Electroweak precision observables for the Higgs coupling determination at the ILC

J. List (DESY) on behalf of the ILD Detector Concept Group

Higgs Couplings 2019, Oxford

Introduction

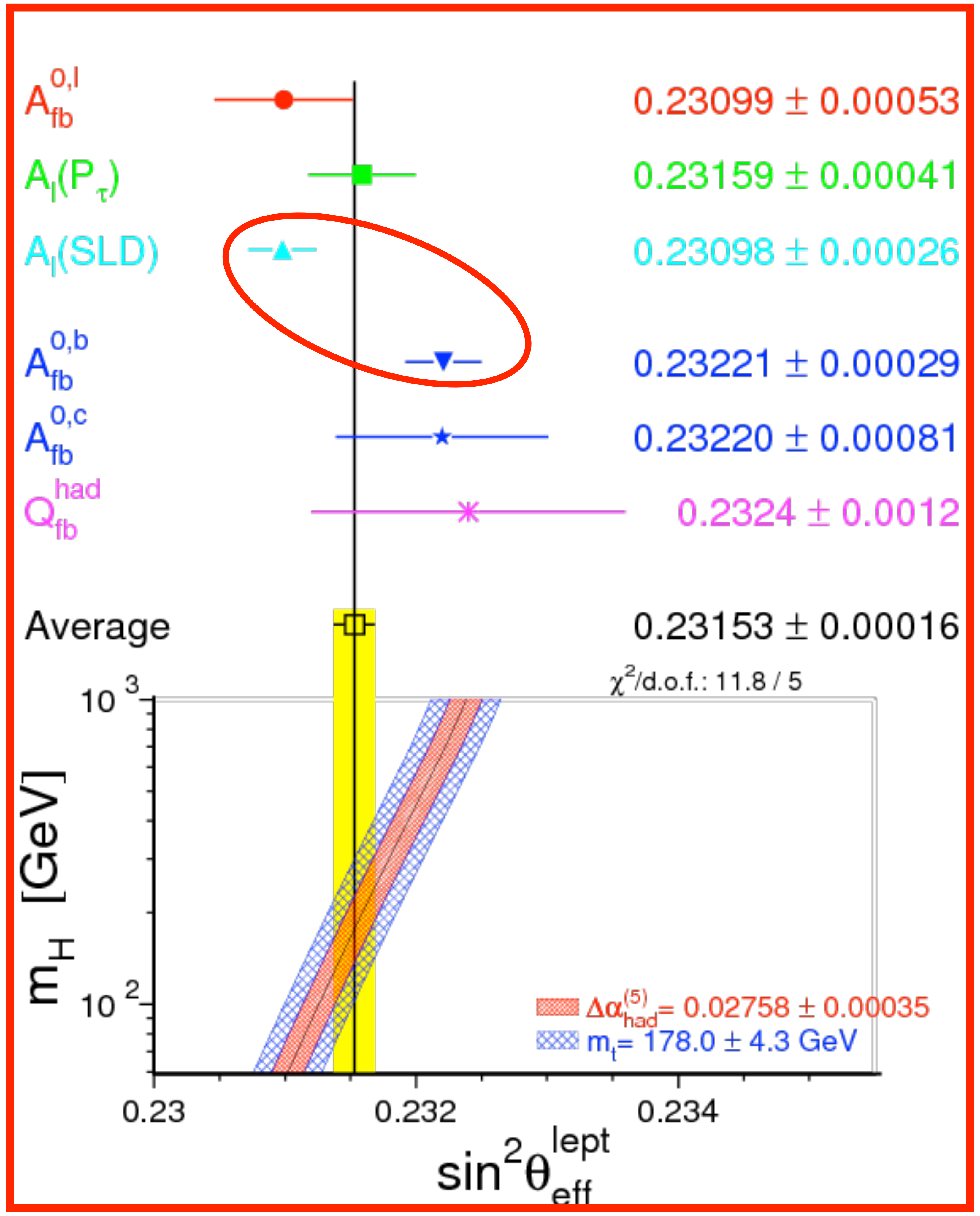
Electroweak observables provide

- **a crucial stress test of the SM**
- important input to SMEFT fit
  => Higgs property determination!
- **BSM sensitivity!**

Received a lot of attention during European Strategy process, eg at Open Symposium in Granada

Required: a lot of Z's ….

Talk based on arXiv:1908.11299



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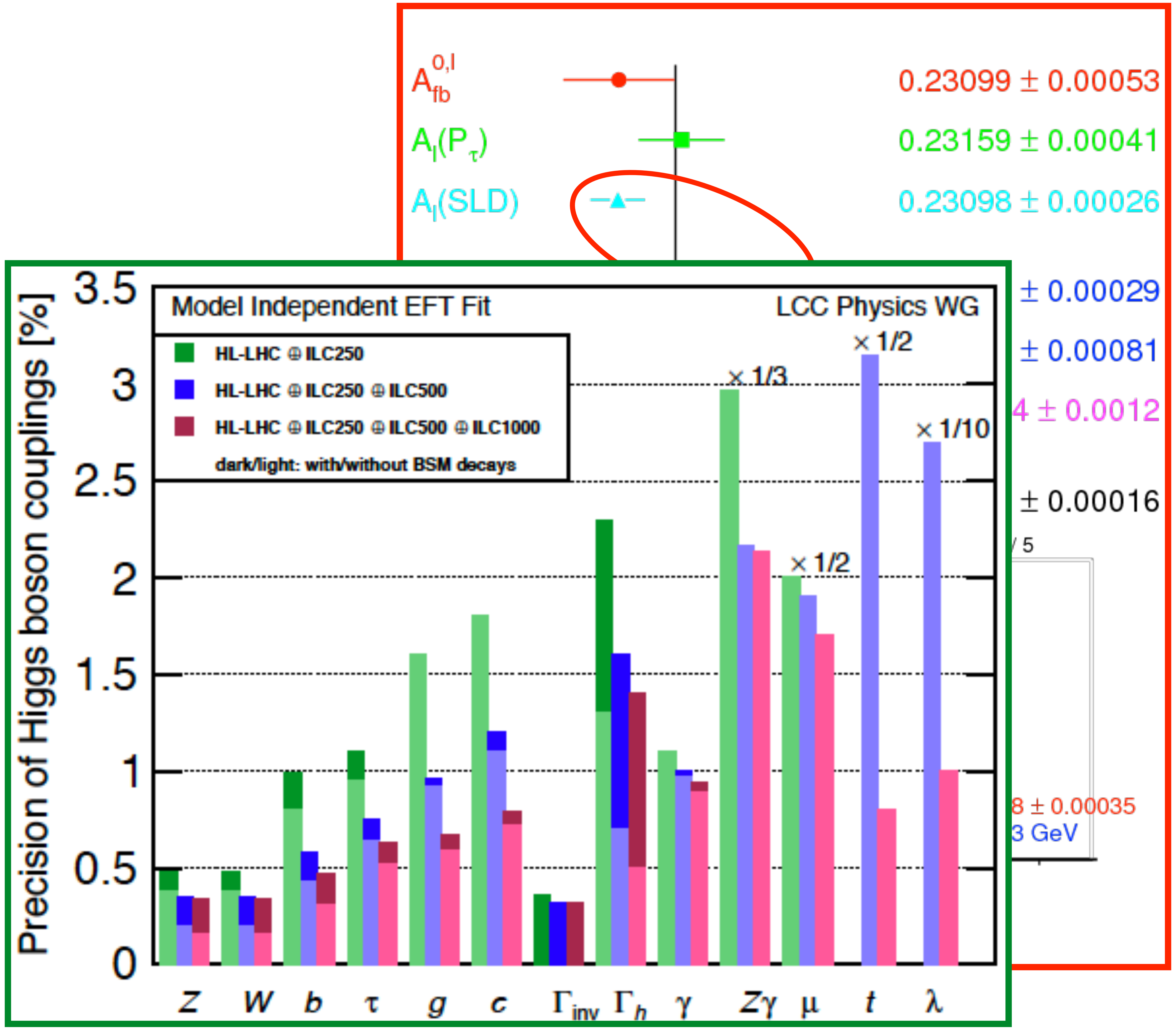


