SUSY at Future Colliders

Jenny List (DESY)
SUSY2024
10-14 June 2024
Madrid

HELMHOLTZ

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

FTX

DESY.

SUSY at the next Future Collider~~s~~

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Outline

Today's menu

- Setting the scene: from (HL-)LHC to our next collider
- Direct SUSY searches at future e+e- colliders
  - Experimental Conditions
  - Ex 1: scalar leptons
  - Ex 2: higgsinos
- Conclusions

Many thanks to all who contributed material!
(with and without being asked ;)

Setting the Scene: From (HL-)LHC to our next collider

An e^+e^- Higgs factory is the highest-priority next collider

A clear message from last EPPSU — and Snowmass

=> e+e- Higgs factory as highest priority next collider re-emphasized in the Snowmass process in the US (2022)

For the five-year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory Detector R&D program,
3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
4. Support critical Detector R&D towards EF multi-TeV colliders.

For the five-year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

https://europeanstrategyupdate.web.cern.ch/welcome

3

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

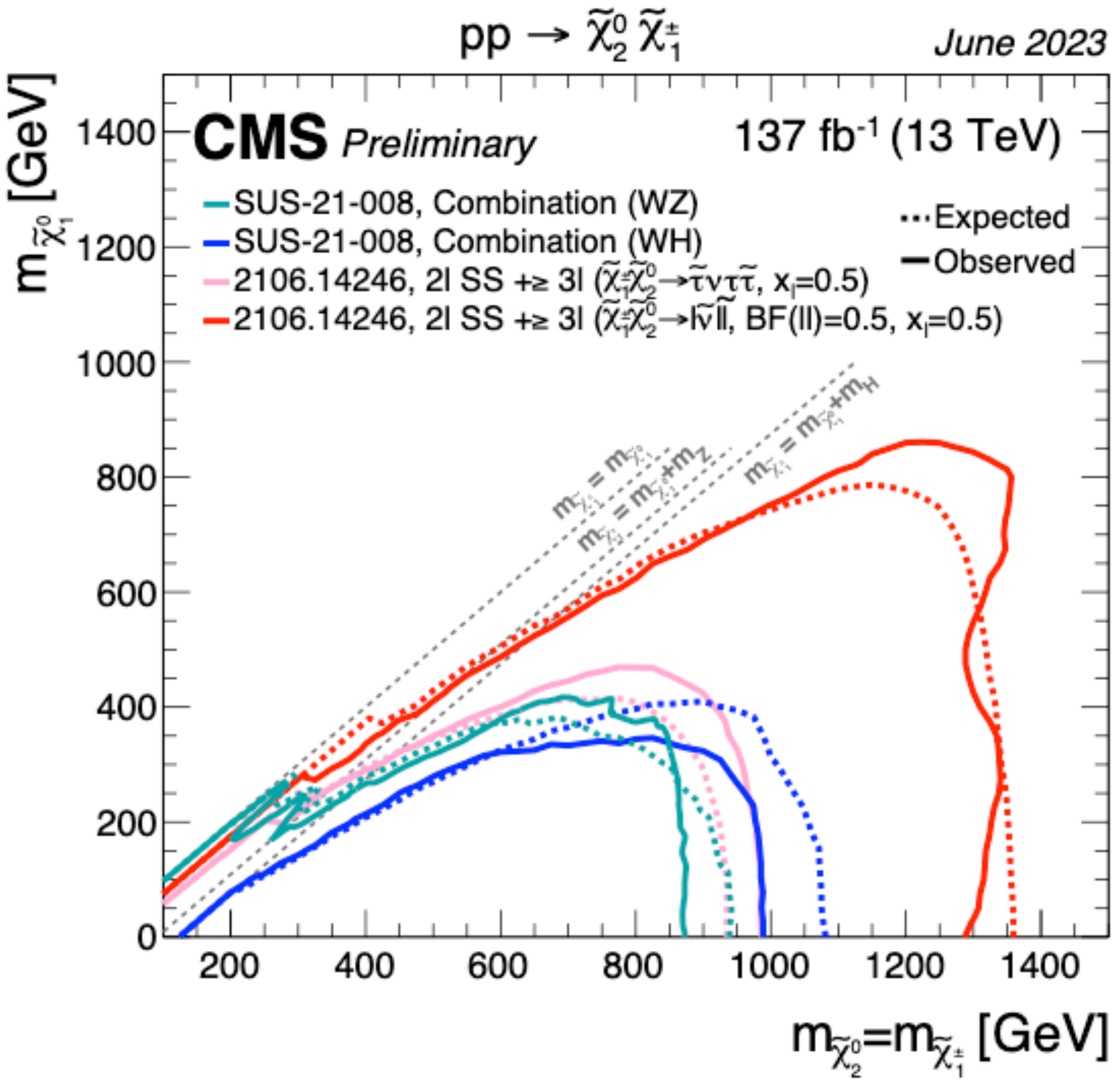
- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

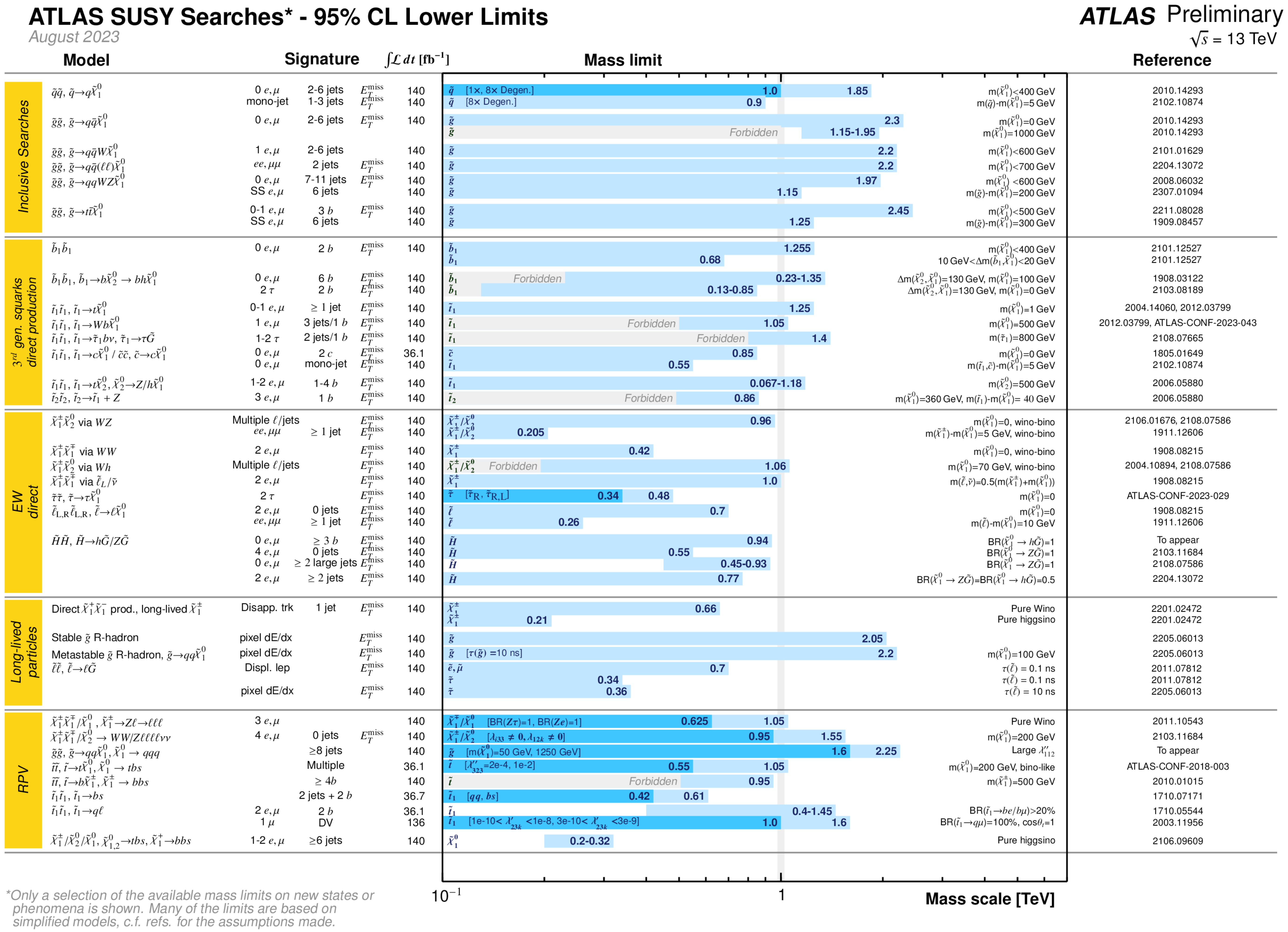
- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

Can a Higgs Factory contribute to SUSY searches?

… in view of LHC exclusions?





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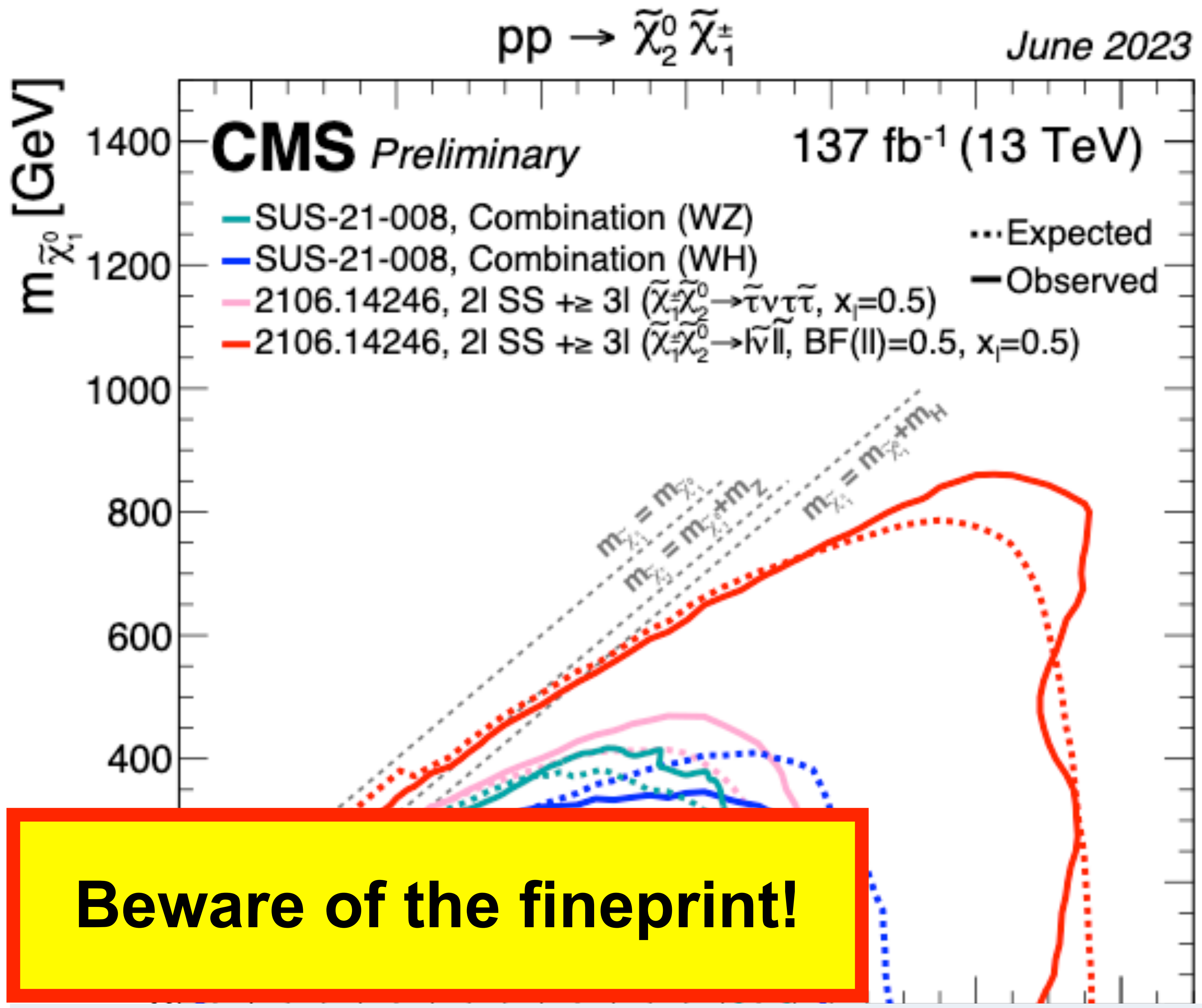
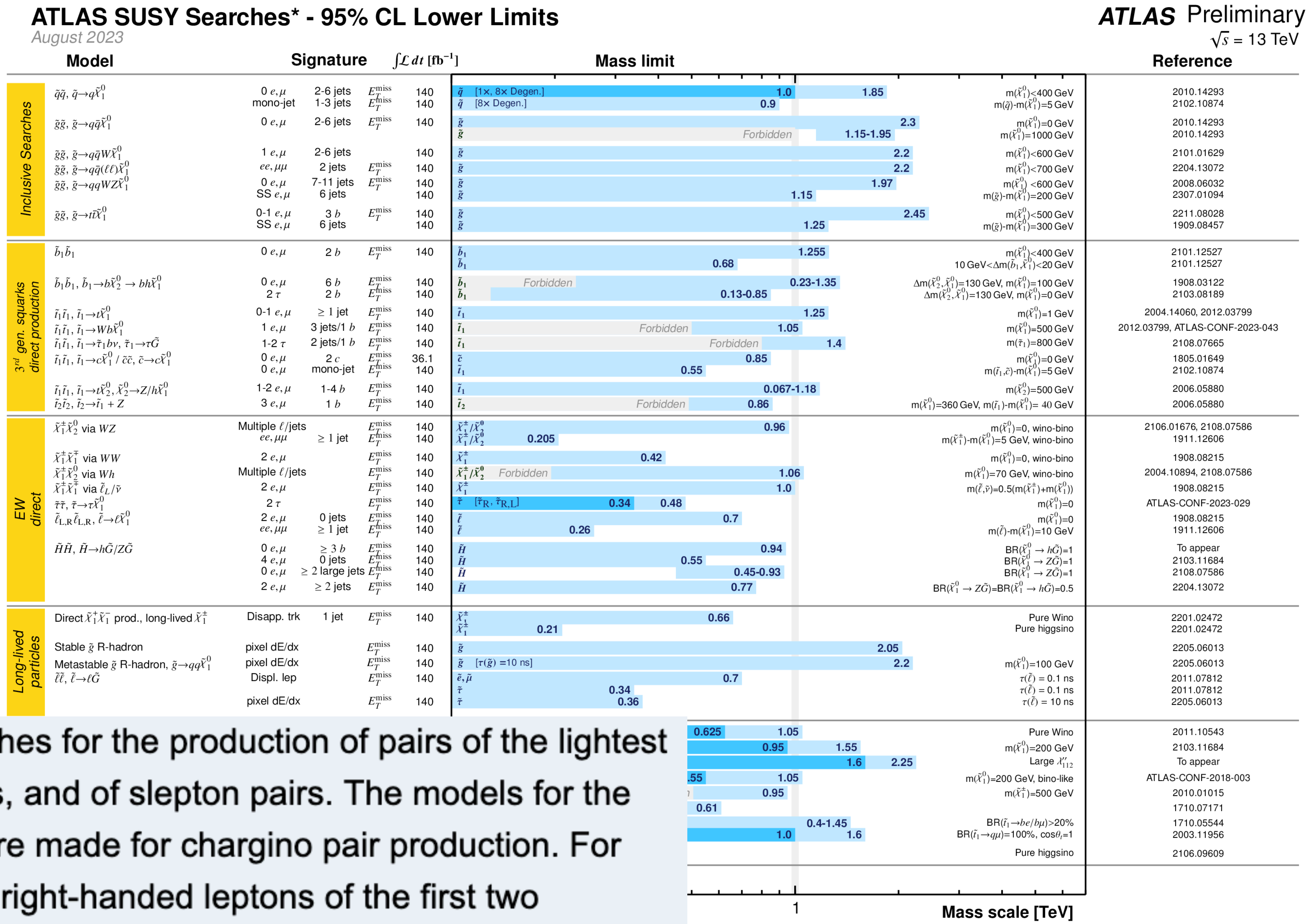


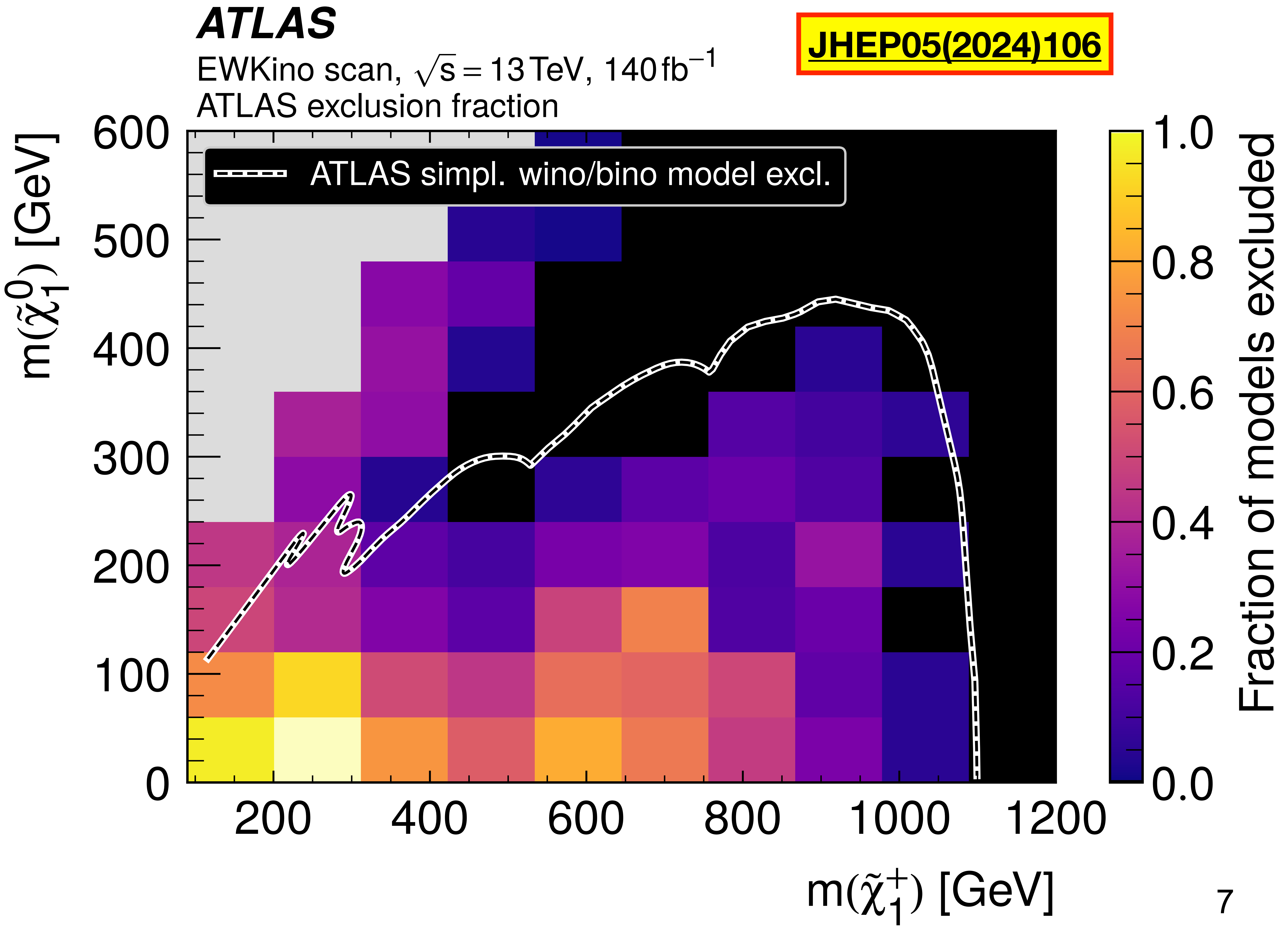


Beware of the fineprint!

Summary of the most stringent limits obtained by CMS searches for the production of pairs of the lightest chargino and the second-lightest neutralino, of chargino pairs, and of slepton pairs. The models for the first category are described above. The same assumptions are made for chargino pair production. For slepton production, the four states corresponding to left- and right-handed leptons of the first two generations are assumed to be mass degenerate.

The ATLAS pMSSM scan

Don't get depressed by simplified models and Manhattan plots…



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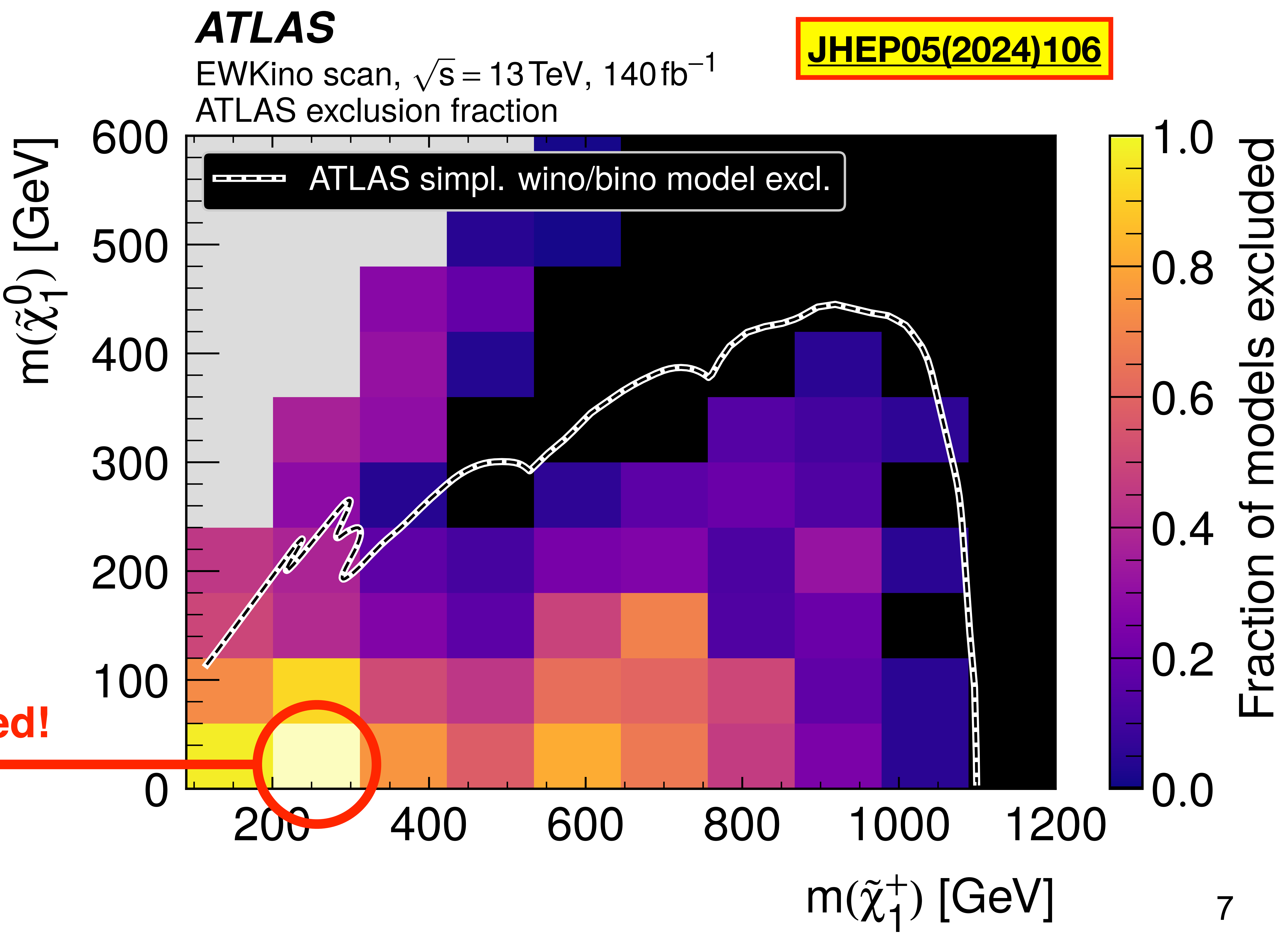


JHEP05(2024)106

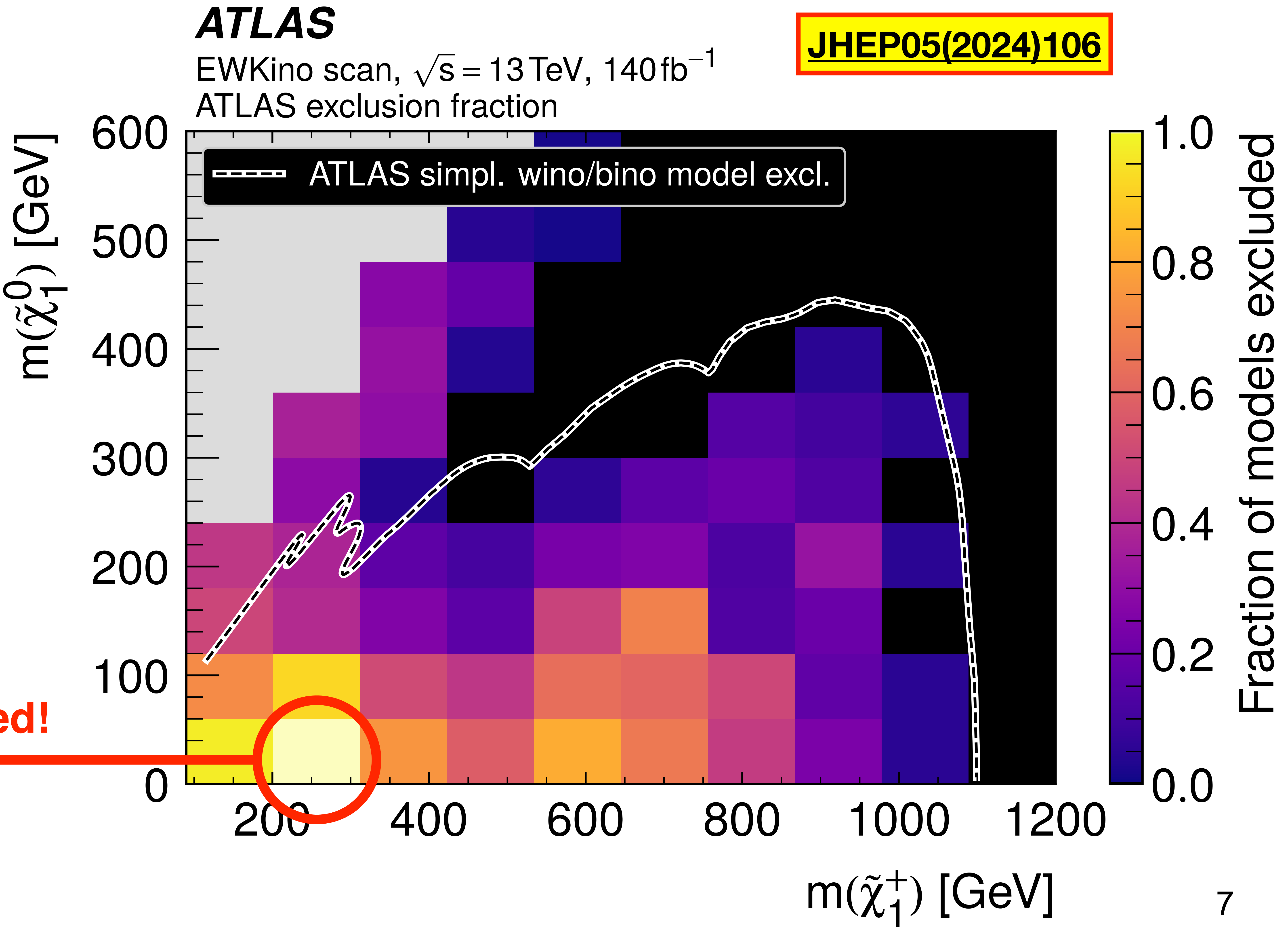
Only in *this bin* all tested model points are actually exluded!

The ATLAS pMSSM scan

Don't get depressed by simplified models and Manhattan plots…

Food for thought:

- How can we communicate the huge impact of LHC on exploring and constraining vast parameter spaces…
- …but without oversimplifying the message and depressing ourselves too much about the up-to-now absence of SUSY particles?



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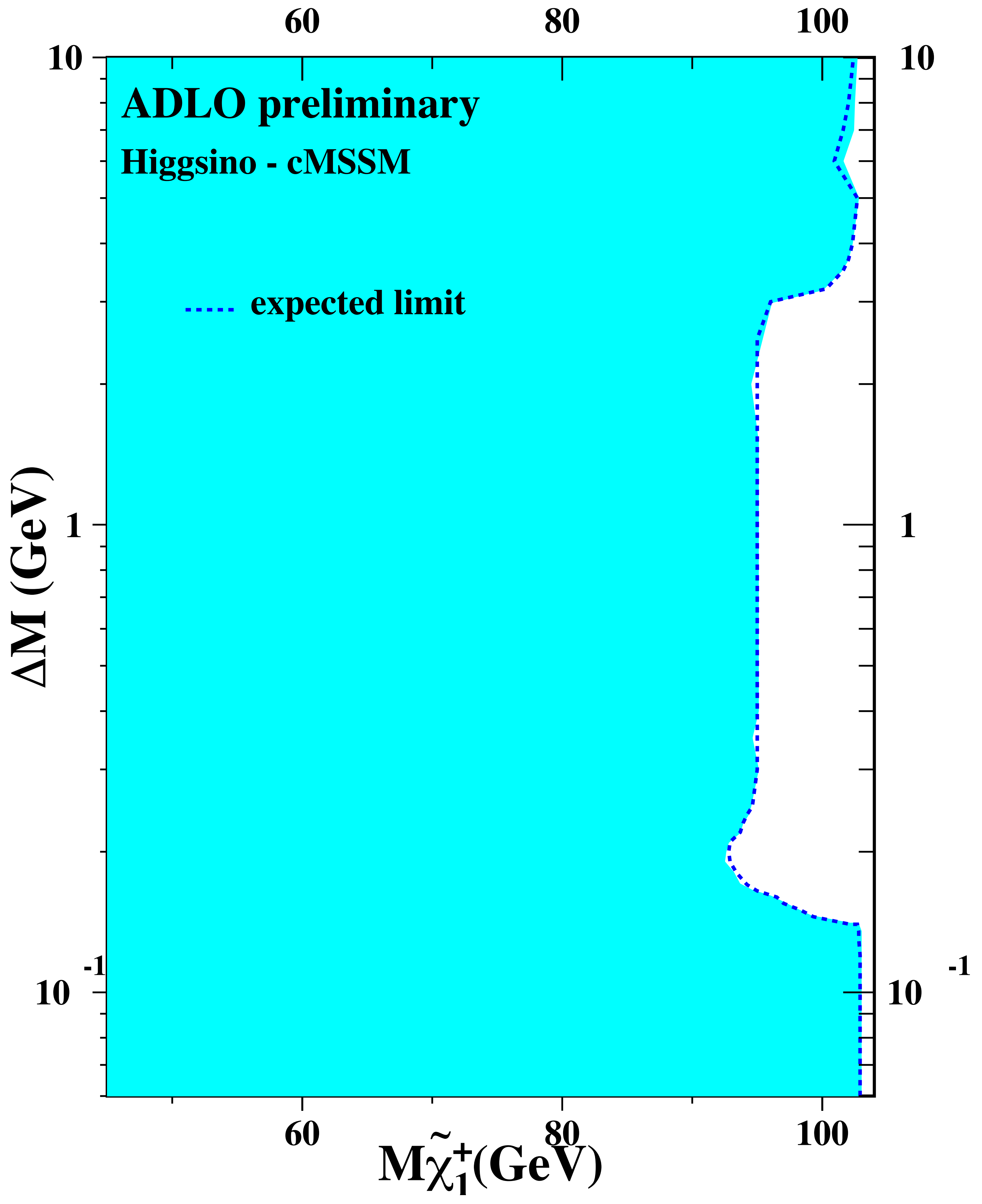
In contrast: remember LEP limit setting

Very little fineprint

Cross sections and branching ratios have been calculated in the framework of the MSSM. Two cases were considered:

1. The unification of gaugino masses at the GUT scale is assumed, leading to the relation M1 = (5/3)tan^2(theta_W) M2 at the electroweak scale, which implies that low values of DM are reached in the higgsino-like region, where $\mu << M_2$.

A mass point is marked as excluded if (and only if) it is excluded for *any choice* of the underlying not-shown parameters (within the above definition)



What do we expect HL-LHC to add here?

Beware of apples and bananas….

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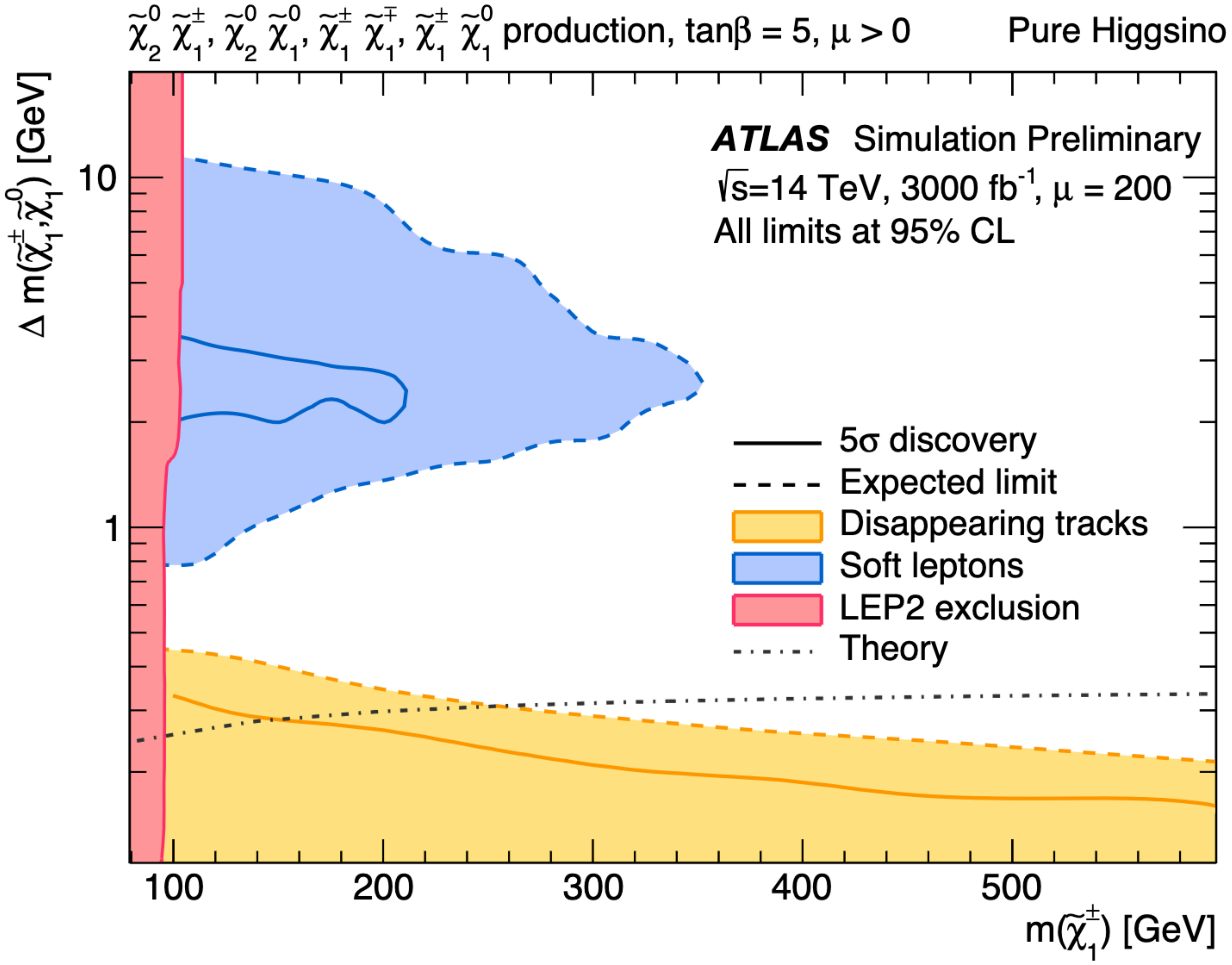

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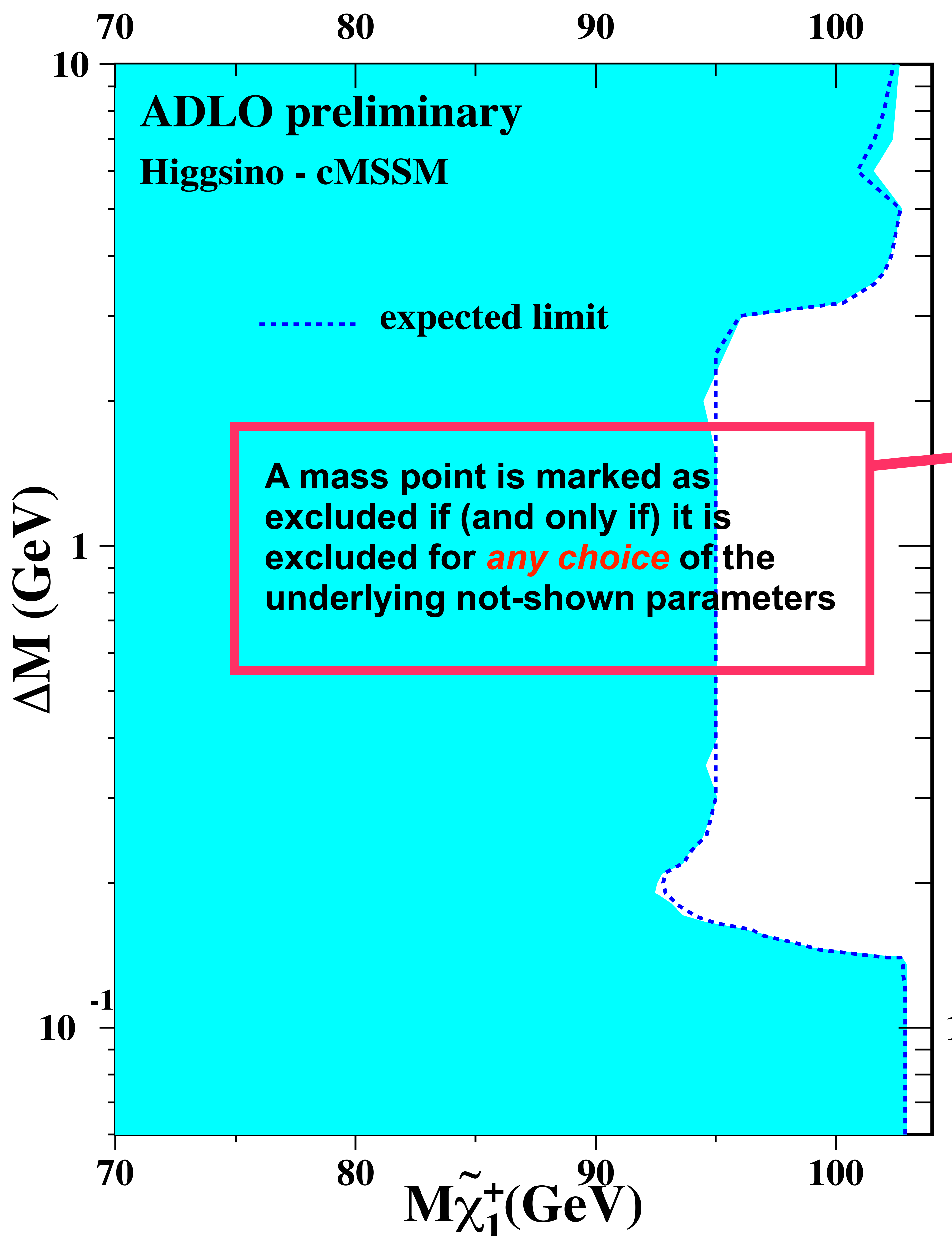

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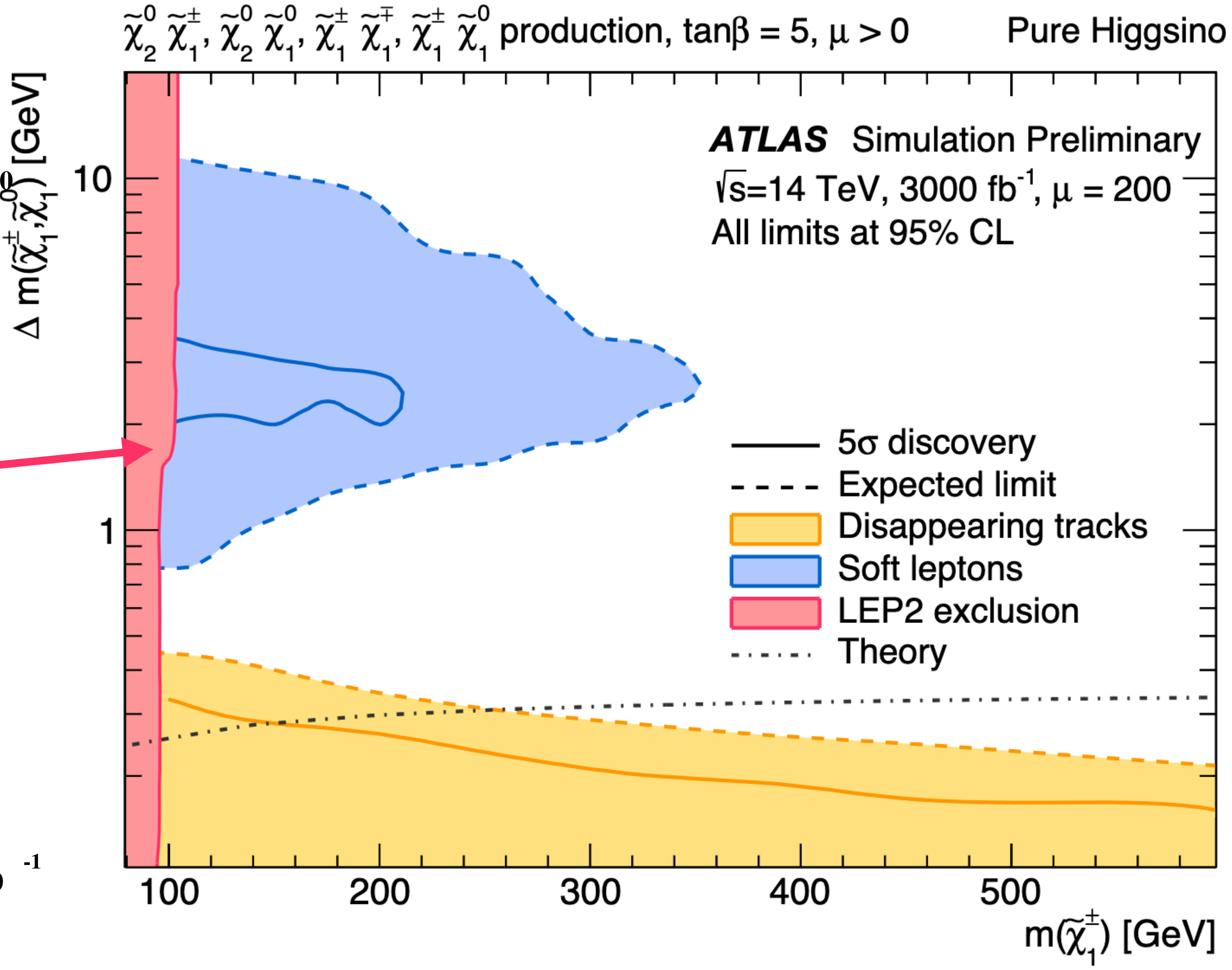

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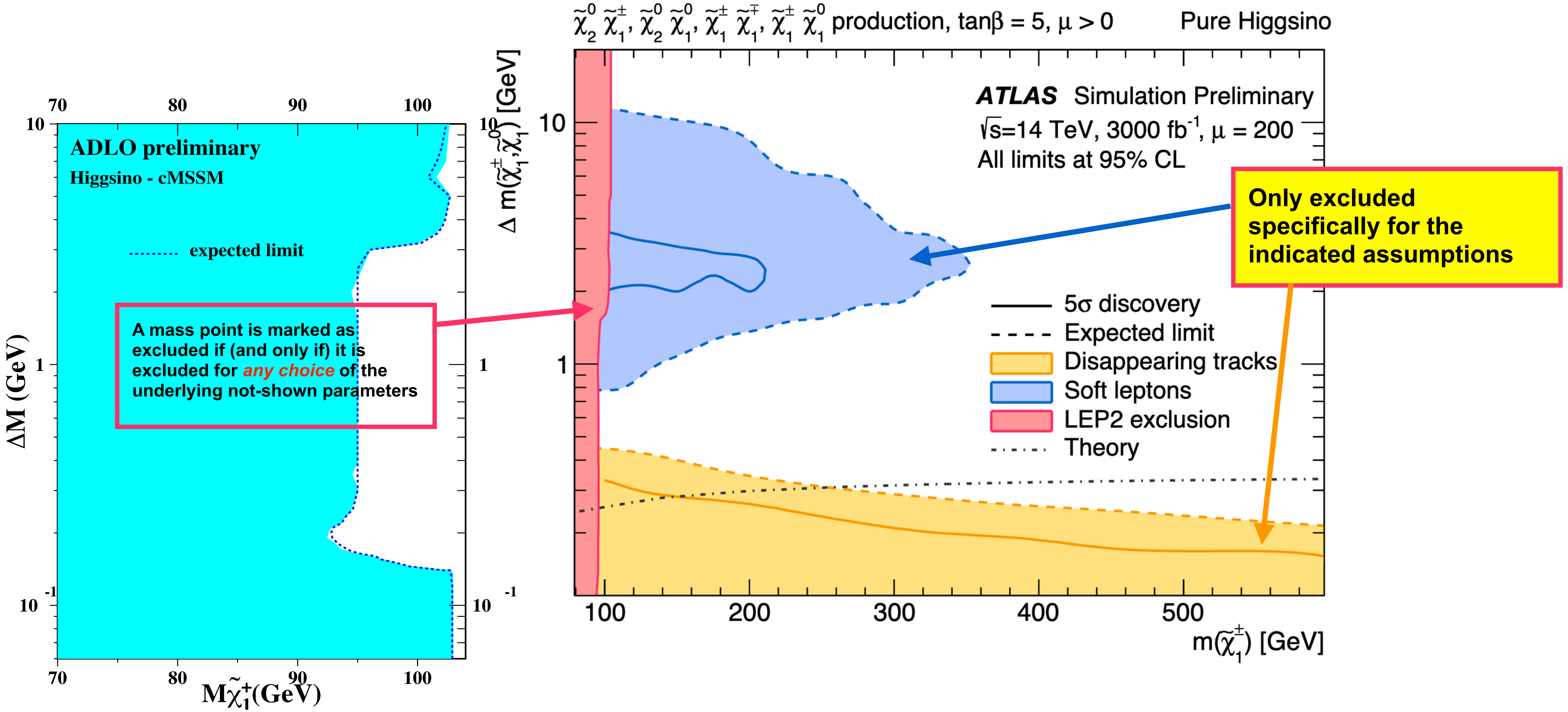

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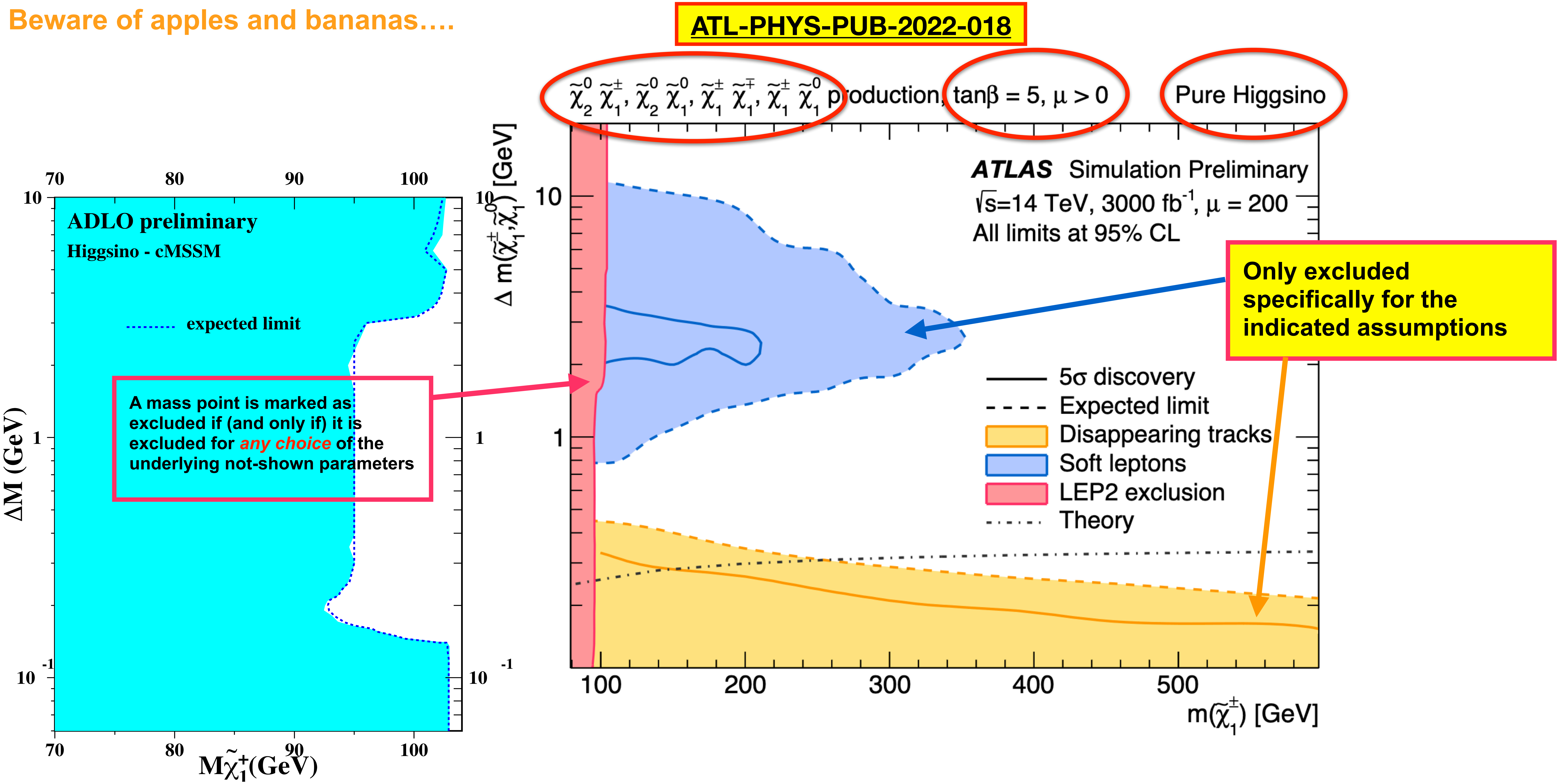

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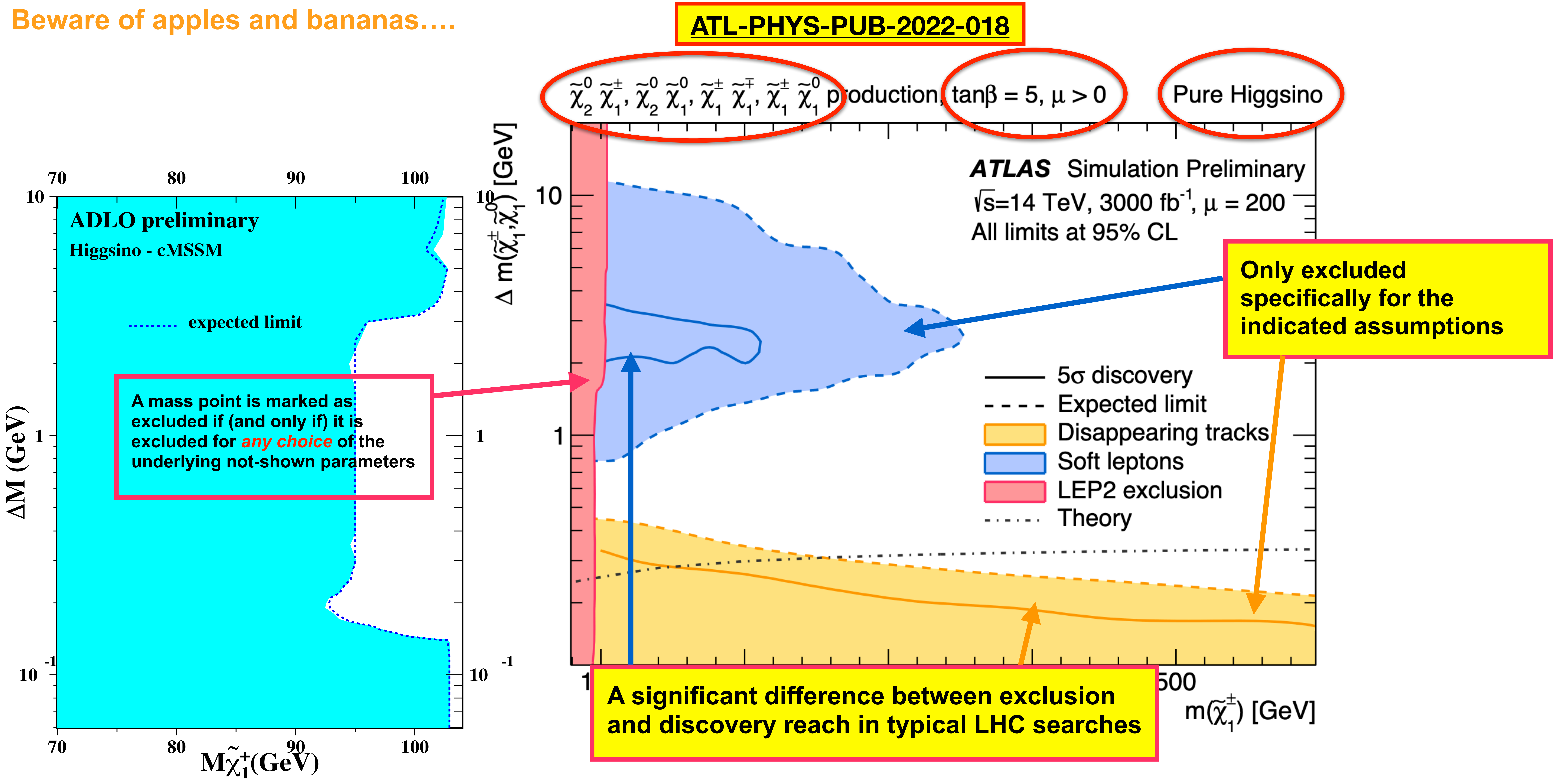

Discovery Potential and Discovery Stories

or: the dilemma in "selling" the BSM case of future machines

- There is no known no-loose theorem for direct discovery of new particles
  => we cannot "promise" discoveries
- But discussing only exclusion limits does not at all convey the excitement and opportunities of exploration
- **The bread&butter physics case of the next collider is given by using Higgs, top, Z, W as magnifying glasses to look into the early universe**
  => important progress independently of direct discoveries
- Still, there could be the possibility to actually also find new particles, even at quite low energies
  => discovery *potential*, complementary to HL-LHC
- **Snowmass 2013 had the concept of "discovery stories"**
  - a collection of hypothetical scenarios
  - in each telling the story of a hypothetical discovery, and what would follow after the discovery - how different colliders & non-collider experiments would play together to find out what the new particle actually is - and the underlying model

=> something to consider for the upcoming EPPSU?

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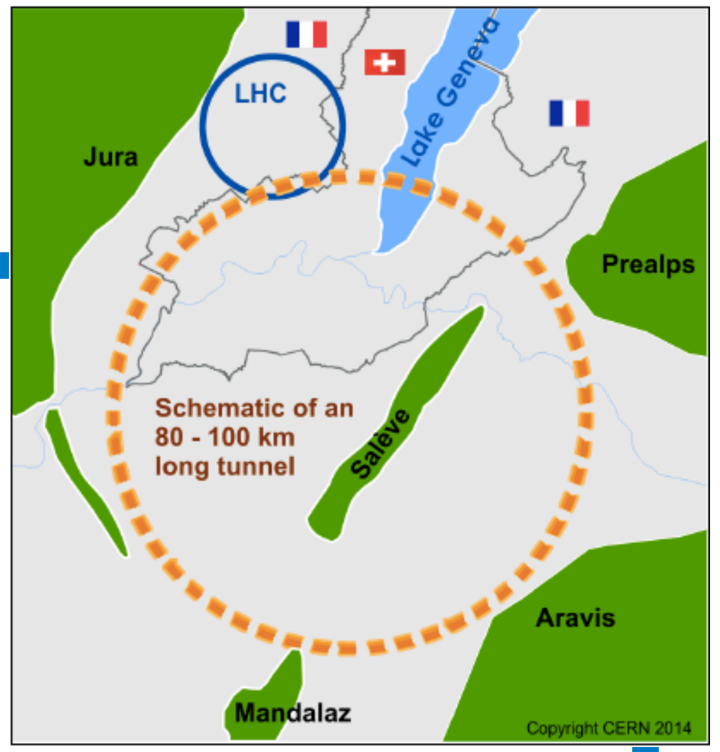
arXiv:1311.0299

▼ 1.3 Discovery Stories
1.3.1 Higgs Beyond the Standard Model
▶ 1.3.2 WIMP Dark Matter
▶ 1.3.3 New gauge bosons
1.3.4 Discovery in Jets + MET: `Simple' Supersymmetry
1.3.5 SUSY with a light stop
1.3.6 Discovery in Leptons+MET
1.3.7 R-parity violating SUSY
1.3.8 Long-lived Heavy Particles
1.3.9 Top Partners
1.3.10 Fermion Compositeness
1.3.11 Warped Extra Dimensions and Flavor
▶ 1.3.12 `Only' the Standard Model

Direct SUSY searches at future e+e- colliders

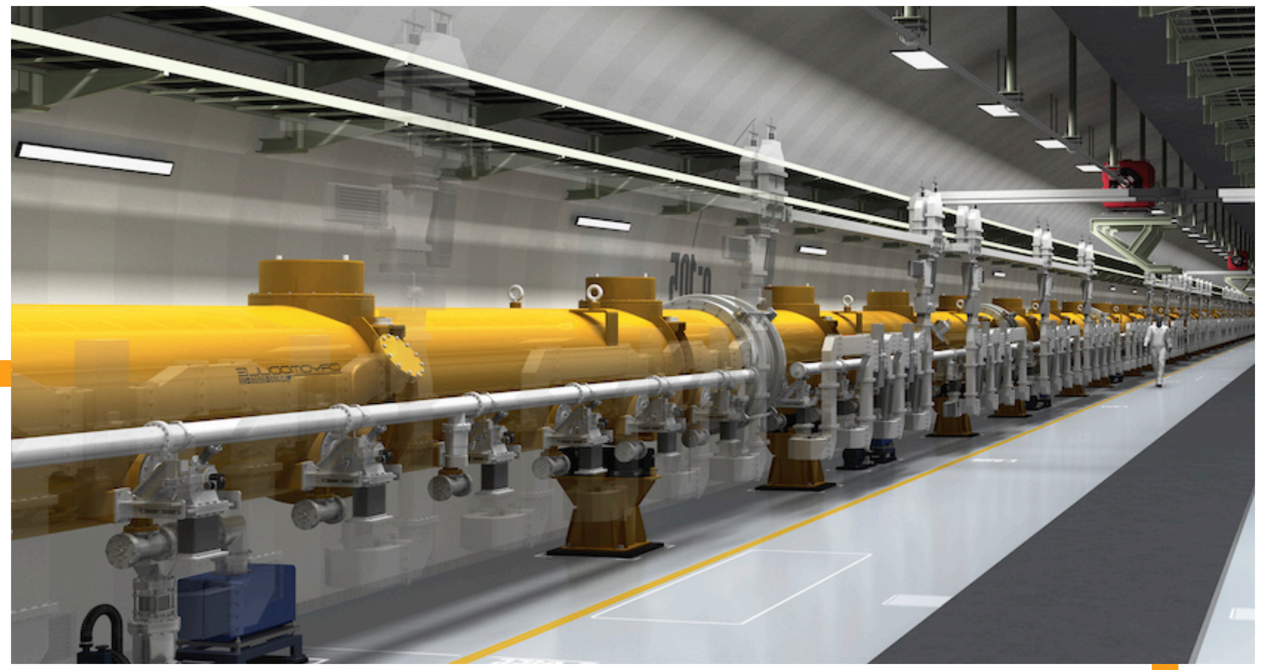
Two complementary approaches

Each has its advantages



Circular e+e- Colliders

- FCCee, CEPC
- length 250 GeV: 90…100km
- high luminosity & power efficiency at **low energies, limited to ~365 GeV**
- **multiple interaction regions**
- very clean: little beamstrahlung etc



Linear Colliders

- ILC, CLIC, C^3, …
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- **longitudinally spin-polarised beam(s)**

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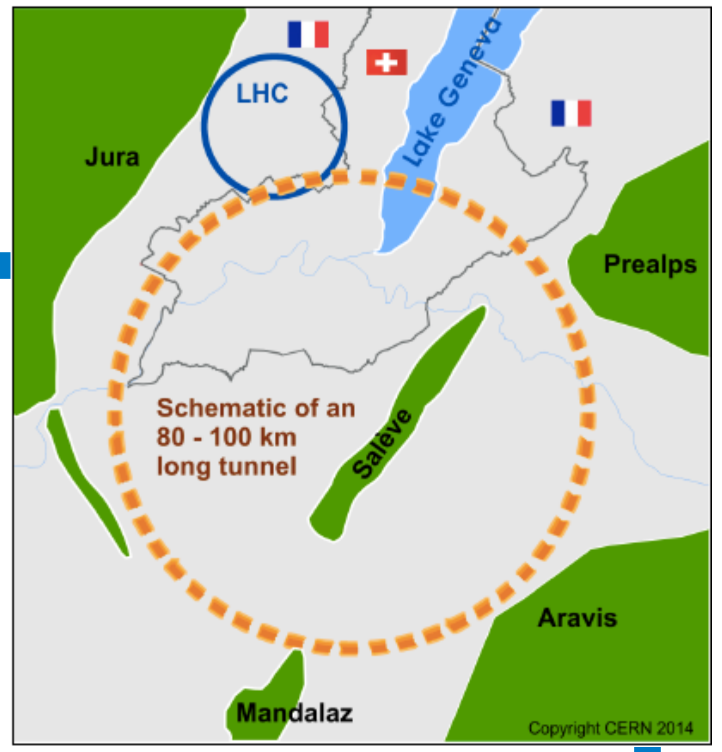

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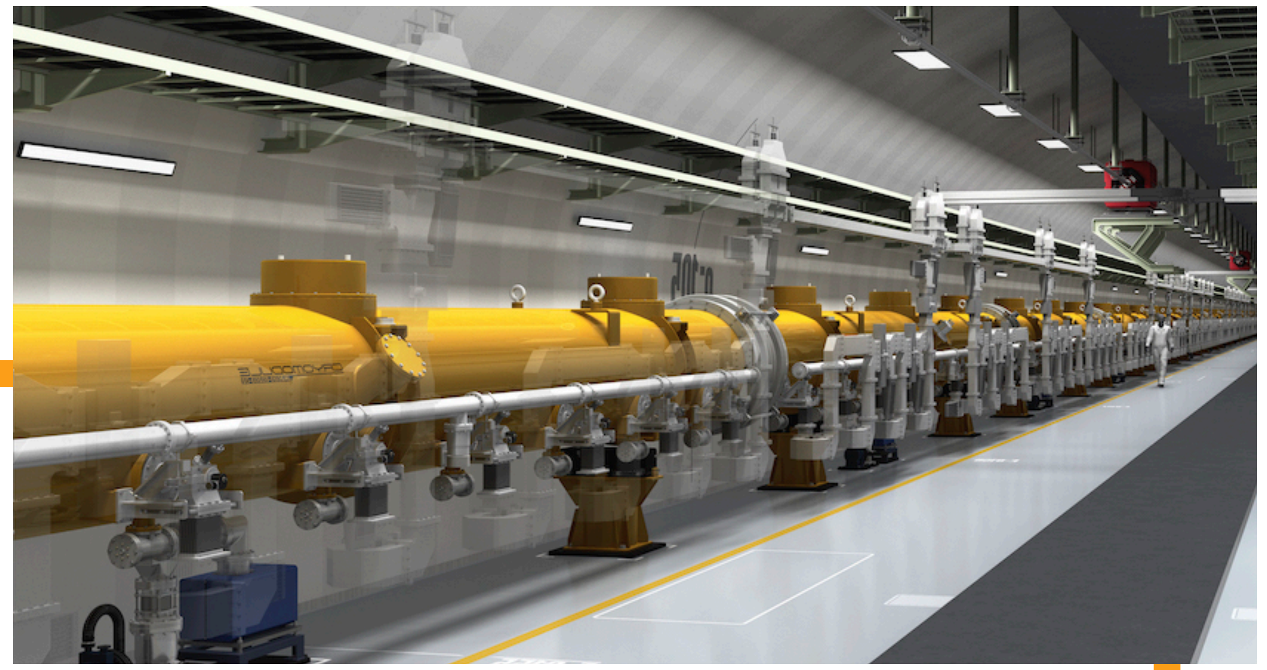
Long-term vision: re-use of tunnel for pp collider

- technical and financial feasibility of required magnets still a challenge



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Long-term upgrades: energy extendability

- same technology: by increasing length
- **or by replacing accelerating structures with advanced technologies**
  - RF cavities with high gradient
  - plasma acceleration ?

Physics benefits of polarised beams

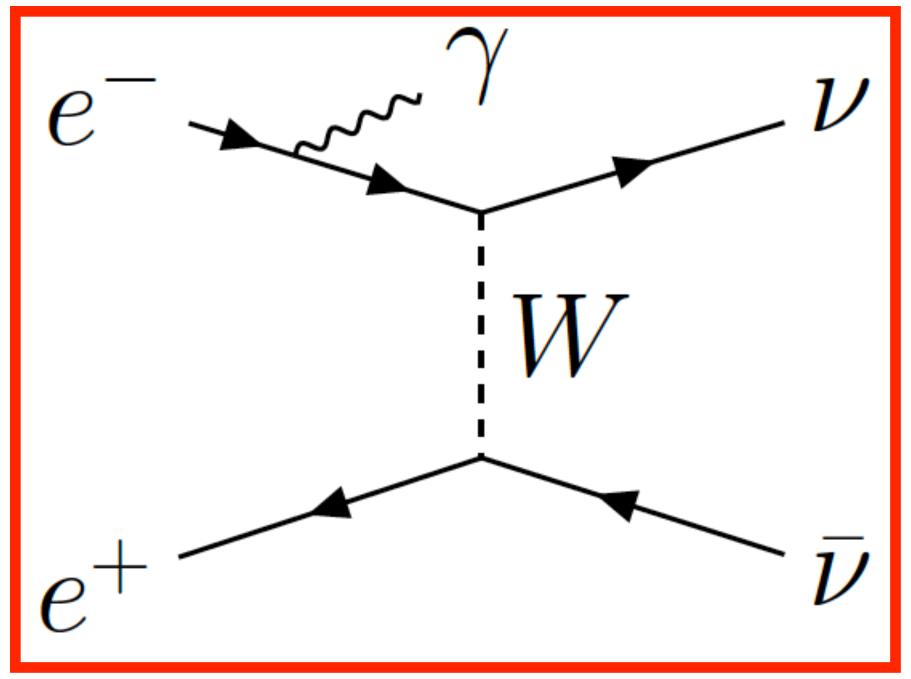
Much more than statistics - especially for SUSY!!!

General references on polarised e^+e^- physics:

- **arXiv:1801.02840**
- **Phys. Rept. 460 (2008) 131-243**

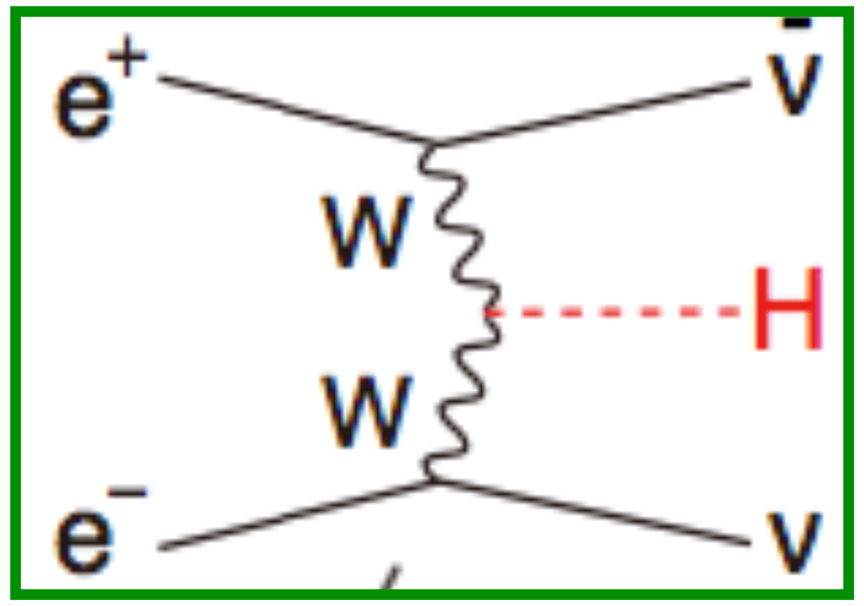
background suppression:

- $e^+e^- \to WW$ / $\nu_e\nu_e$
  strongly P-dependent
  since t-channel only
  for $e^-_L e^+_R$



signal enhancement:

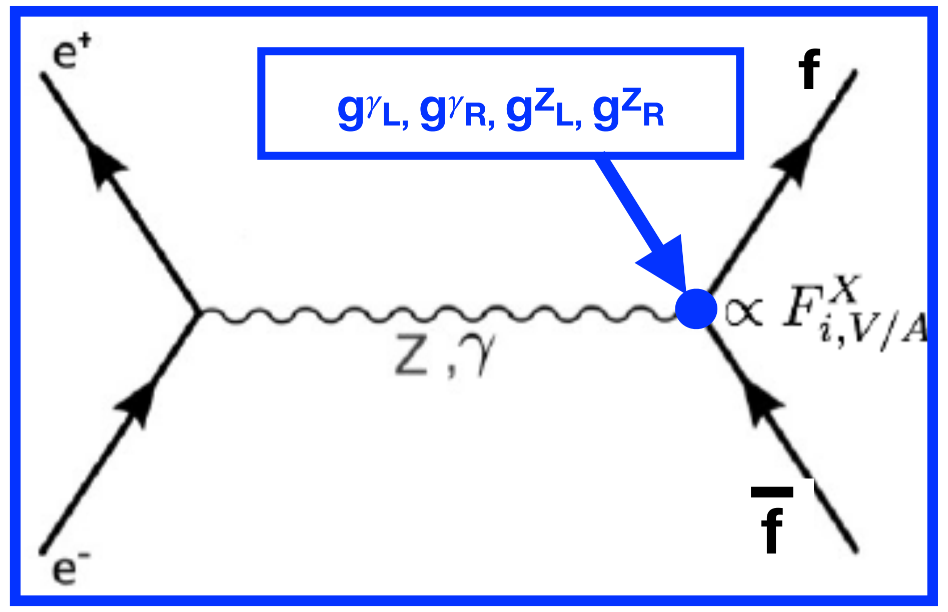
- Higgs production
  in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in
  couplings to left- and
  right-handed fermions



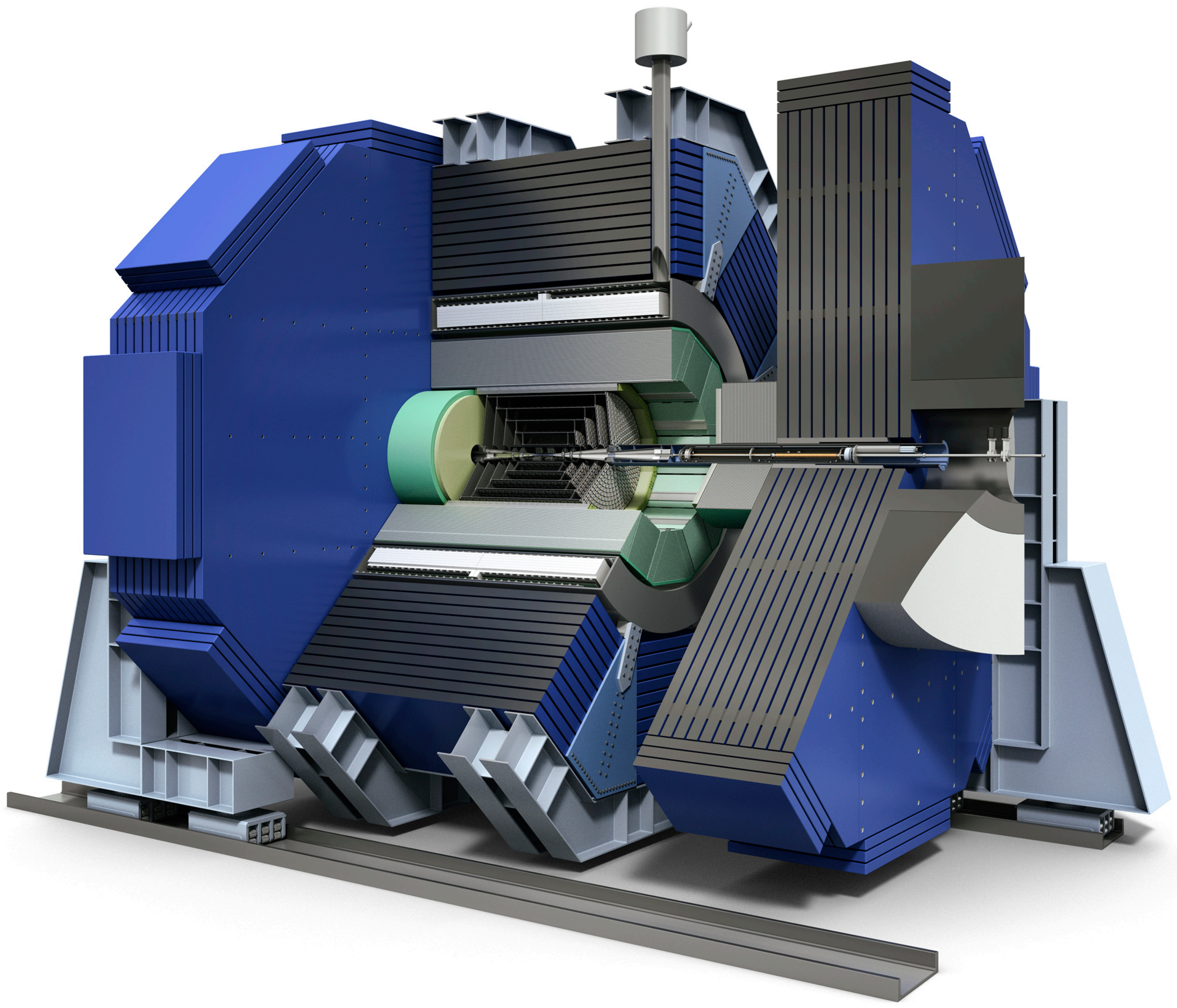
- BSM:
  chiral structure unknown, needs to be determined!

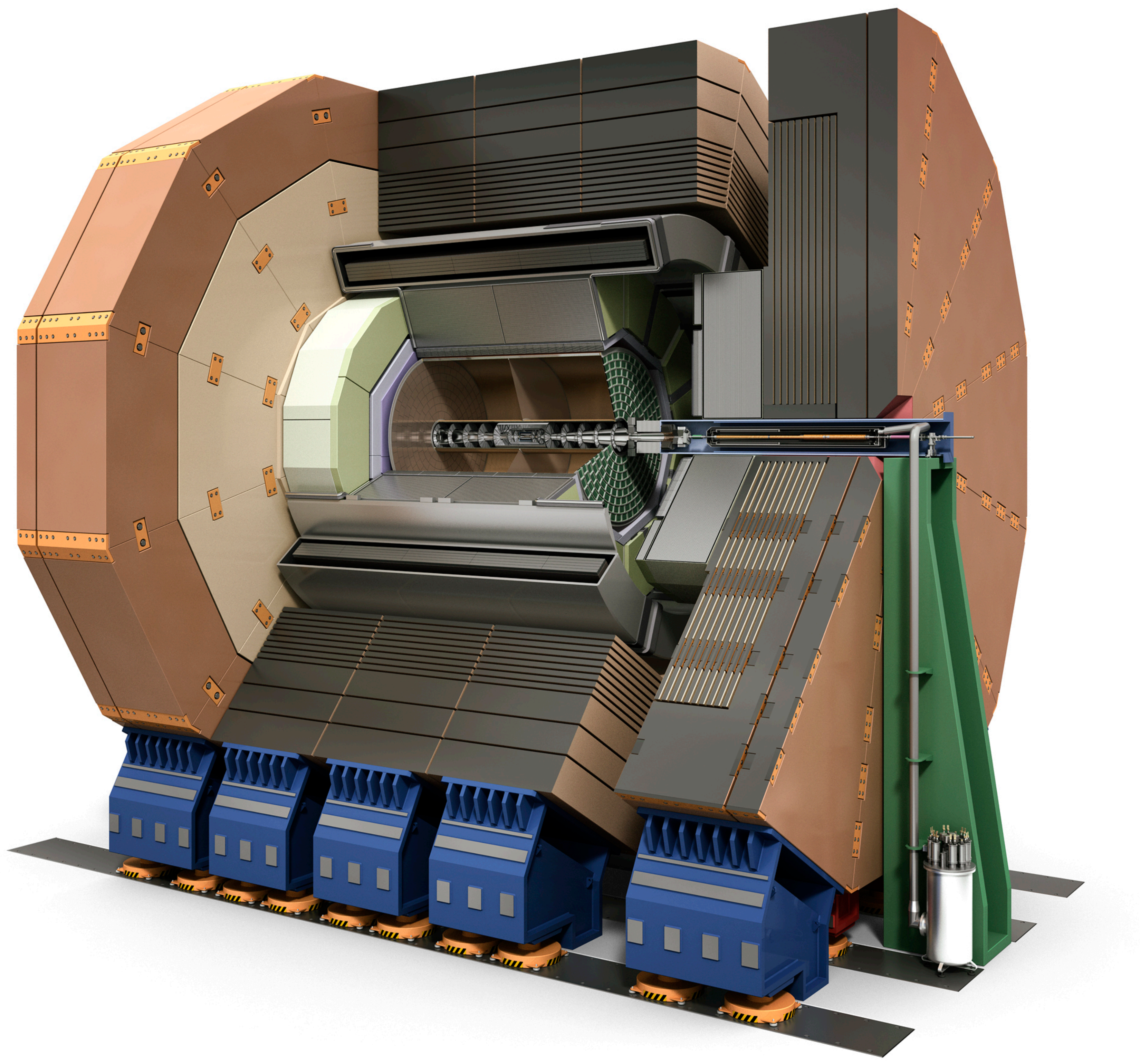
redundancy & control of systematics:

- "wrong" polarisation yields "signal-free" control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

Higgs Factory Detector Concepts

for linear & circular





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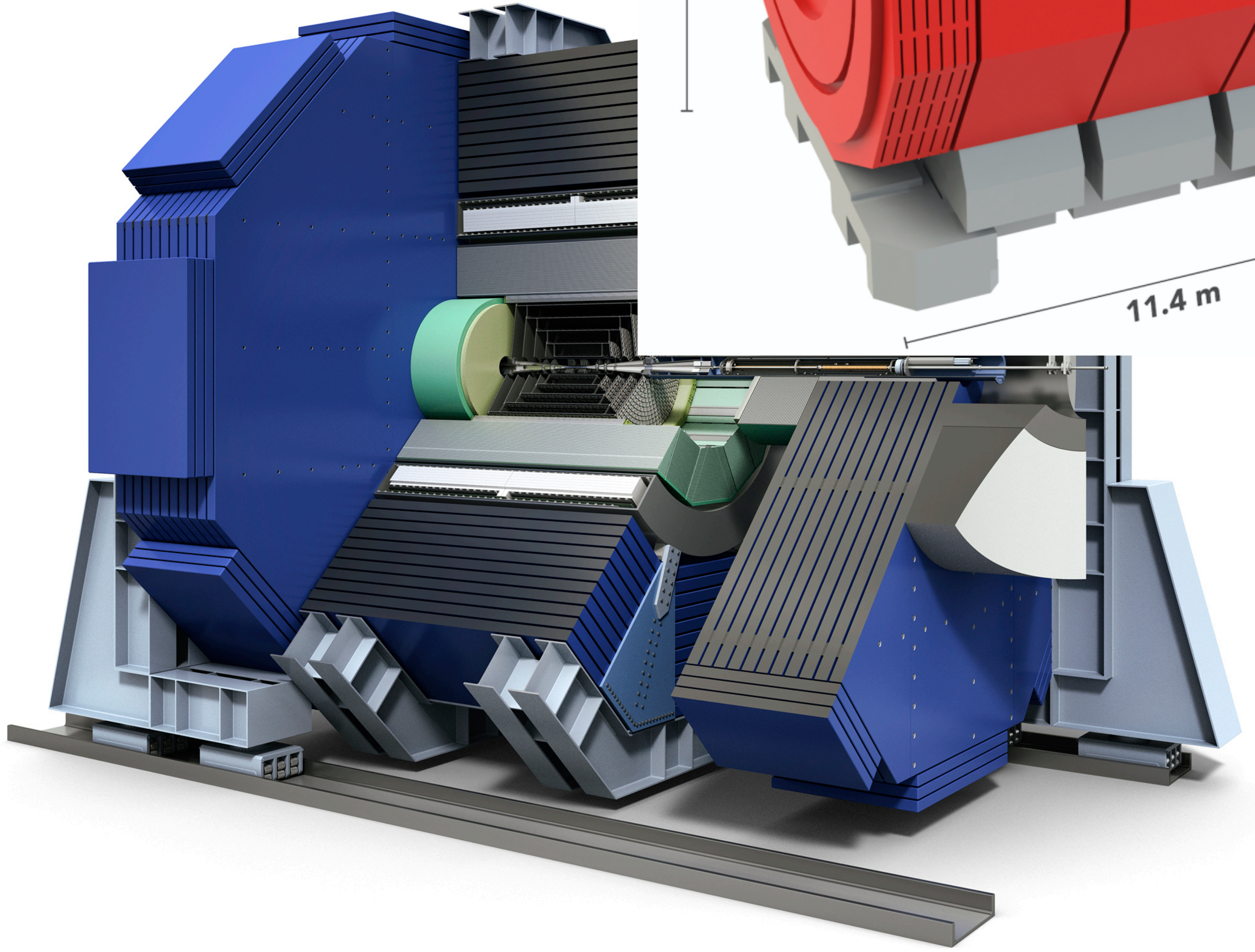

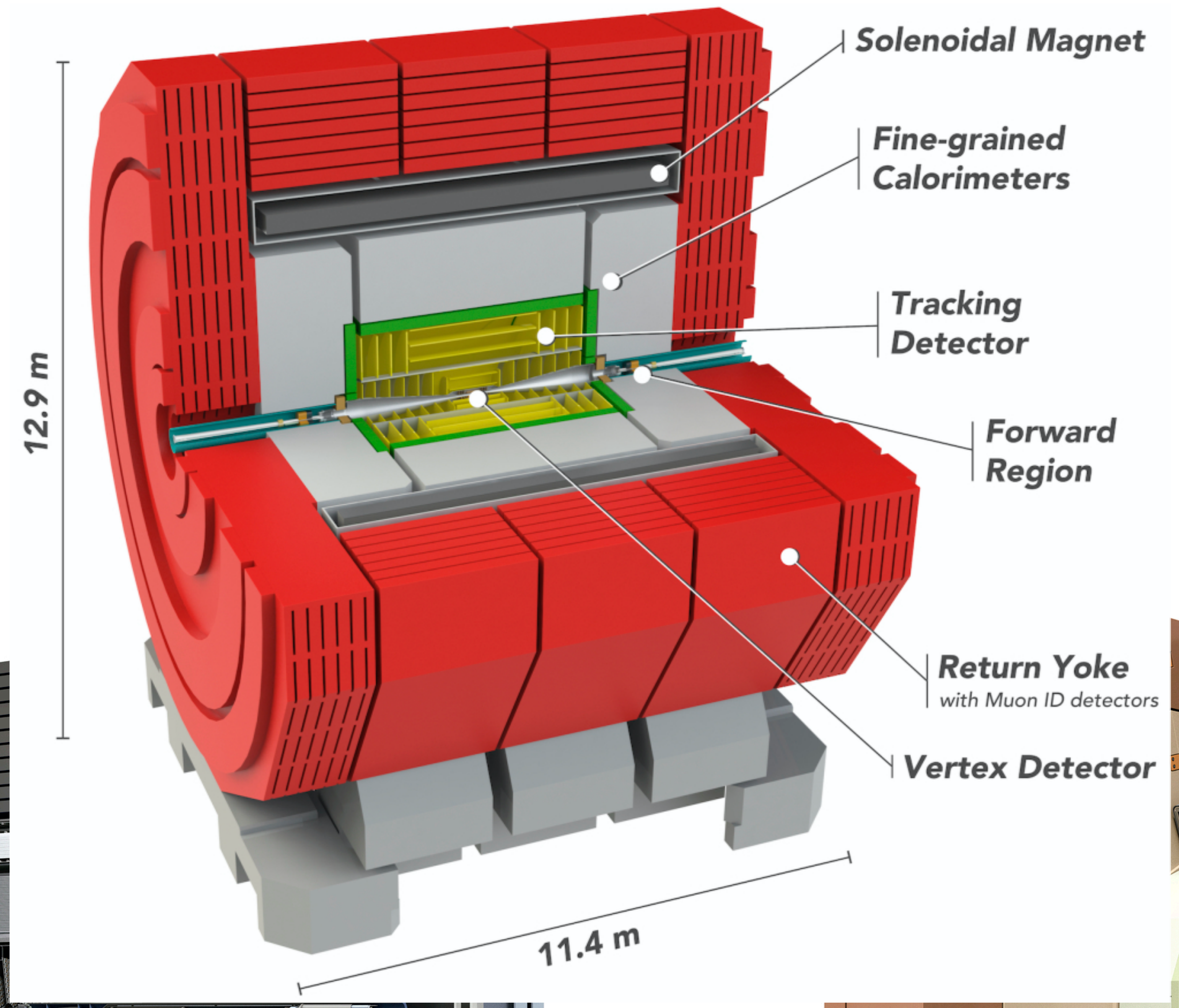

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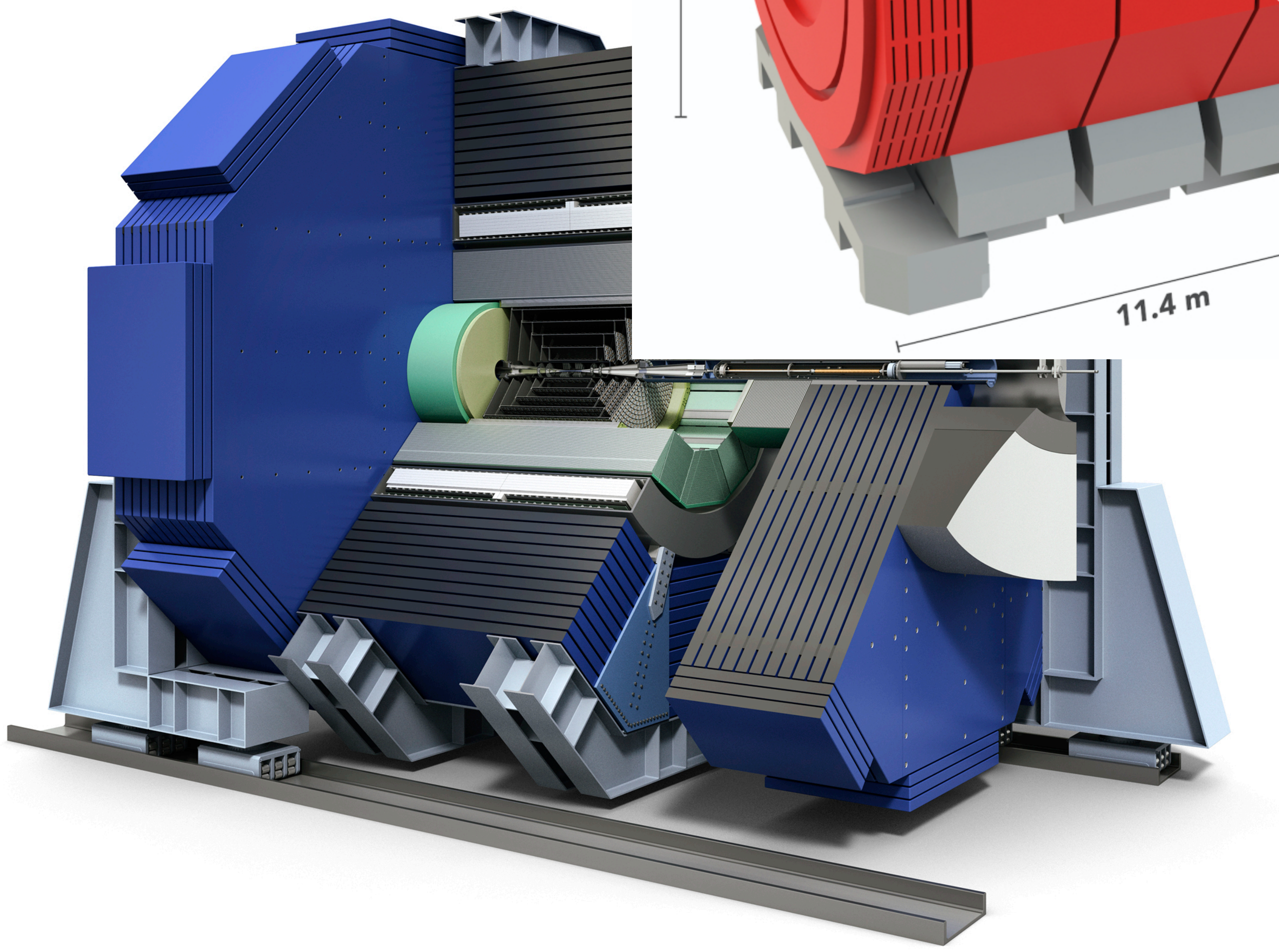

