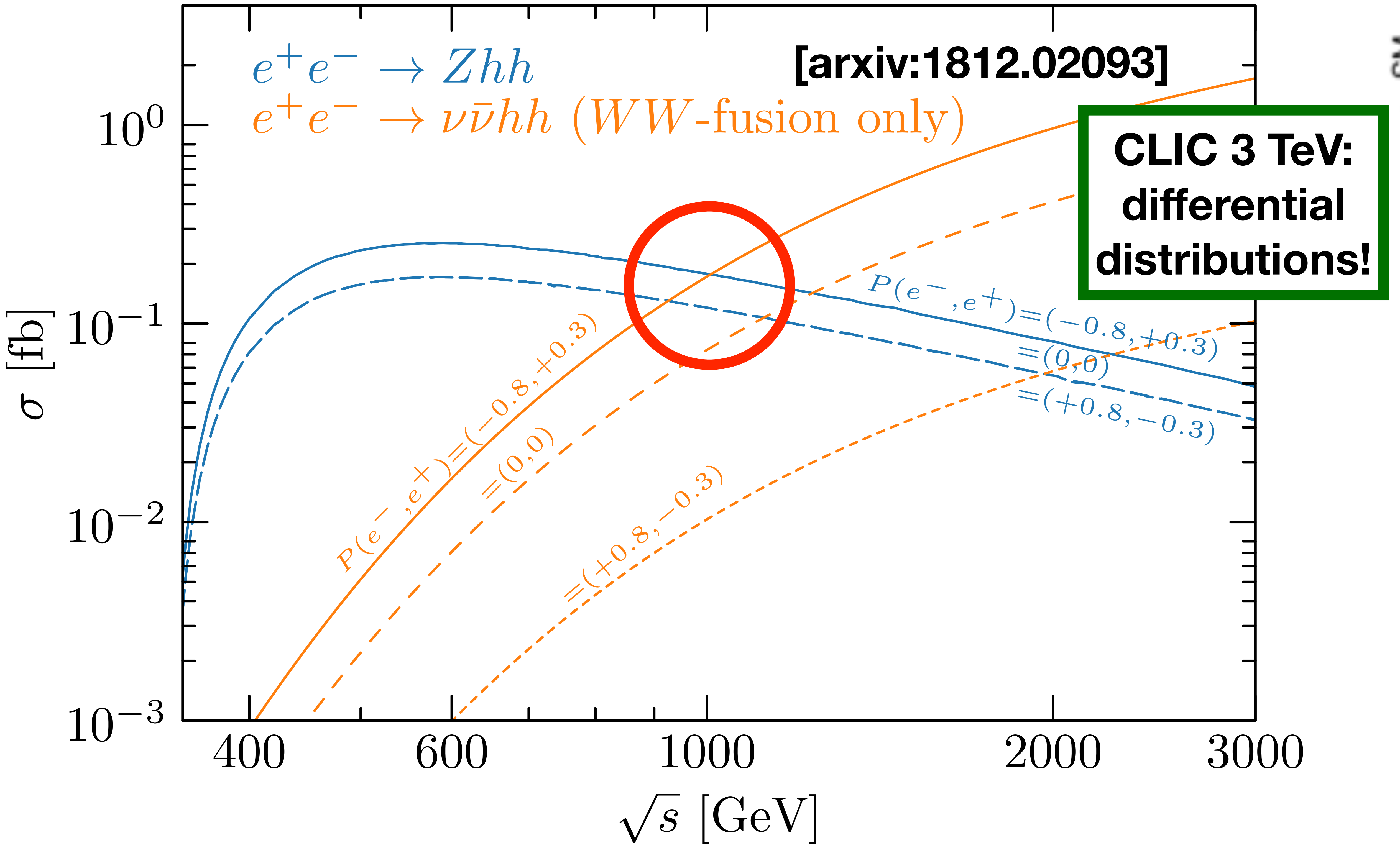

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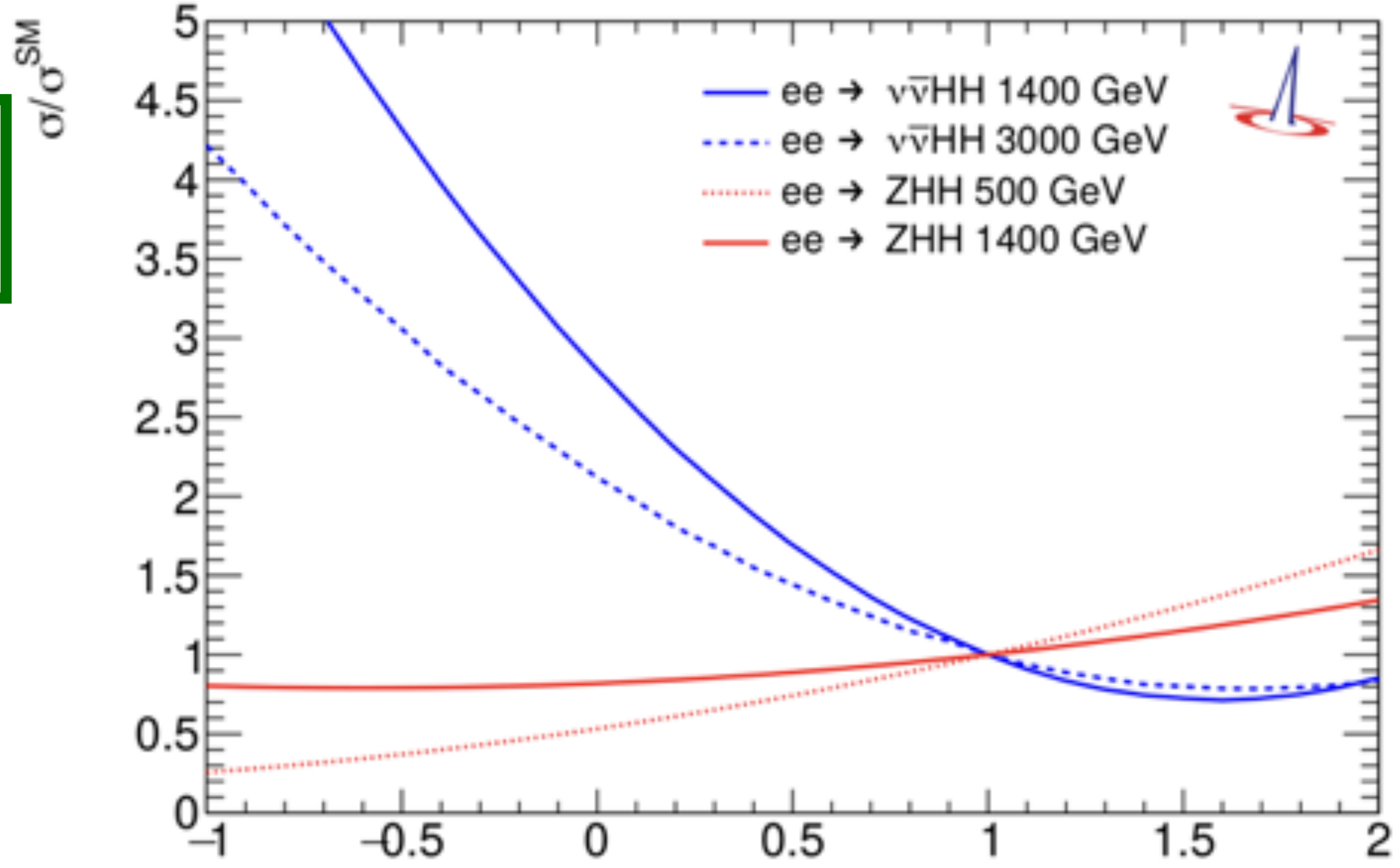
[J.Reuter]



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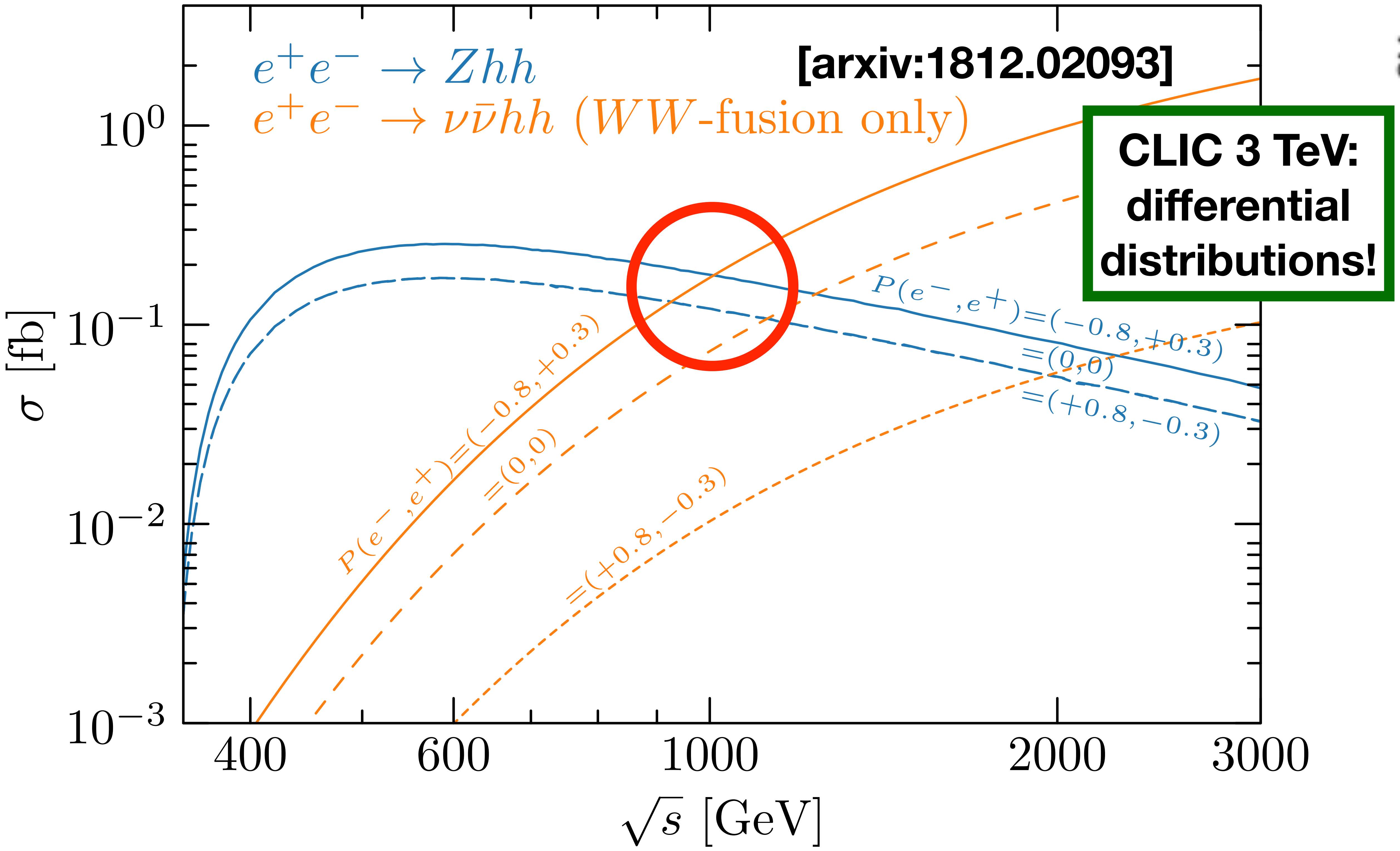