ILC running modes - and Z production

ILC e^+e^- collider

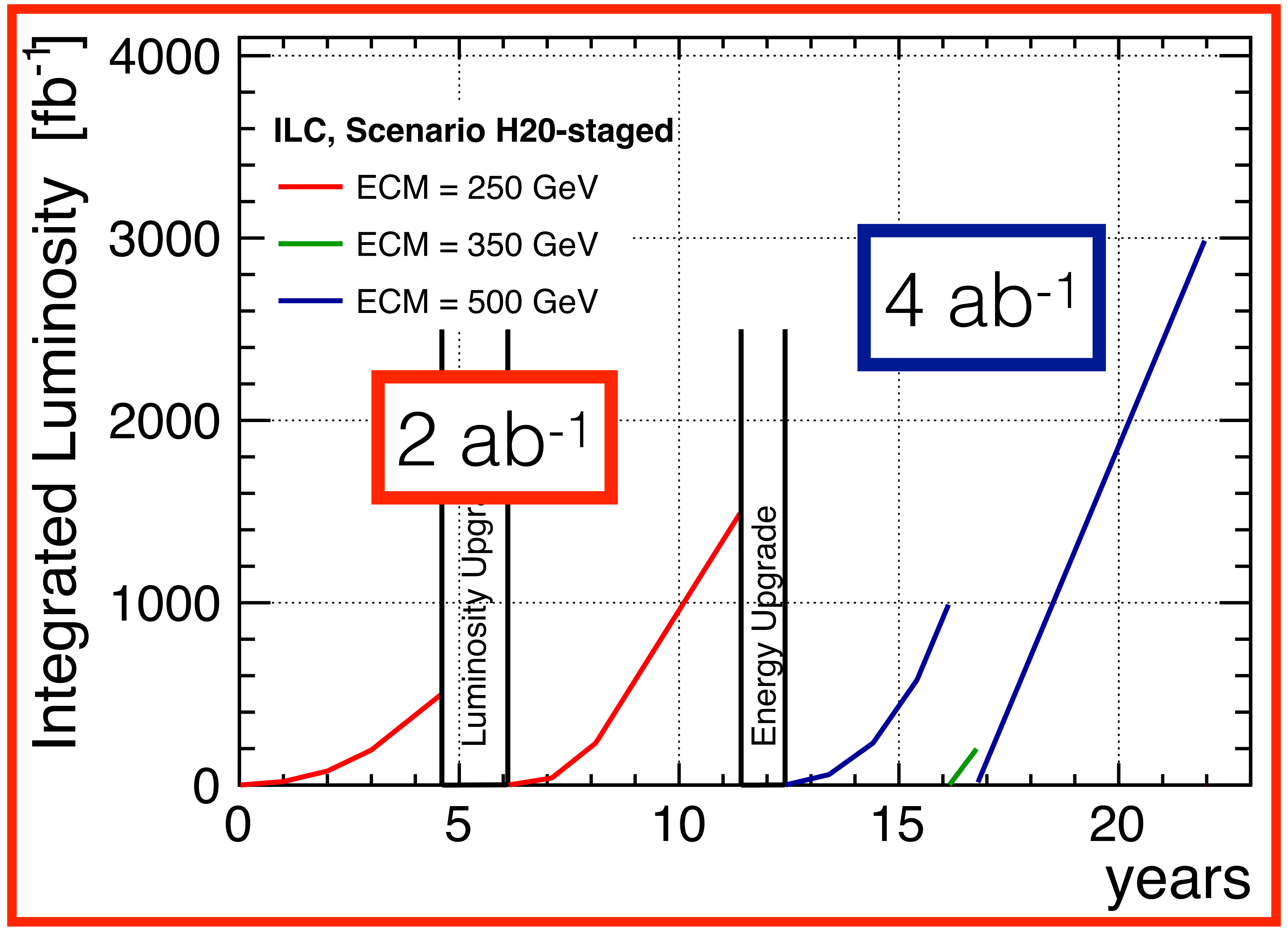
- **first stage: 250 GeV**
- **GigaZ & WW threshold possible**
- upgrades: 500 GeV, 1 TeV

polarised beams

- **$P(e^-) \geq \pm80\%$,**
- **$P(e^+) = \pm30\%$,** at 500 GeV upgradable to 60%

Since 2015 arXiv:1506.07830

$\sqrt{s}$	$\int \mathcal{L} dt$
250 GeV	2 ab^{-1}
350 GeV	0.2 ab^{-1}
500 GeV	4 ab^{-1}
1 TeV	8 ab^{-1}
91 GeV	0.1 ab^{-1}
161 GeV	0.5 ab^{-1}



(radiative) Z's in 2 ab^{-1} at **250 GeV**:

- ~77 10^6 Z->qq
- ~12 10^6 Z->ll

=> substantial increase over LEP,
….and polarised!

Z's in 0.1ab^{-1} at **91 GeV**:

- ~3.4 10^9 Z->qq
- ~0.5 10^9 Z->ll

~1-2 years of running (after lumi upgrade)

Accelerator implementation - arXiv:1908.08212

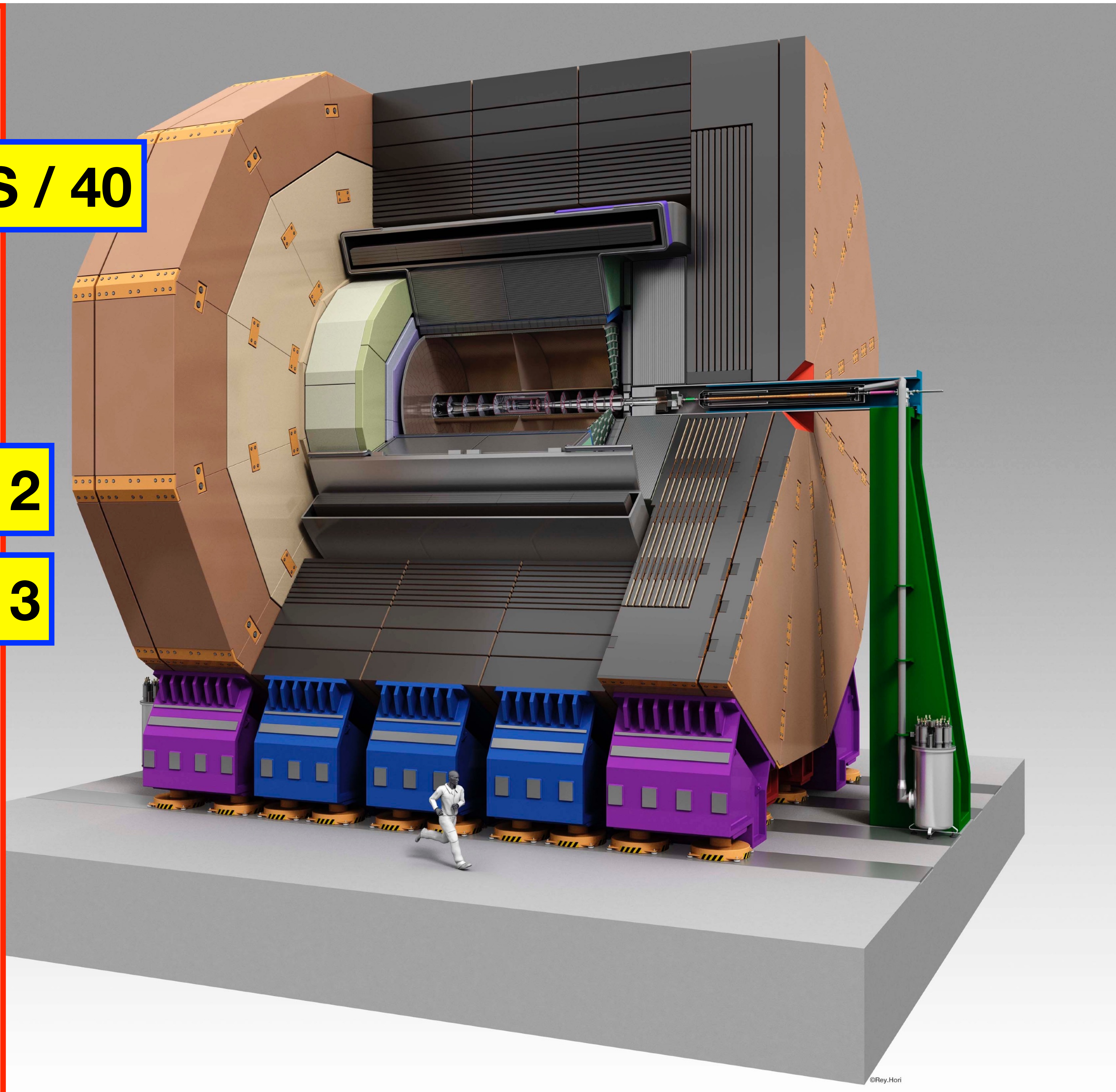
The ILD Concept

From key requirements from 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 → bb/cc/ττ)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu\mathrm{m}$
  ≈ CMS / 4
- **jet energy resolution** (H → invisible) 3-4% **≈ ATLAS / 2**
- **hermeticity** (H → invis, BSM) θ_{min} = 5 mrad **≈ ATLAS / 3**