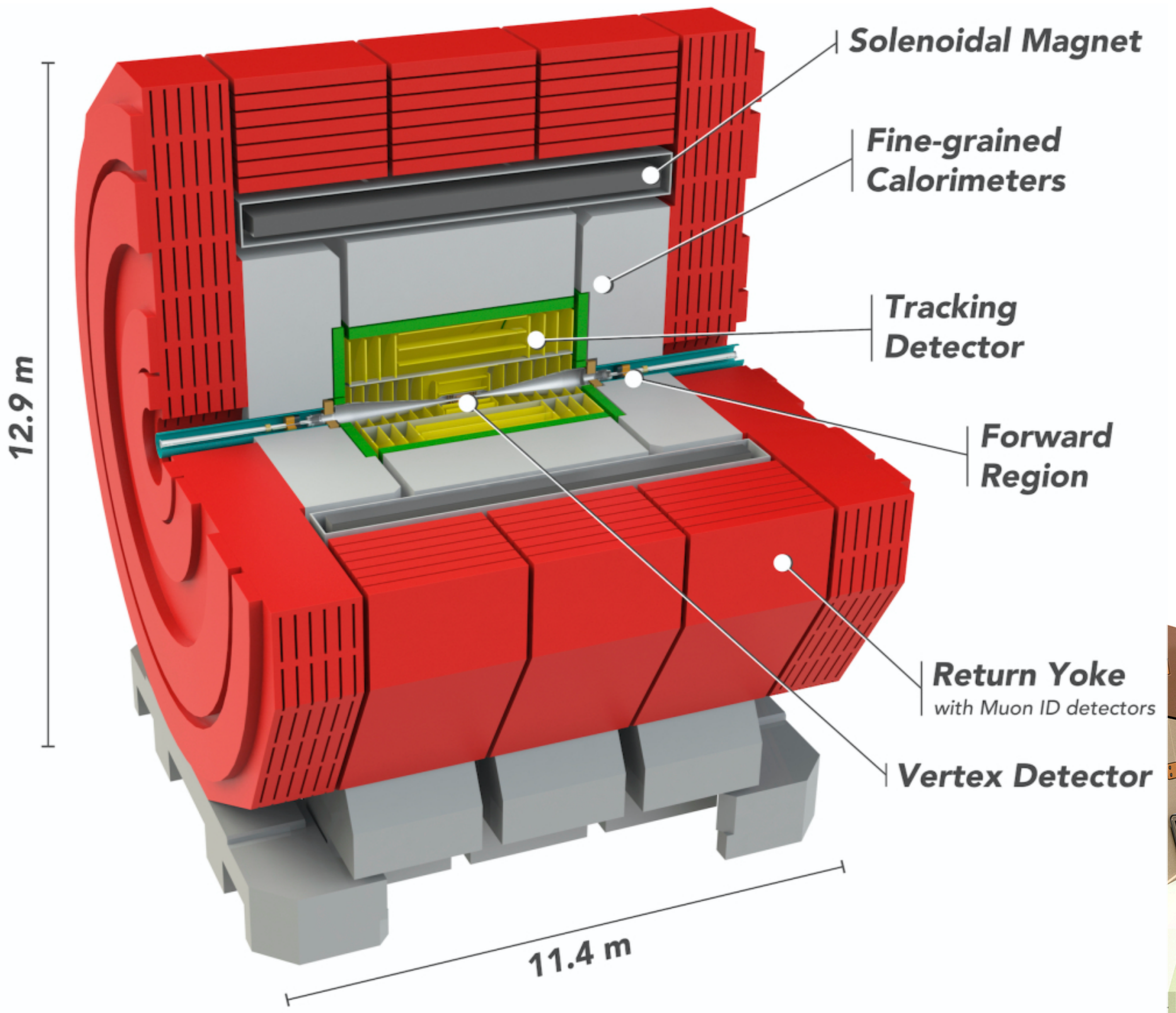

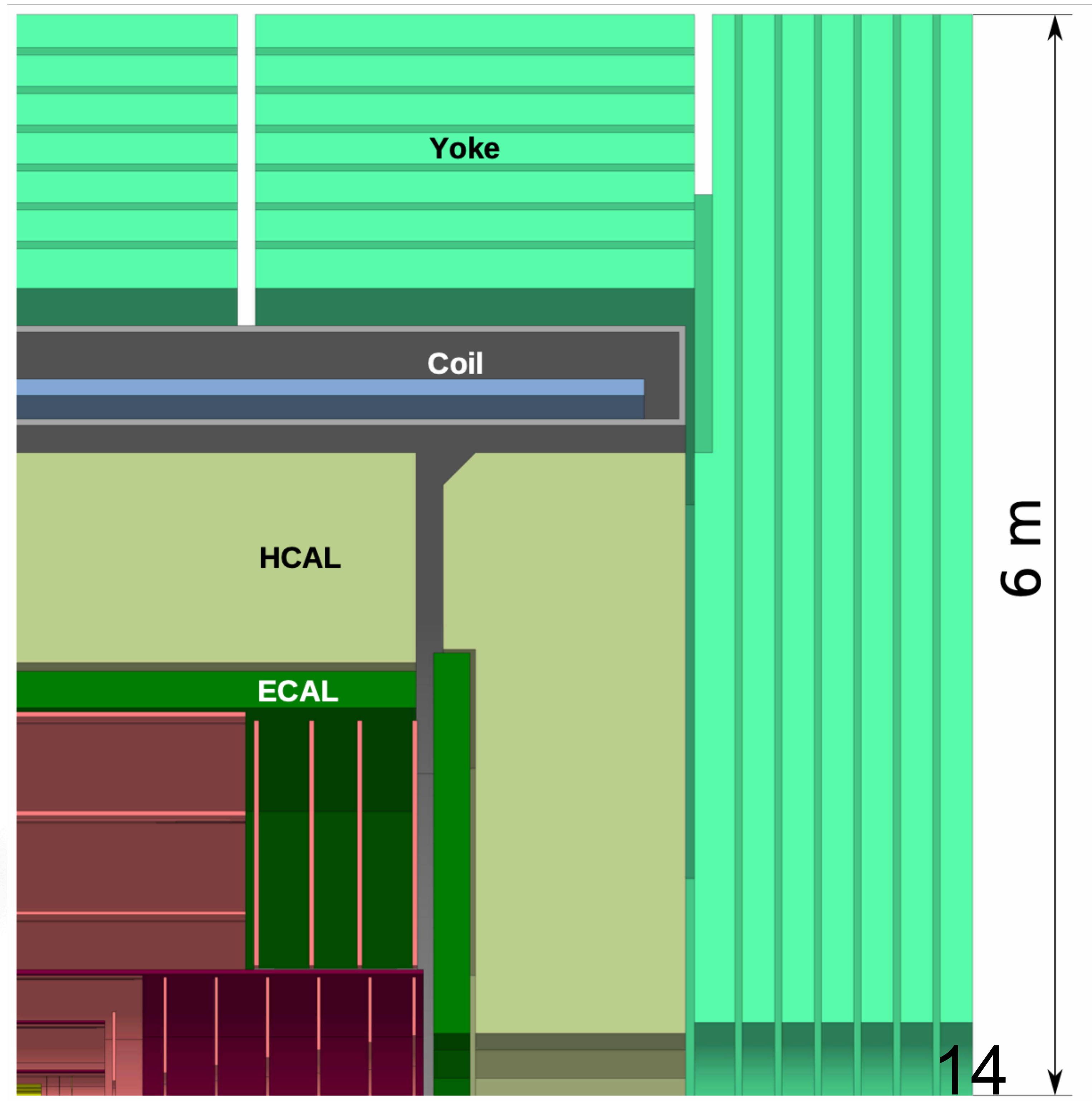

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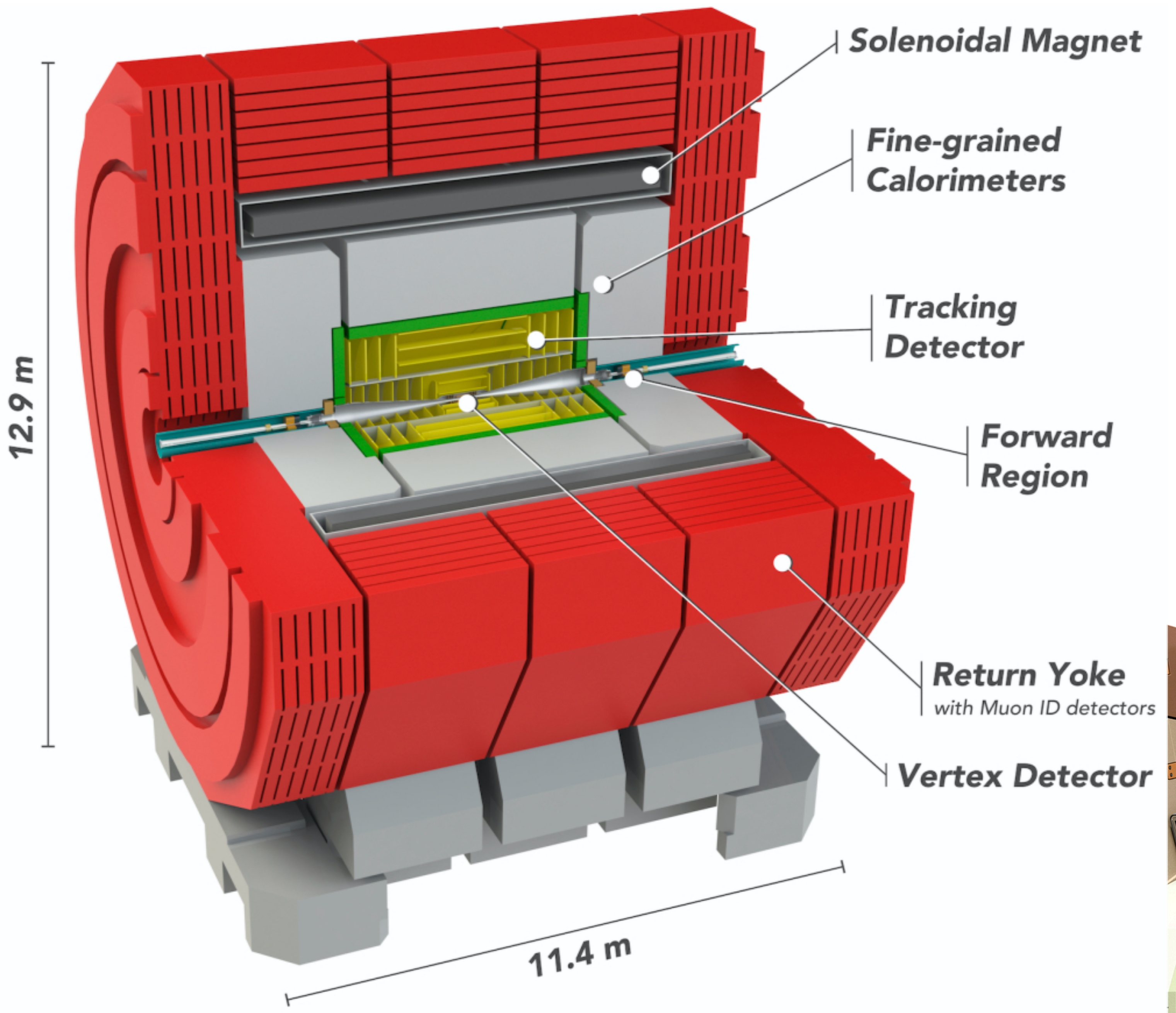

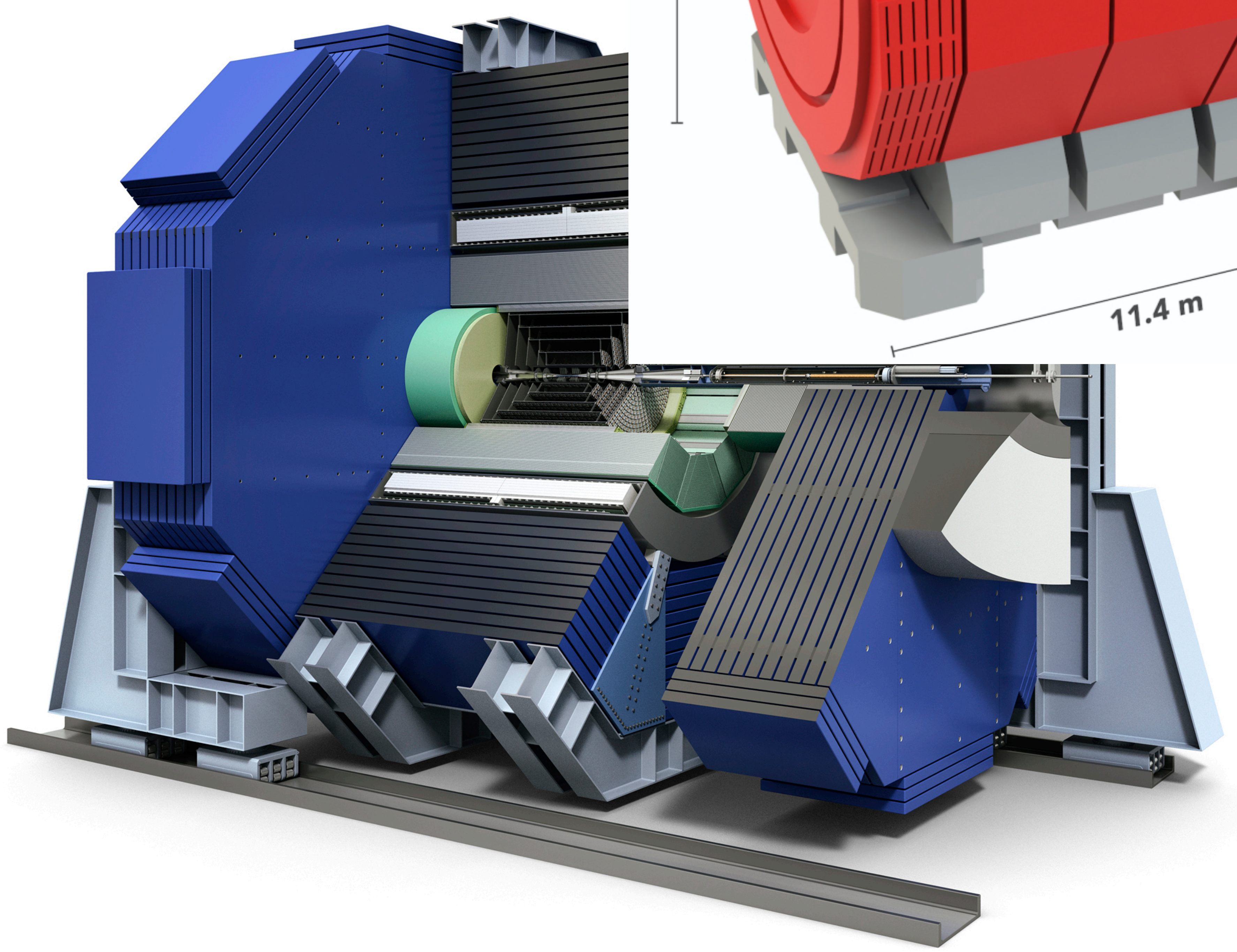

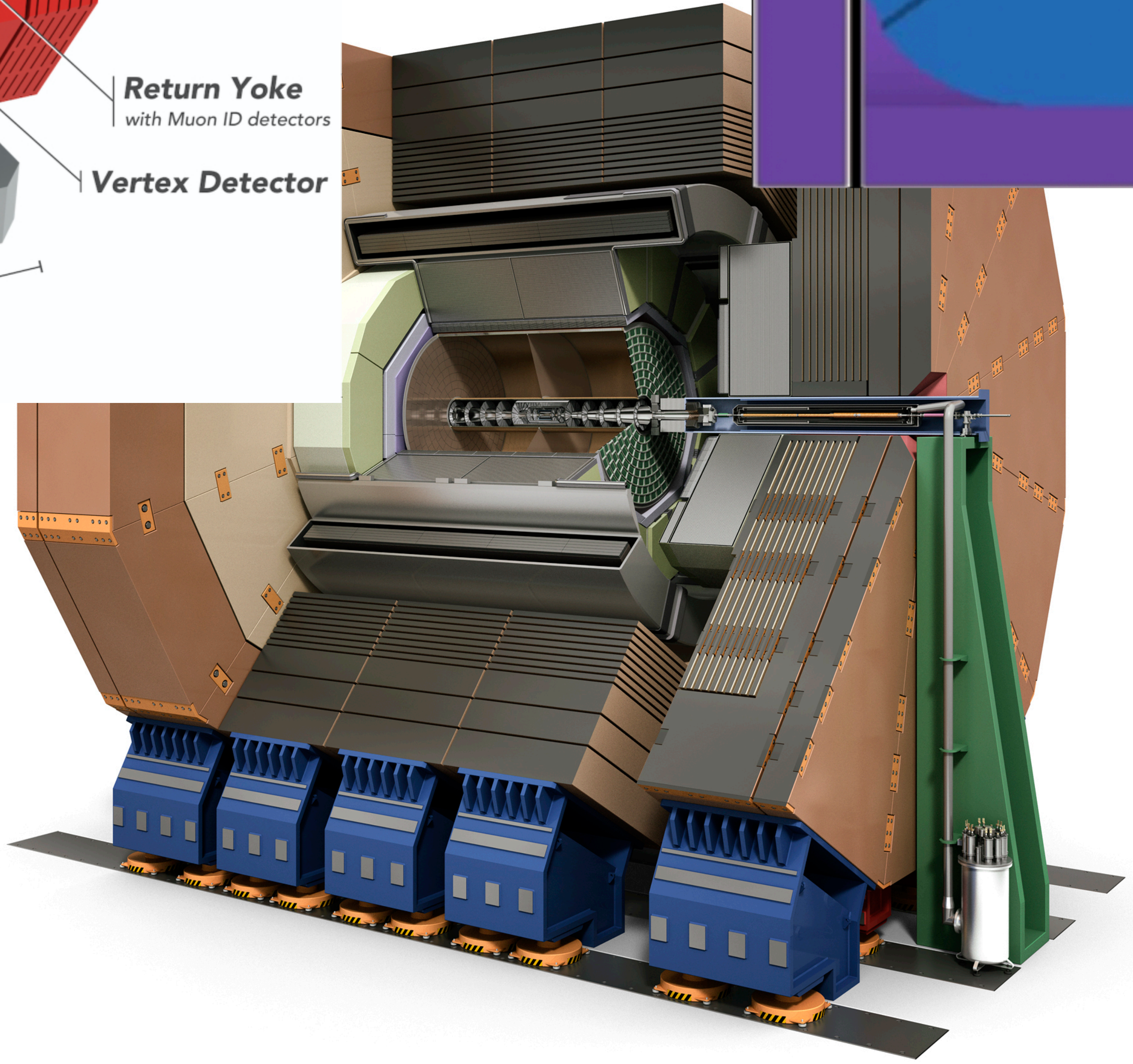

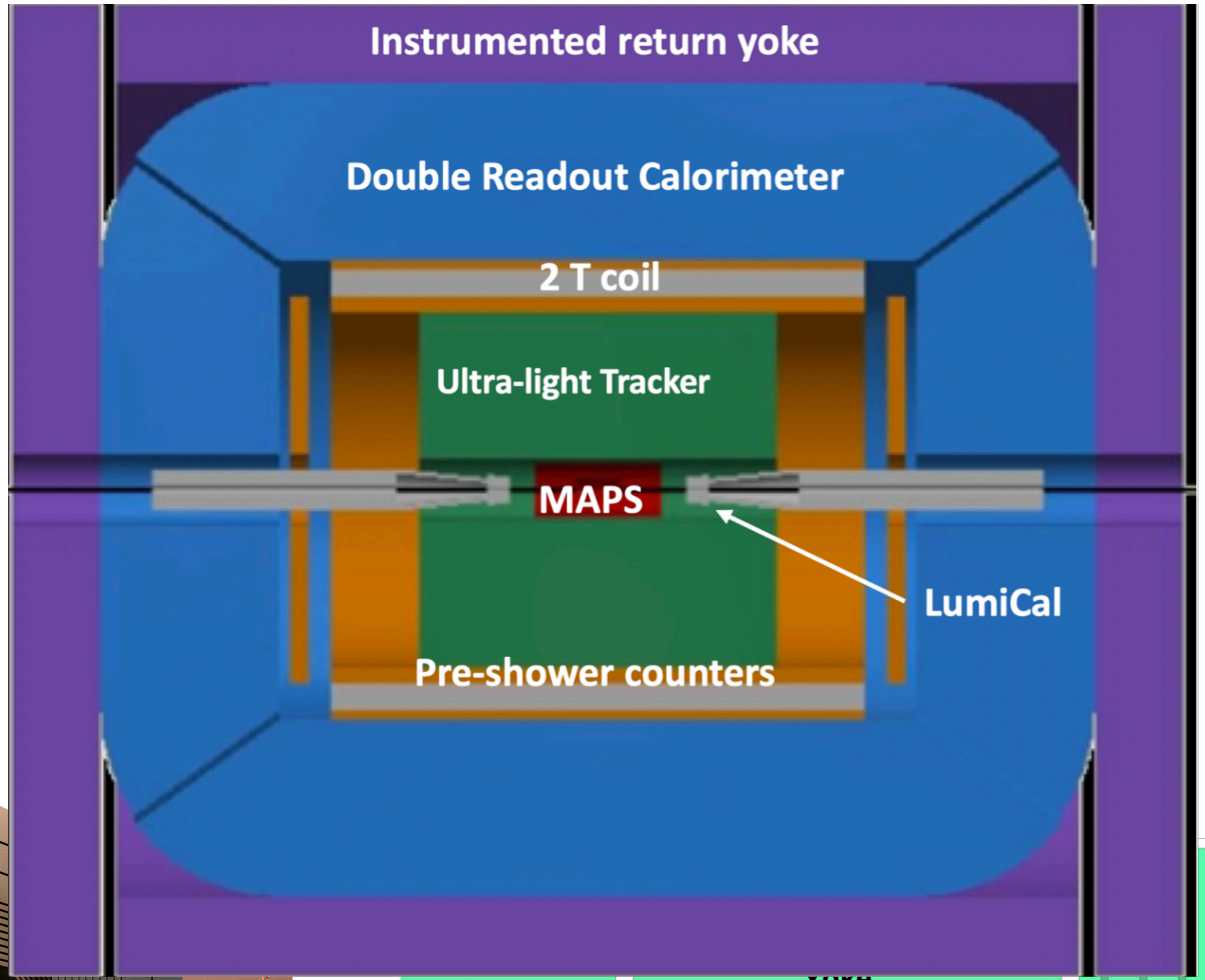

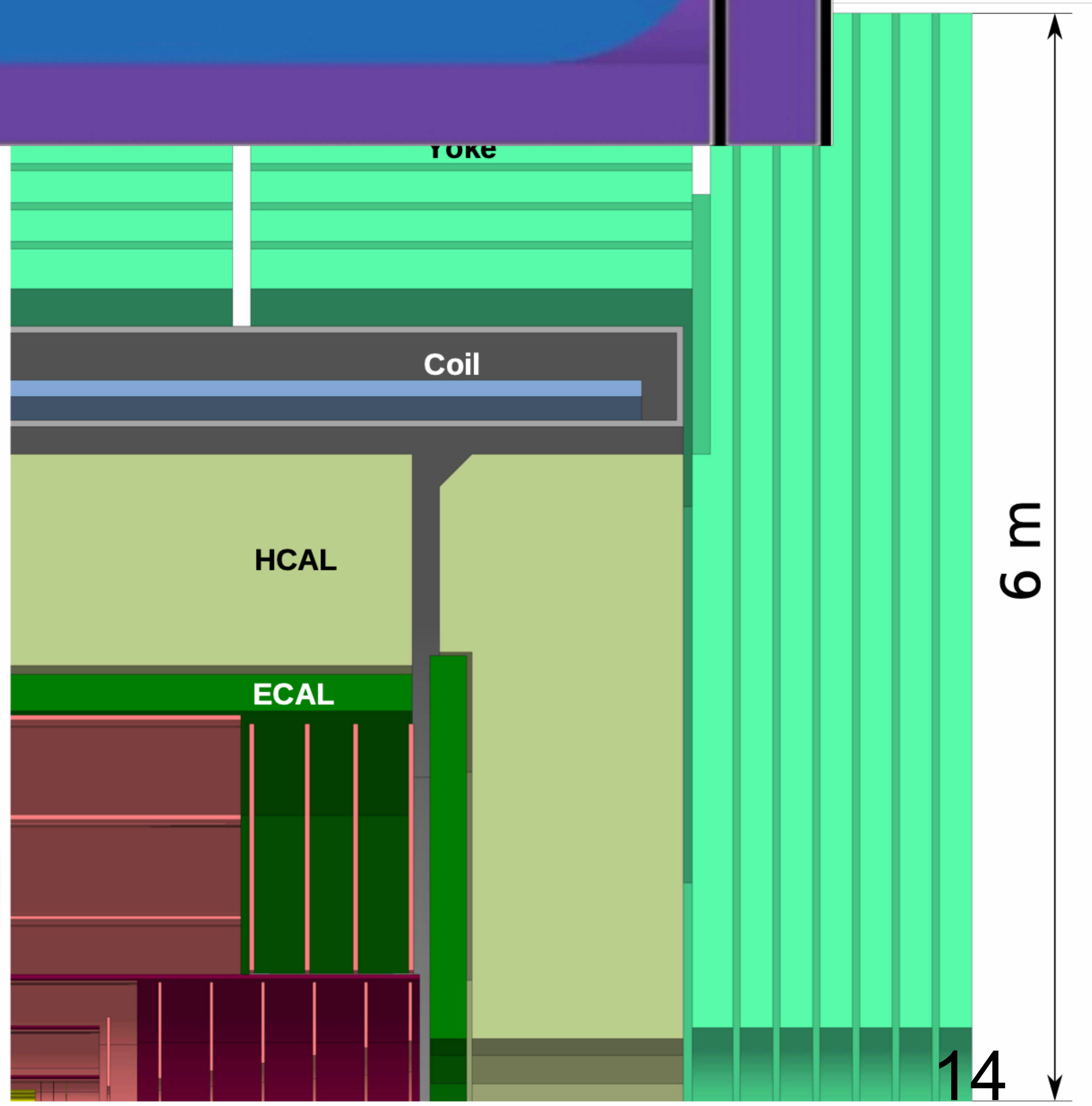

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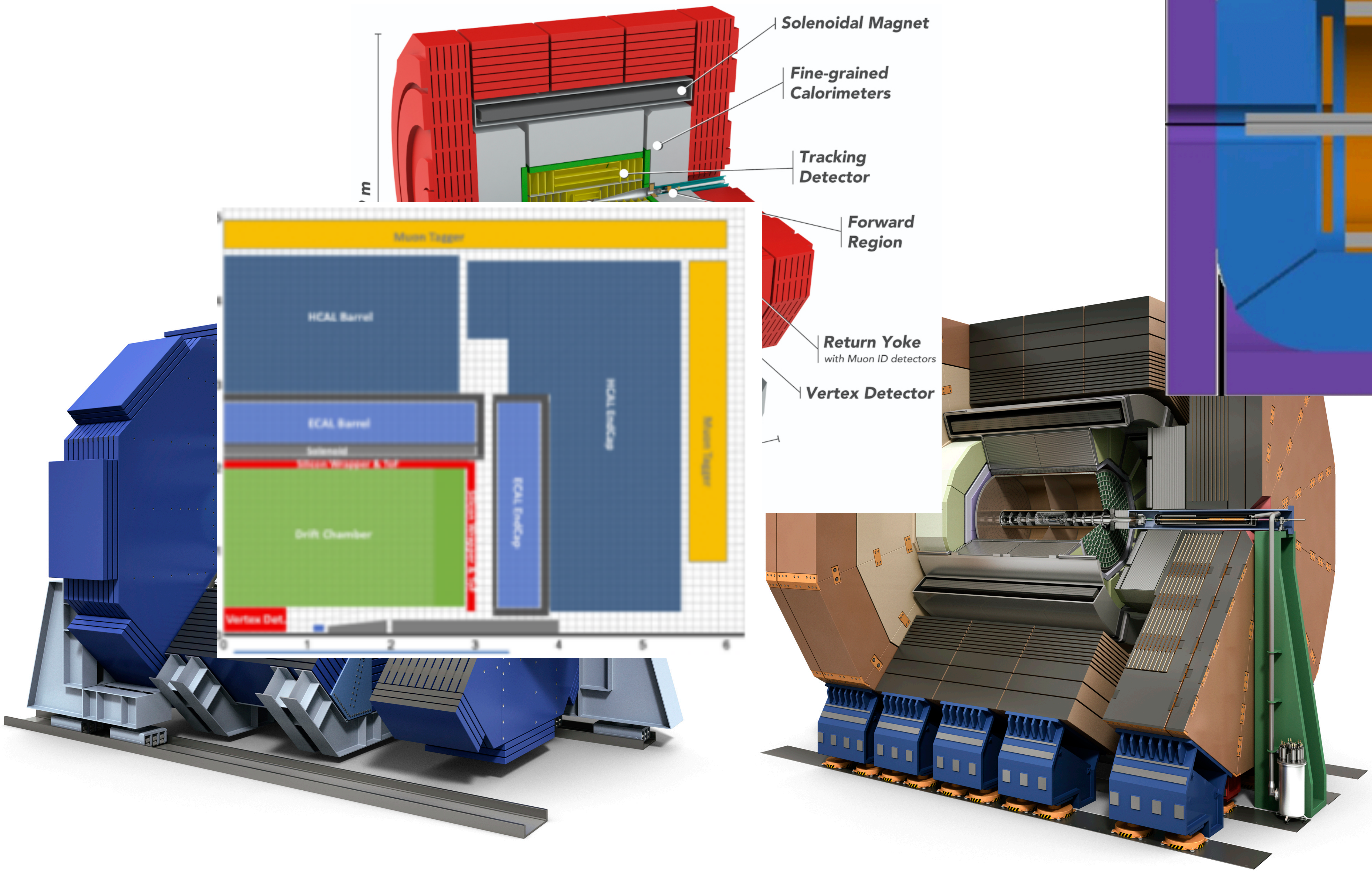

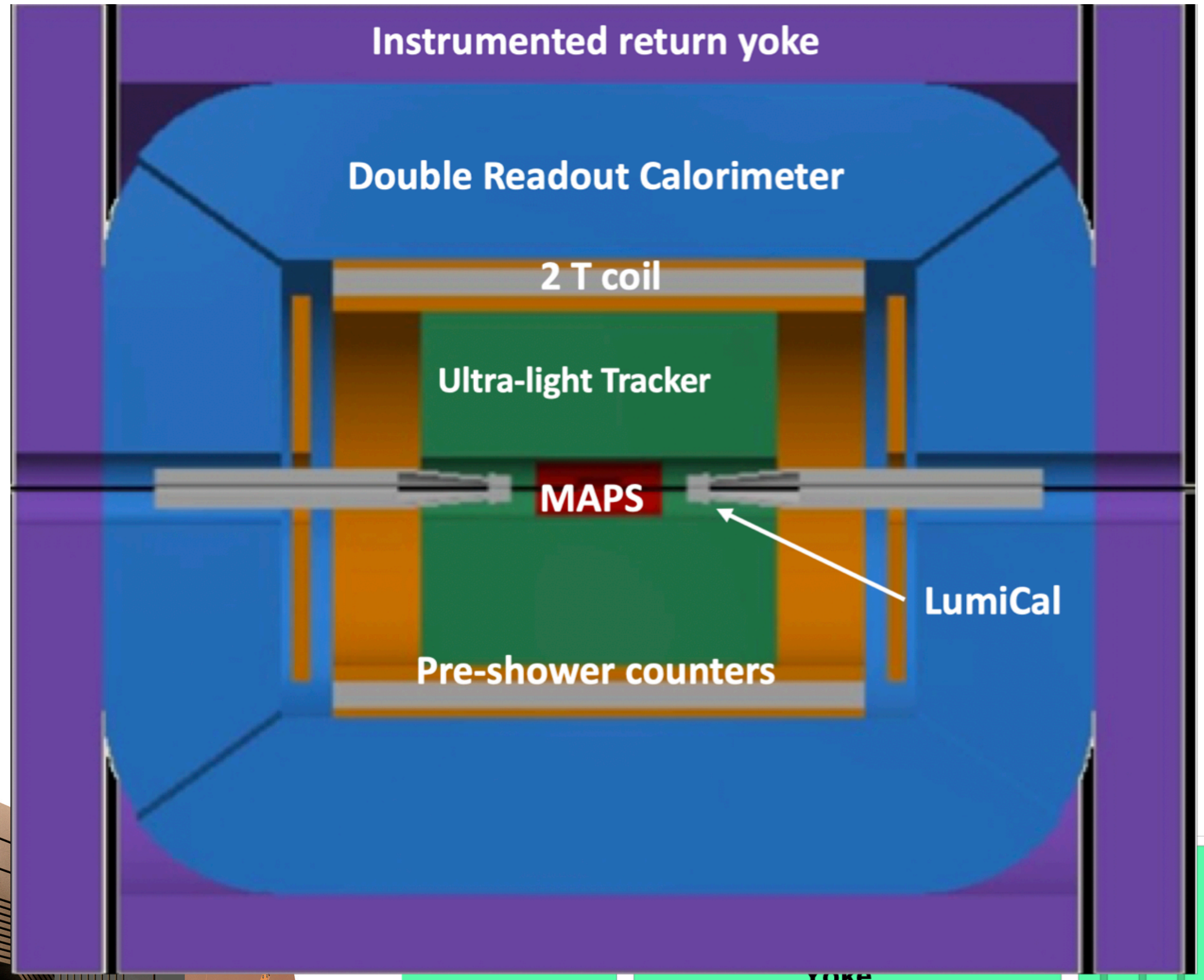

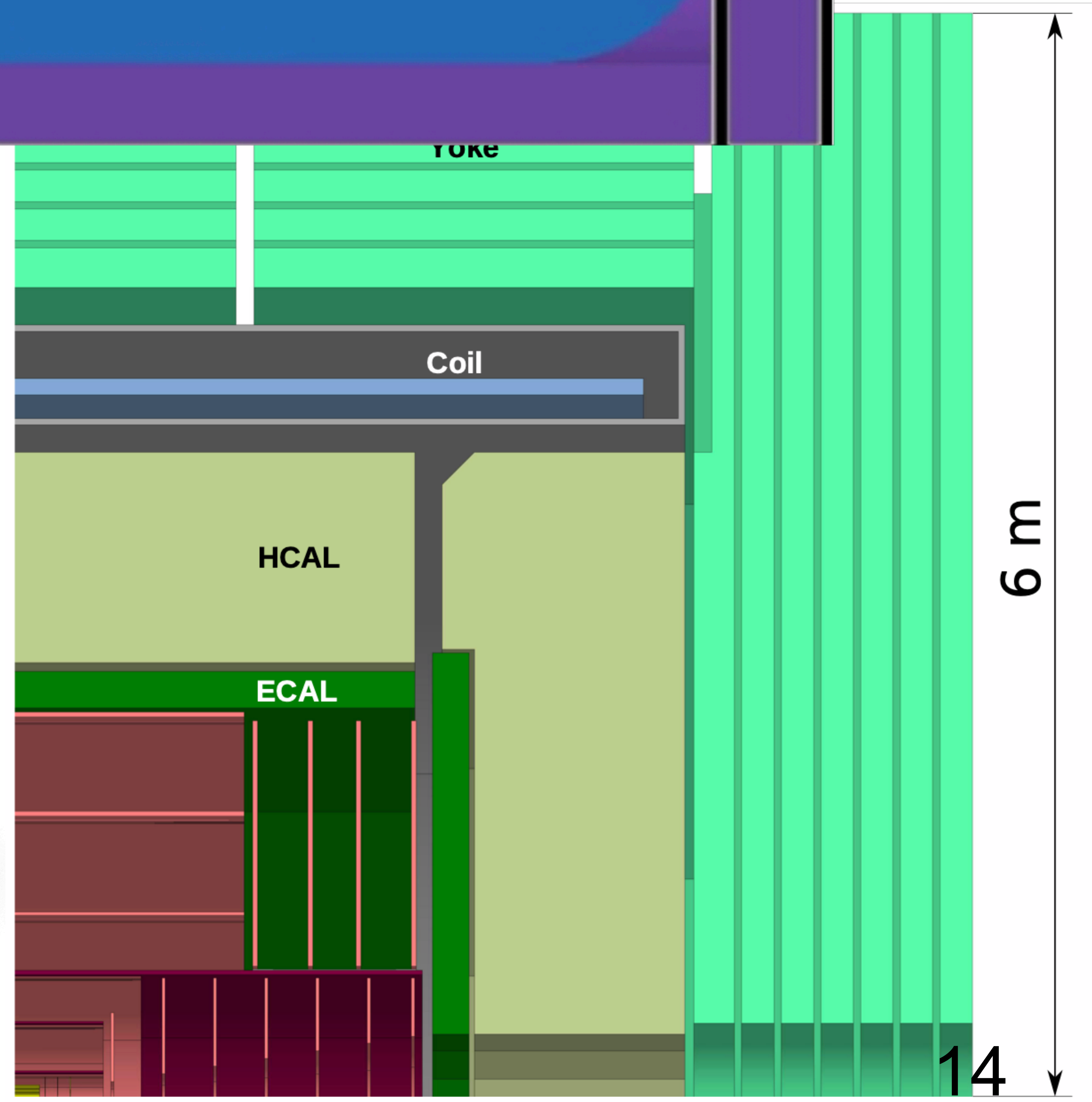

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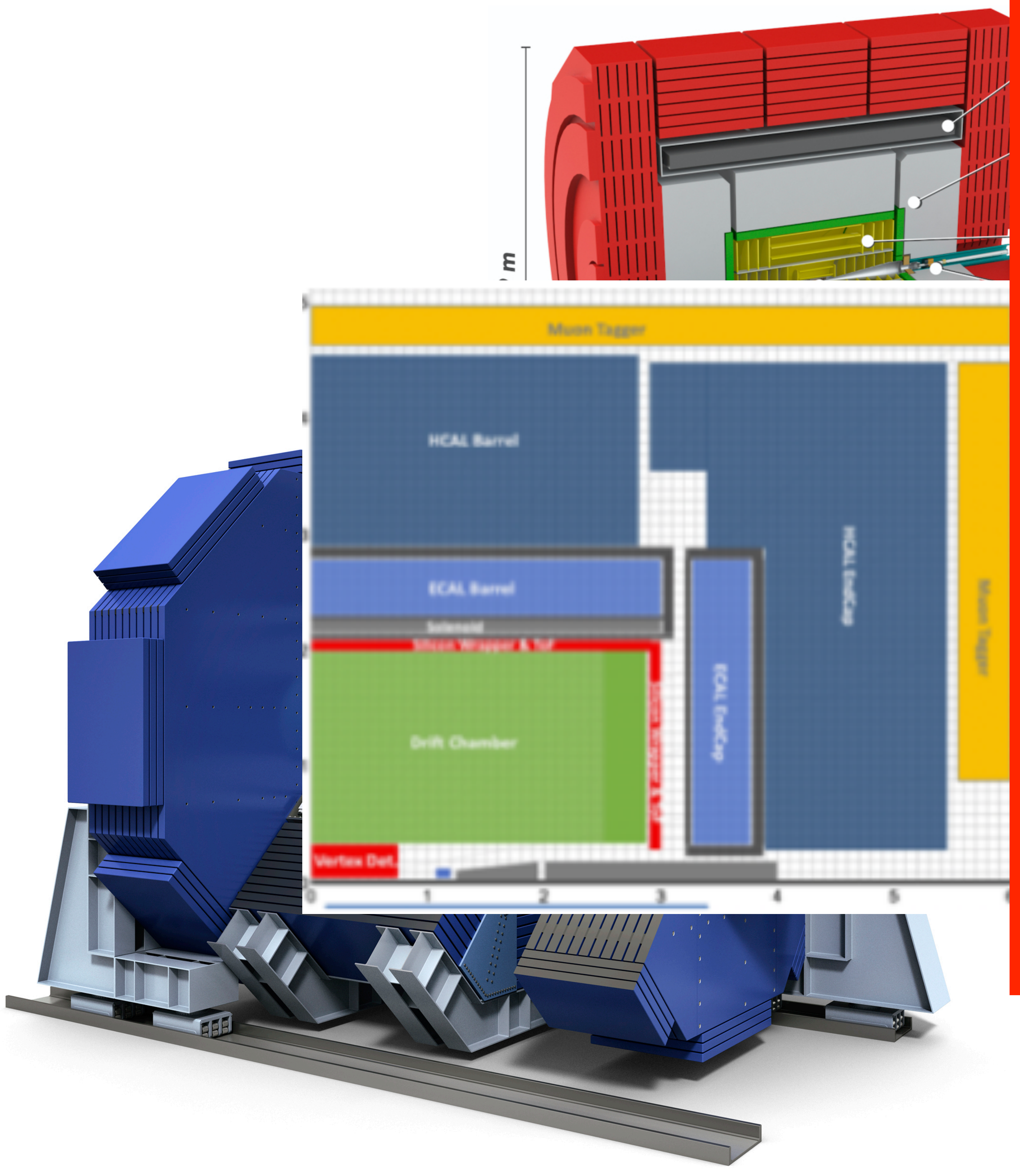
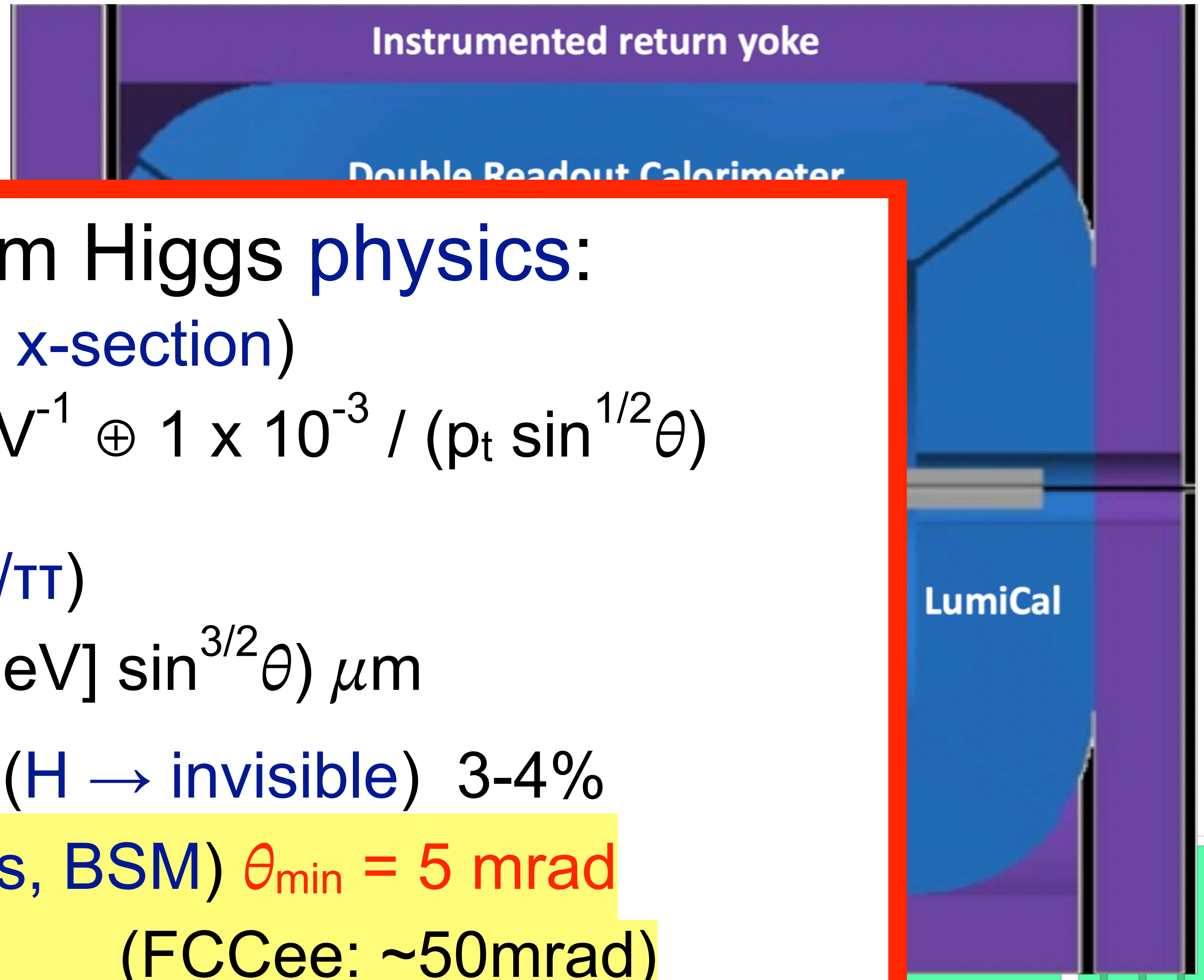


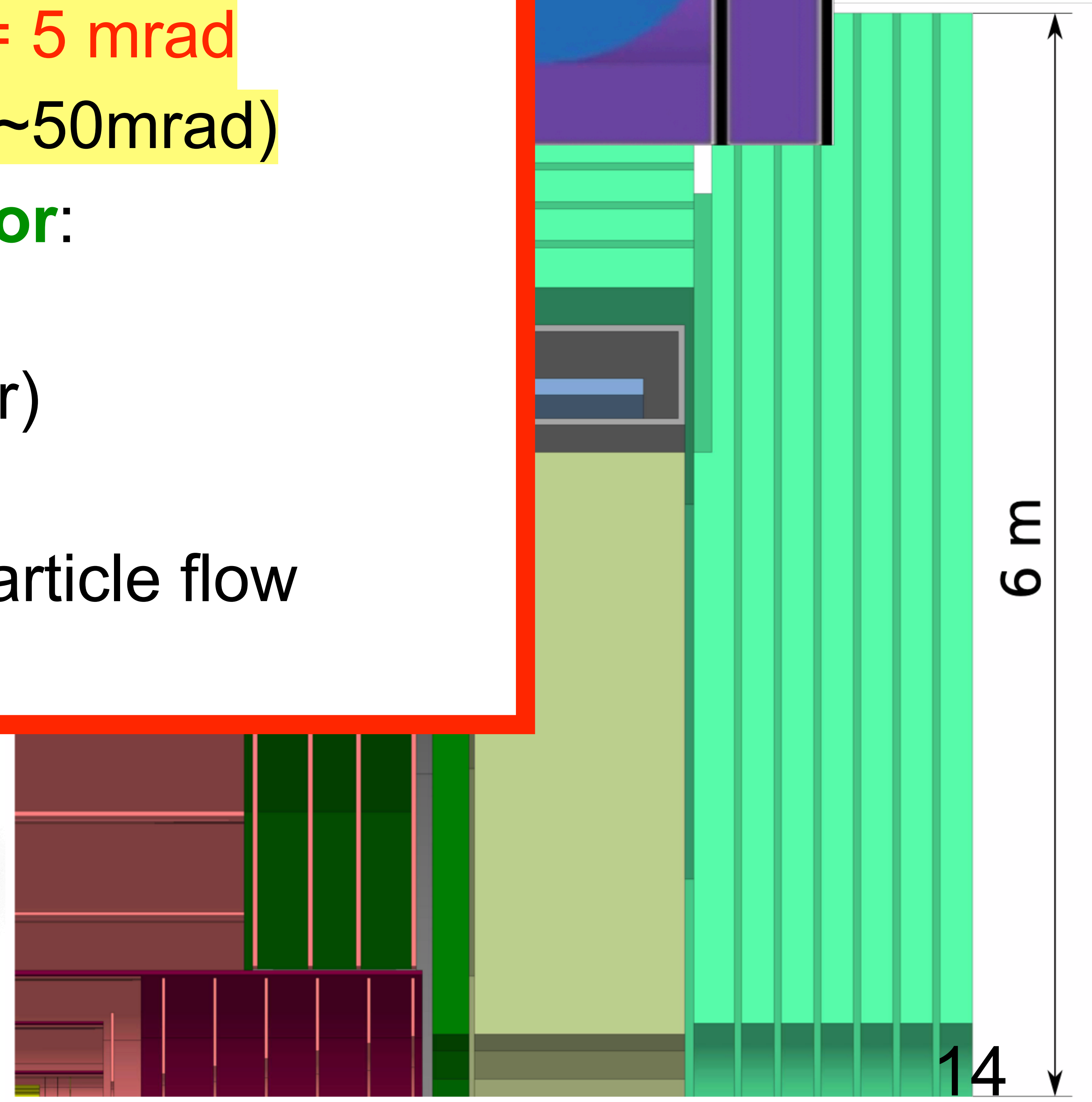
Key requirements from Higgs physics:

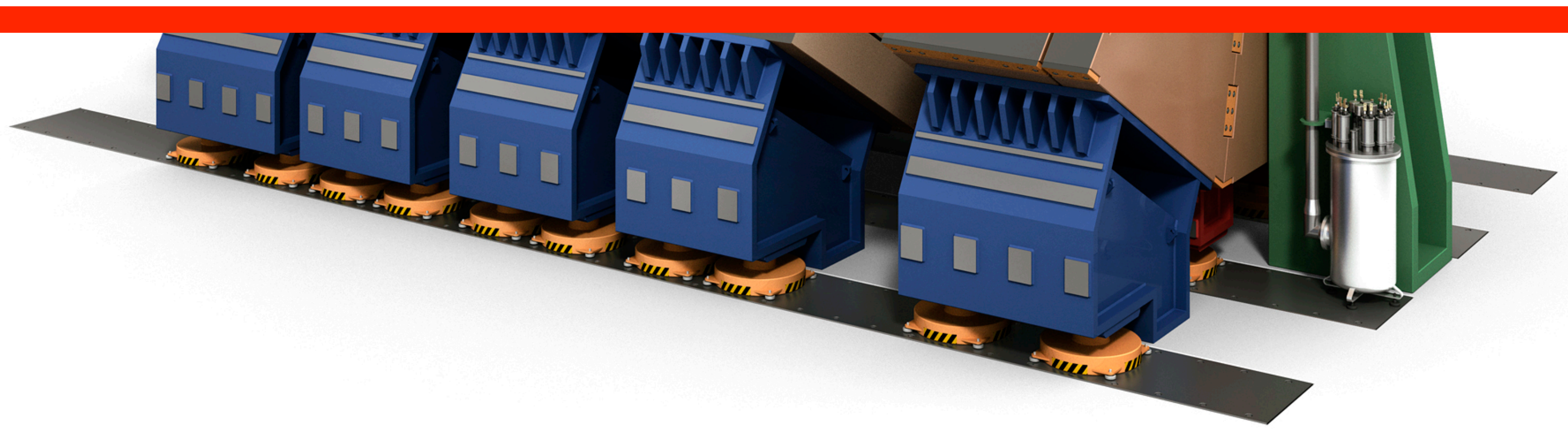
- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
- **vertexing** ($H \to bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$
- **jet energy resolution** ($H \to$ invisible) 3-4%
- **hermeticity** ($H \to$ invis, BSM) θ_{min} = 5 mrad
  (FCCee: ~50mrad)

Determine to key features of the detector:

- **low mass tracker:**
  eg VTX: 0.15% rad. length / layer)
- **calorimeters**
  - **highly granular,** optimised for particle flow
  - or dual readout, LAr, …







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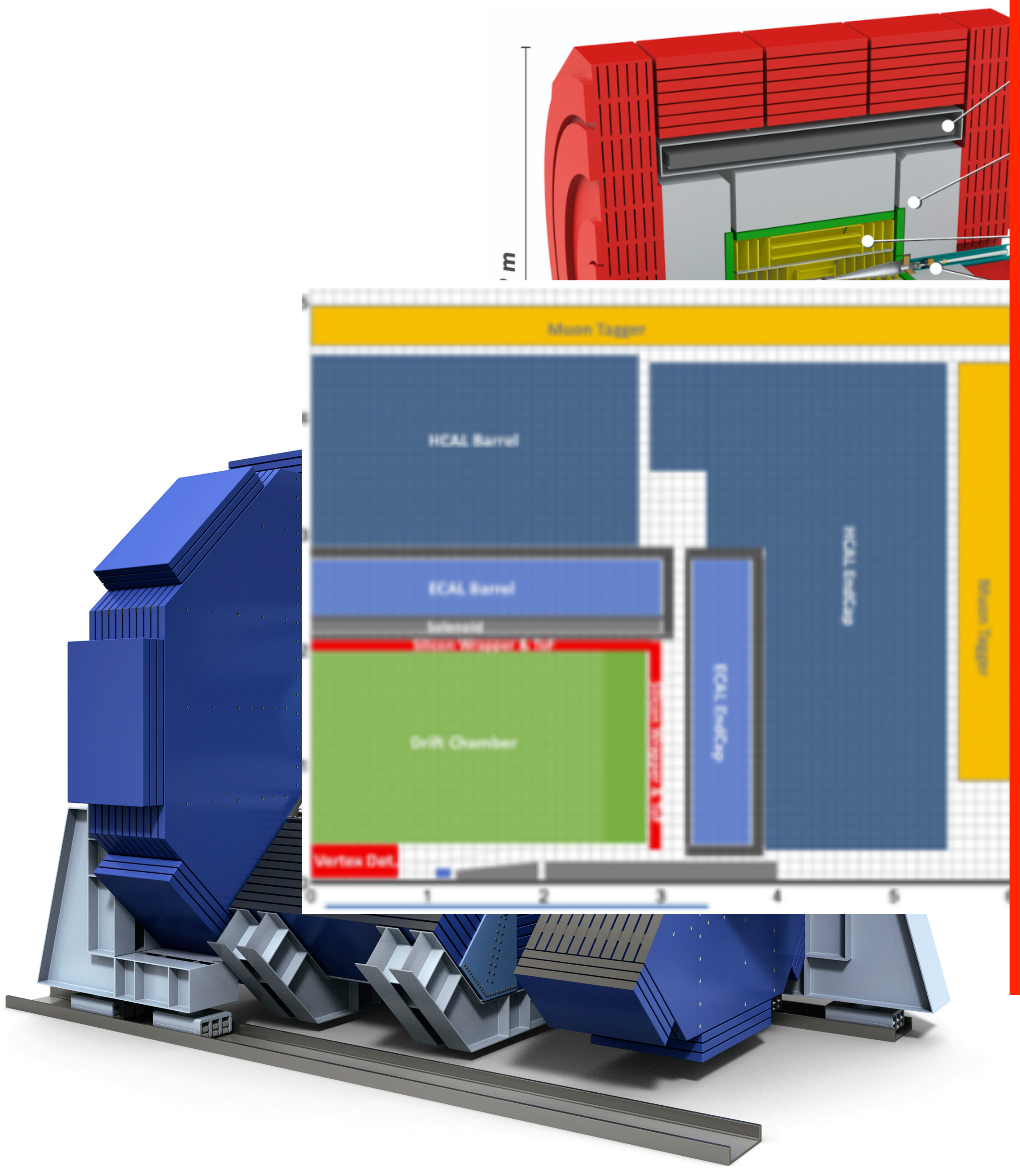

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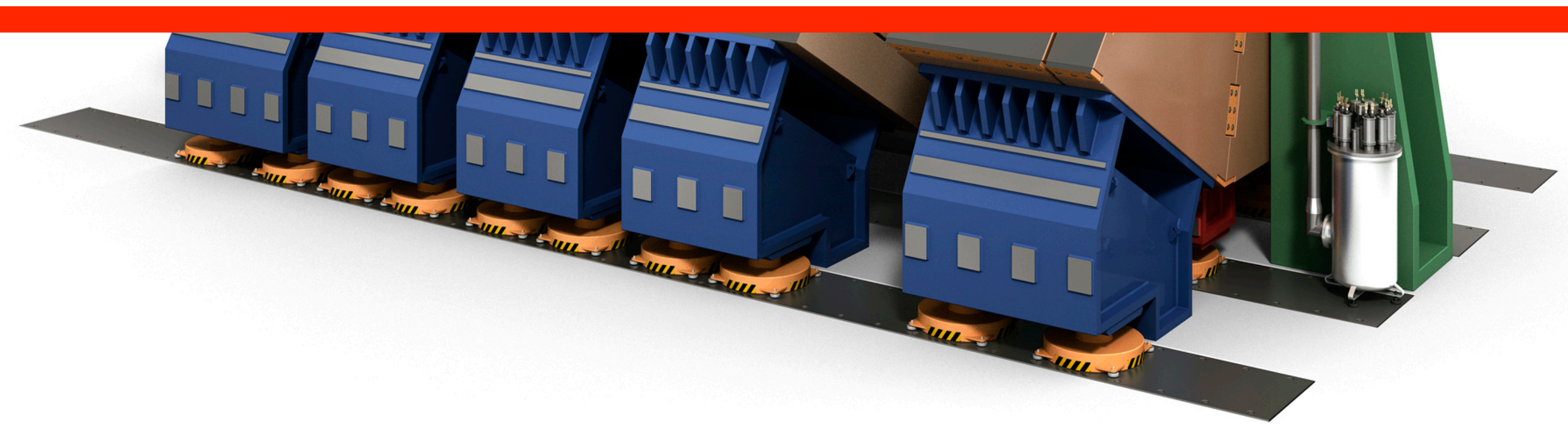

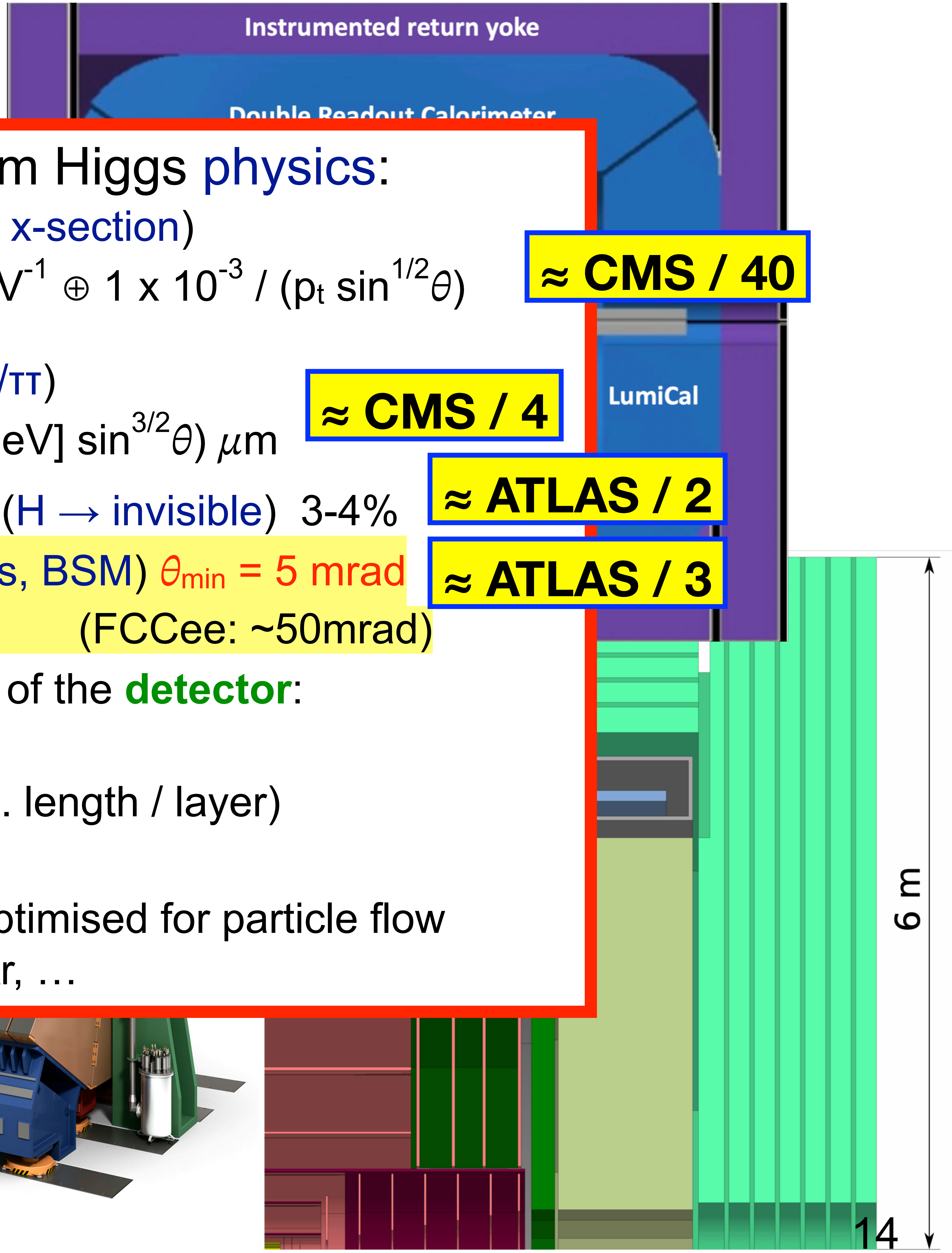

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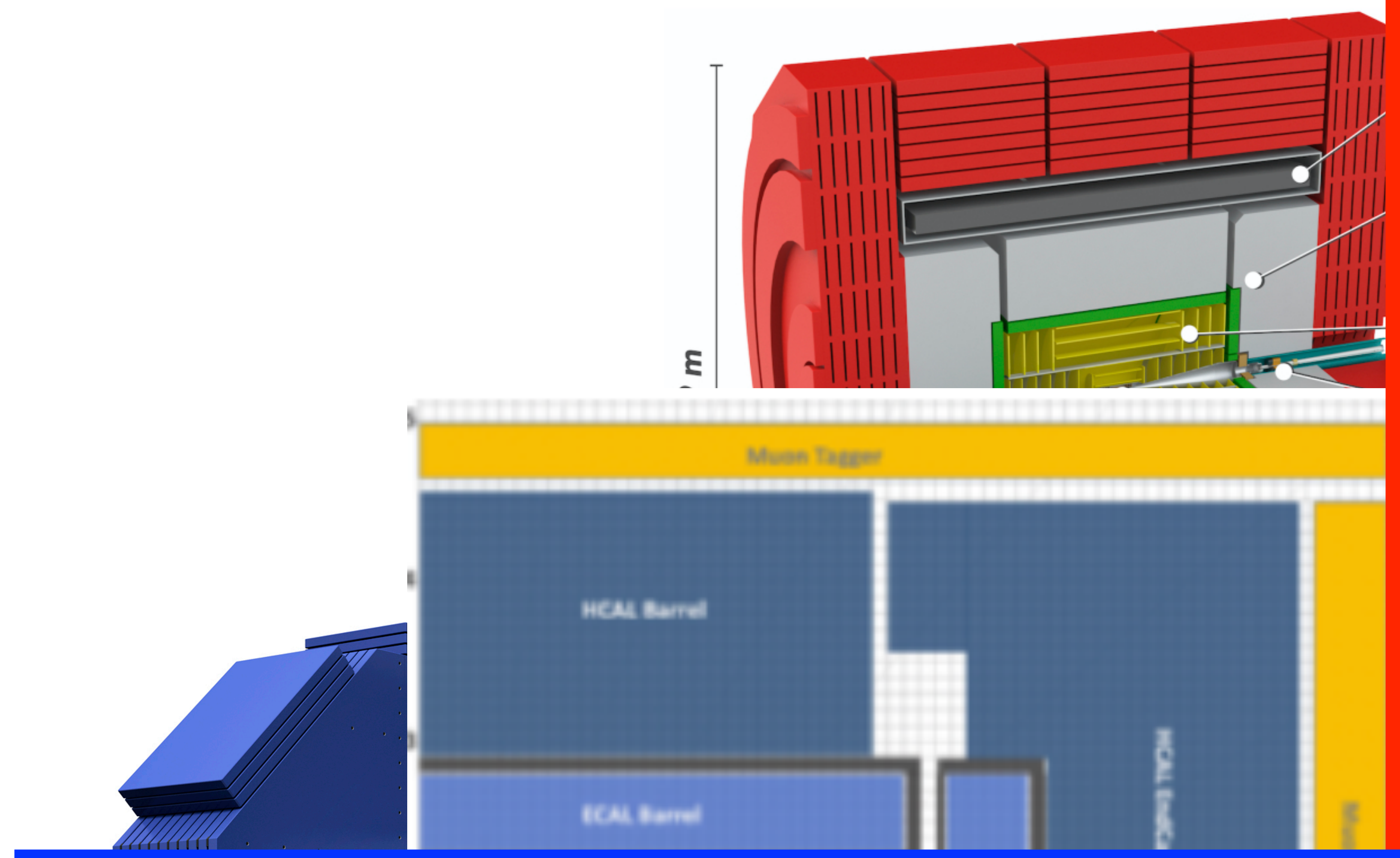

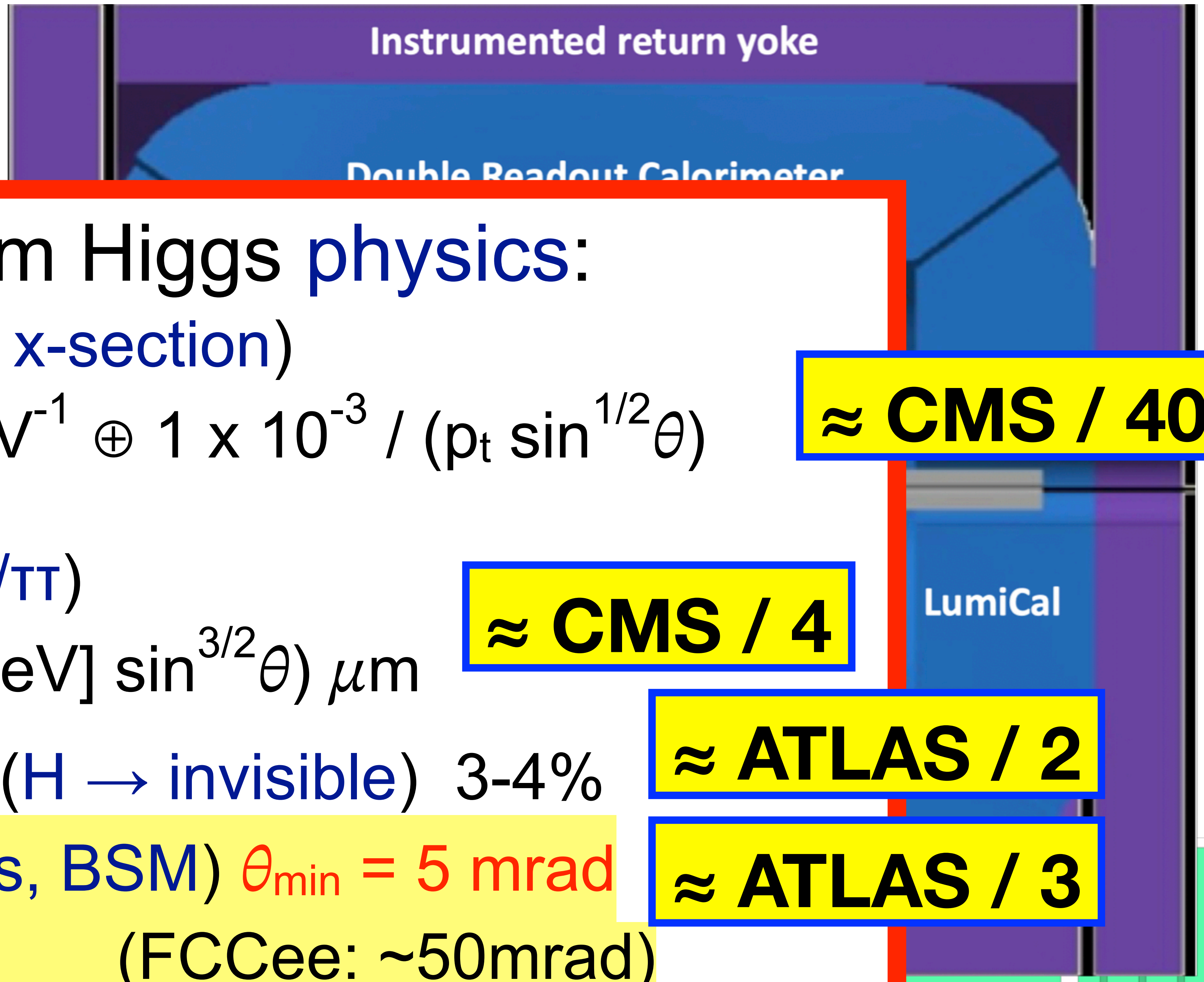

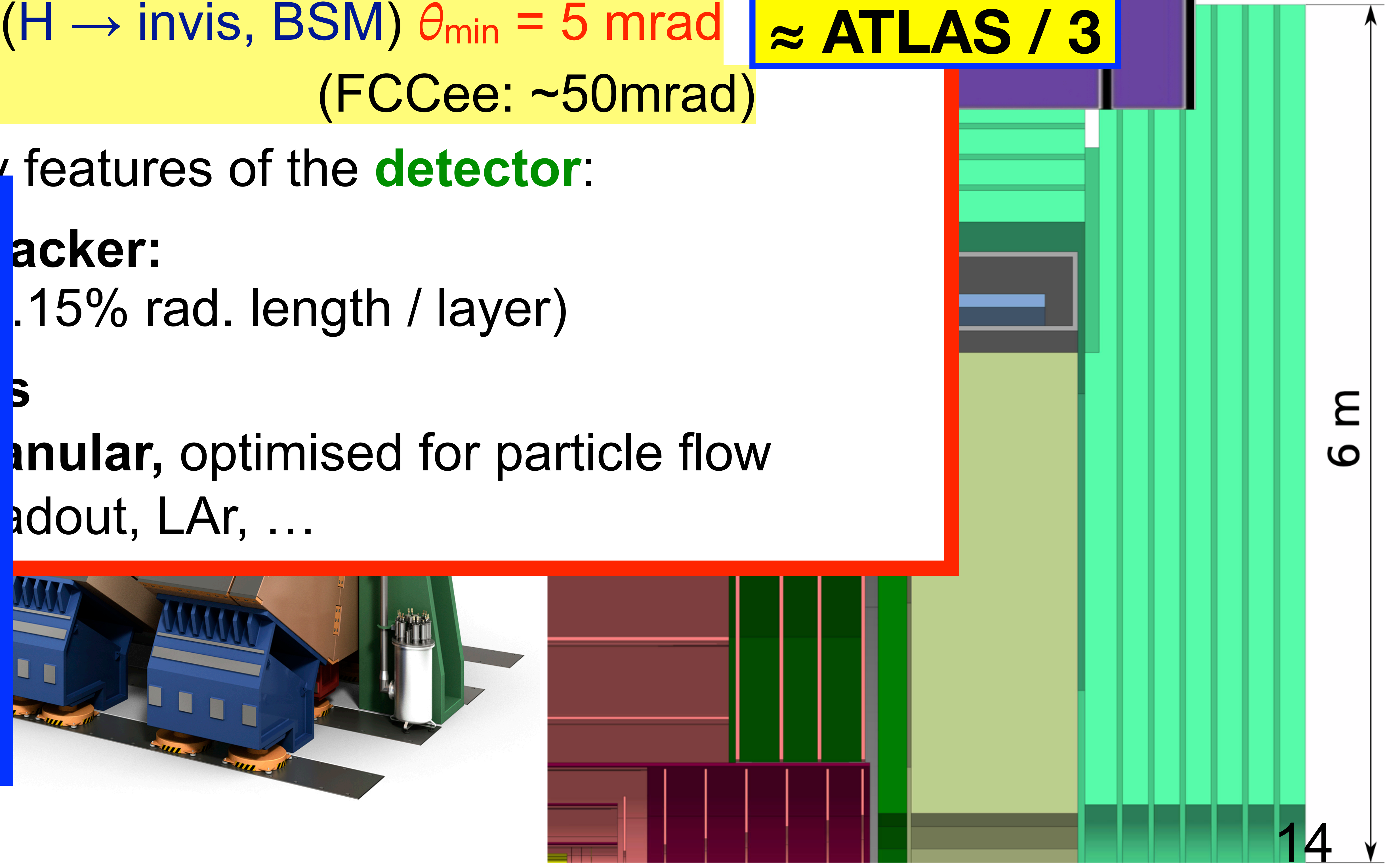

Key requirements from Higgs physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$ **≈ CMS / 40**
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$ **≈ CMS / 4**
- **jet energy resolution** ($H \rightarrow$ invisible) 3-4% **≈ ATLAS / 2**
- **hermeticity** ($H \rightarrow$ invis, BSM) θ_{min} = 5 mrad **≈ ATLAS / 3**
  (FCCee: ~50mrad)

Determine to key features of the **detector**:

acker:

.15% rad. length / layer)

s

anular, optimised for particle flow

adout, LAr, …

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

- much lower backgrounds
- much less radiation

only Linear Colliders: lower collision rate enables

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

Example 1: Scalar Leptons

SUSY jumping into your eye at a lepton collider

- s-electrons after
  - a week (5fb-1)
  - 2-3 years (500fb-1)
- s-muons, s-taus
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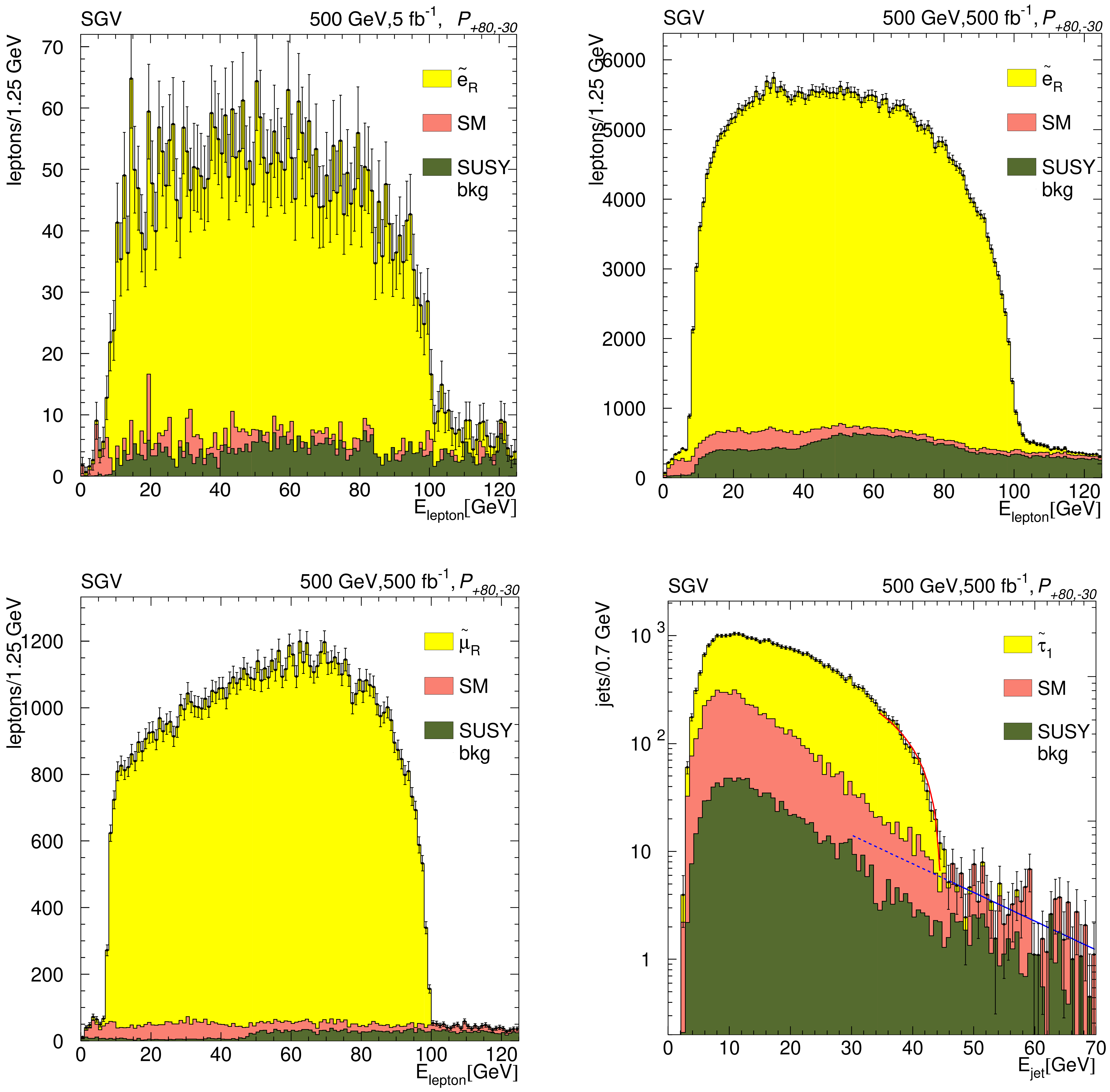
Eur.Phys.J.C 76 (2016) 4, 183



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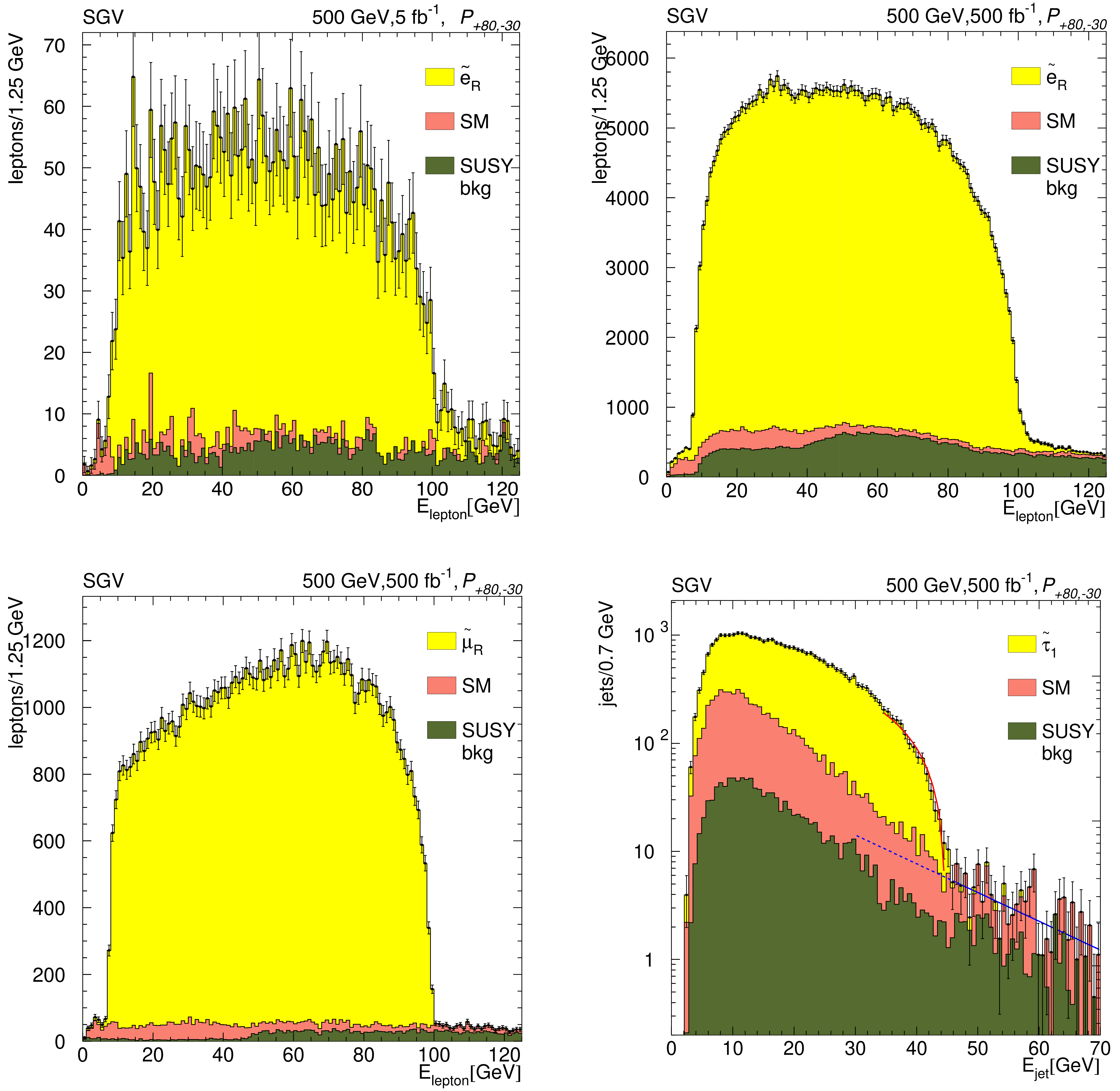
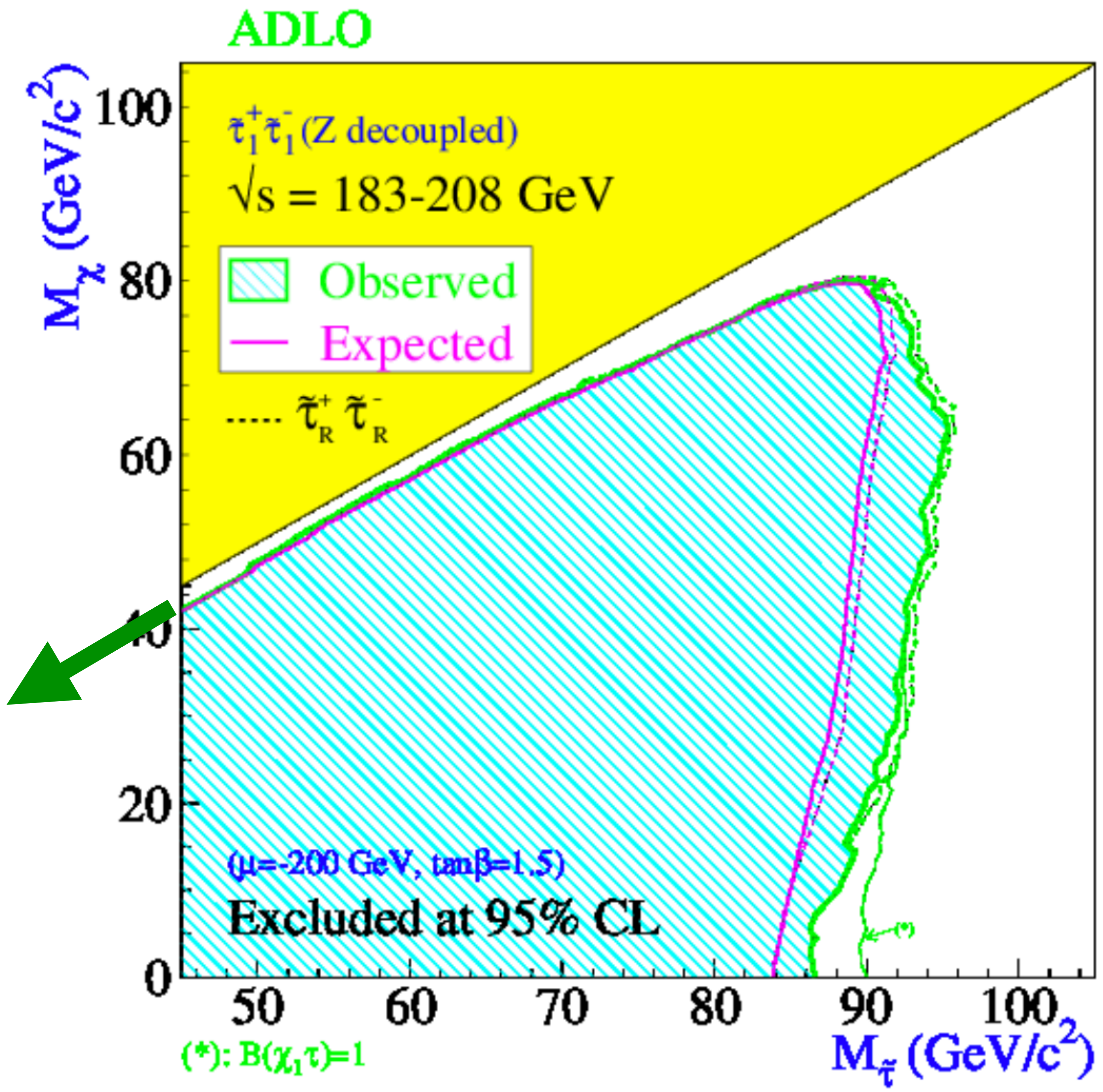


- what is the generically 'worst case'?
- parameter scan for staus - low mass splitting, mixing such that cross-section minimal, ….