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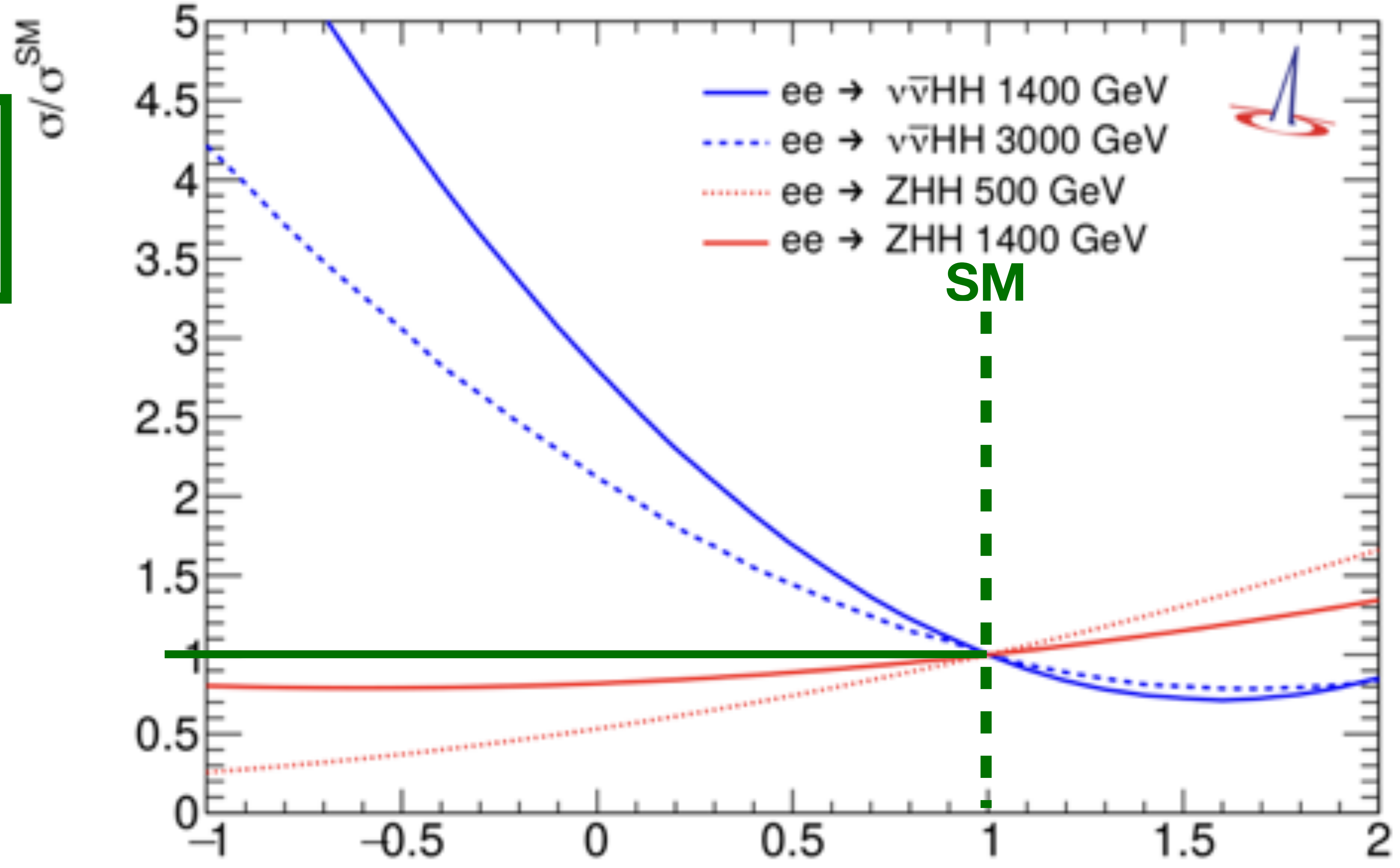

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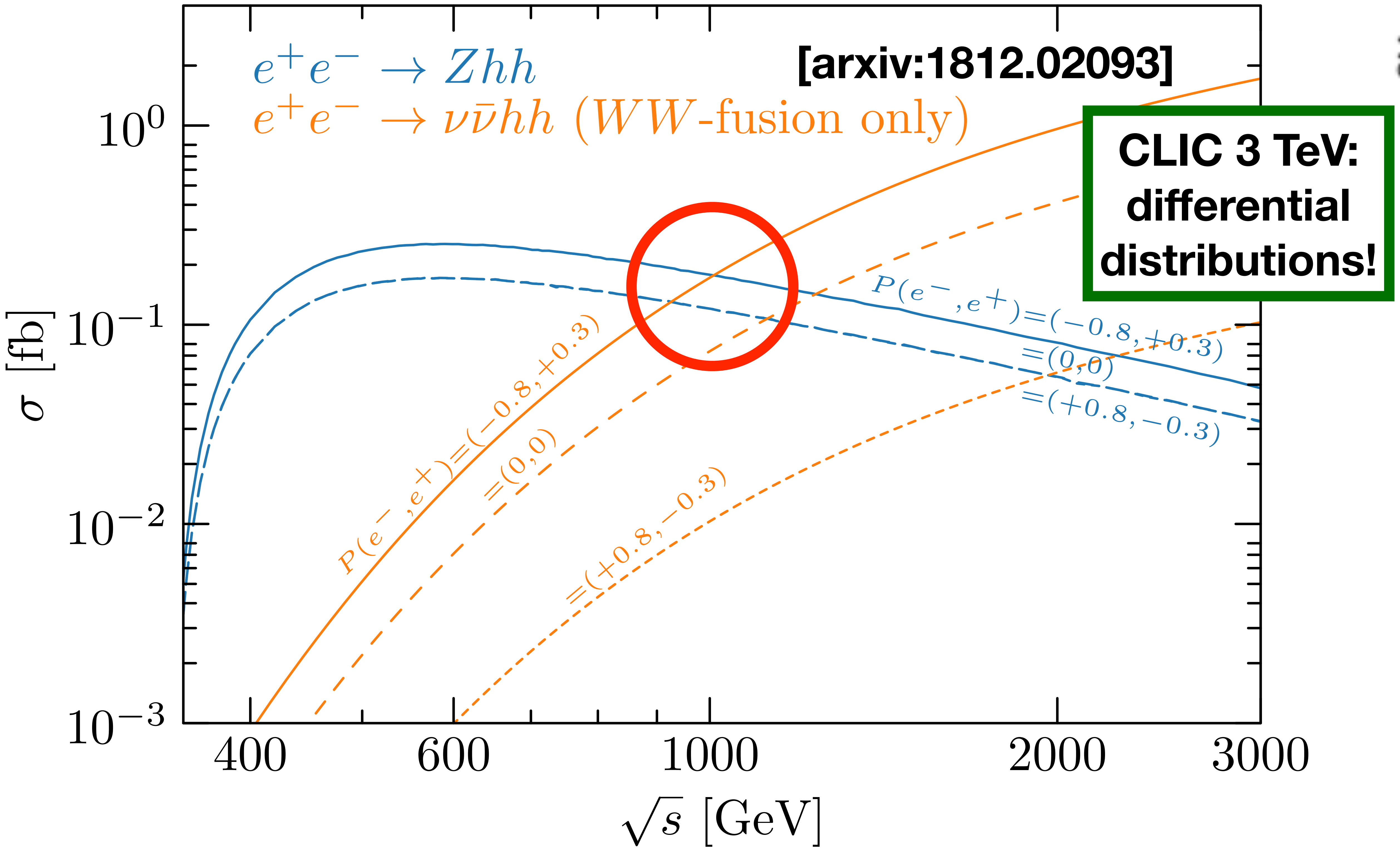

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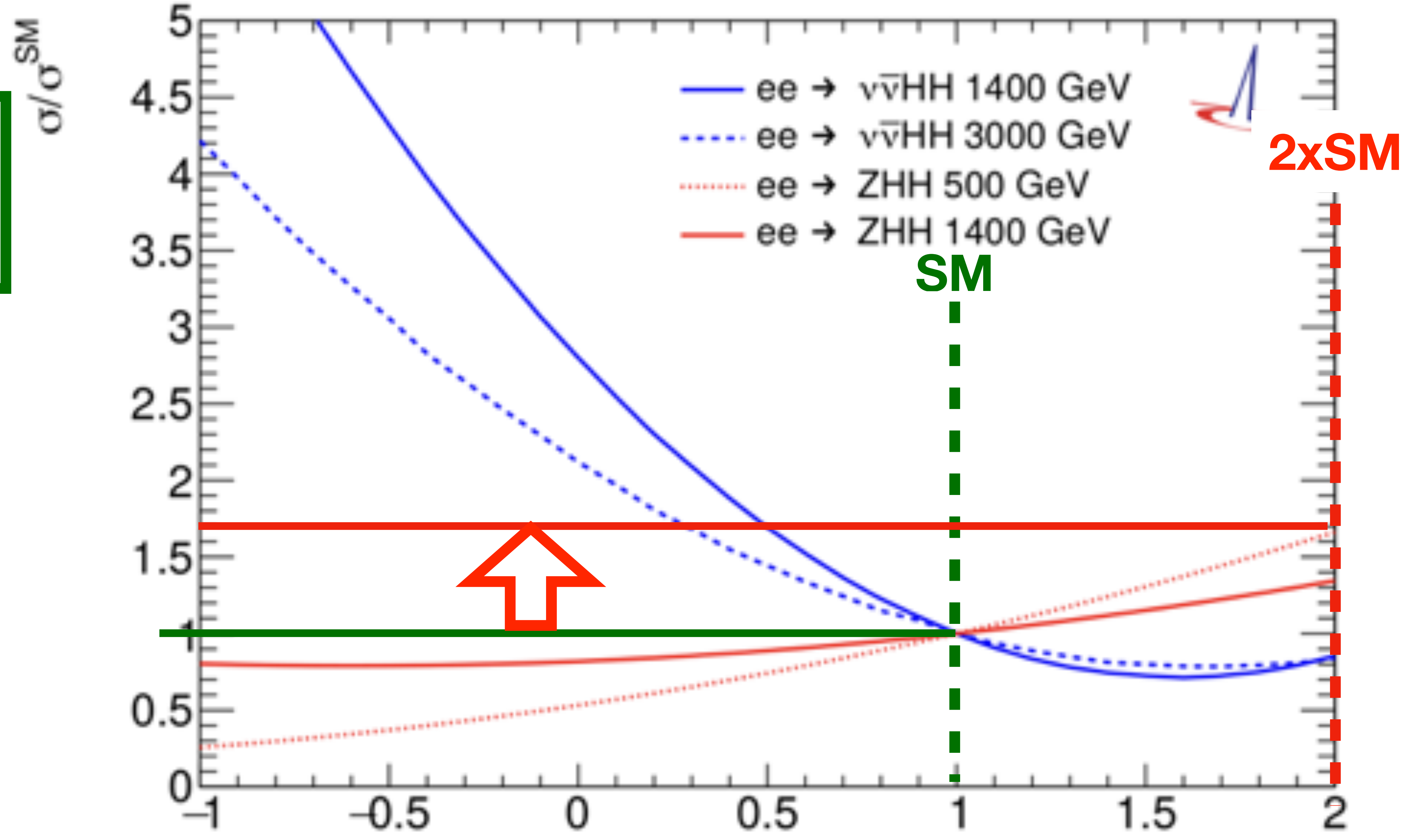