To key features of the detector:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow



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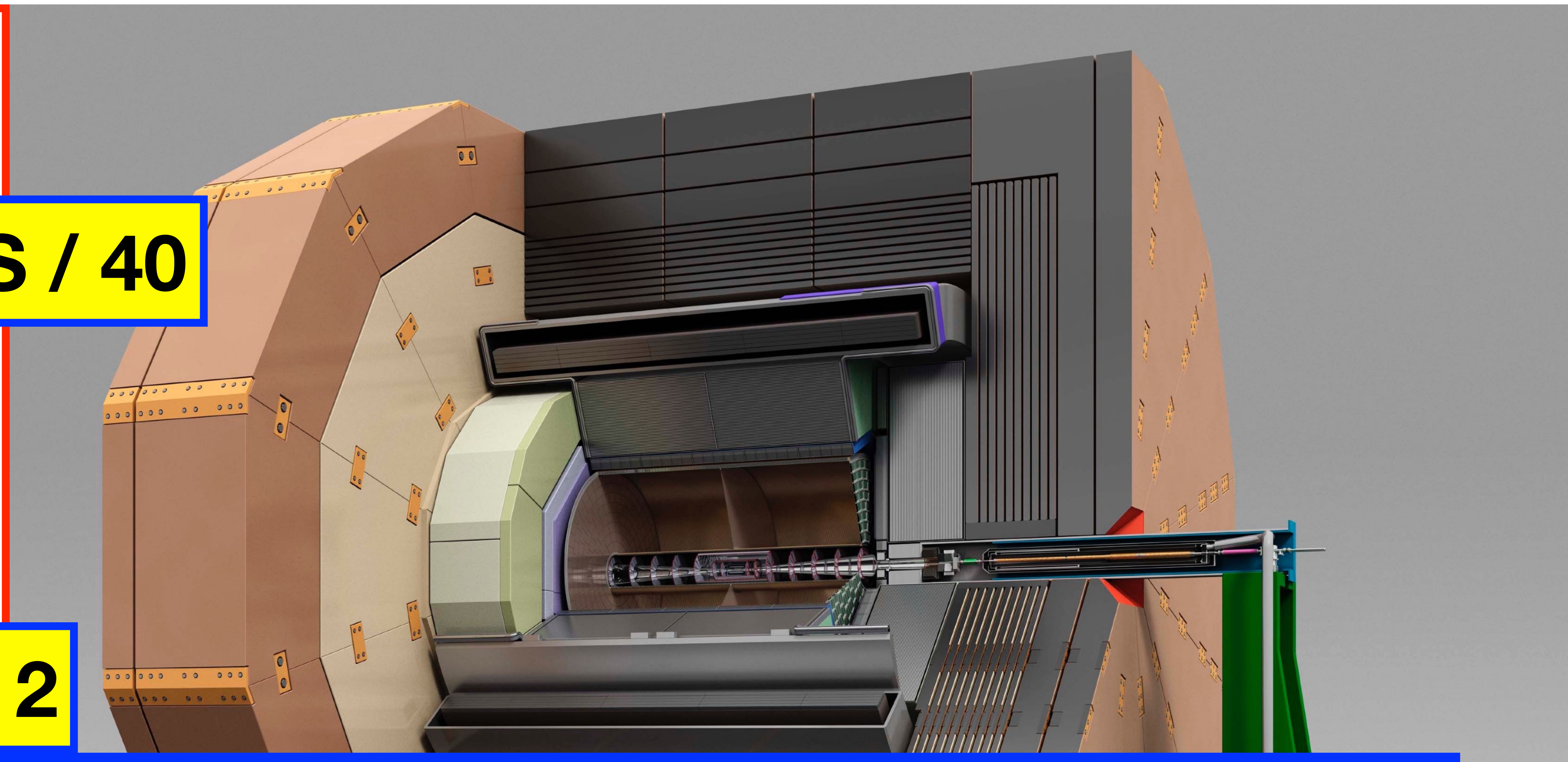


Possible since experimental environment at ILC very different from LHC:

- **much lower backgrounds**
- **much less radiation**
- **much lower collision rate**

enable

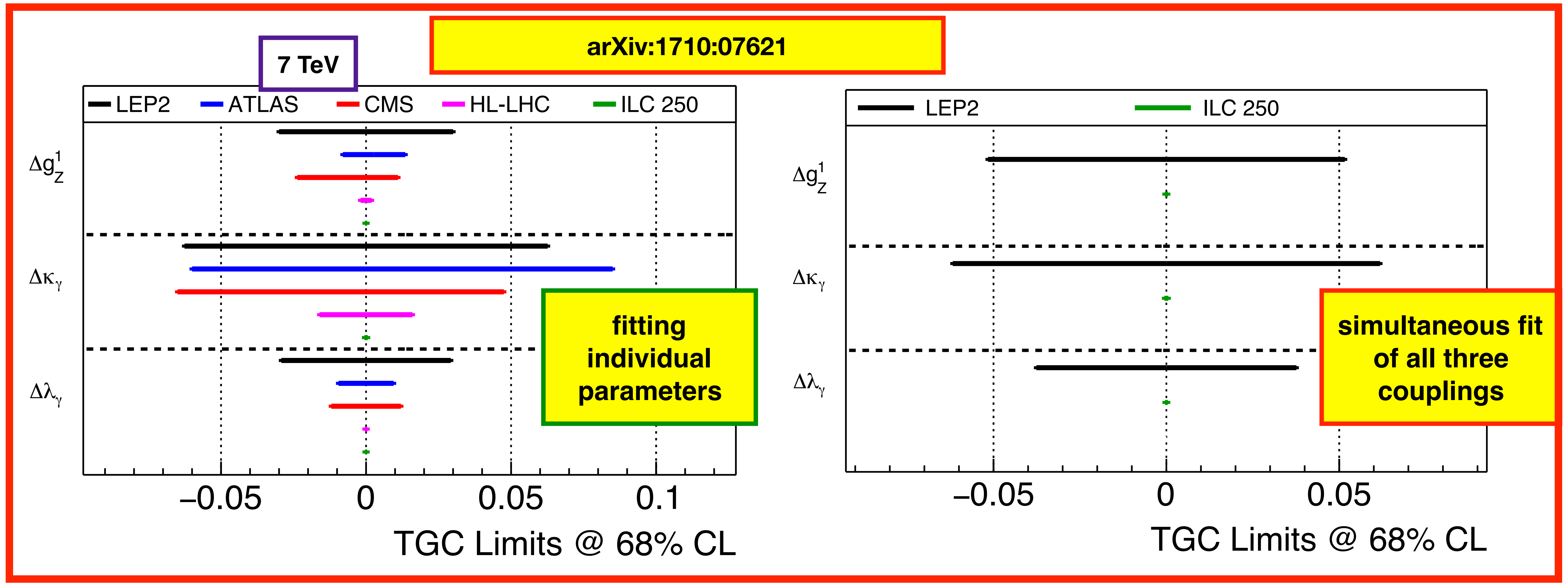
- **power pulsing => low material budget!**
- **triggerless operation**