Scalar Taus

A closer look at the difficult case

- current general lower mass limit on staus (any mass splitting > m(tau), any mixing, …): **26.3 GeV** (DELPHI, Eur. Phys. J. C 31 (2003), 421-479)
- extremely difficult at HL-LHC - especially in realistic cases with MstauR < MstauL



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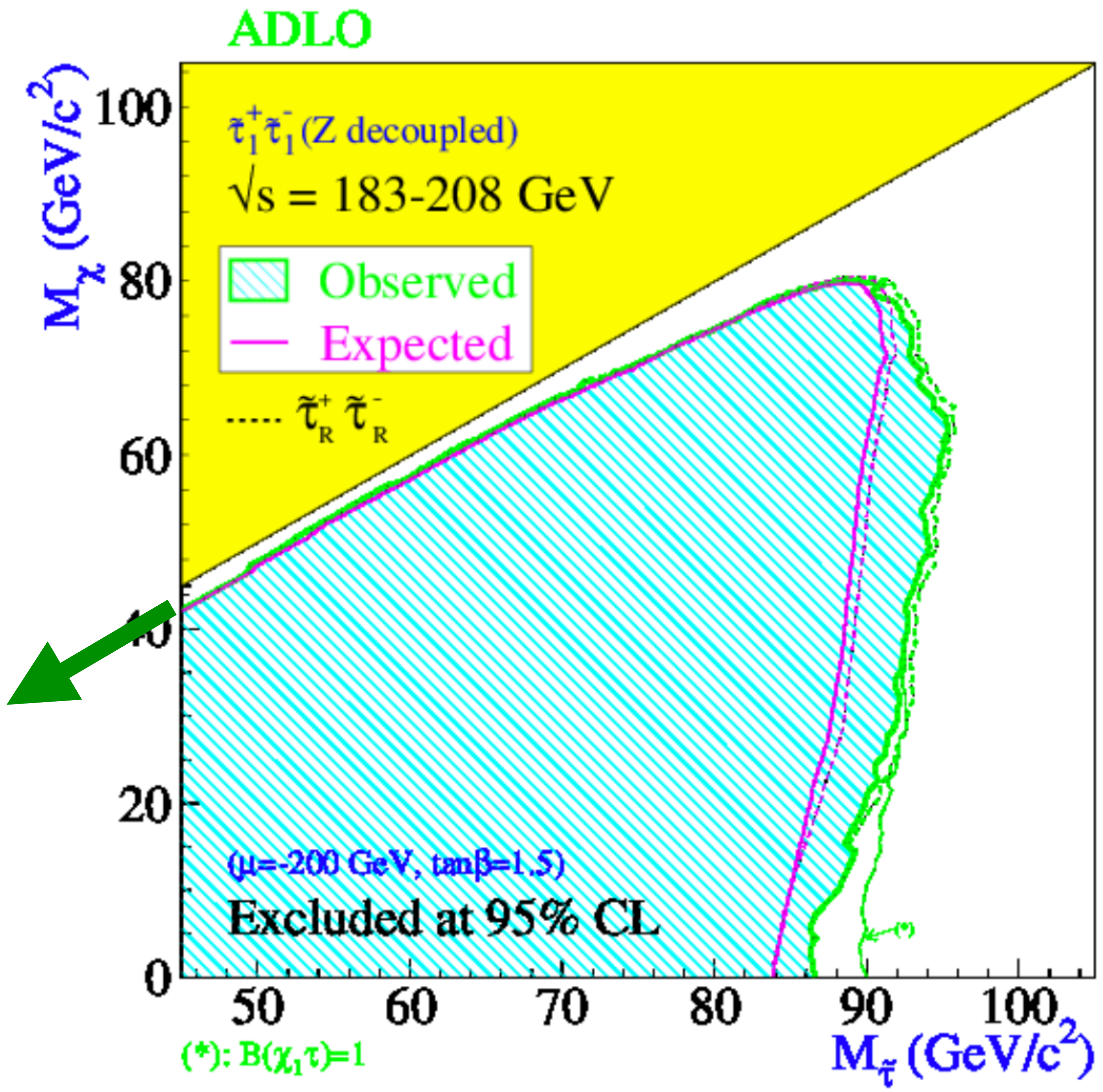

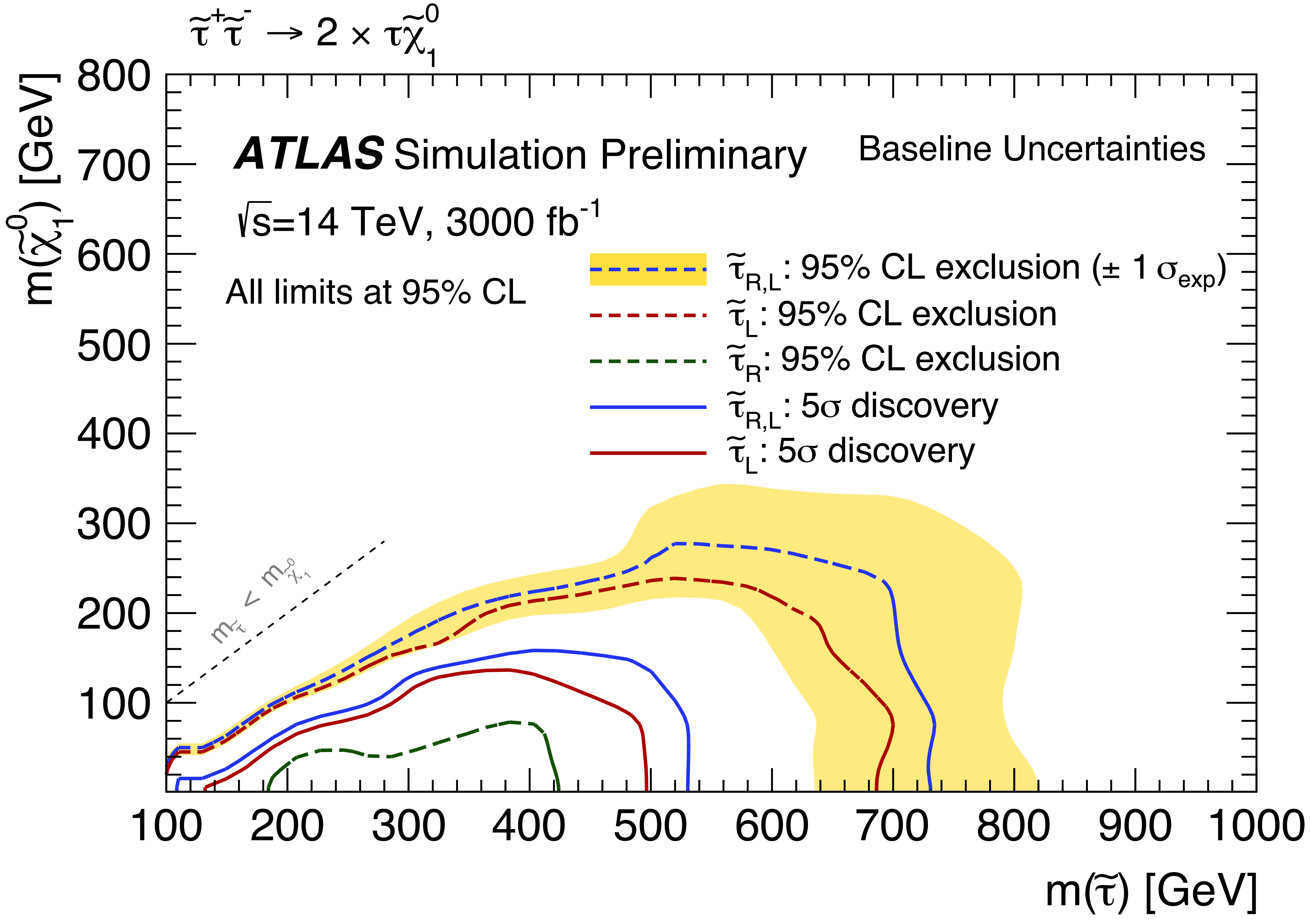

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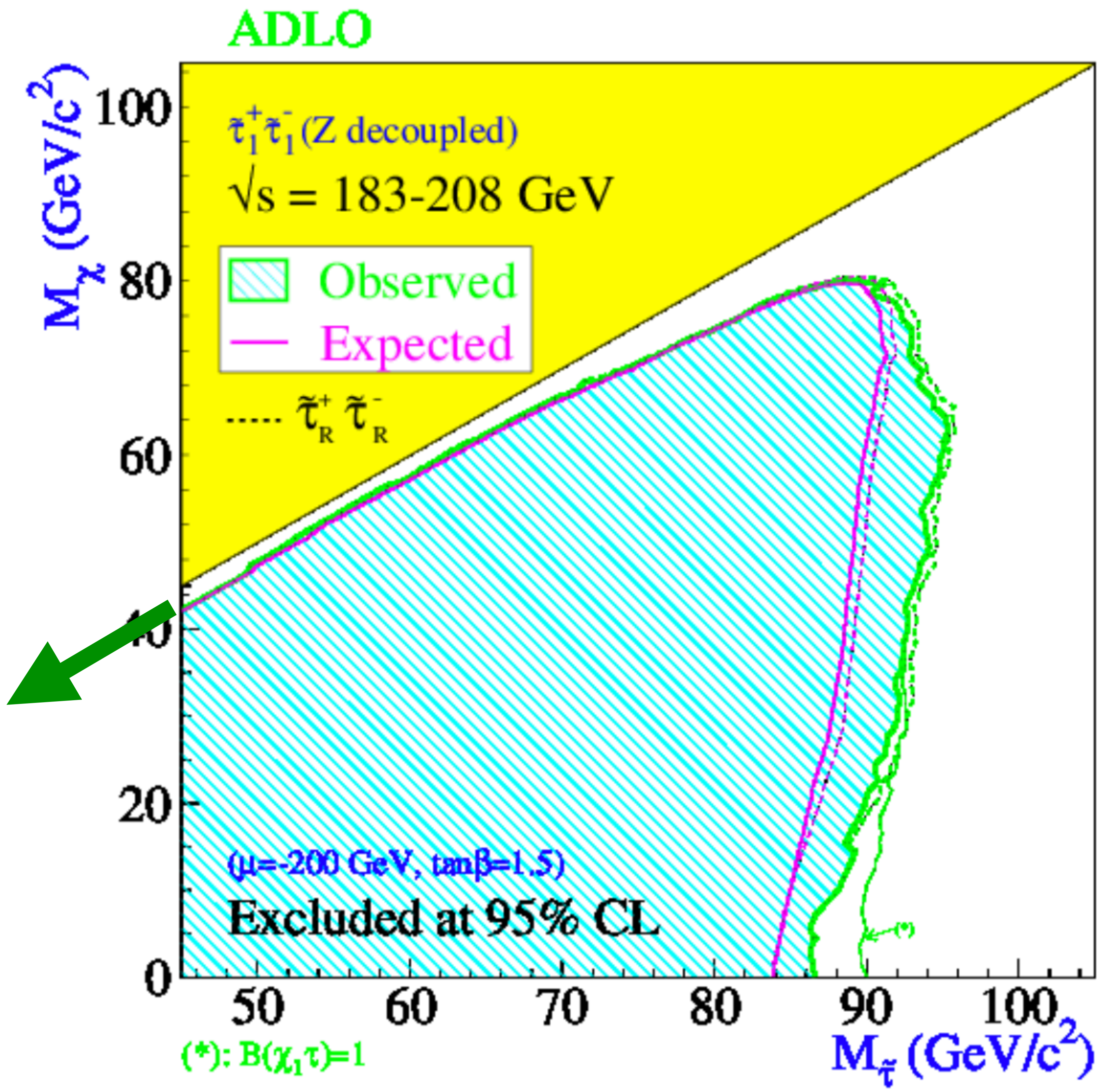
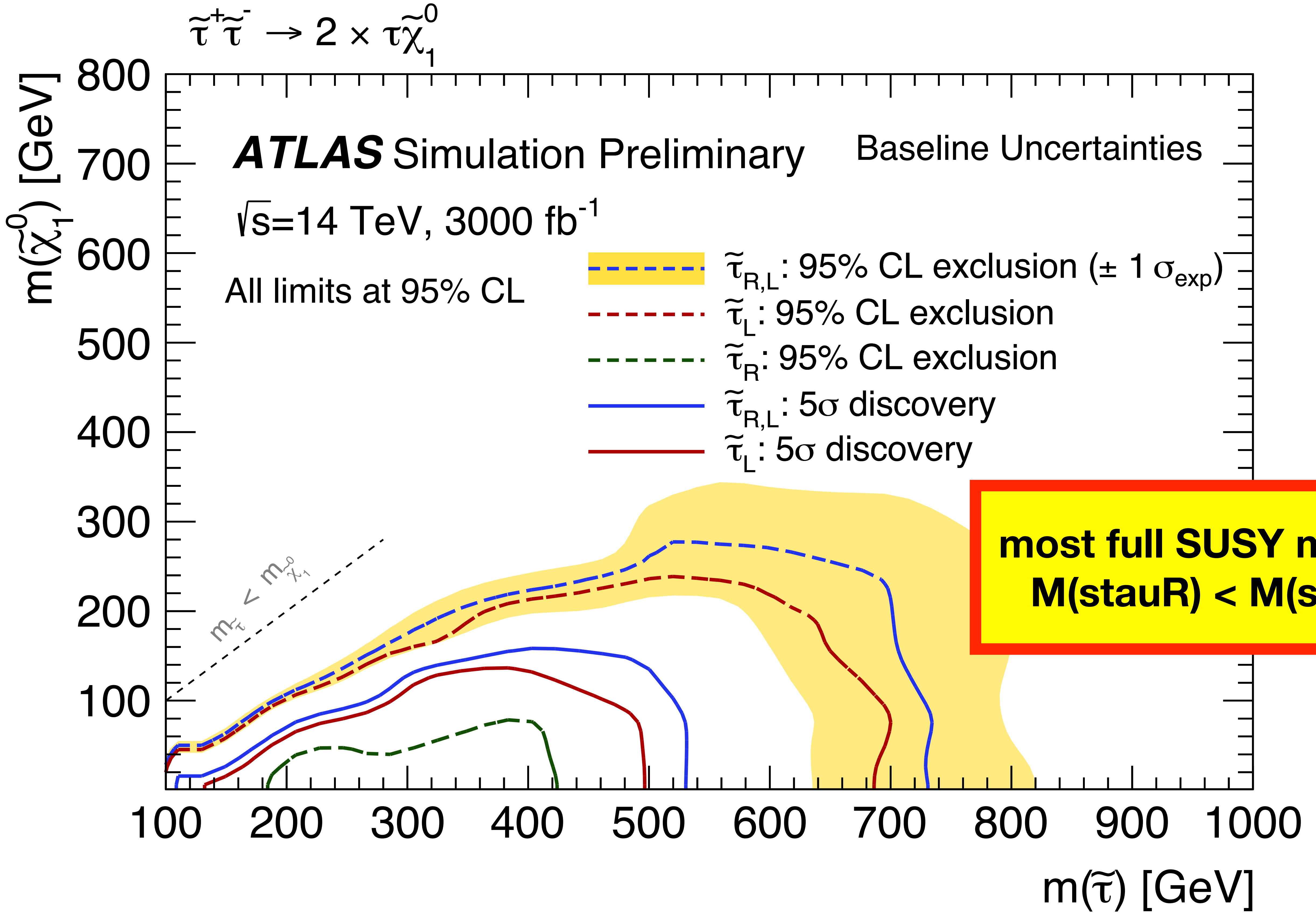
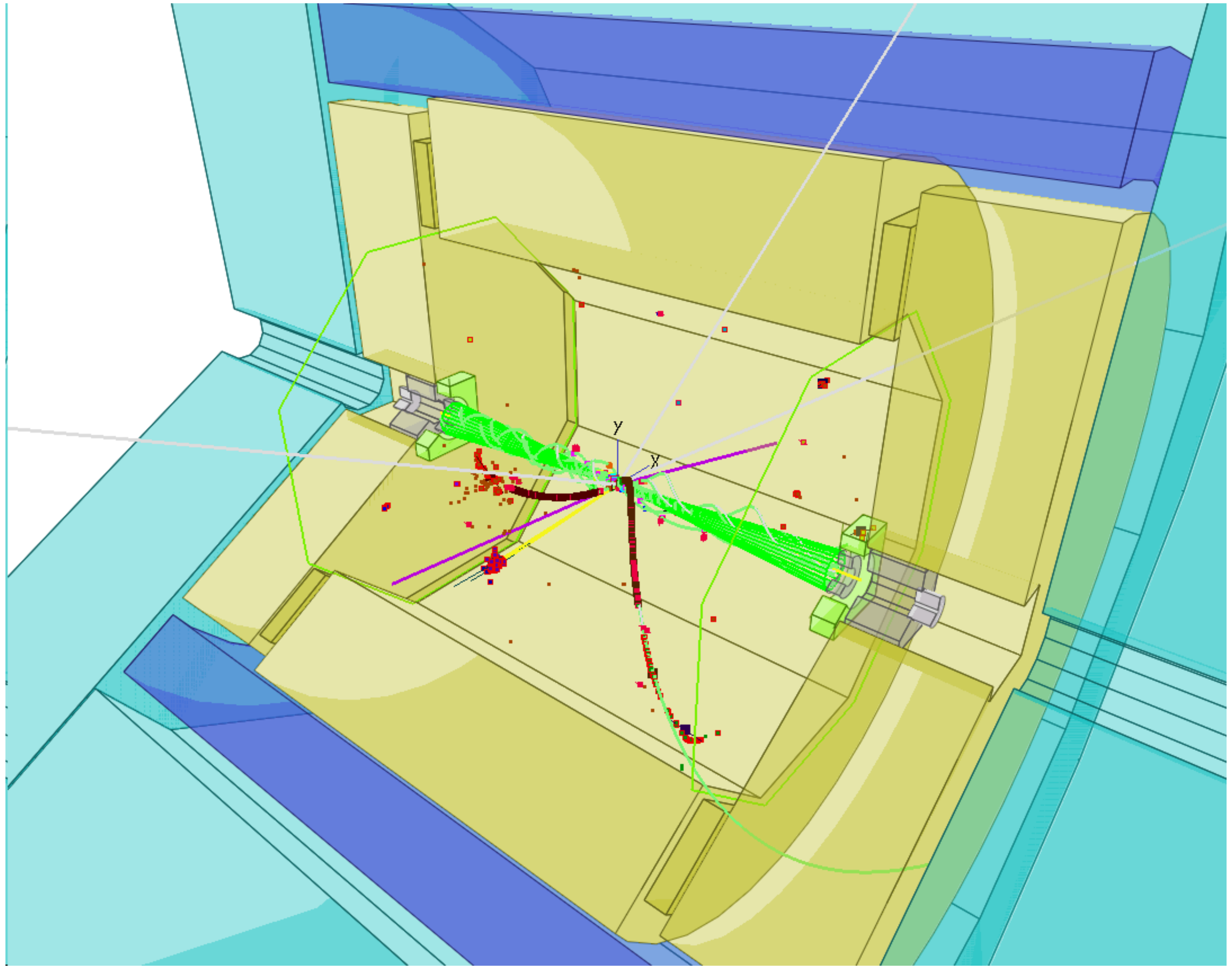


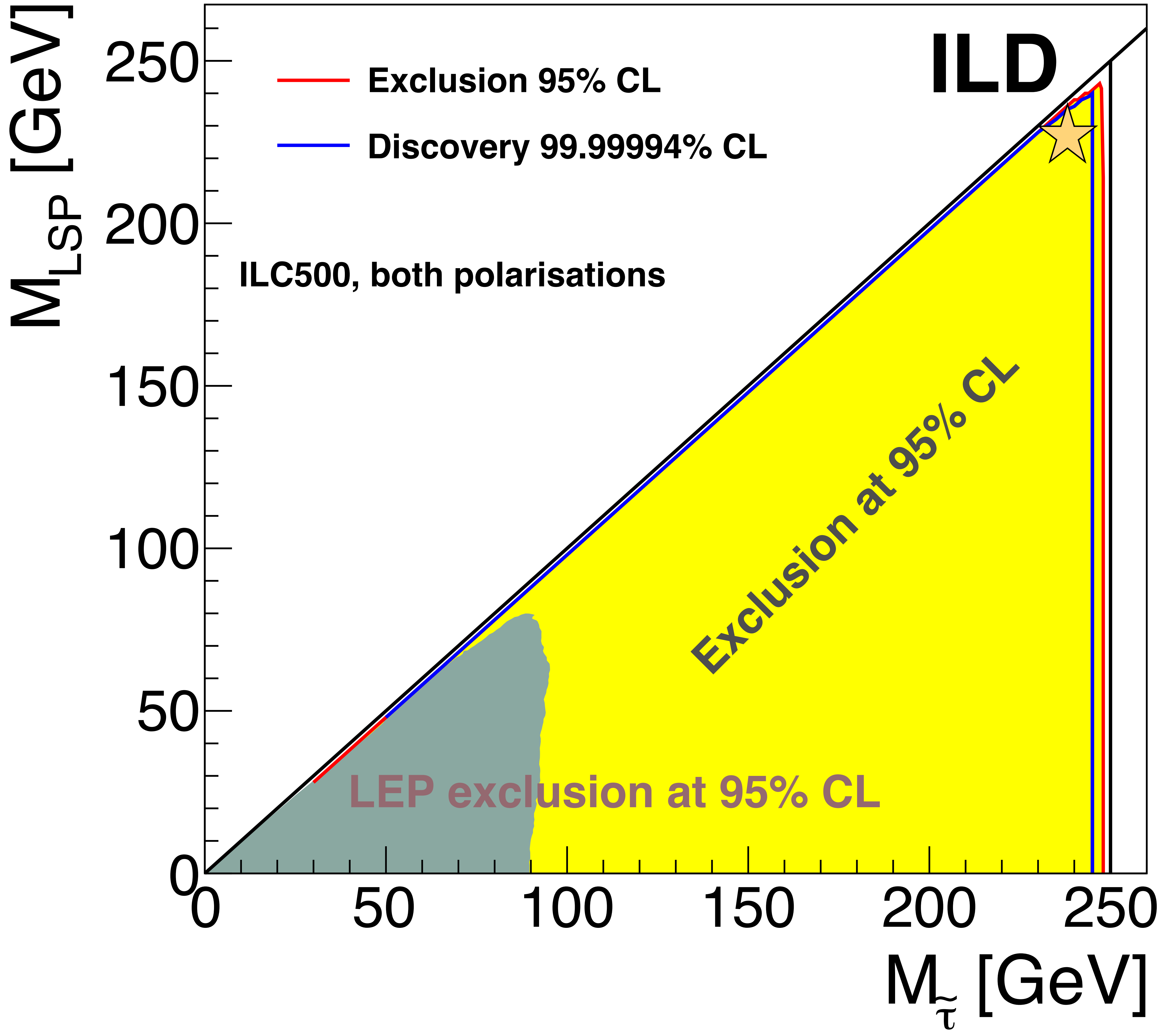


most full SUSY models: M(stauR) < M(stauL)

Scalar Tau Prospects at ILC

picking the worst-case choice for non-shown parameters





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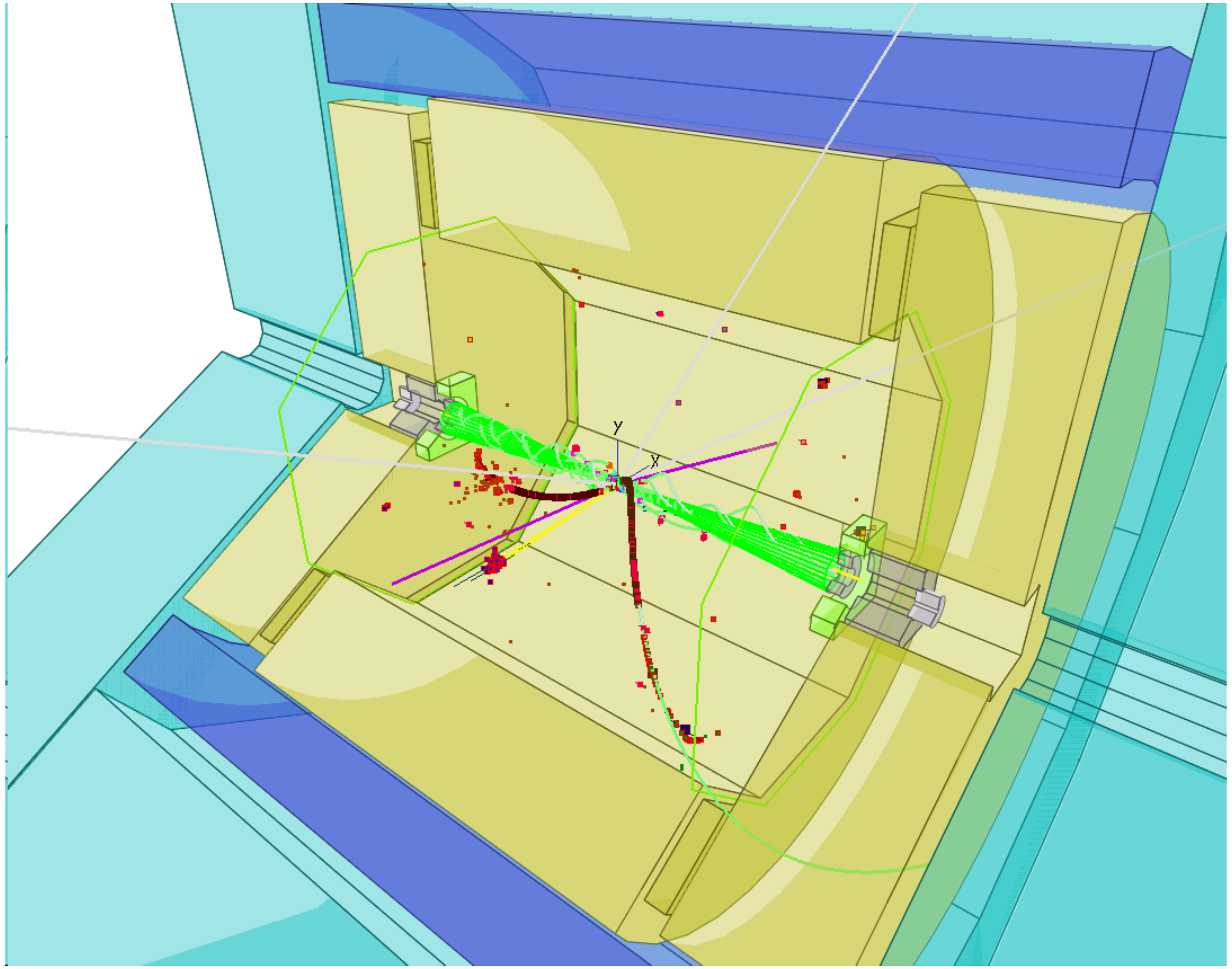

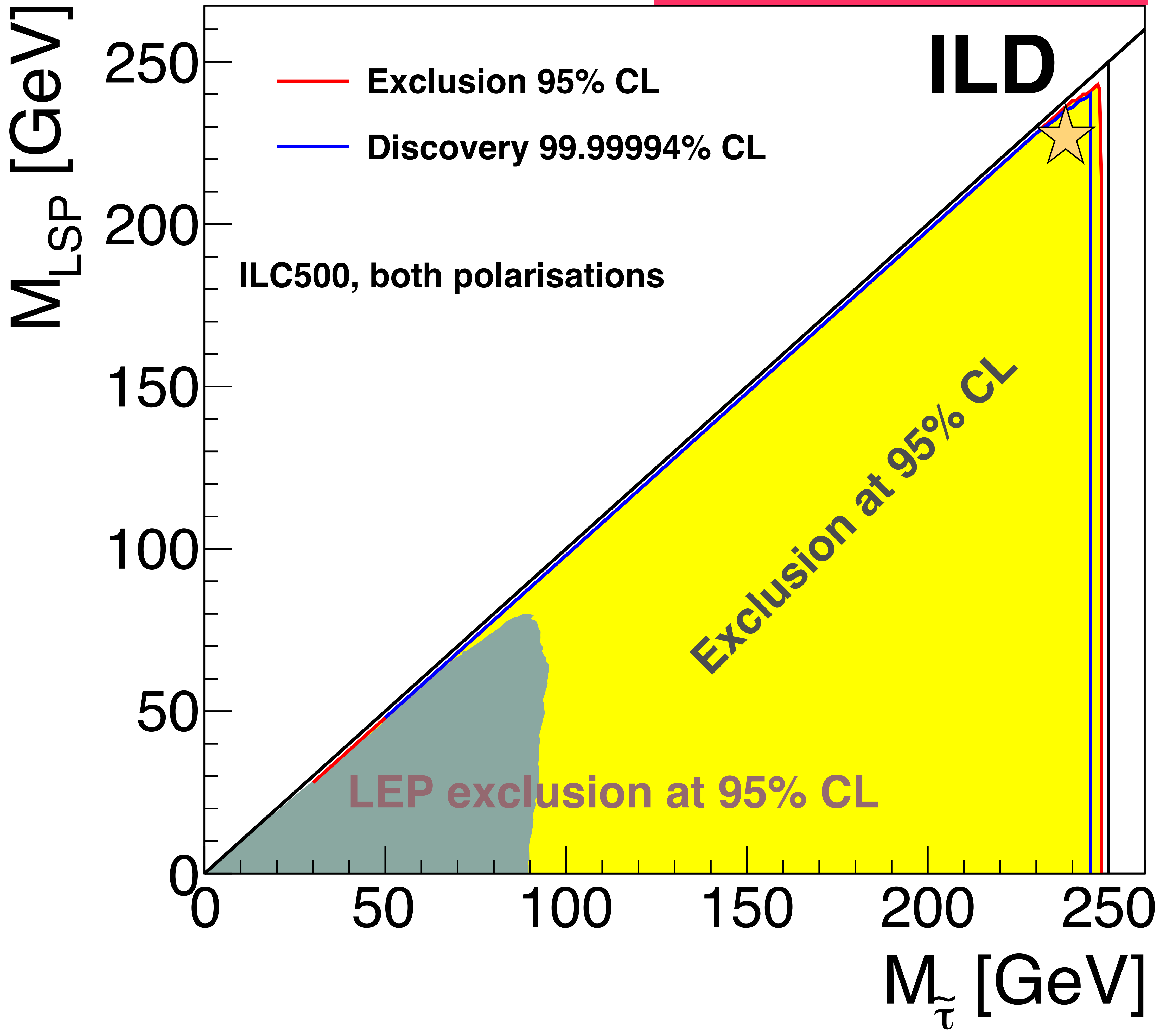

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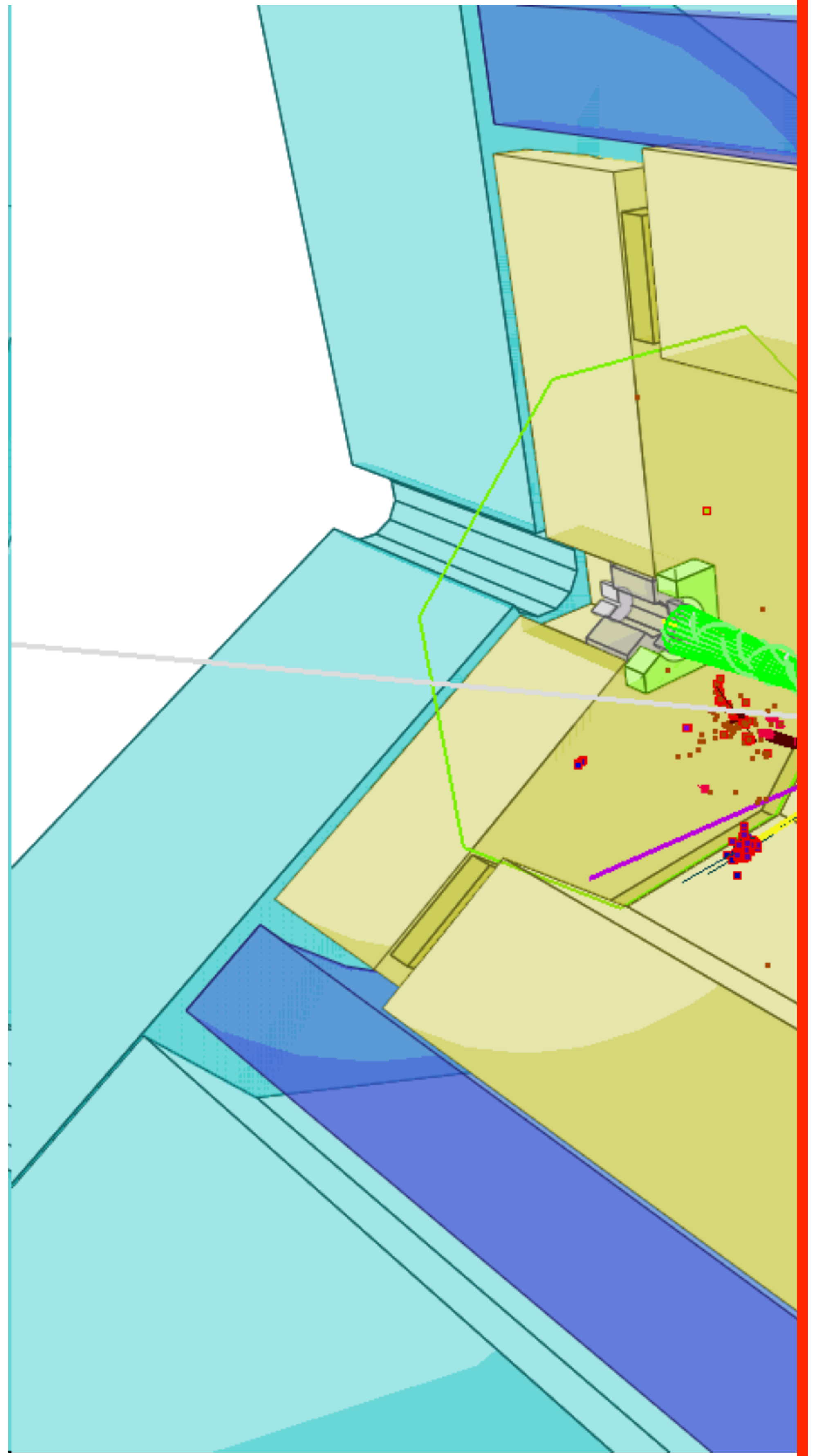
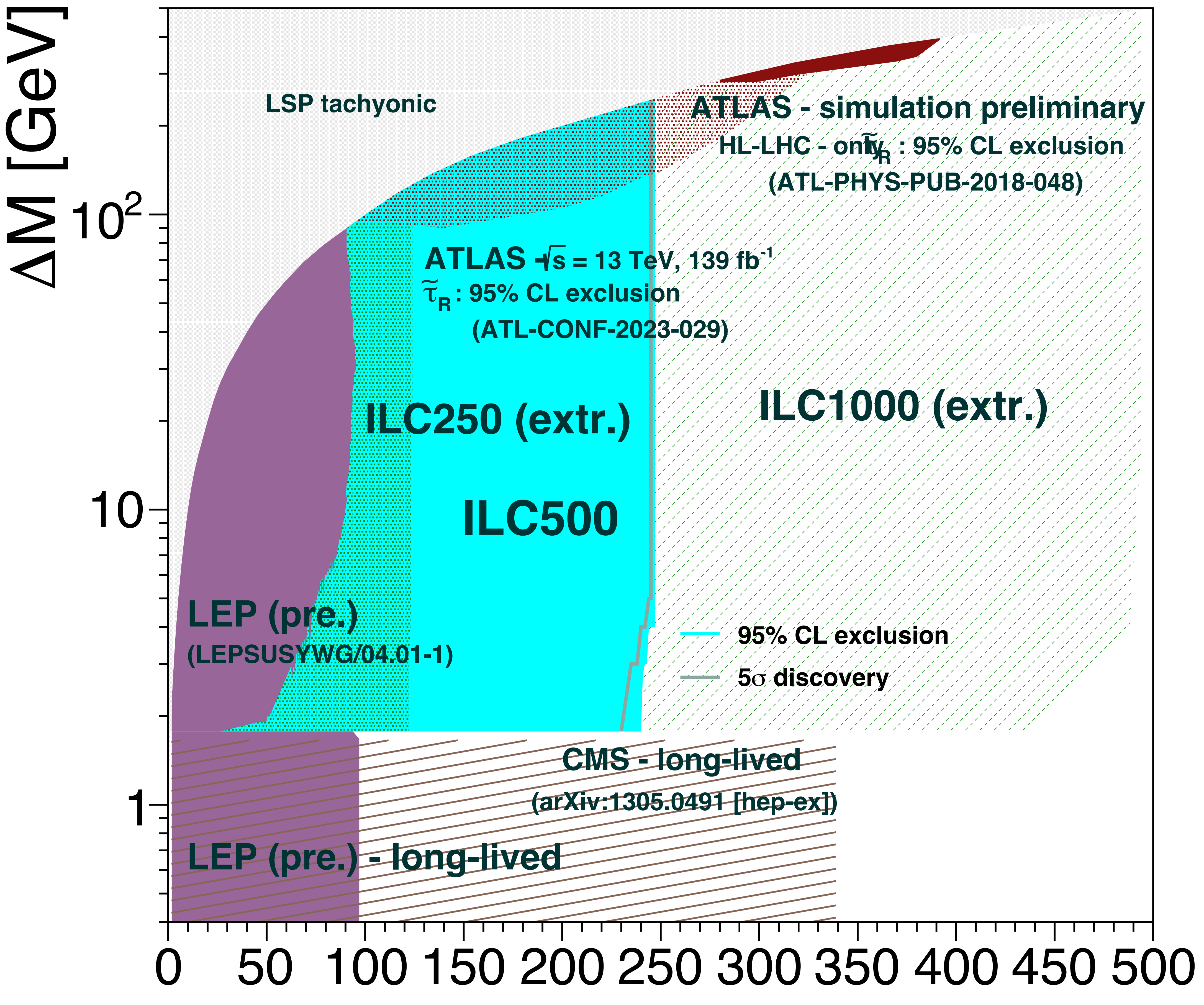
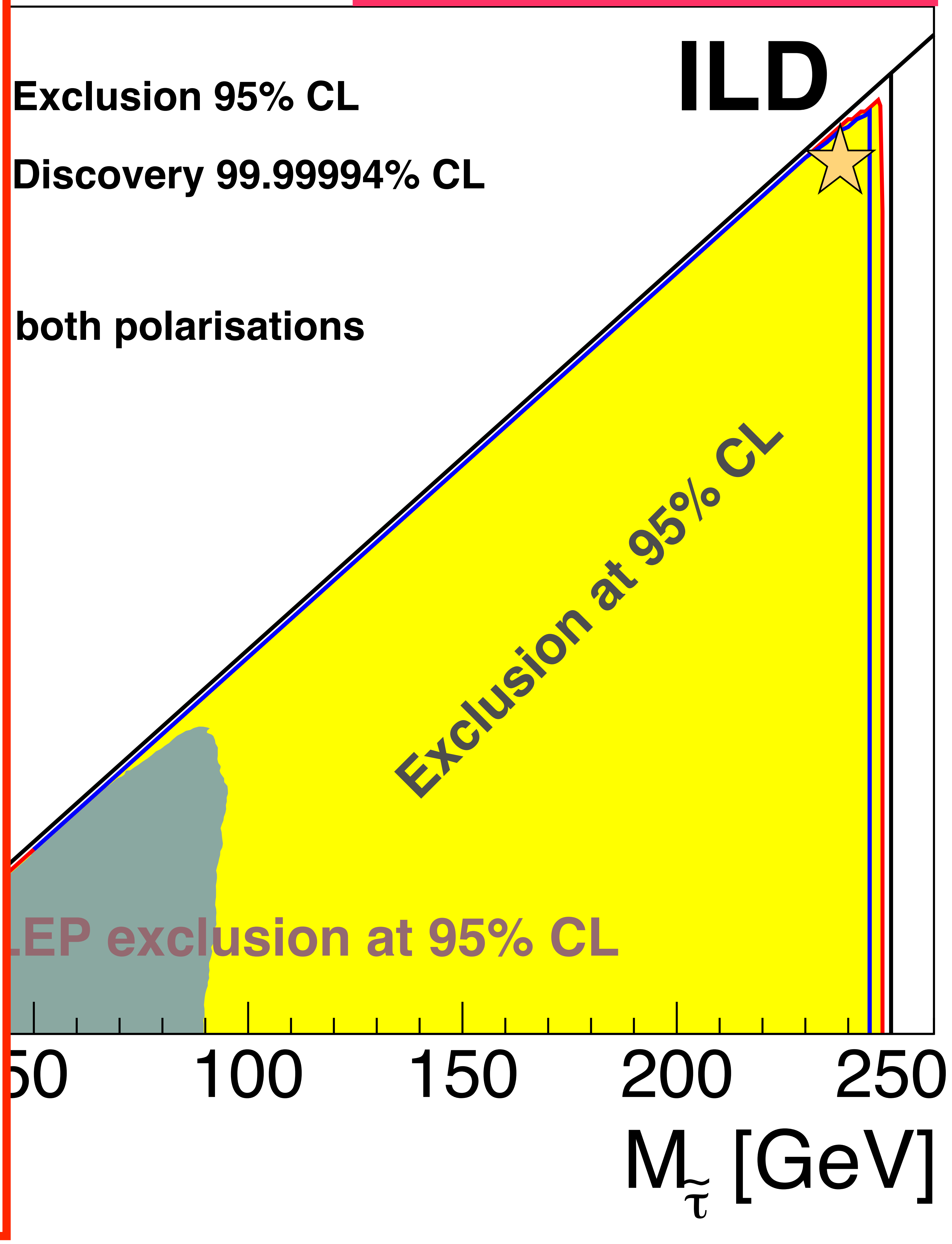




arXiv:2210.14639



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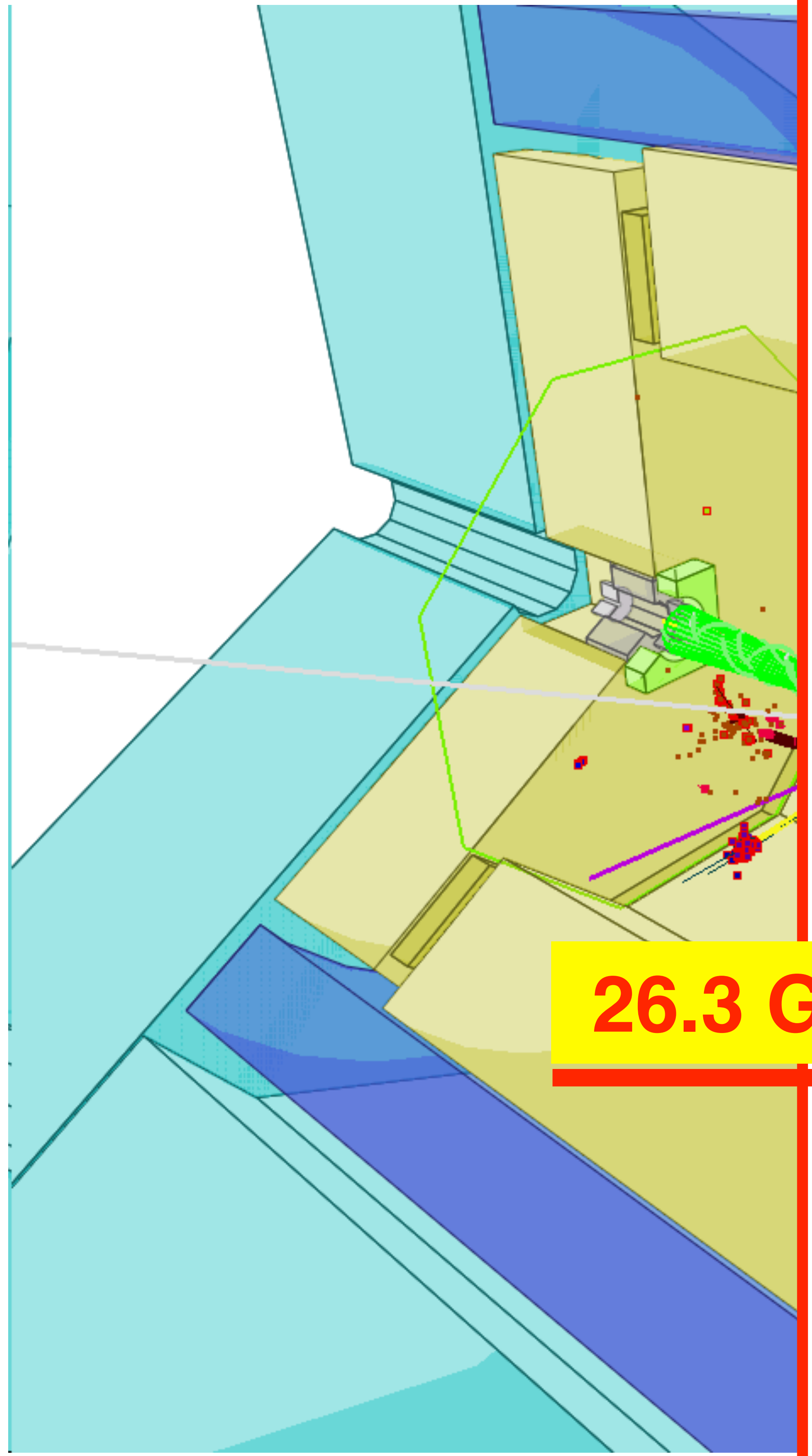

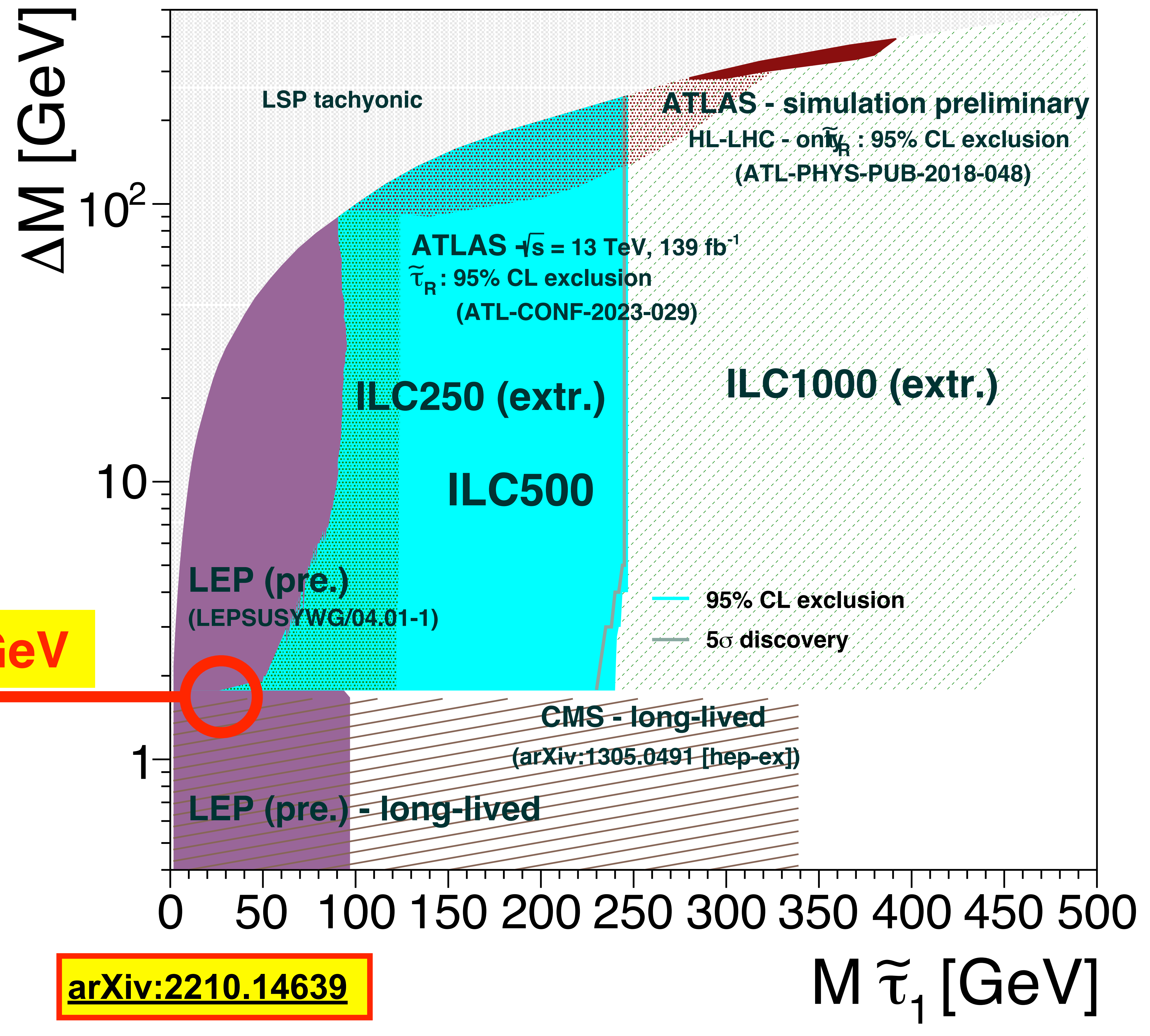

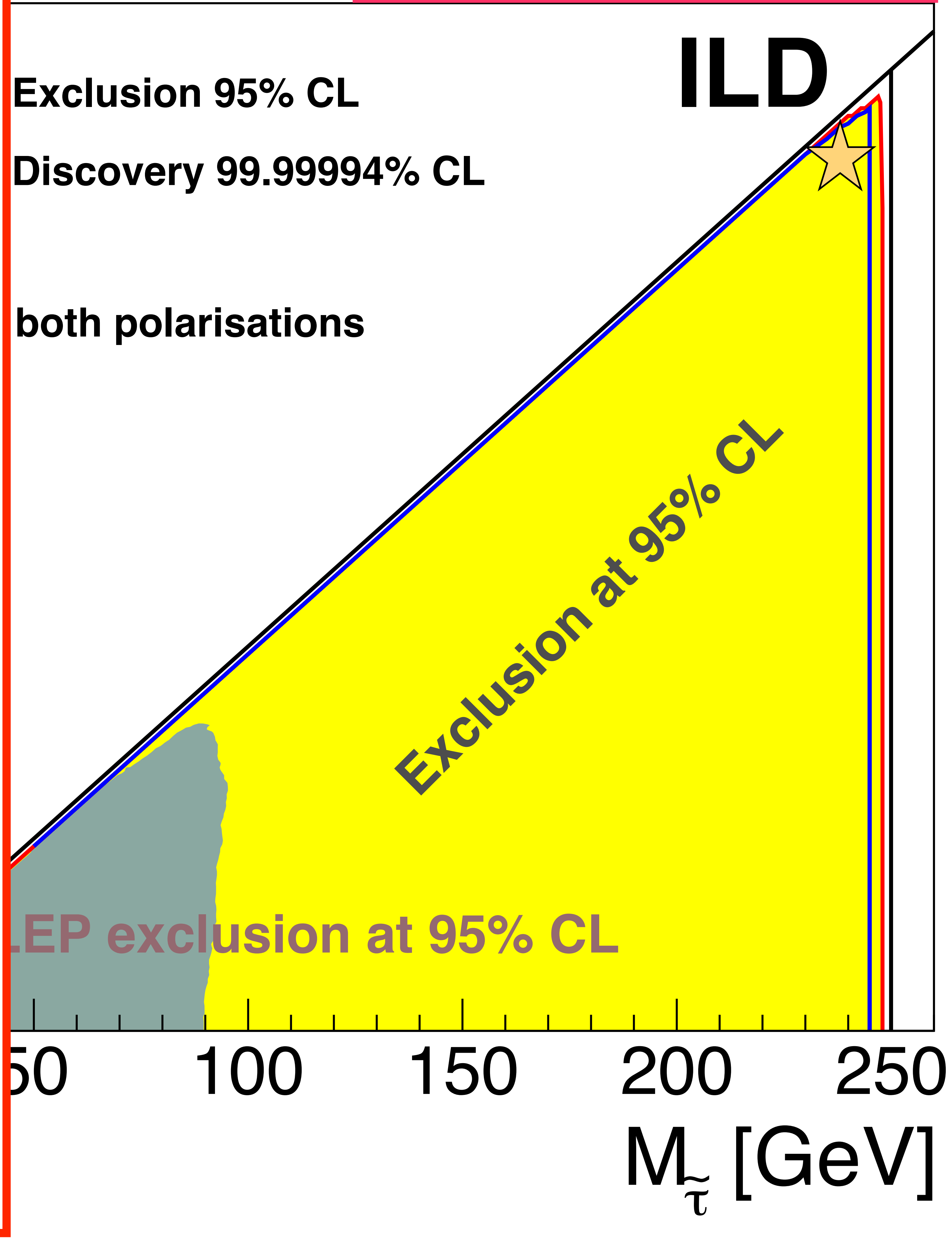

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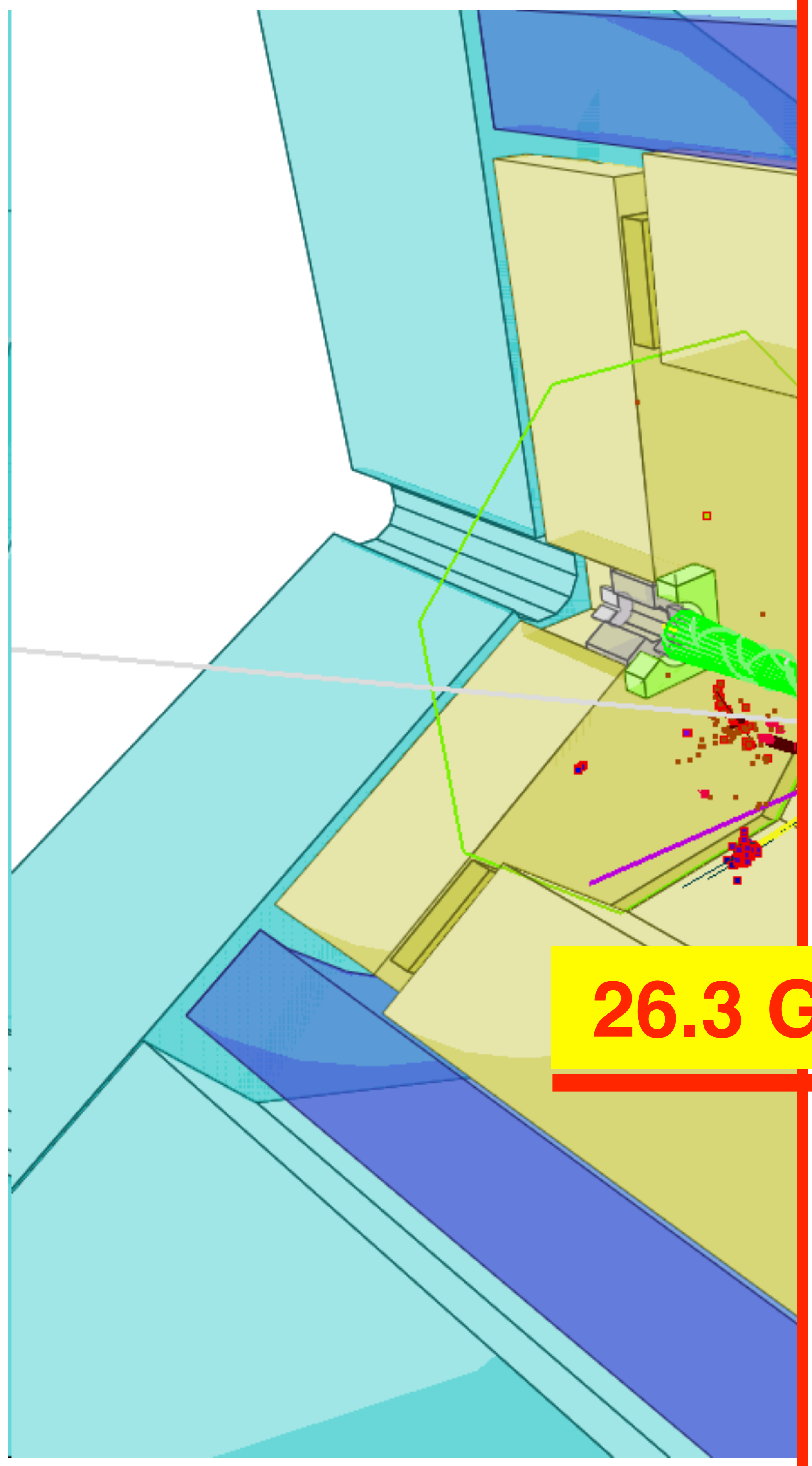

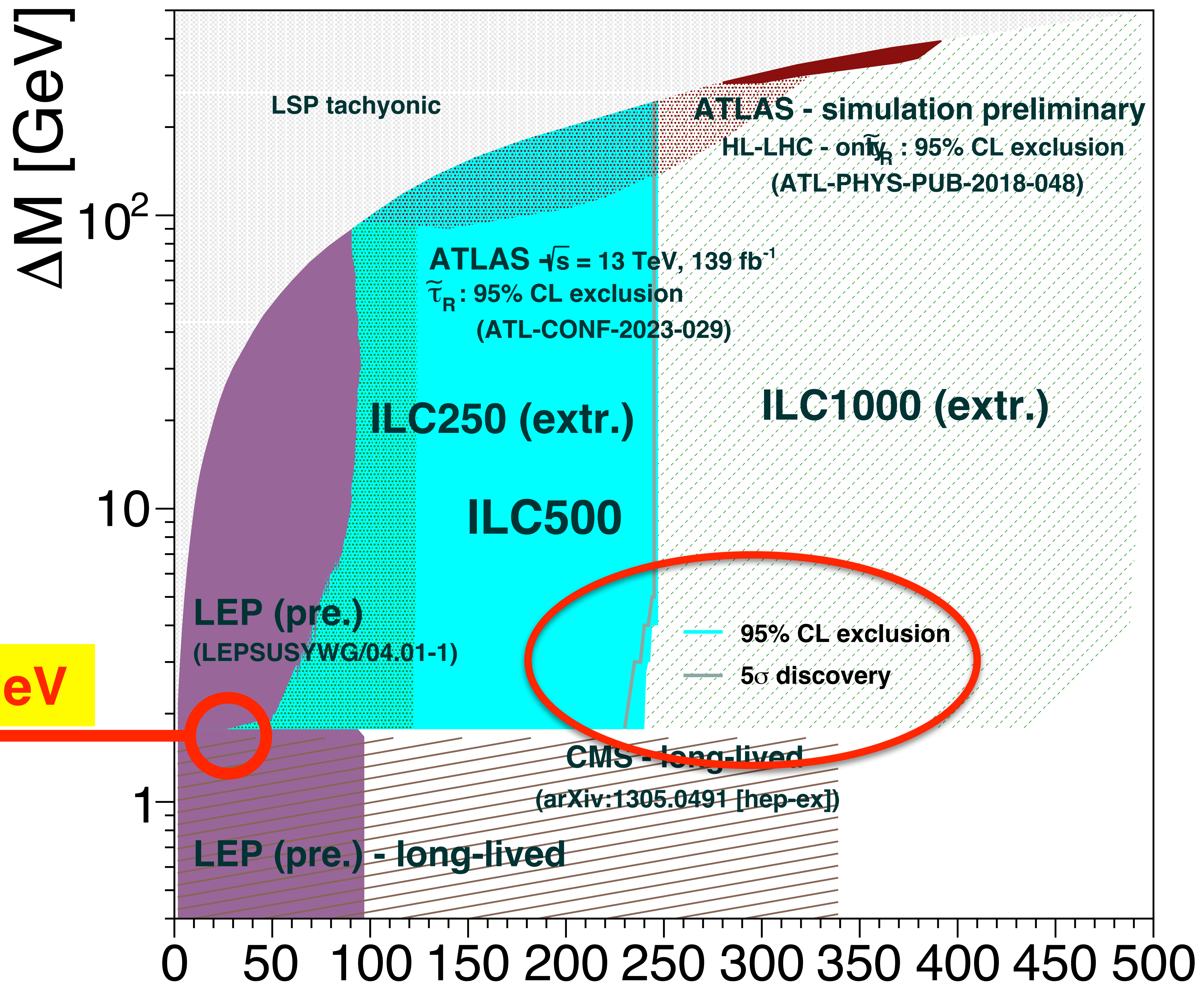

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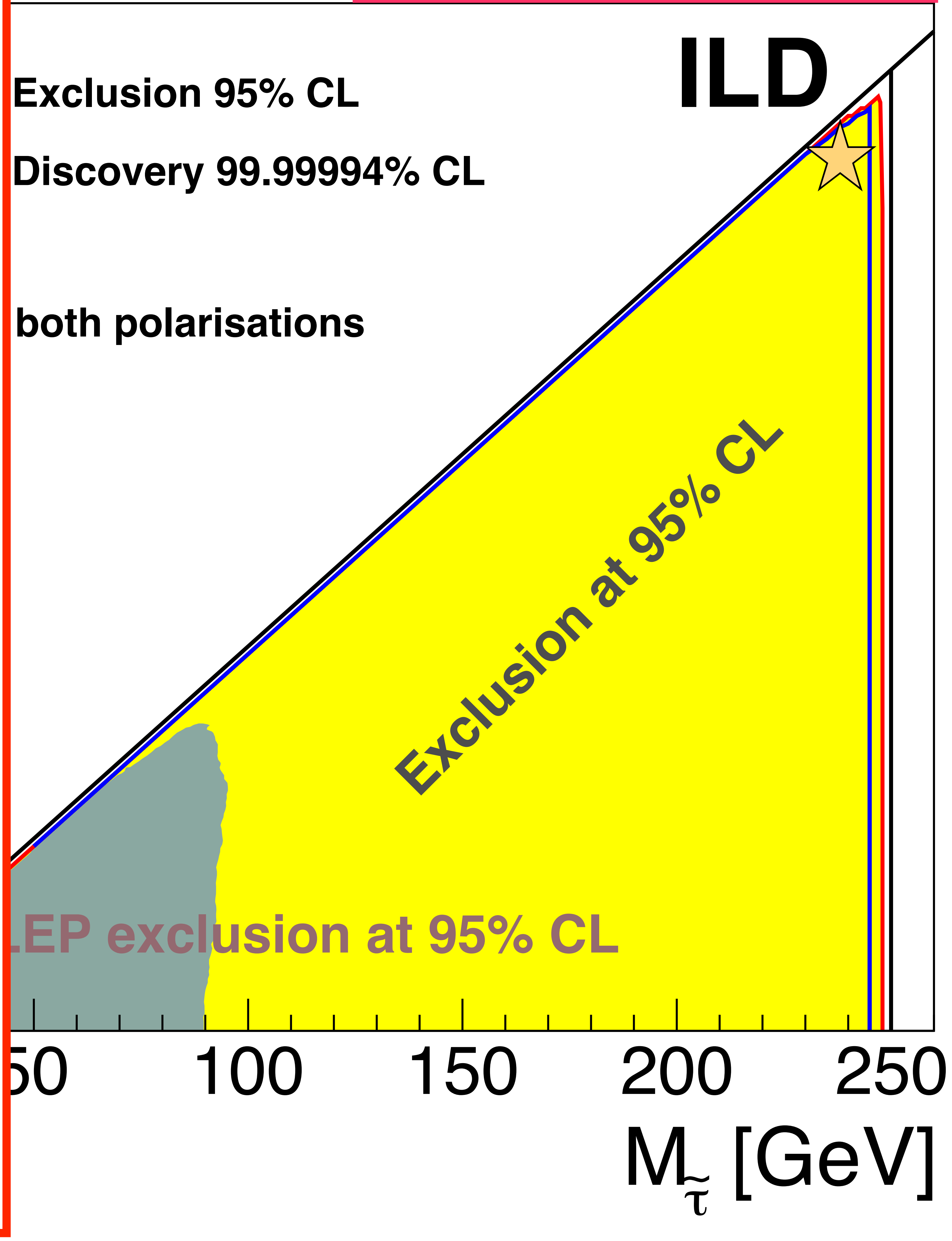

Example 2: Electroweakinos

Definition of "worst case" for e+e- collider => defines the benchmark for "LEP-style" definition of sensitivity

- MSSM, R-parity conservation (R-parity violation always easier at e^+e^-)
    - Caveat: also CP-conservation. The experimental implication of CP violation needs study
- sfermions not NLSP (idem, except $\tilde{\tau}$ but even worse for FCChh...)
- Then: LSP is Bino, Wino, or Higgsino (more or less pure), same for the NLSP
- M_1, M_2 and μ are the main-players.
- Consider any values, and combinations of signs, up to values that makes the bosinos out-of-reach for any new facility $\sim$ a few TeV.
- Also vary other parameters (β, M_A, $M_{sfermion}$) with less impact.
- No other prejudice.

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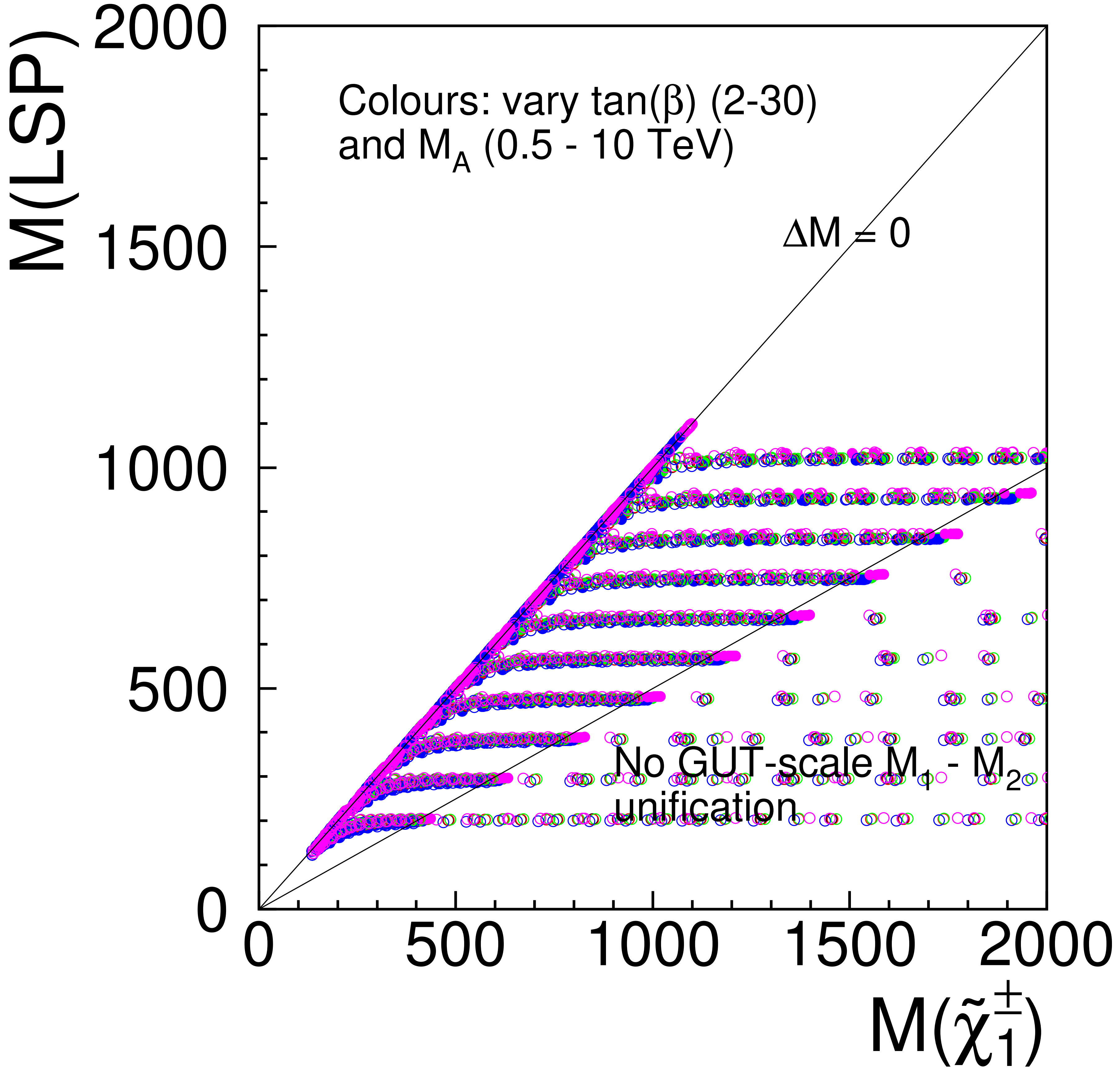
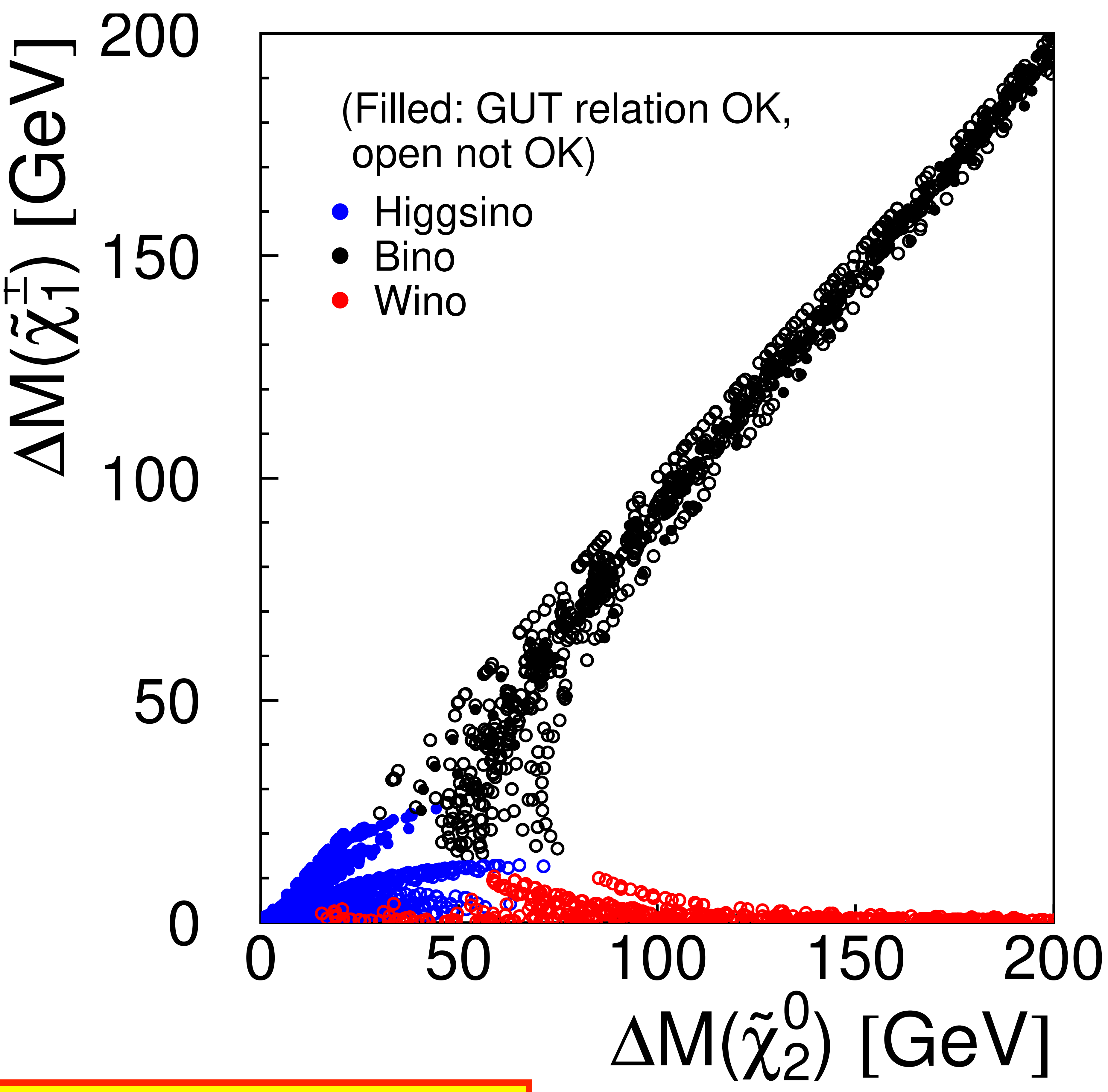
- with this definition even more generic than LEP:
- no GUT-scale gaugino mass unification enforced!

Electroweakino parameter space with this definition

Definition of "worst case" for e+e- collider => defines the benchmark for "LEP-style" definition of sensitivity





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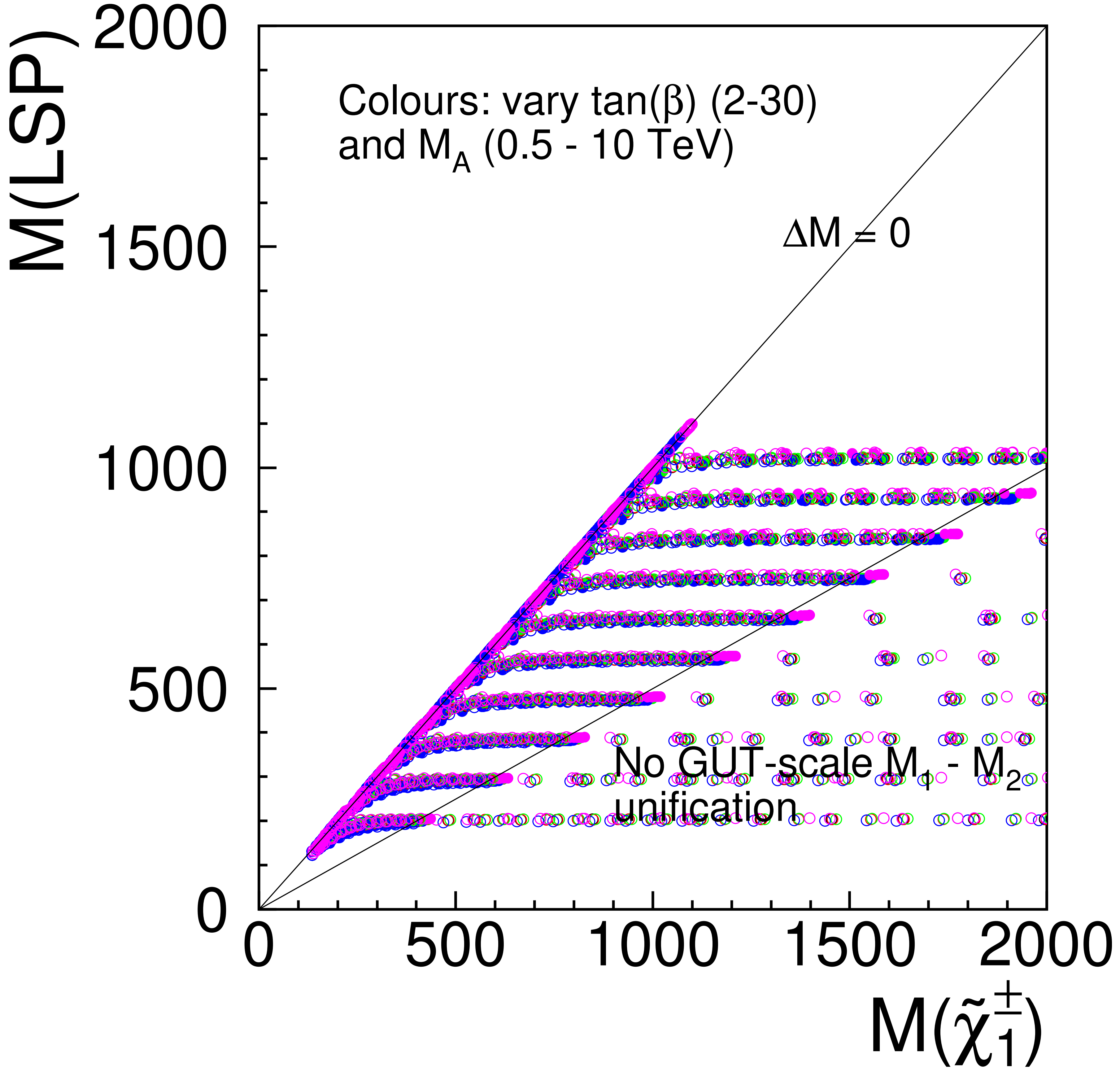
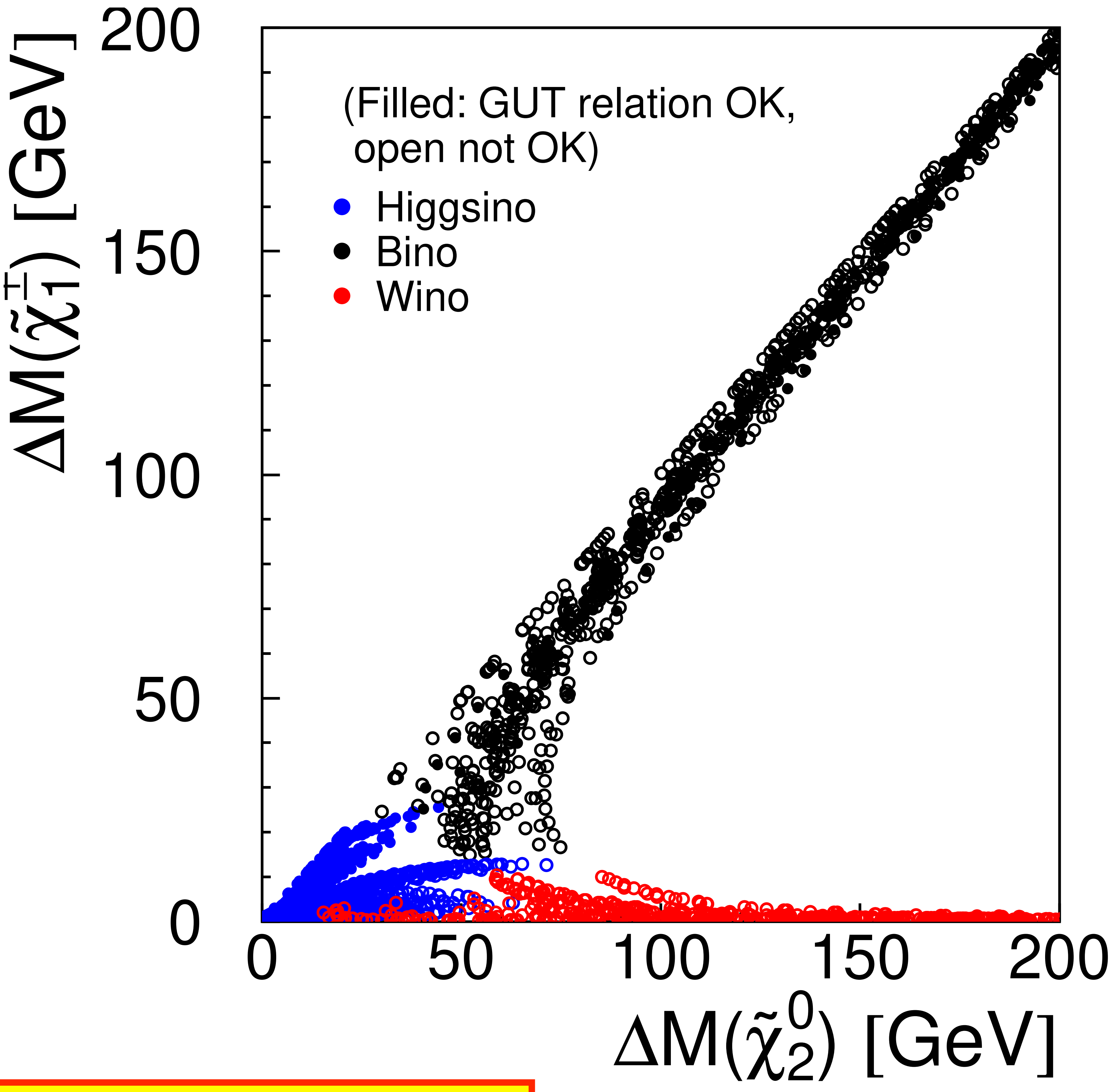


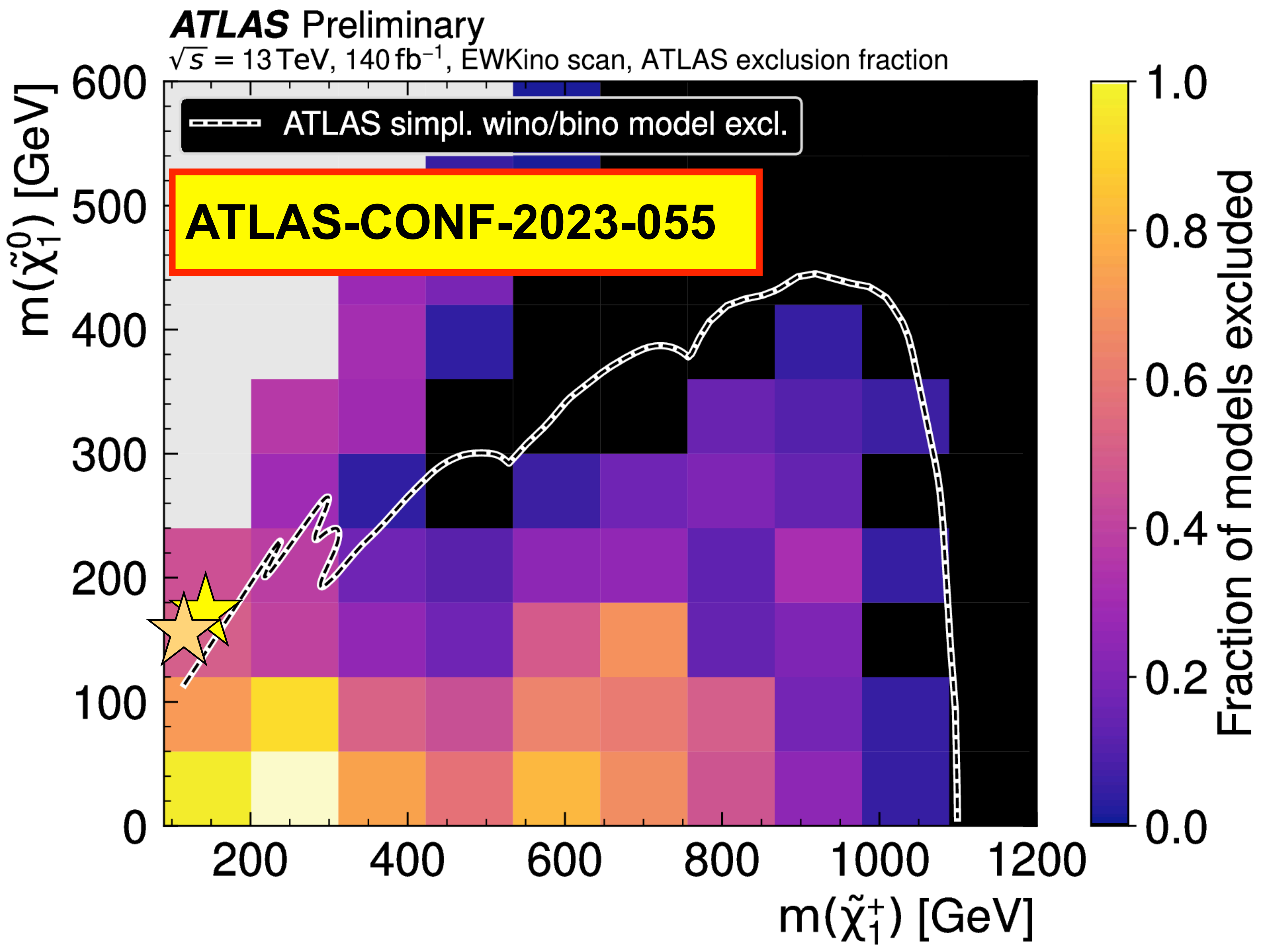


arXiv:2003.12391

- assumption of M(cha1)=M(neu2) often not fulfilled
- even for Higgsinos-like cases
- beware of simplified models with this assumption

Light Higgsinos

Detailed simulation studies with ILD detector for ILC



- ILD study of full detector simulation for various benchmark points
- E.g. ☆☆ motivated by leptogenesis & gravitino DM - and extrapolation to full plane
- Fast-simulation and LEP-data informed extrapolation to whole parameter plane

=> “loop-hole free” discovery / exclusion potential up to ~ half E_{CM}

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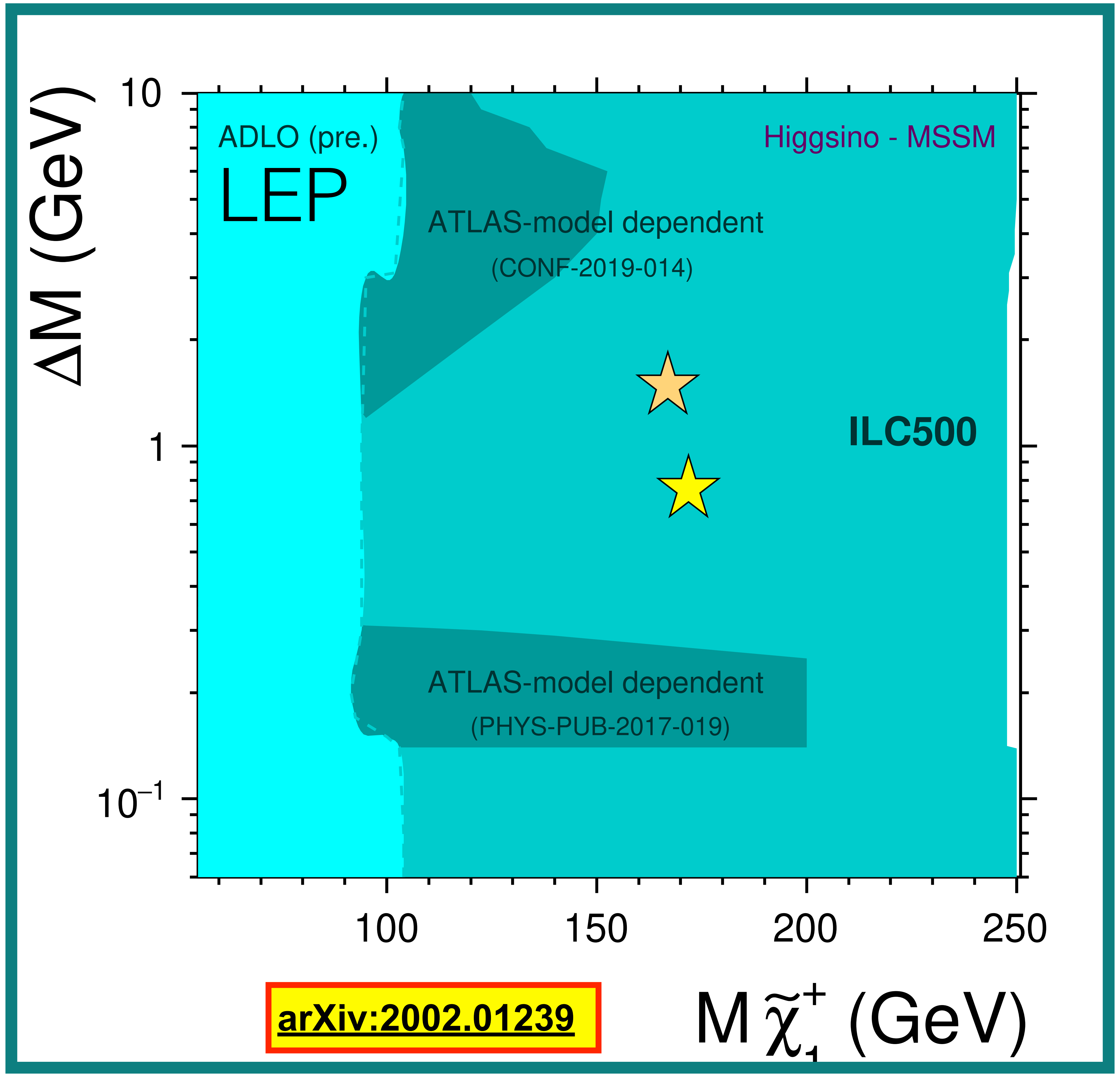

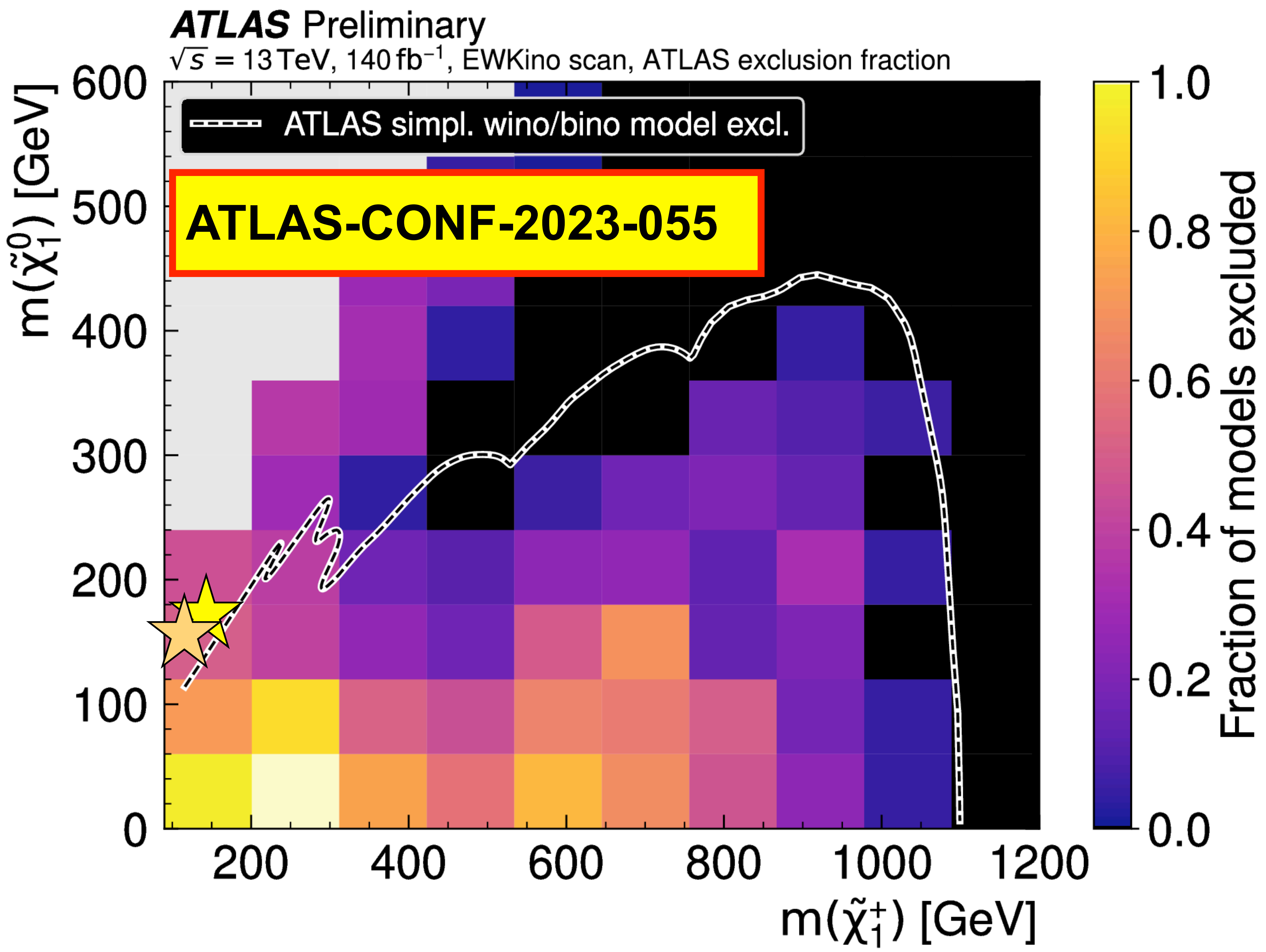

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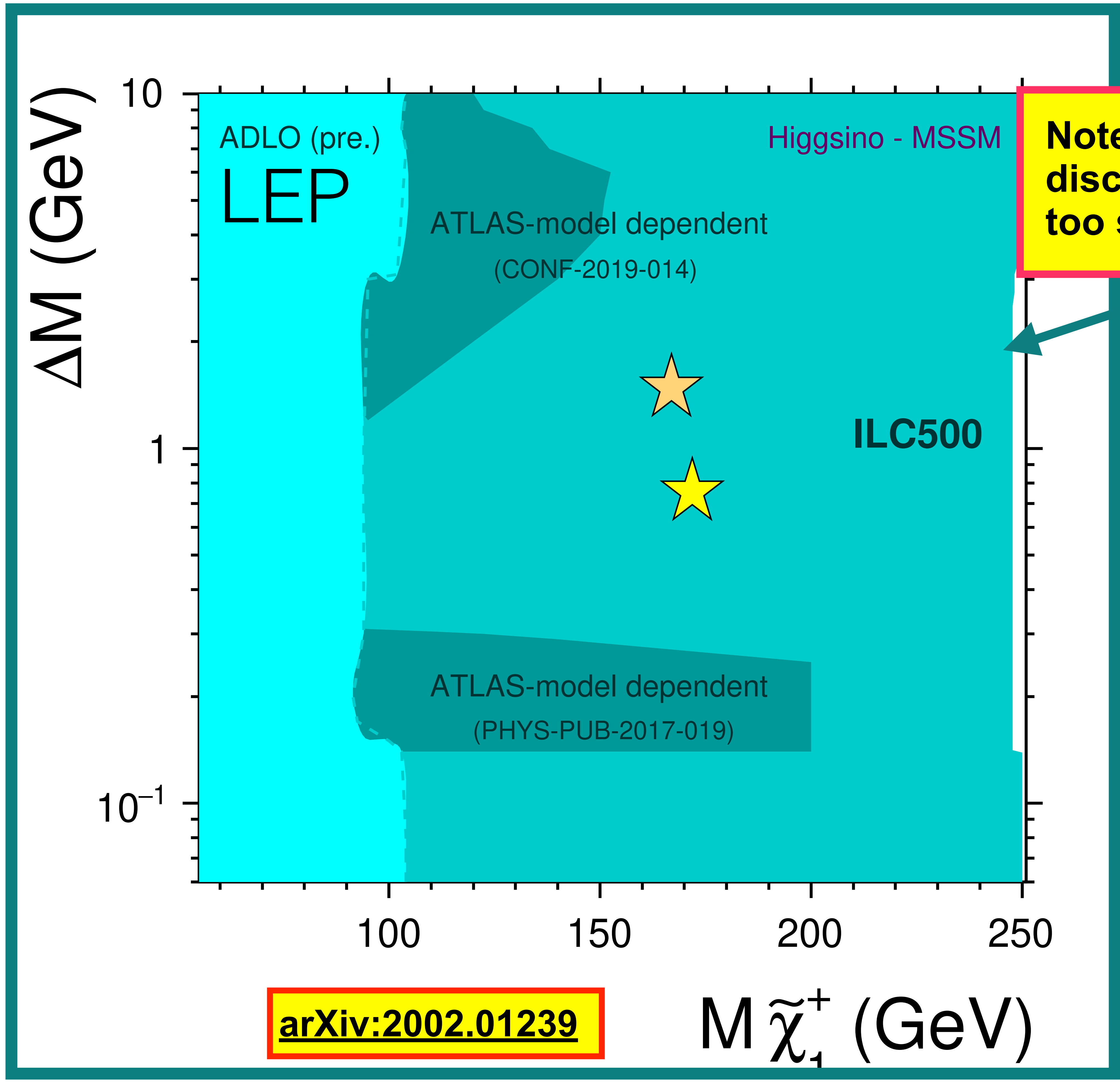
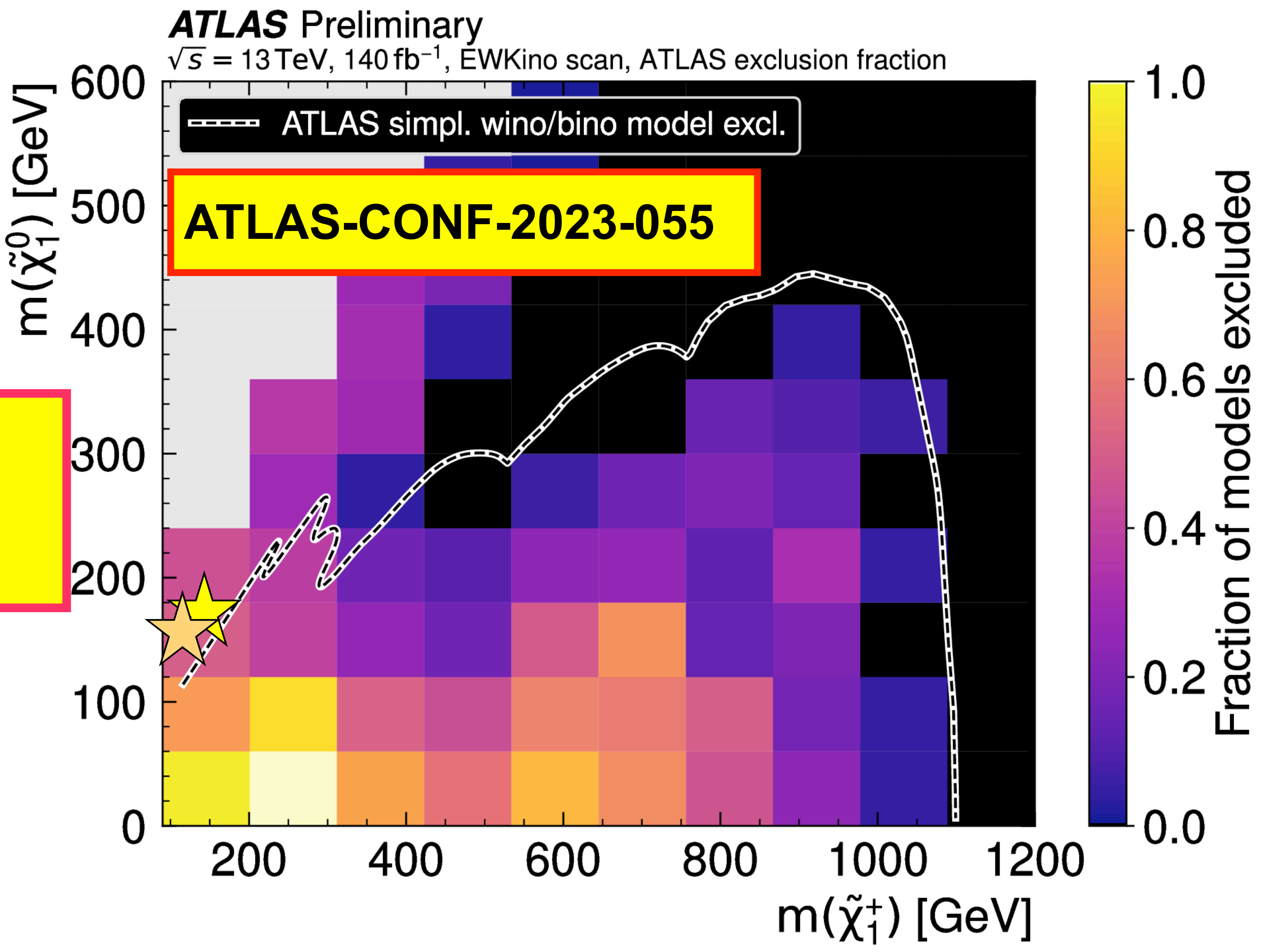


Note: difference between discovery and exclusion reach too small to be visible here!