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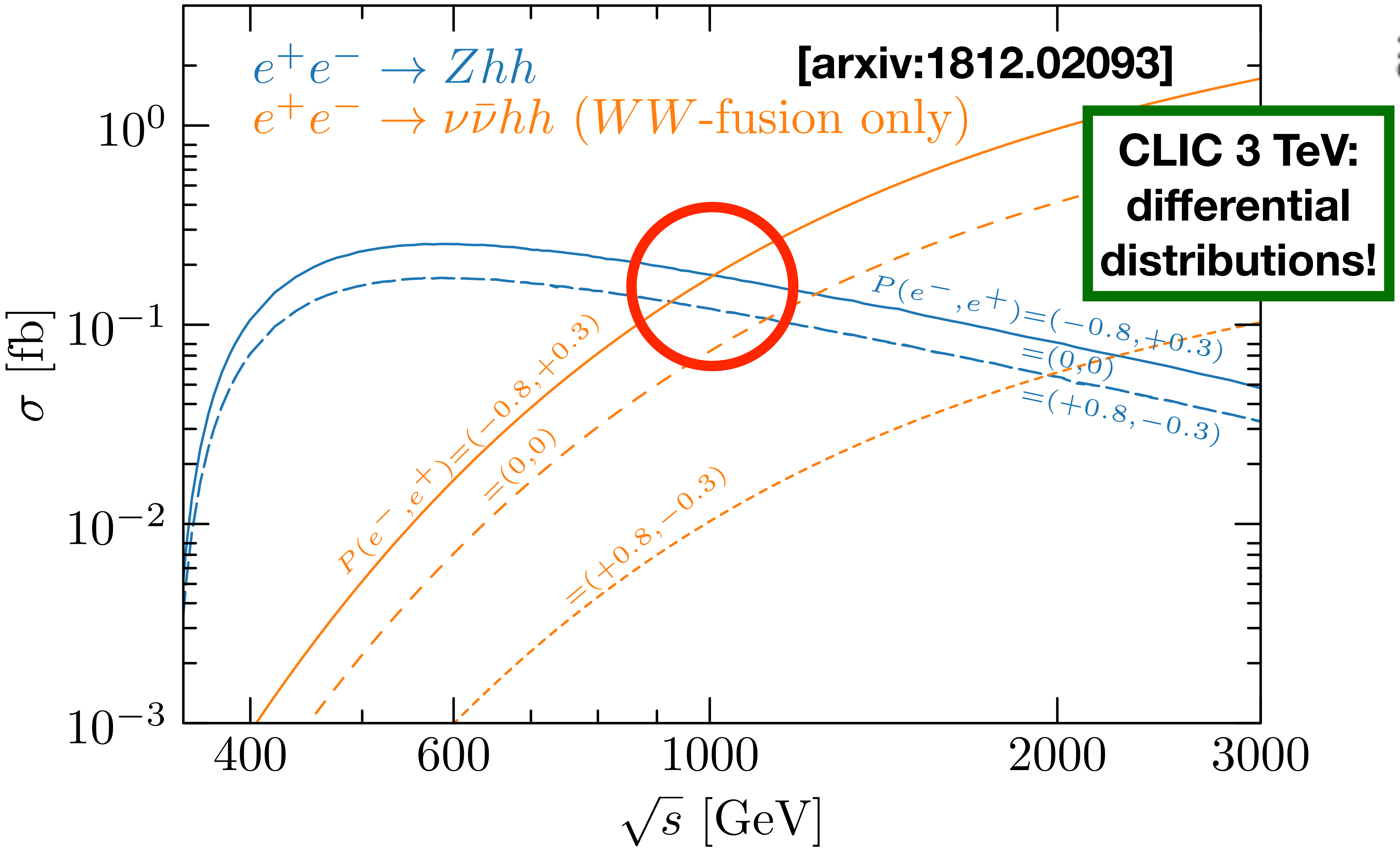

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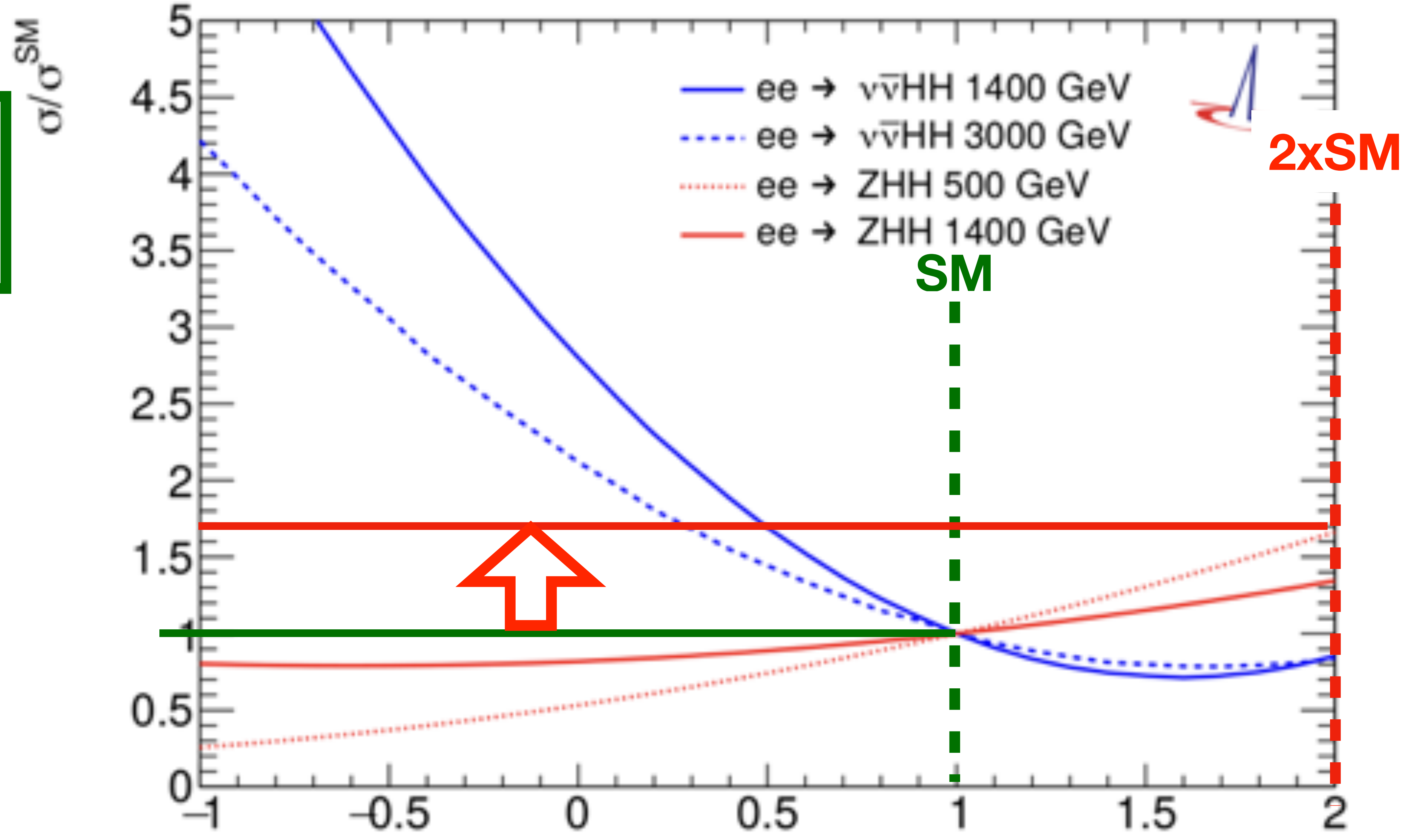
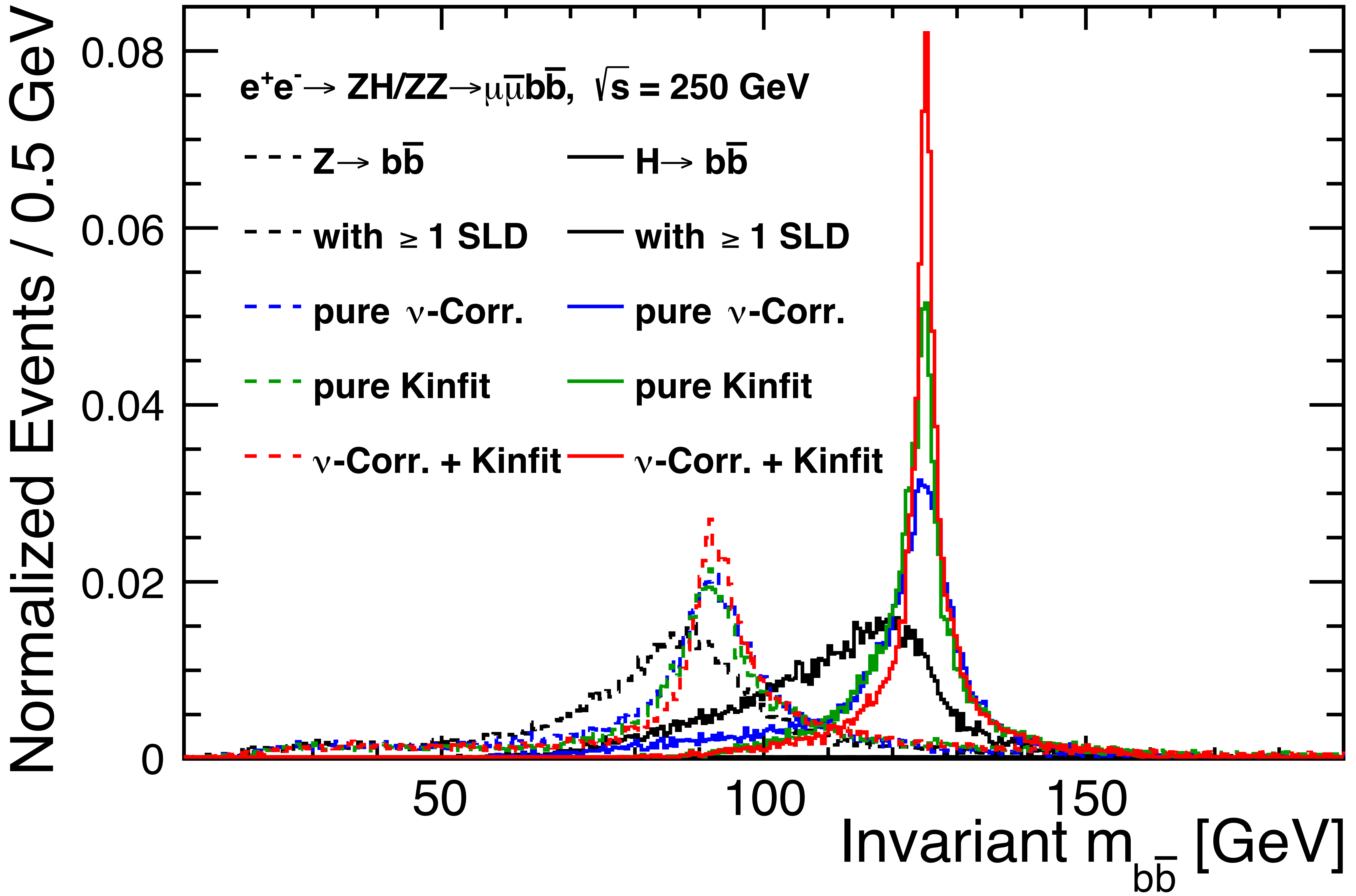


=> VBF(ee/pp)- and Higgsstrahlung (ee) di-Higgs production have orthogonal BSM behaviour

Recent developments

Improvements in reconstructing Z/H -> hadrons (Y. Radkhorrami, L. Reichenbach)