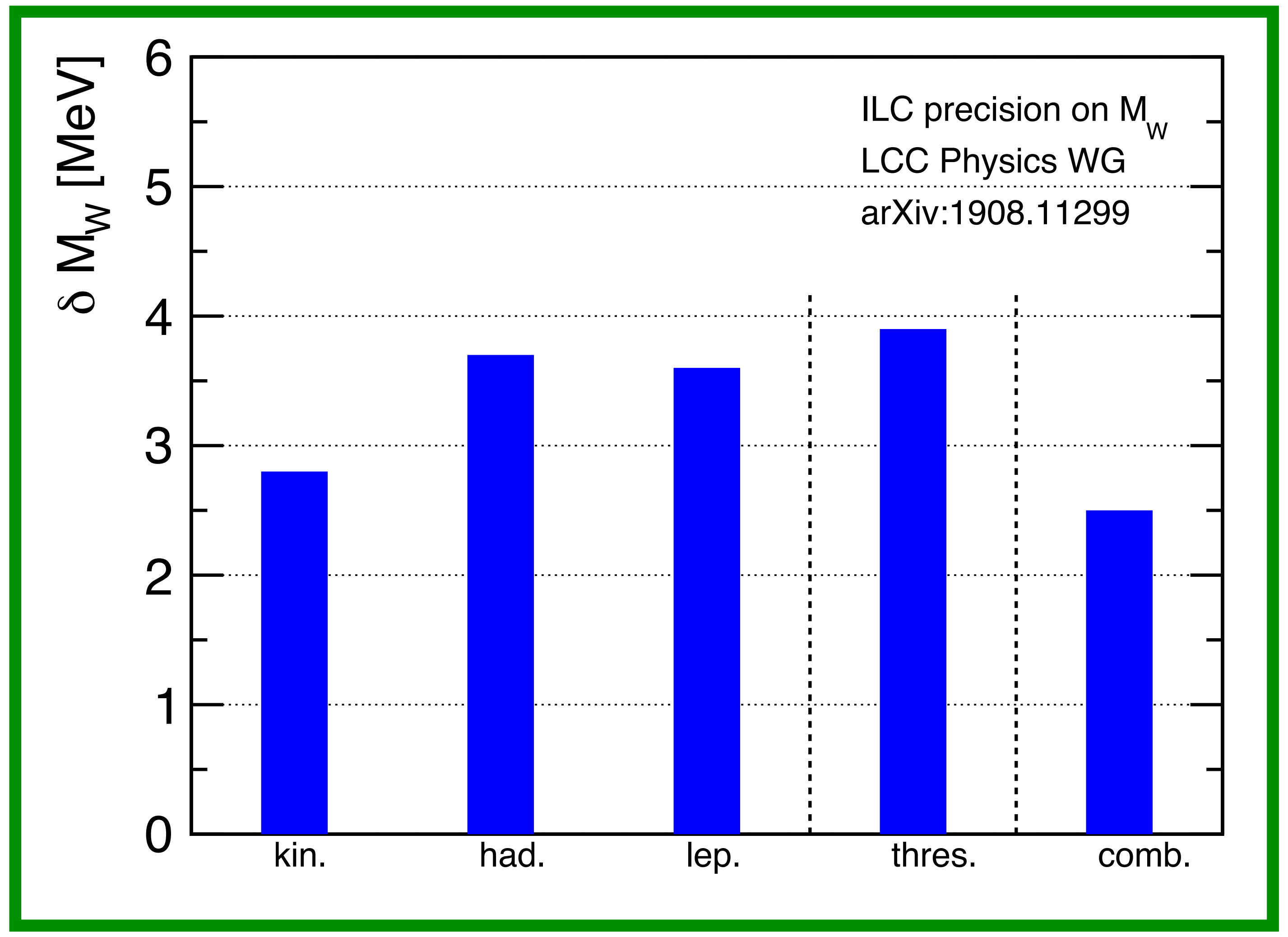
Interludium: Precision W measurements

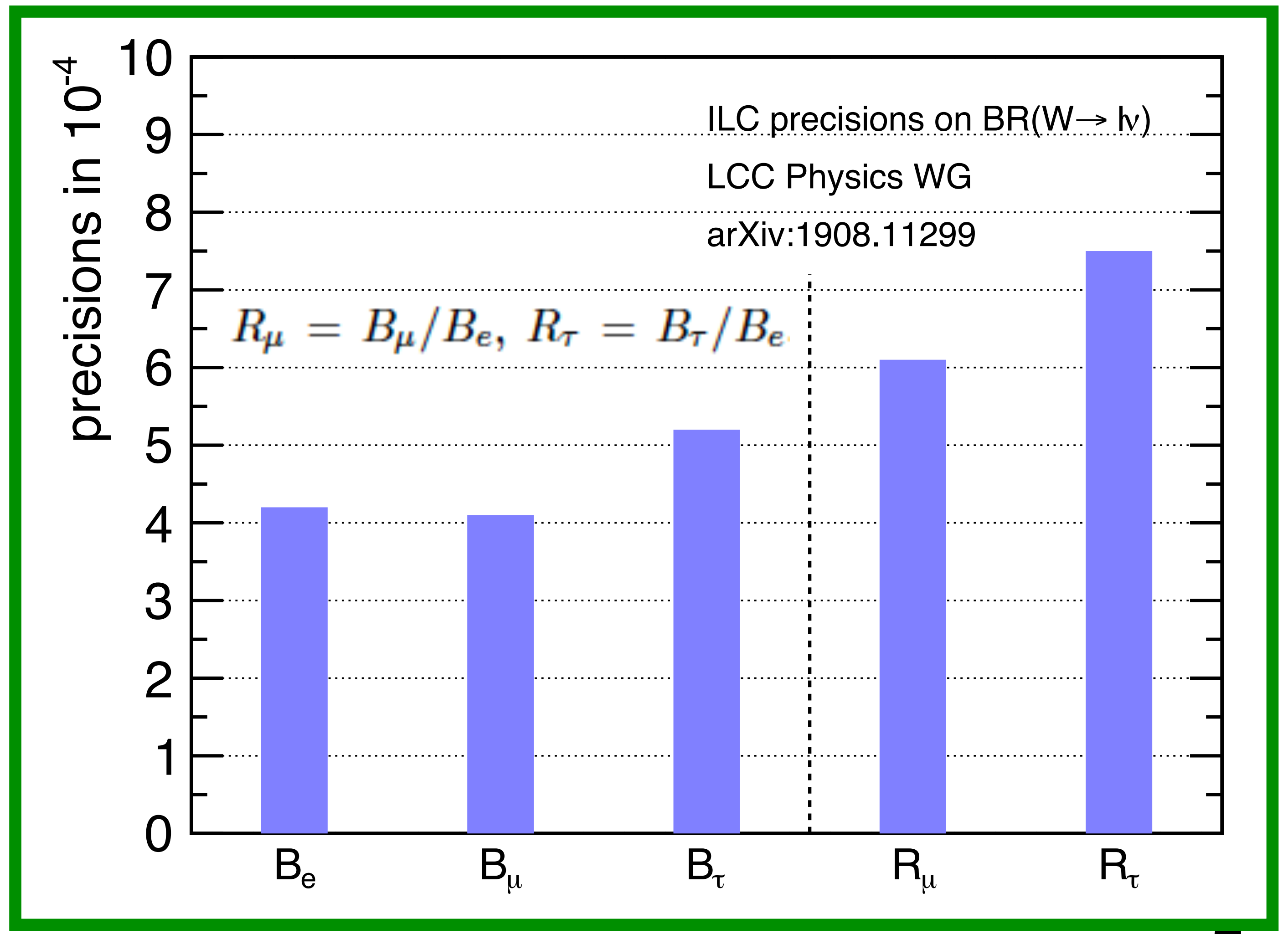
- Triple Gauge Couplings: few 10^{-4}, 1-2 orders of magnitude improvement over HL-LHC => input to SMEFT fit!
- W mass at 250 GeV - several methods *with very different systematic limitations*
- W mass from threshold scan - with ~1 year dedicated running:

$$\Delta m_W\,(\mathrm{MeV}) = 2.4\,(\mathrm{stat}) \oplus 3.1\,(\mathrm{syst}) \oplus 0.8\,(\sqrt{s}) \oplus \mathrm{theory}$$