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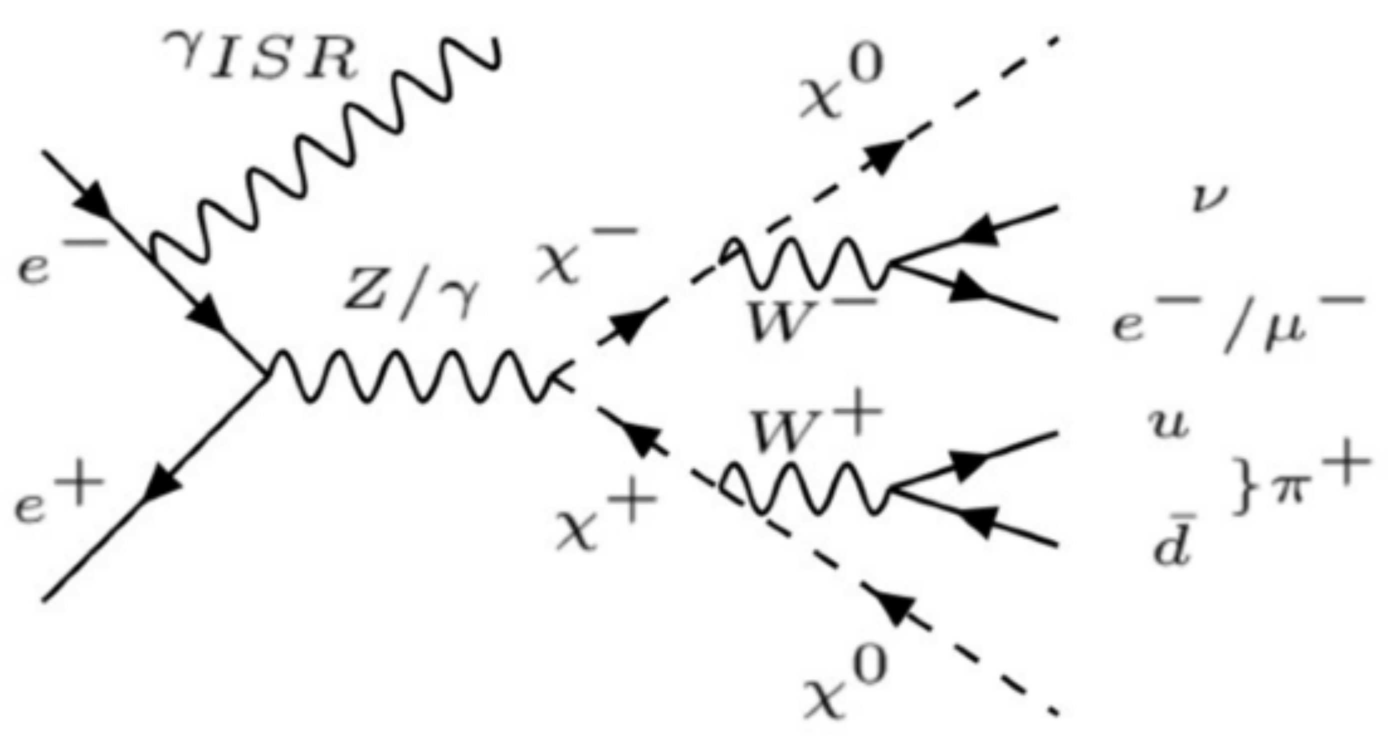
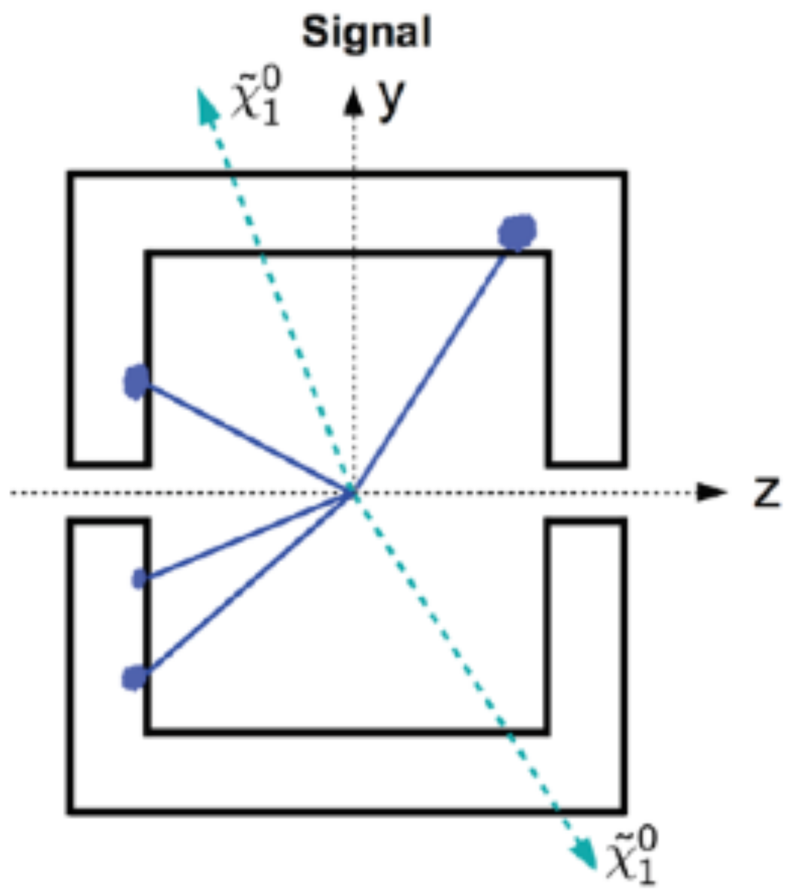
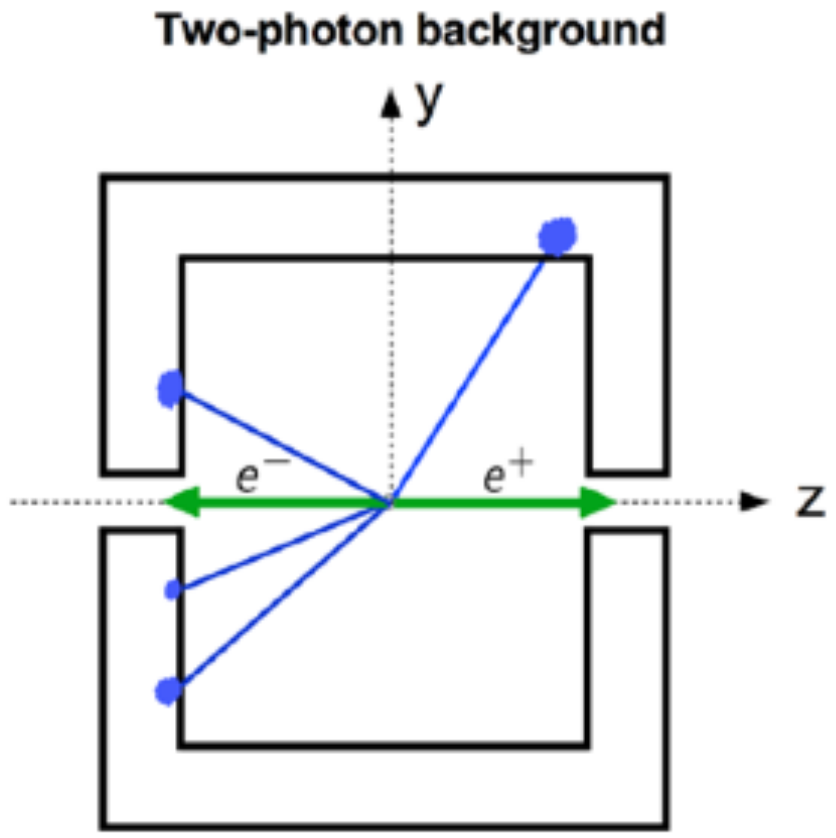
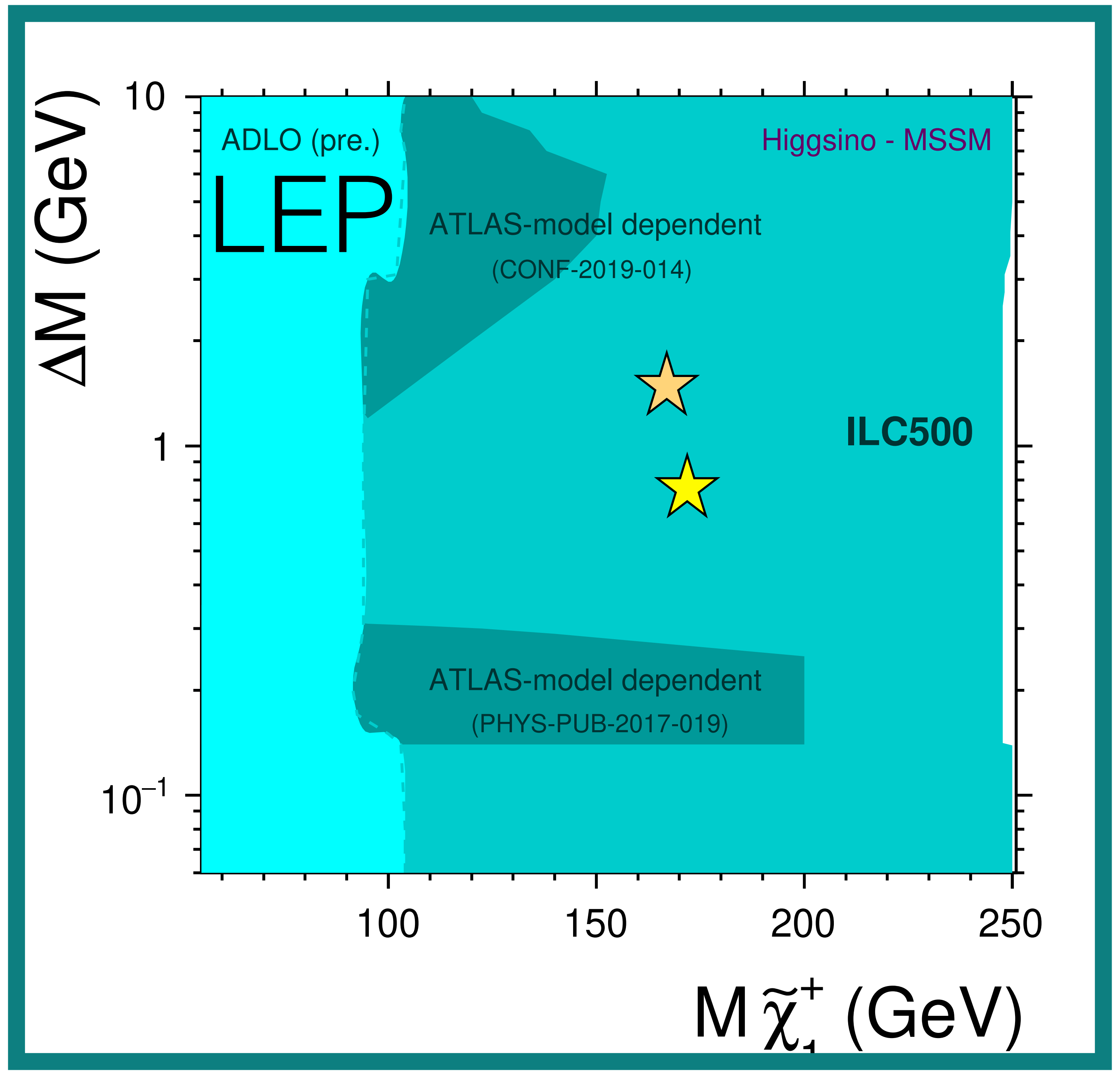
Light Higgsinos

From mass and cross-section measurements to SUSY parameters









- **Δ**M ~ 1 GeV: charginos decay to single, very soft **π**± / **μ** / e
- pt < 2…4 GeV
- ISR photon required to distinguish from two-photon processes
- even in these most challenging cases:
  - few % precision on masses & cross-sections
  - SUSY parameter determination, cross-check with cosmology
- **prediction of gaugino masses**

=> energy scale for next pp collider!

Light Higgsinos

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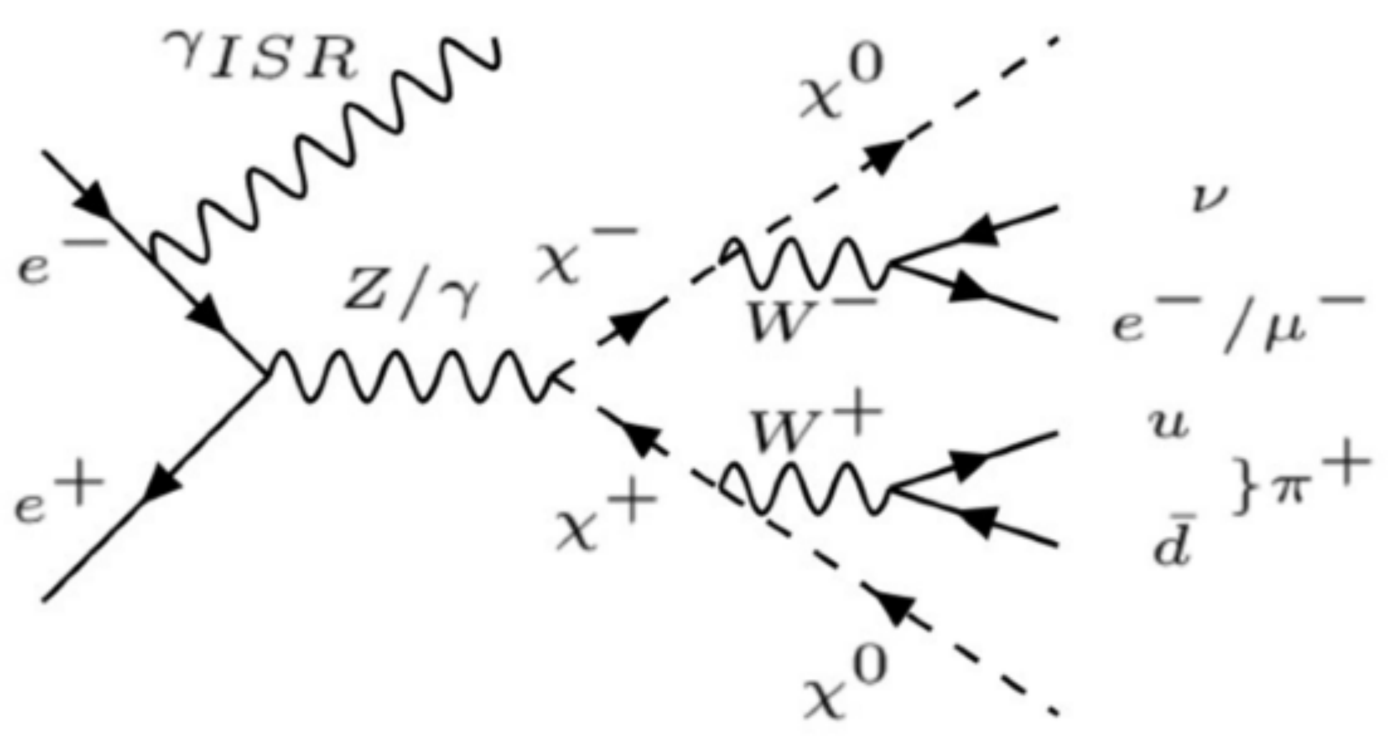

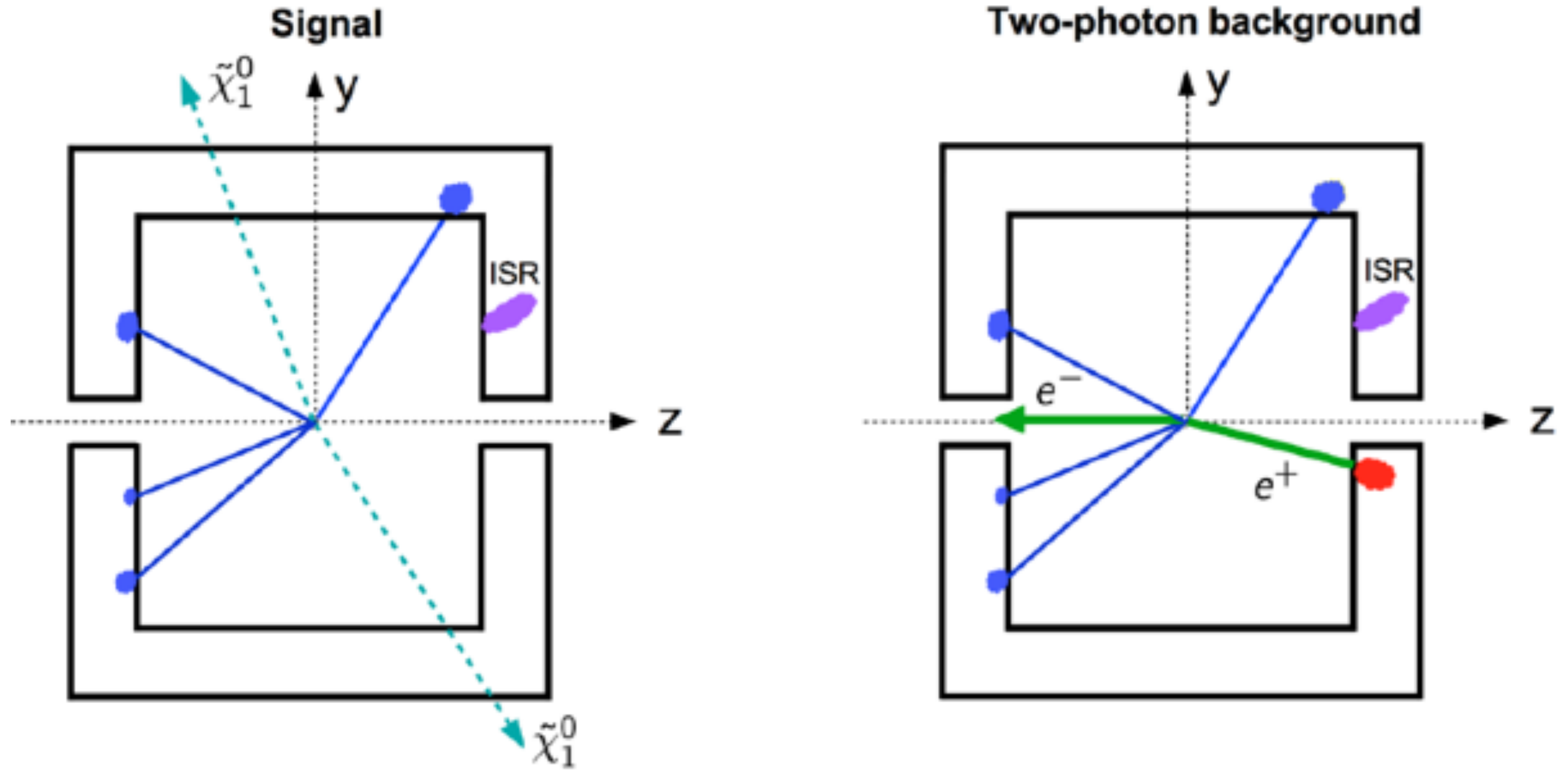

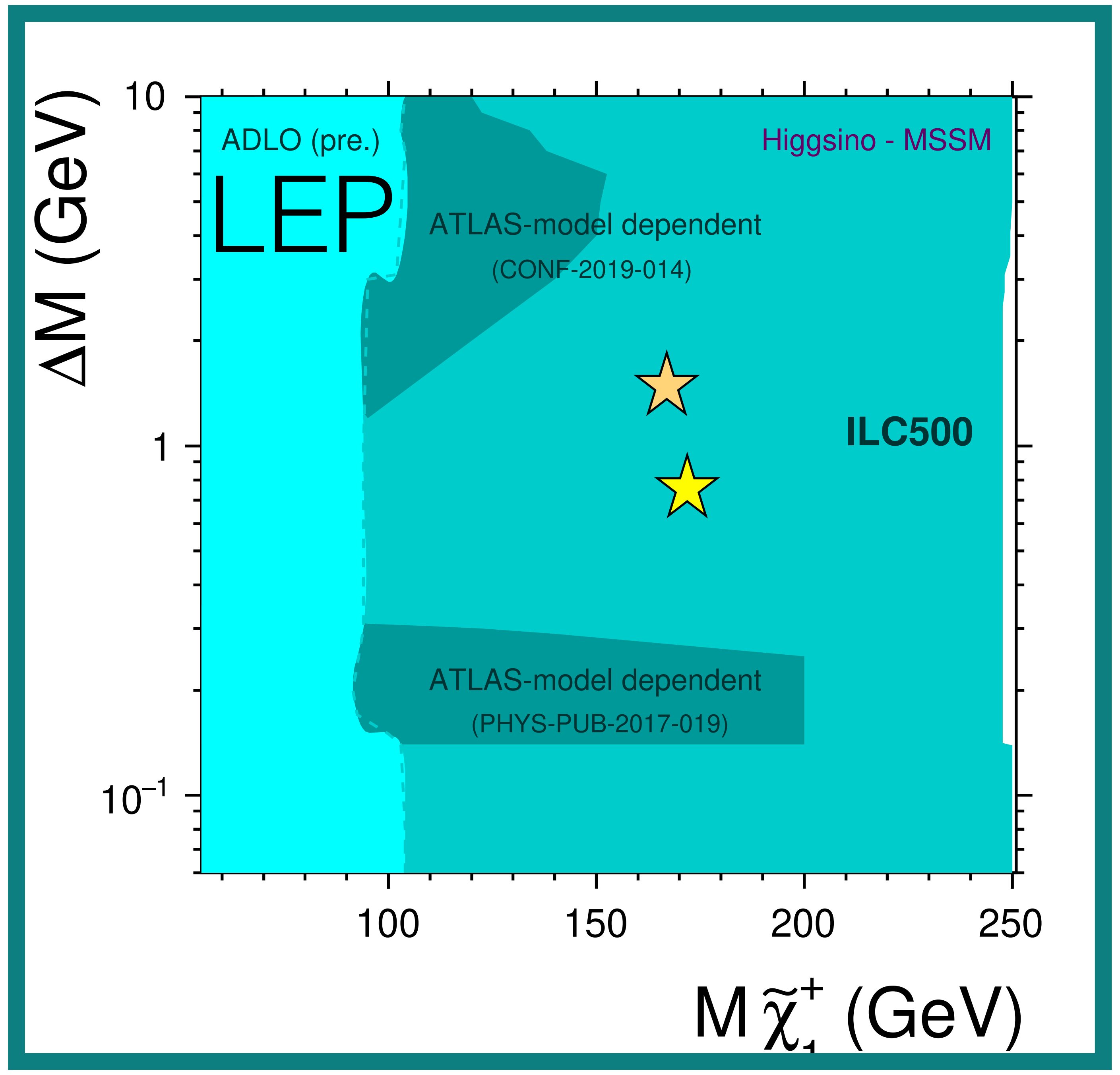

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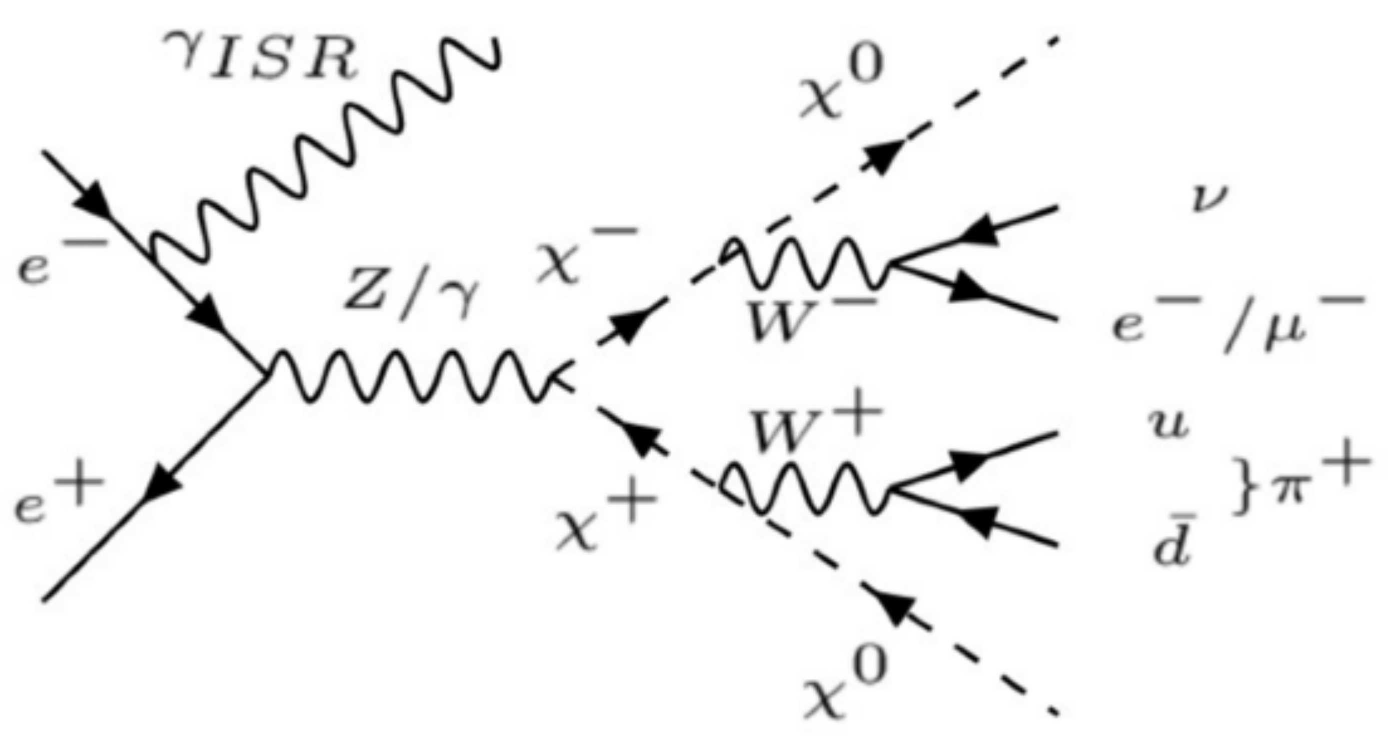
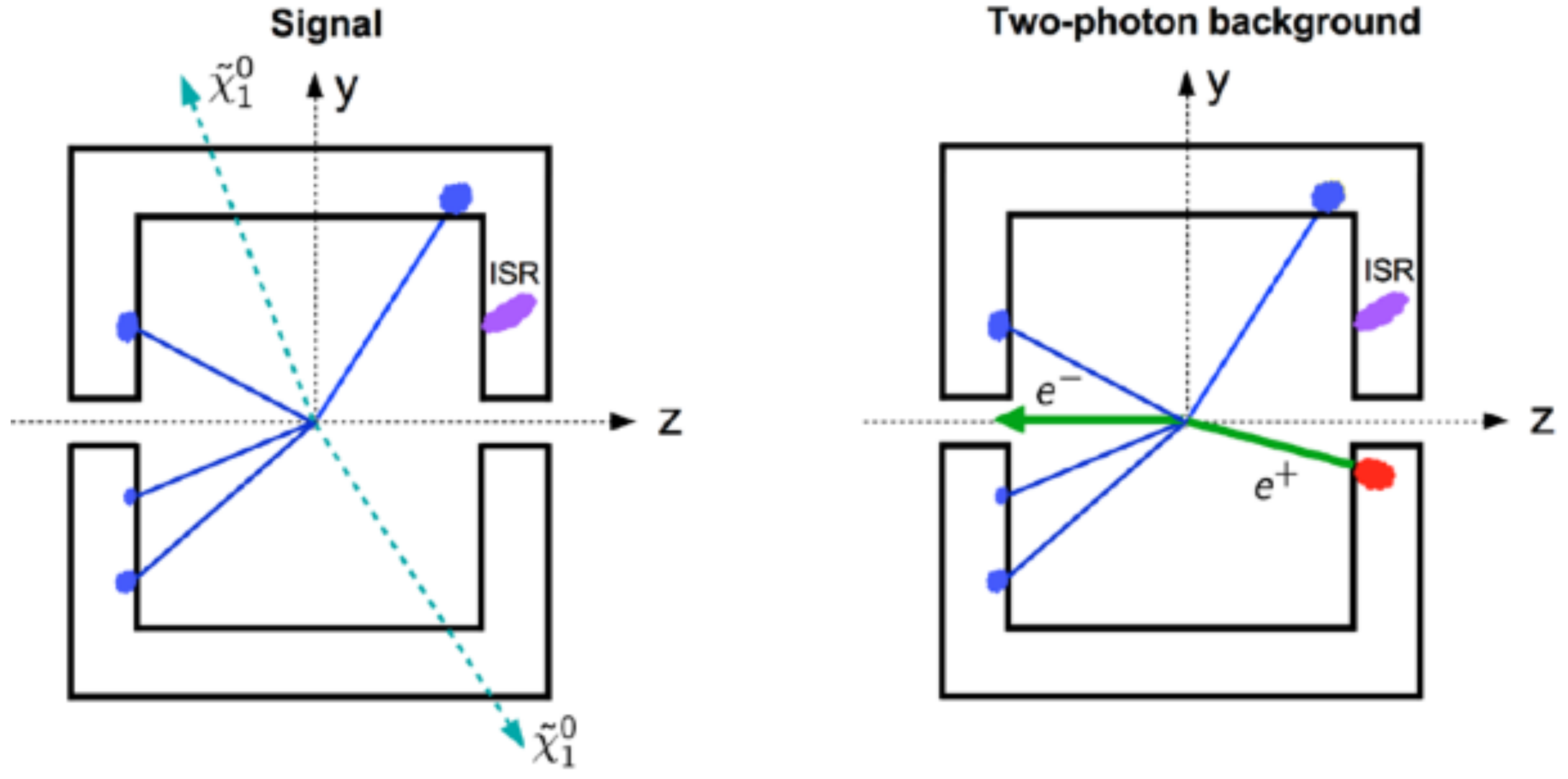
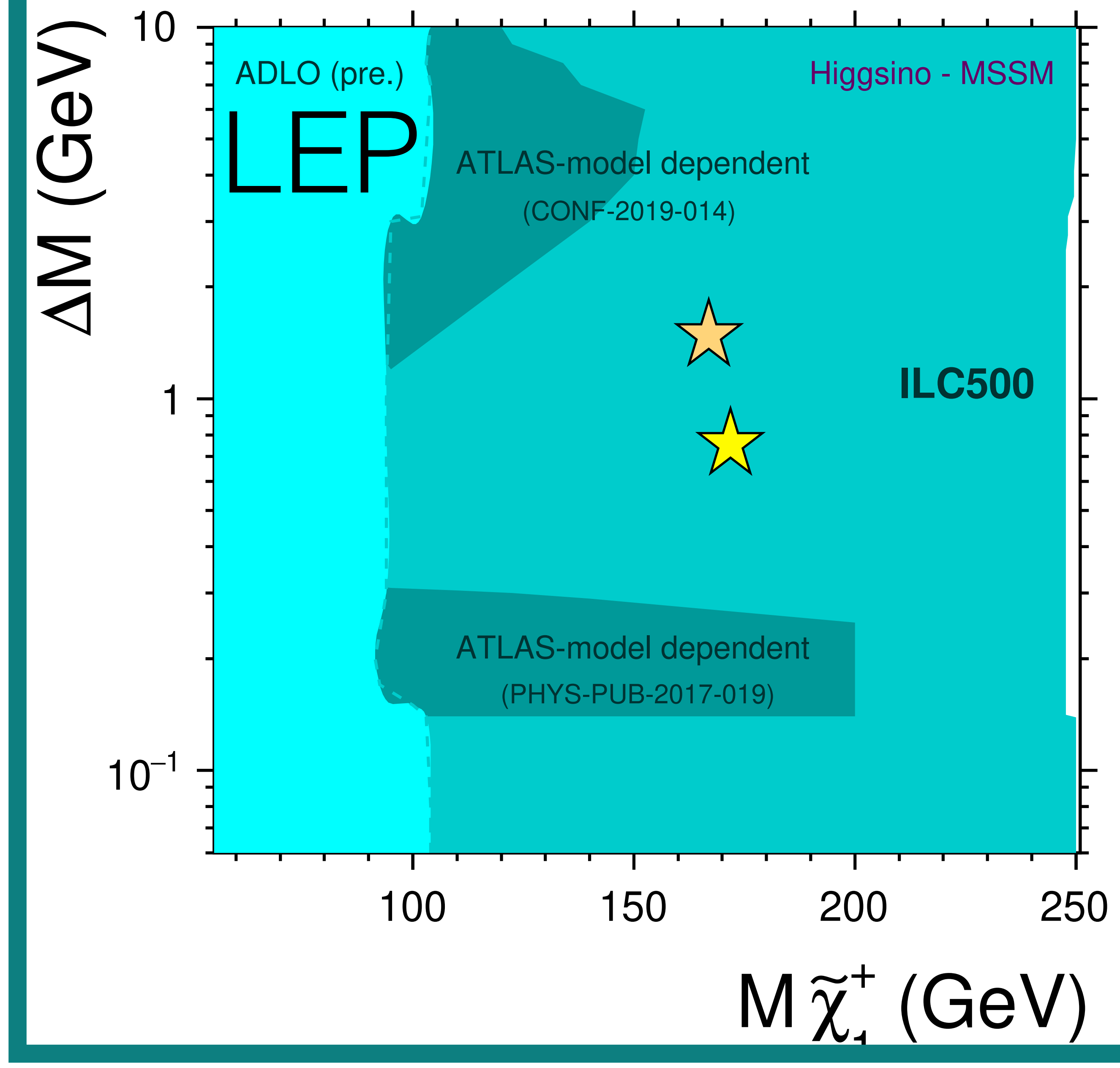
From mass and cross-section measurements to SUSY parameters

detector hermeticity is crucial!







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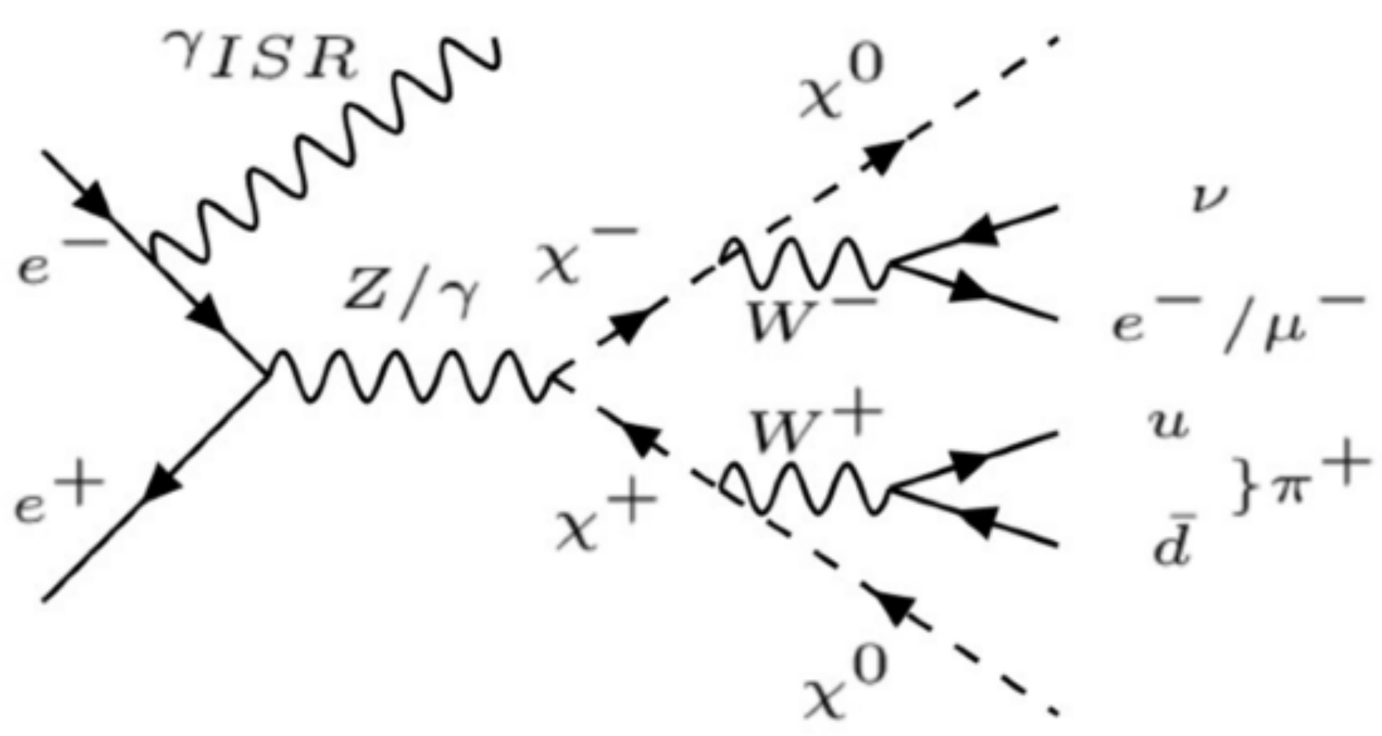
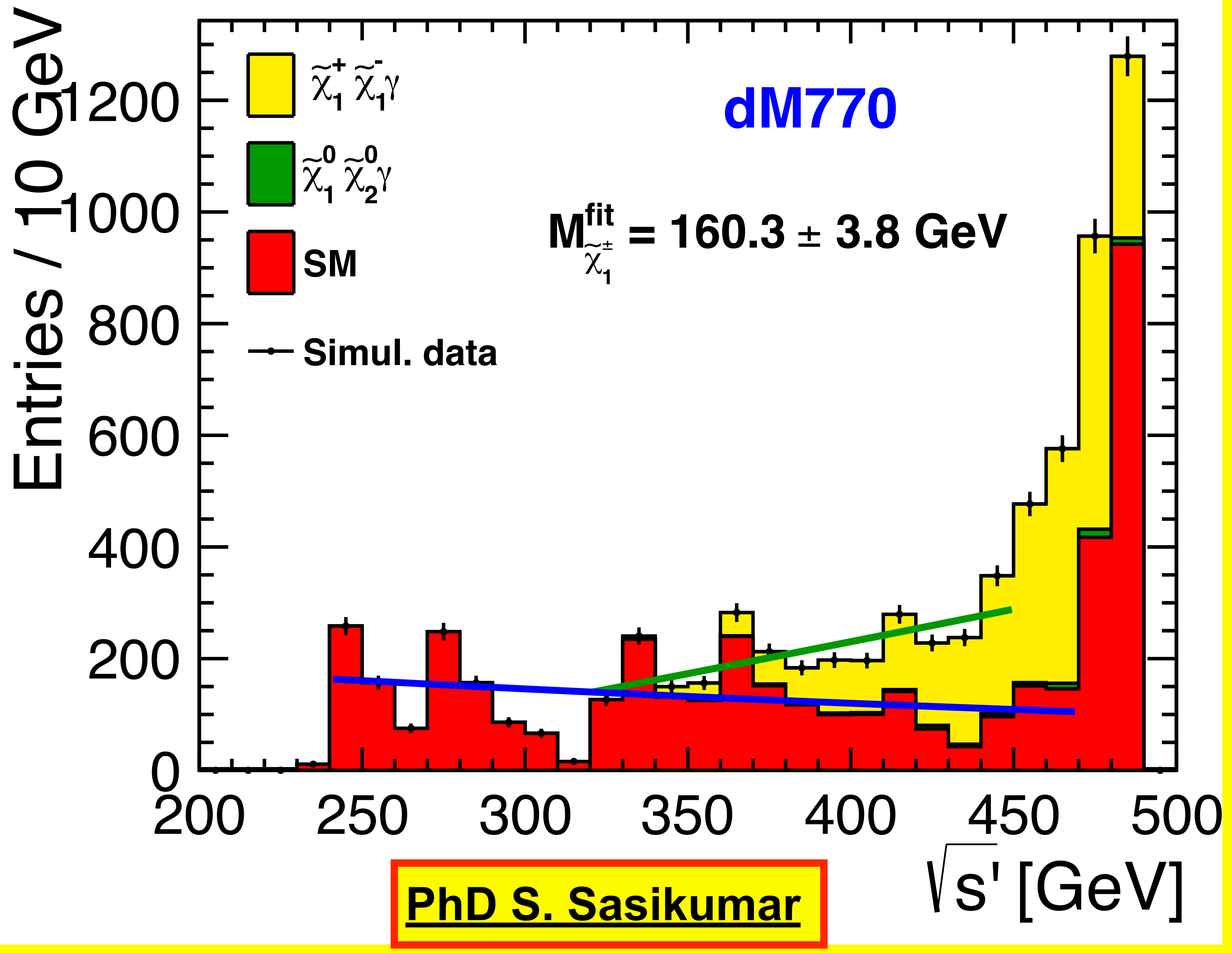
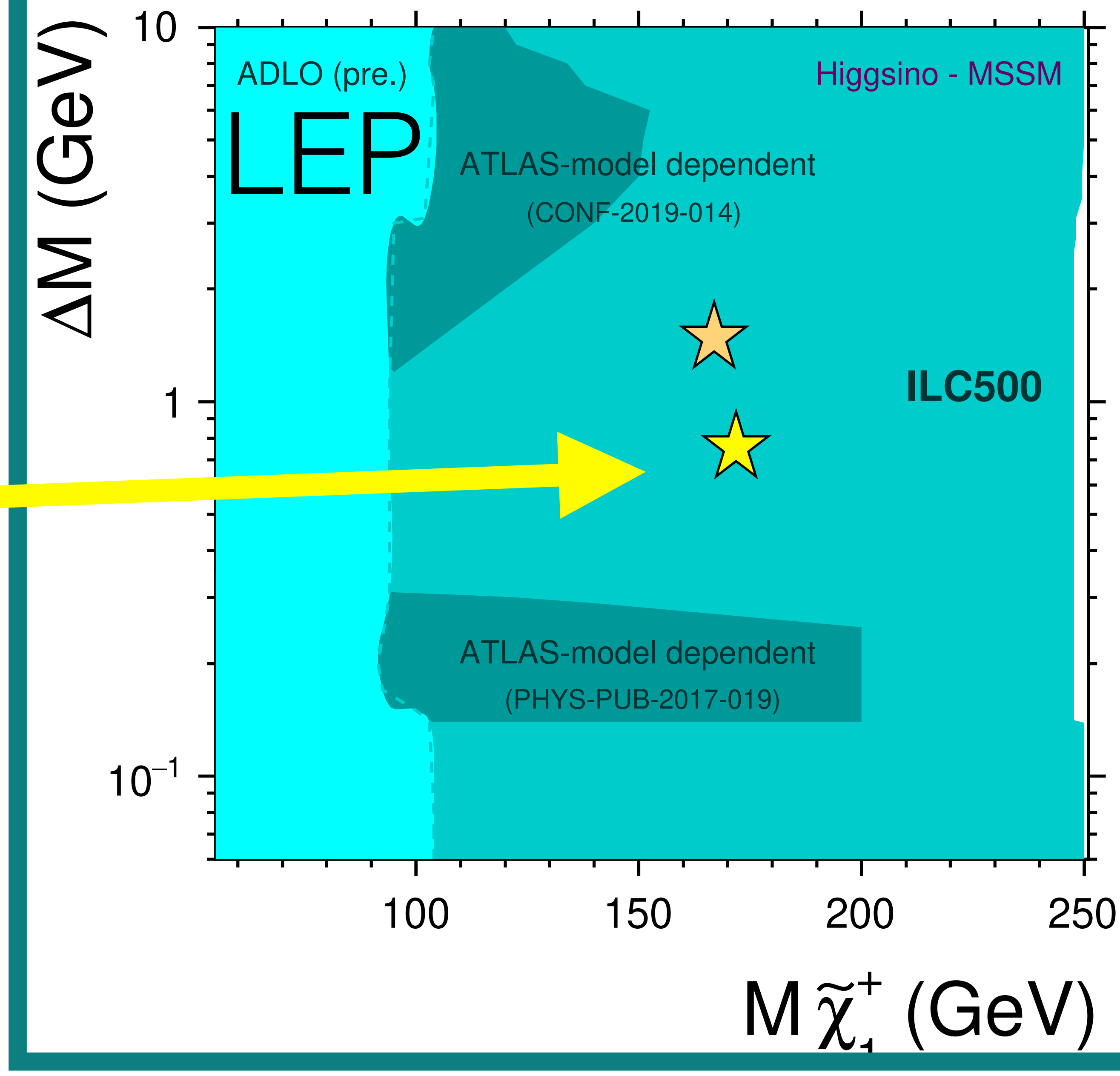




PhD S. Sasikumar



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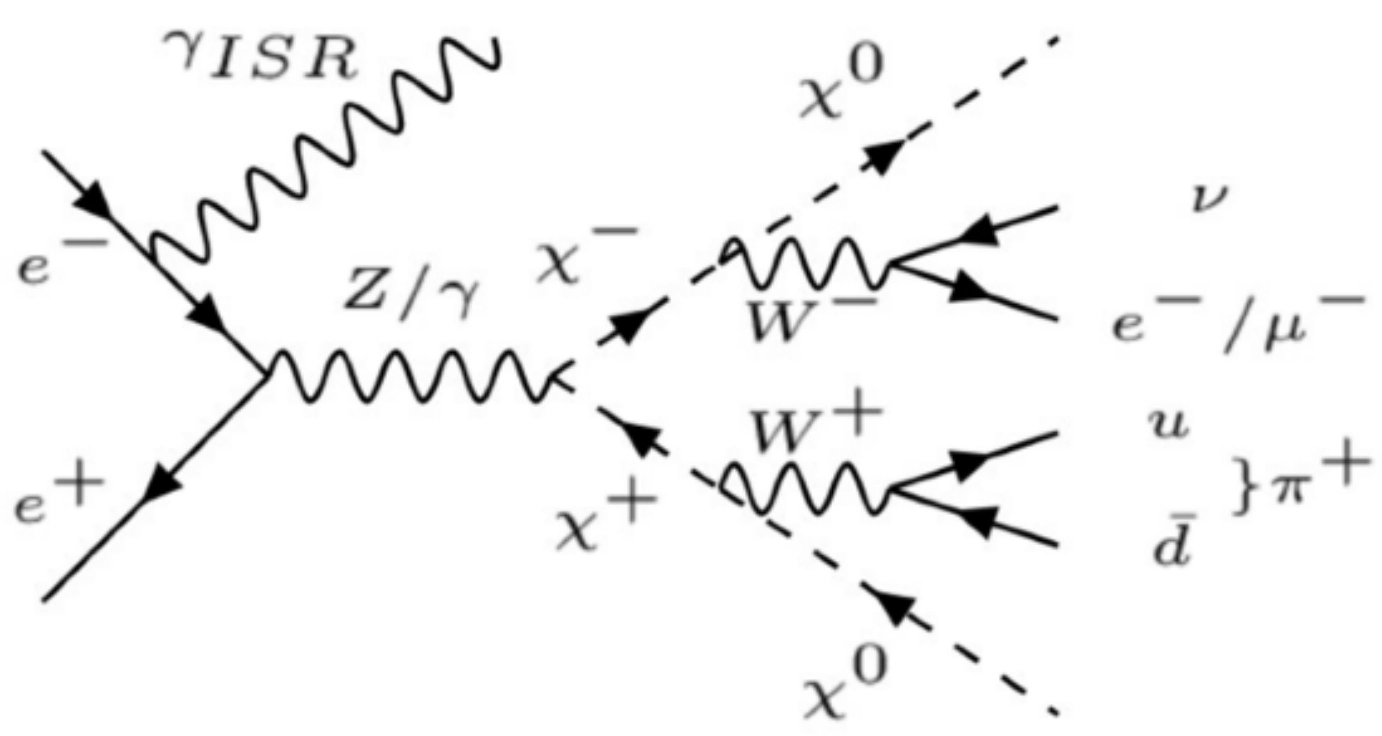

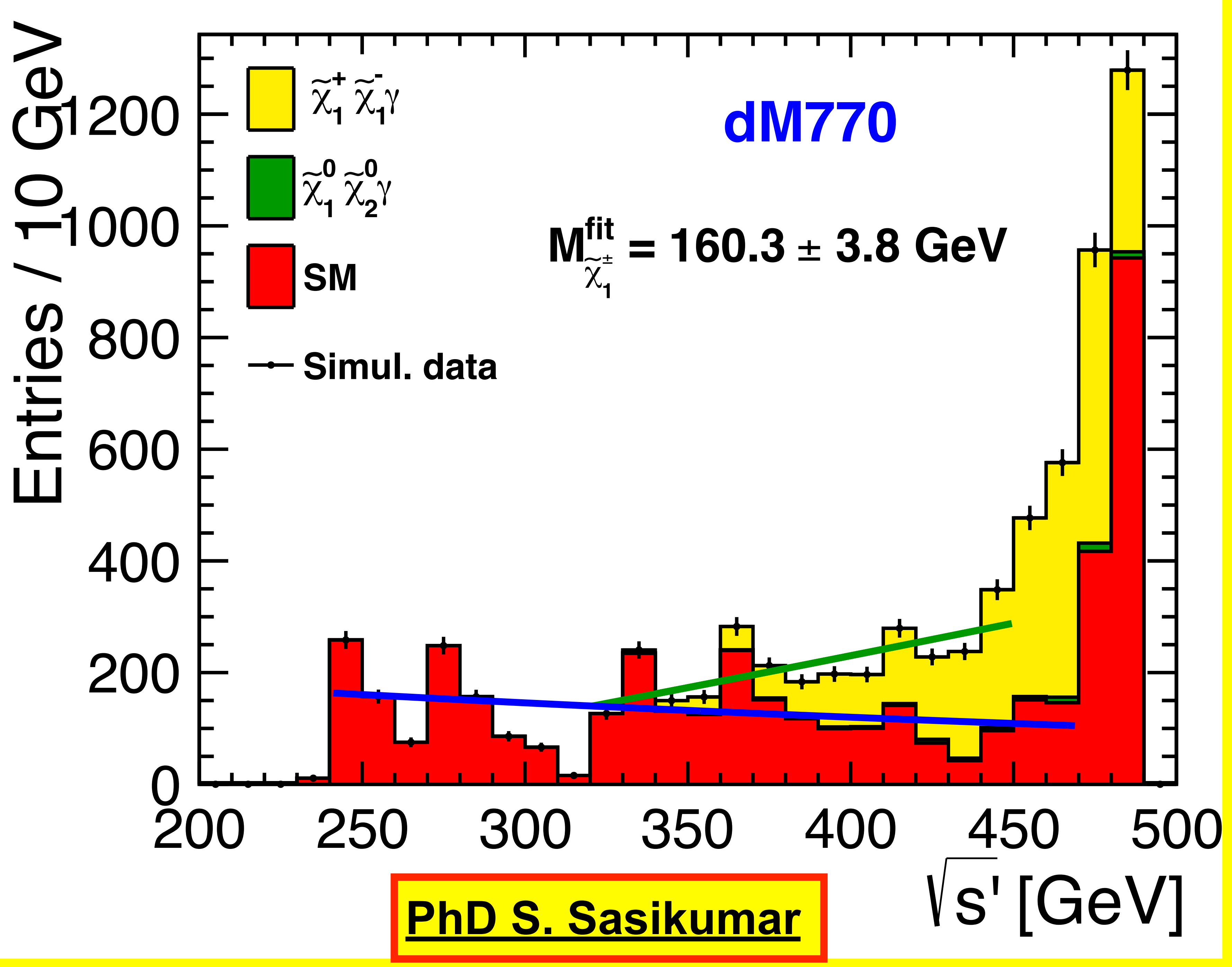

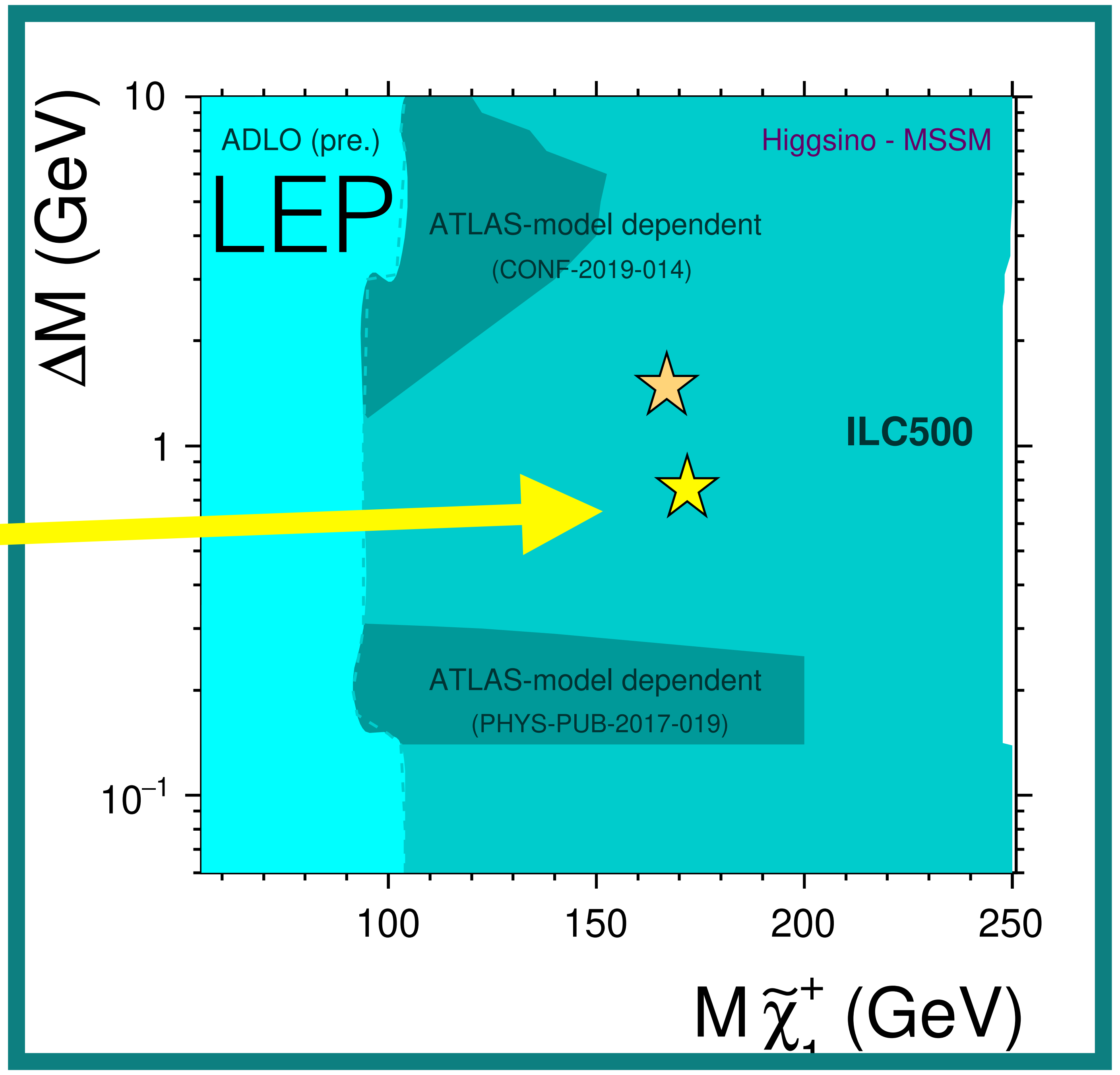

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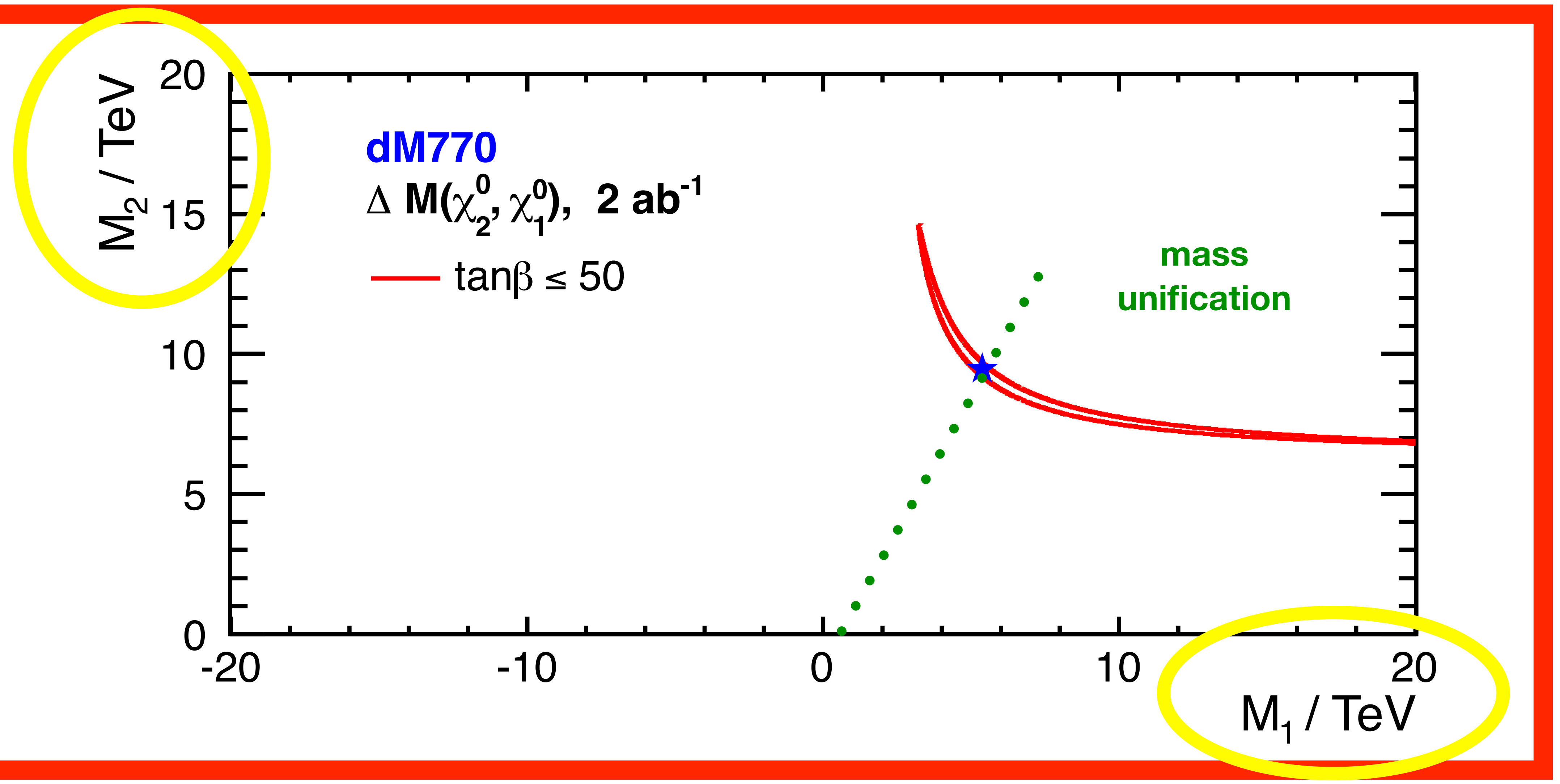

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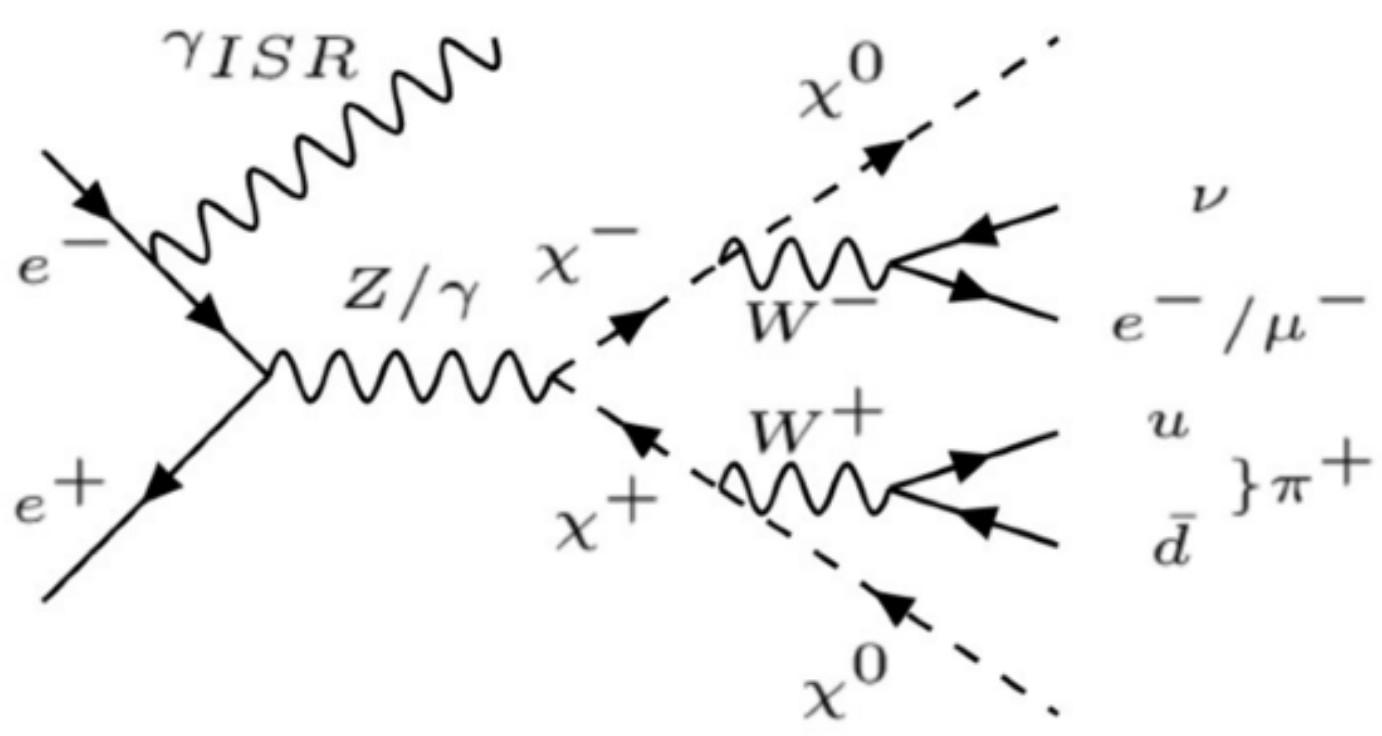

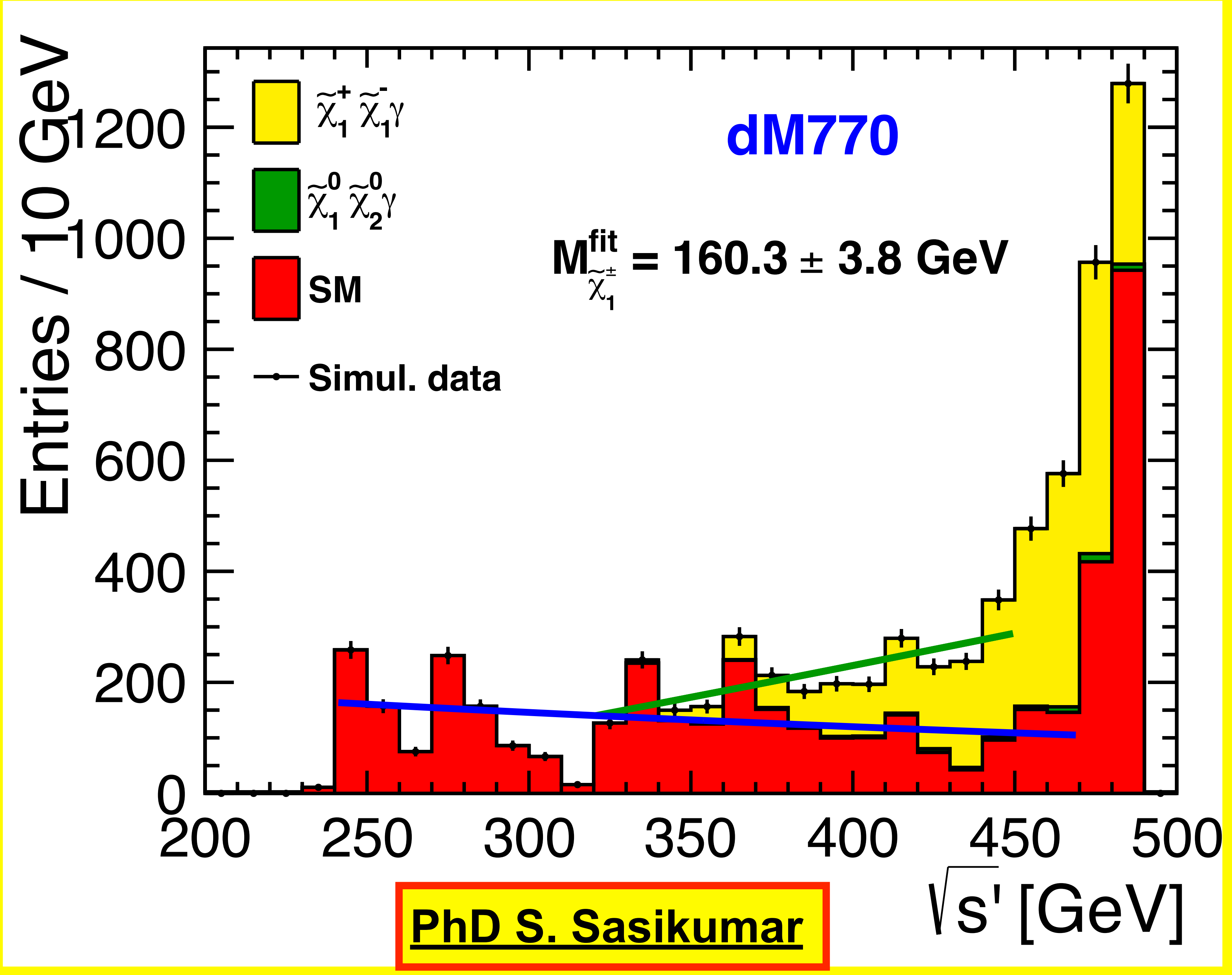

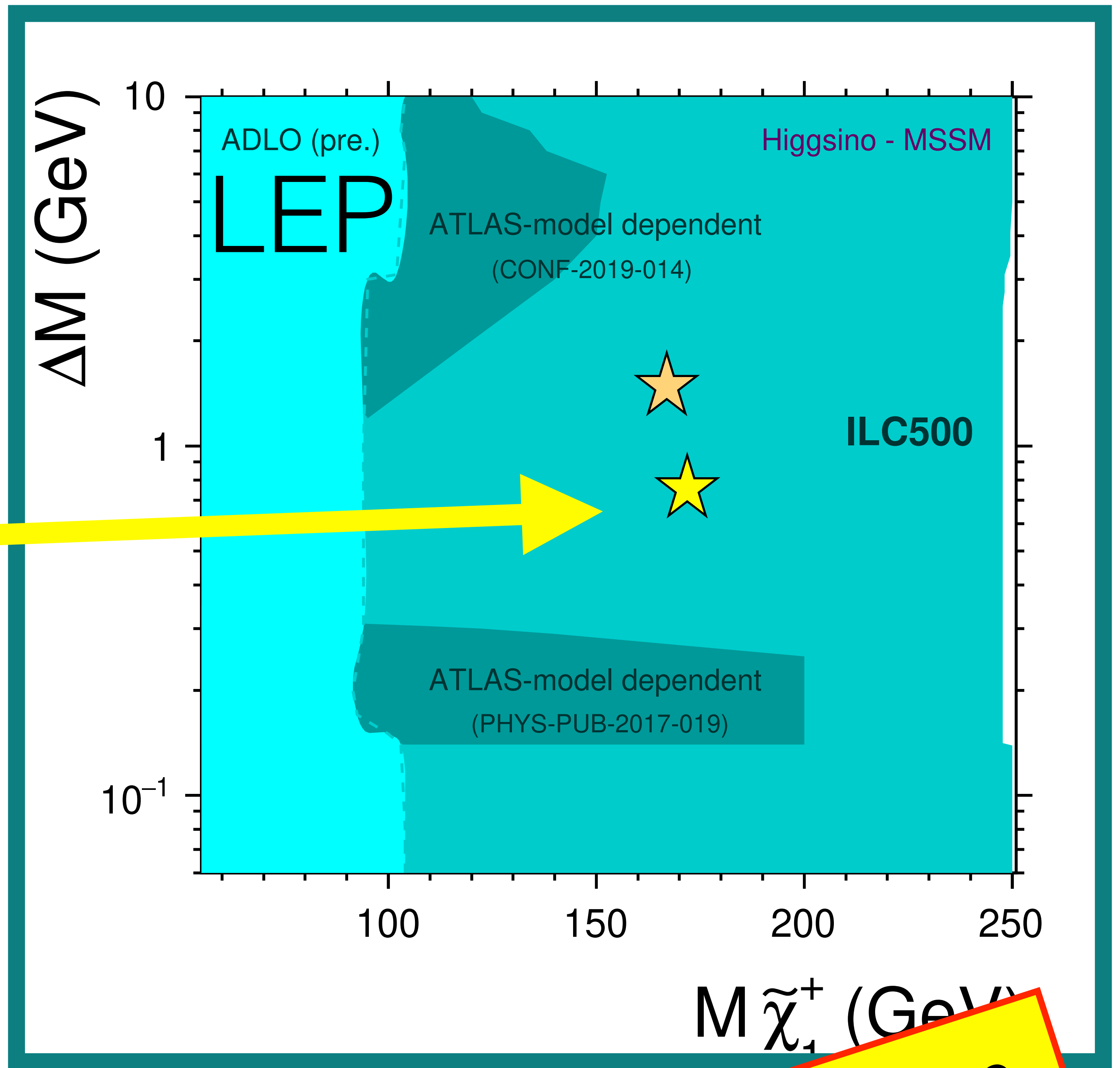

=> important guidance for 100 TeV pp collider!

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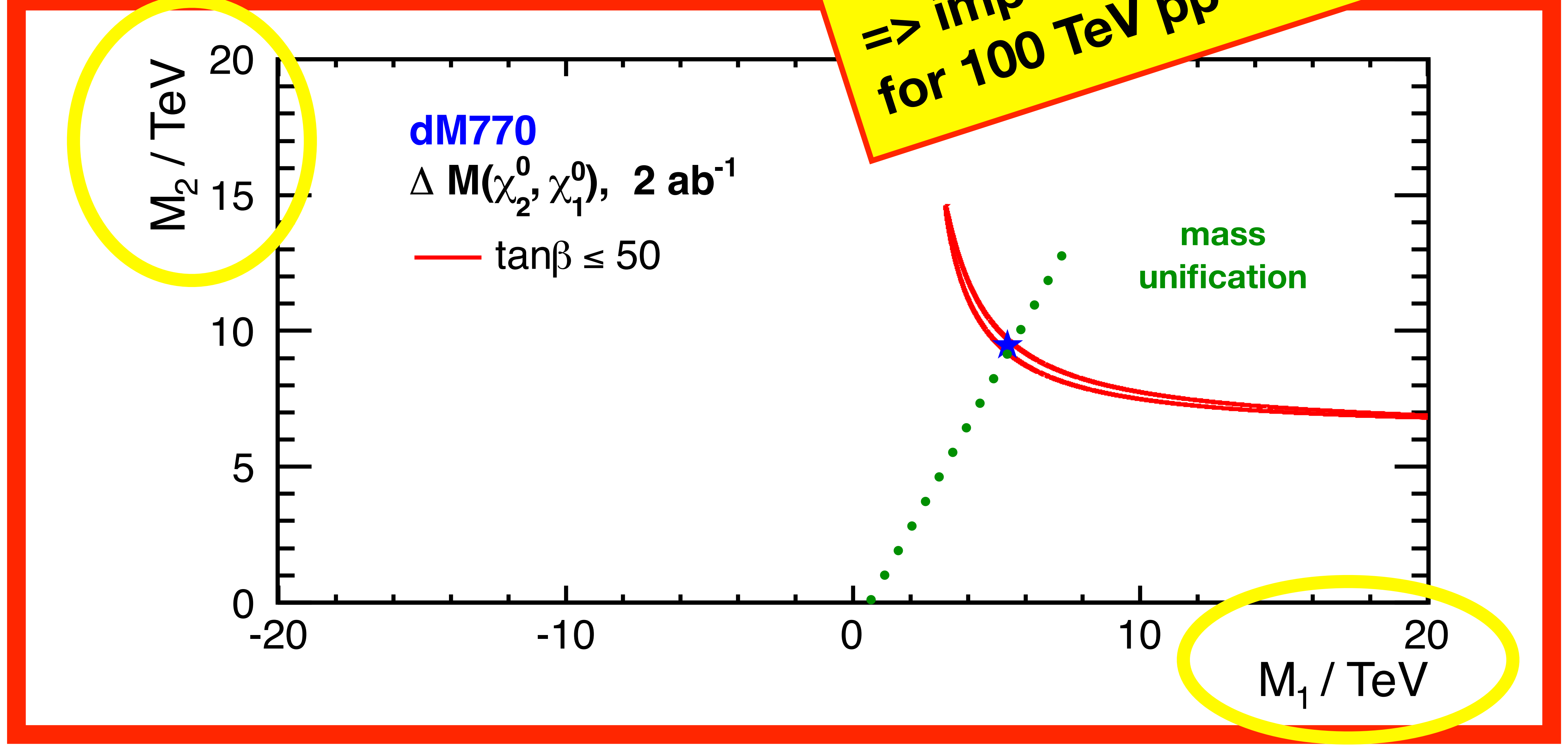
=> energy scale for next pp collider!



Conclusions

And personal remarks

- **weak scale SUSY is by far not excluded - e.g. general MSSM limits on M(stau) still from LEP**
  - beware of the fine-print - and let's do not depress ourselves by simplified exclusion plots
  - return to LEP-style limit setting? At least for main NLSP candidates? More pMSSM scans?
- **SUSY searches at e+e- colliders are very complementary to those at hadron colliders**
  - electroweakinos, sleptons, low-deltaM, … "easy"
  - triggerless operation, single-particle acceptance from pt = 100 MeV, nearly hermetic detectors,..
  - much less fine-print required **=> turn all the stones which are difficult for hadron colliders!**
  - beam polarisation for background suppression and chiral analysis of signal
  - precision spectroscopy allows to predict mass ranges of heavier sparticles => energy scale for pp collider ?
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Most importantly:
Any Future Collider can only happen based on broad support within HEP community
=> get engaged and make it happen!

Backup

Ready to take on one of these challenges?

How to contribute

- **Get involved**
  - **ECFA set up a workshop series on Physics, Experiments and Detectors at a Higgs, Top and Electroweak factory cf https://indico.cern.ch/event/1044297/**
    - address topics in common between all e^+e^- colliders, i.e. theory prediction, assessment of systematic uncertainties, software tools
    - will give important input to next update of European Strategy

  you don't won't to commit to a specific collider project ?
  => this is your way to contribute => get in touch!

- **All Higgs factories are using the same software framework (Key4HEP):**
  - share algorthmic developments
  - share / exchange data sets for comparable analyses etc

  => anybody who'd like to shape the experiments of the next collider would be wise to build up expertise on Key4HEP *now*

Straight to the Future An adaptable e+e- LC facility for the world

- A LC facility can be extended in length for higher energies, using the same or improved versions of the same technology, e.g. as suggested for ILC, CLIC, C3 and HALHF
- It is also possible and realistic to change to more performant (usually higher gradient) technologies in an upgrade, e.g. from ILC to CLIC or C3, maybe even plasma
- Starting point for fast implementation: ILC has the most mature linac technology for large scale implementation, that is also well established in all regions and in industry - it is based on a ~20 km long tunnel
- The physics at higher energies – Higgs sector and extended models with increased reach and precision, top in detail well above threshold, searches and hopefully new physics – will open for a very exciting long term e+e- programme
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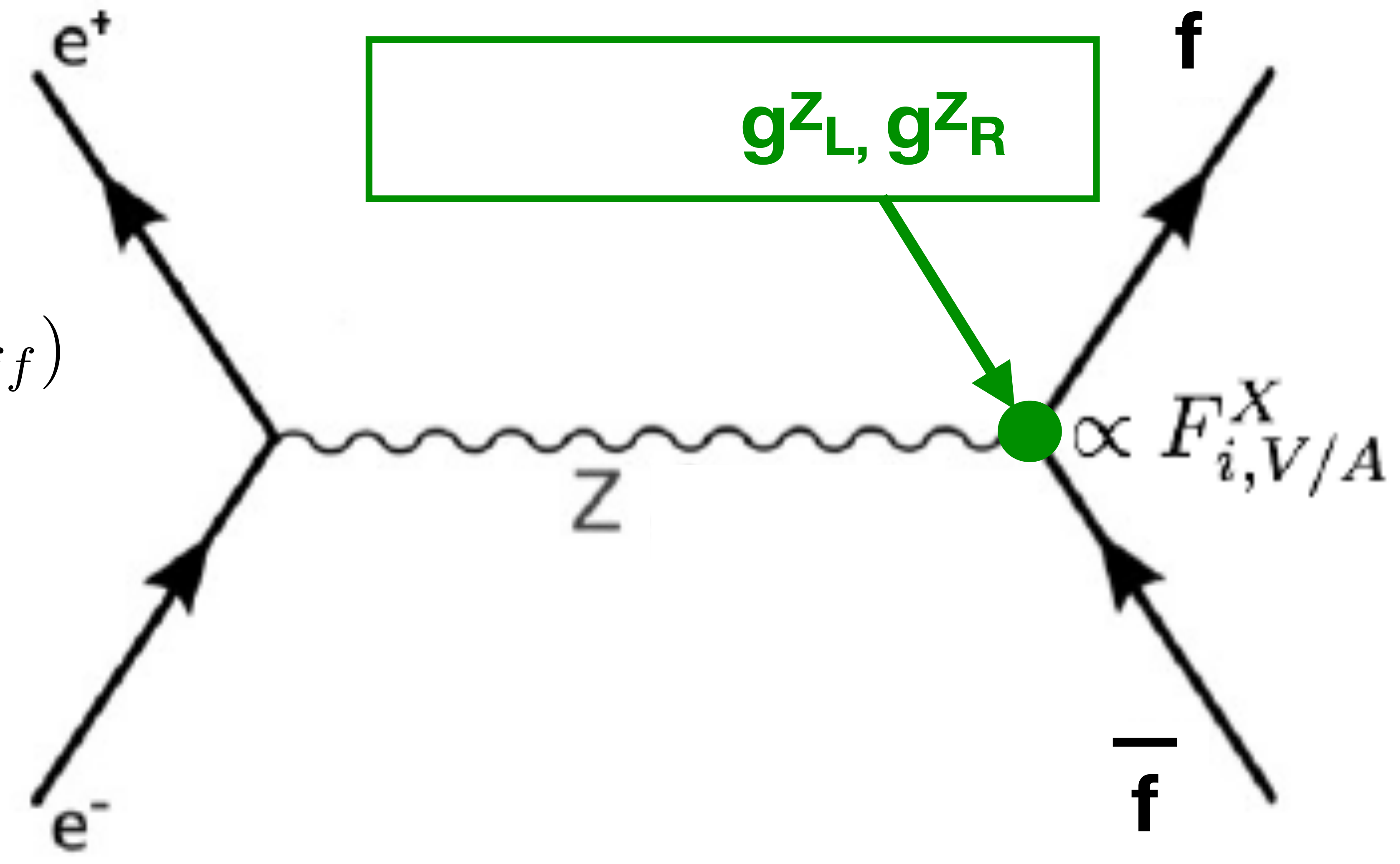
Polarisation & Electroweak Physics

let's first recall at the Z pole situation

g_{Lf}, g_{Rf} : helicity-dependent couplings of Z to fermions - at the Z pole:

=> $$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$$

specifically for the electron: $$A_e = \frac{(\frac{1}{2} - \sin^2\theta_{eff})^2 - (\sin^2\theta_{eff})^2}{(\frac{1}{2} - \sin^2\theta_{eff})^2 + (\sin^2\theta_{eff})^2} \approx 8(\frac{1}{4} - \sin^2\theta_{eff})$$



at an *un*polarised collider:

$$A^f_{FB} \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{3}{4} A_e A_f$$

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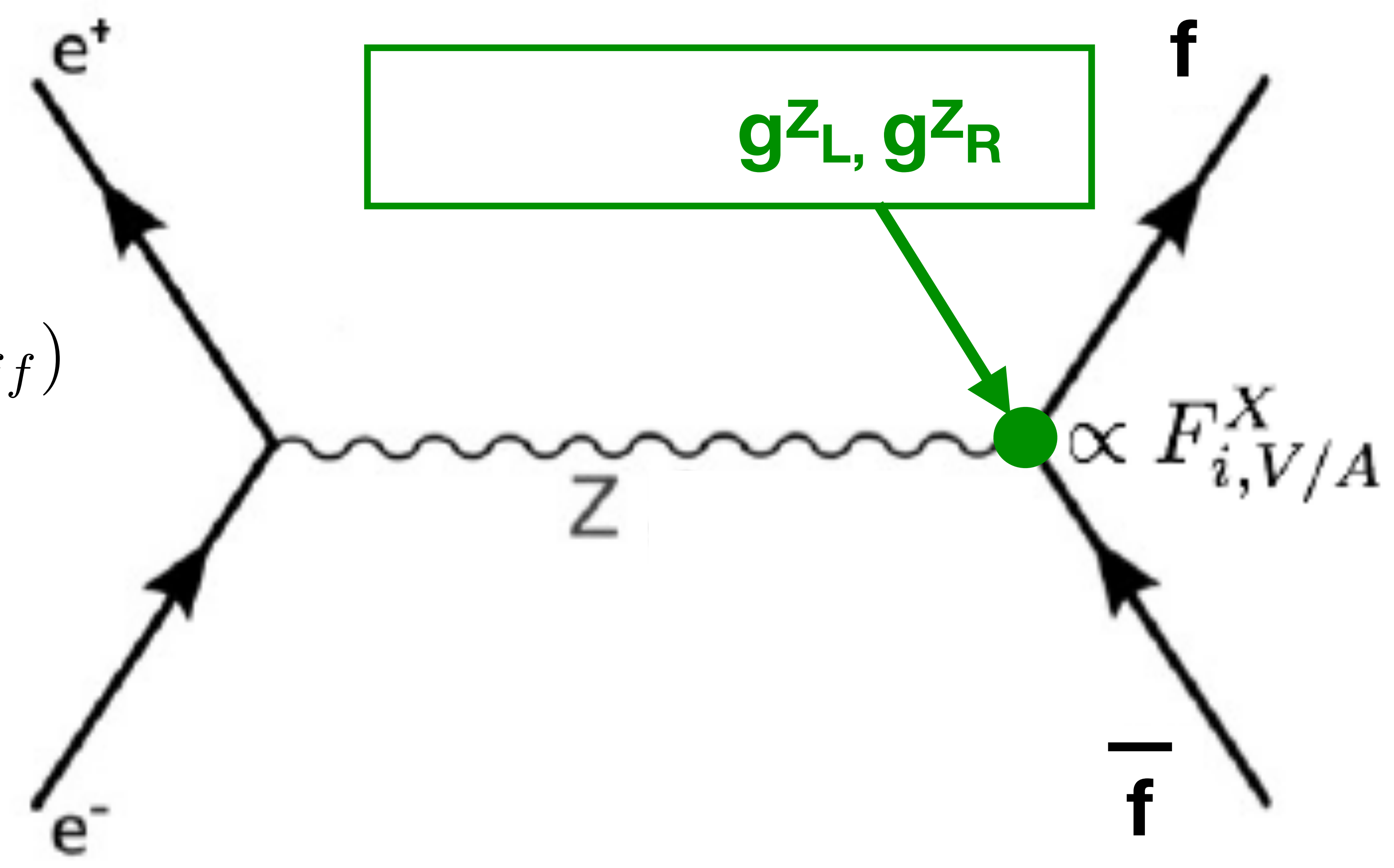

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trading theory uncertainty:

the **polarised** $A^f_{FB,LR}$ receives 7 x smaller radiative corrections than the **unpolarised** A^f_{FB} !