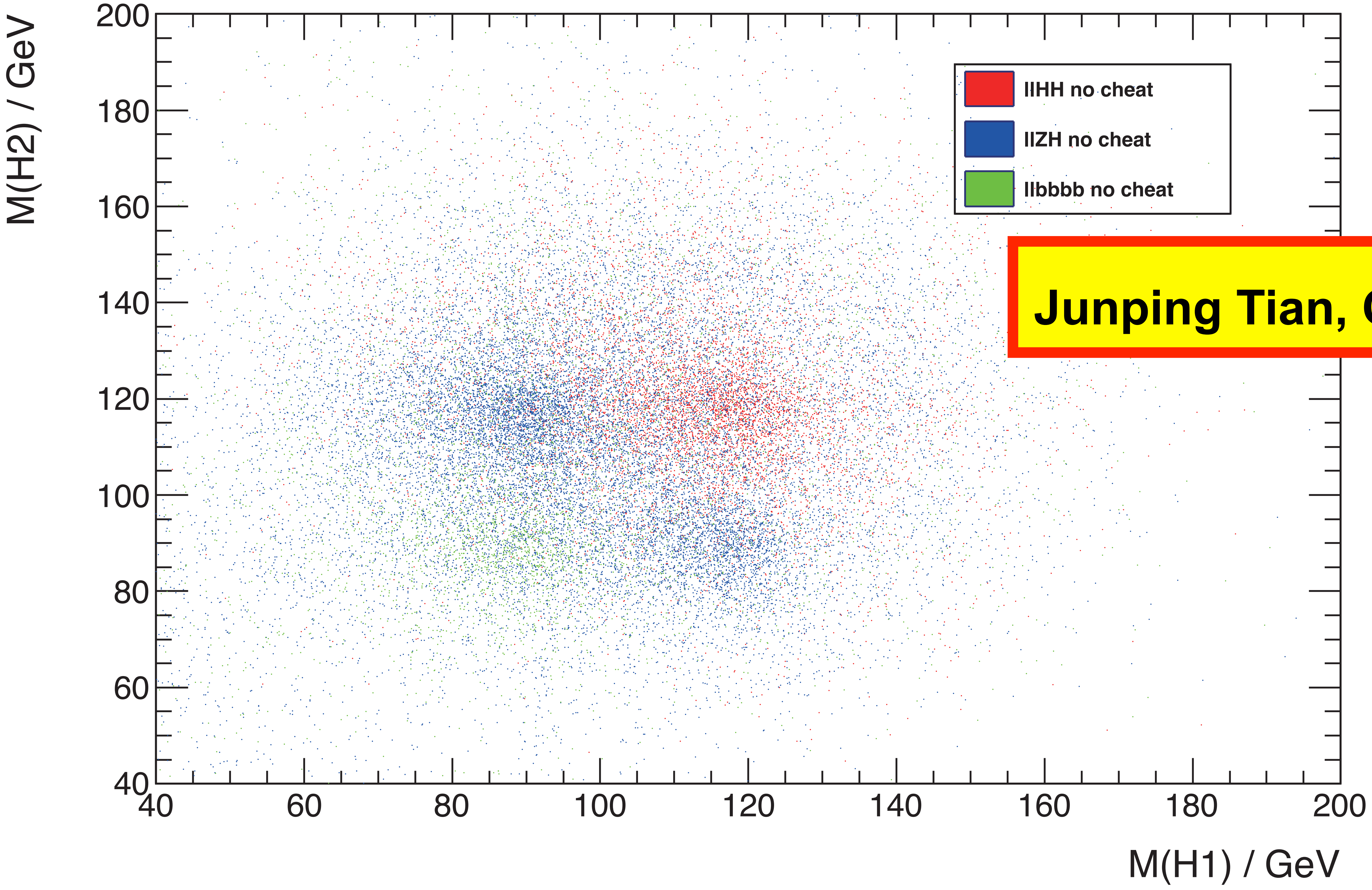
- correct semi-leptonic b/c decays
  - identify leptons in c- / b-jets
  - associate them to secondary / tertiary vertex
  - reconstruct neutrino kinematics (2-fold ambiguity)
- ErrorFlow (jet-by-jet covariance matrix estimate)
- feed both into kinematic fit
- (very) significant improvement in H->bb/cc and Z->bb/cc reconstruction
- ready to be applied to many analyses…

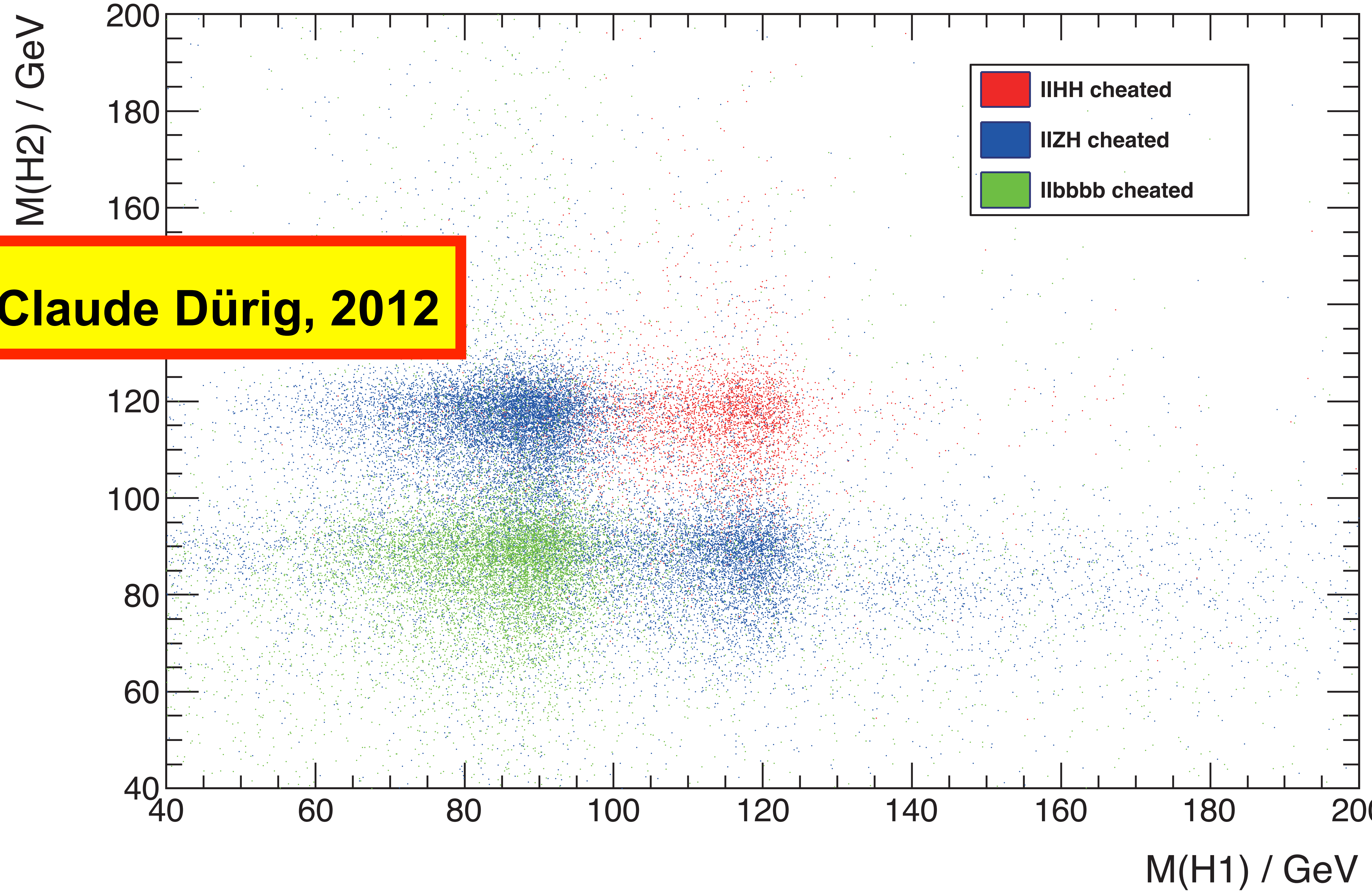


arXiv:2111.14775

Urgently wanted: modern jet clustering

… bottle-neck for Higgs self-coupling precision





Junping Tian, Claude Dürig, 2012

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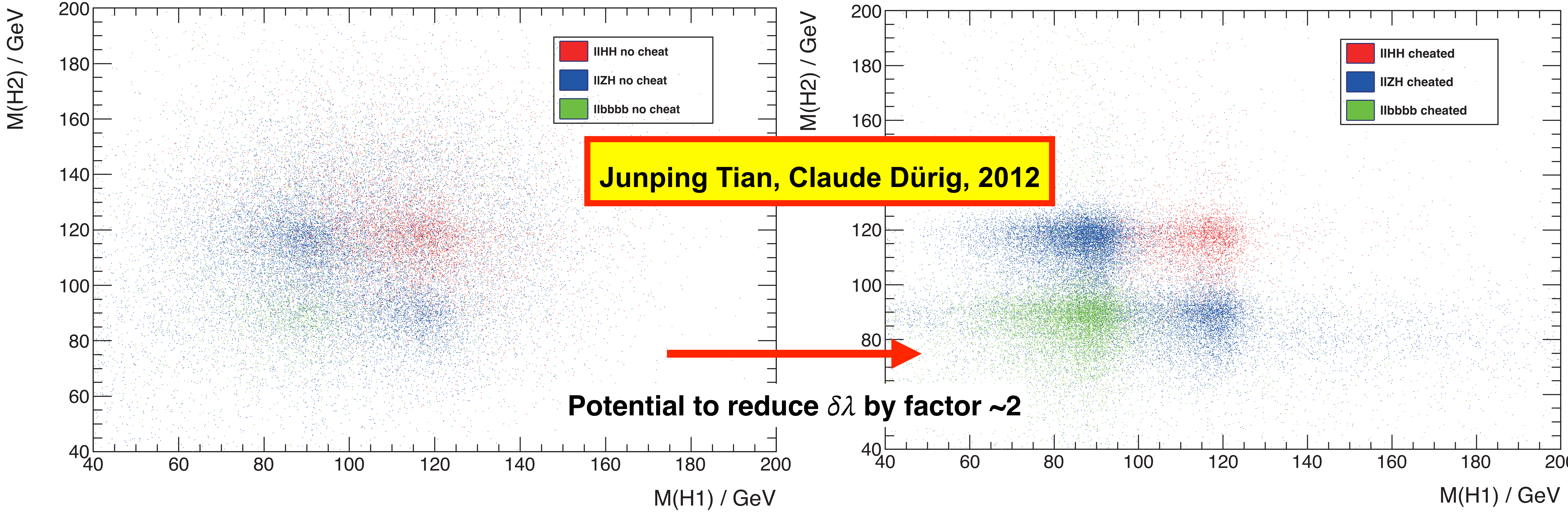