- W branching ratios: simultaneous fit to all 10 σ_{tot} x BR for σ_{tot} and BR's (4 parameters)
- W width: $\Delta\Gamma_W$ = 3.2 MeV





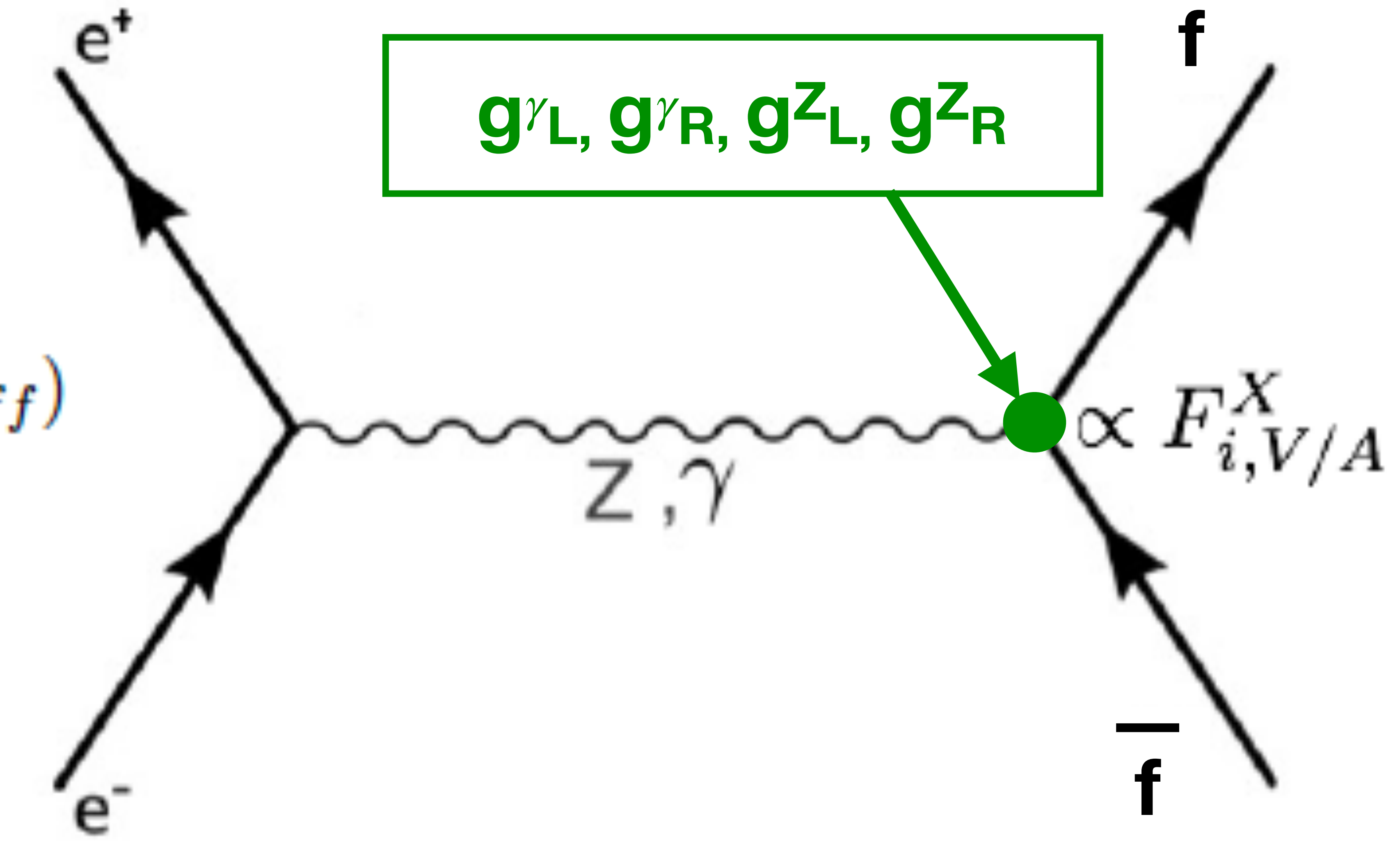


Electroweak precision observables

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

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

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:

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

=> no direct access A_e, only via tau polarisation

While at a ***polarised*** collider:

$$A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)}$$

and

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

Furthermore R_q and R_l:

$$R_q = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \text{hadrons})} \ , \quad 1/R_\ell = \frac{\Gamma(Z \to \ell^+\ell^-)}{\Gamma(Z \to \text{hadrons})} \quad \Rightarrow \quad R_q \ , \ 1/R_\ell \propto (g_{Lf}^2 + g_{Rf}^2)$$

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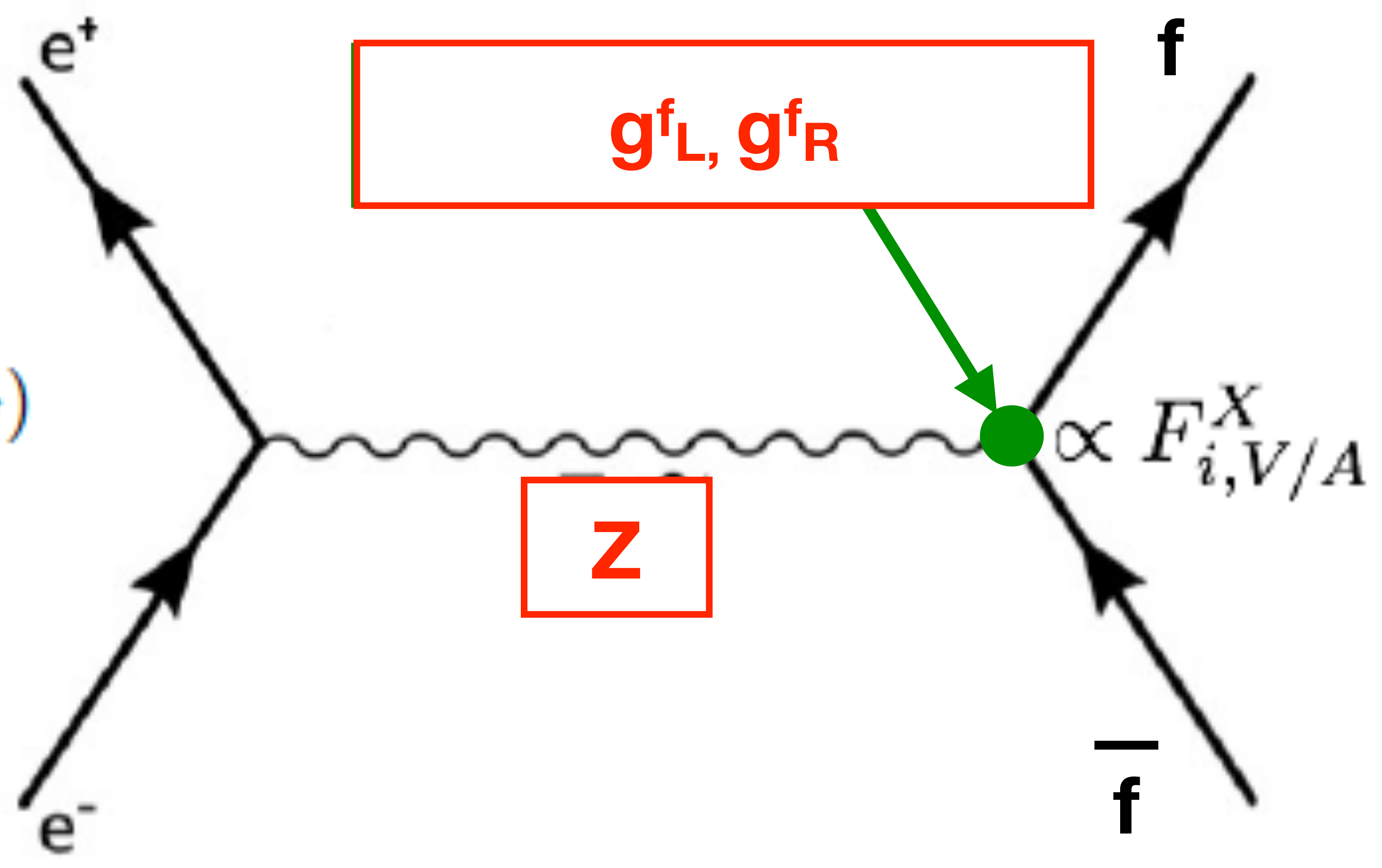