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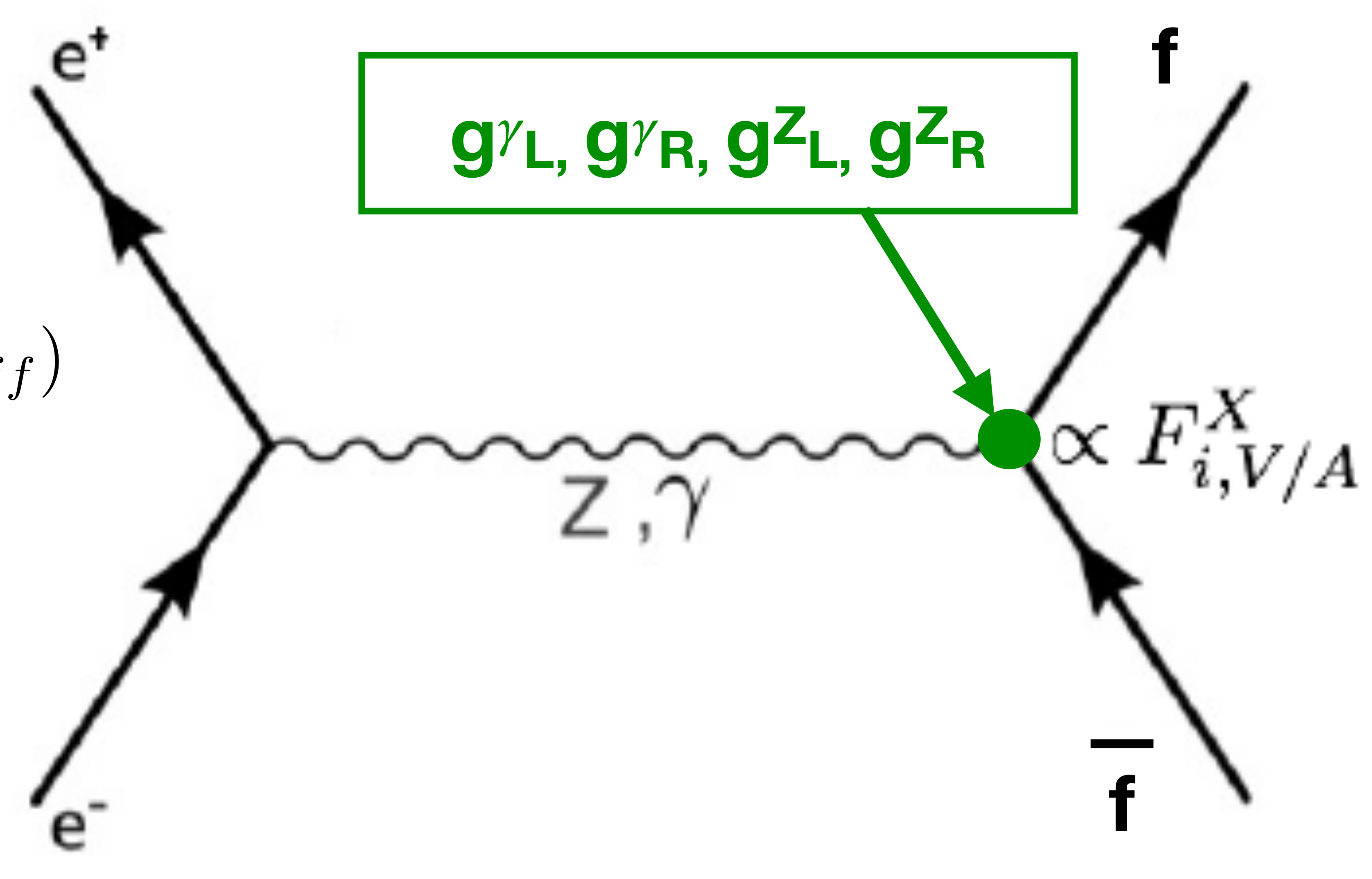

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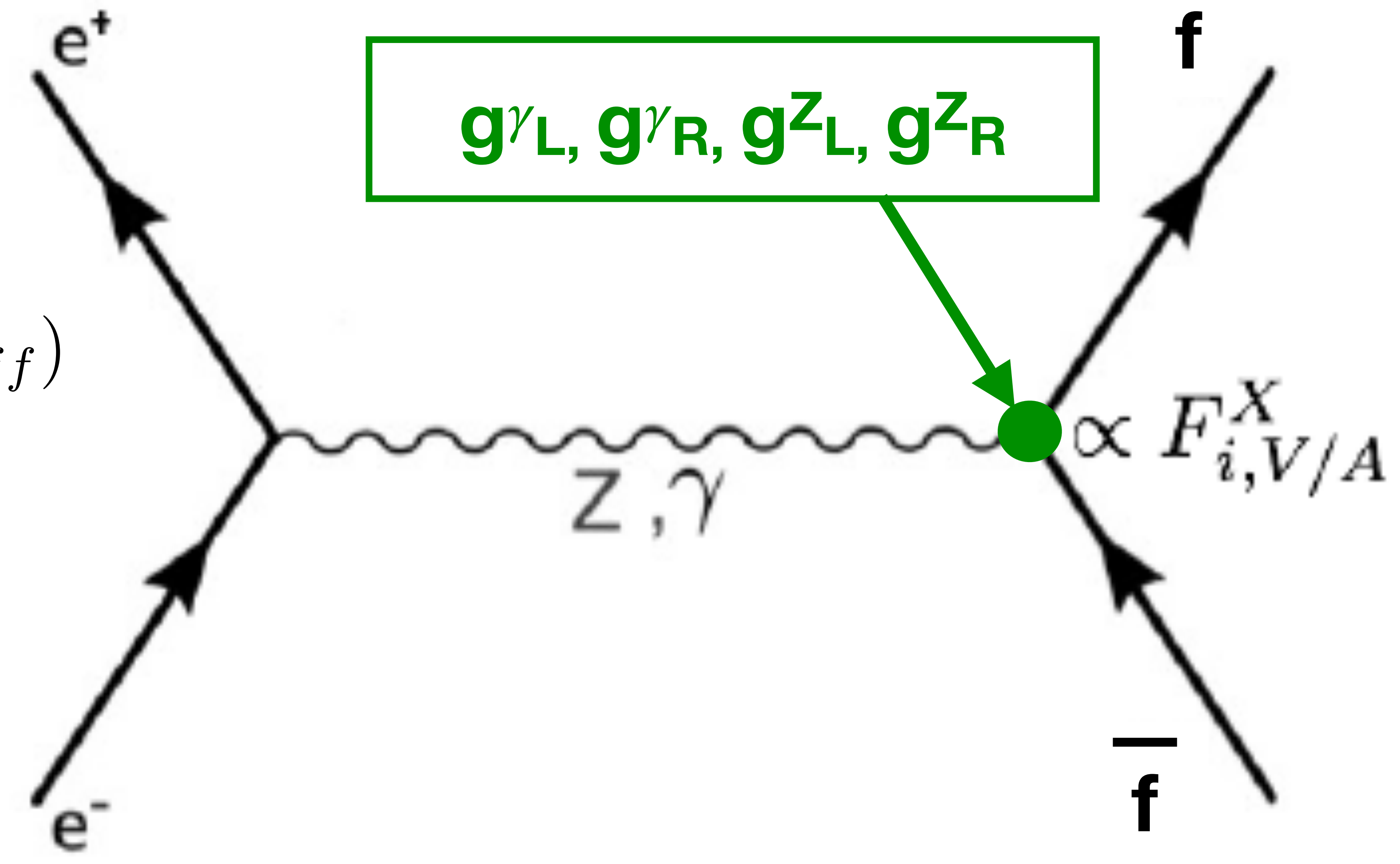

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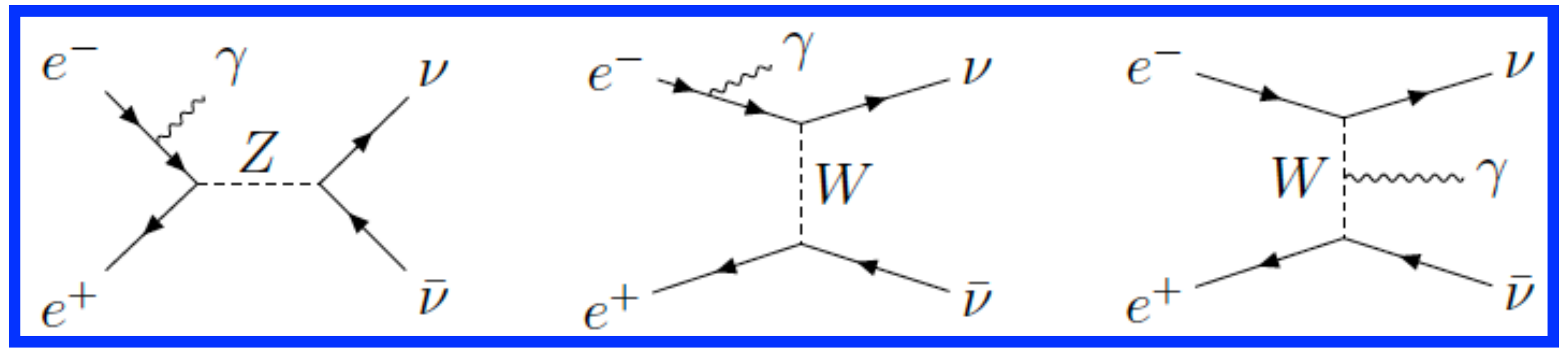
above Z pole, polarisation essential to disentangle Z / γ exchange in $e^+e^- \to f\bar{f}$

Phys. Rev. D 101 (2020) 7

Polarisation & Beyond the SM: Dark Matter

Background reduction & Systematics

- mono-photon search $e^+e^- \rightarrow \chi\chi\gamma$
- main SM background: $e^+e^- \rightarrow \nu\nu\gamma$



reduced ~10x with polarisation

- shape of observable distributions changes with polarisation sign
  => combination of samples with sign(P) = (–,+), (+,–), (+,+), (–,–)
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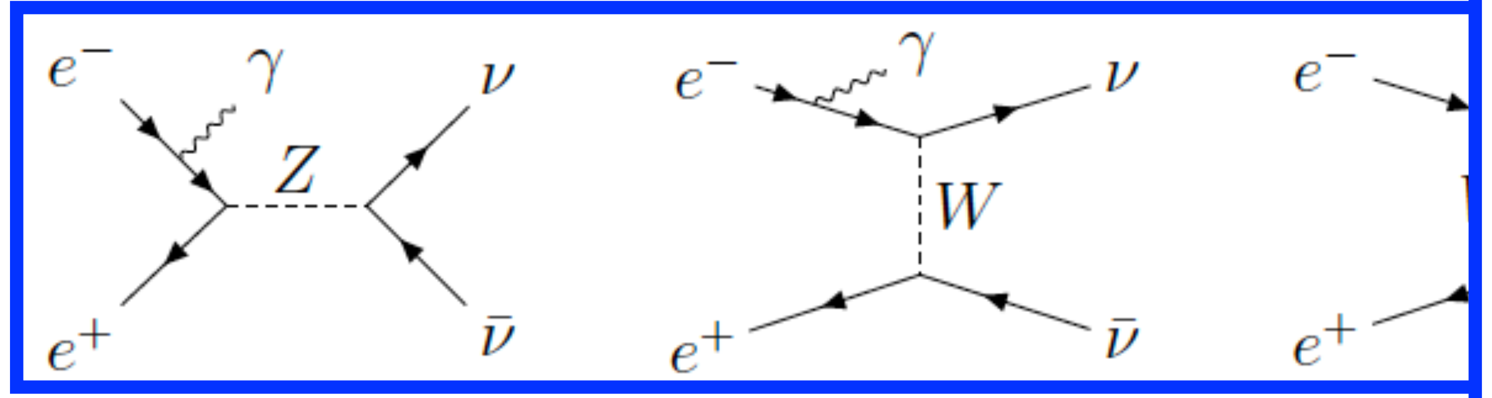

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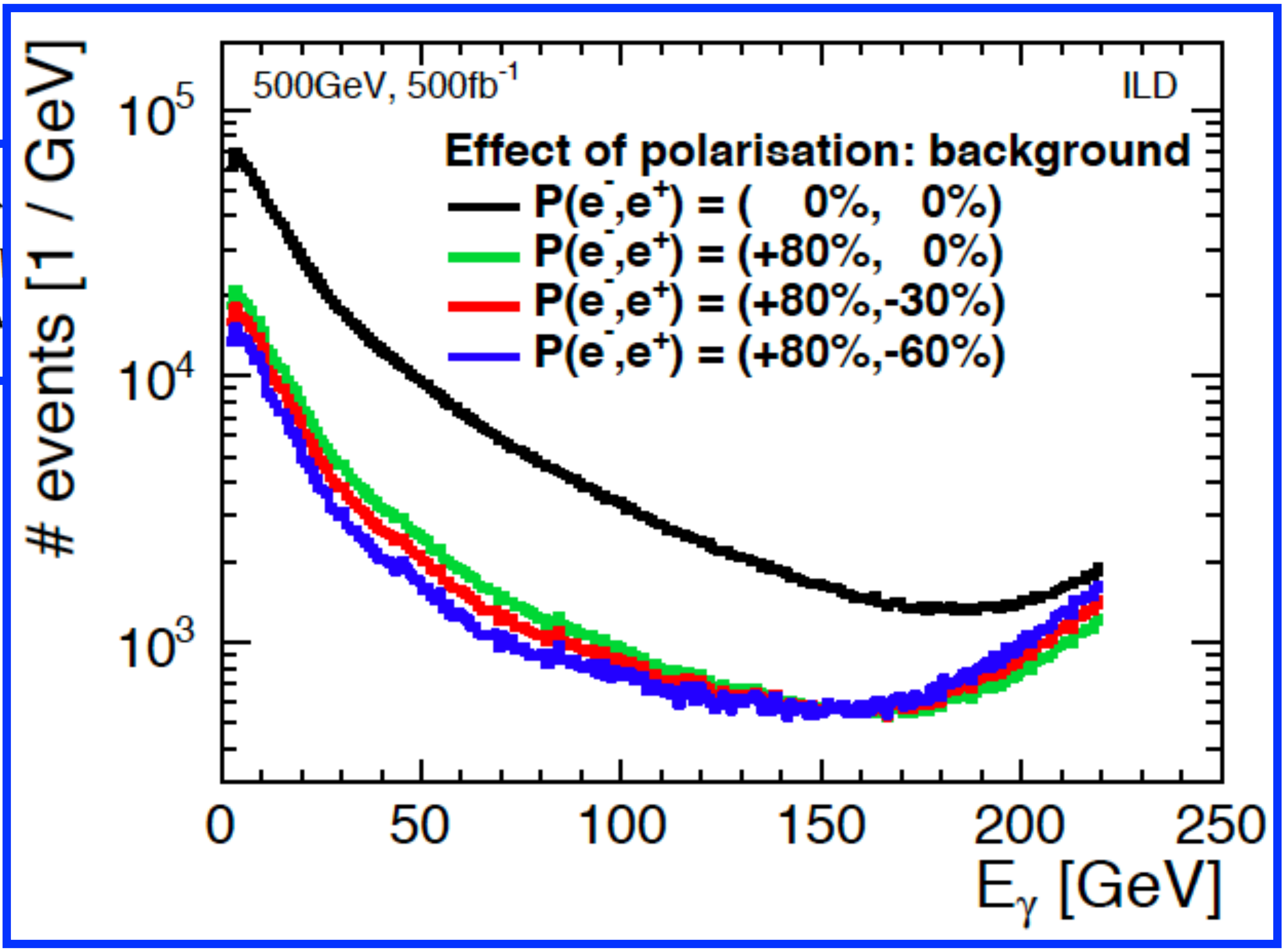

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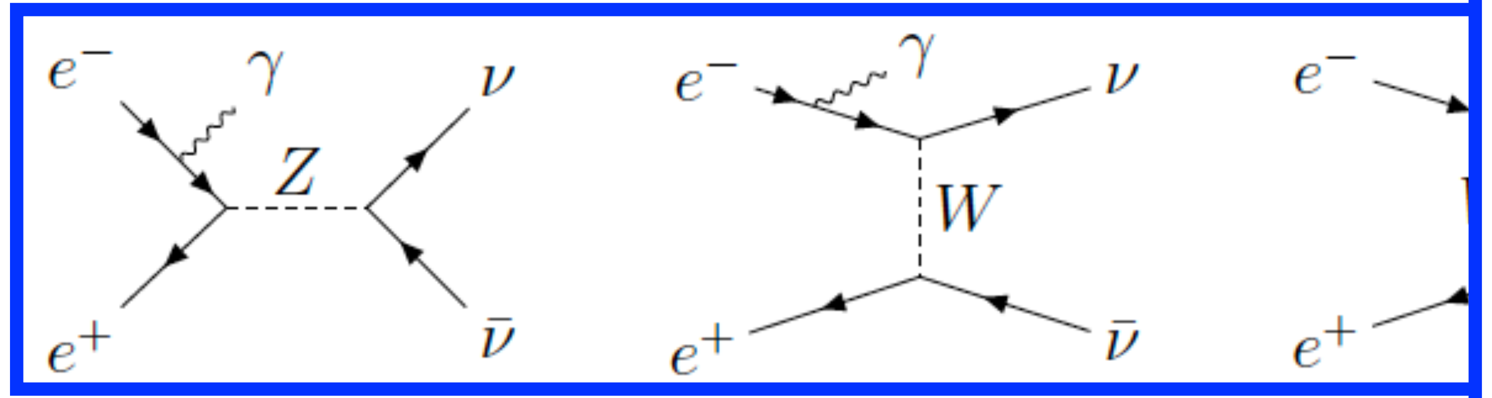

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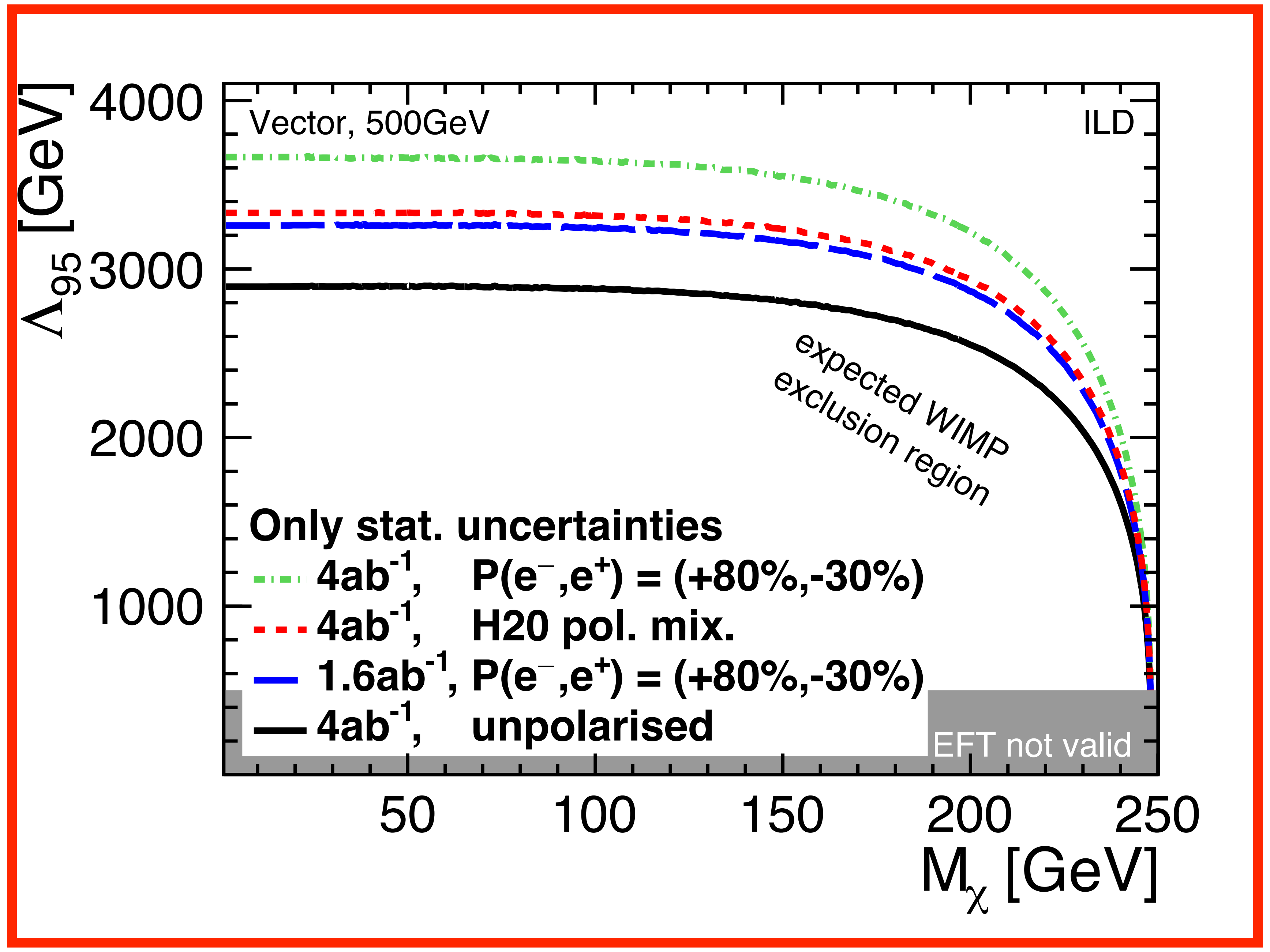

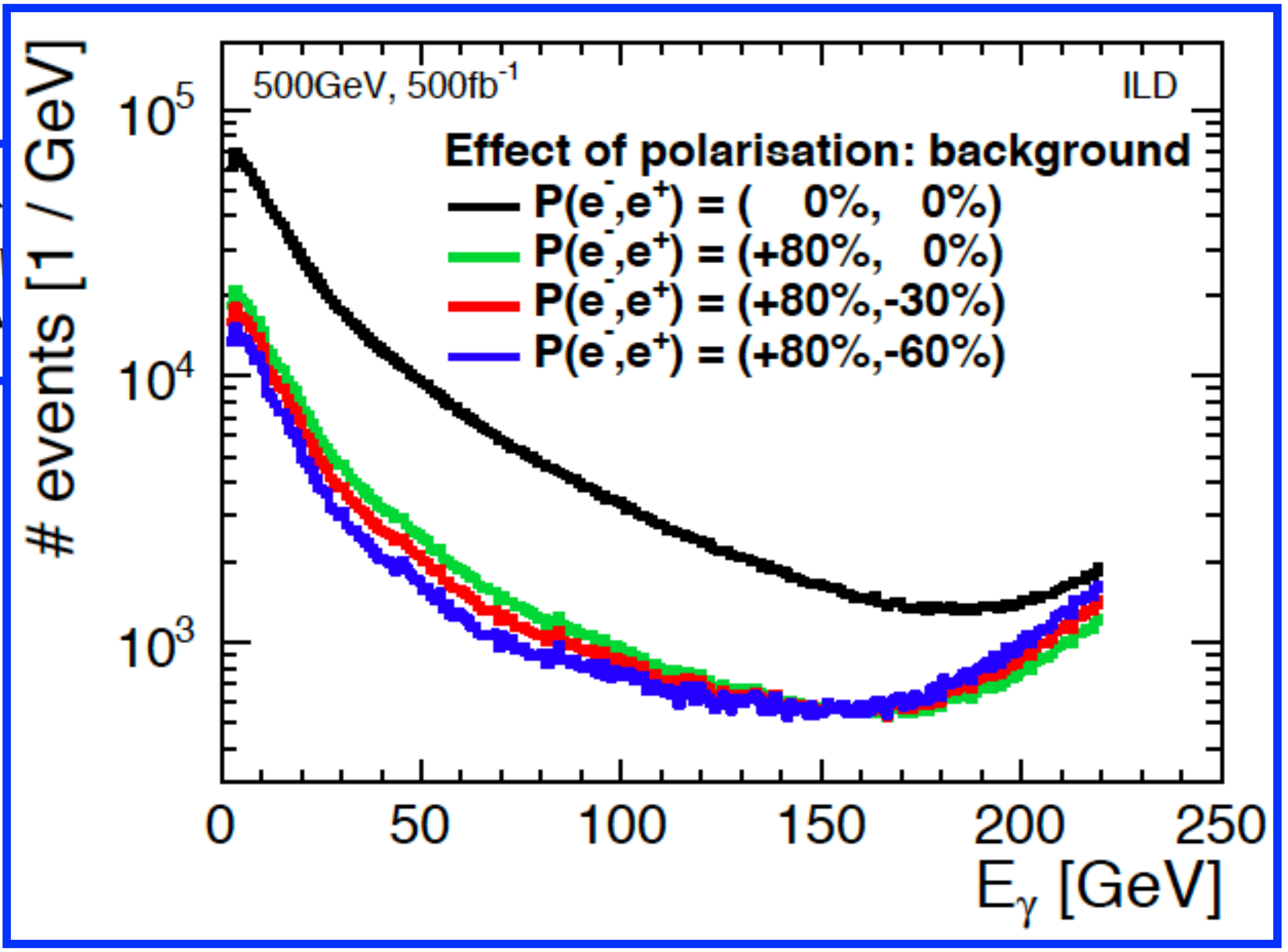

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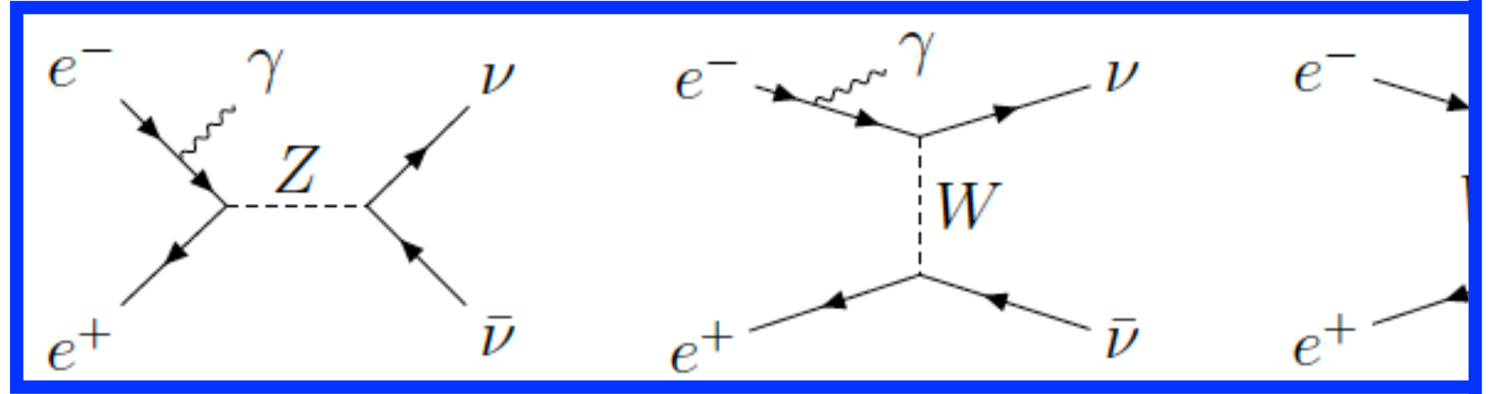

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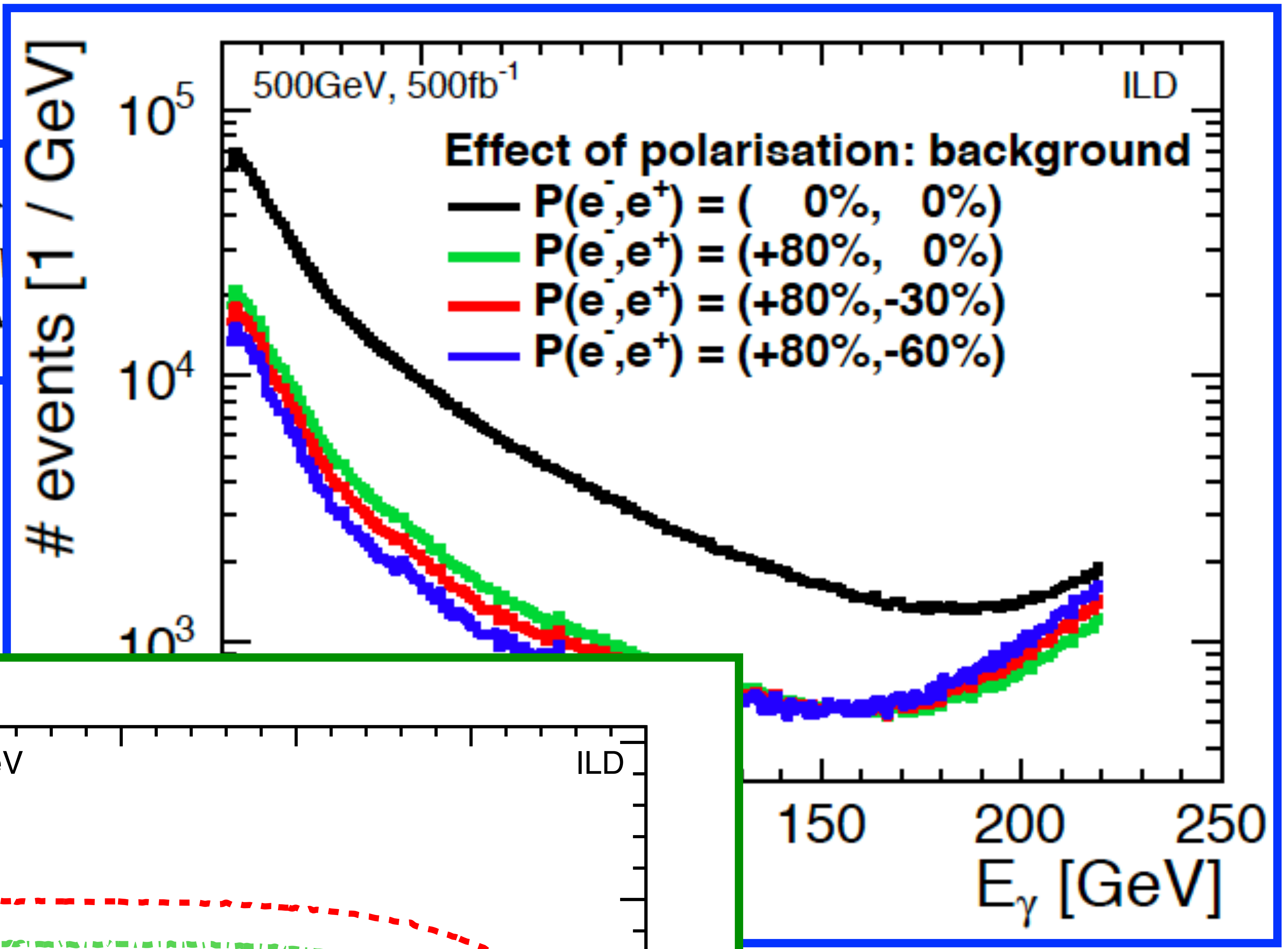

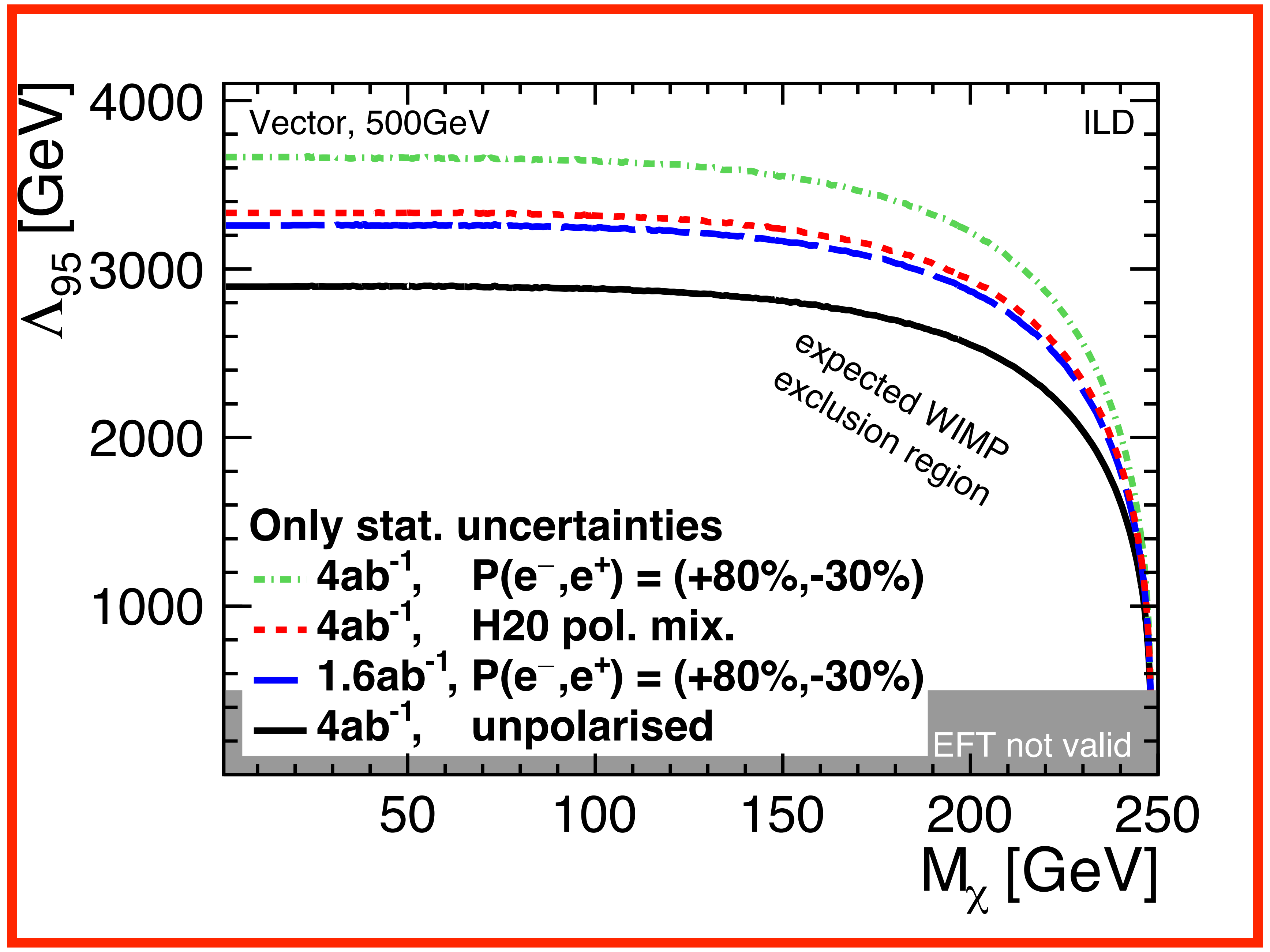

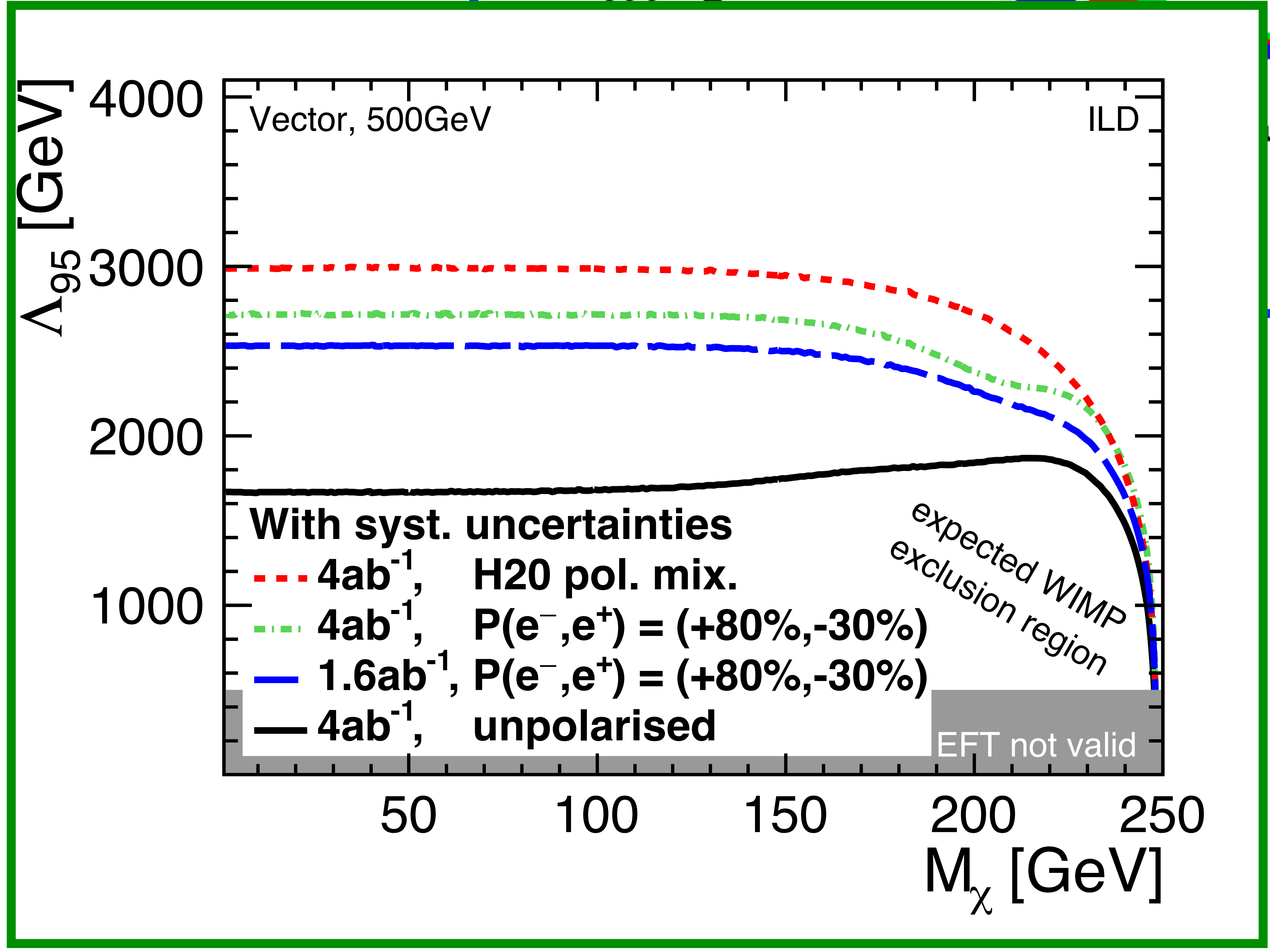

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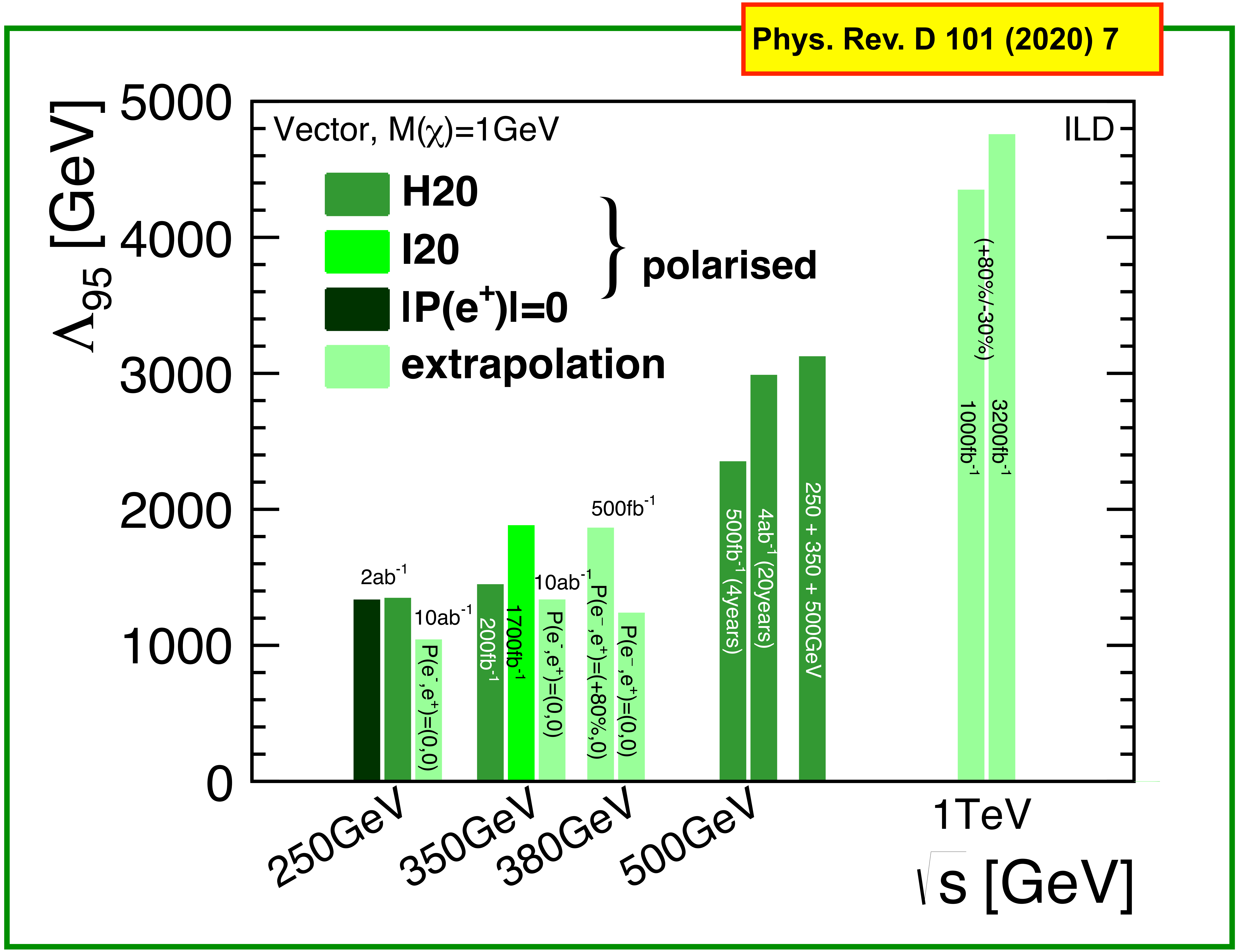
Exmaple: Impact on reach in vector mediator case



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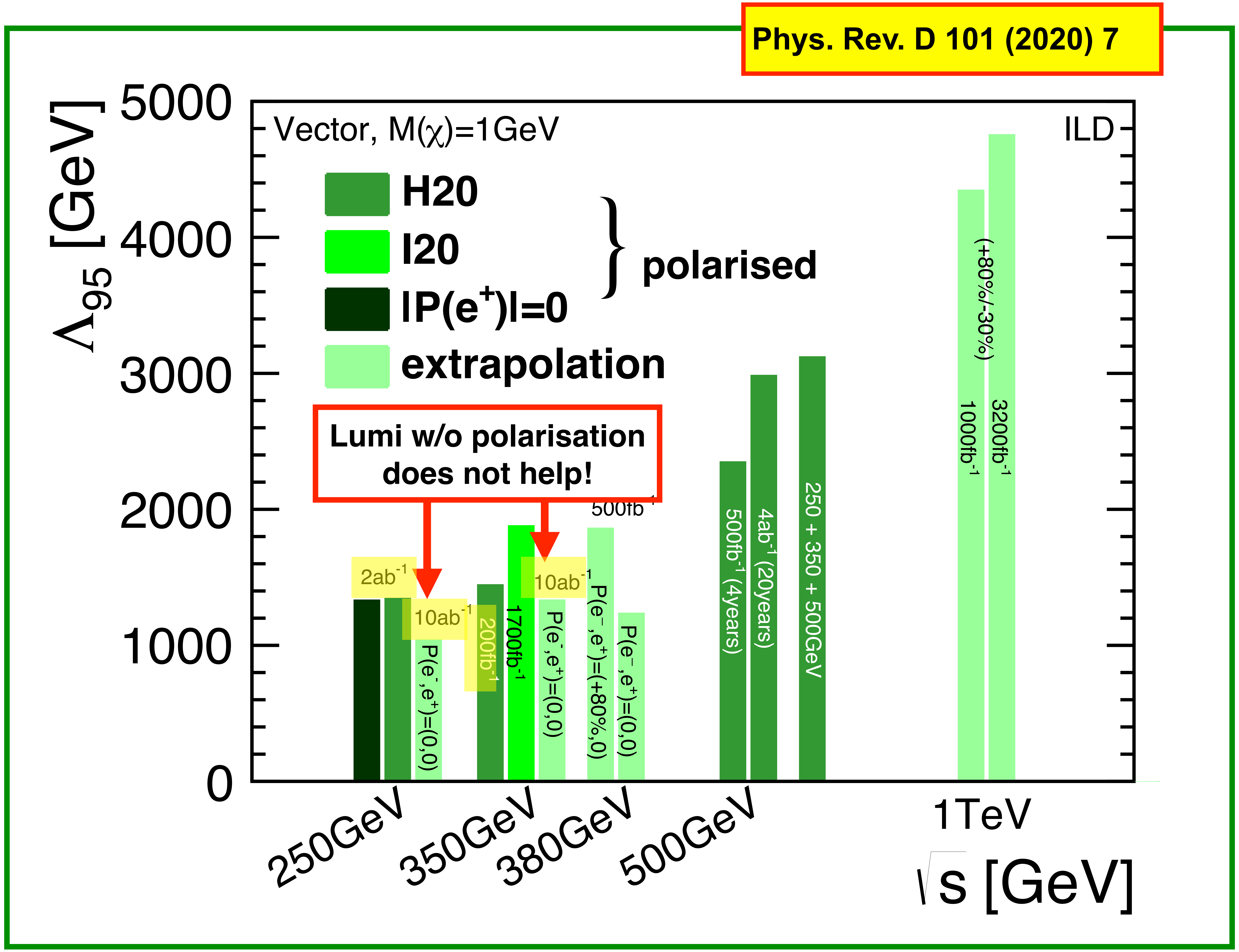

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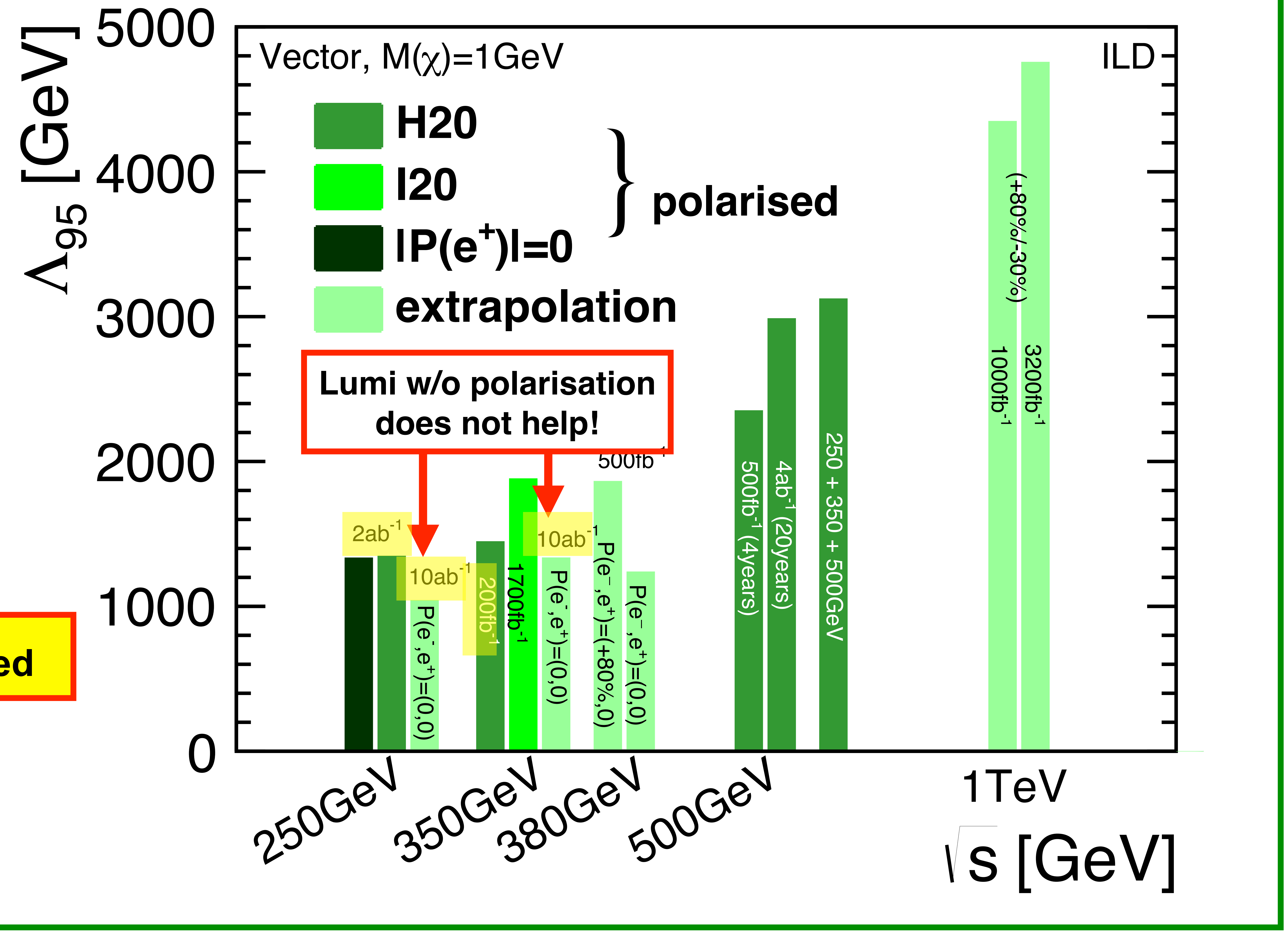

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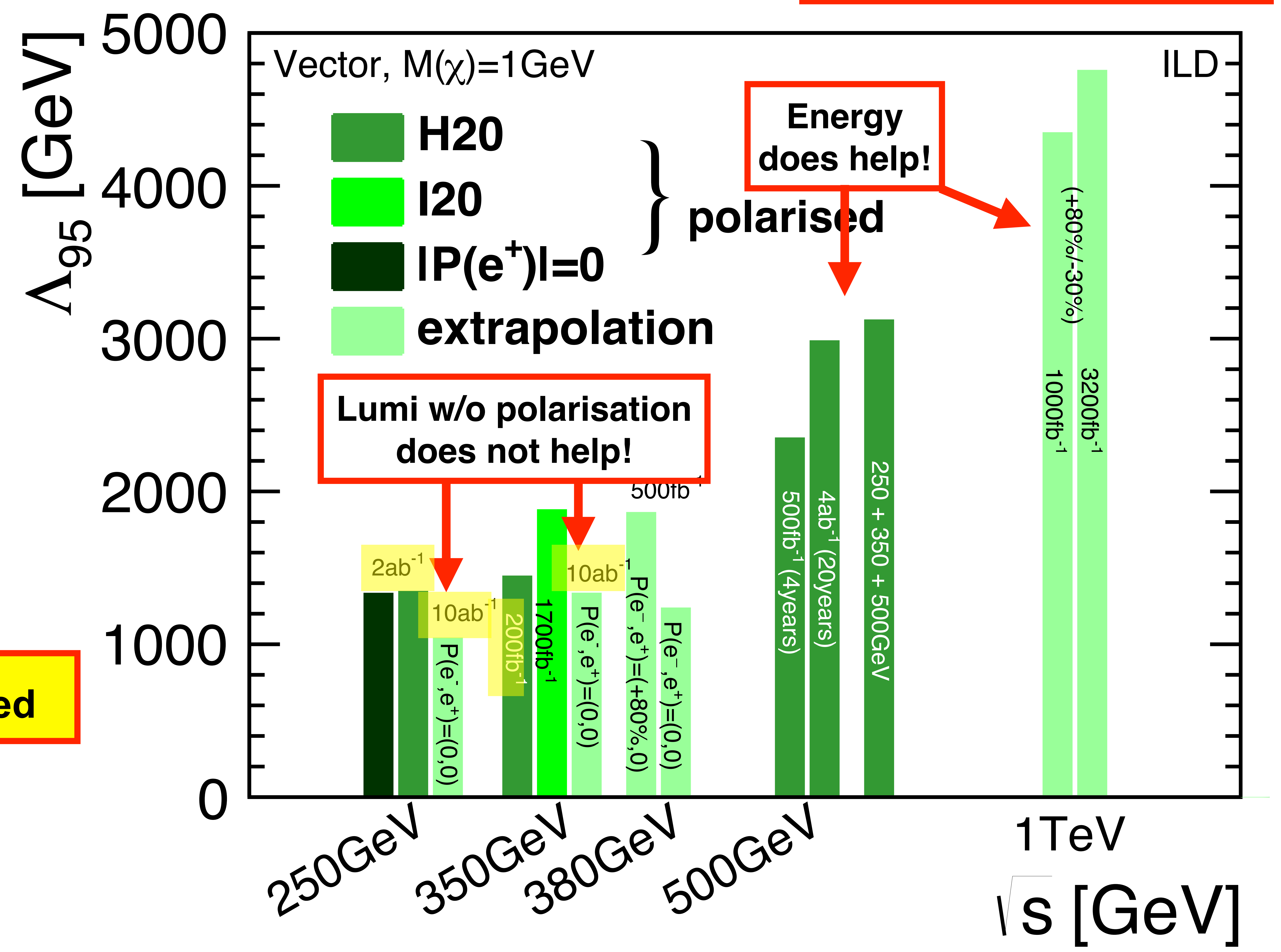

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BSM reach of ee → cc / bb

arXiv:2403.09144

Forward-backward and left-right asymmetries above the Z pole

Study of ee → cc / bb

- full Geant4-based simulation of **ILD**

BSM example: Gauge-Higgs Unification models

- Higgs field = fluctuation of Aharonov-Bohm phase in warped extra dimension
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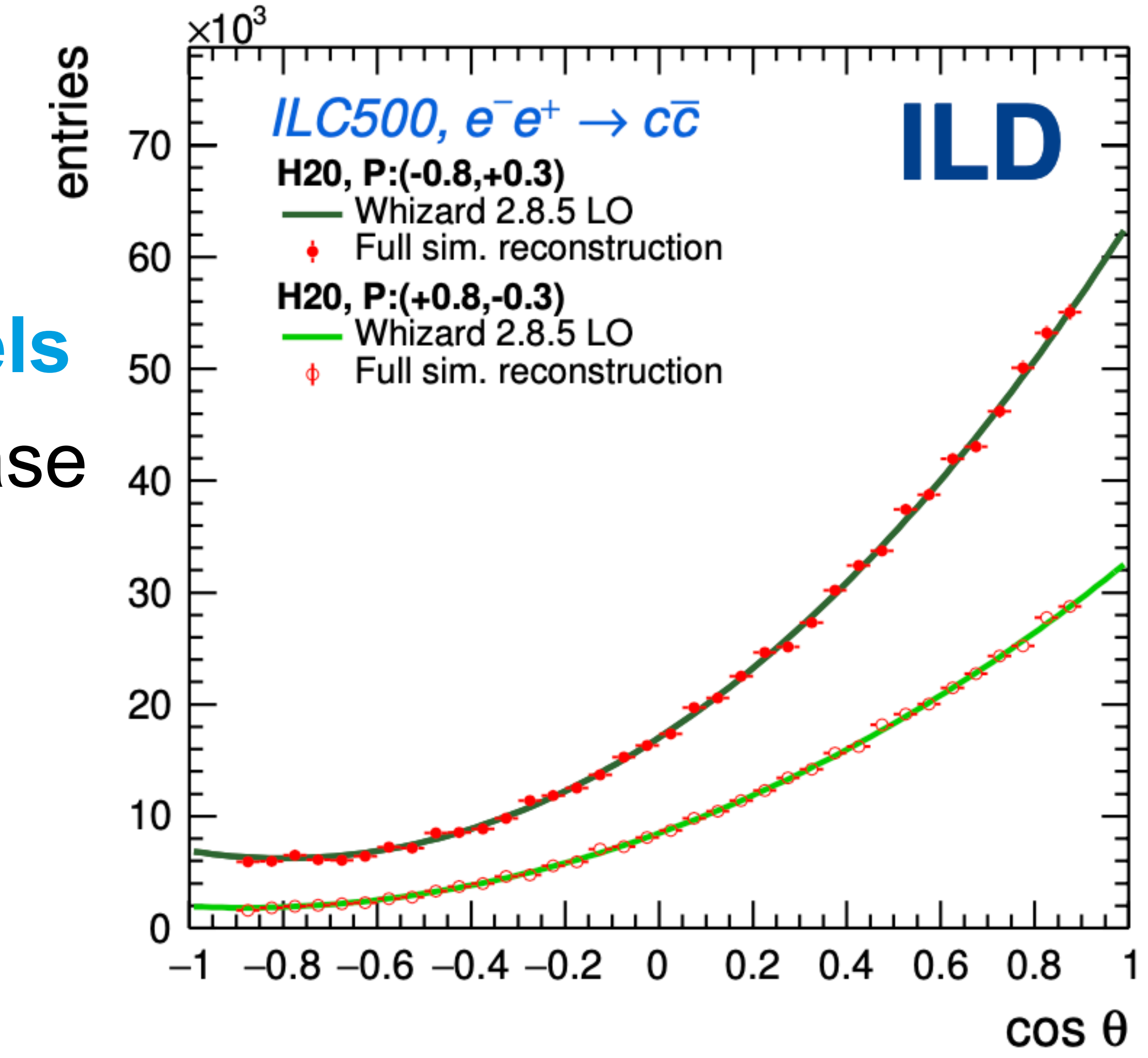

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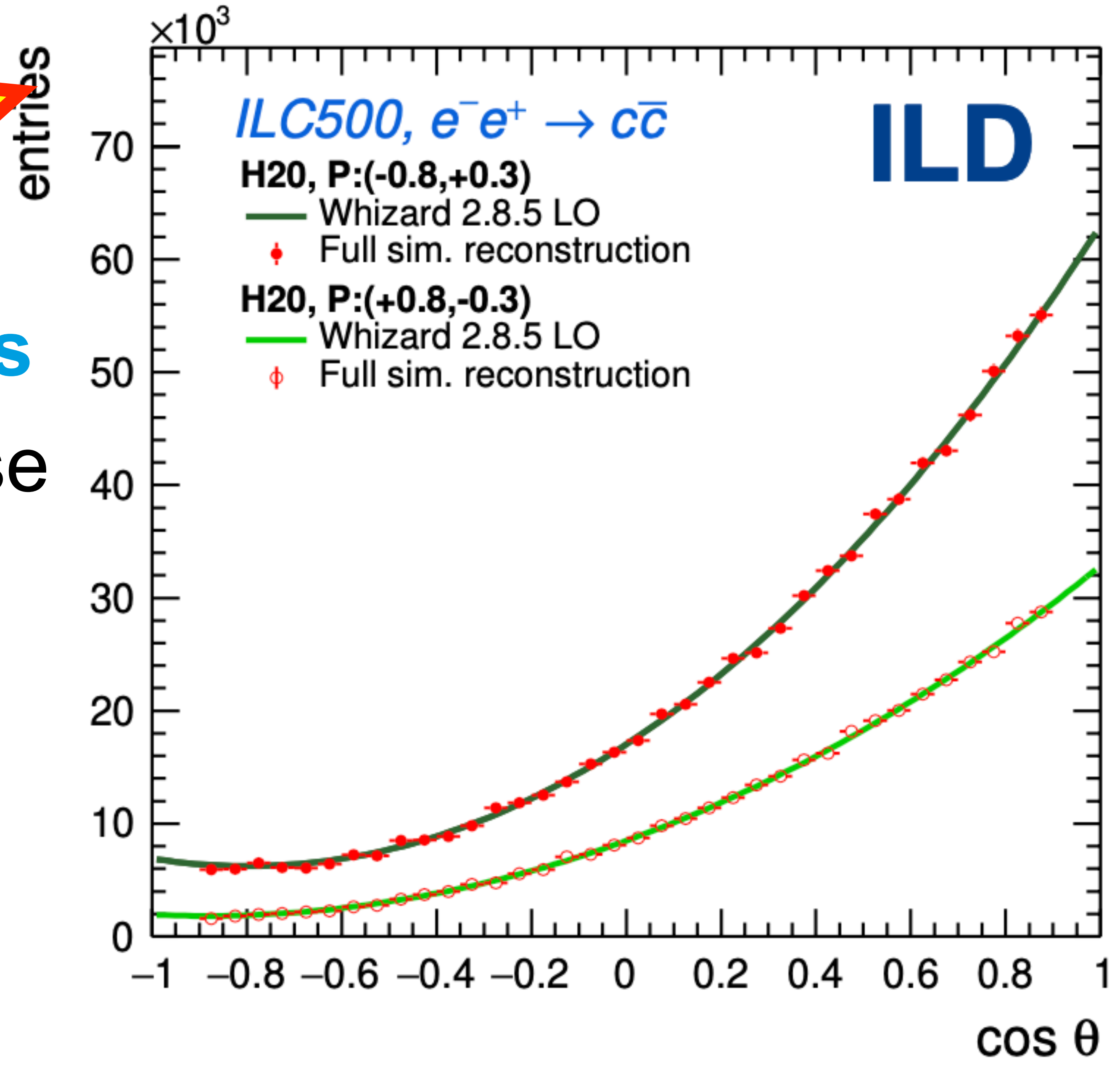

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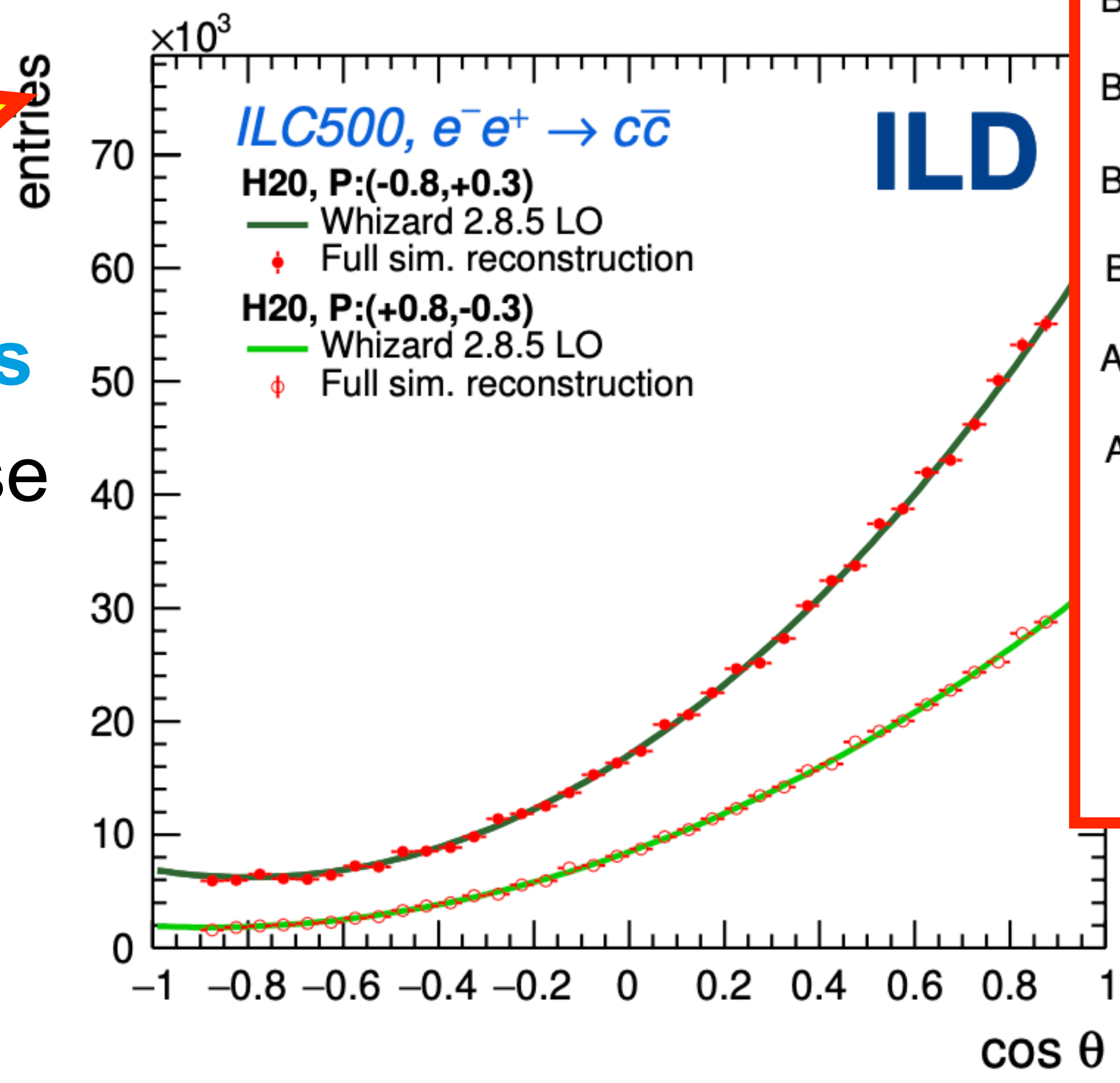

ILD

GHU vs SM discrimination power (σ-level)

	O	E	N	O	E	N	O	E	N	O	E	N
B_3^+	0.3	0.4	0.4	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.5	0.7	0.7	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	1.1	1.5	1.6	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	0.6	1.2	1.4	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	2.2	3.2	3.3	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	2.7	3.8	3.9	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10
	ILC250♦ (no pol.)			ILC250			ILC250 +500			ILC250 +500 +1000*		

Ch. had. PID
- O: No PID
- E: $\frac{dE}{dx}$
- N: $\frac{dN}{dx}$

< 3 σ | 3-4 σ | 4-5 σ | > 5 σ

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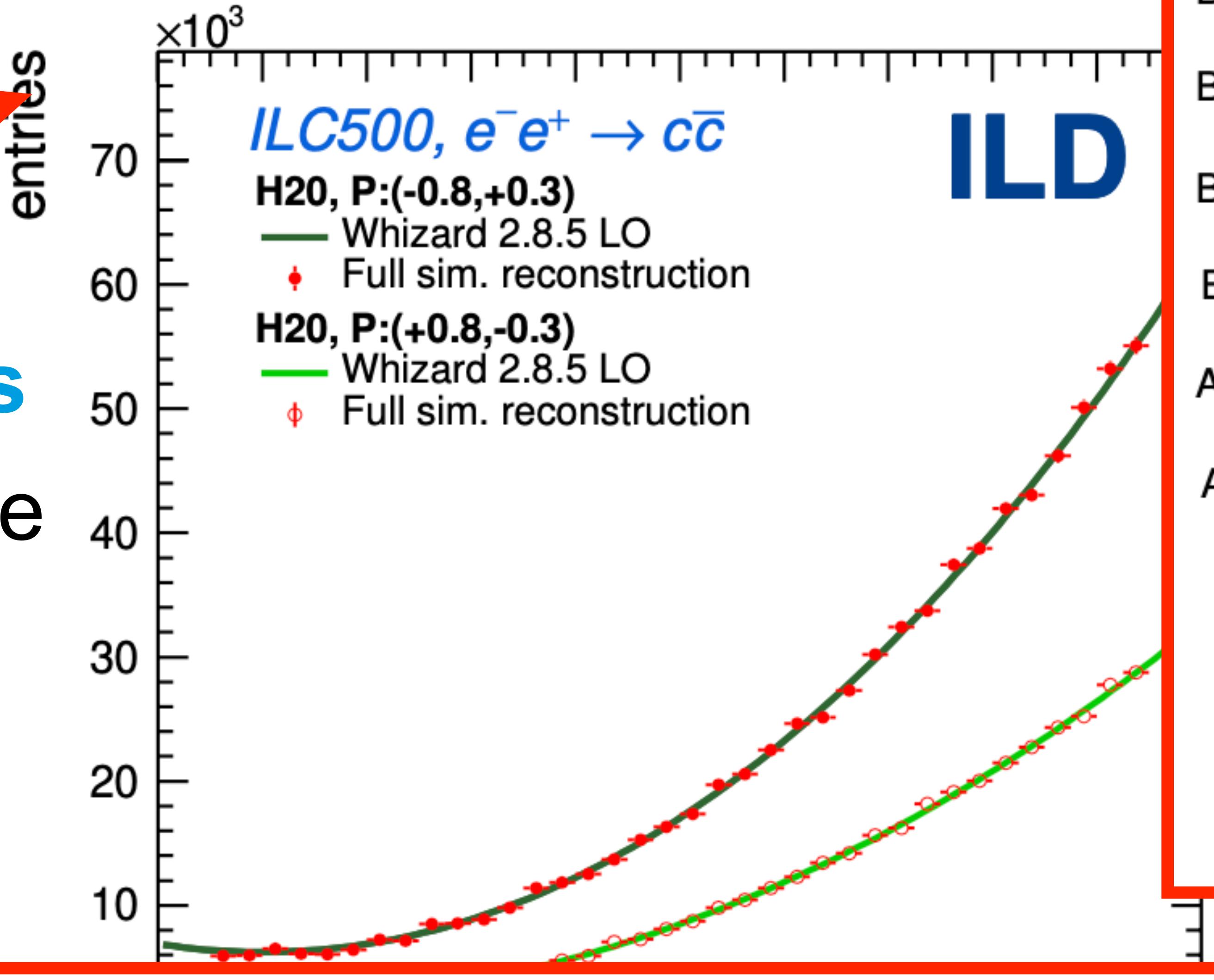

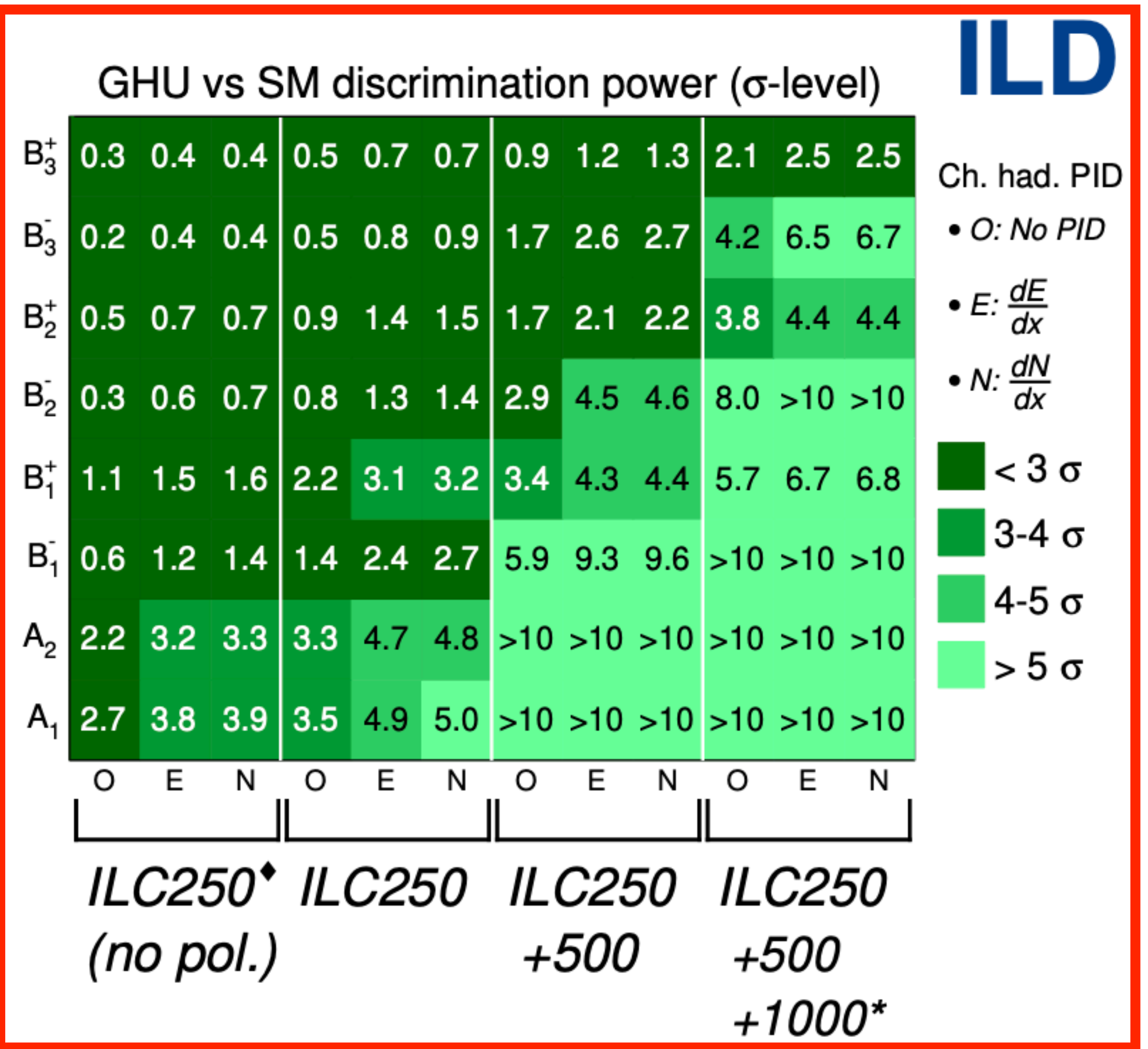

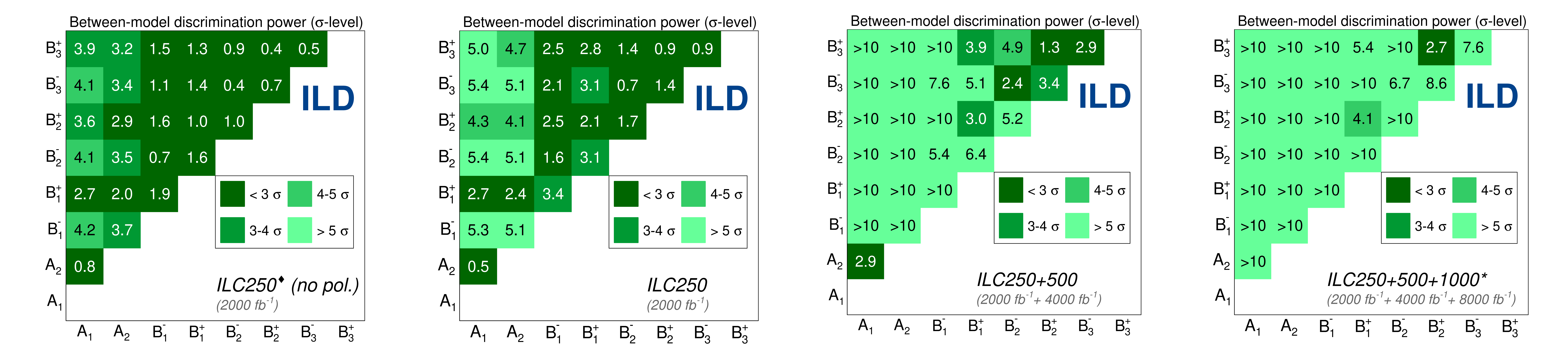

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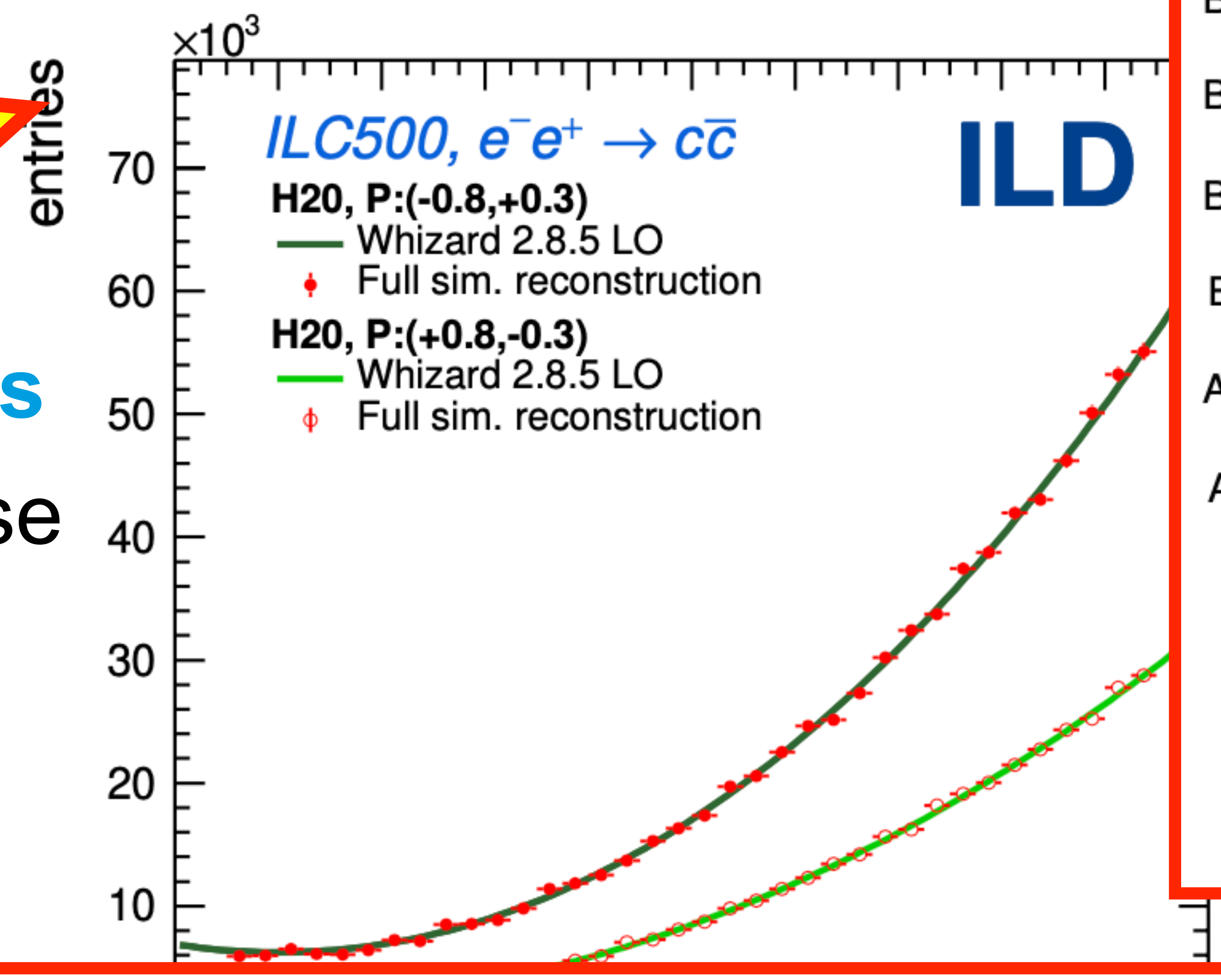

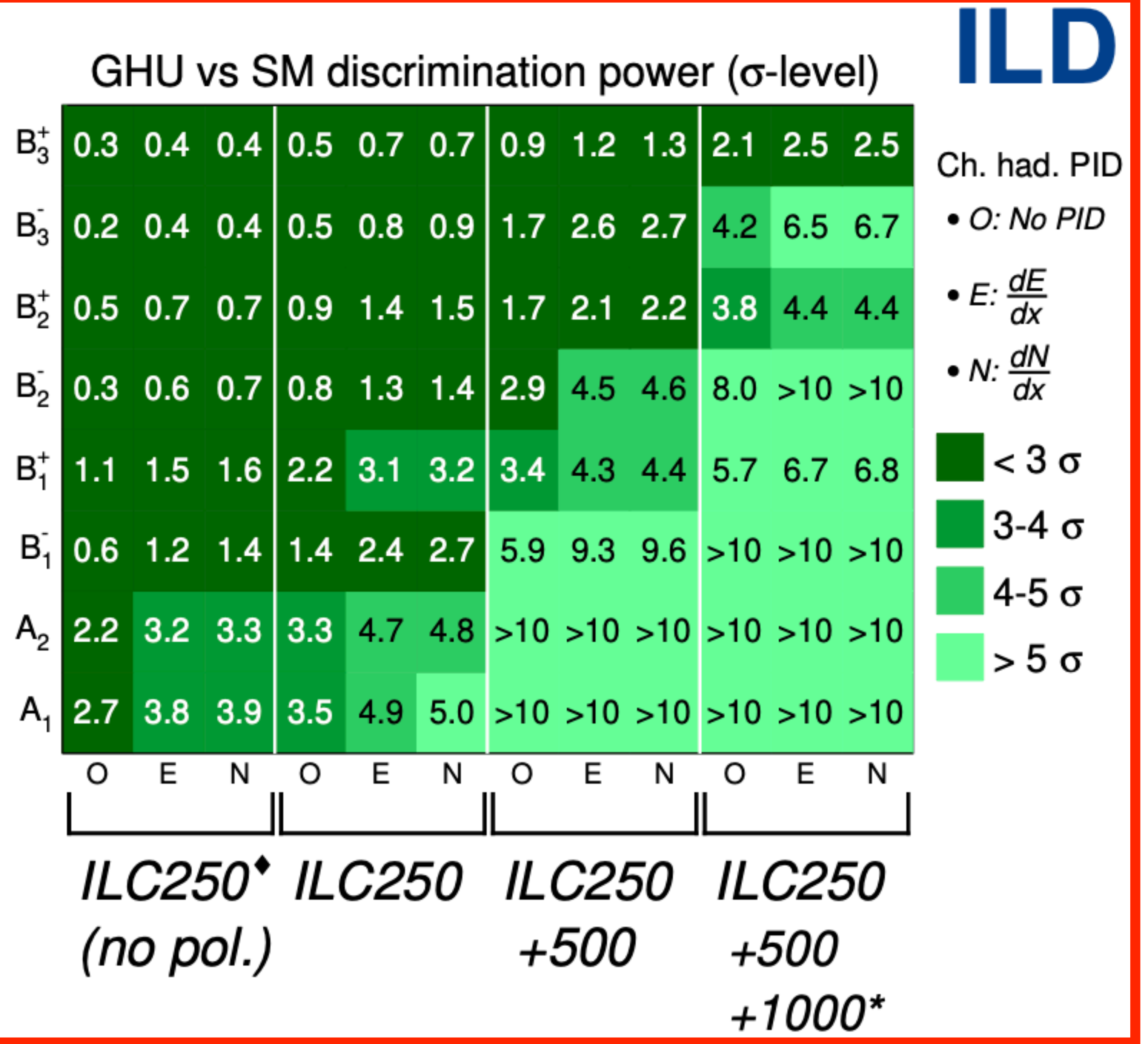

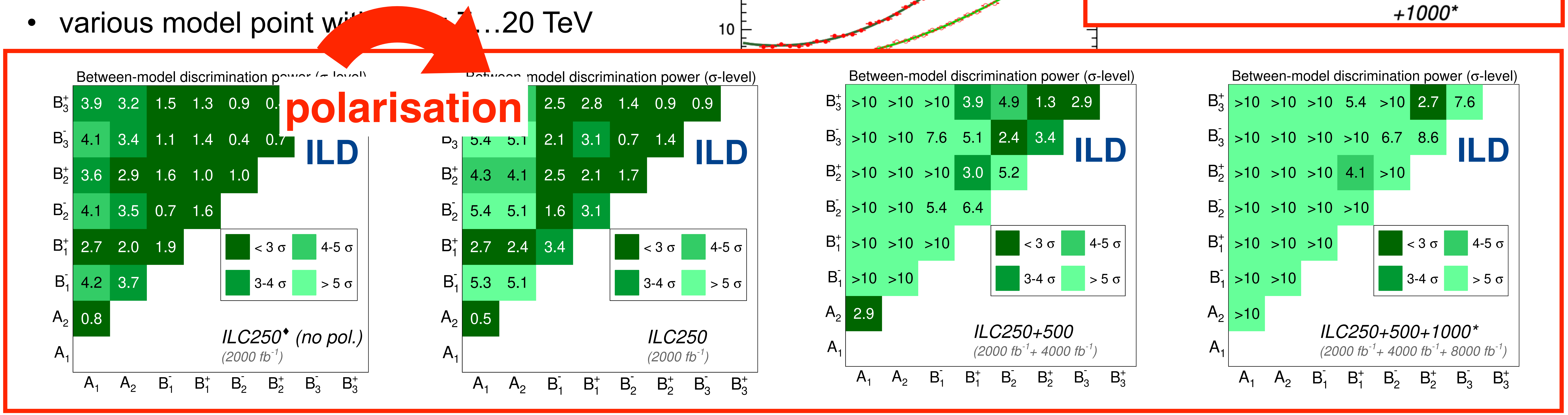

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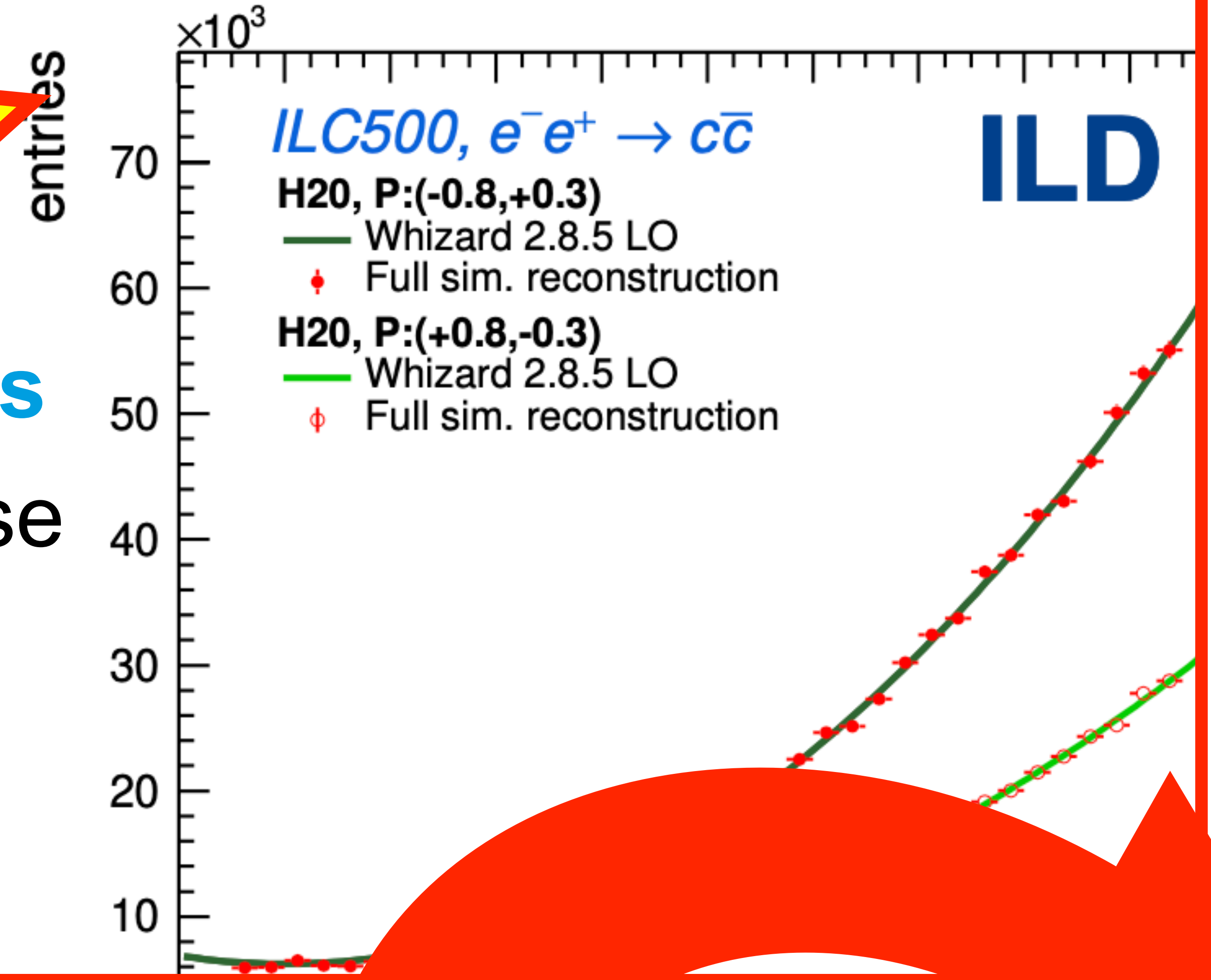
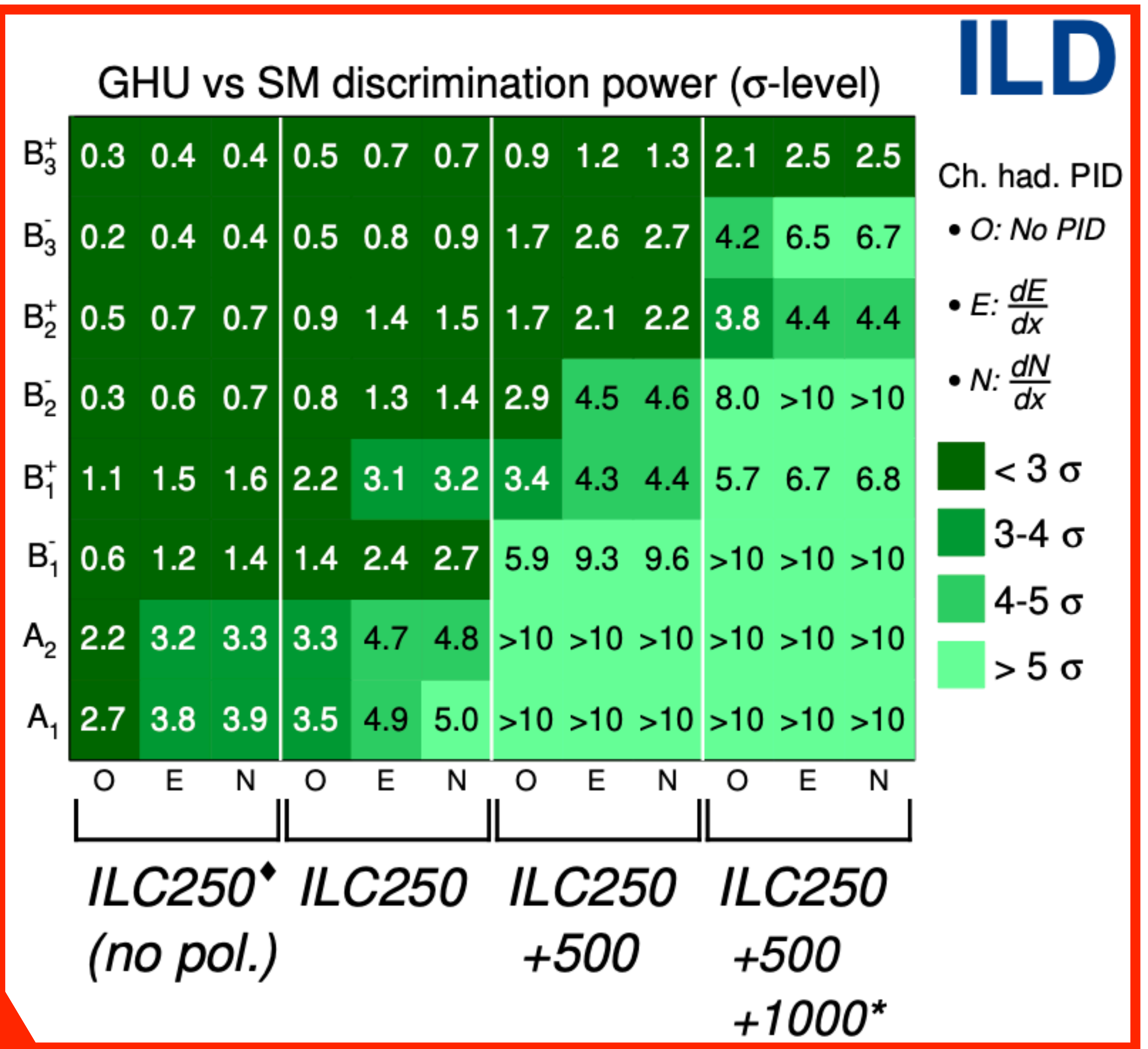
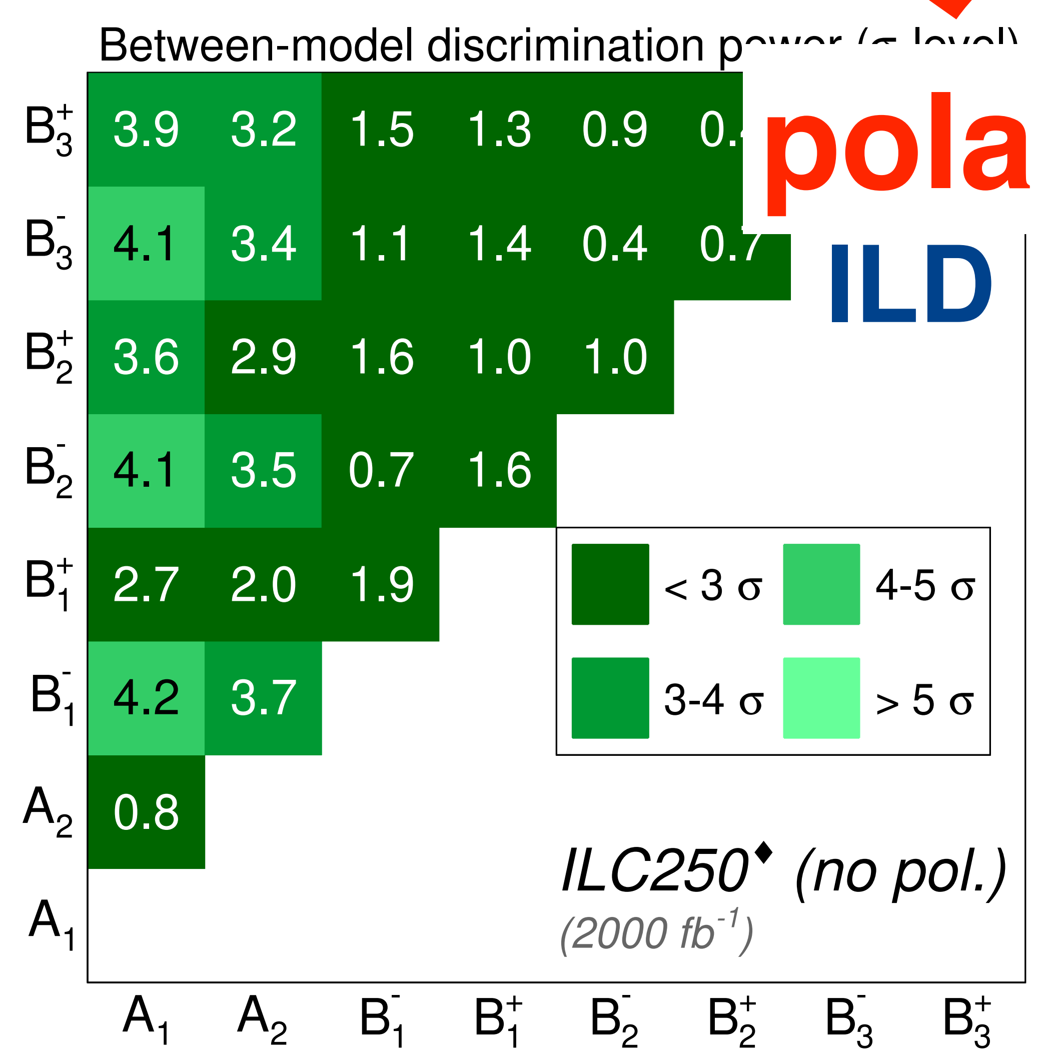
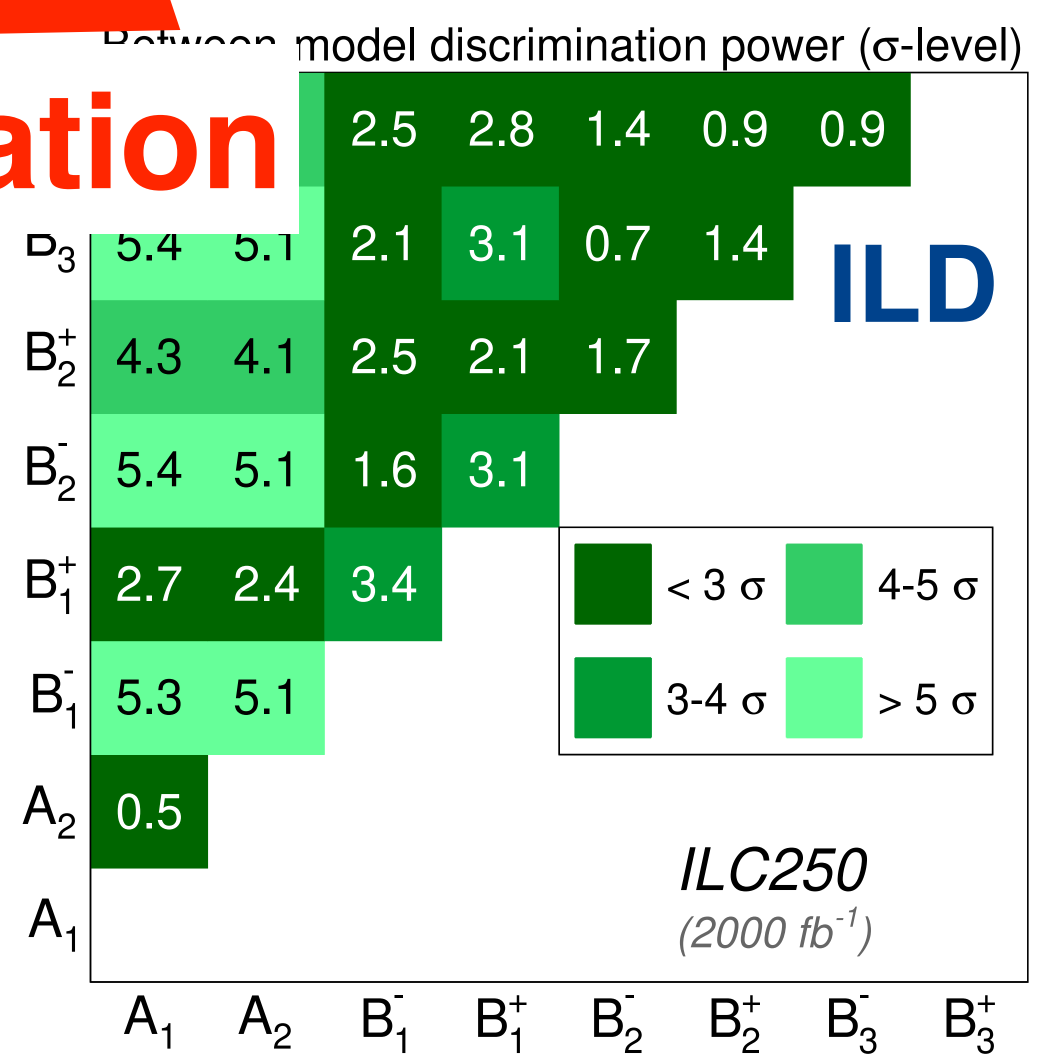
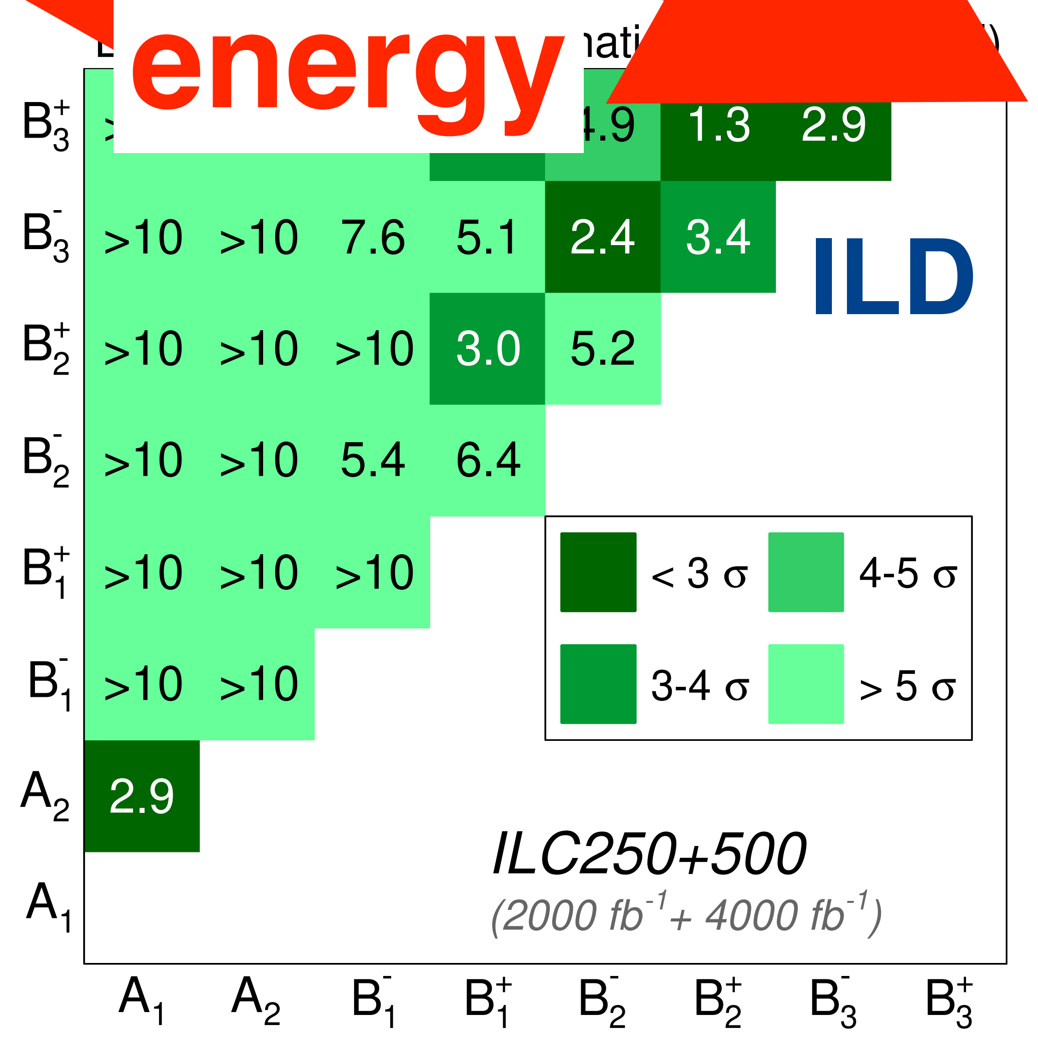
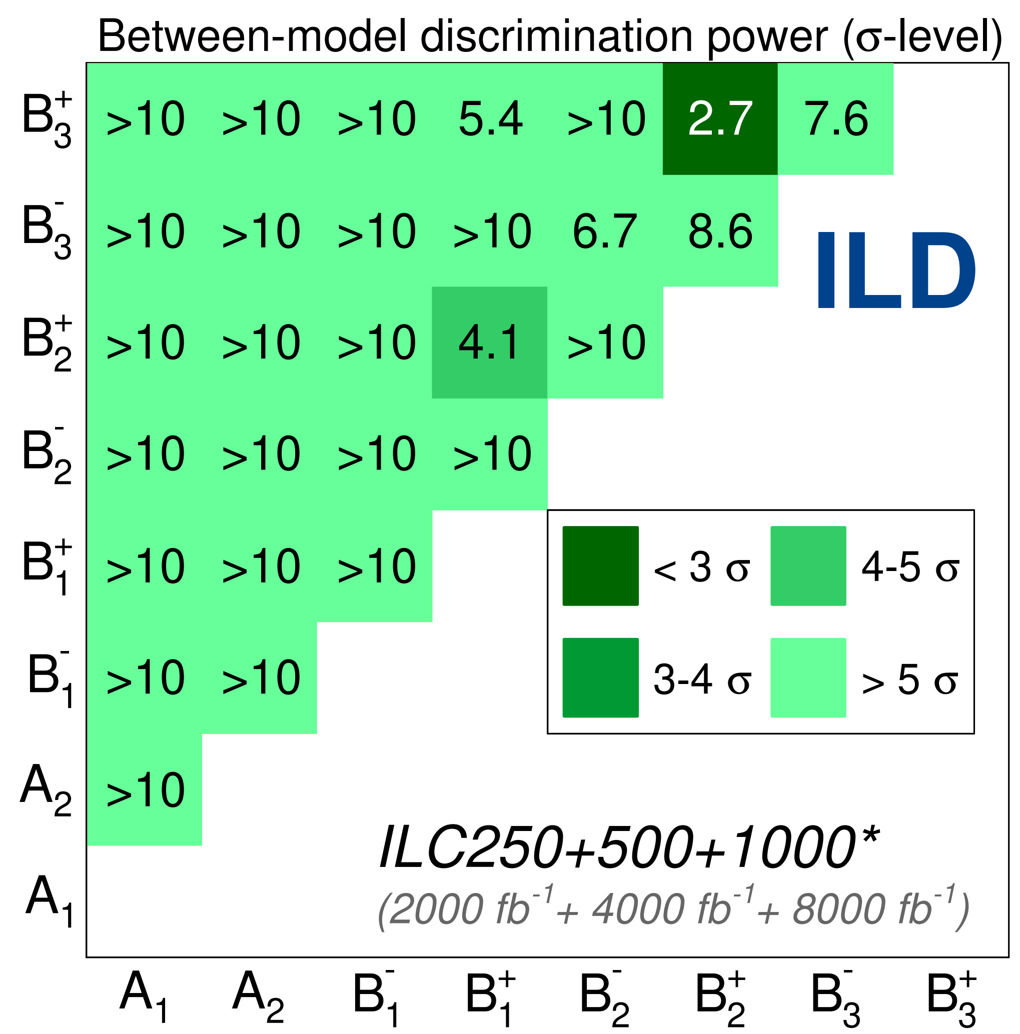