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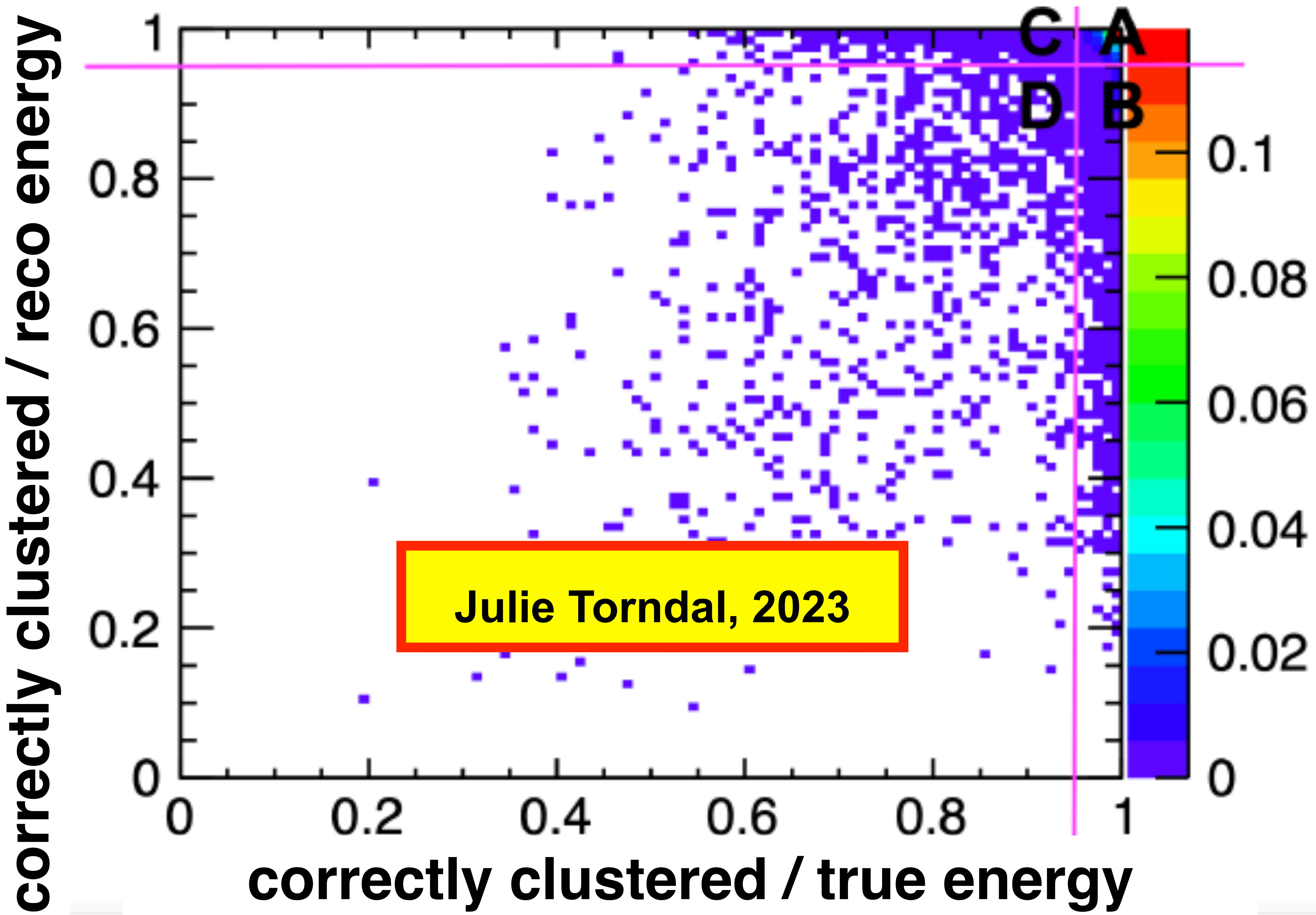

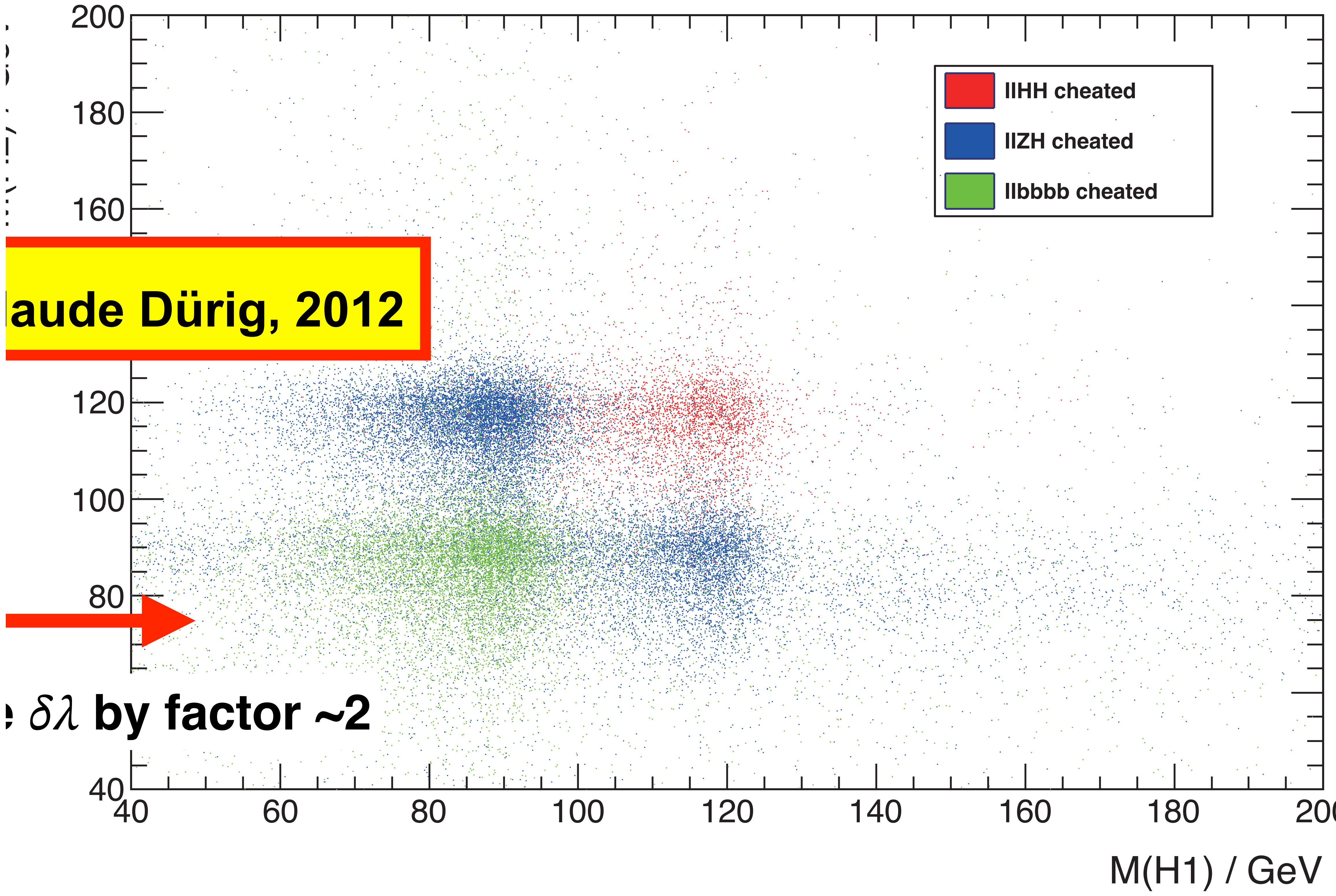

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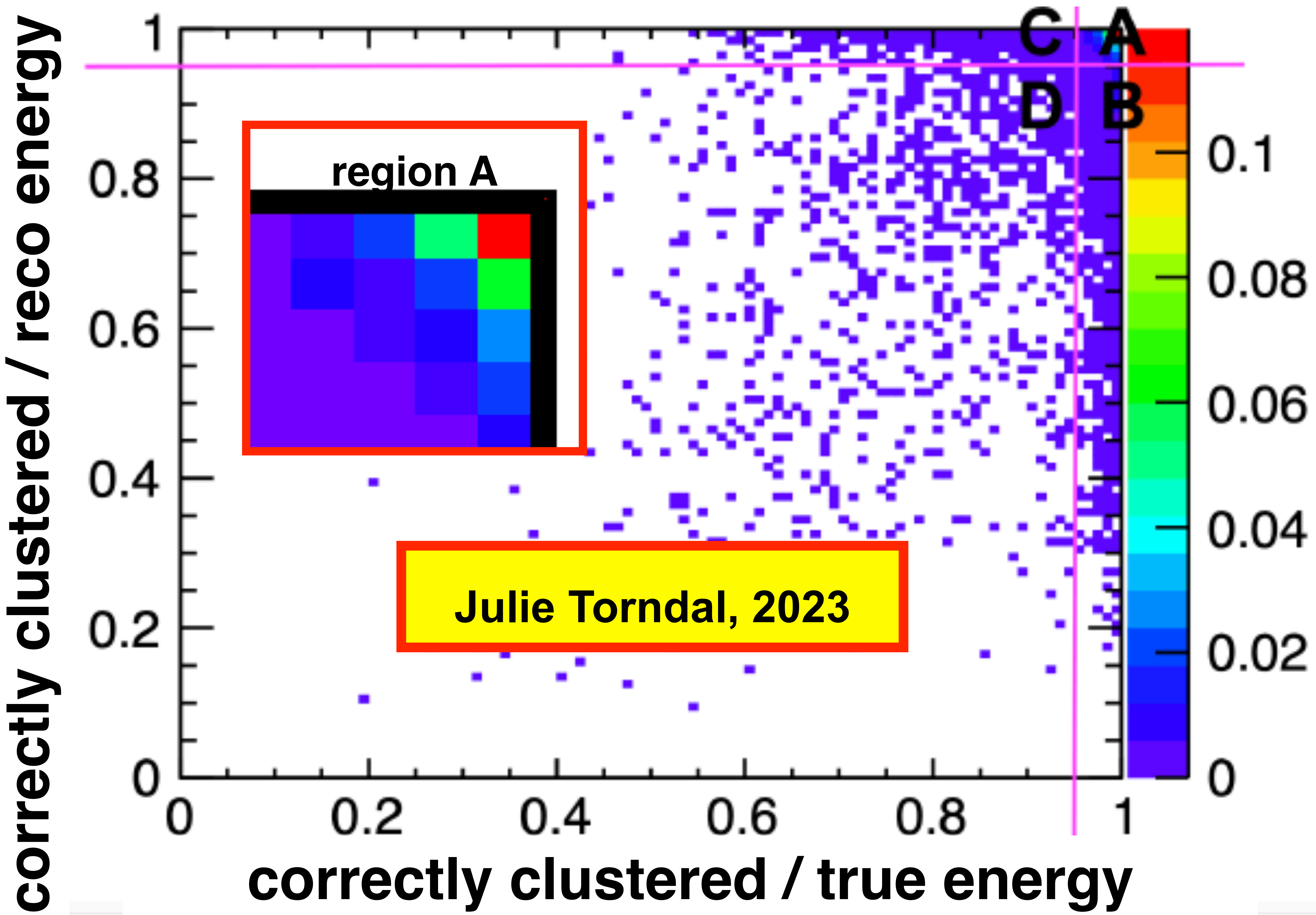