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Precision EW at 250 GeV from radiative return

- e^+e^- -> Z γ : Z boosted by $\beta \approx 0.76$

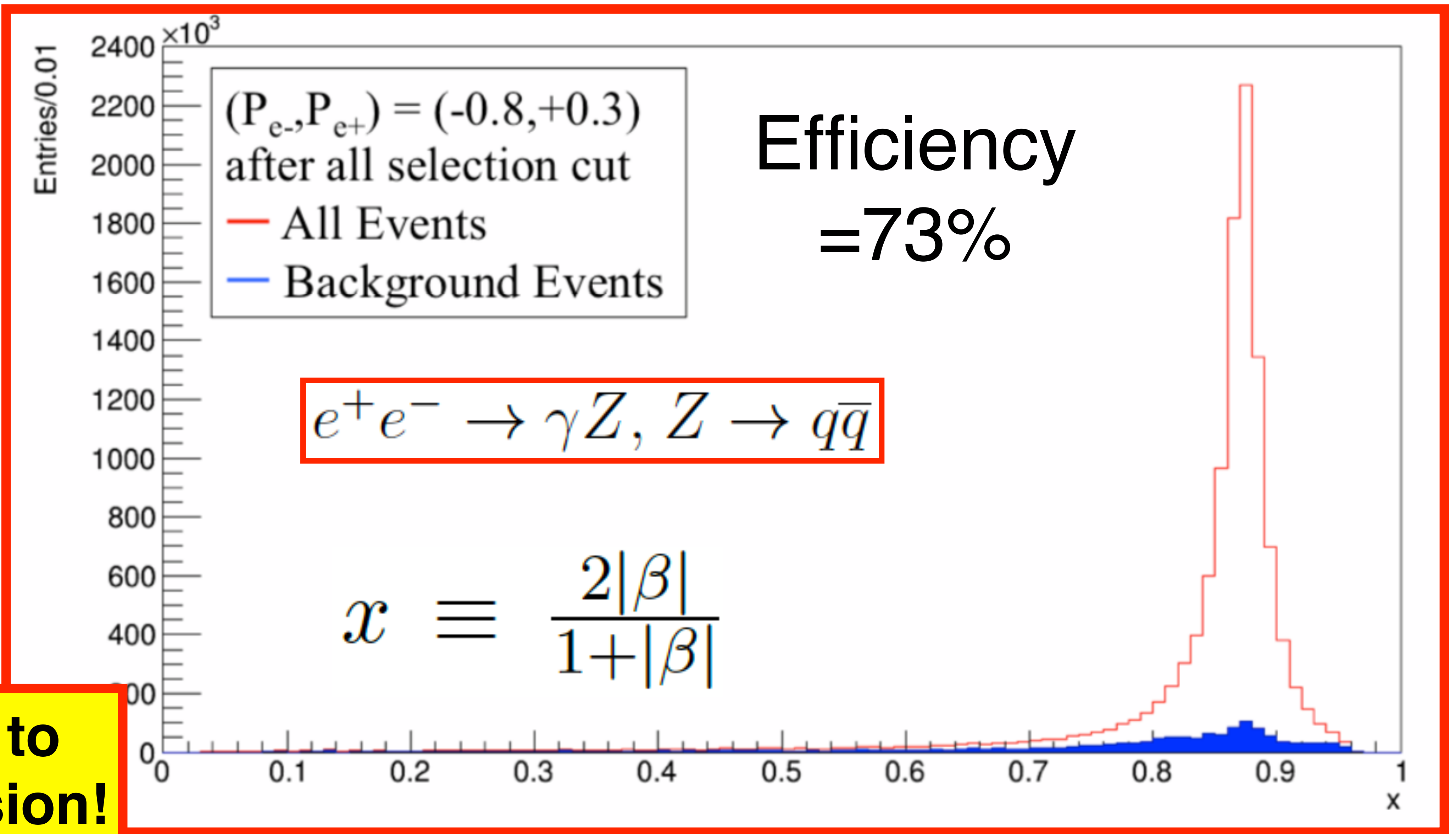
$$|\beta| = \frac{|E_1\cos\theta_1 + E_2\cos\theta_2|}{E_1+E_2} = \frac{|\sin(\theta_1+\theta_2)|}{\sin\theta_1+\sin\theta_2}$$

$$m_{12}^2 = \frac{1-|\beta|}{1+|\beta|}\cdot s$$

=> reconstruct from angles only!
=> clean sample with high efficiency

- Polarised beams: $A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L+\sigma_R)}$
=> rel. stat.: $\delta A_e = 9.5\times10^{-4}$
dom. syst. from polarisation: 3×10^{-4}

P(e^+) essential to reach this precision!



- factor 10 improvement over current value “for free”! => ~12% improvement on g_{HZZ}

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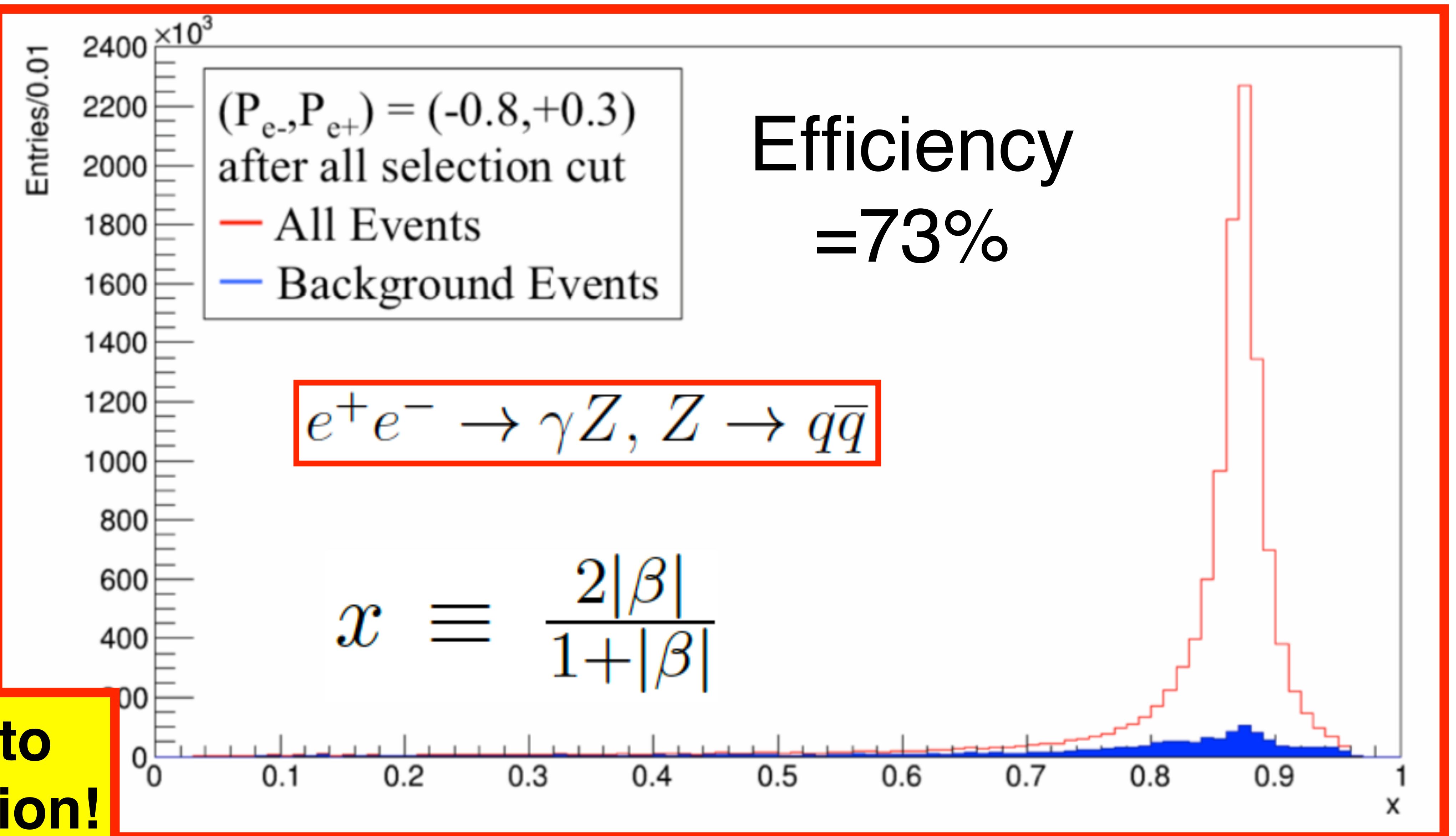