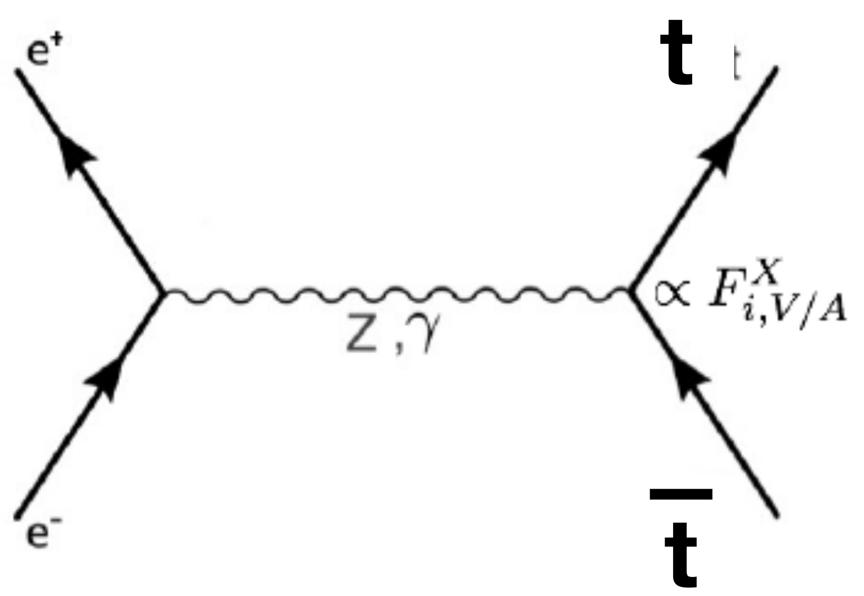




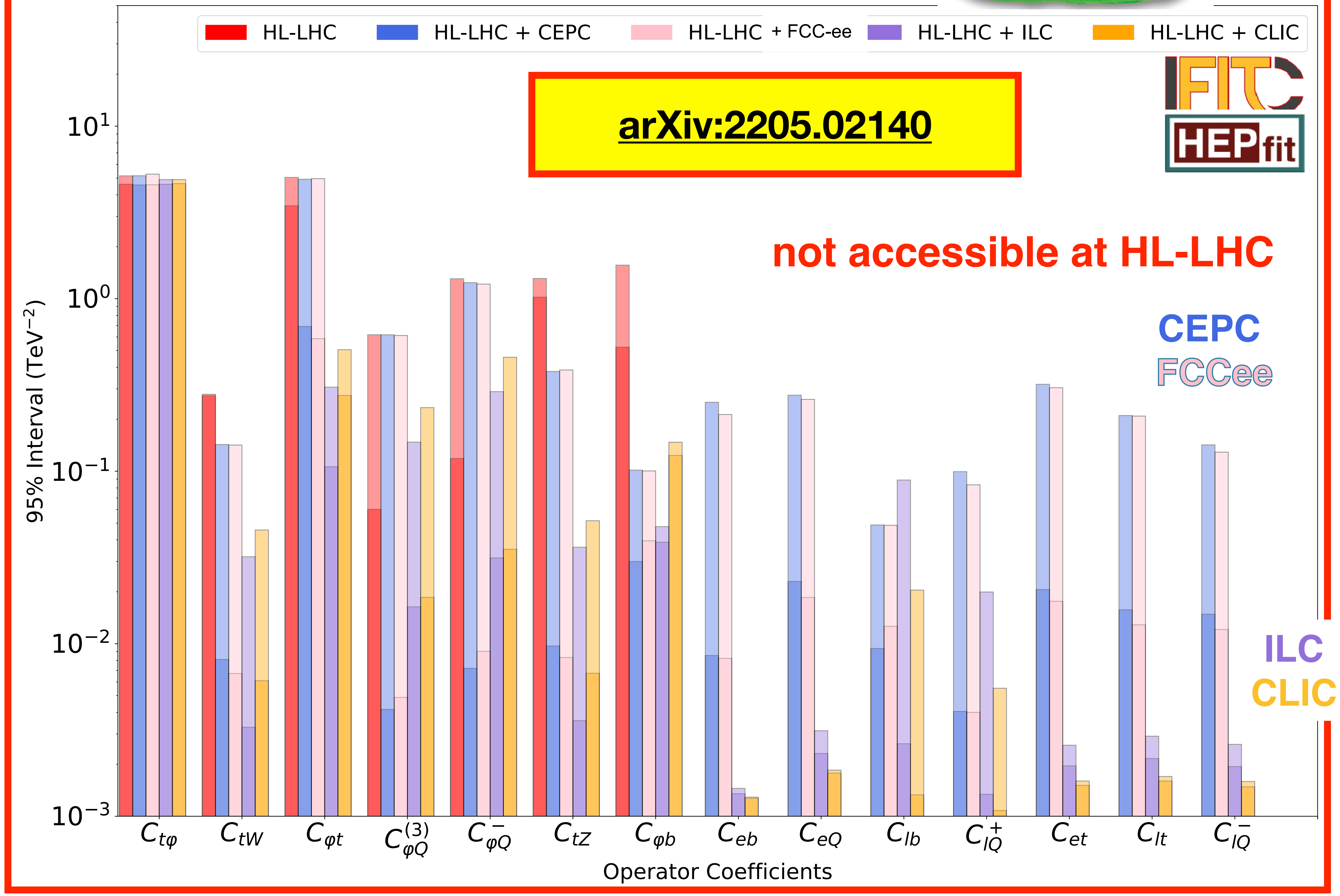


Full SMEFT analysis of Top Quark sector

Essential to understand special relation of top quark and Higgs boson



- expected precision on Wilson coefficients for HL-LHC alone and combined with various e+e- proposals
- e+e- at **high center-of-mass energy** and with **polarised beams** lifts degeneracies between operators



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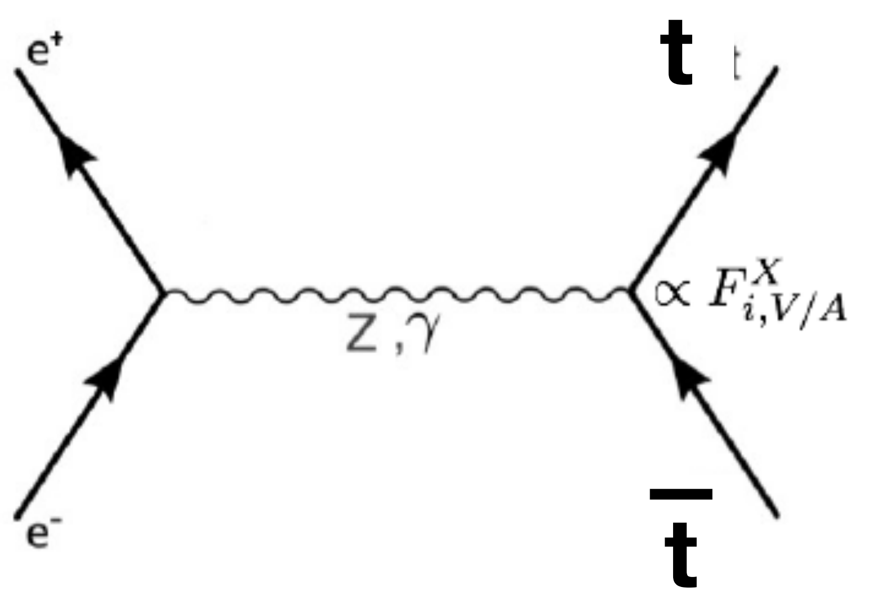

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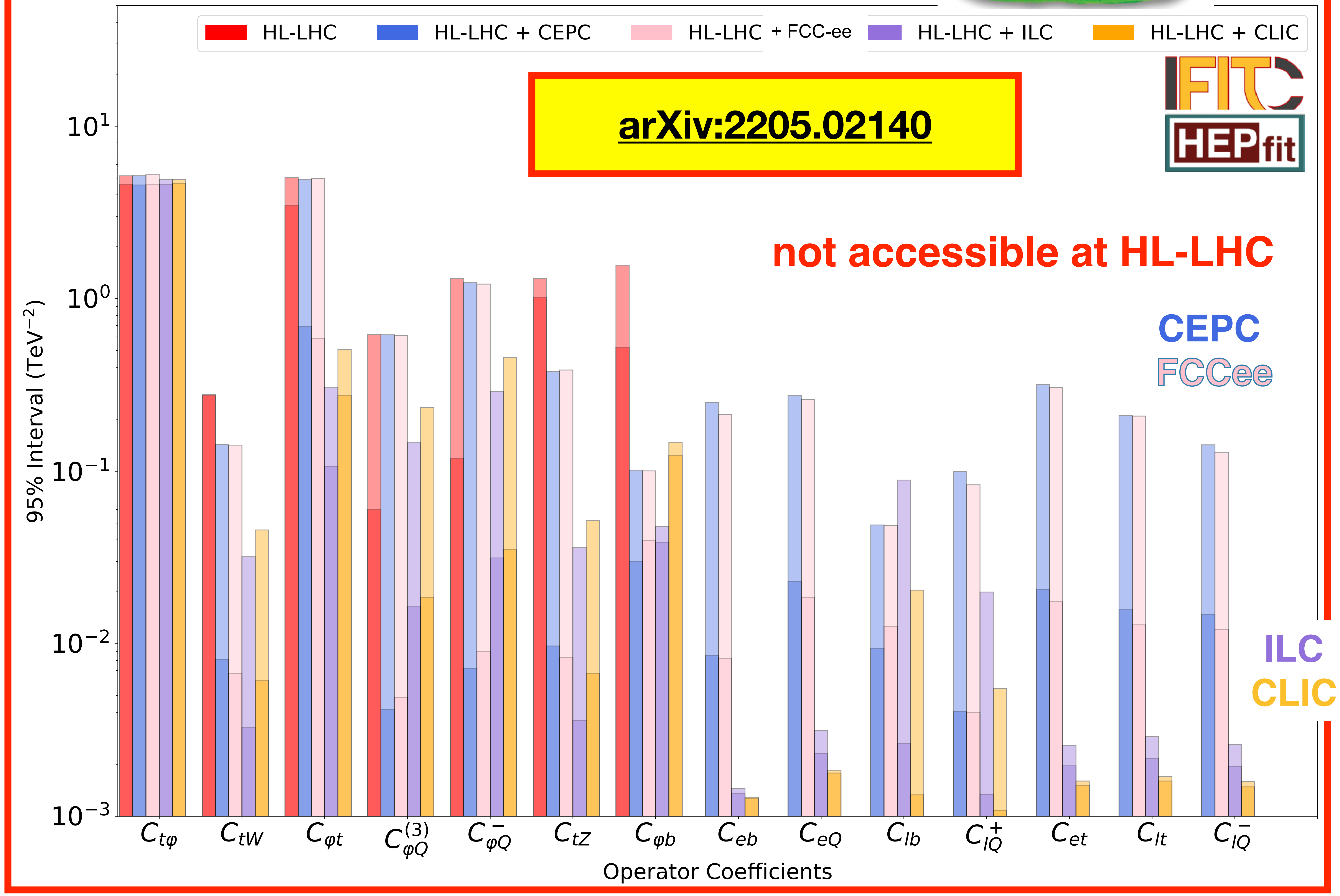
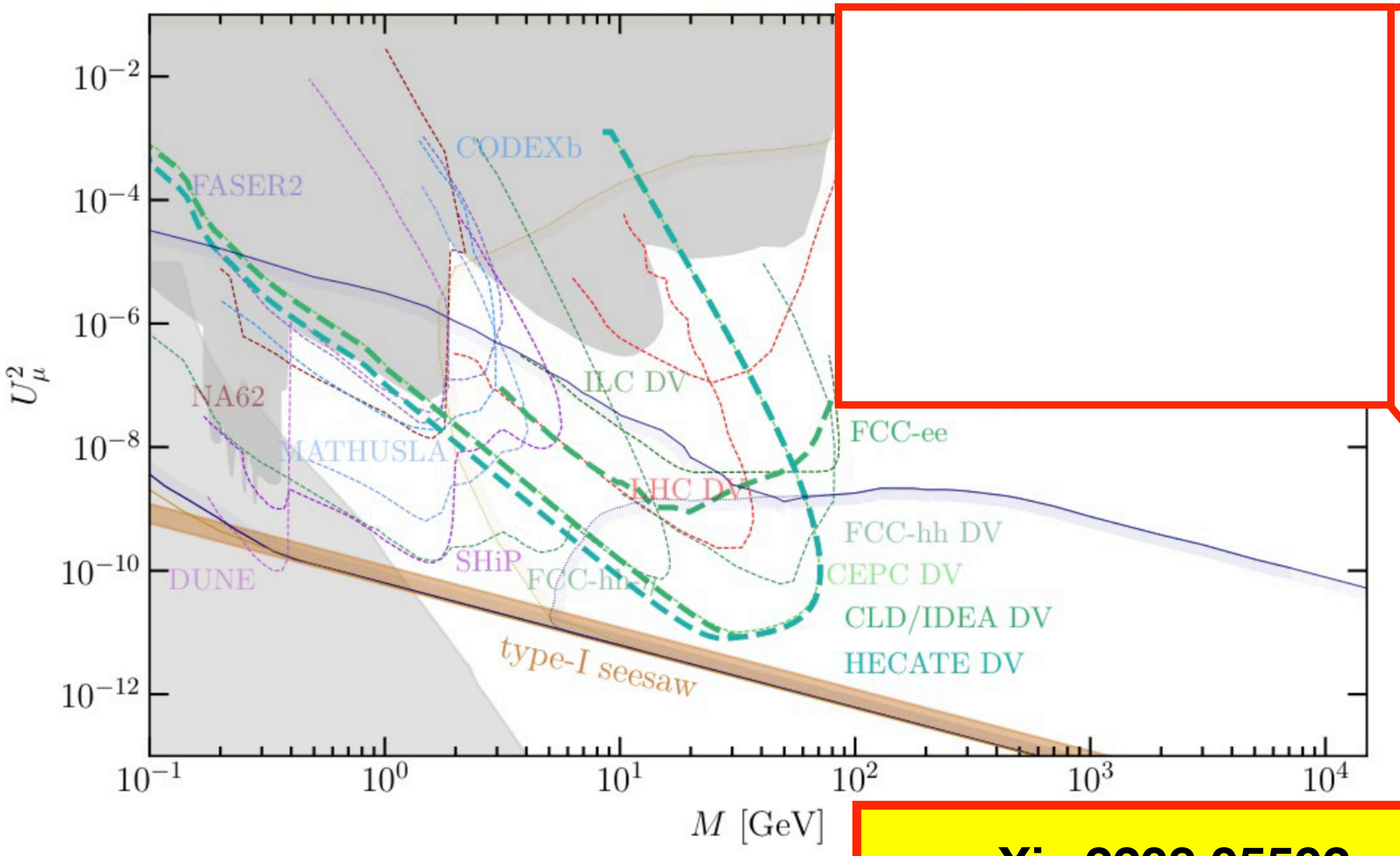
top-quark physics requires high center-of-mass energy AND polarised beams



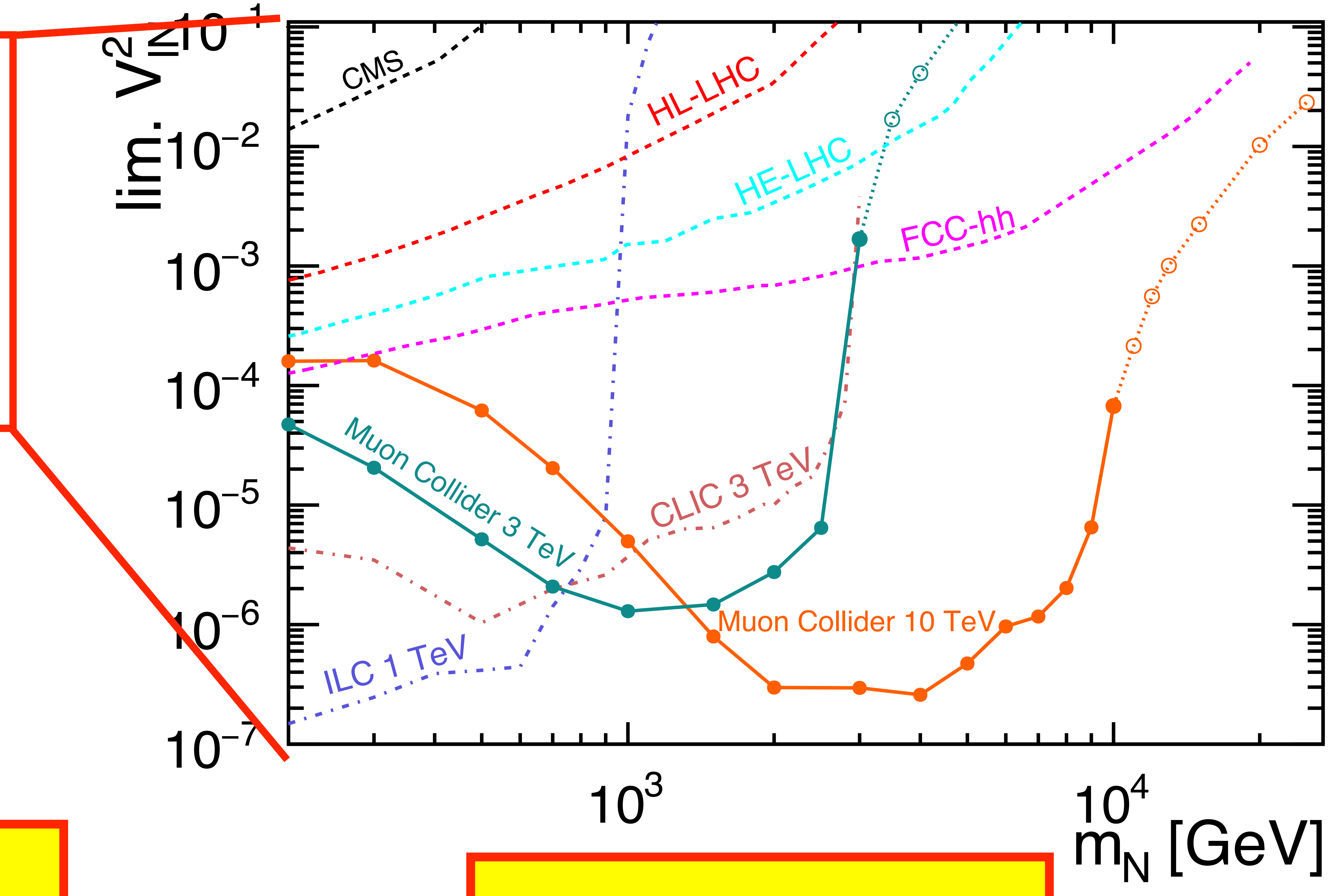
Heavy Neutral Leptons

Discovery reach for lepton colliders - complementary to FCC-hh

in Z decays with displaced vertices… …and at high masses in prompt decays



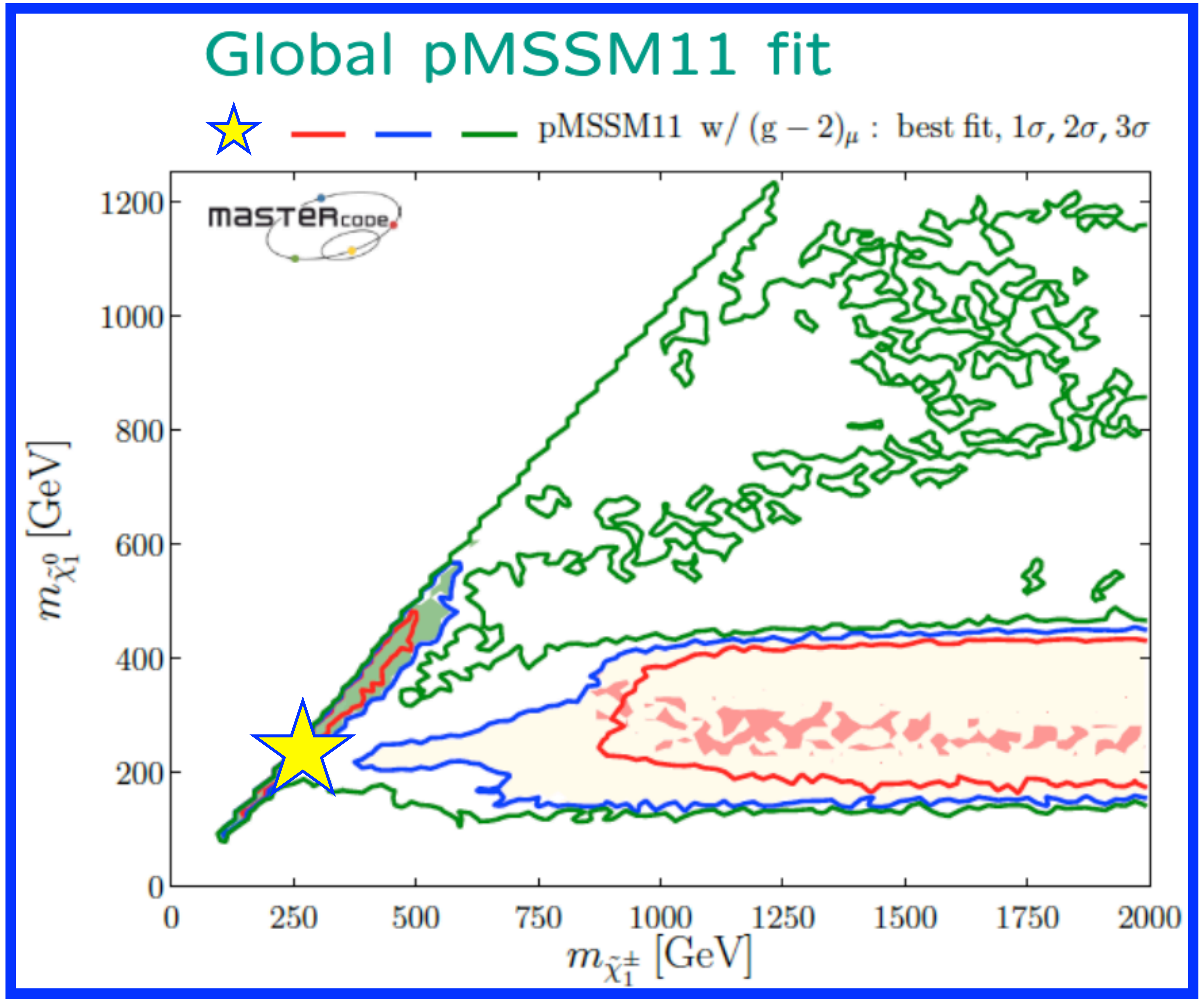
arXiv:2203.05502



arXiv:2301.02602

Higgsinos ?

- lowish ΔM is THE region preferred by data, e.g. for charginos & neutralinos
  => no *general* limit above LEP



Eur.Phys.J. C78 (2018) no.3, 256

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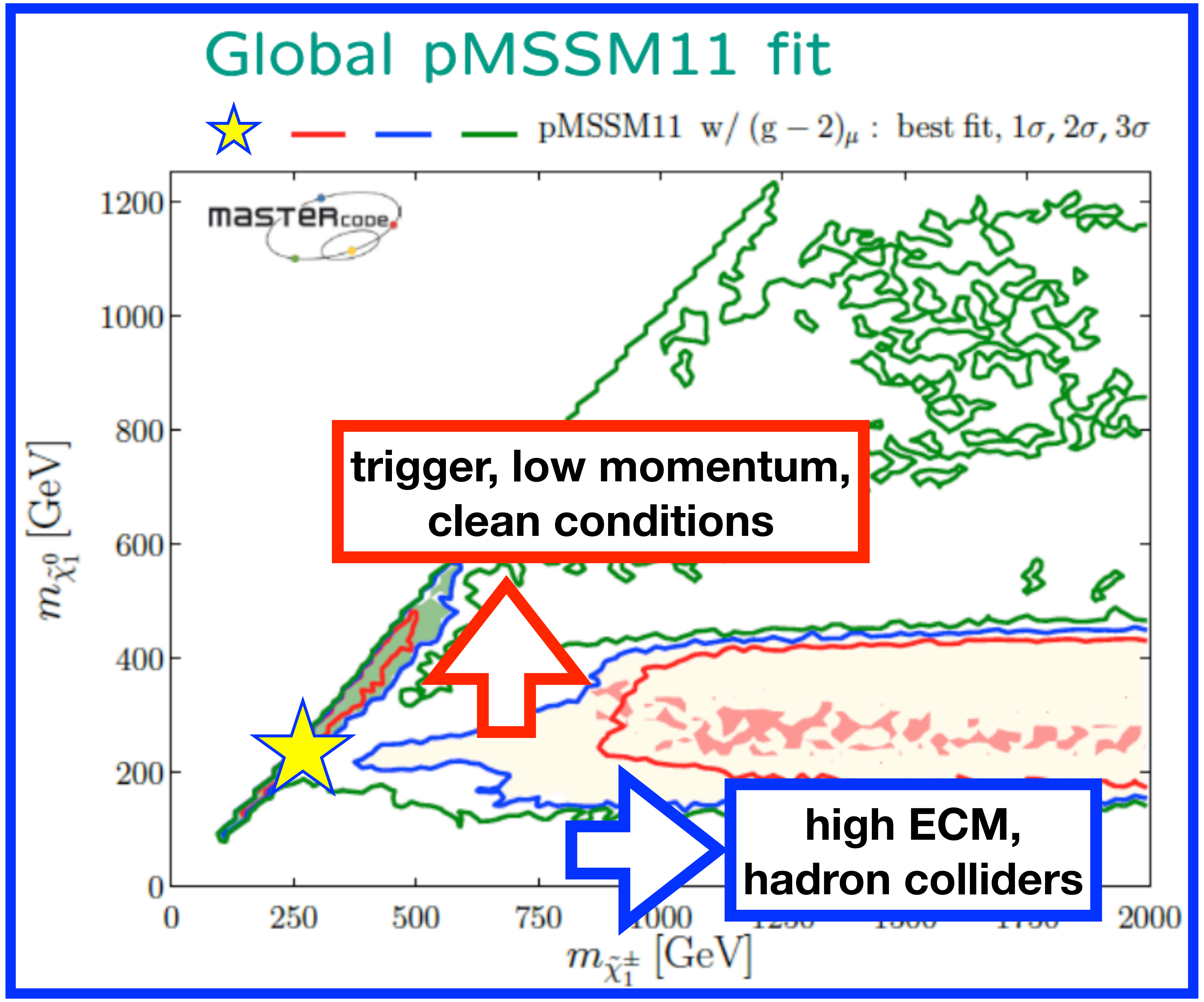

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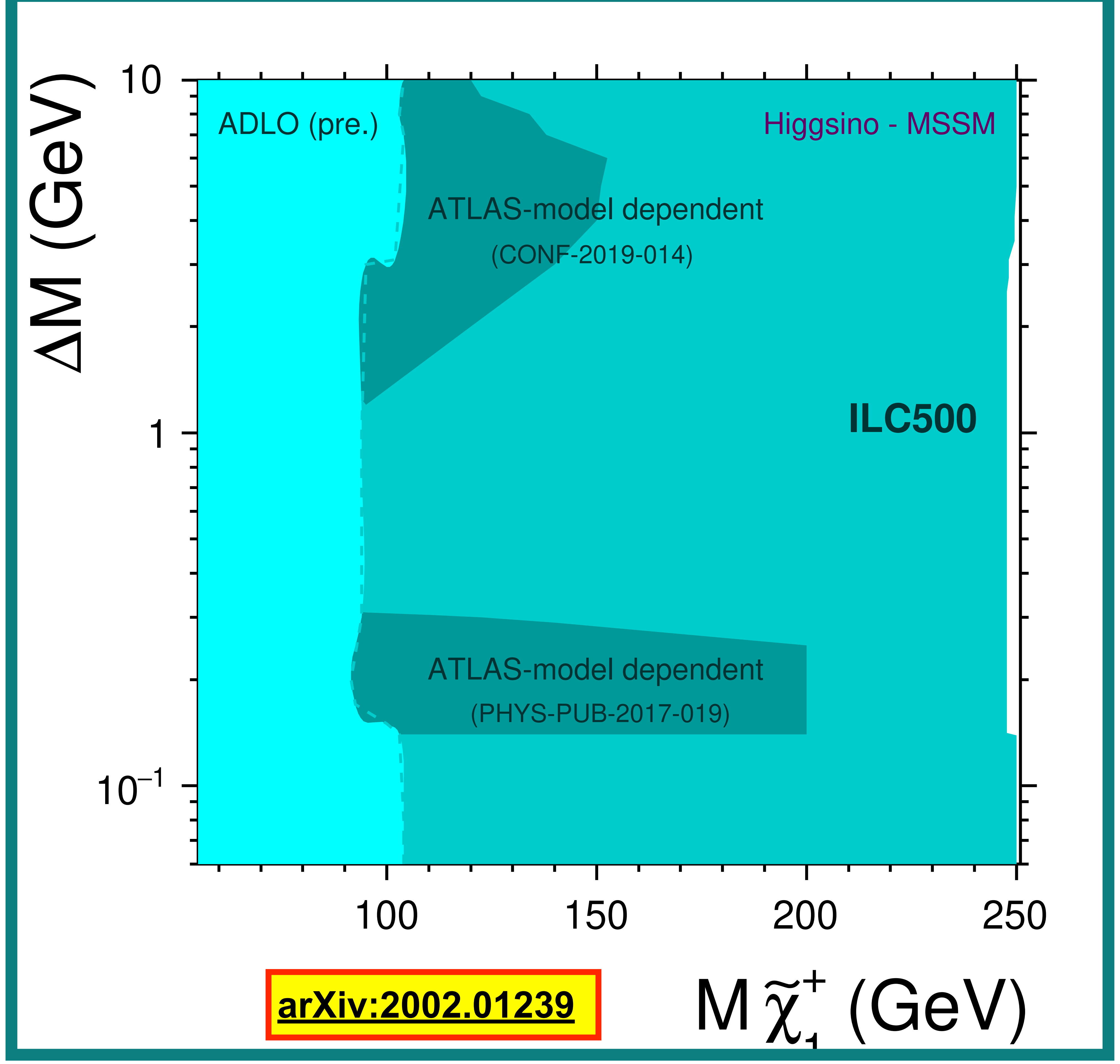
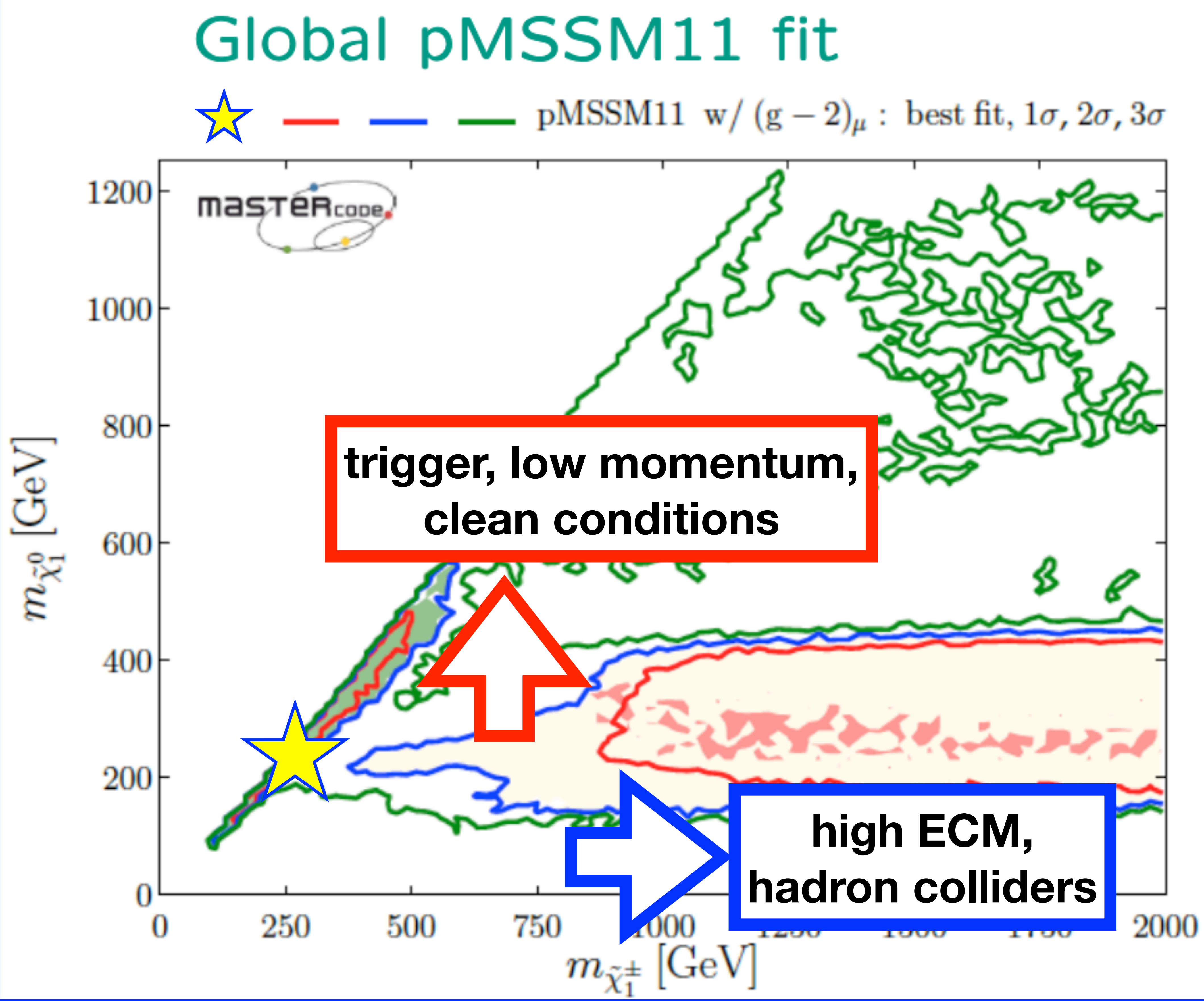


arXiv:2002.01239



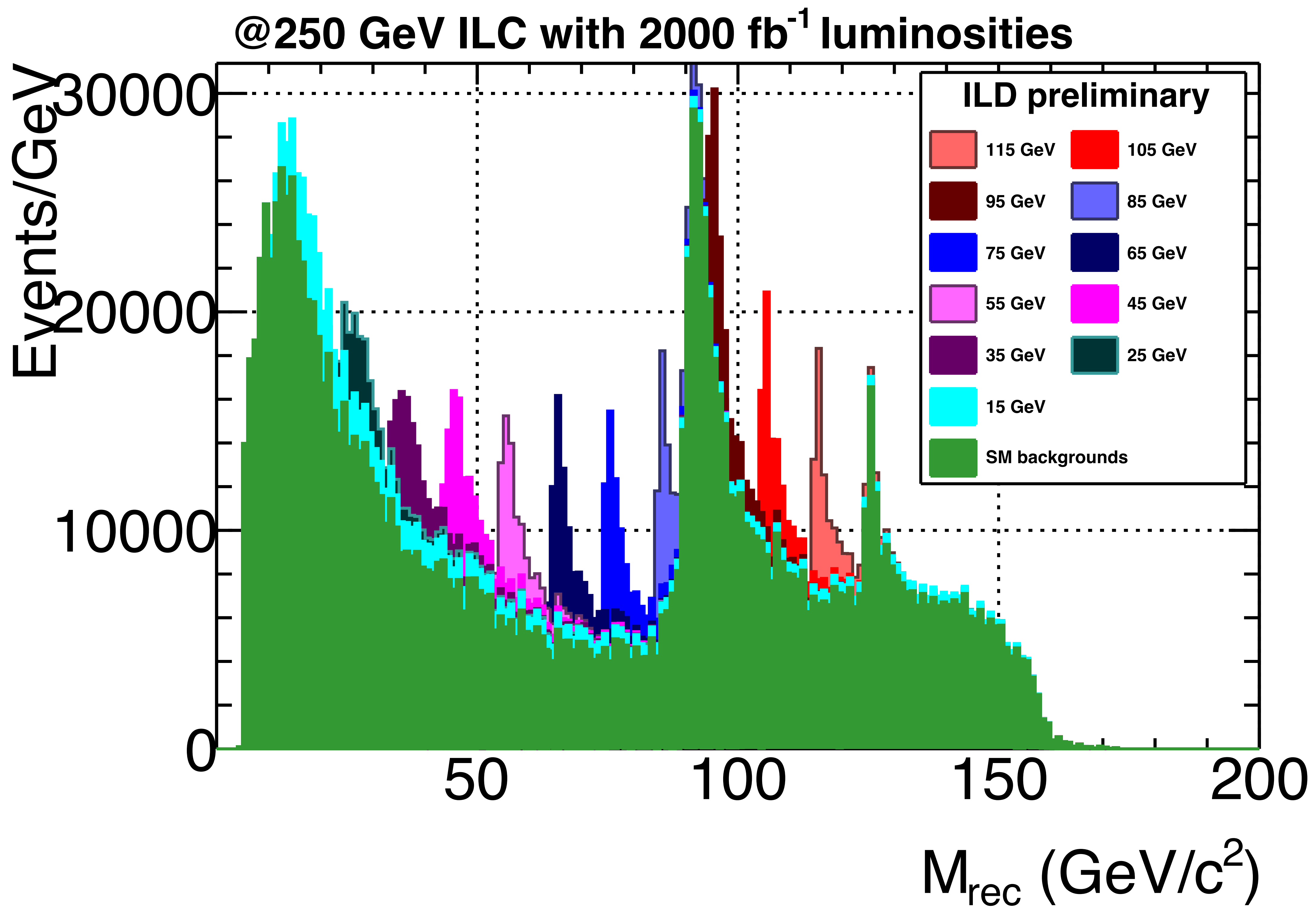
Eur.Phys.J. C78 (2018) no.3, 256

Extra Higgs Bosons ?

Siblings of the Higgs

- must “share” coupling to the Z with the 125-GeV guy:
  - $g_{HZZ}^2 + g_{hZZ}^2 \leq 1$
  - 250 GeV Higgs measurements:
    $g_{hZZ}^2 < 2.5\%\ g_{SM}^2$ excluded at 95% CL
- probe smaller couplings by ***recoil* of h against Z**

=> decay mode independent!



ILD full detector simulation
@ ILC 250 GeV & 500 GeV,
arxiv:2005.06265

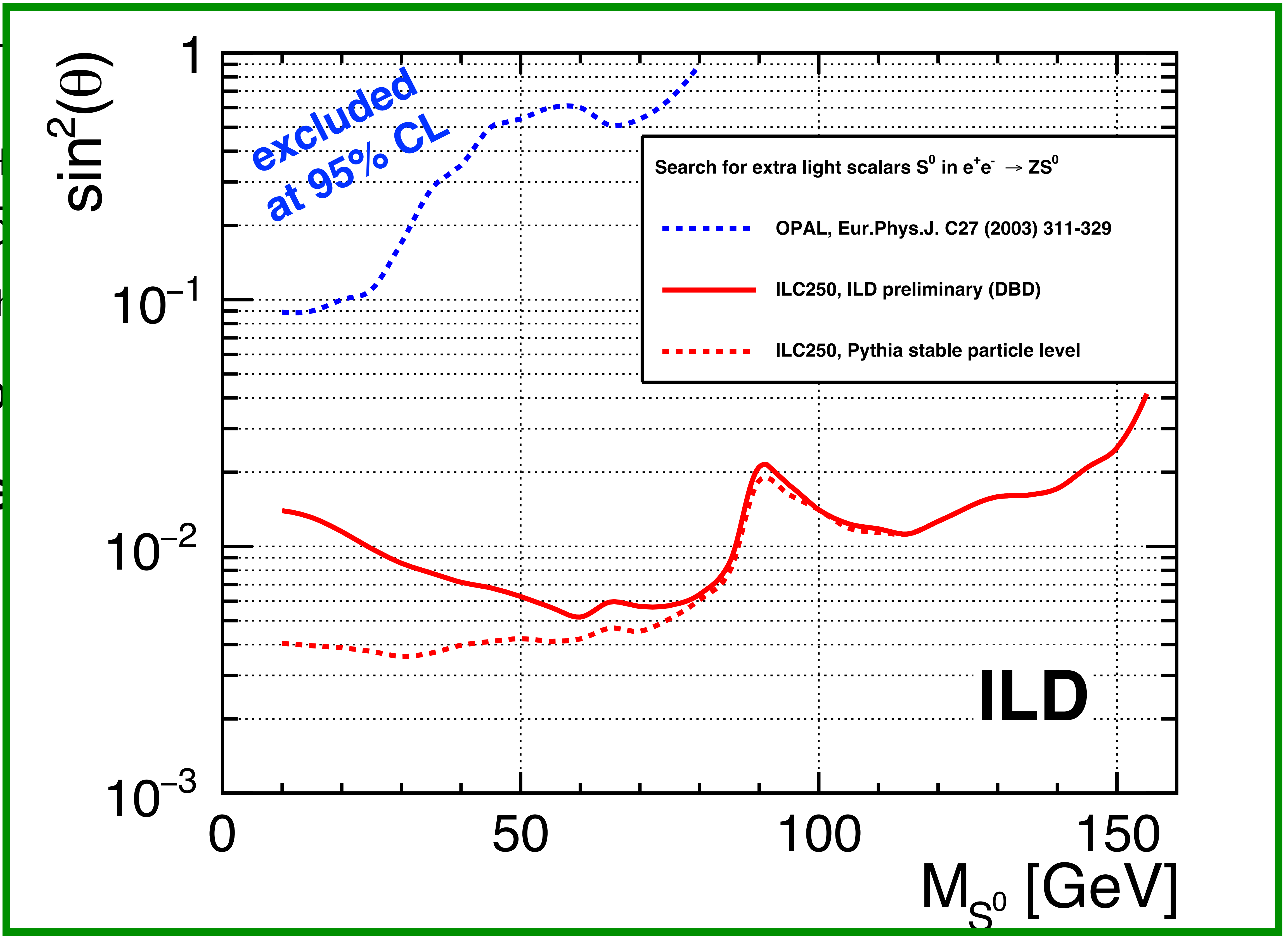
- **fully complementary to measurement of ZH cross section**
- **other possibility: ee -> bbh (via Yukawa coupling)**

Extra Higgs Bosons ?

Siblings of the Higgs

- must
  - gH
  - 25
    gH
- prob

=> de



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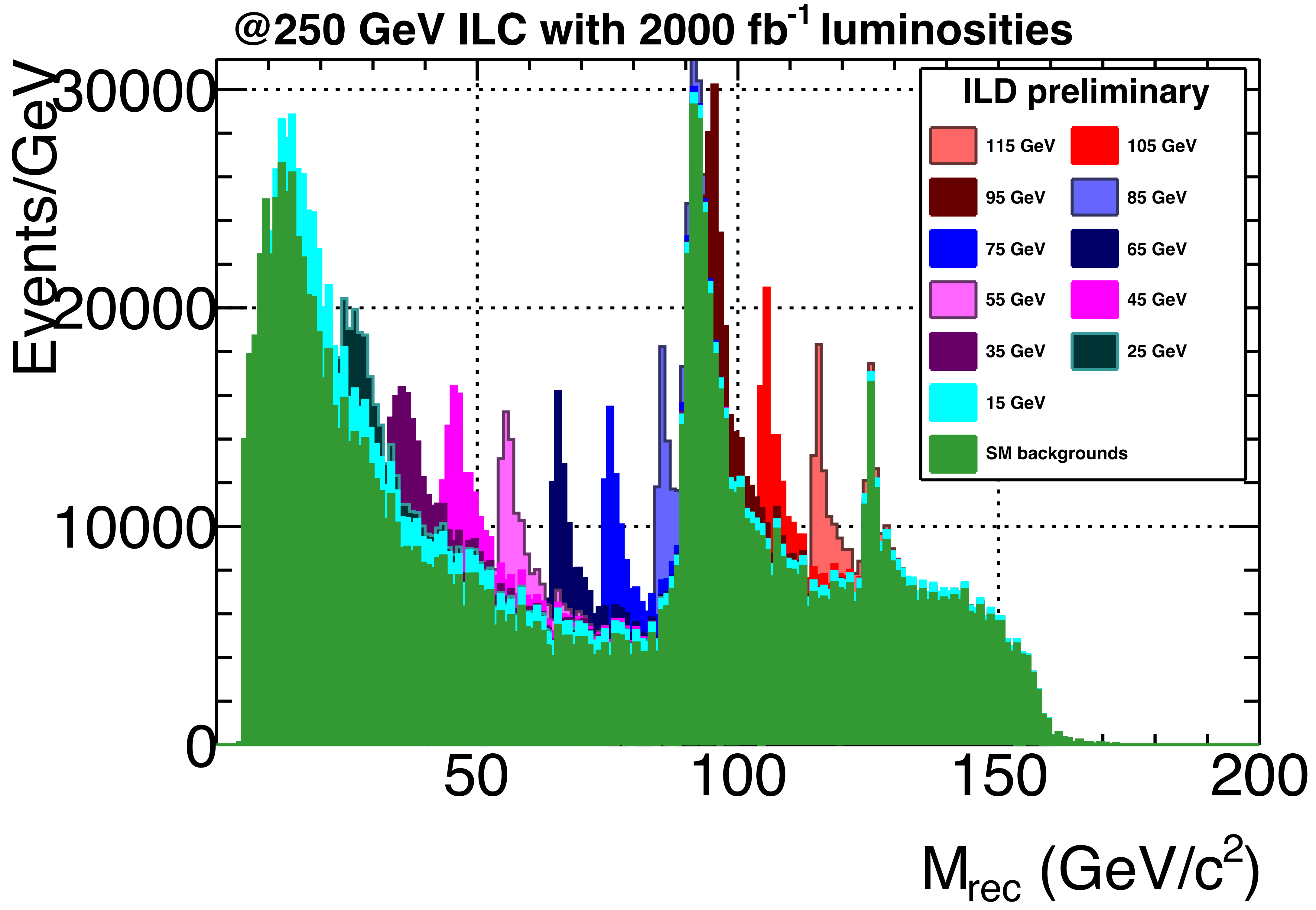

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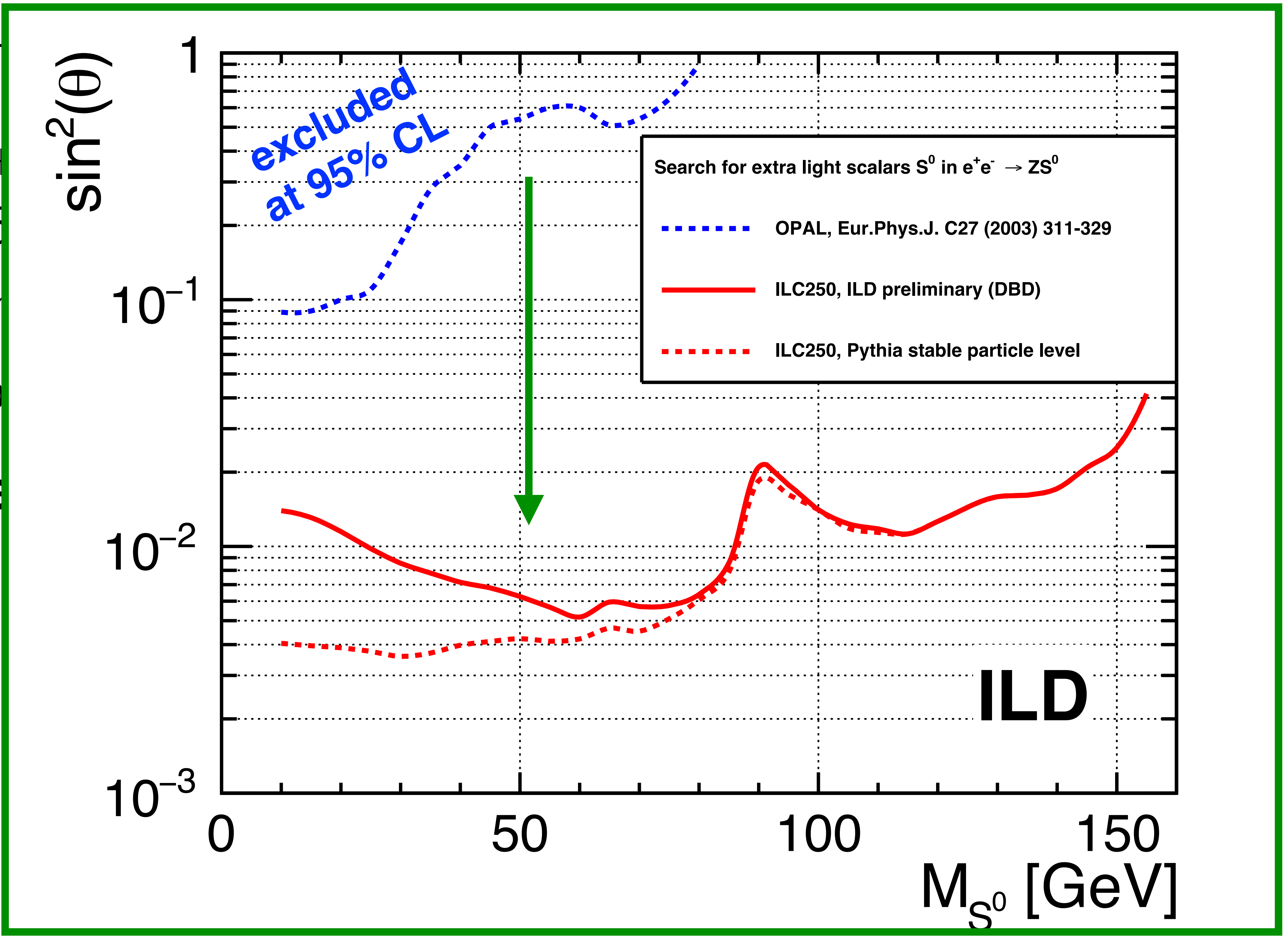

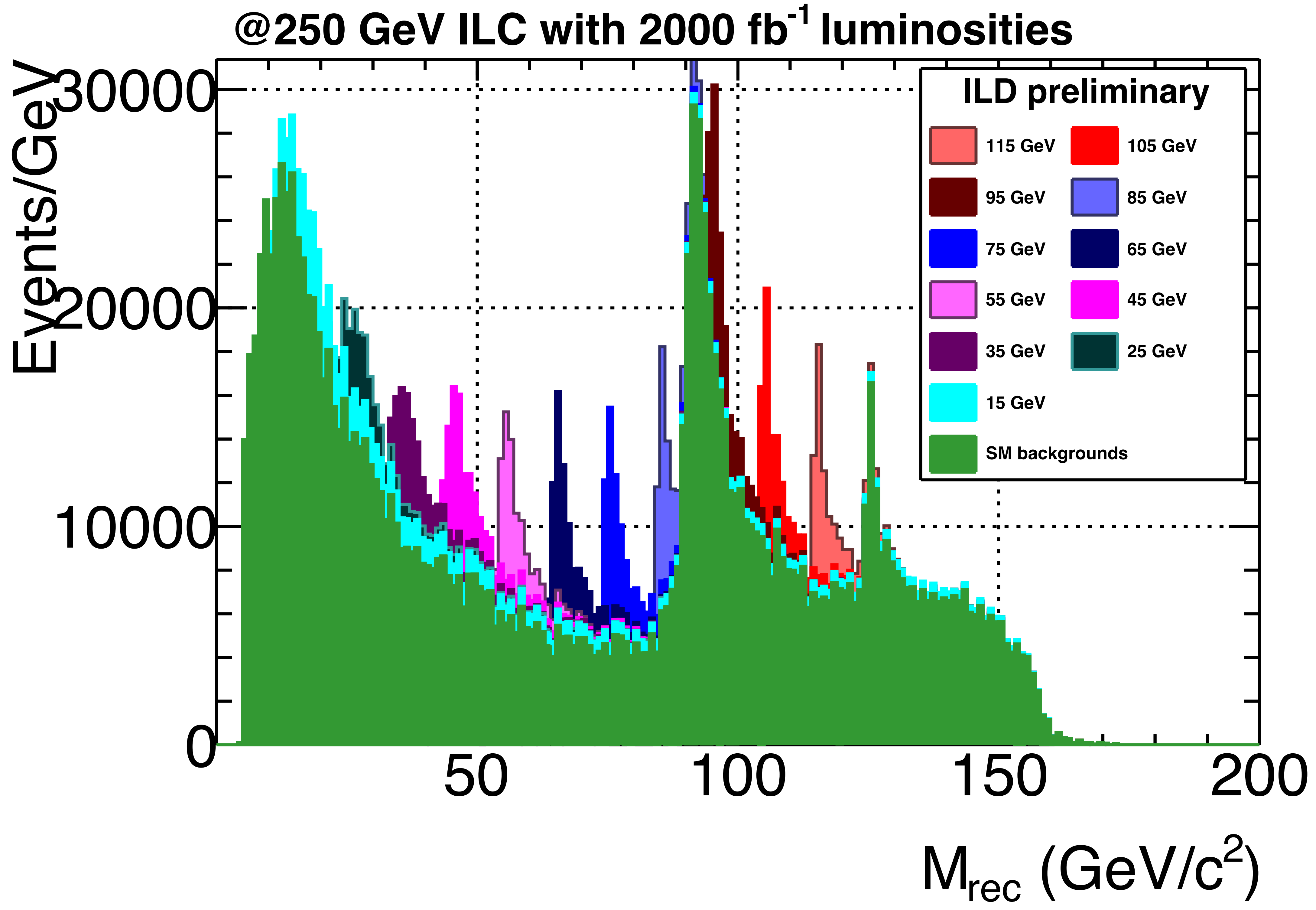

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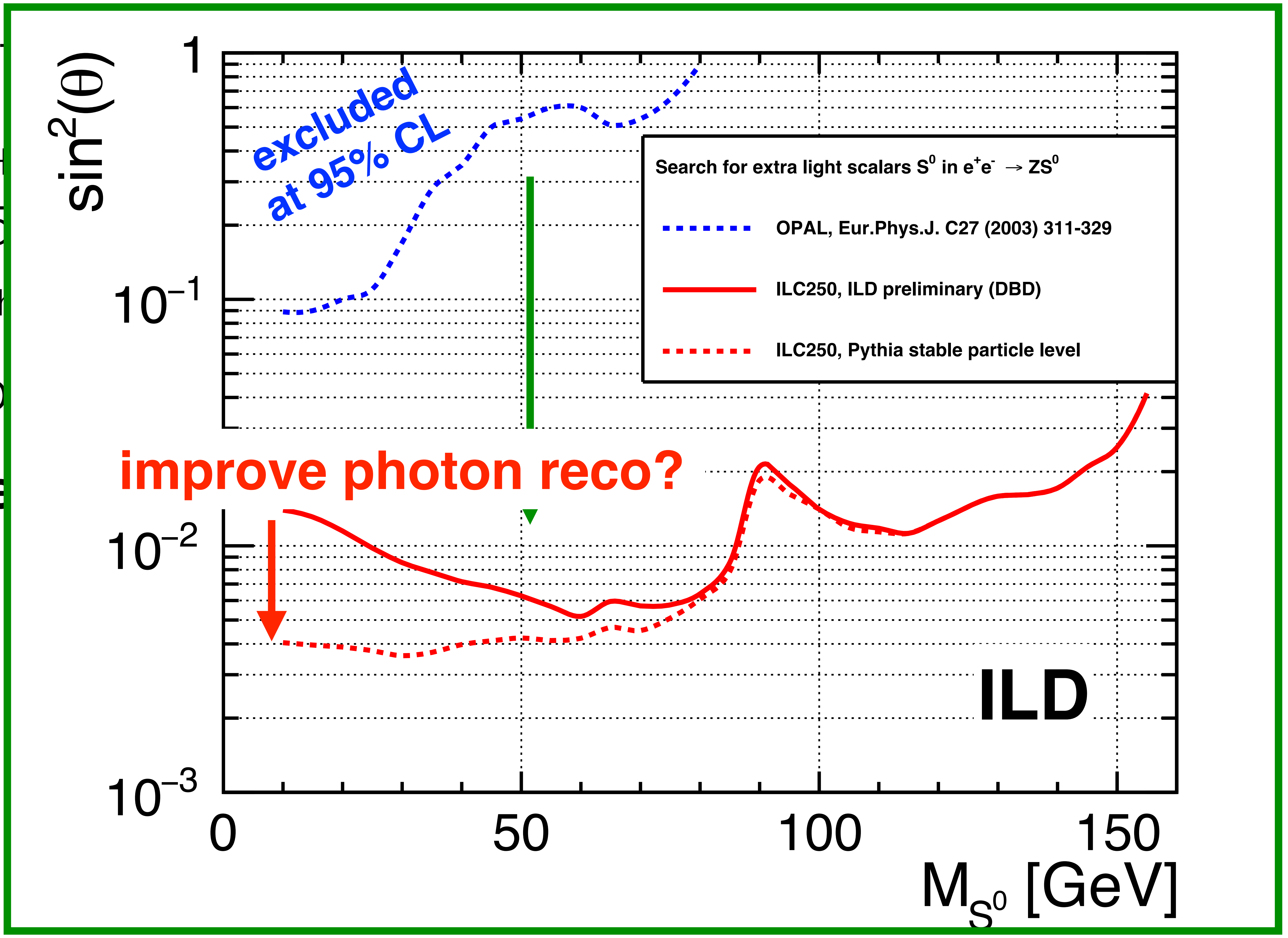

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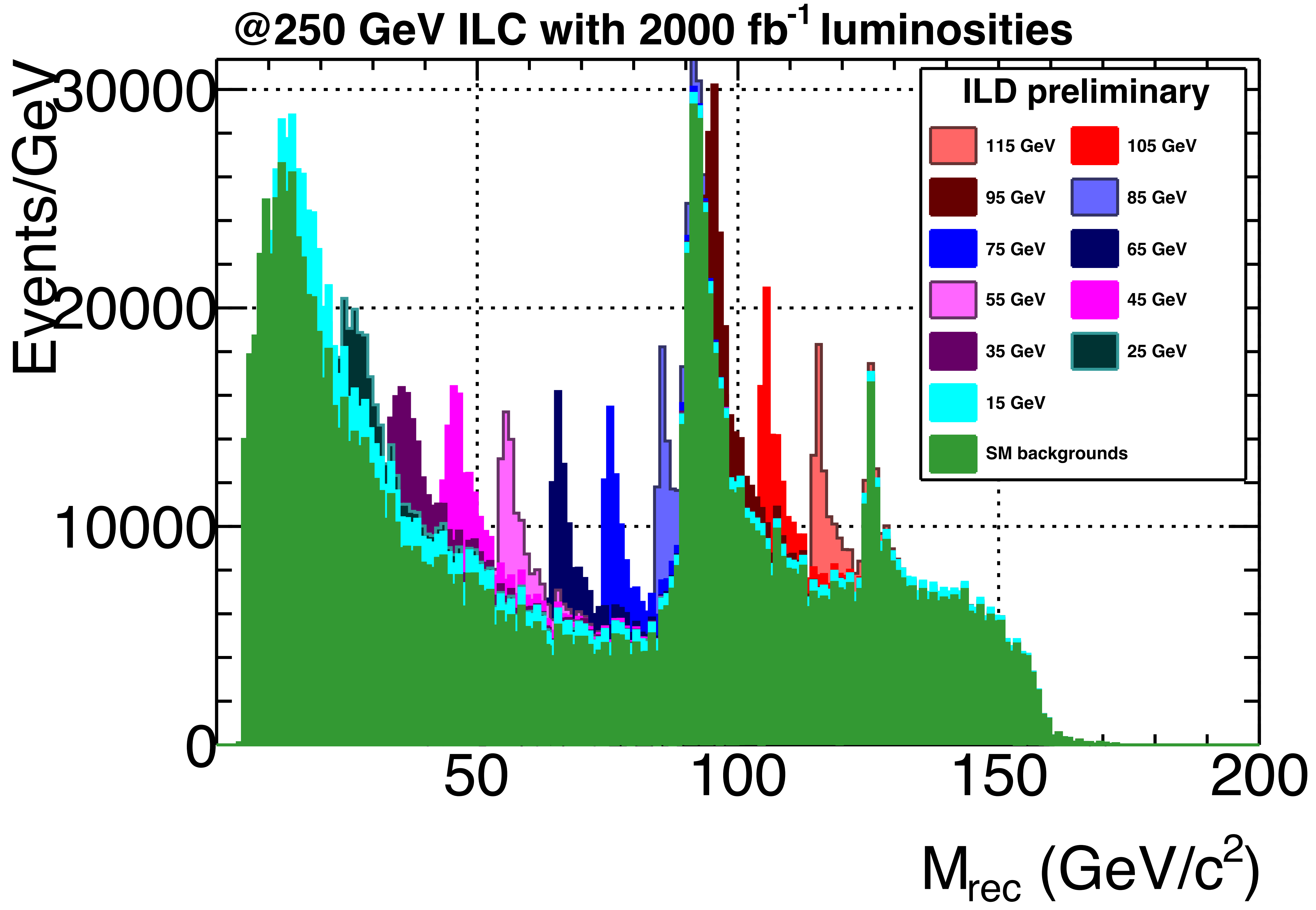

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Why do we need to know the couplings of the Higgs boson?

Discovering new phenomena

- Any deviation from the SM prediction is a discovery of a new phenomenon
- Higgs couplings allow finger-printing new phenomena via their different *patterns* of deviations
- *size* of deviations depends on energy scale of new particles:
  the more precise the measurement, the larger the discovery potential
- need at least 1%-level of precision for Higgs couplings
- **all proposed Higgs factories can deliver this program - (HL-)LHC cannot do this**

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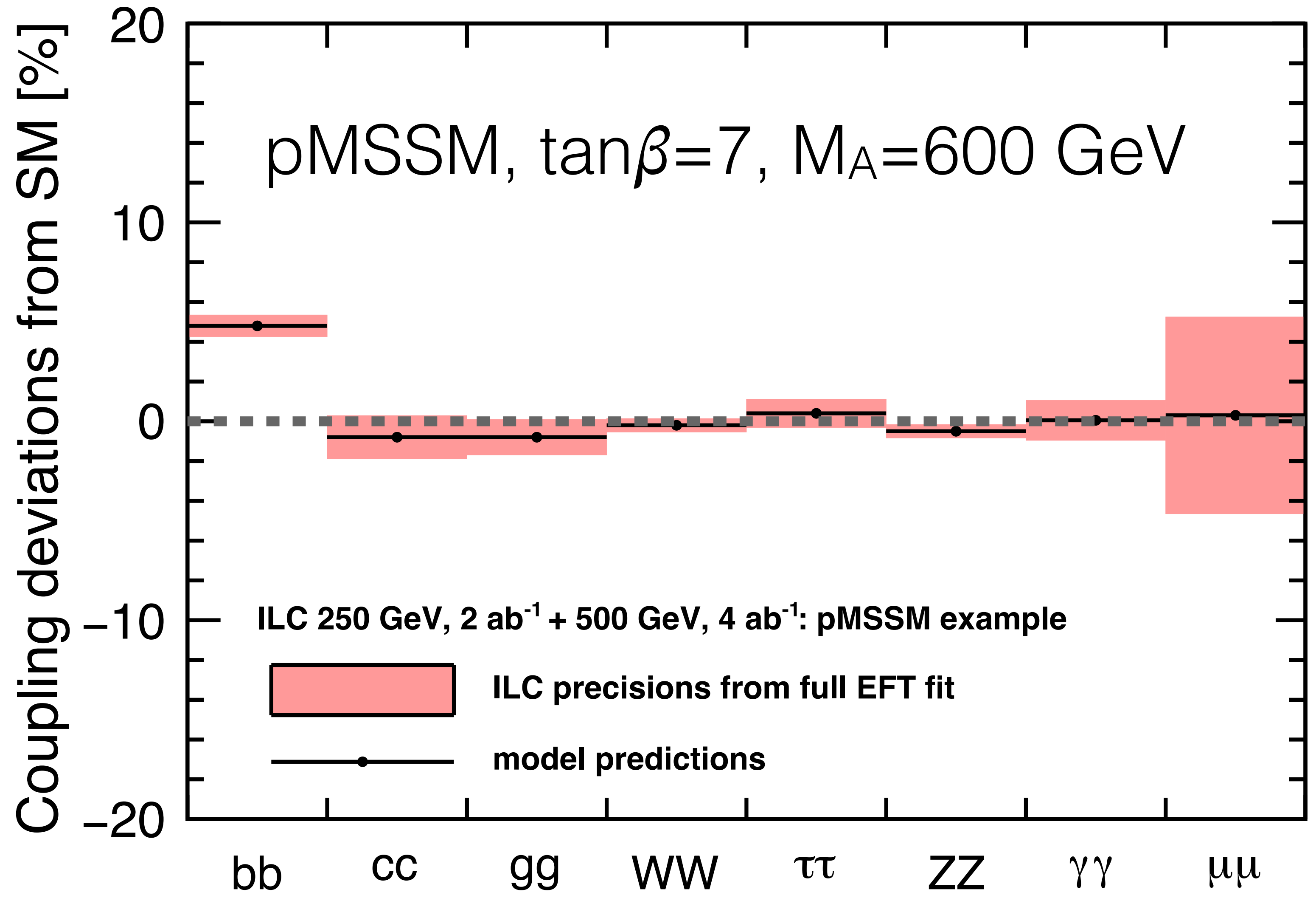

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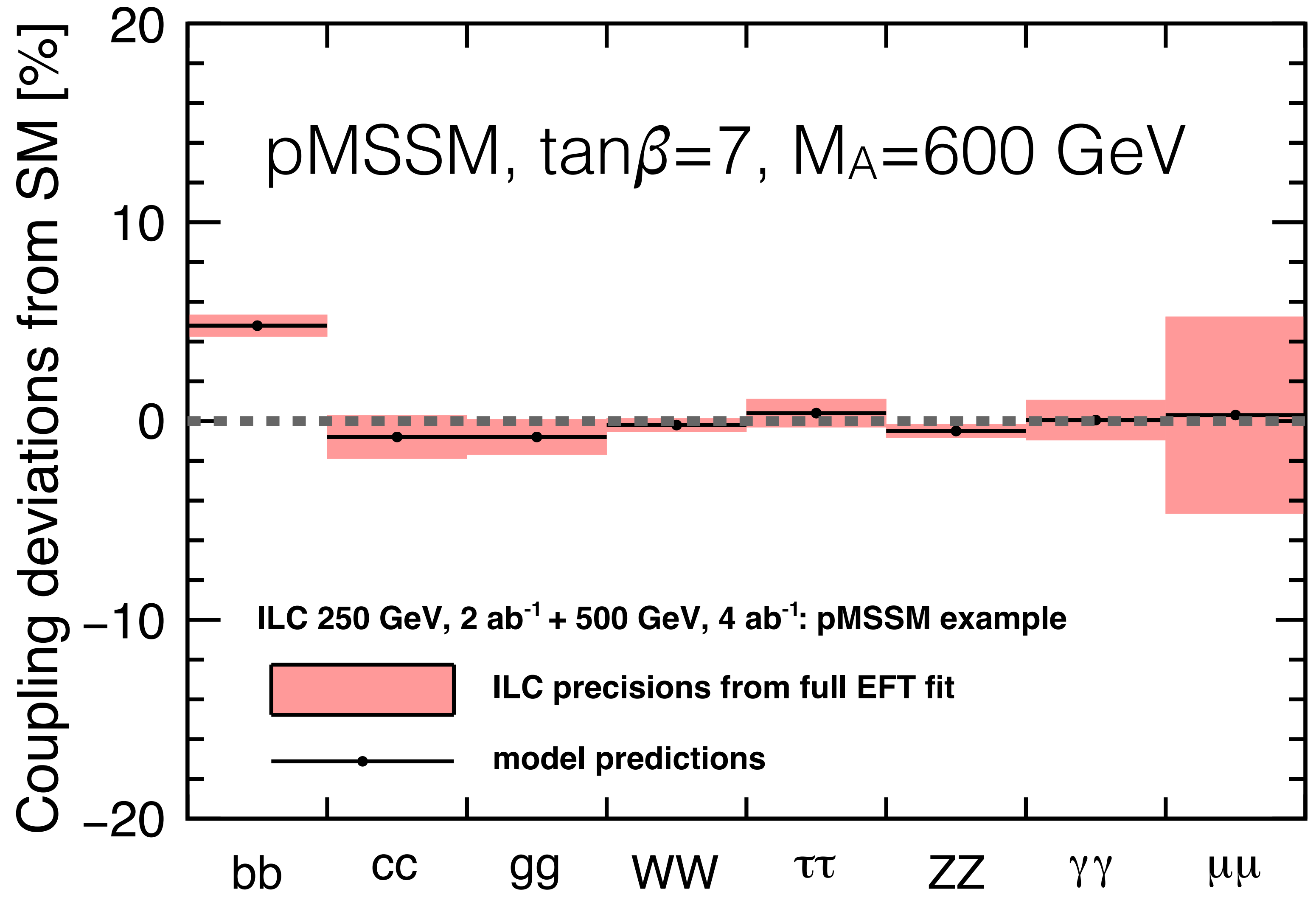

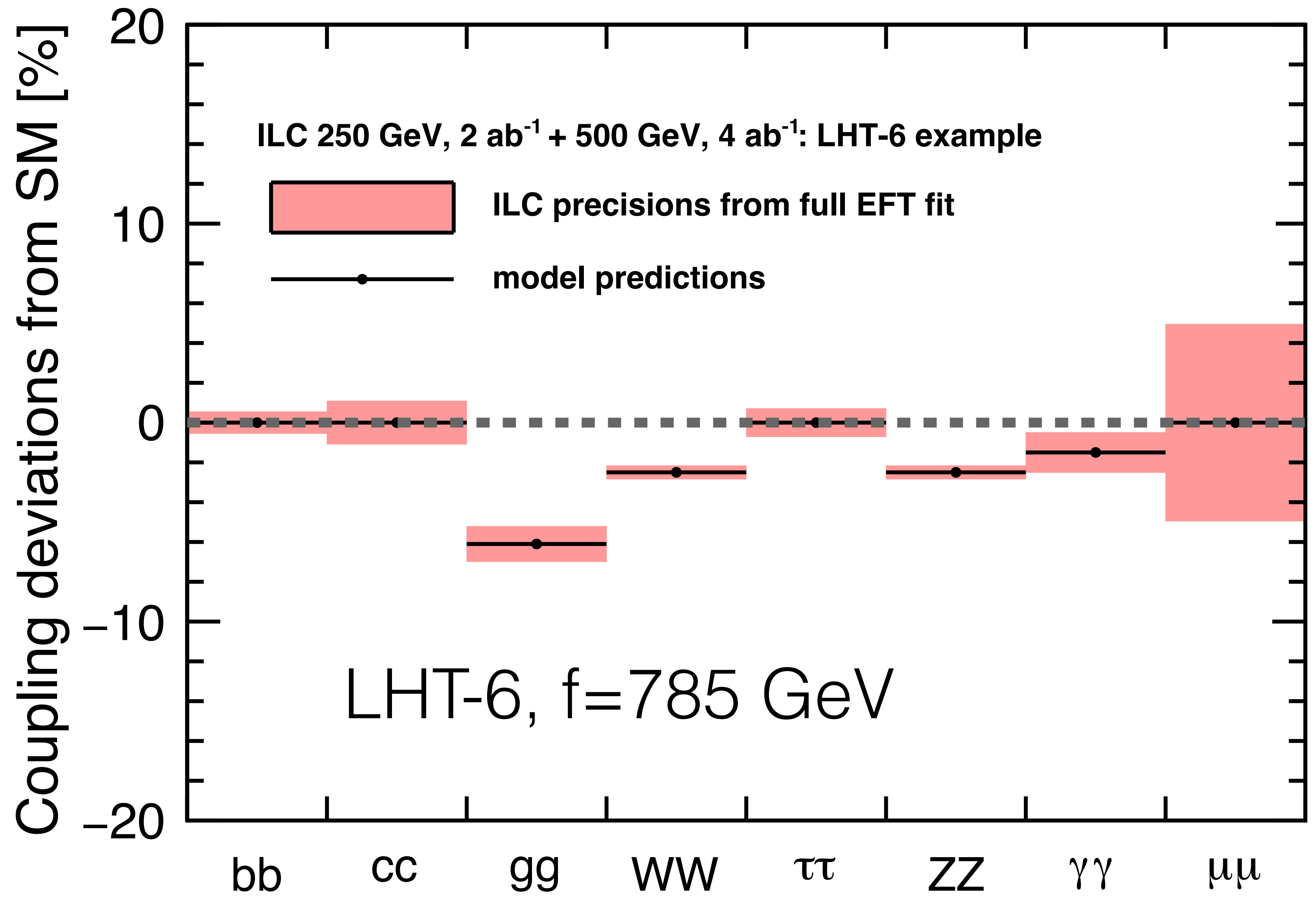

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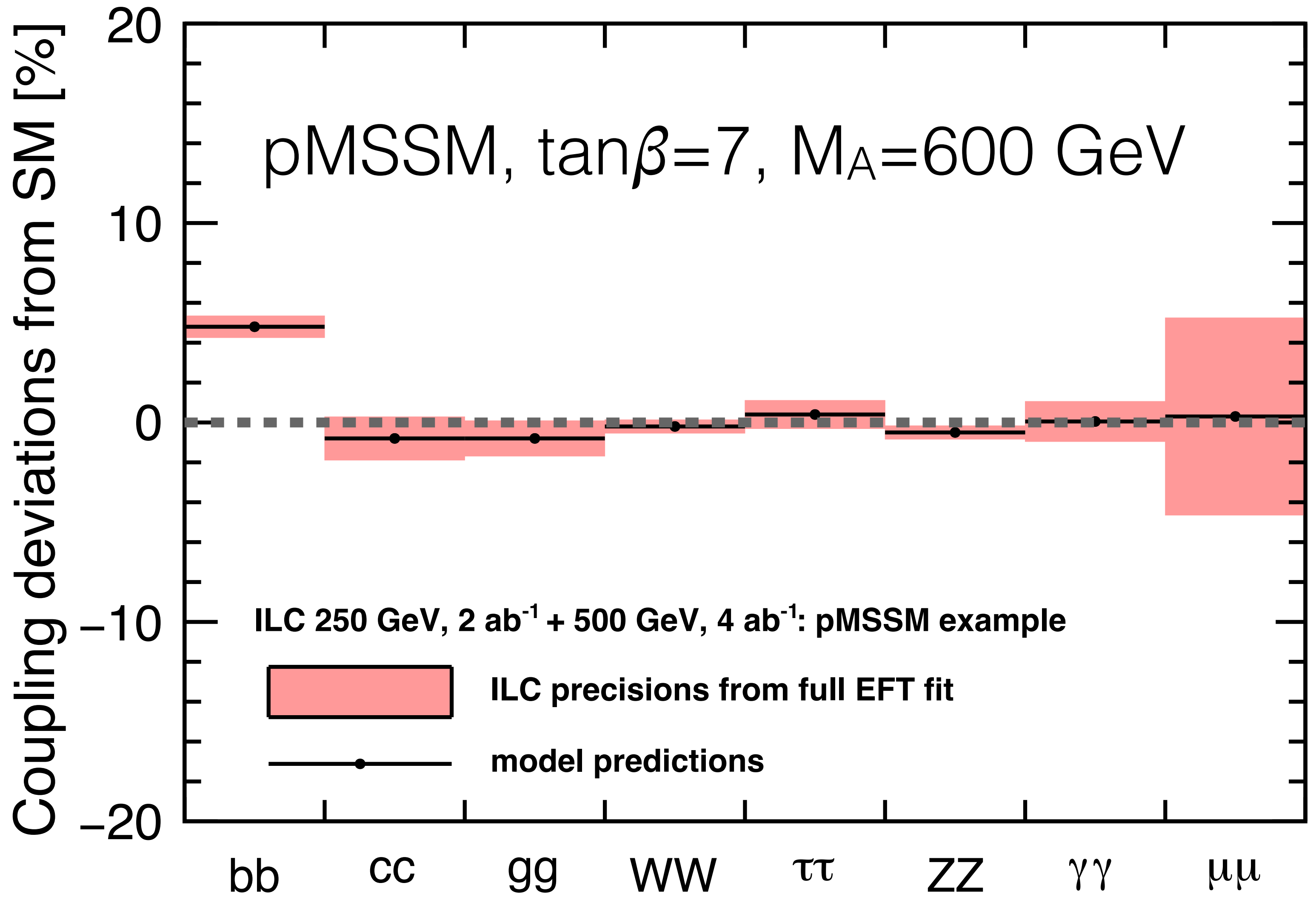

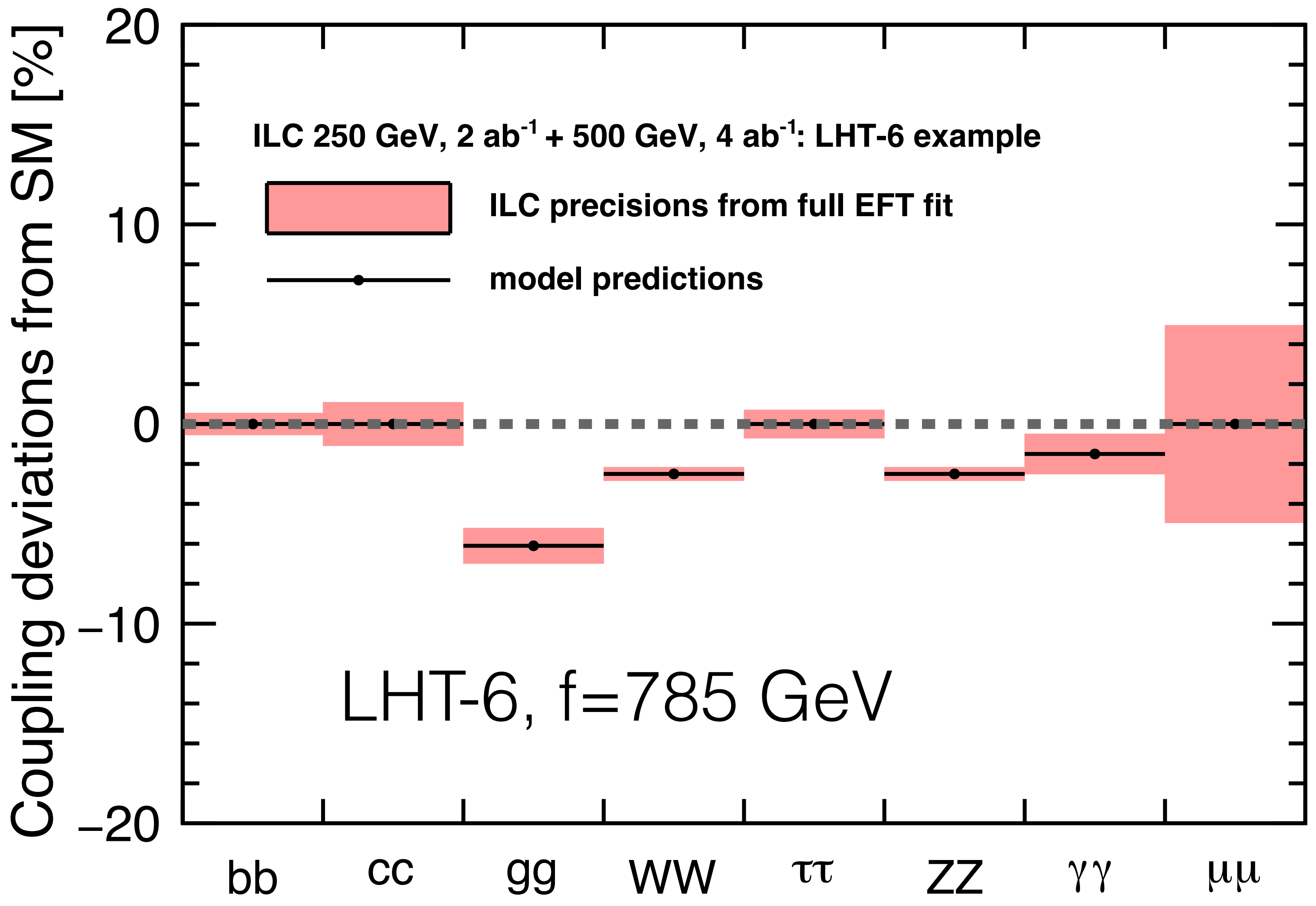

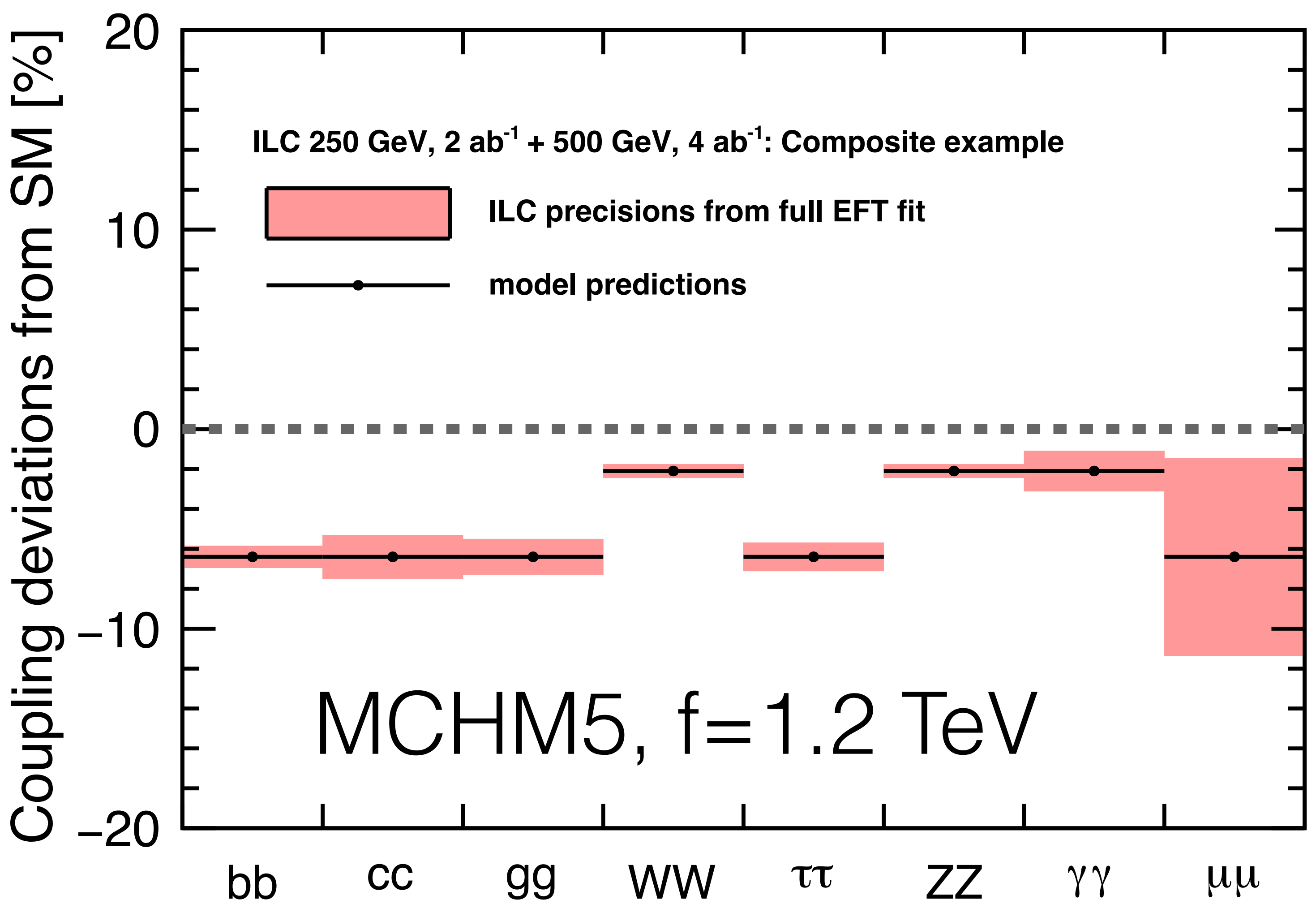

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New Physics Interpretation of Higgs & EW

Illustrating the principle - based on older fit!