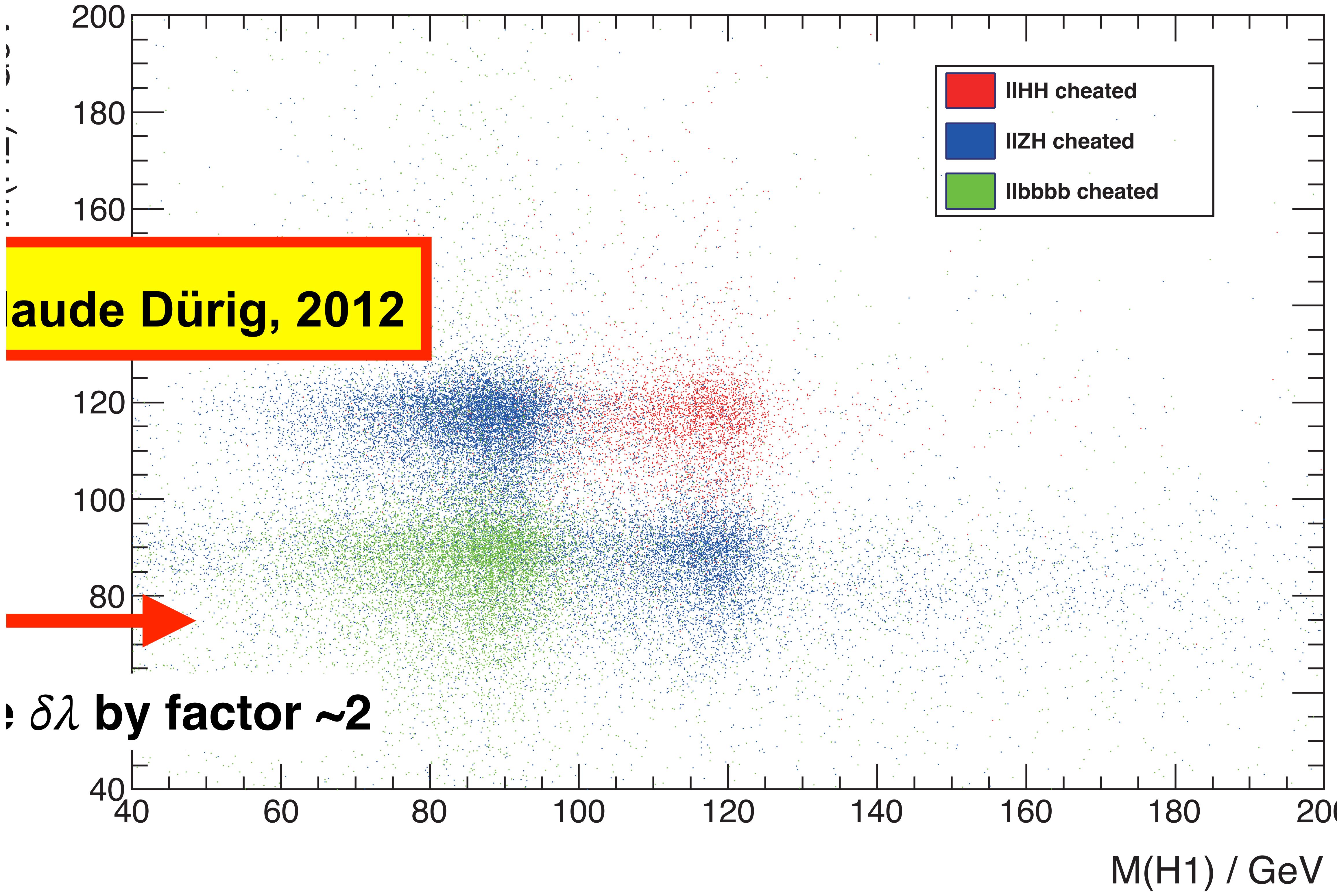

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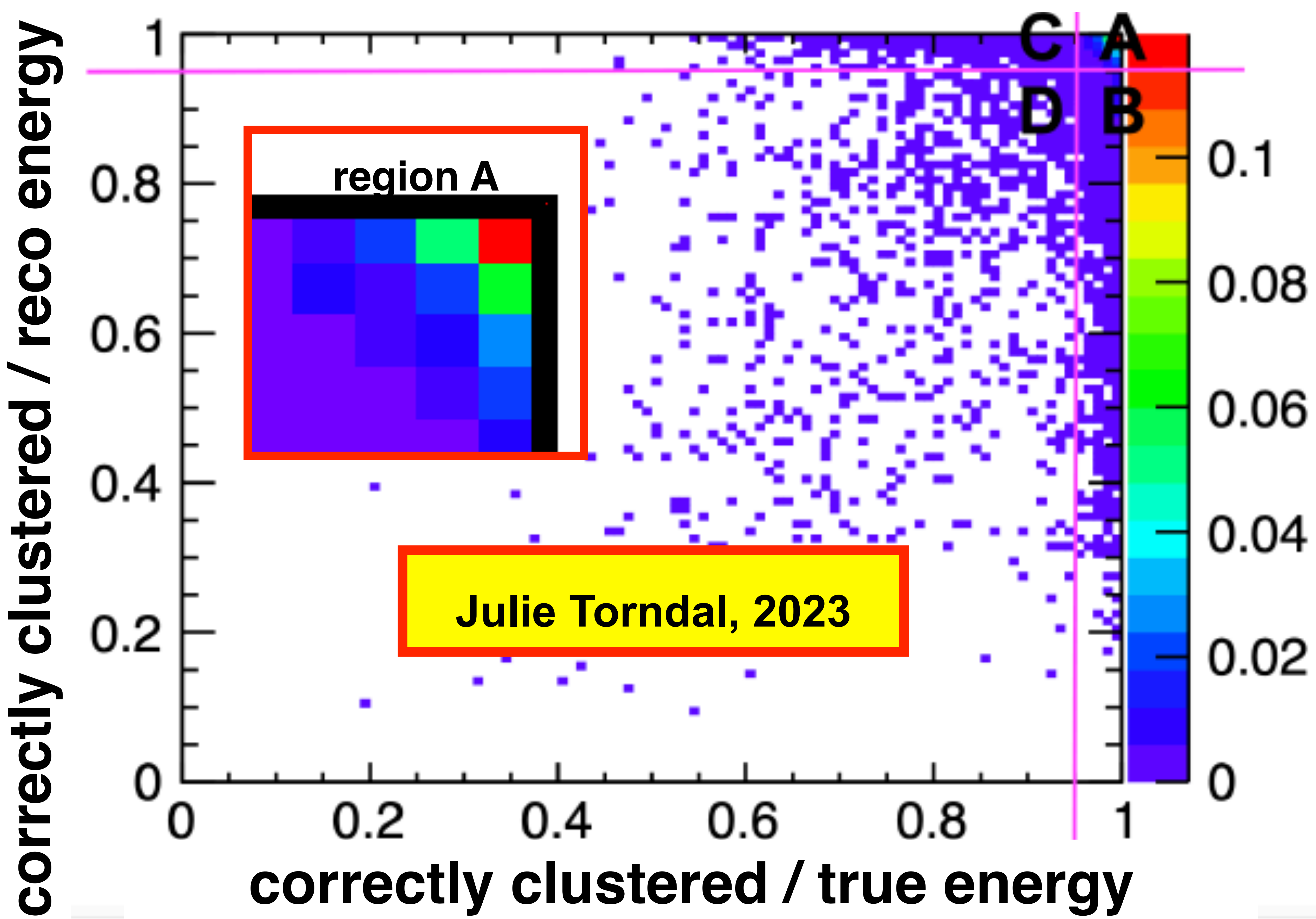