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Important:

- **Near √s =M$_Z$,** $A_{obs} = A_e + \Delta A$ has strong dependence on √s due to Z-γ interference
=> requires excellent knowledge of √s!
- **At √s =250 GeV**, this dependence is at least 1000 x weaker! => not an issue…

Precision EW at the GigaZ

- ~250 x LEP, with beam polarisation => expect at least factor 10 improvement!
- Measure A_e via A_{LR} as before - **now crucial:** knowledge of $\sqrt{s}$!
  - Exploit excellent momentum measurement of ILD (or SiD)
  - calibrate with $J/\psi \to \mu^+\mu^-$
    => **obtain $\sqrt{s}$** from $\mu^+\mu^-\gamma$ events **to 1 MeV precision => $\delta A_e(\sqrt{s})$=2 x 10^{-5}**, comparable to stat. error.
    => final number dominated by polarisation uncertainty
- Fermion asymmetries for μ / τ /c /b: **new, detailed ILD studies in 2019 -** profit from
  - **tiny ILC beam spot (@91.2 GeV): 1.12 μm x 14.6 nm x 410 μm**
  - large statistics & excellent detector => **use double-tagged events only for q /anti-q separation!**

=> drastic reduction of systematic uncertainties wrt LEP

Accelerator - arXiv:1908.08212

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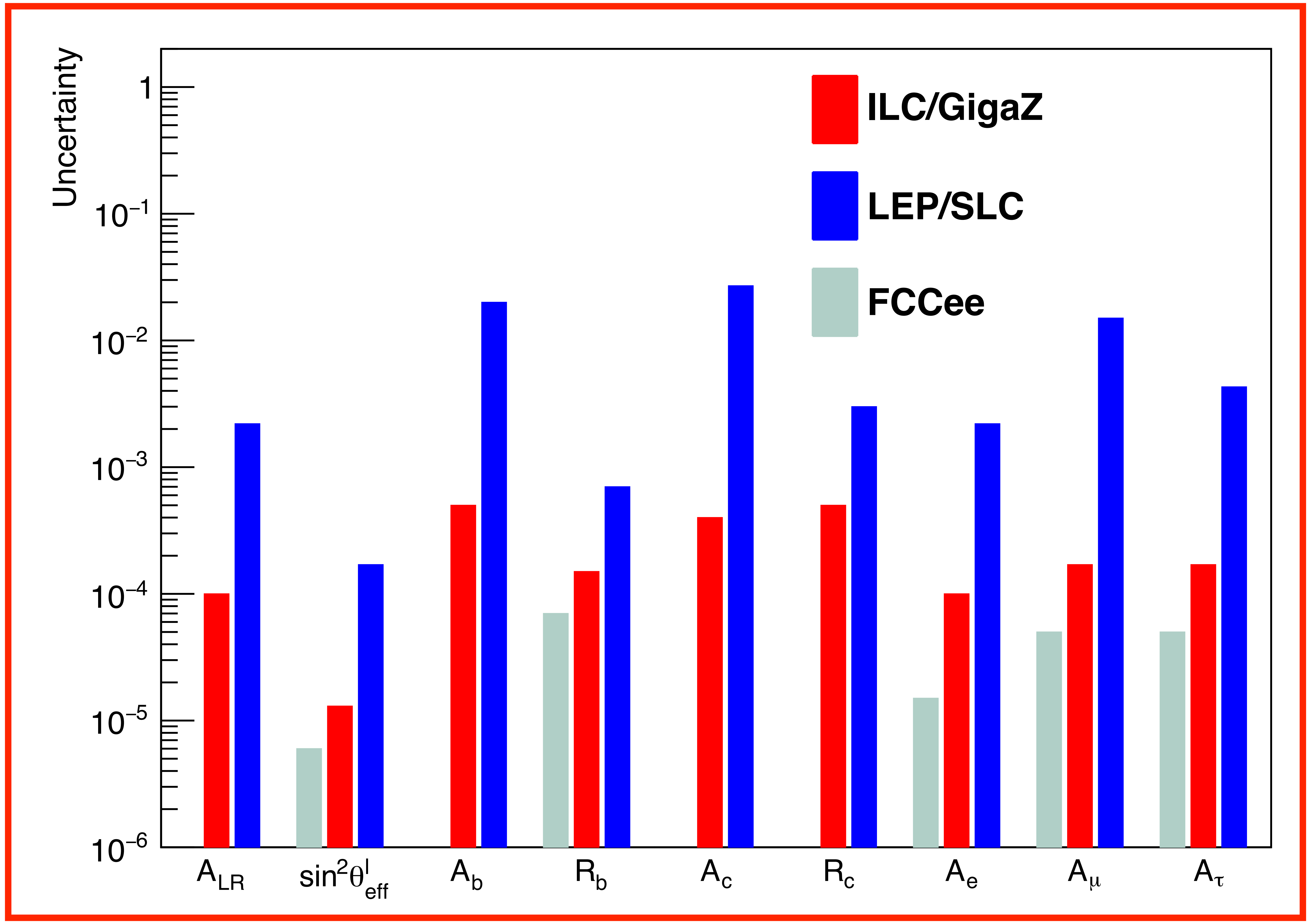
In particular: hemisphere correlations found negligible! (Geant4-based detector simulation)

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

GigaZ: results of new detailed ILD studies

- as expected, at least factor 10 improvement over LEP/SLC
- note in particular:
  - **A_c nearly 100 x better** thanks to excellent charm / anti-charm tagging:
    - excellent vertex detector
    - tiny ILC beam spot
    - Kaon-ID via dE/dx in ILD's TPC
- typically only factor 2-3 less precise than FCCee's unpolarised *TeraZ*



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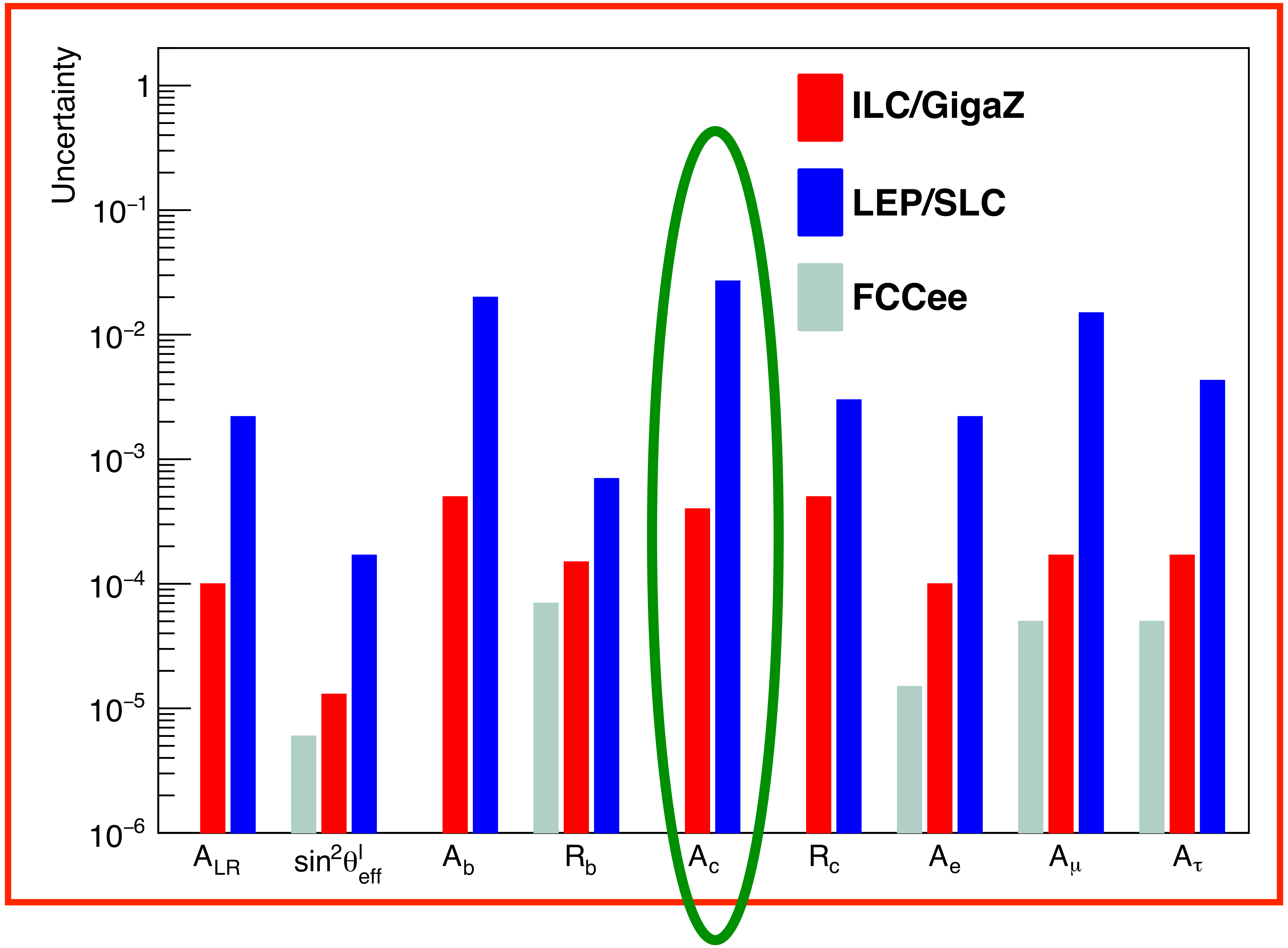