Test various example BSM points - all chosen such that no hint for new physics at HL-LHC

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [36]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [35]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [39]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
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9	Higgs Singlet [41]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Table 3: Percent deviations from SM for Higgs boson couplings to SM states in various new physics models. These model points are unlikely to be discoverable at 14 TeV LHC through new particle searches even after the high luminosity era ($3\,\mathrm{ab}^{-1}$ of integrated luminosity). From [15].

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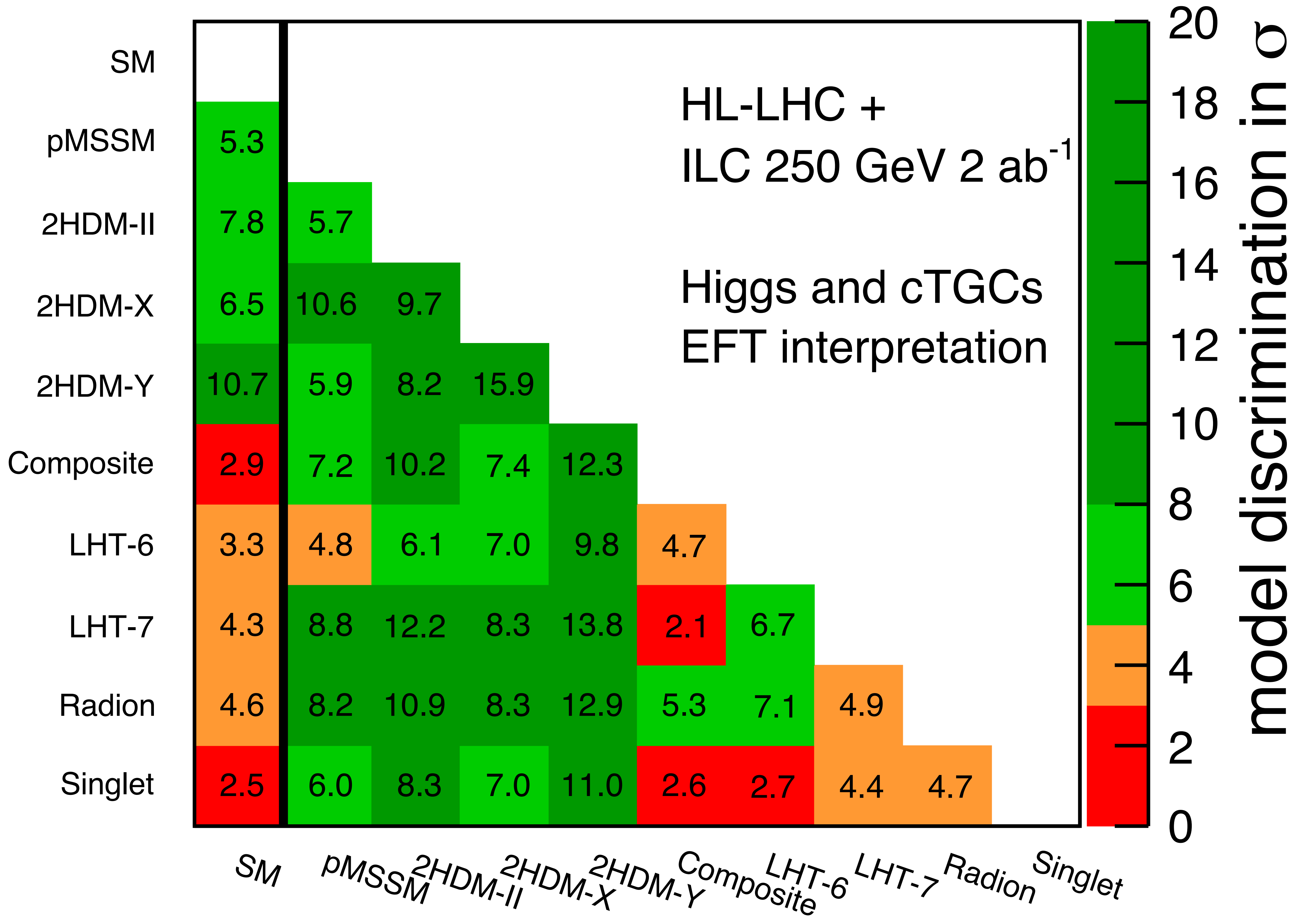

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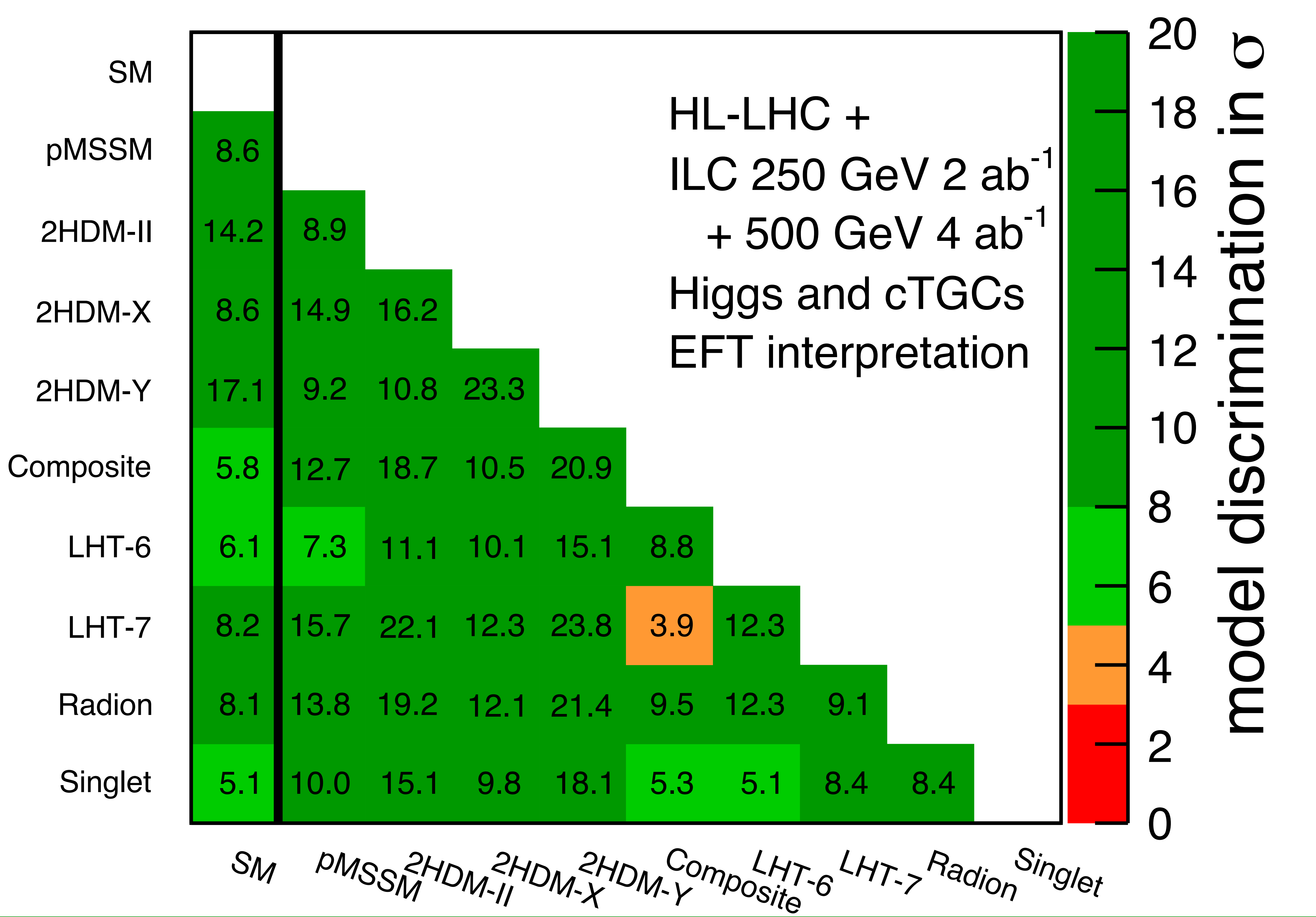

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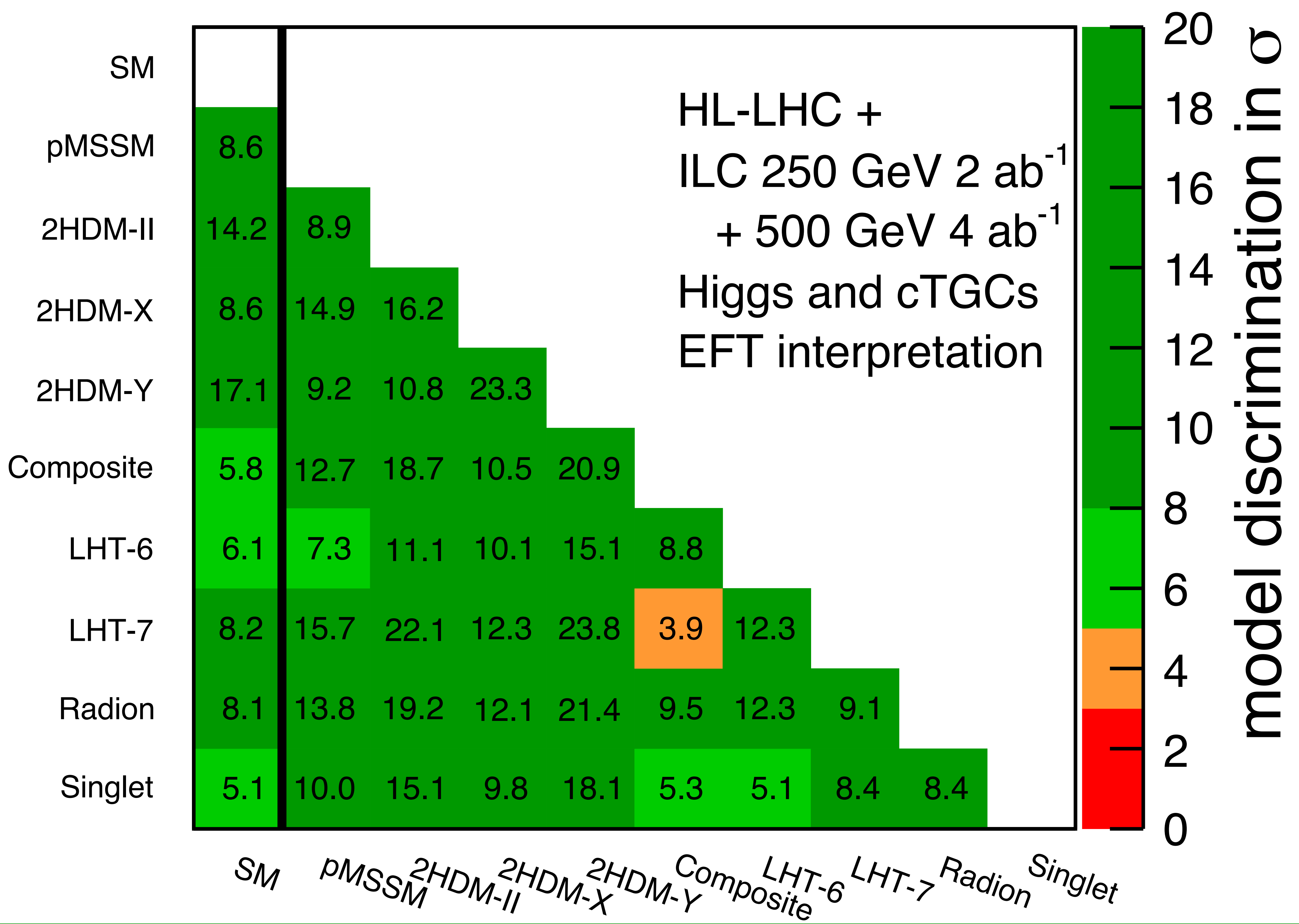
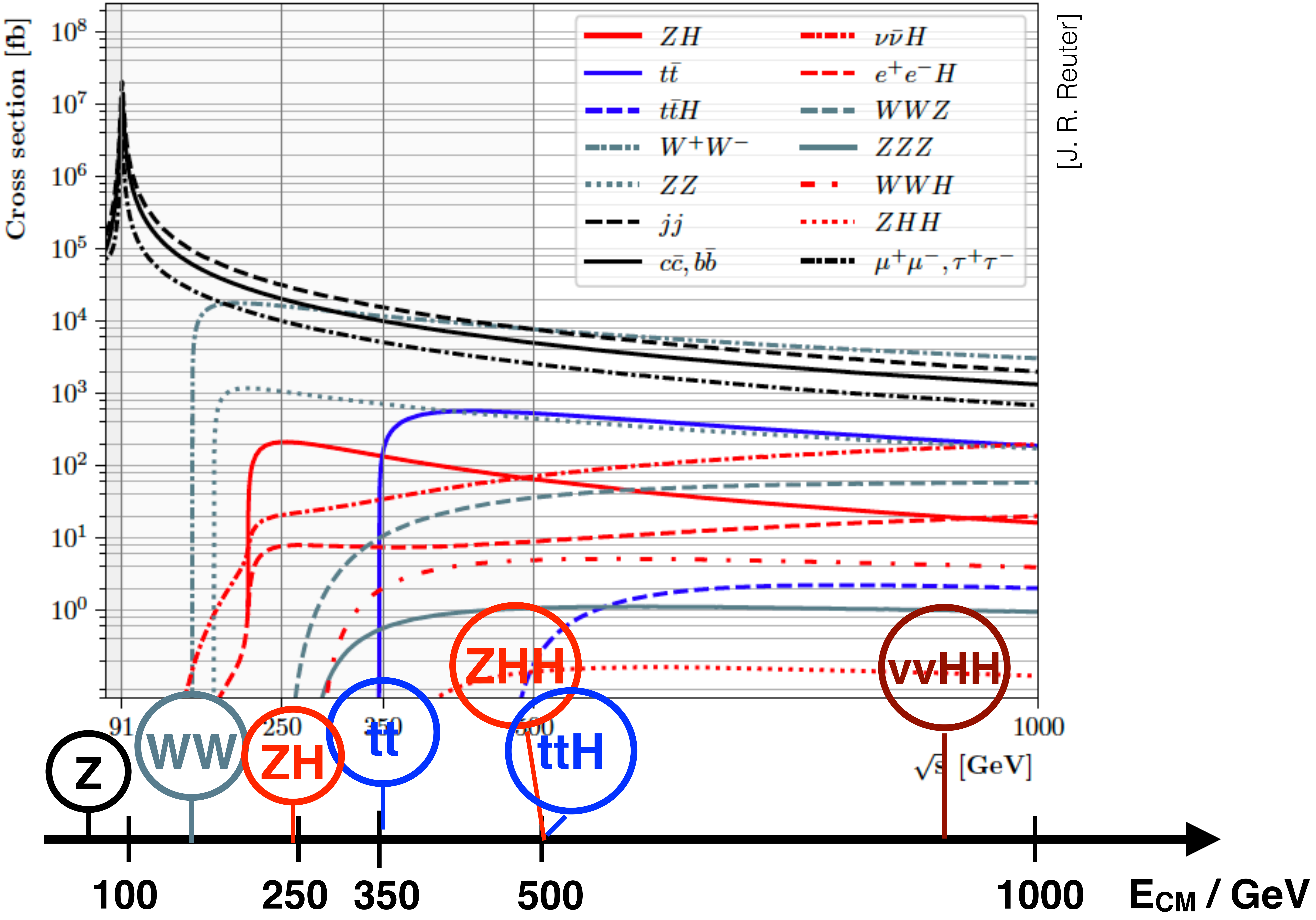


illustrates the ILC's discovery and identification potential - complementary to (HL-)LHC!

The key physics at a Higgs Factory

Production rates vs collision energy



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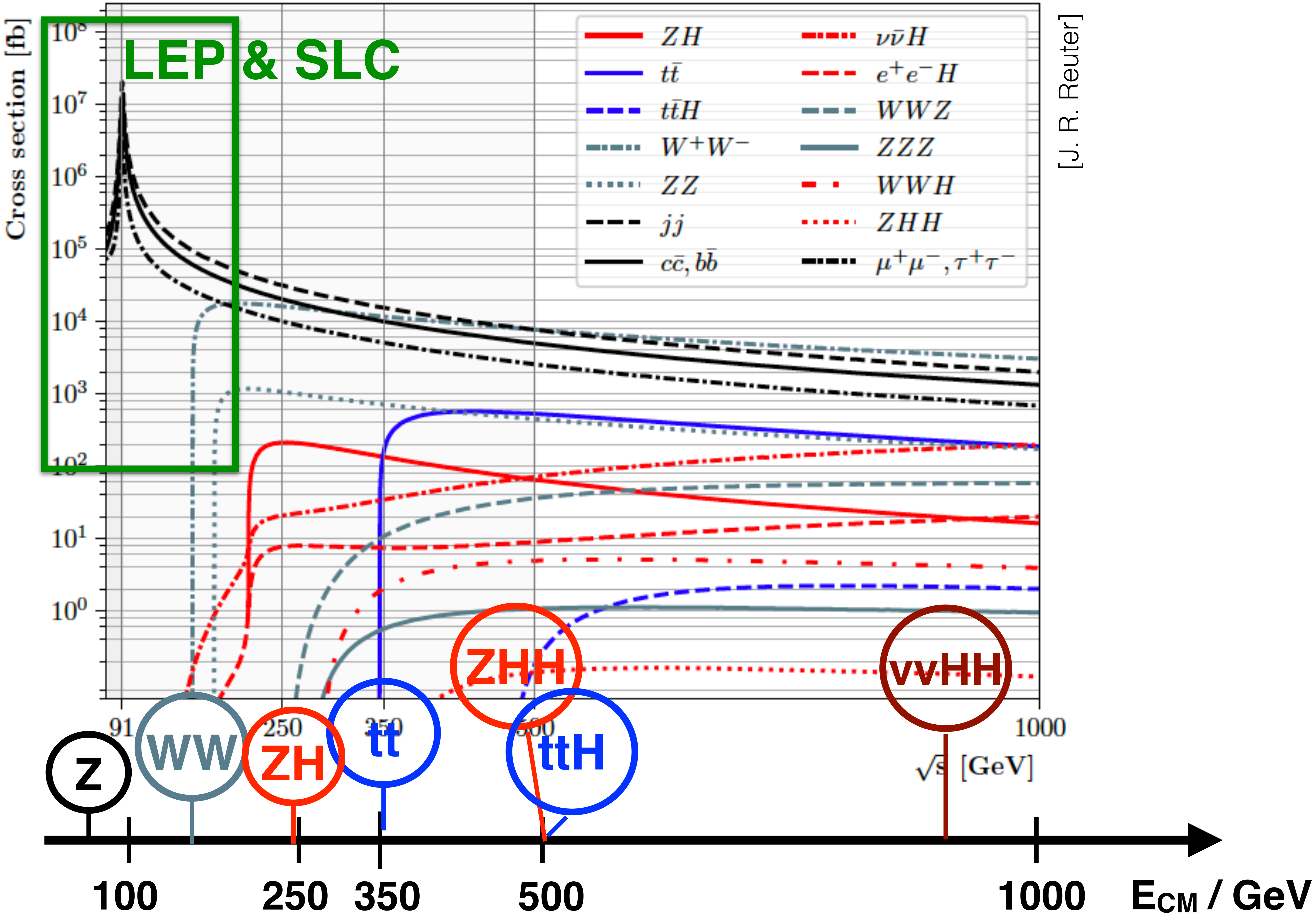

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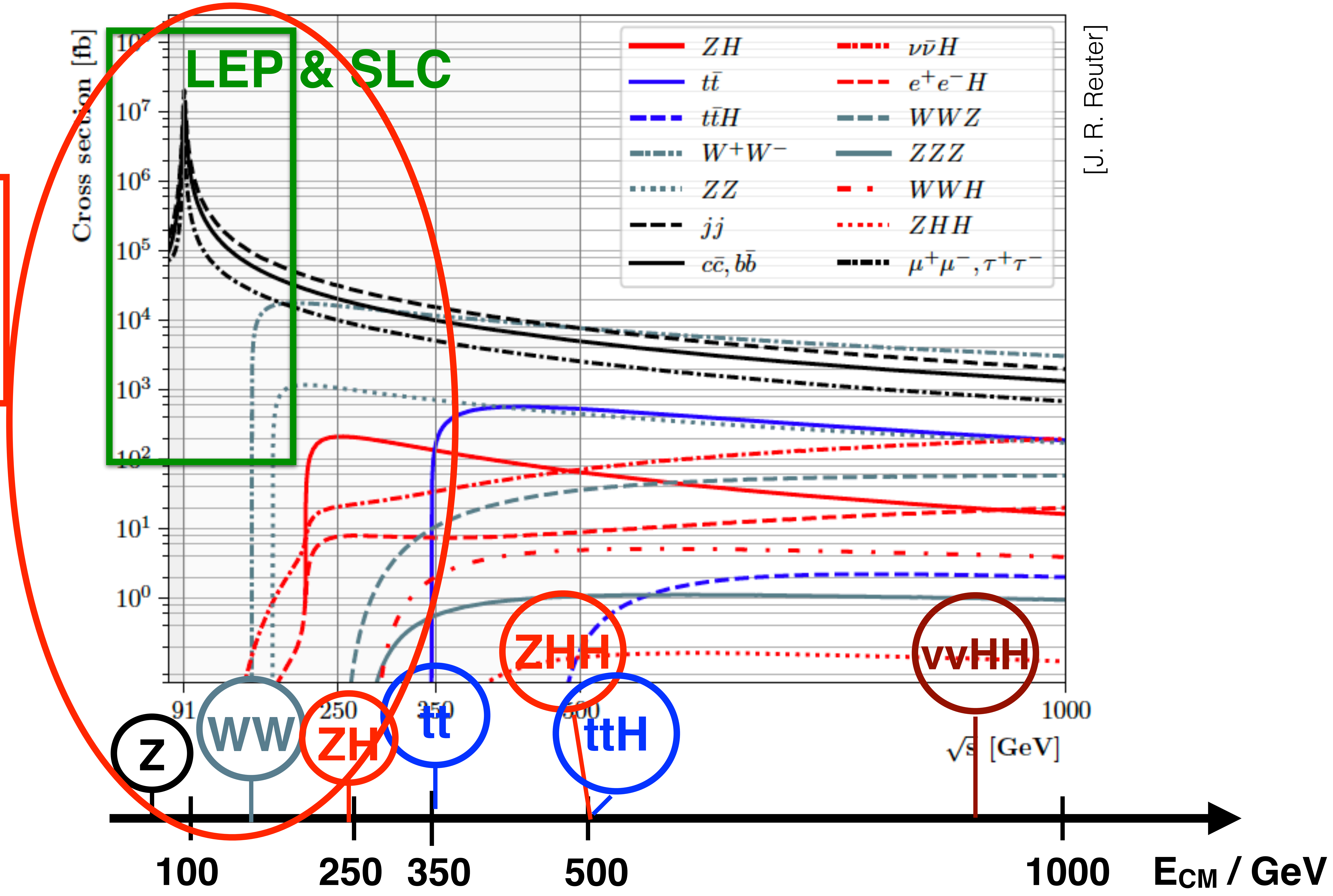

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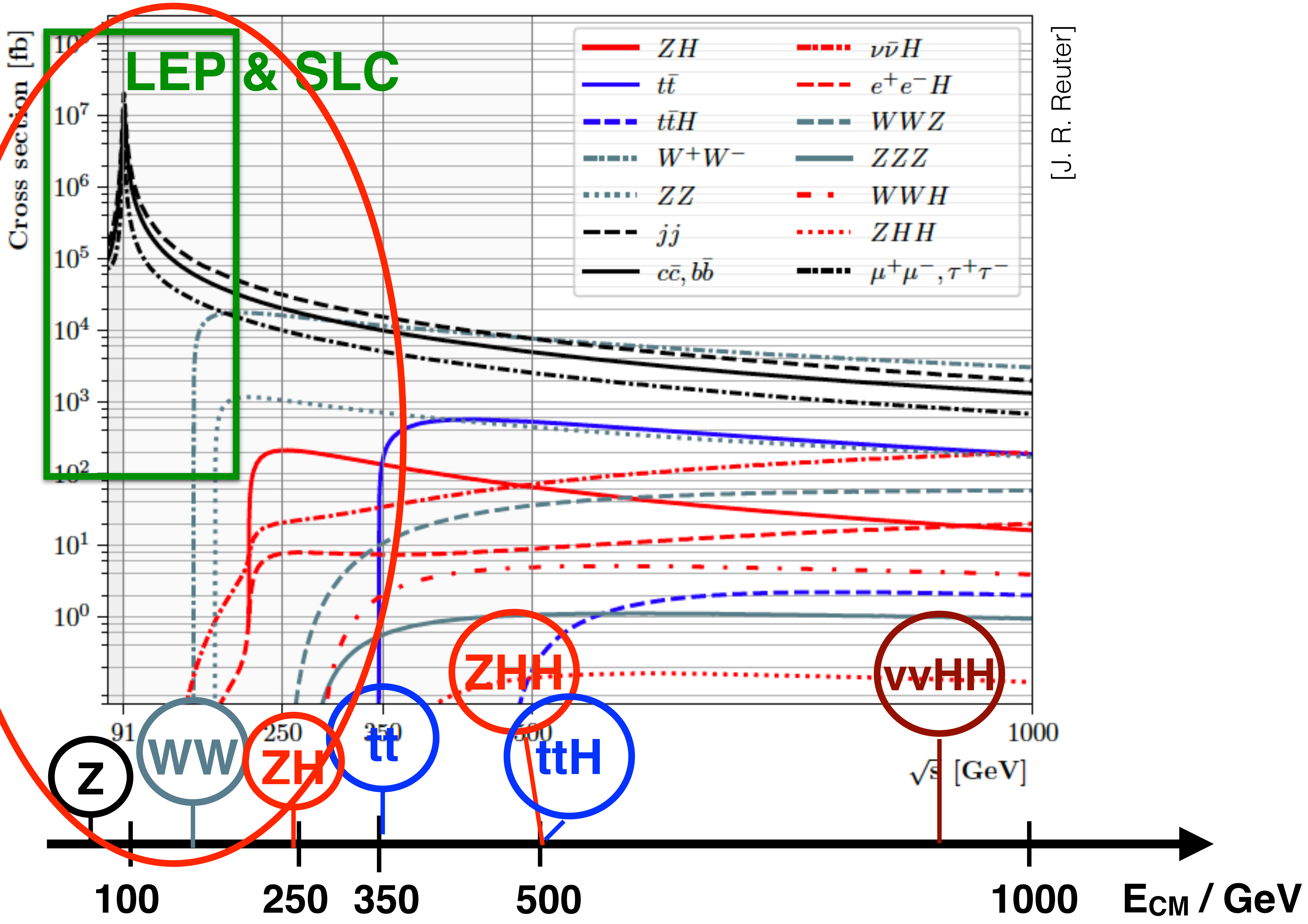
Circular Colliders



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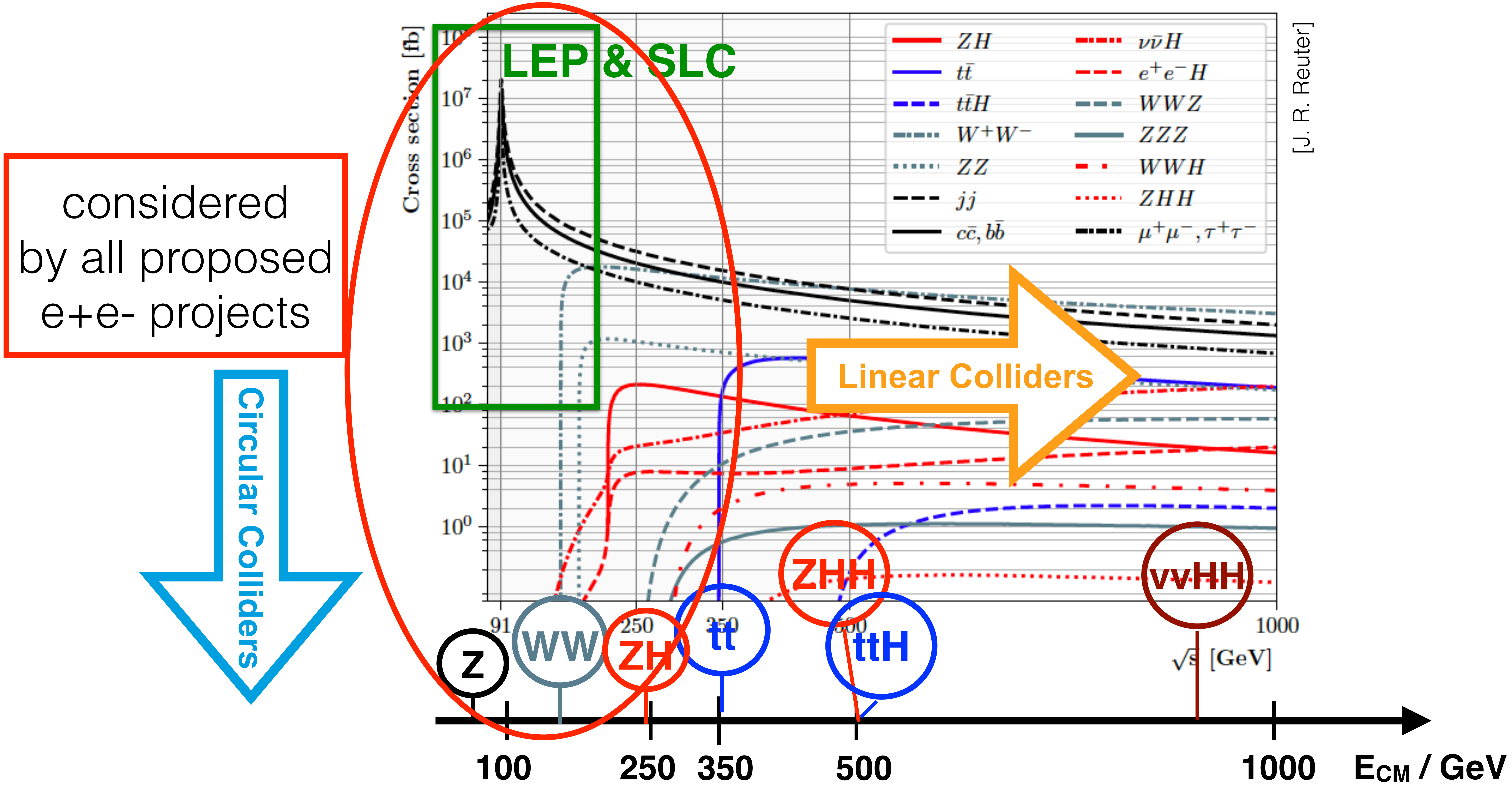

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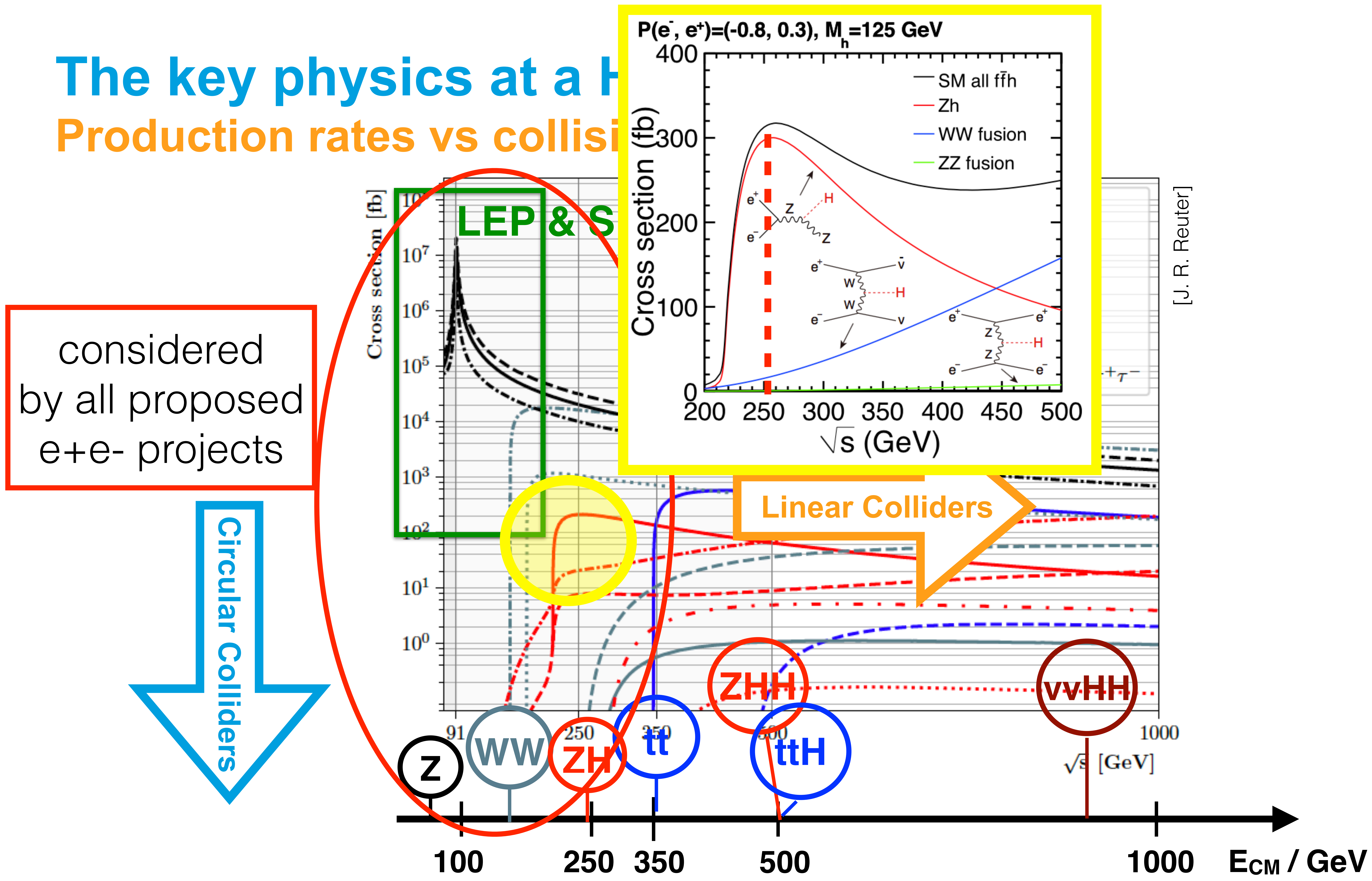

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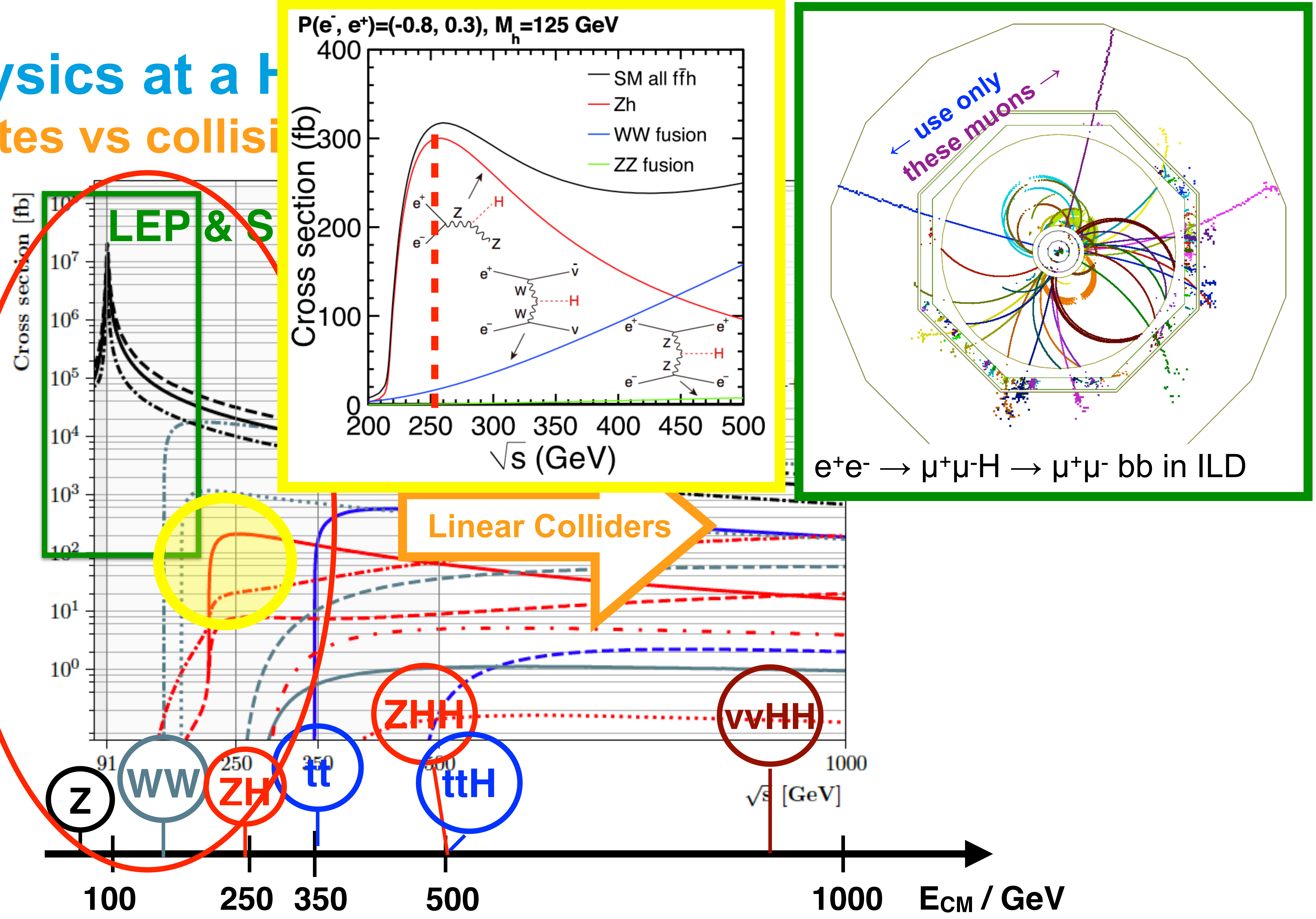

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e+e- projects

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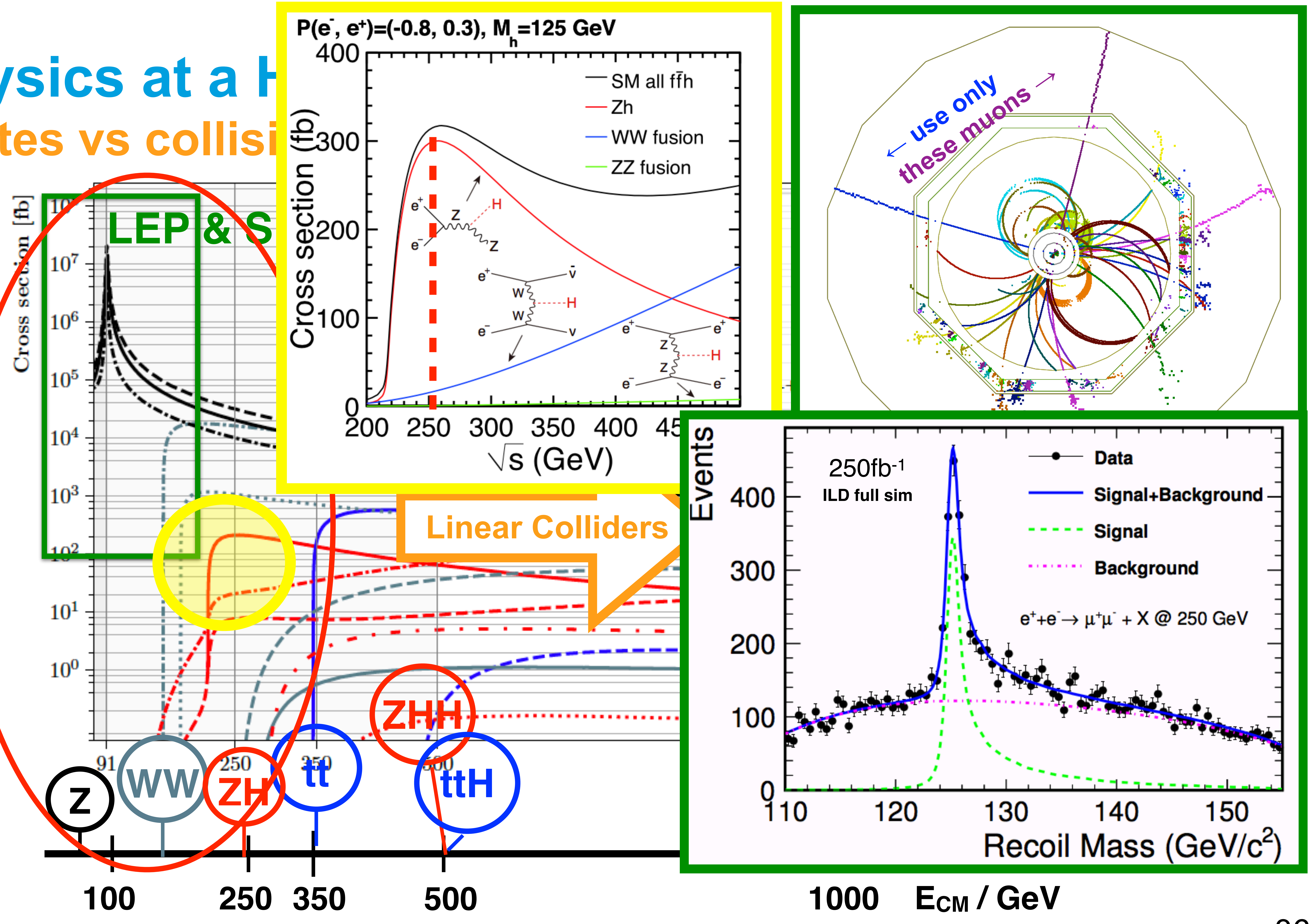
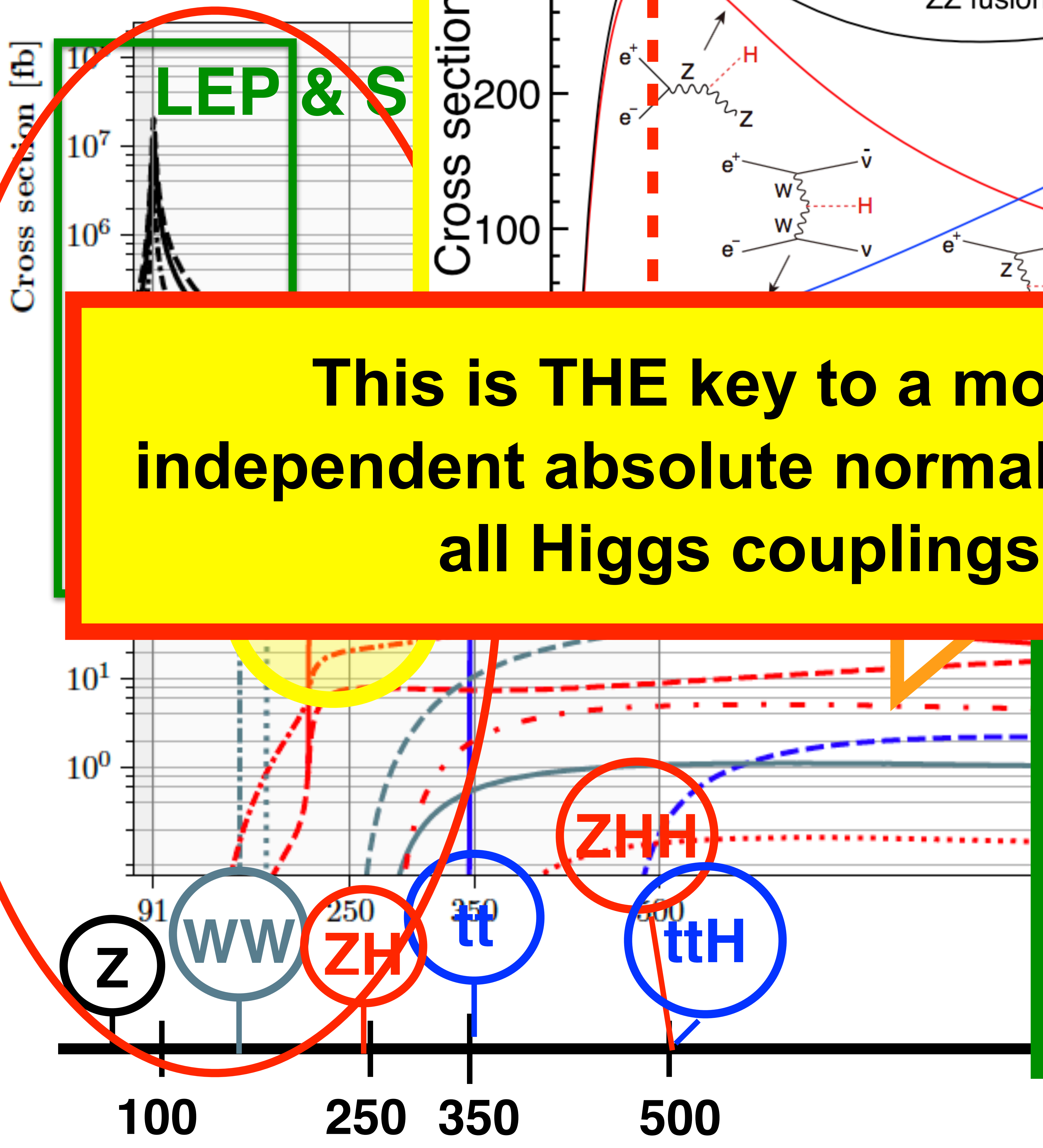


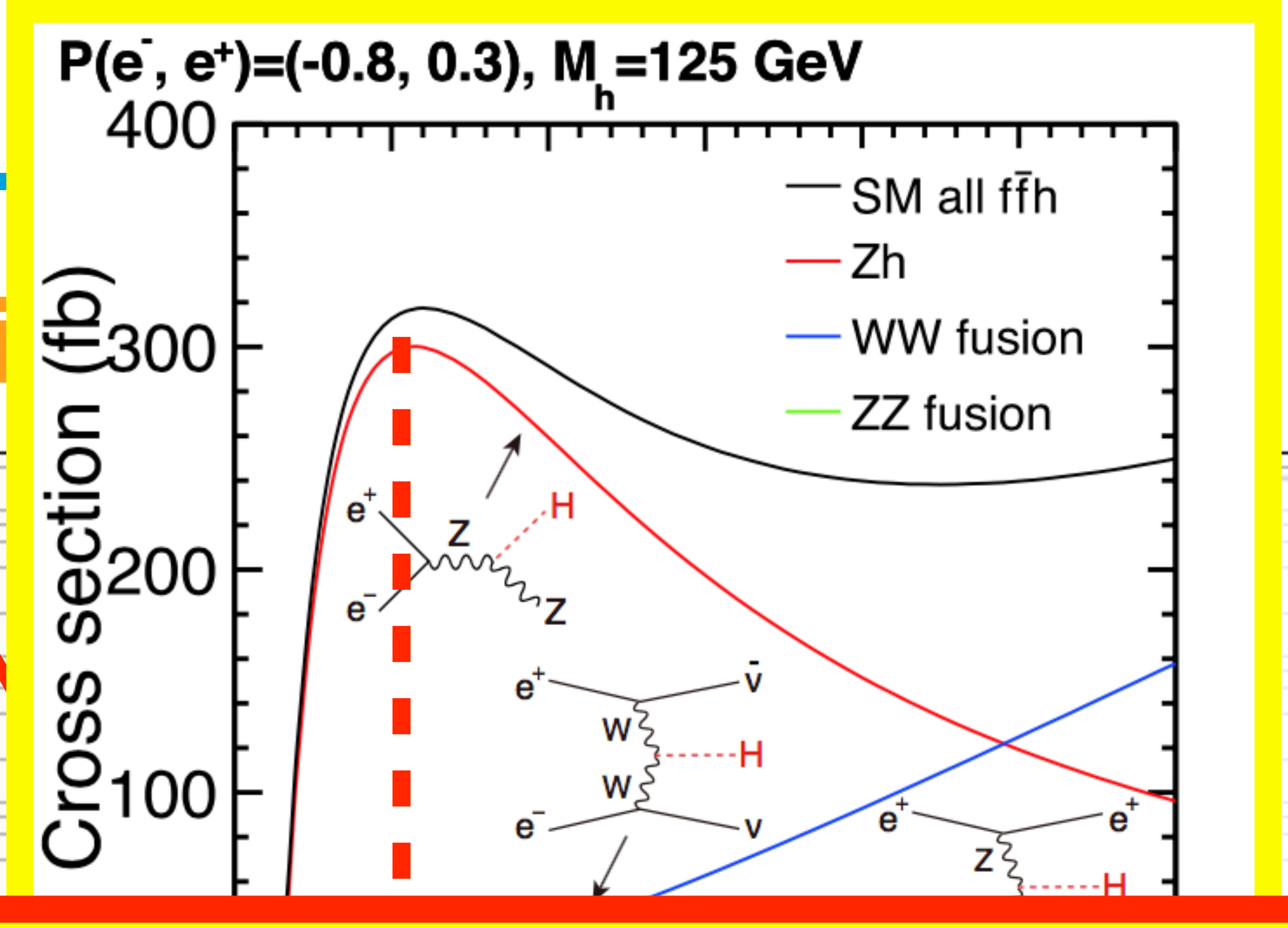
The key physics at a H

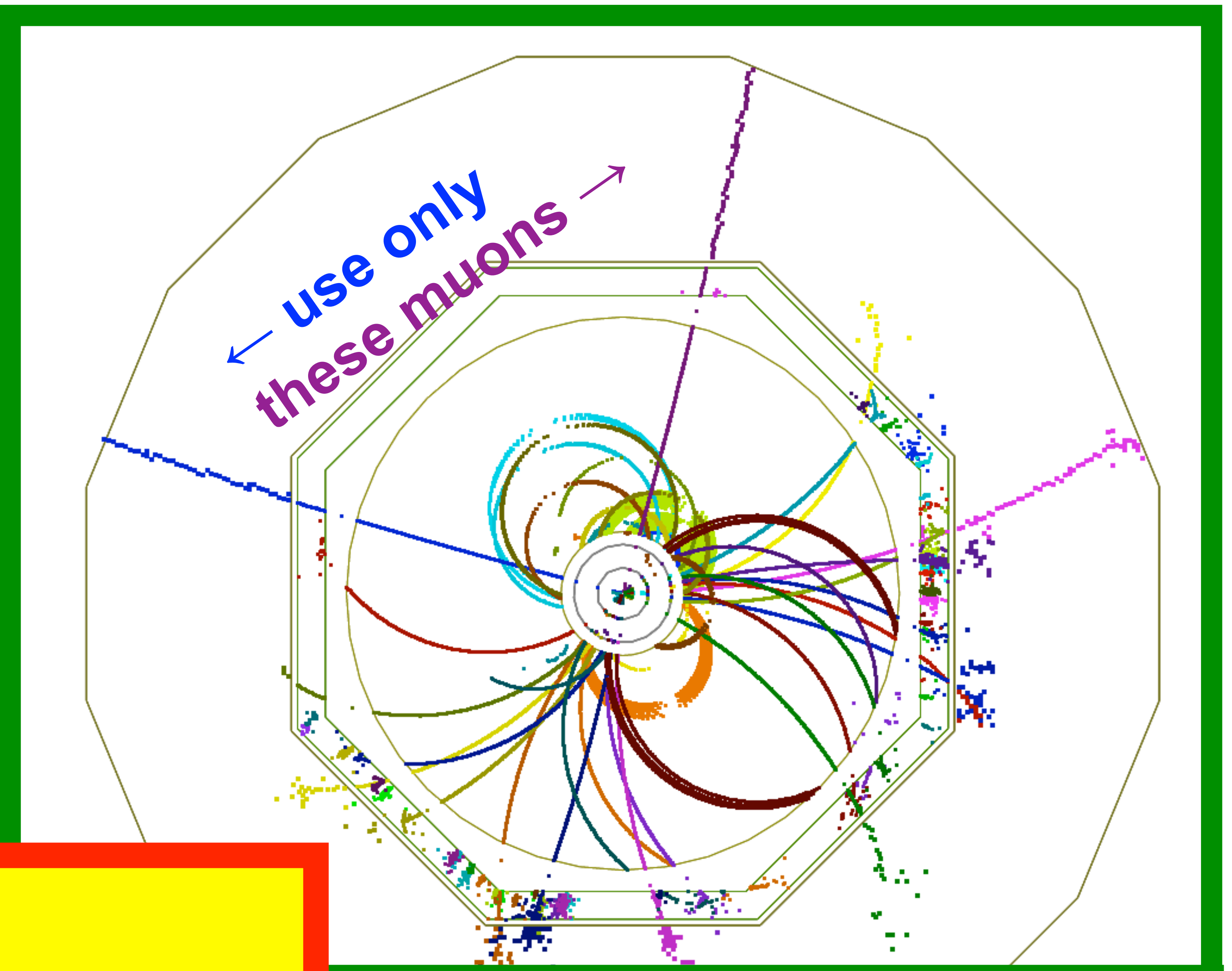
Production rates vs collisi

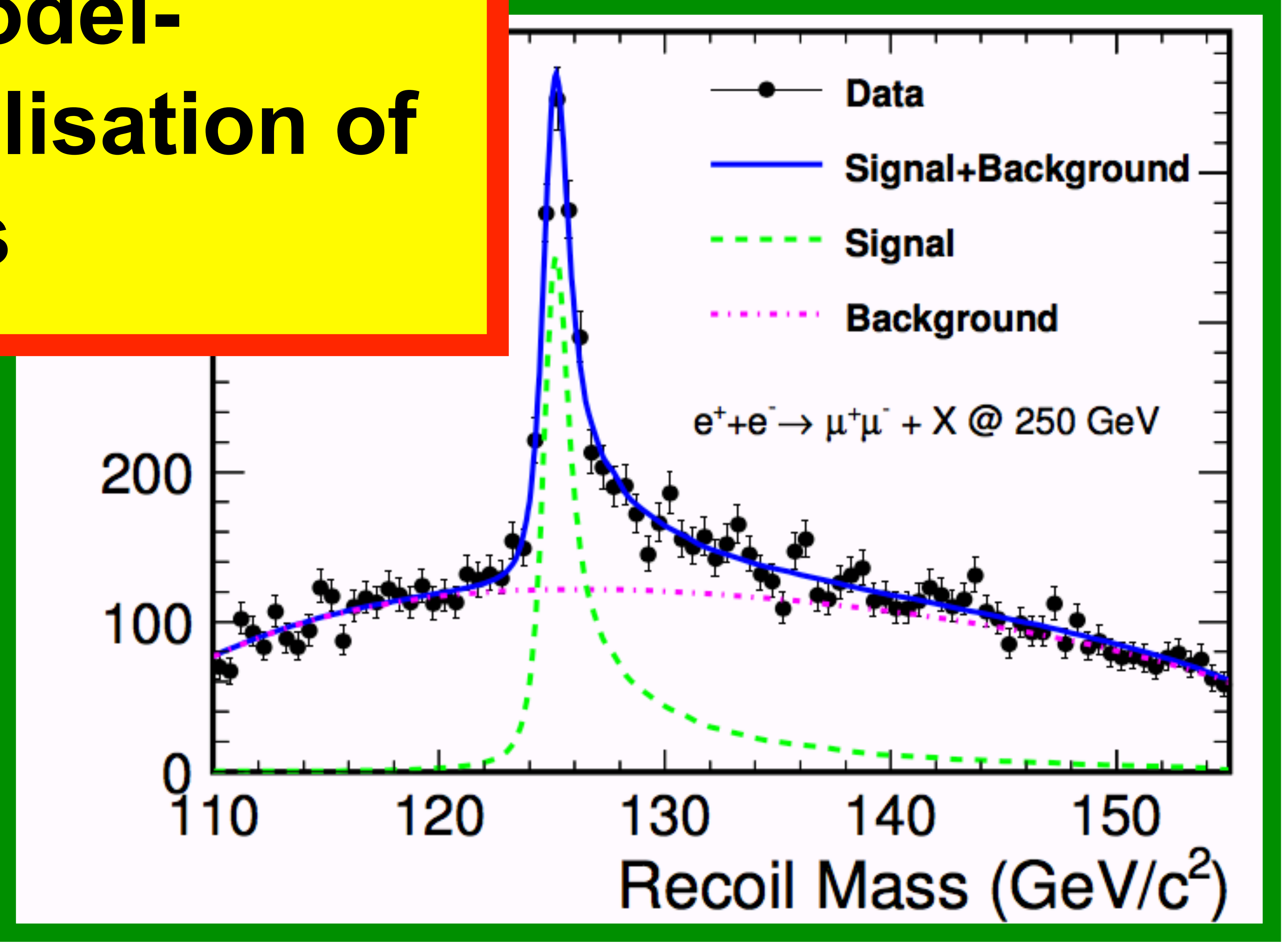
considered by all proposed e+e- projects

Circular Colliders







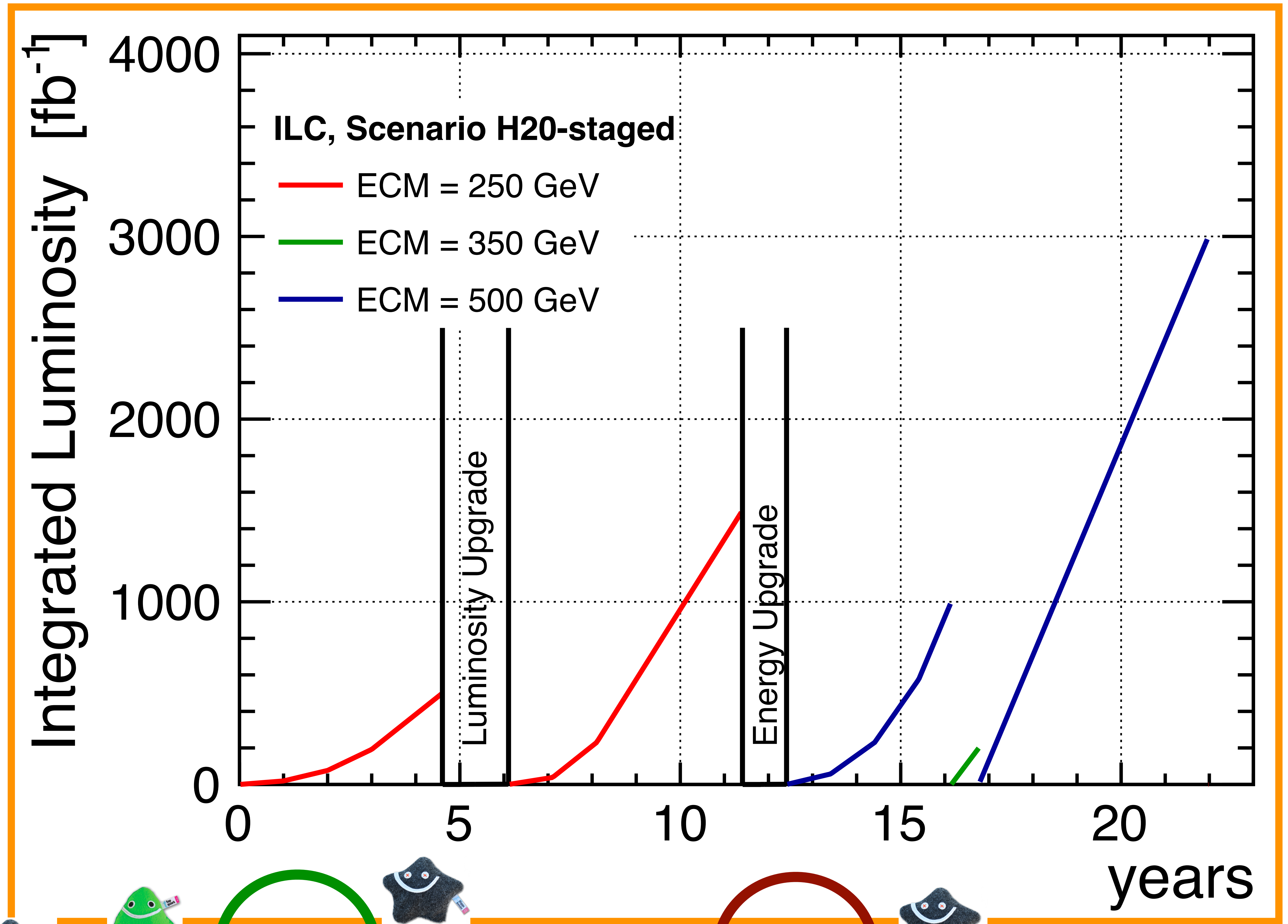


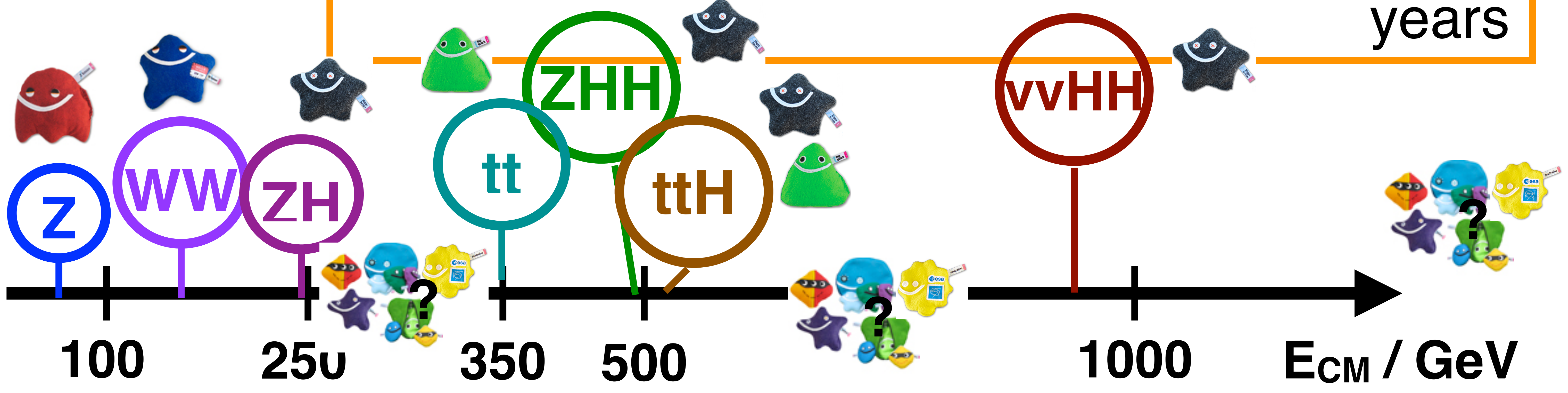
This is THE key to a model-independent absolute normalisation of all Higgs couplings

A physics-driven operating scenario for a Linear Collider

All with at least P(e-) > 80%

- **250 GeV, 2ab-1:**
  - precision Higgs mass and total ZH cross-section
  - basic ffbar and WW program
  - incl Z pole run with O(10^3)xLEP for EWPOs
  - optional: WW threshold scan
- **350 GeV, 200 fb-1:**
  - precision top mass from threshold scan
- **500…600 GeV, 4 ab-1:**
  - Higgs self-coupling in ZHH
  - top quark ew couplings
  - top Yukawa coupling incl CP structure
  - improved Higgs, WW and ffbar
- **1…1.5 TeV, 8ab-1:**
  - Higgs self-coupling in VBF
  - further improvements in tt, ff, WW, ….





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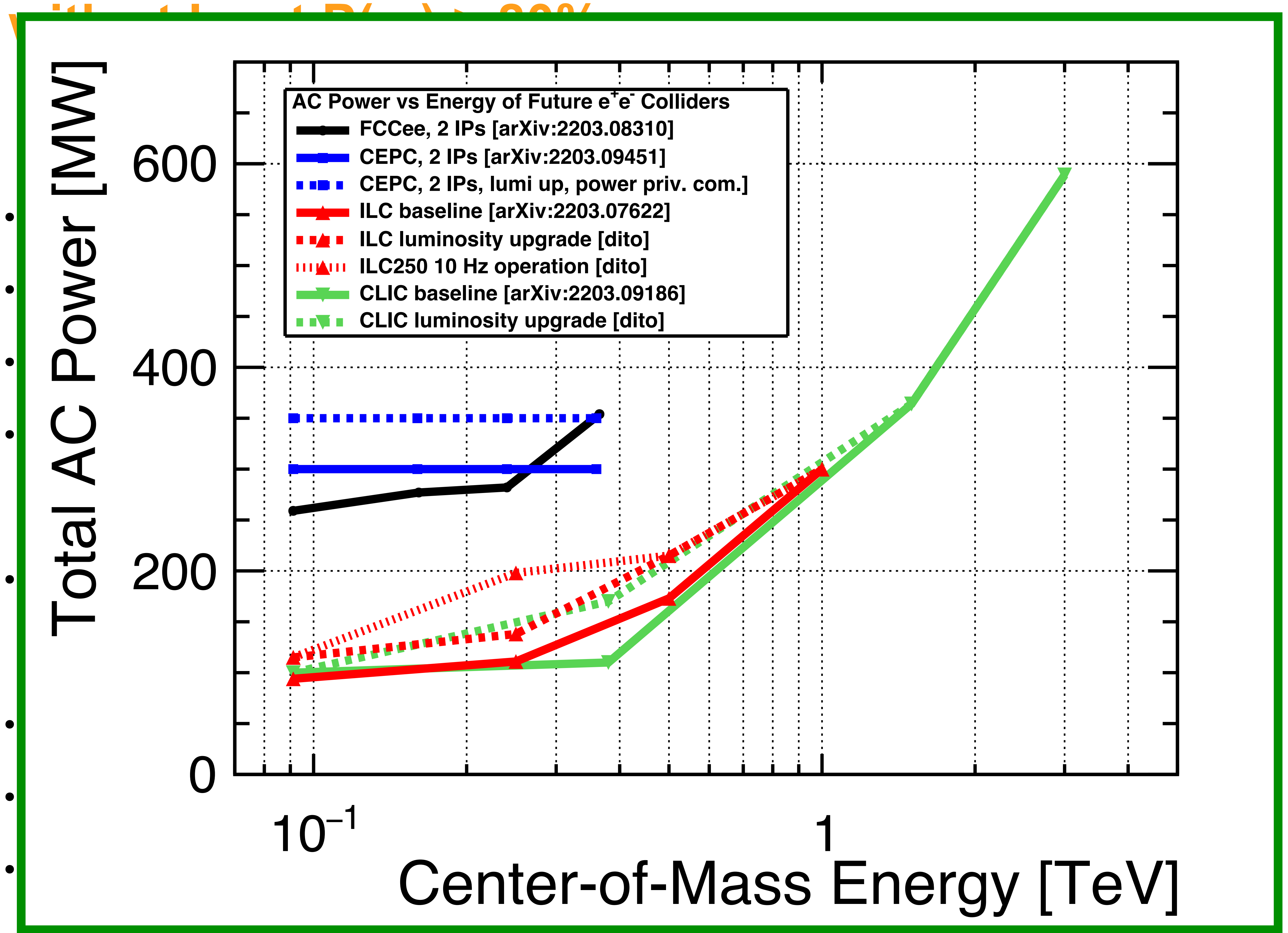

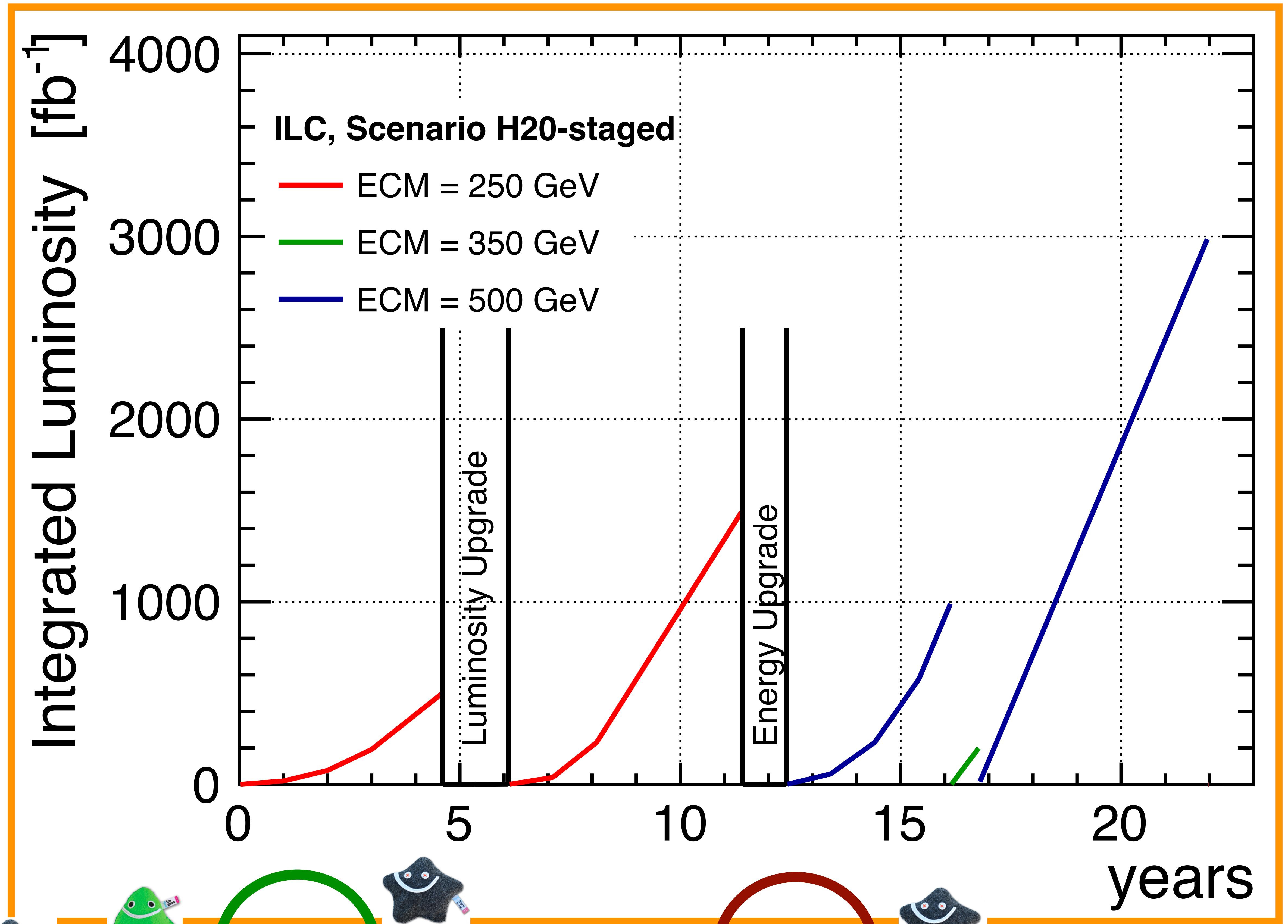

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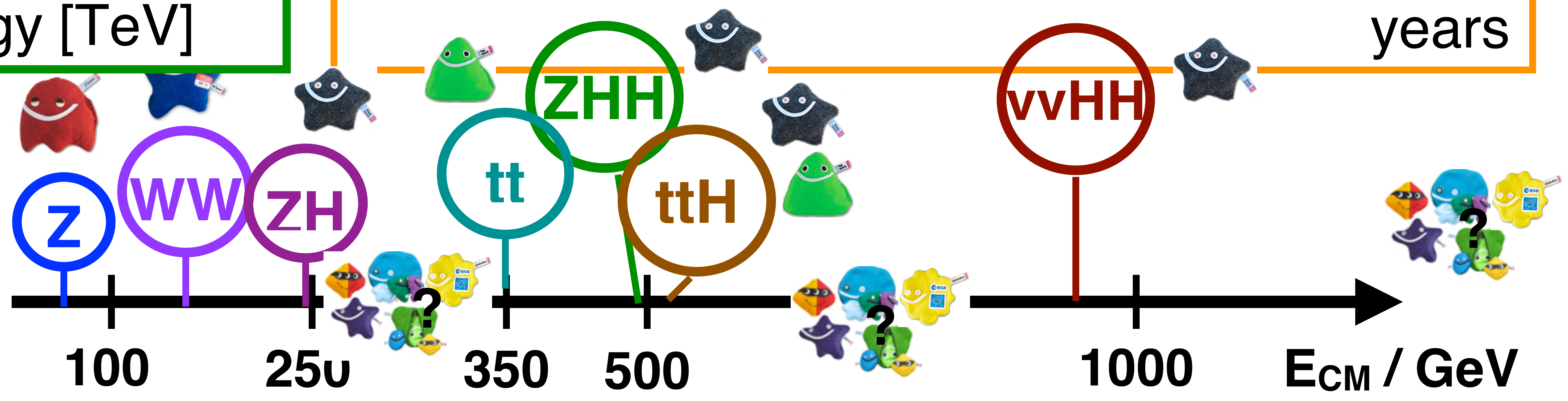

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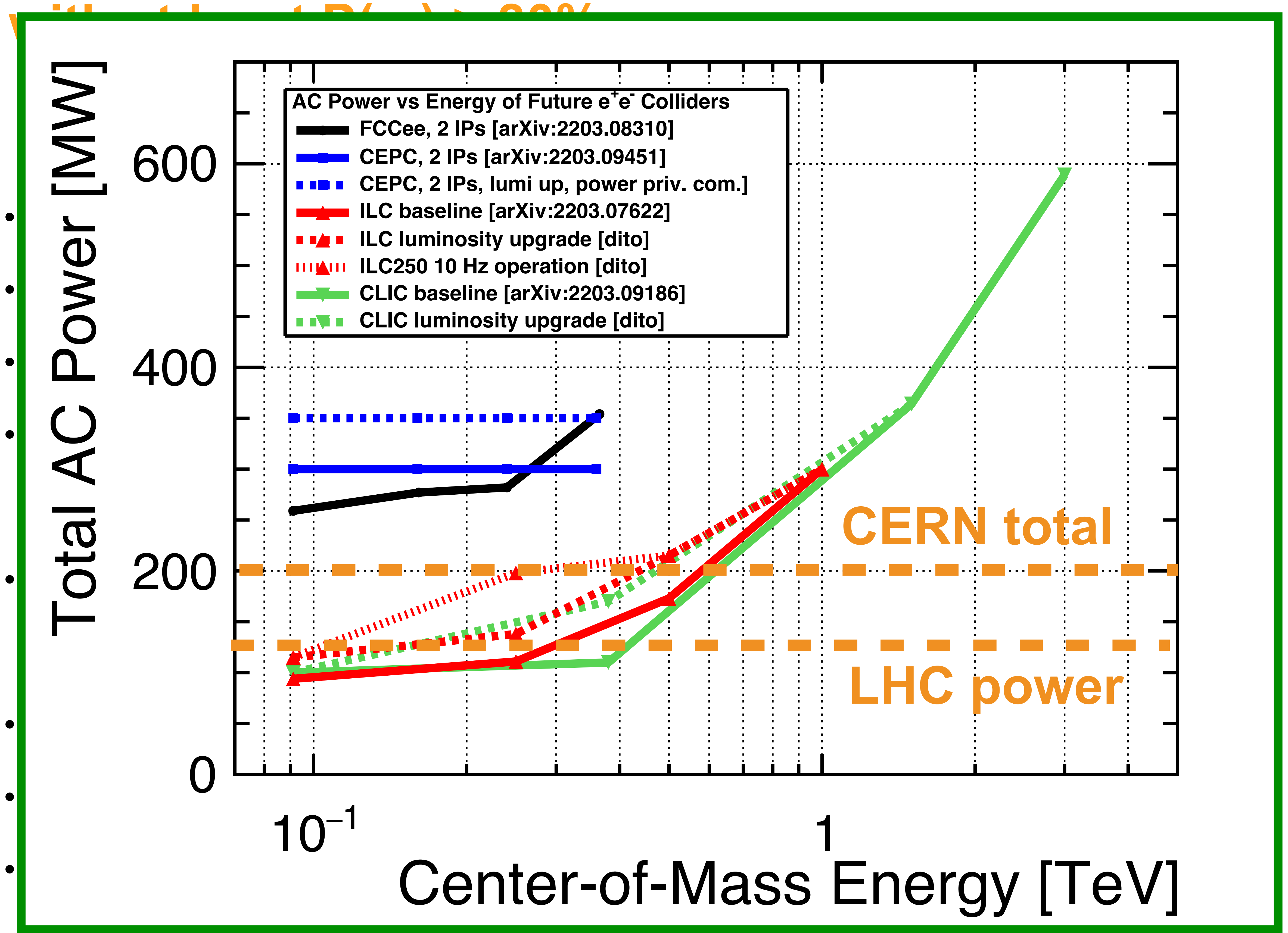

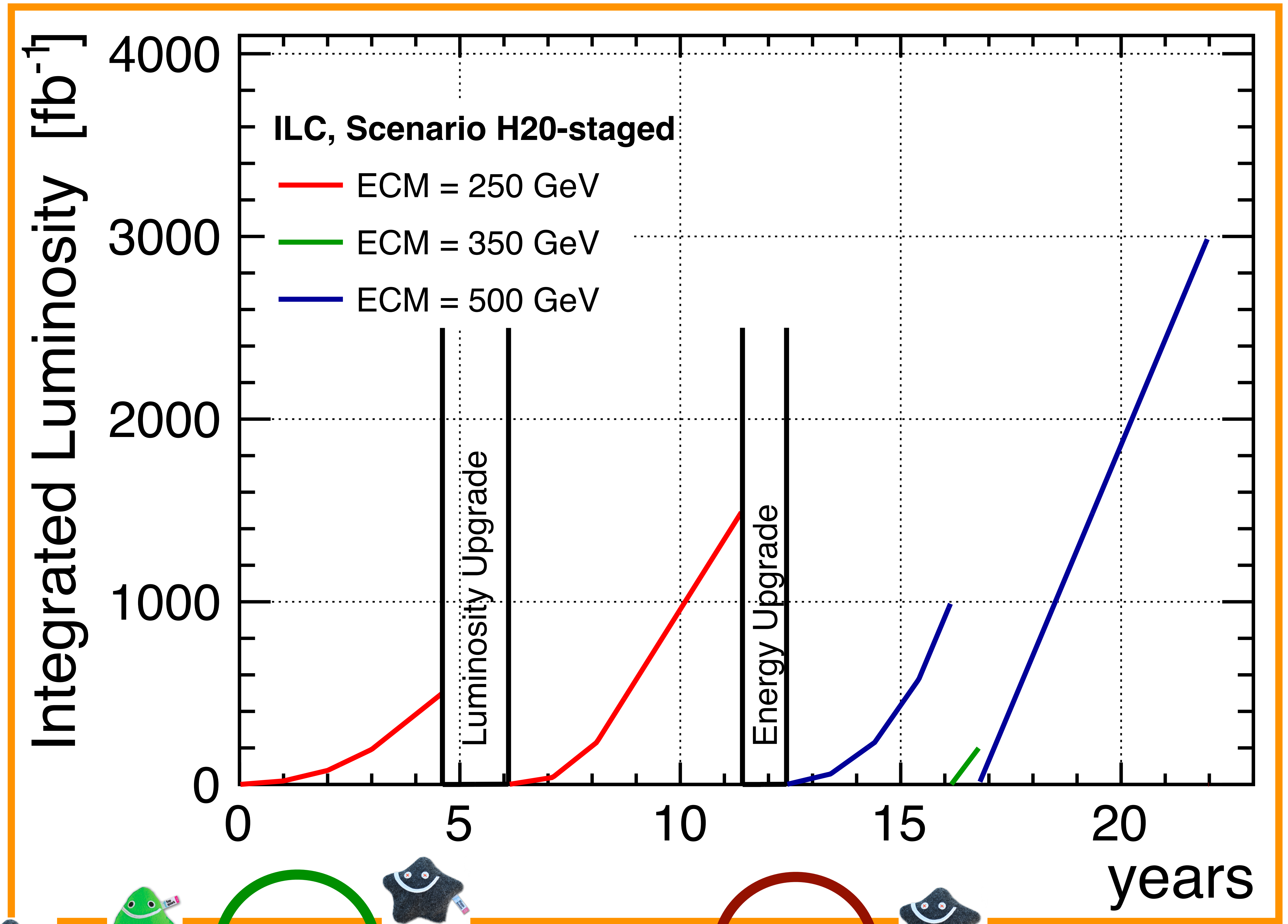

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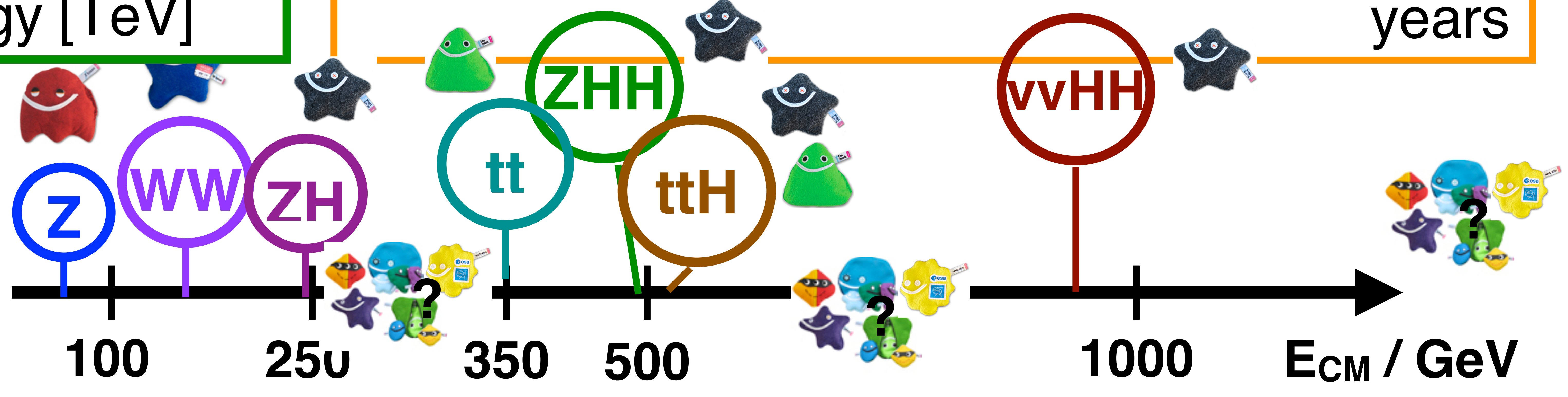
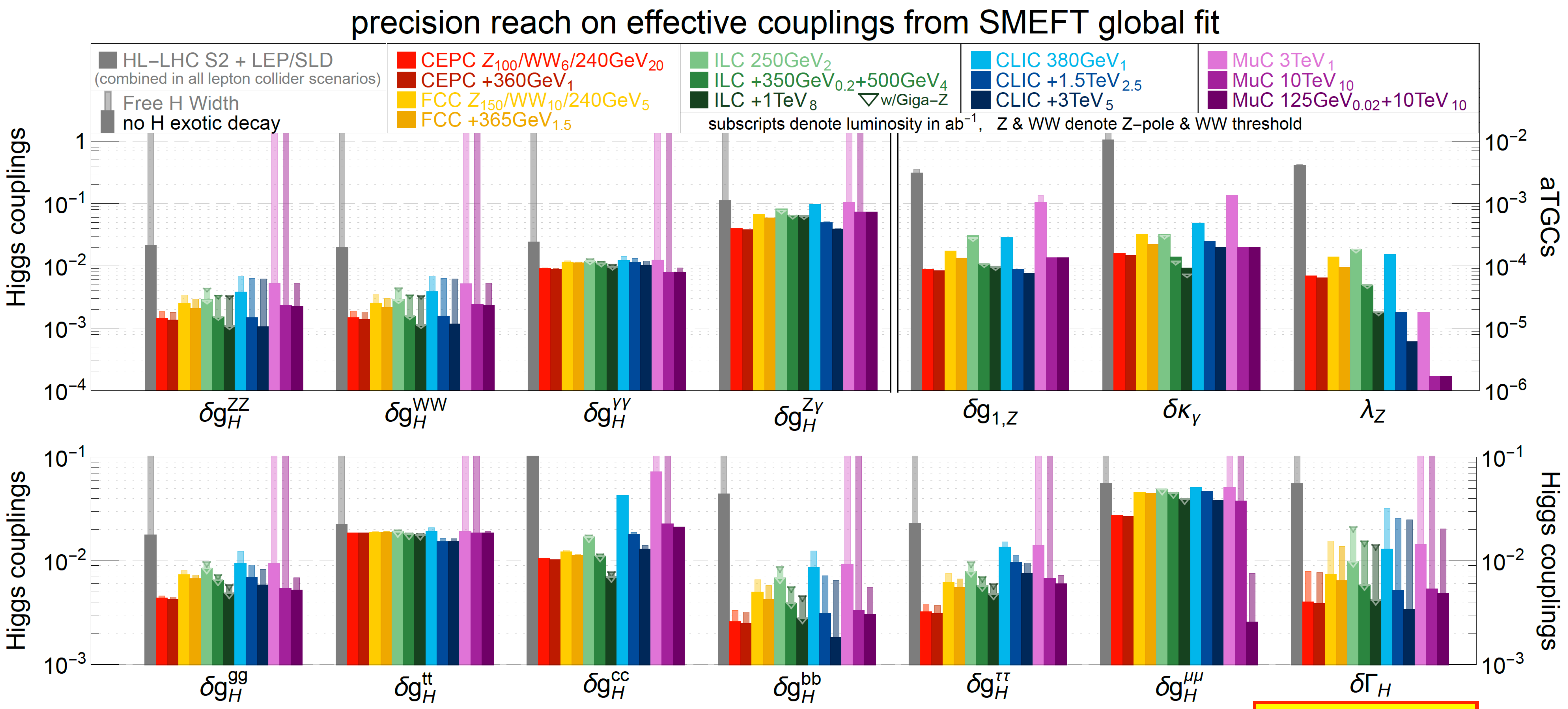


Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



arXiv:2206.08326

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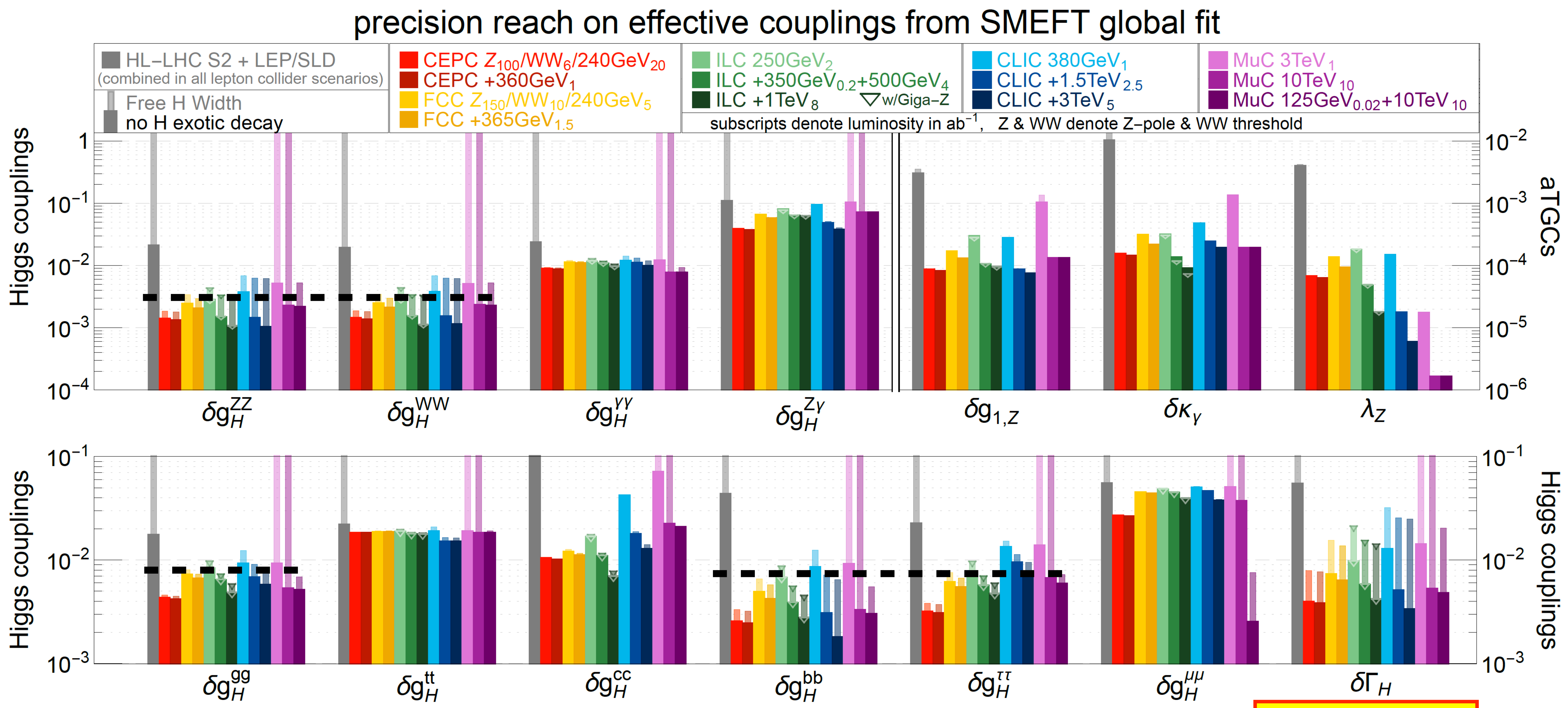

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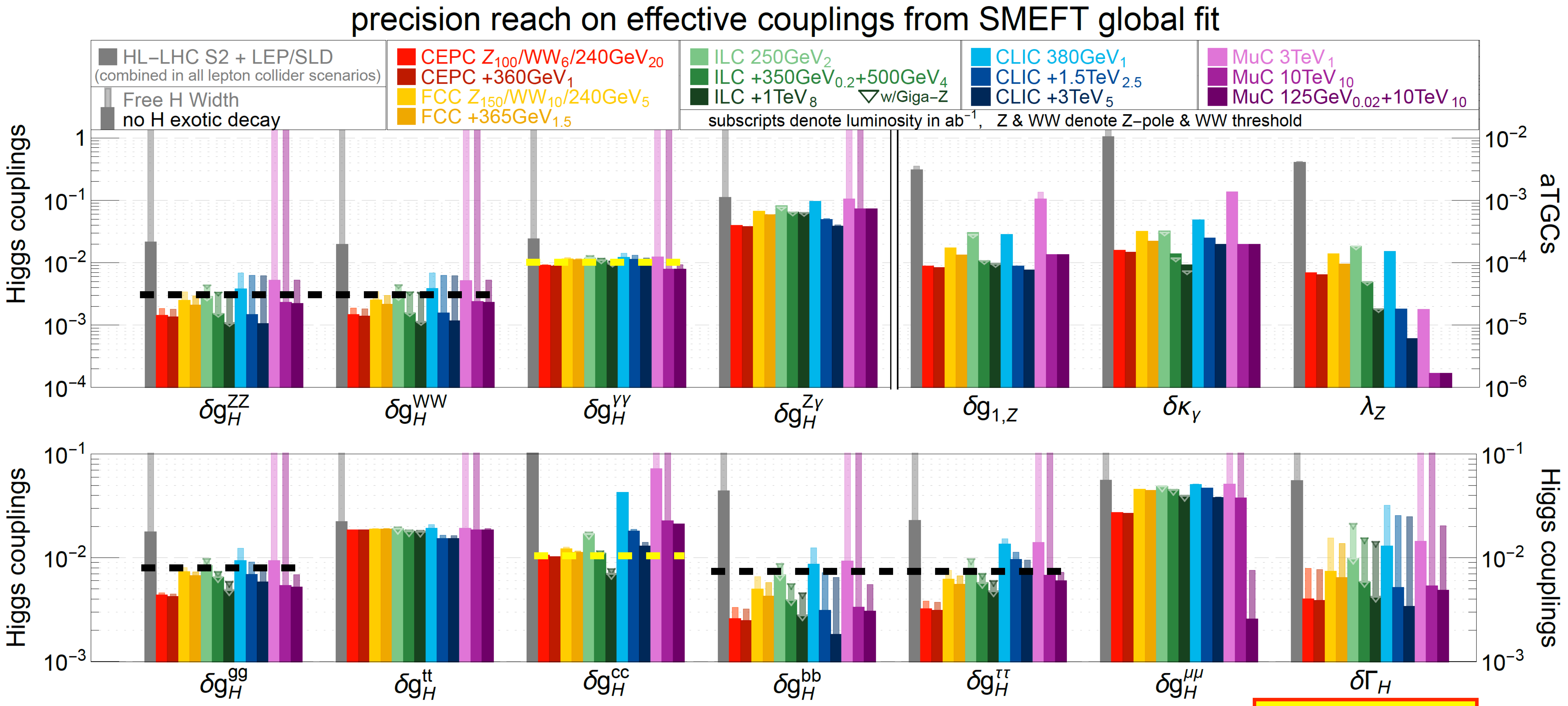

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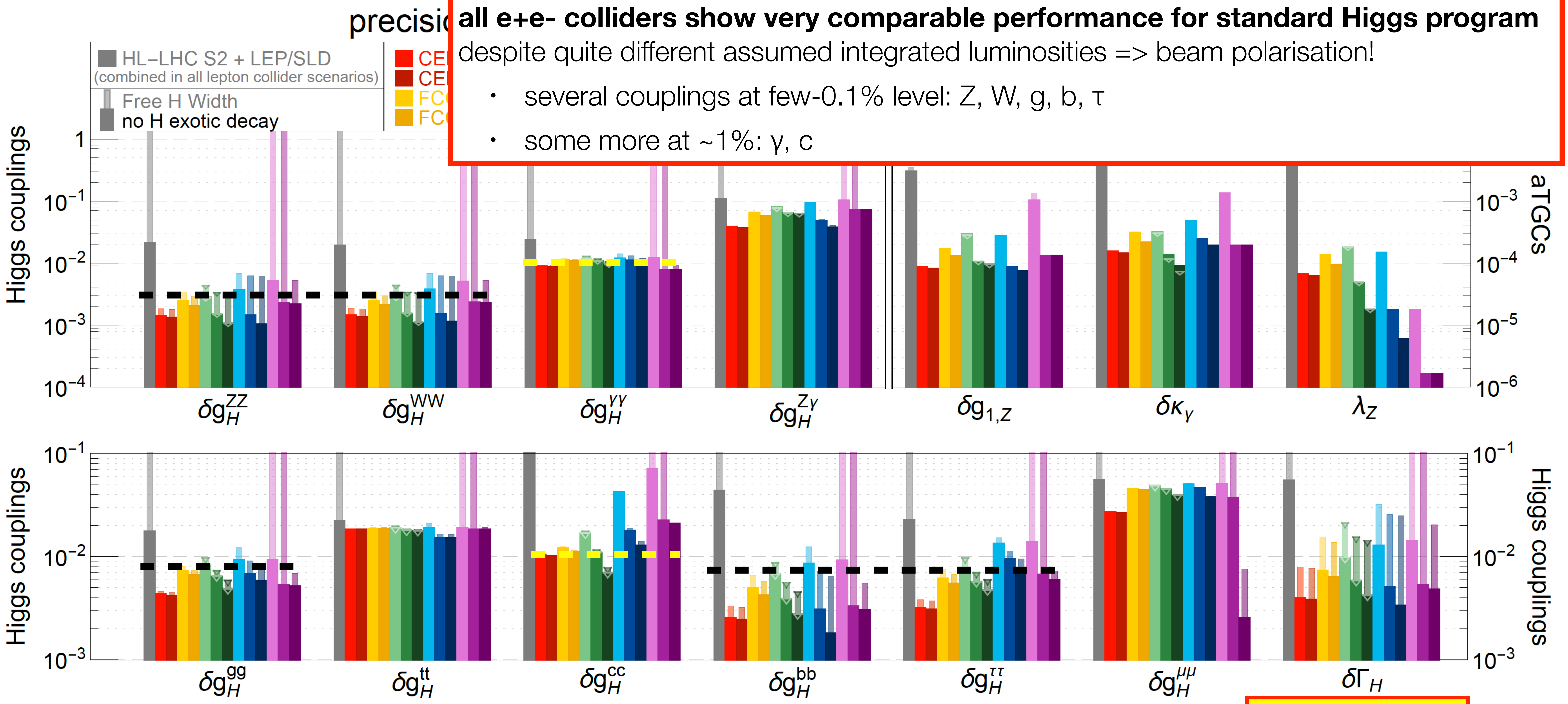
all e+e- colliders show very comparable performance for standard Higgs program

despite quite different assumed integrated luminosities => beam polarisation!

- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c



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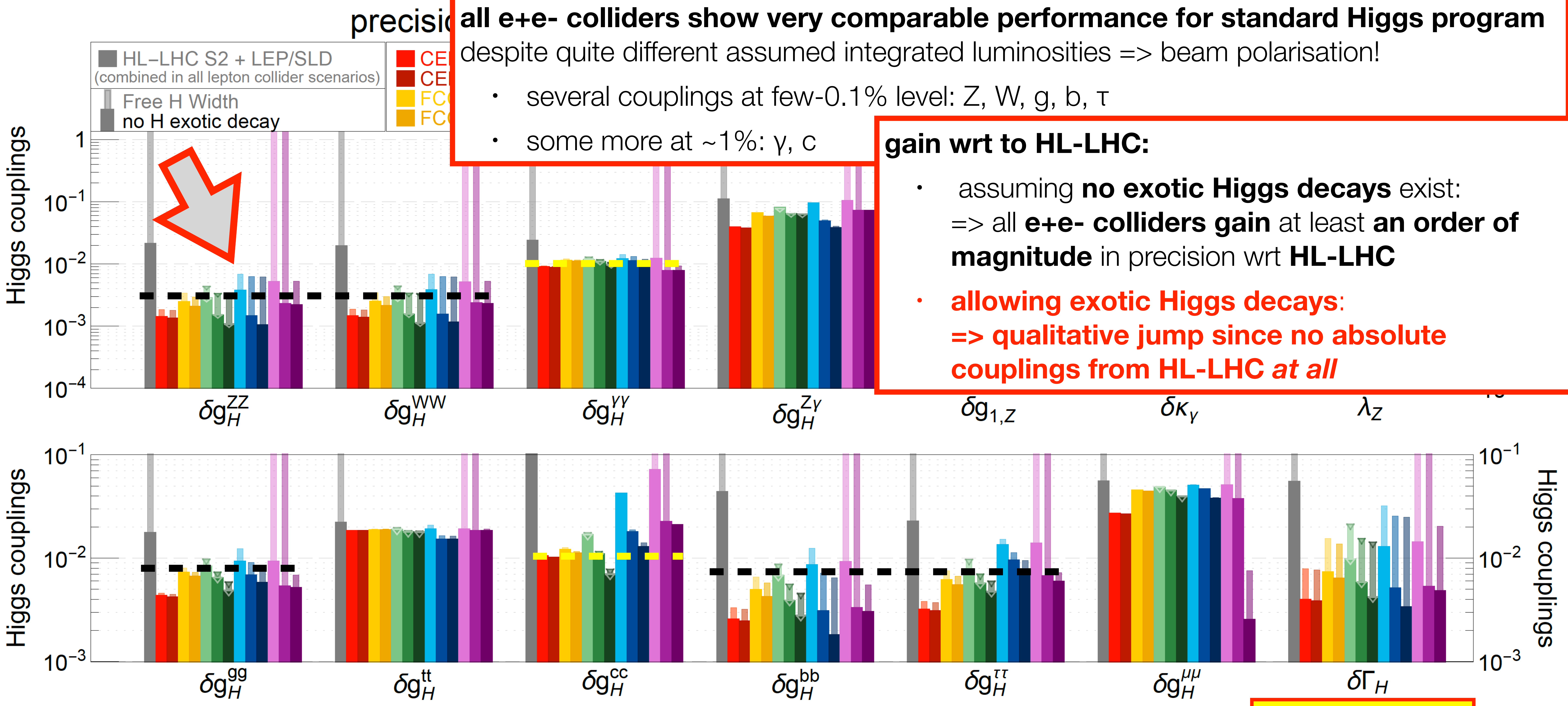

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gain wrt to HL-LHC:

- assuming **no exotic Higgs decays** exist:
  => all **e+e- colliders gain** at least **an order of magnitude** in precision wrt **HL-LHC**
- **allowing exotic Higgs decays**:
  => qualitative jump since no absolute couplings from HL-LHC *at all*

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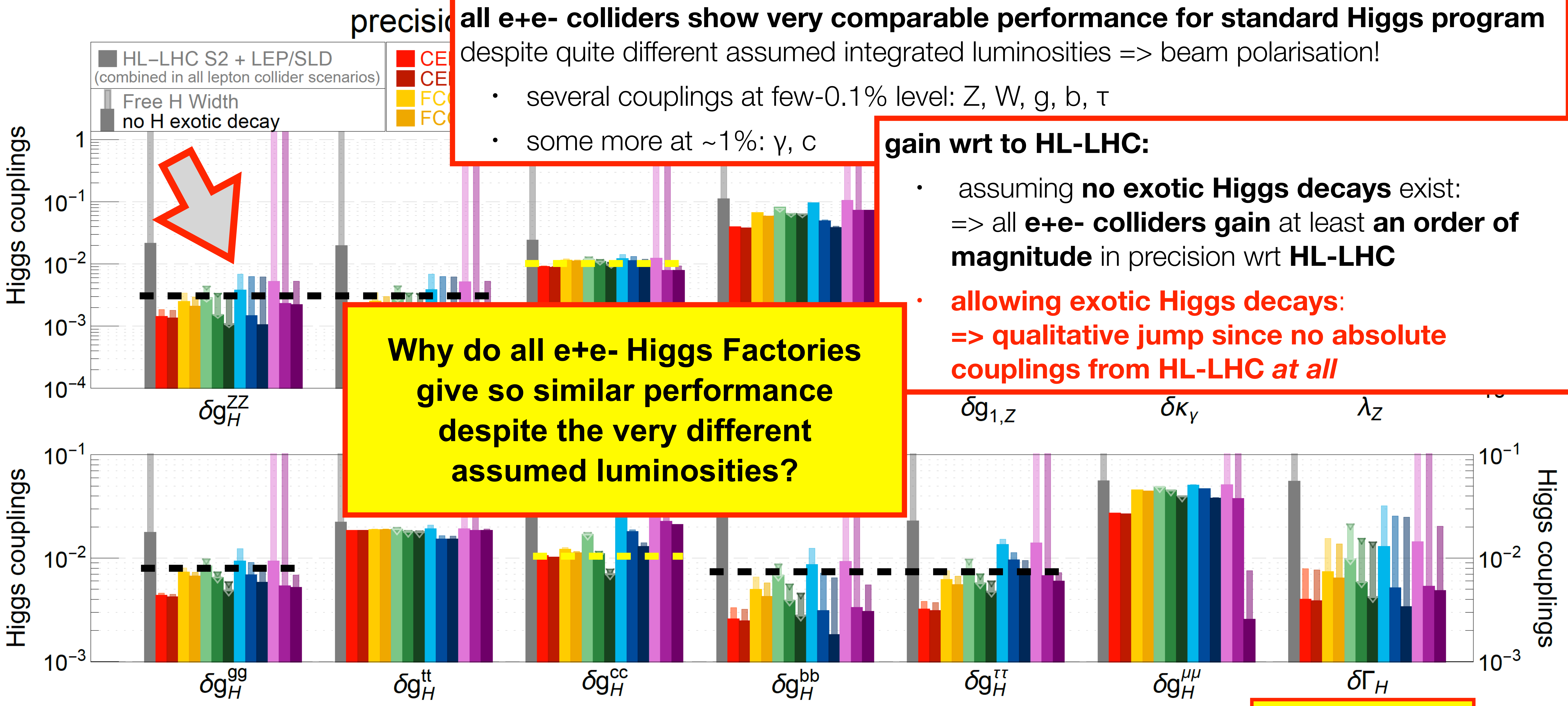

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Why do all e+e- Higgs Factories give so similar performance despite the very different assumed luminosities?

arXiv:2206.08326

Interlude: Chirality in Particle Physics

Just a quick reminder…

- Gauge group of weak x electromagnetic interaction: $SU(2)_L \times U(1)$
- L: left-handed, spin anti-|| momentum*
  R: right-handed, spin || momentum*

- **left-handed particles are fundamentally different from right-handed ones:**
  - only left-handed fermions (e^-) and right-handed anti-fermions (e^+) take part in the charged weak interaction, i.e. couple to the W bosons
  - there are (in the SM) no right-handed neutrinos
  - right-handed quarks and charged leptons are singlets under $SU(2)_L$
  - also couplings to the Z boson are different for left- and right-handed fermions

$$P = \frac{N_R - N_L}{N_R + N_L}$$

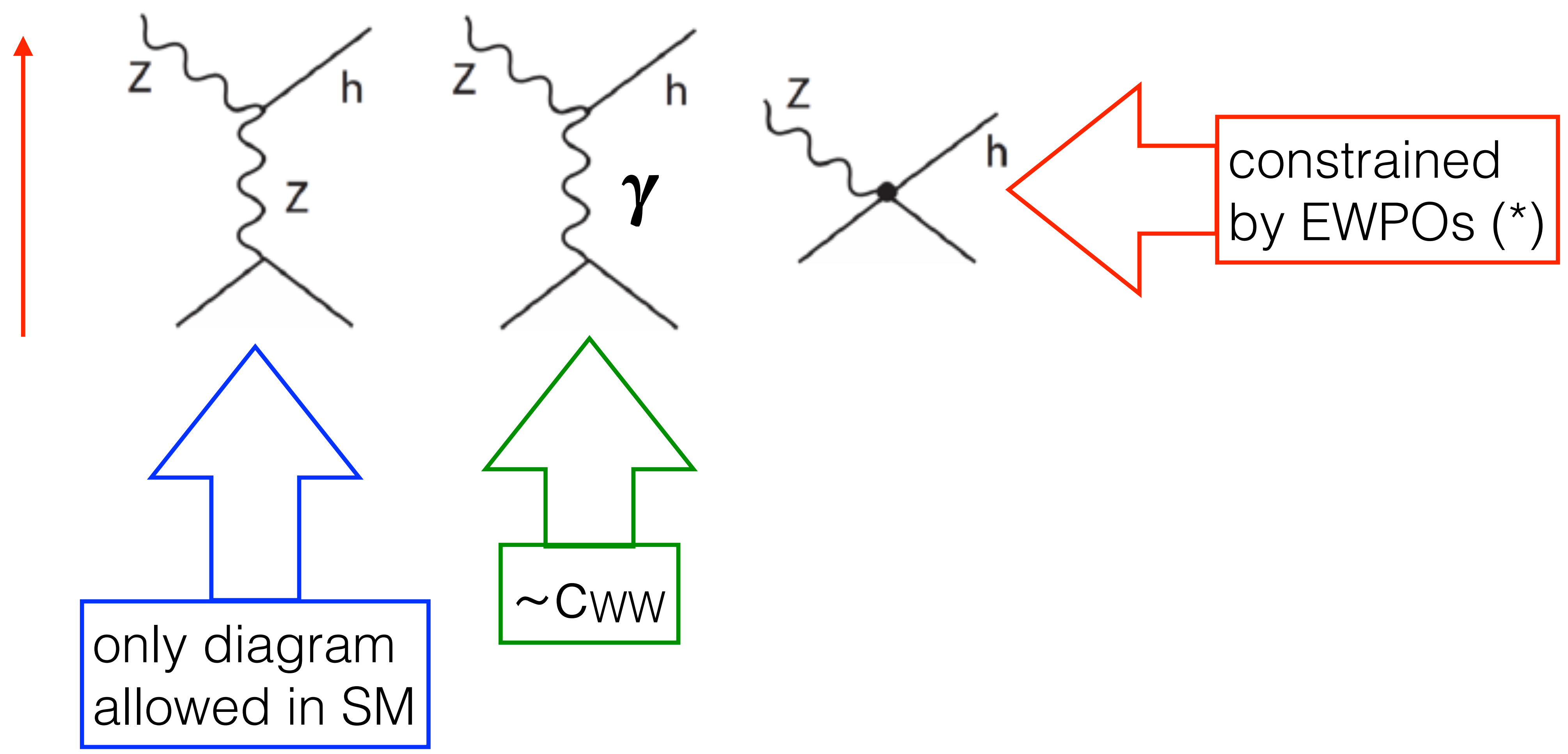
- **checking whether the differences between L and R are as predicted in the SM is a very sensitive test for new phenomena!**

* for massive particles, there is of course a difference between chirality and helicity, no time for this today, ask at the end in case of doubt!

Polarisation & Higgs Couplings

A relationship only appreciated a few years ago…

- **THE key process** at a Higgs factory:
  Higgsstrahlung $e^+e^- \rightarrow Zh$
- **A_{LR}** of Higgsstrahlung: very important to **disentangle** different **SMEFT operators!**



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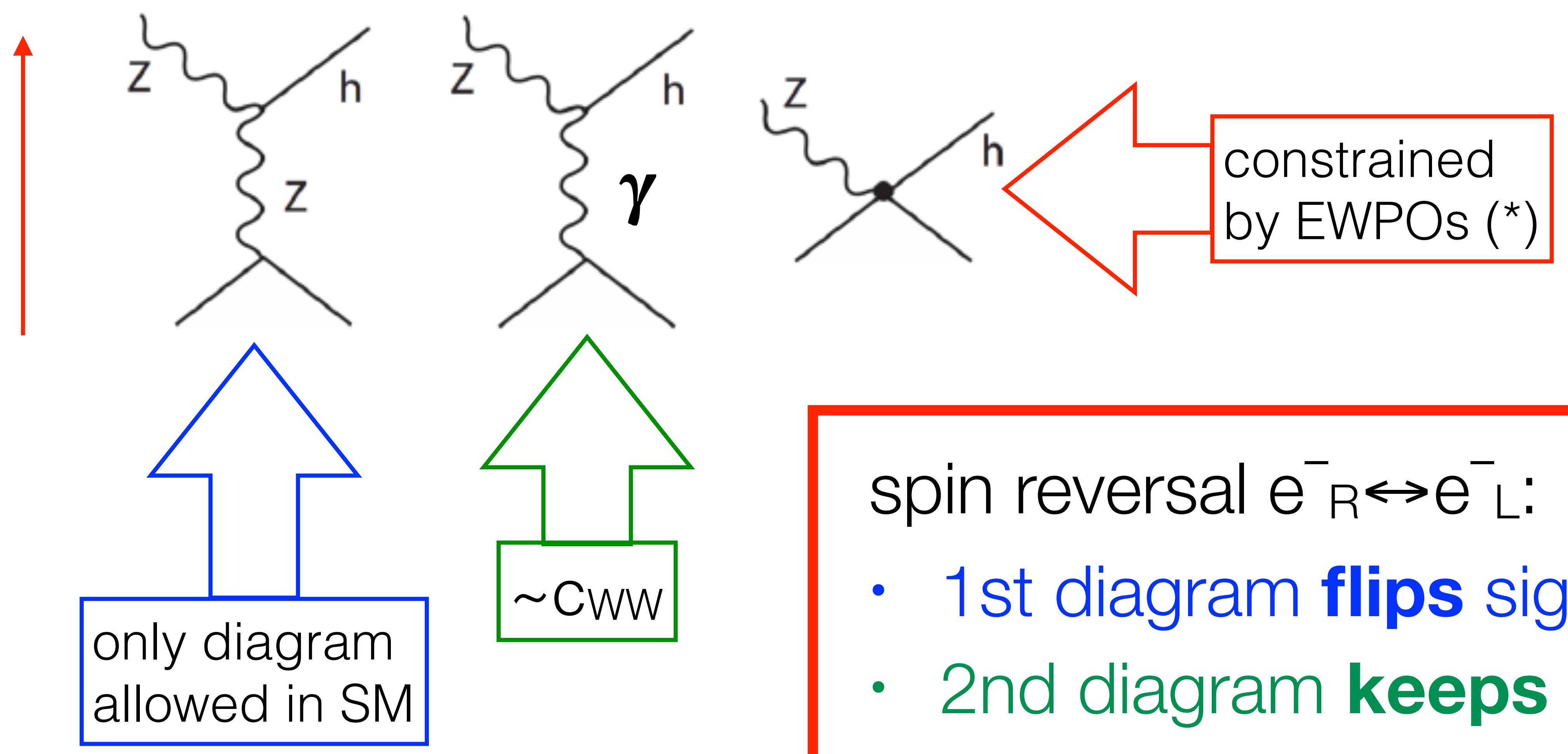

spin reversal $e^-_R \leftrightarrow e^-_L$:

- 1st diagram **flips** sign
- 2nd diagram **keeps** sign

⇒ A_{LR} lifts degeneracy between operators!

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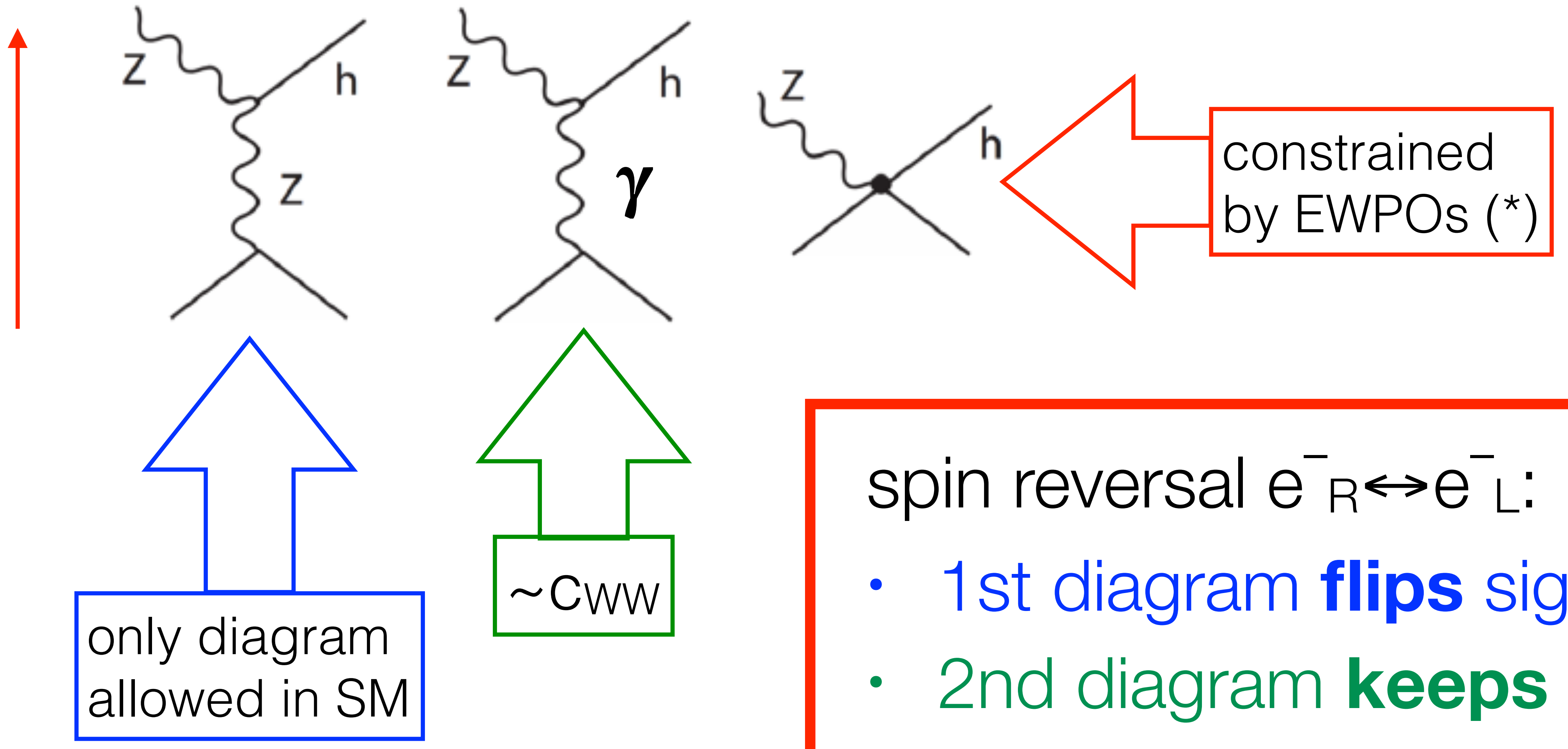

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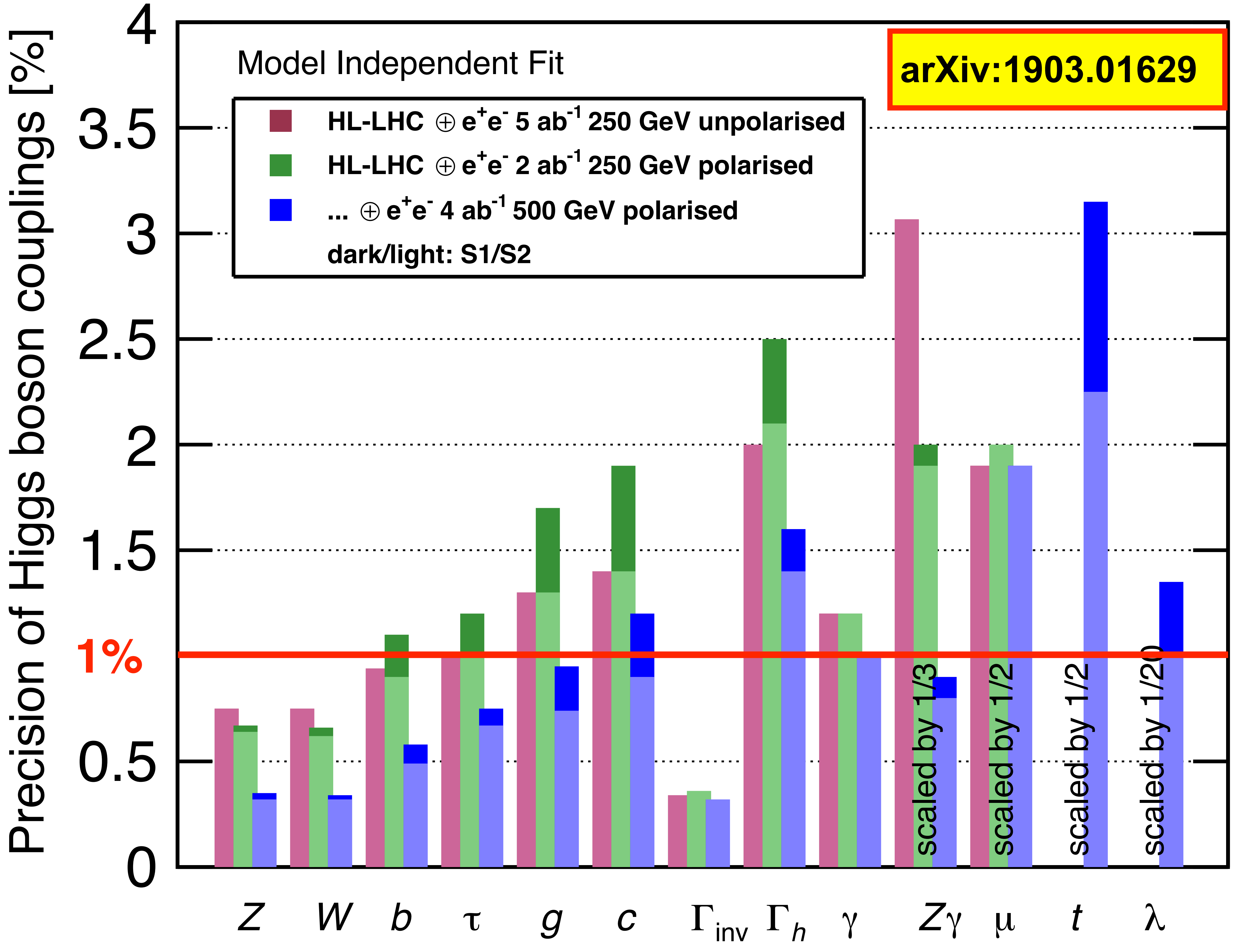

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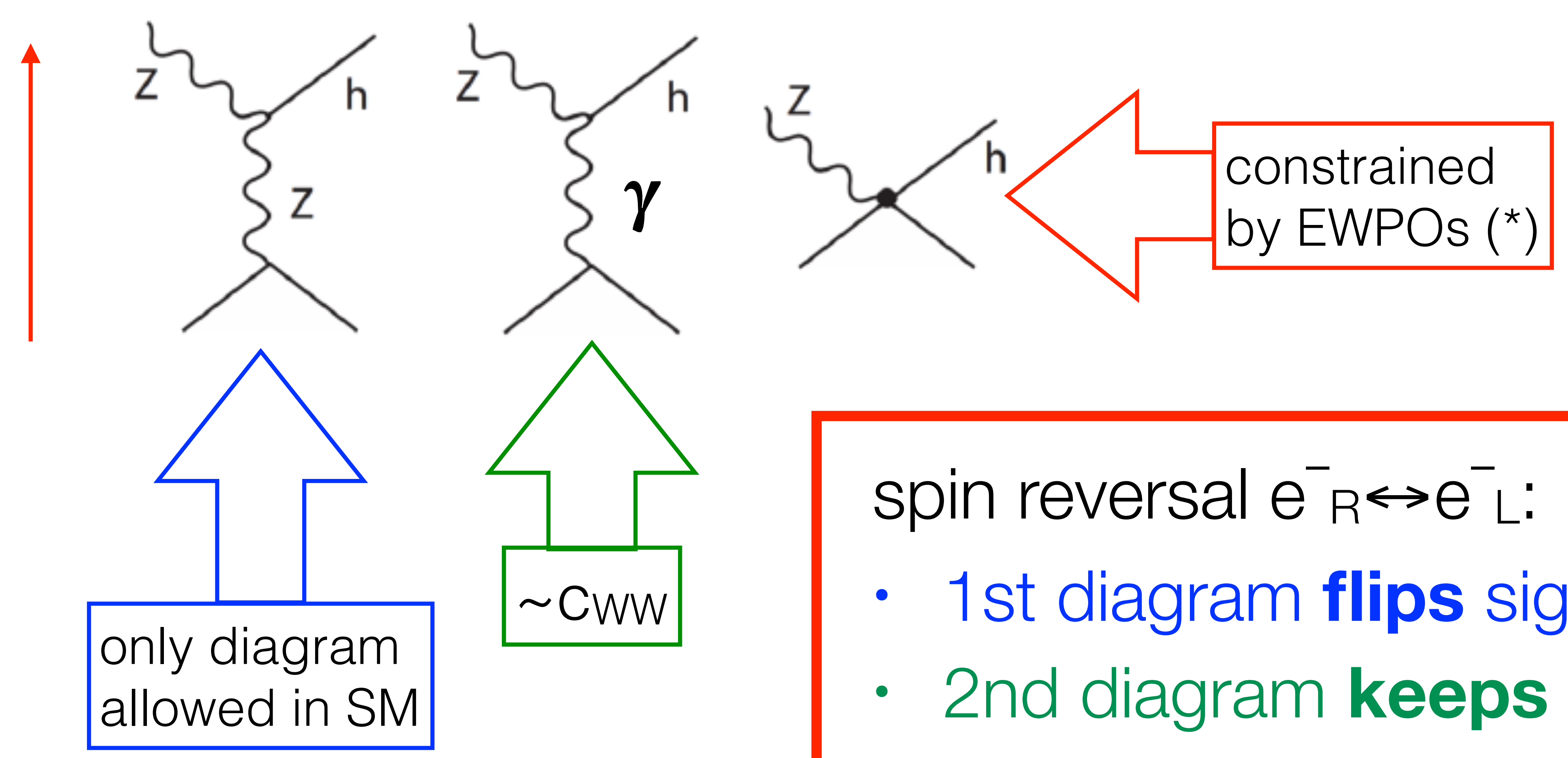

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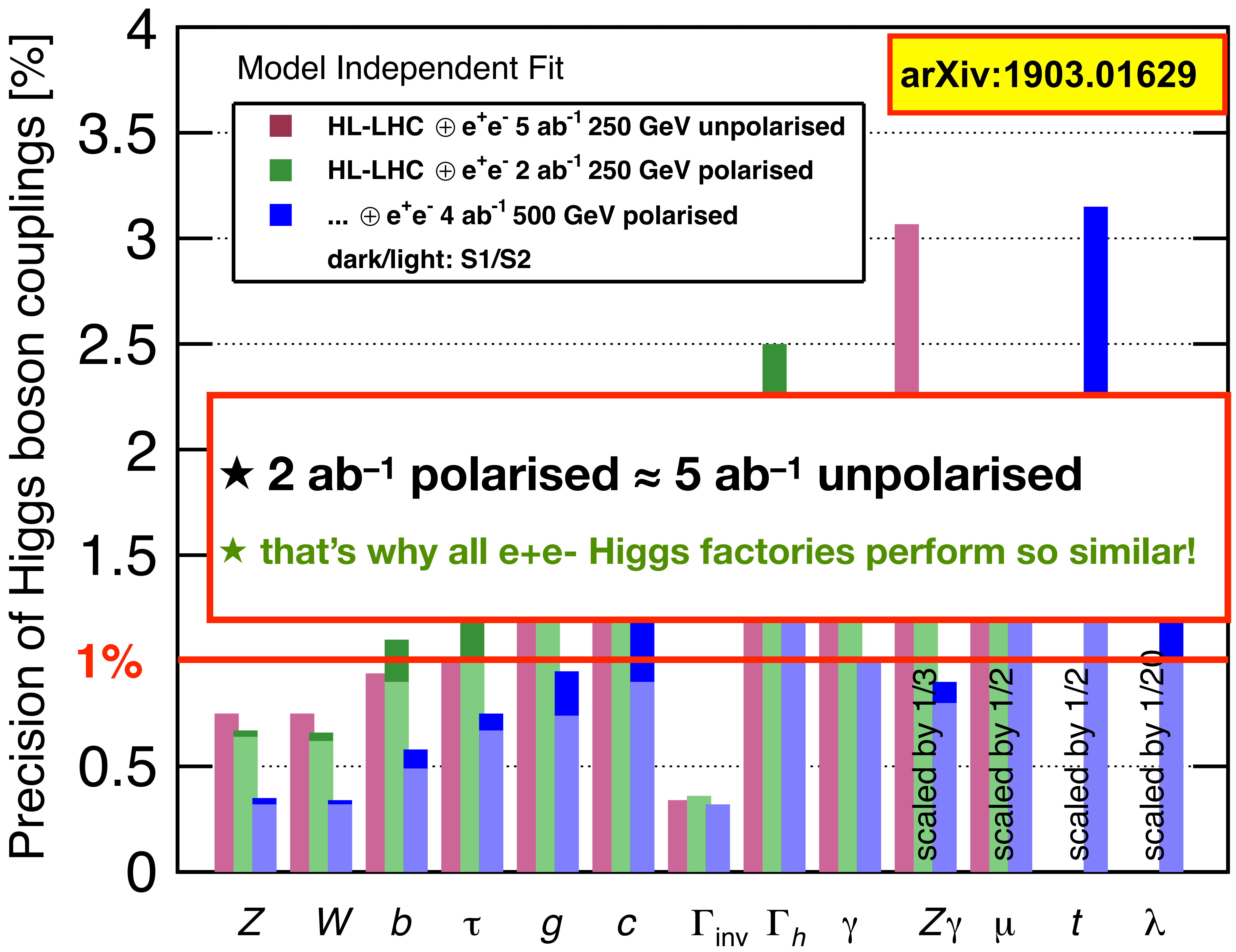
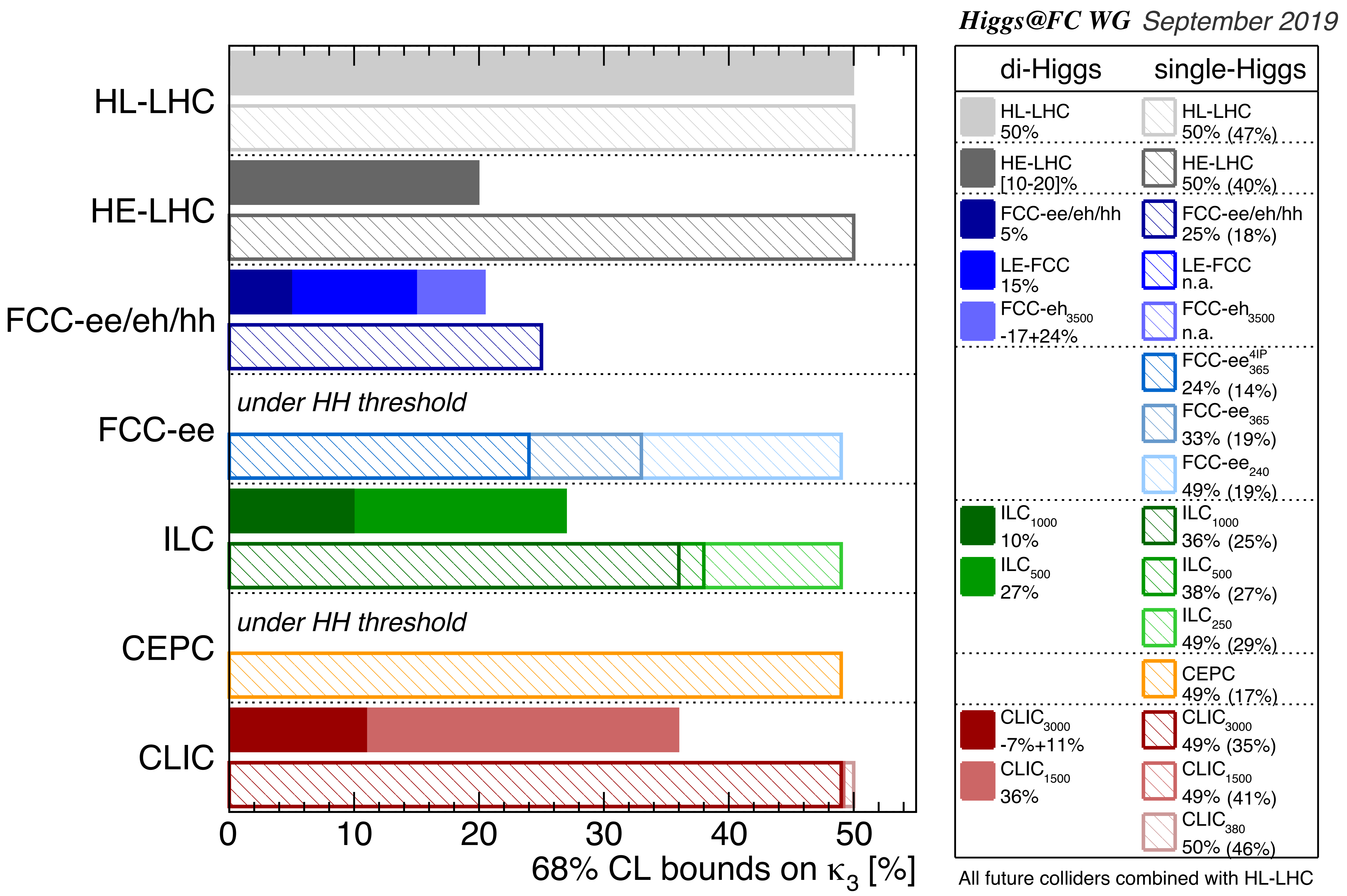


★ **2 ab⁻¹ polarised ≈ 5 ab⁻¹ unpolarised**

★ **that's why all e+e- Higgs factories perform so similar!**

The ECFA Higgs@Future Report



At lepton colliders, double Higgs-strahlung, $e^+e^- \to ZHH$, gives stronger constraints on positive deviations ($\varkappa_3 > 1$), while VBF is better in constraining negative deviations, ($\varkappa_3 < 1$). While at HL-LHC, values of $\varkappa_3 > 1$, as expected in models of strong first order phase transition, result in a smaller double-Higgs production cross section due to the destructive interference, at lepton colliders for the *ZHH* process they actually result in a larger cross section, and hence into an increased precision. For instance at ILC_{500}, the sensitivity around the SM value is 27% but it would reach 18% around $\varkappa_3 = 1.5$.

This figure applies ONLY for $\lambda = \lambda_{SM}$
no studies of BSM case apart from ILC

ILC Sensitivity vs Lambda

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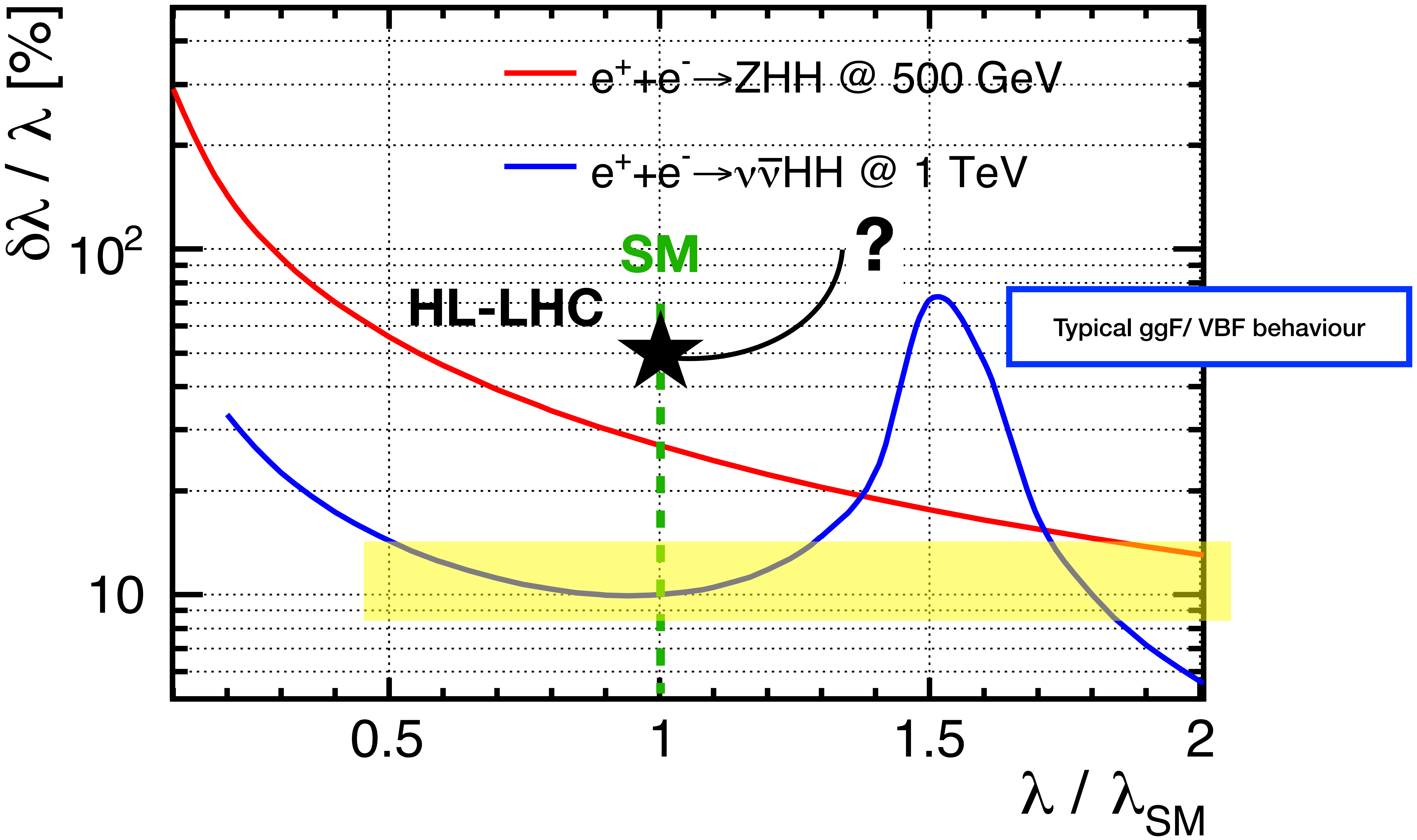
[J.Tian, C.Duerig]



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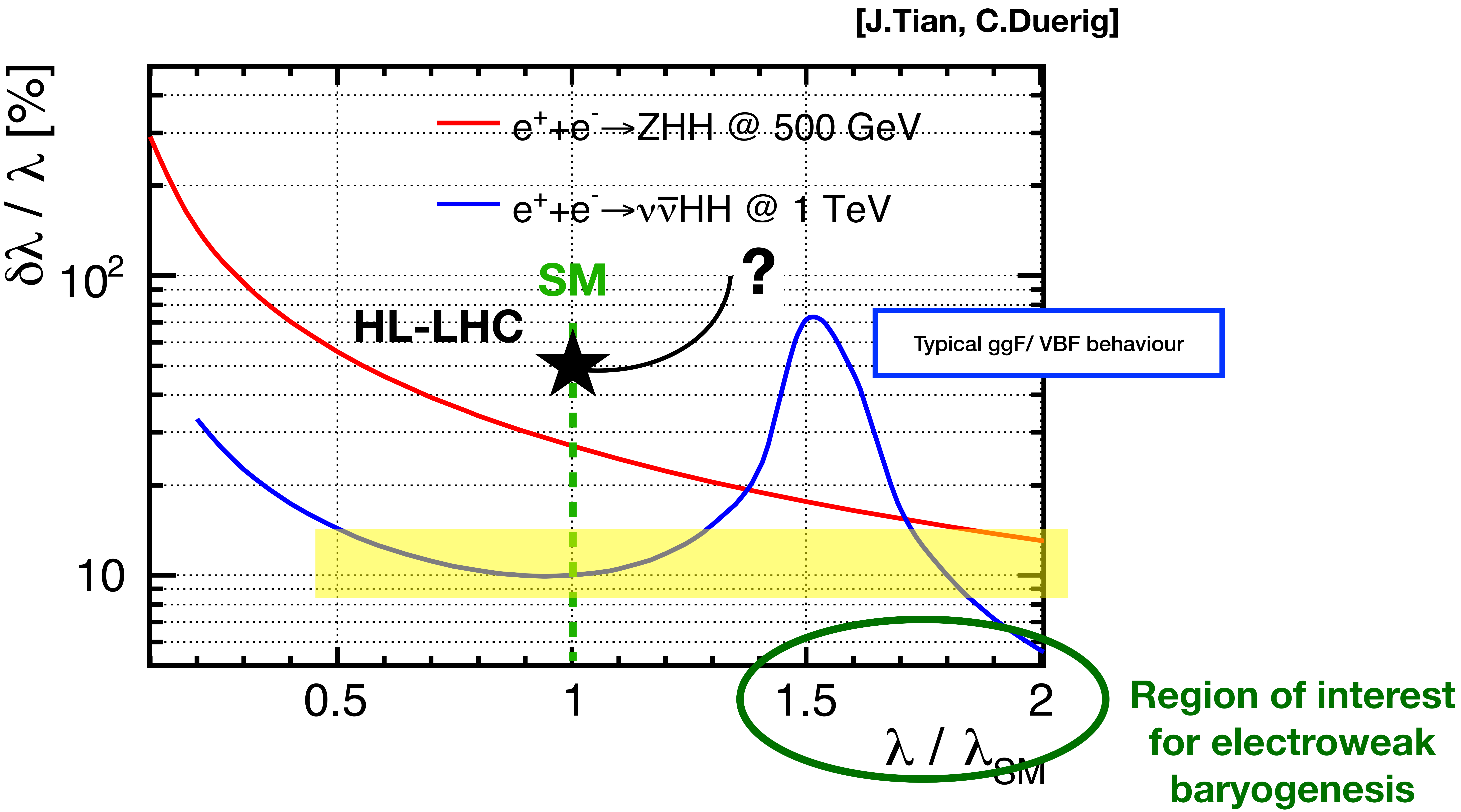

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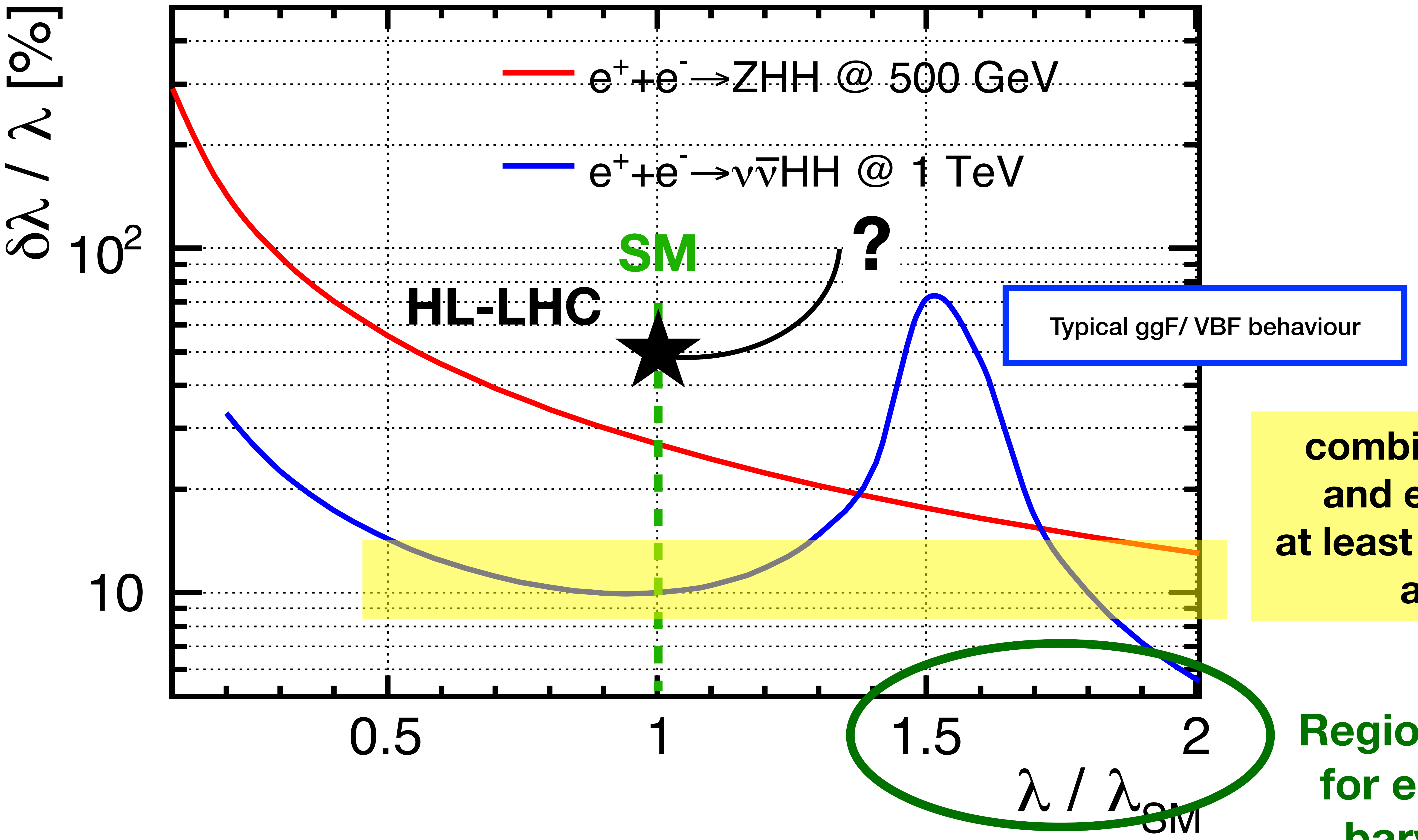
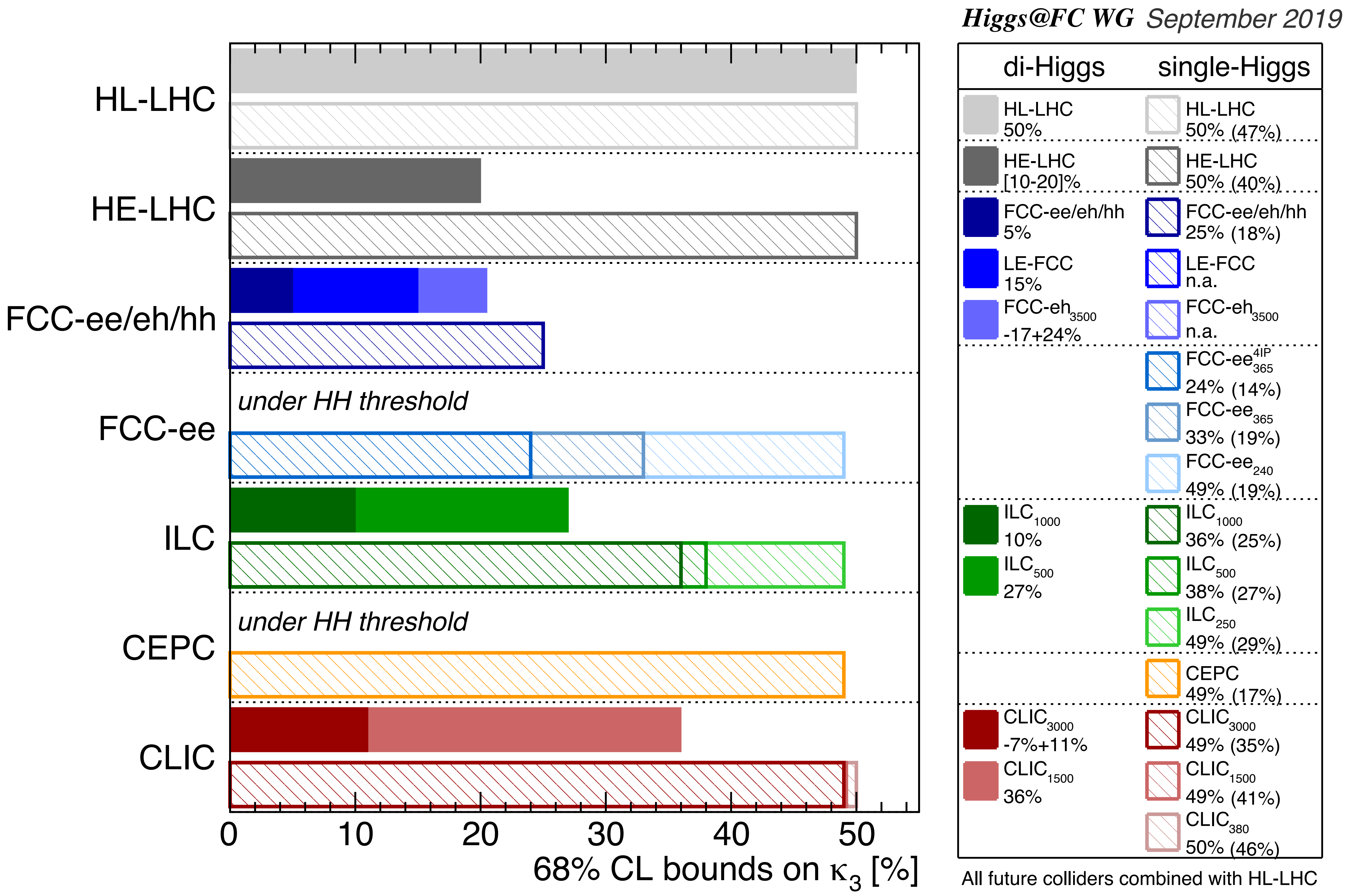


combination of e^+e^- -> ZHH and e^+e^- -> ννHH ensures at least 10-15% precision over a wide range in λ

Region of interest for electroweak baryogenesis

Higgs self-coupling

Electroweak Baryogenesis?



most detailed ILC ref: PhD Thesis C.Dürig
Uni Hamburg, **DESY-THESIS-2016-027**
UPDATE ONGOING!

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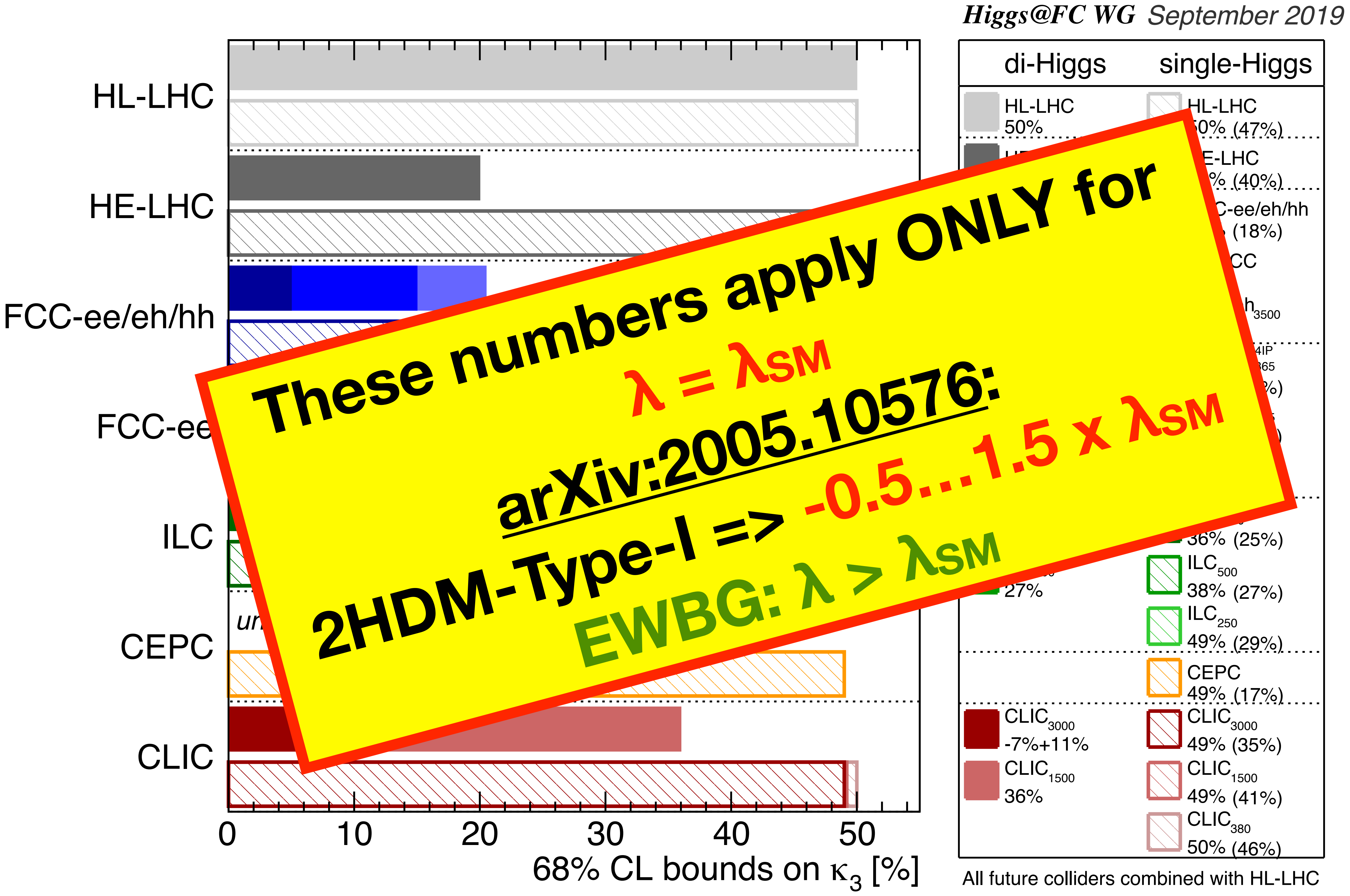

These numbers apply ONLY for $\lambda = \lambda_{SM}$

arXiv:2005.10576:

2HDM-Type-I => -0.5…1.5 x λ_{SM}

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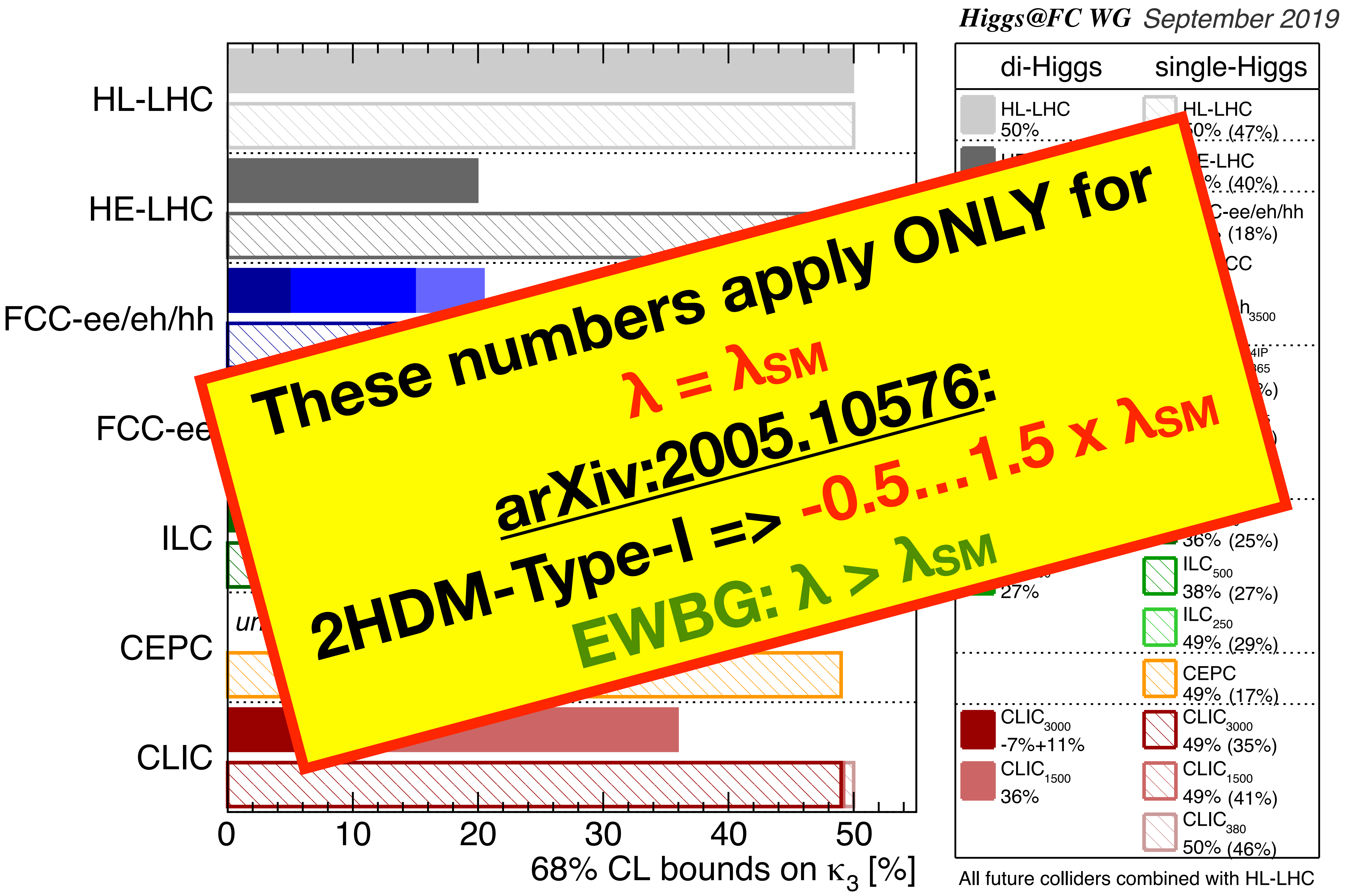

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- **pp cross section drops**
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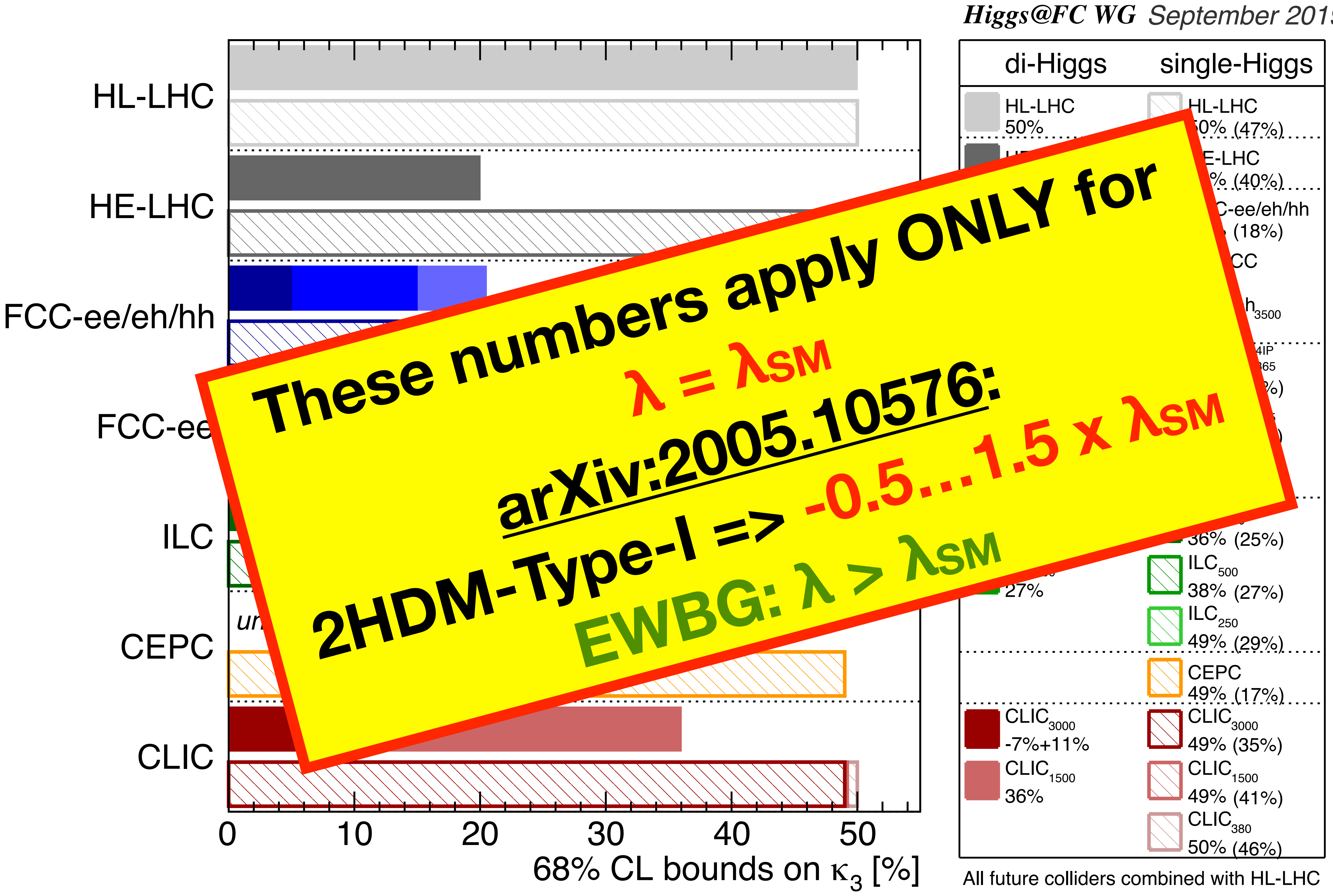

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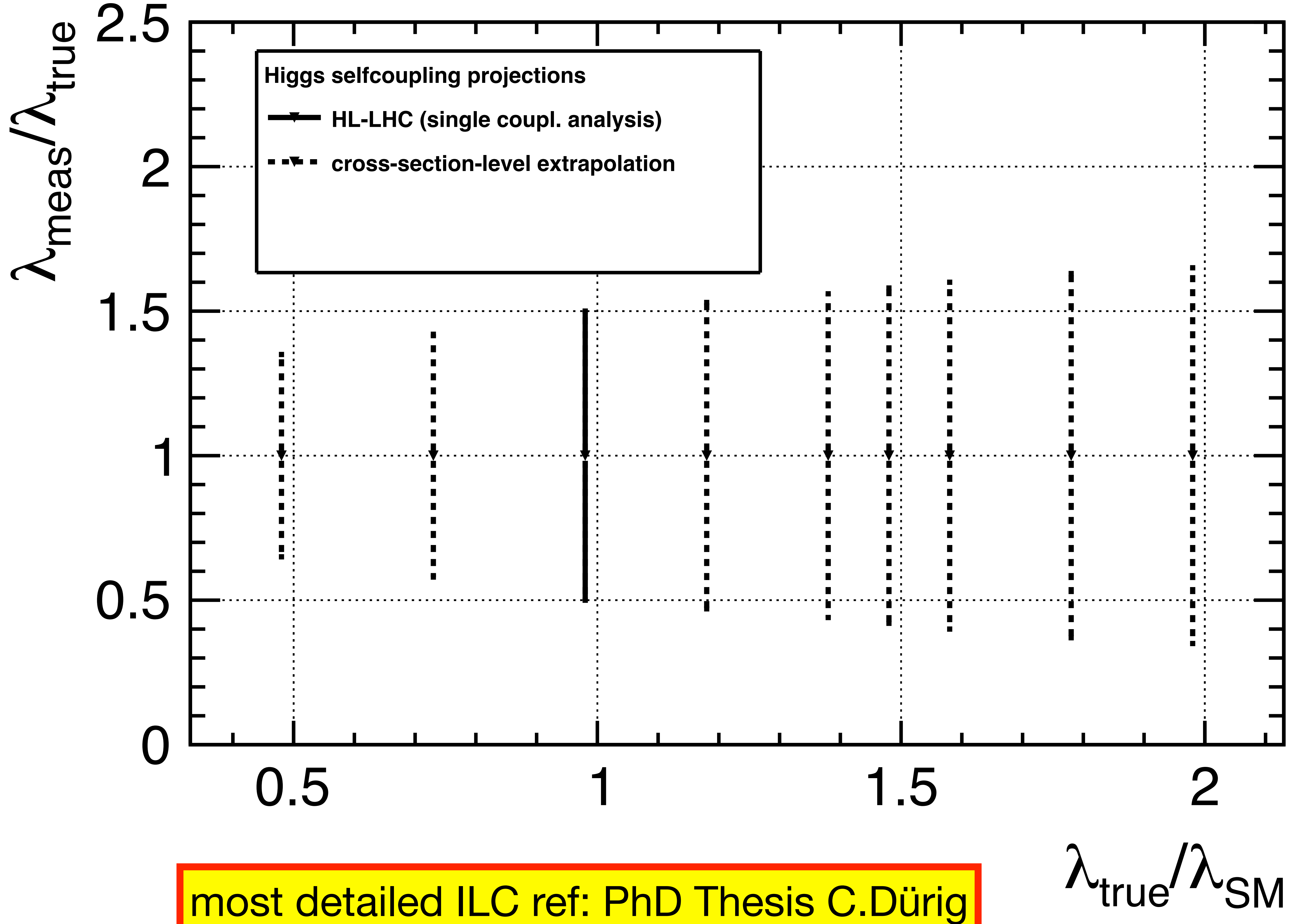

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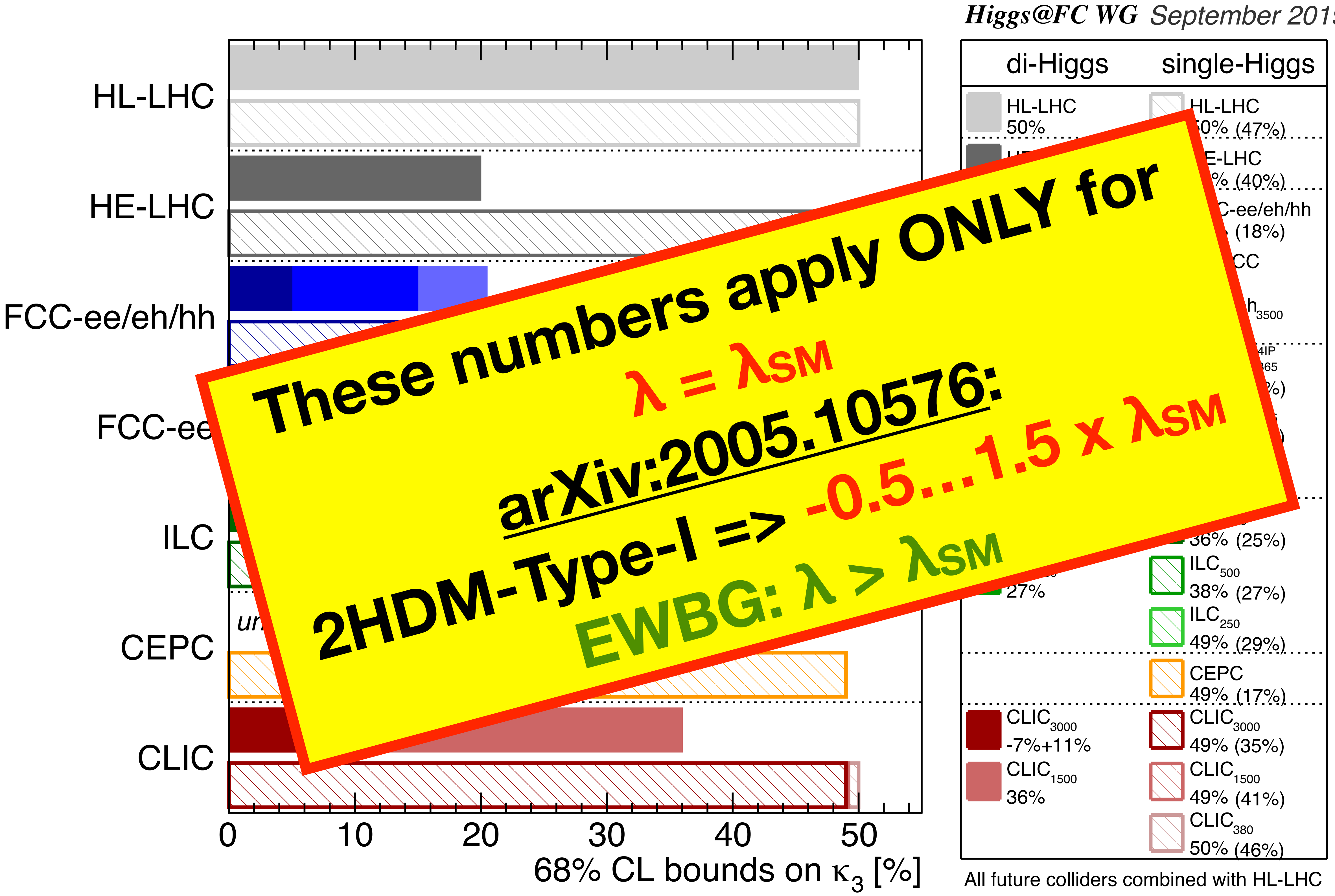

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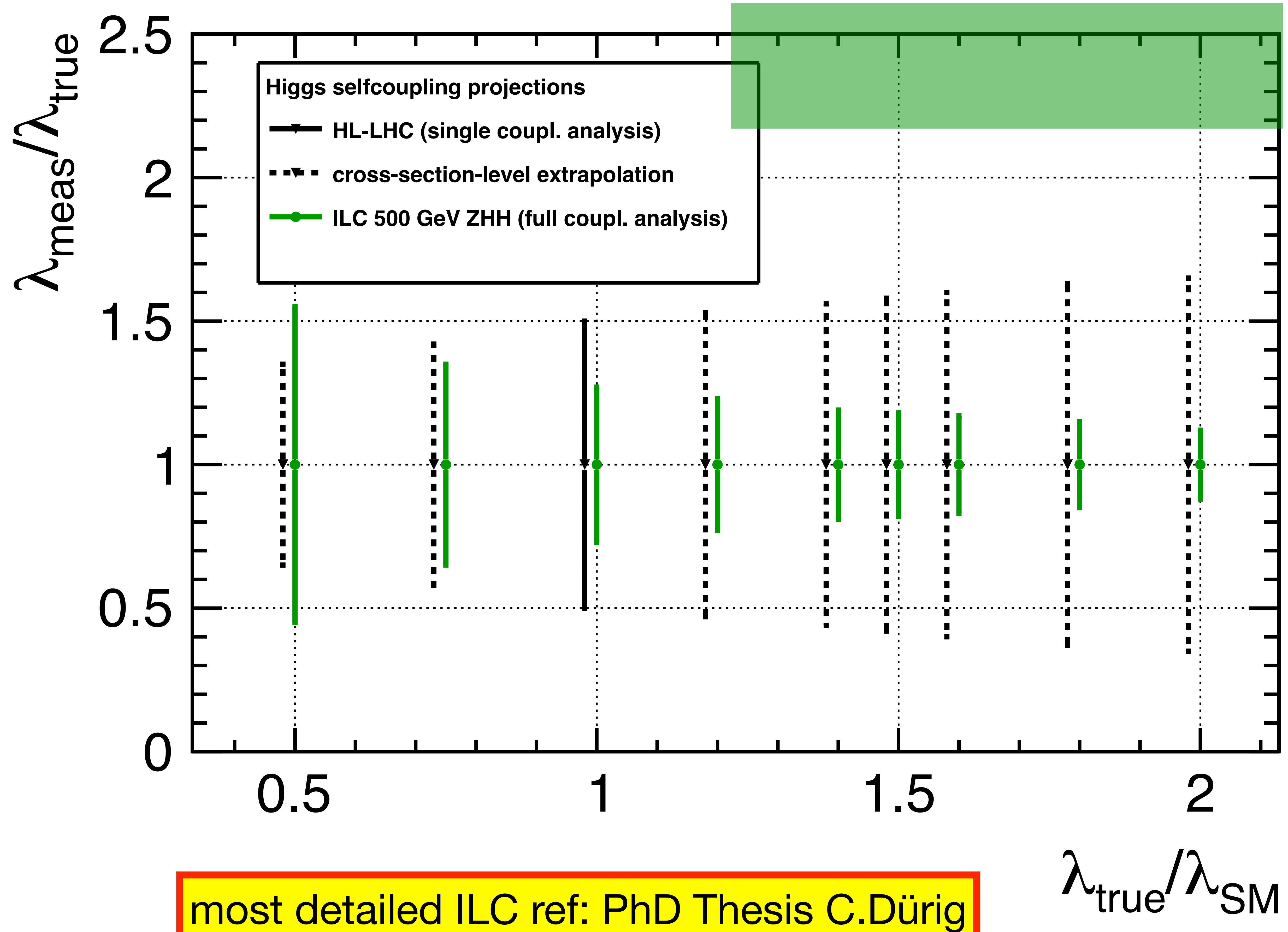

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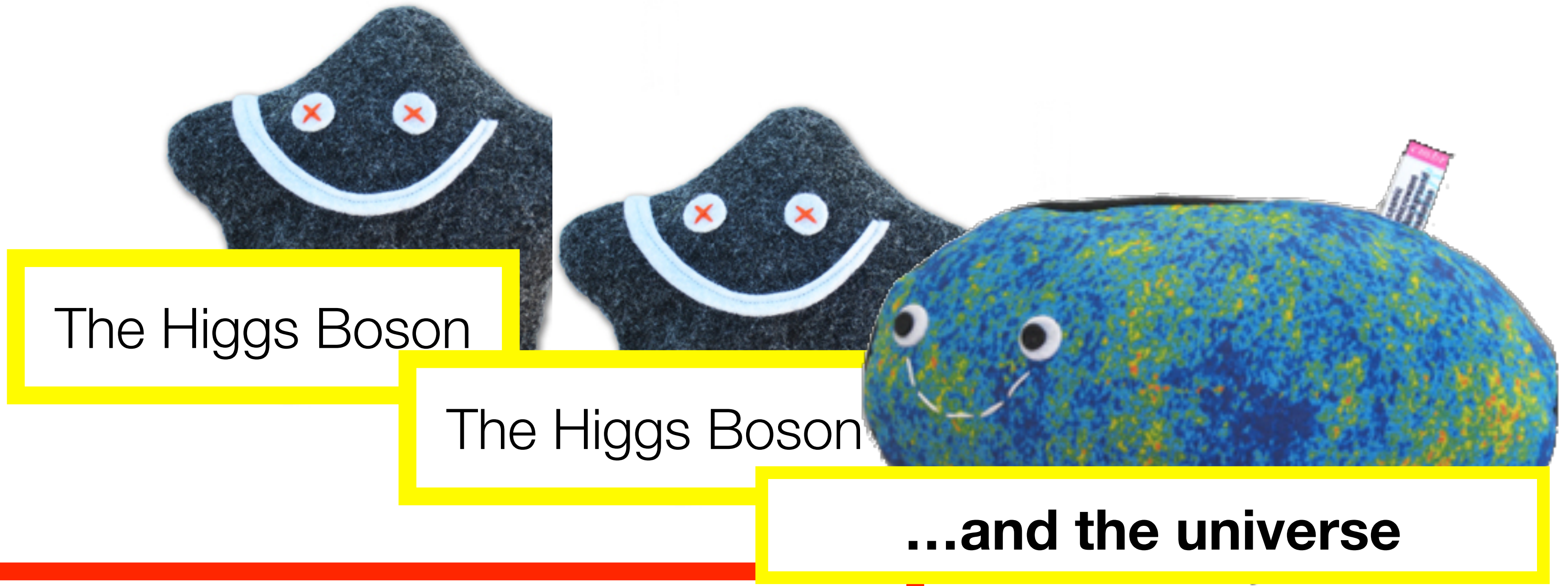

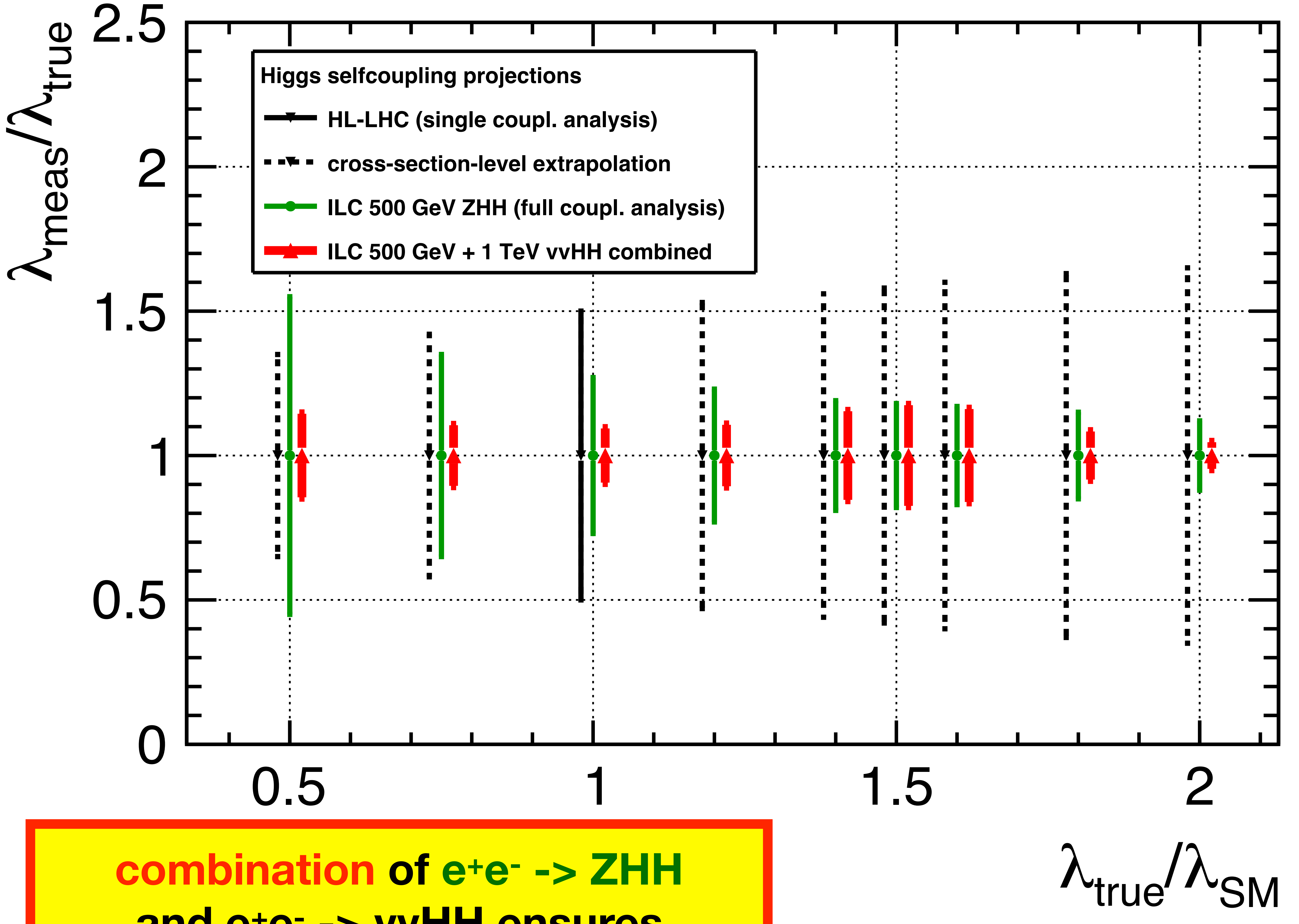

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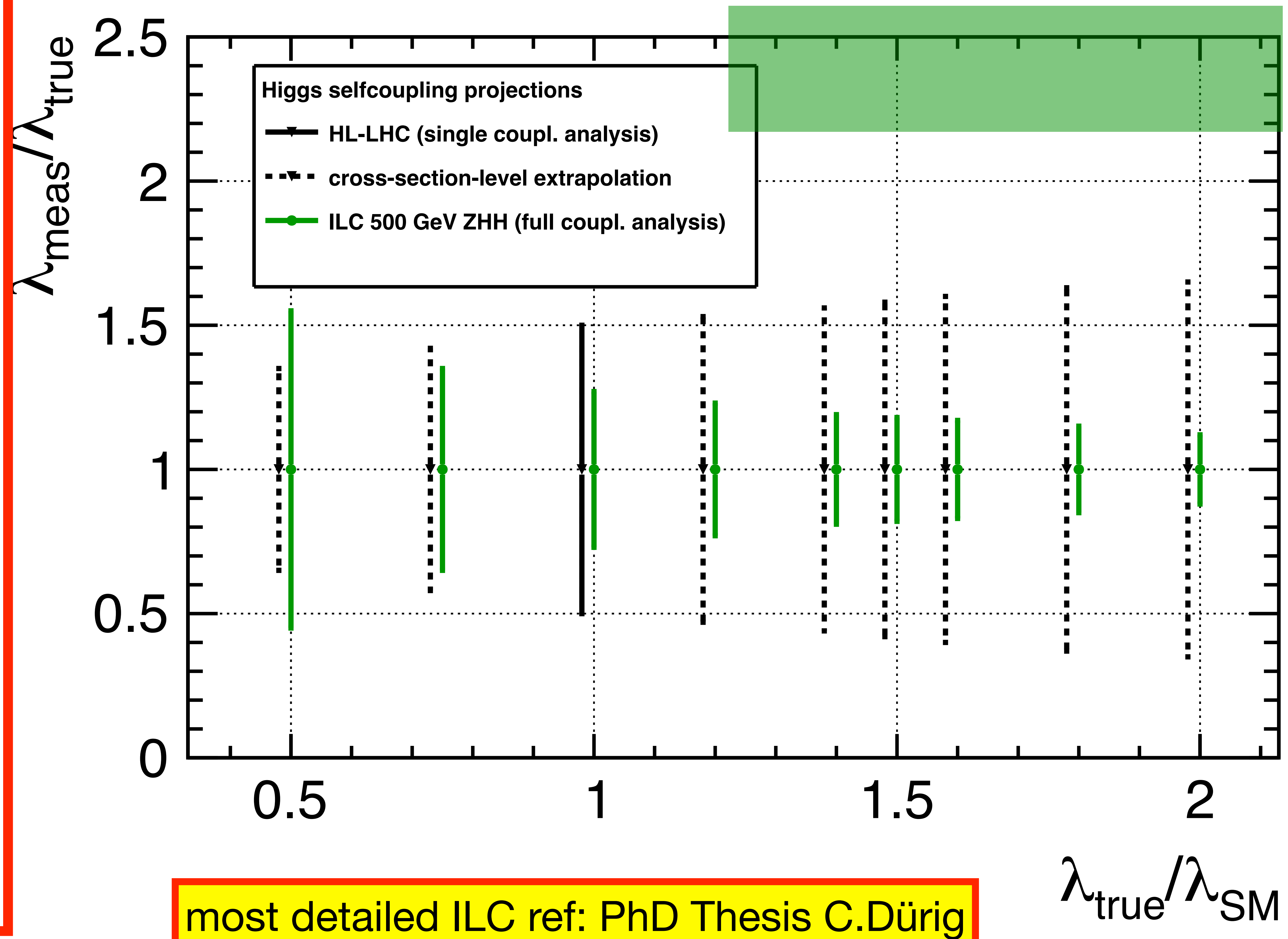

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