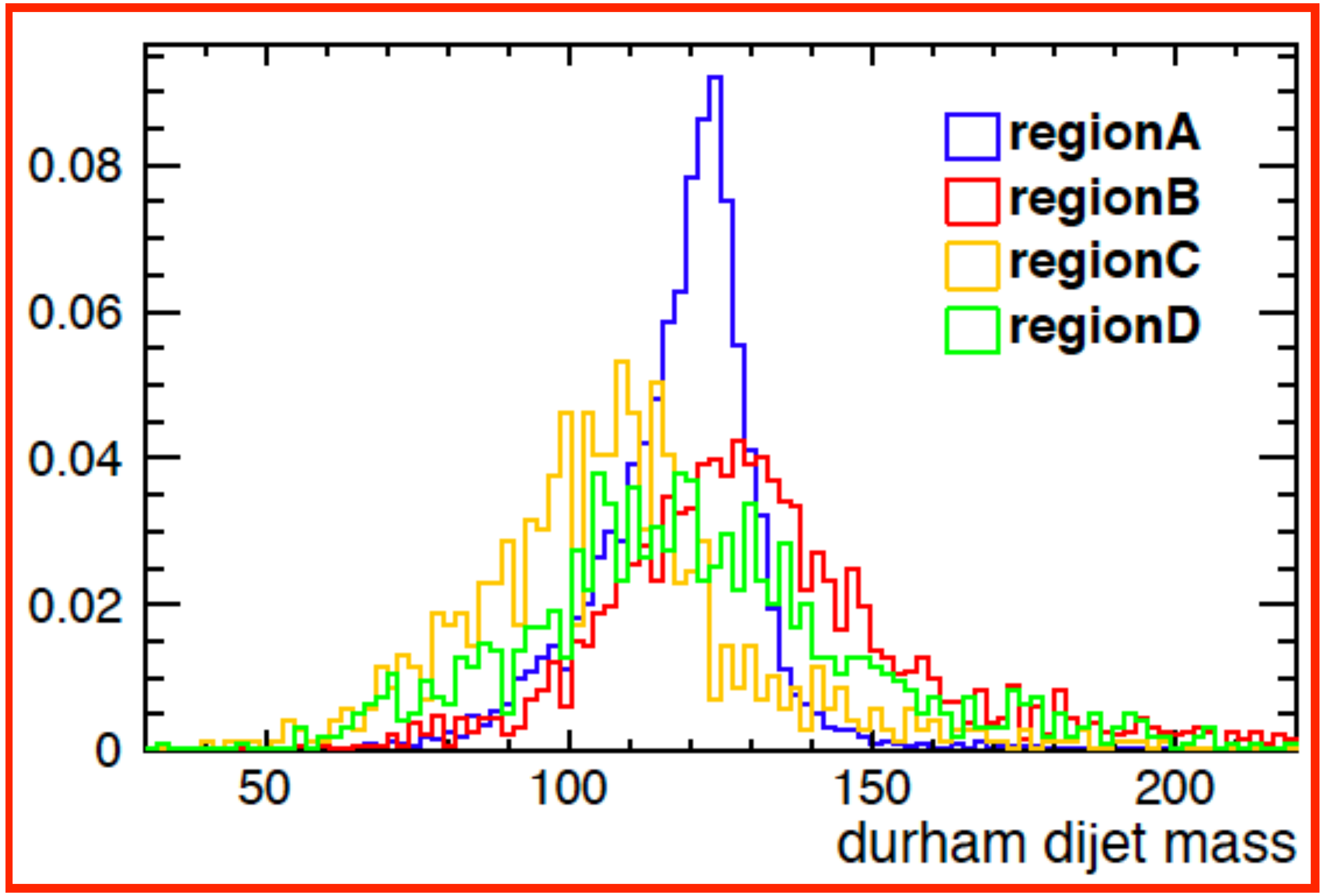

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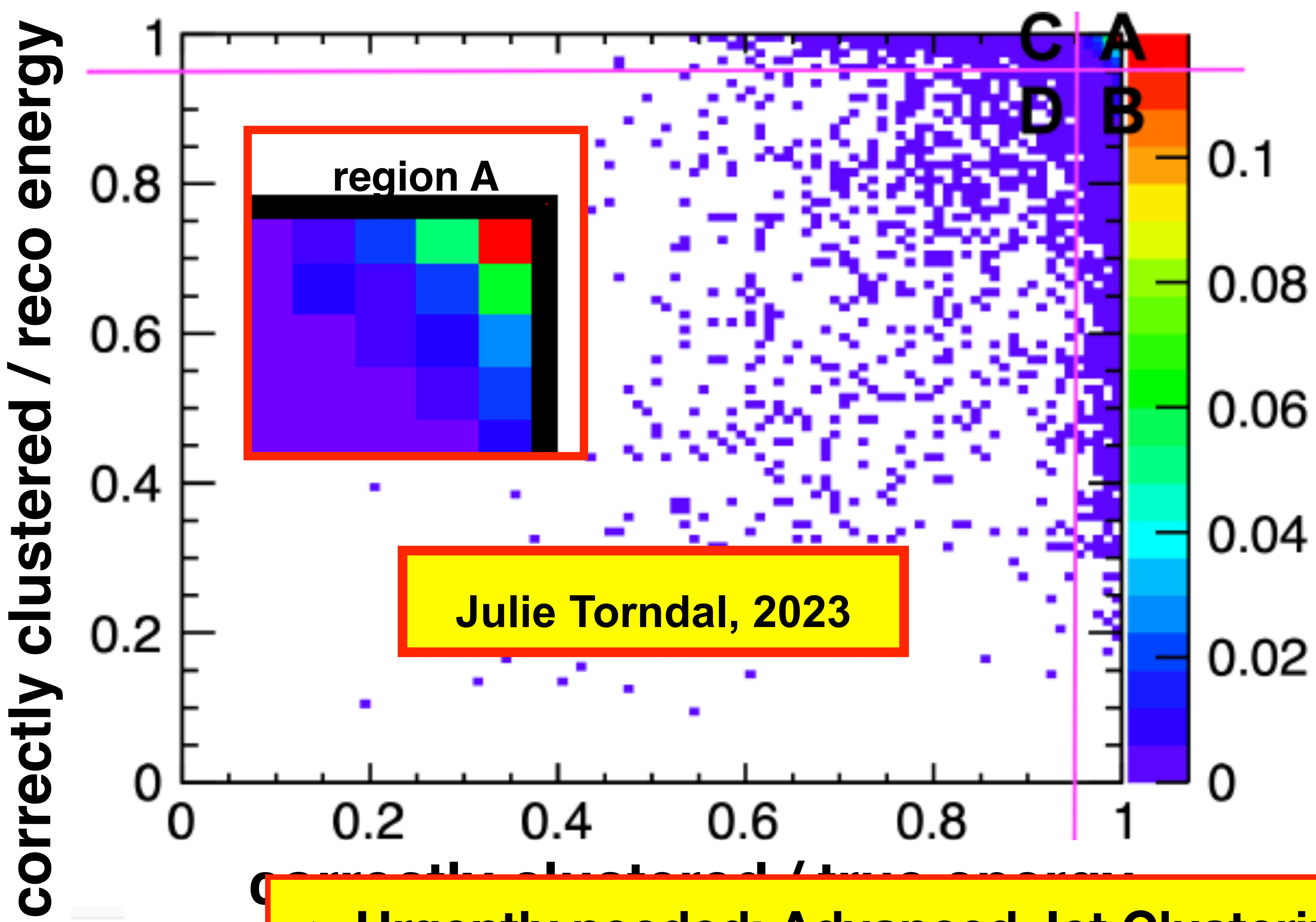
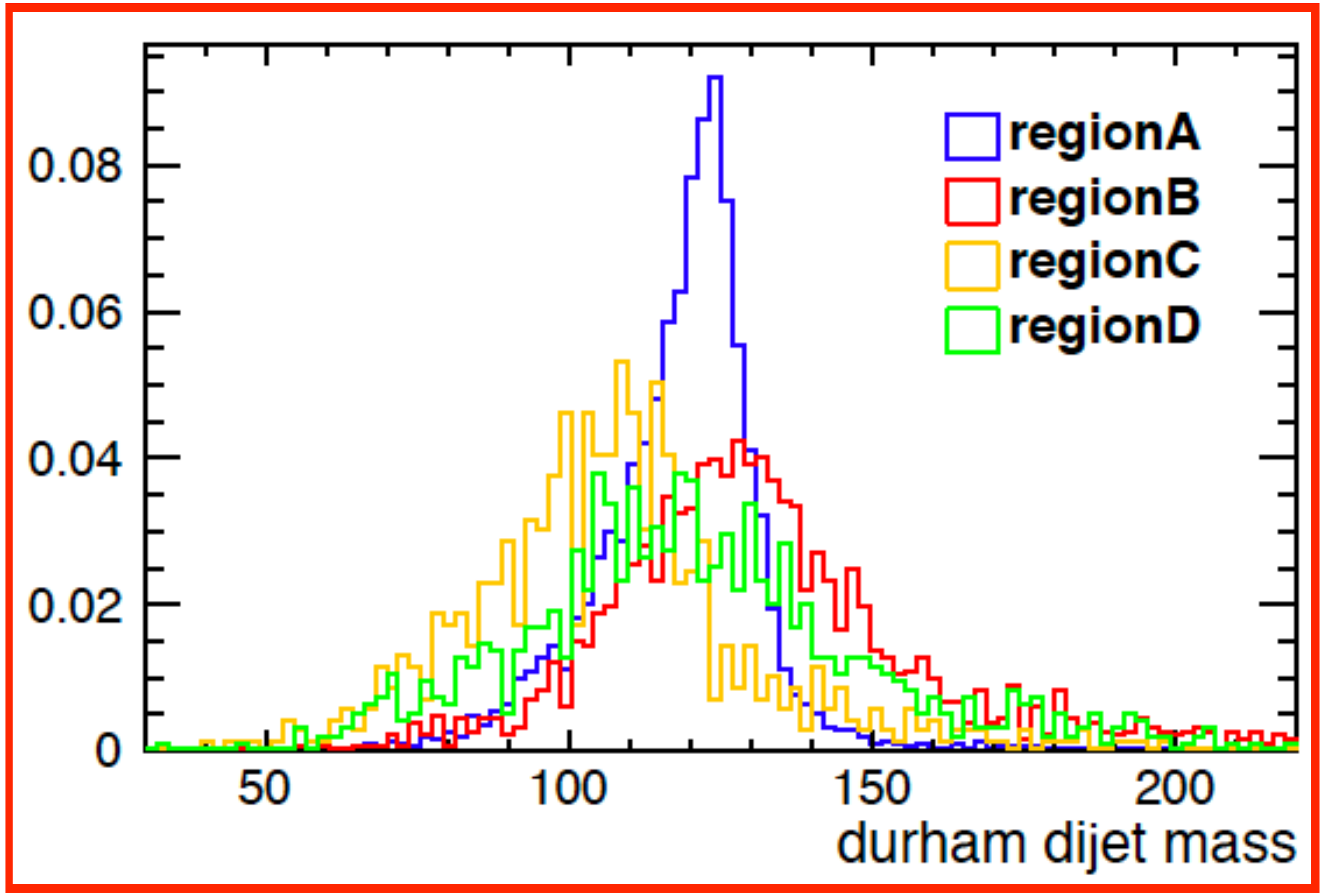




=> Urgently needed: Advanced Jet Clustering, ML, …can we get rid of B, C, D ???

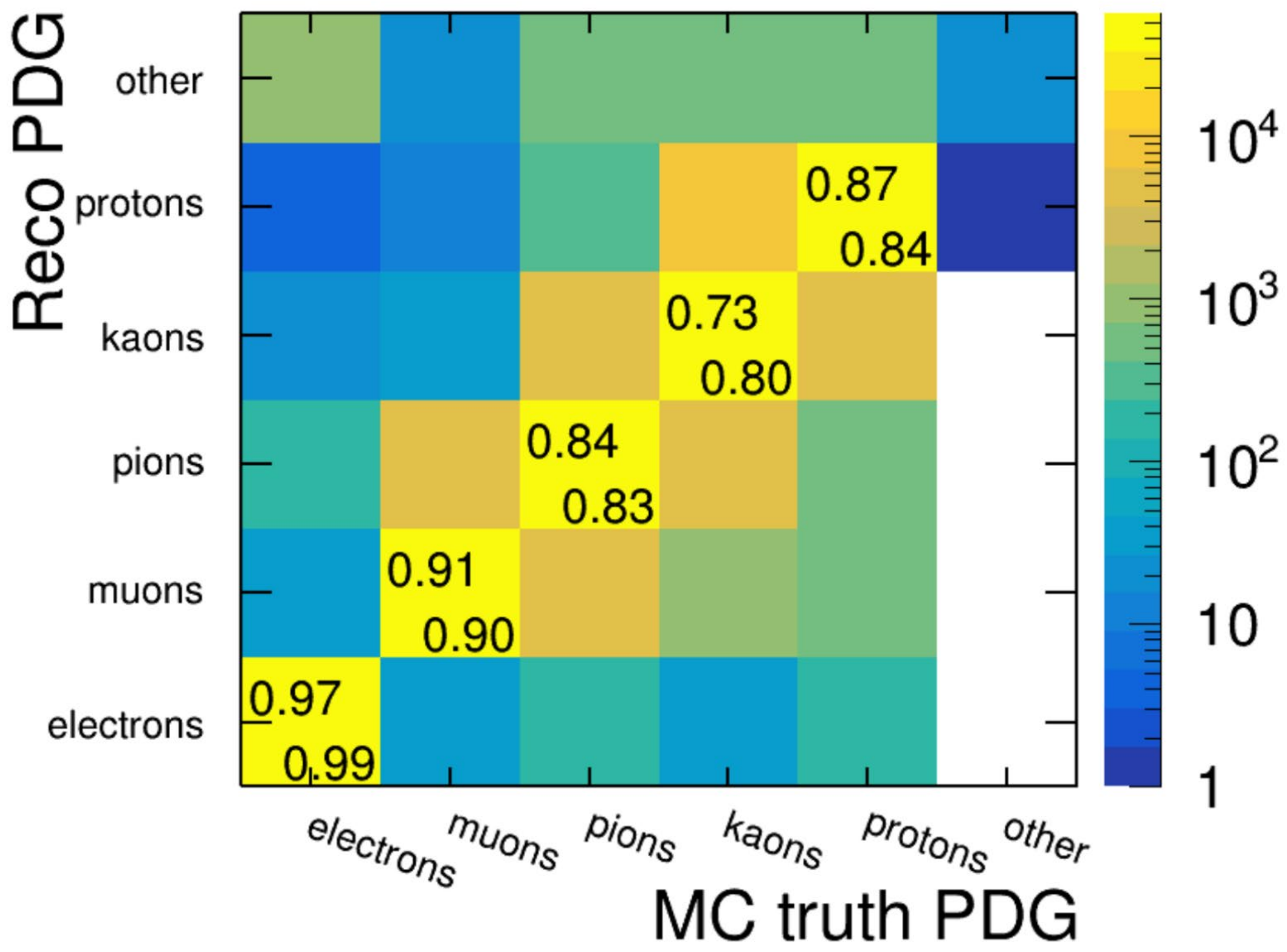
which additional detector information would help?

This has the potential to reduce $\delta\lambda/\lambda$(SM) from 20% to 10% !

Comprehensive Particle Identification (CPID)

Full exploitation of PID information

- modular and highly configurable PID toolkit
  - “plug-and-play“ of multiple data sources
    e.g. at ILD: dE/dx, TOF, cluster shape
  - extension through custom inference modules
    e.g. MVA/ML models etc.
- includes default weights for BDT model
- status: in production (in MarlinReco)



Confusion matrix for single charged partilces at ILD.
U. Einhaus (2023)

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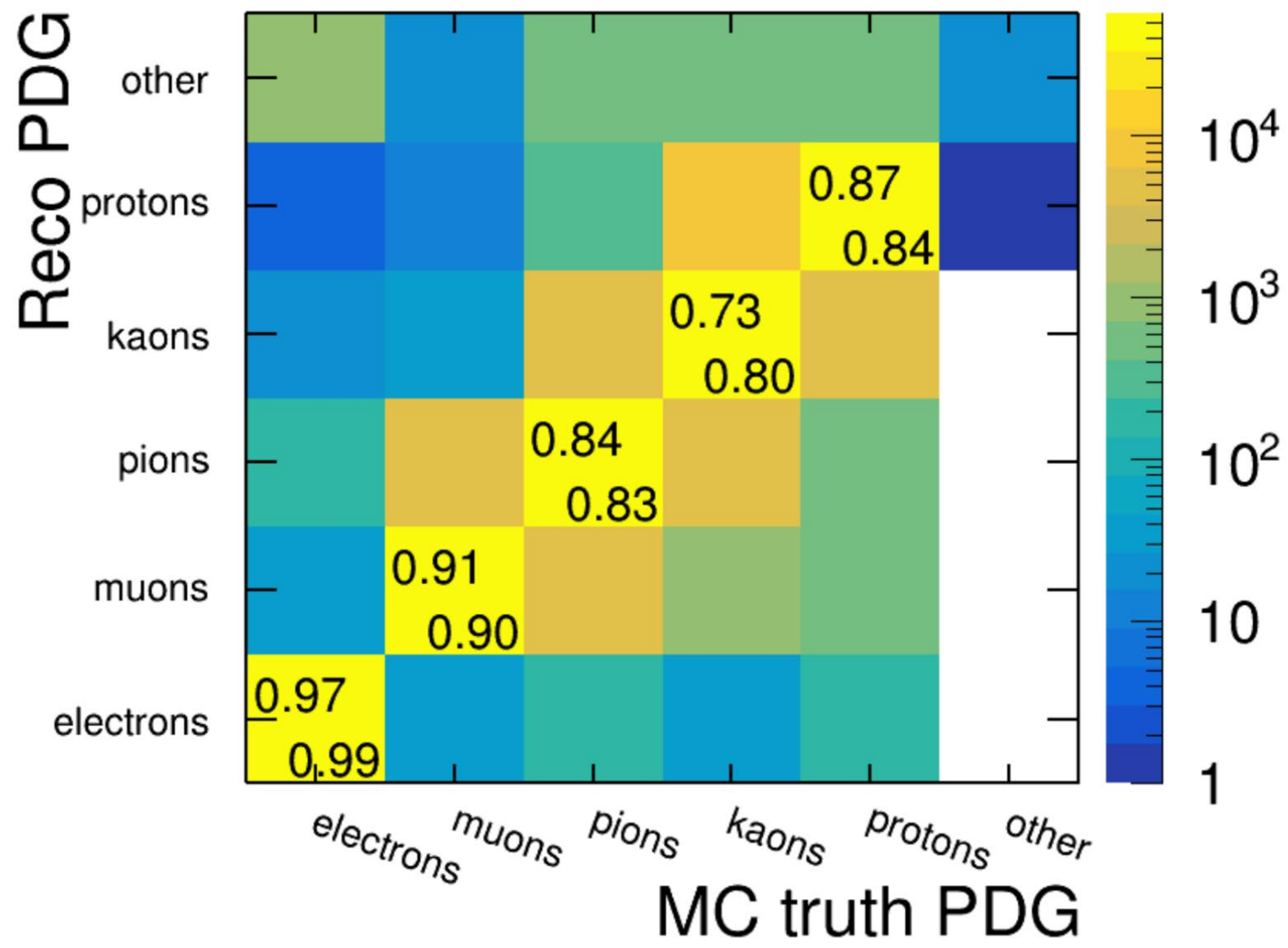

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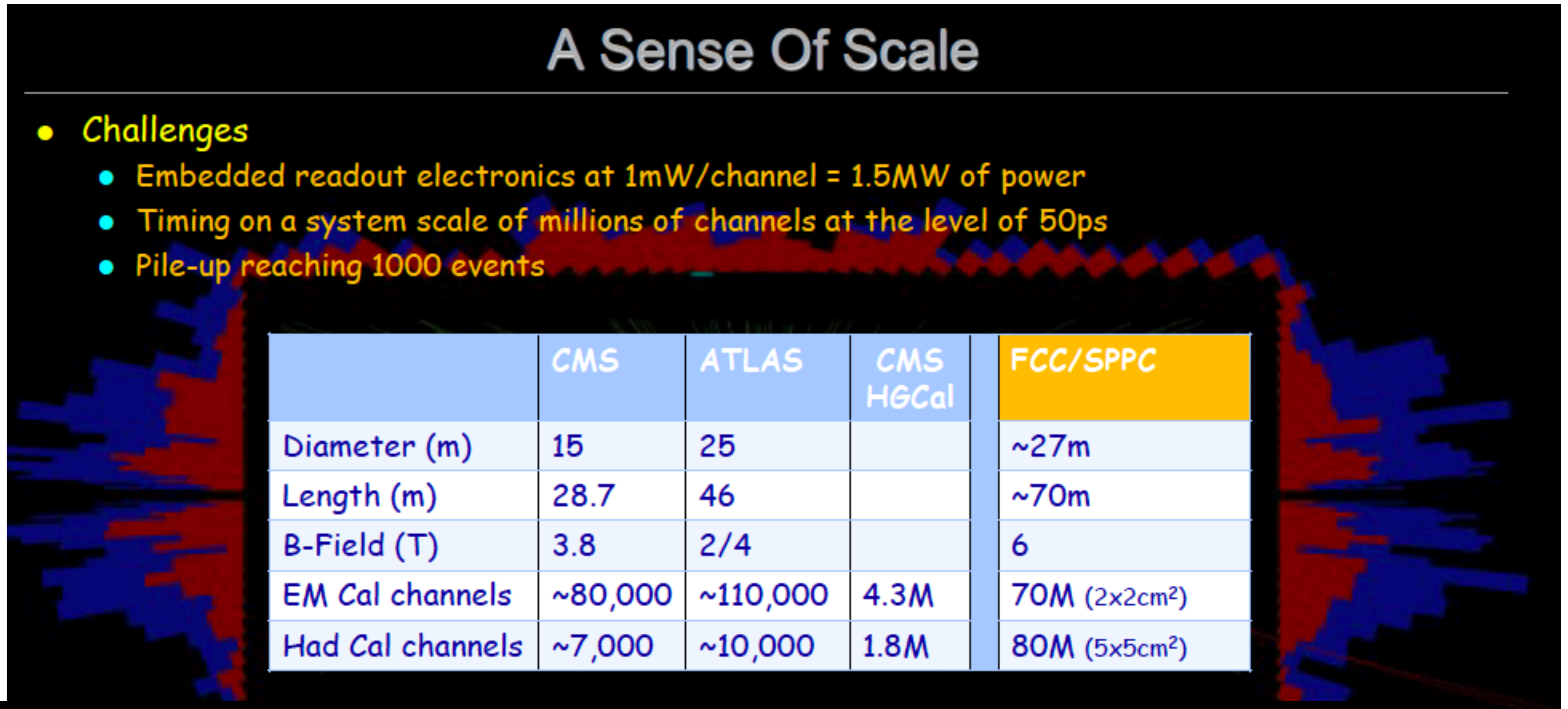
U. Einhaus (2023)

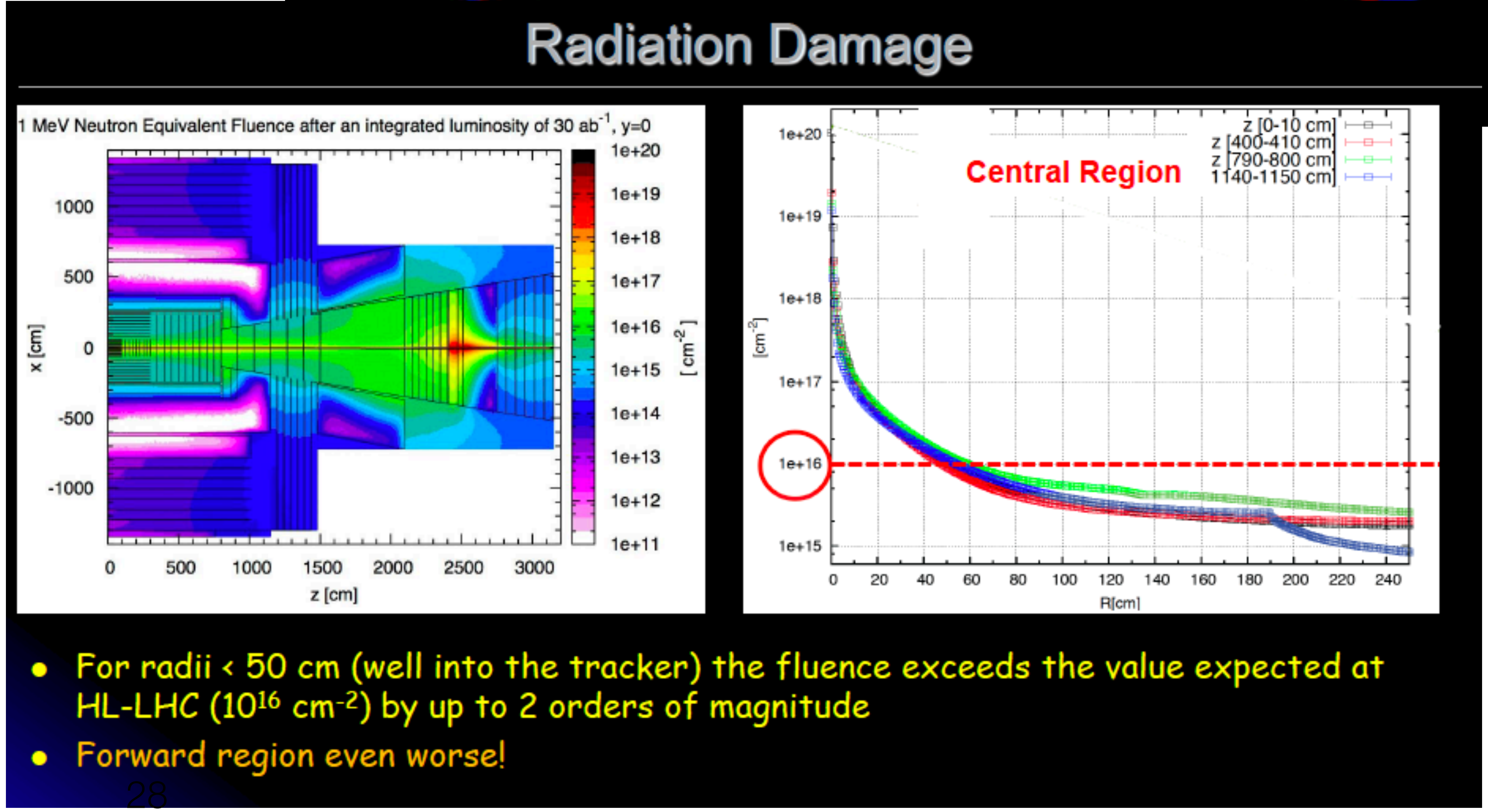
Retrain ML-FlavourTaggers incl. this information => even more improvement?

FCChh

- quoted precision on $\delta\lambda_{SM}/\lambda_{SM}$ = 5%
- assumes net detector performance equivalent to current LHC
- to get an idea what this implies, I recommend eg recent presentation by Marcel Demarteau (Argonne) at HiggsCouplings 2019 (Oxford)



	CMS	ATLAS	CMS HGCal	FCC/SPPC
Diameter (m)	15	25		~27m
Length (m)	28.7	46		~70m
B-Field (T)	3.8	2/4		6
EM Cal channels	~80,000	~110,000	4.3M	70M (2x2cm²)
Had Cal channels	~7,000	~10,000	1.8M	80M (5x5cm²)



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