Conclusions

- **Electroweak observables are an important part of the physics case of future e^+e^- colliders**
- ILC offers significant progress over LEP already at 250 GeV
- Even more improvement from dedicated Z pole running
- Beam polarisation boosts "return on invested ab^{-1}"
- ILC GigaZ program has been scrutinized, again, in summer 2019 following discussions in Granada => results are now included in SMEFT fits by the ECFA WG on HiggsCouplings@ Future Colliders for the Briefing Book of the European Strategy Update!
- Tiny ILC beam spot leverages excellent 2ndary vertex resolution
- Kaon identification via dE/dx in ILD TPC enhances b- and c-charge separation
- **ILC offers a very attractive and competitive electroweak precision program!**

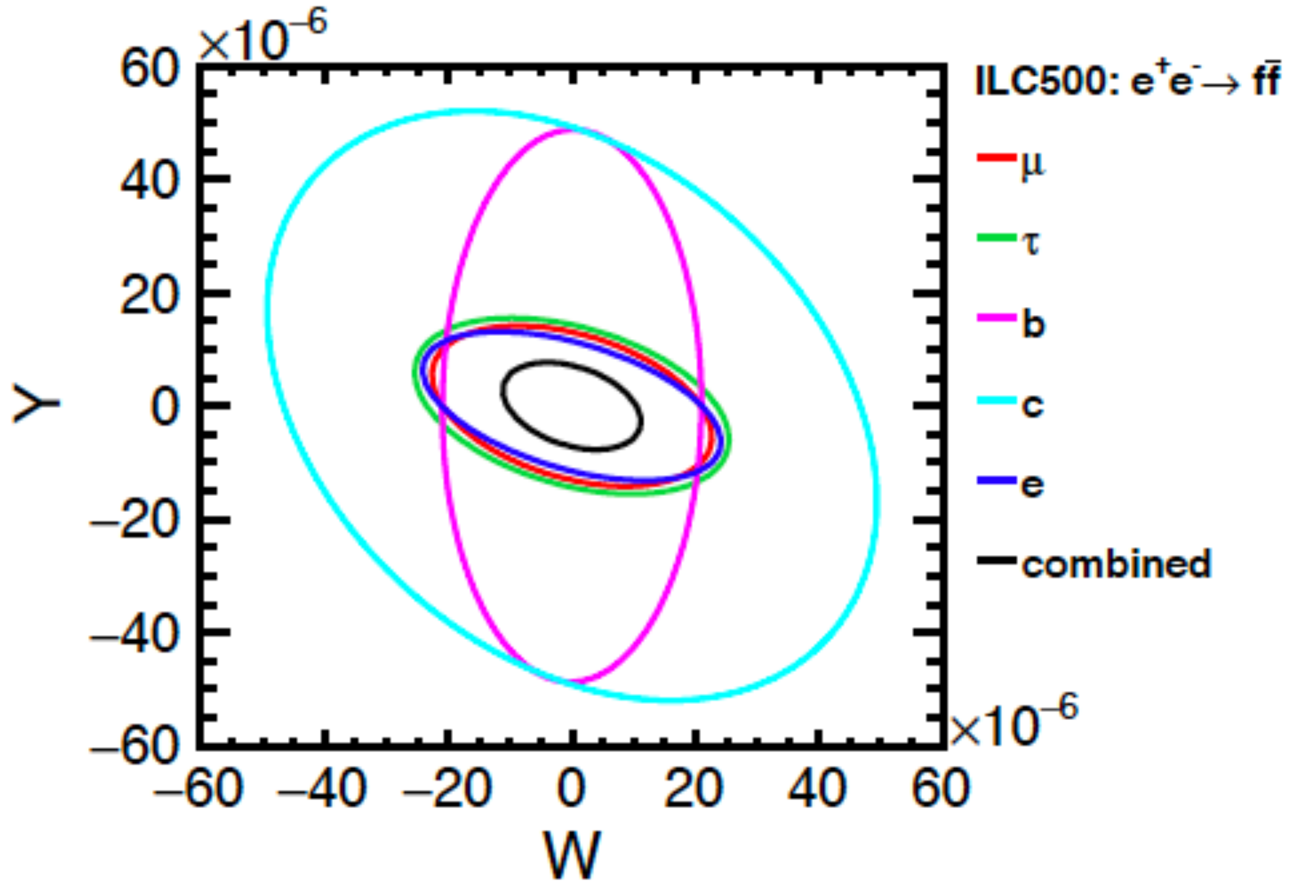
Backup

4-Fermion Processes

$\sqrt{s}$	Λ_{LL}	Λ_{RR}	Λ_{VV}	Λ_{AA}
universal Λ's				
ILC250	108	106	161	139
ILC500	189	185	280	240
ILC1000	323	314	478	403
$e^+e^- \to e^+e^-$				
ILC250	71	70	118	71
ILC500	114	132	214	135
ILC1000	236	232	376	231
$e^+e^- \to \mu^+\mu^-$				
ILC250	80	79	117	104
ILC500	134	133	198	177
ILC1000	224	222	332	296
$e^+e^- \to \tau^+\tau^-$				
ILC250	72	72	109	97
ILC500	127	126	190	168
ILC1000	215	214	321	286
$e^+e^- \to b\bar{b}$				
ILC250	78	73	103	106
ILC500	134	124	175	178
ILC1000	226	205	292	296
$e^+e^- \to c\bar{c}$				
ILC250	51	52	75	68
ILC500	90	90	130	117
ILC1000	153	151	220	199

Model	250 GeV, excl.	2 ab^{-1} disc.	500 GeV, excl.	4 ab^{-1} disc.	1 TeV, excl.	8 ab^{-1} disc.
SSM	7.8	4.9	13	8.4	22	14
ALR	9.5	6.0	17	11	25	18
χ	7.0	4.5	12	7.8	21	13
ψ	3.7	2.4	6.4	4.1	11	6.8
η	4.2	2.7	7.3	4.6	12	7.9

$\sqrt{s}$	ΔW	ΔY	ρ
HL-LHC	15×10^{-5}	20×10^{-5}	-0.97
ILC250	3.4×10^{-5}	2.4×10^{-5}	-0.34
ILC500	1.1×10^{-5}	0.78×10^{-5}	-0.35
ILC1000	0.39×10^{-5}	0.27×10^{-5}	-0.38
500 GeV, no beam pol.	2.0×10^{-5}	1.2×10^{-5}	-0.78

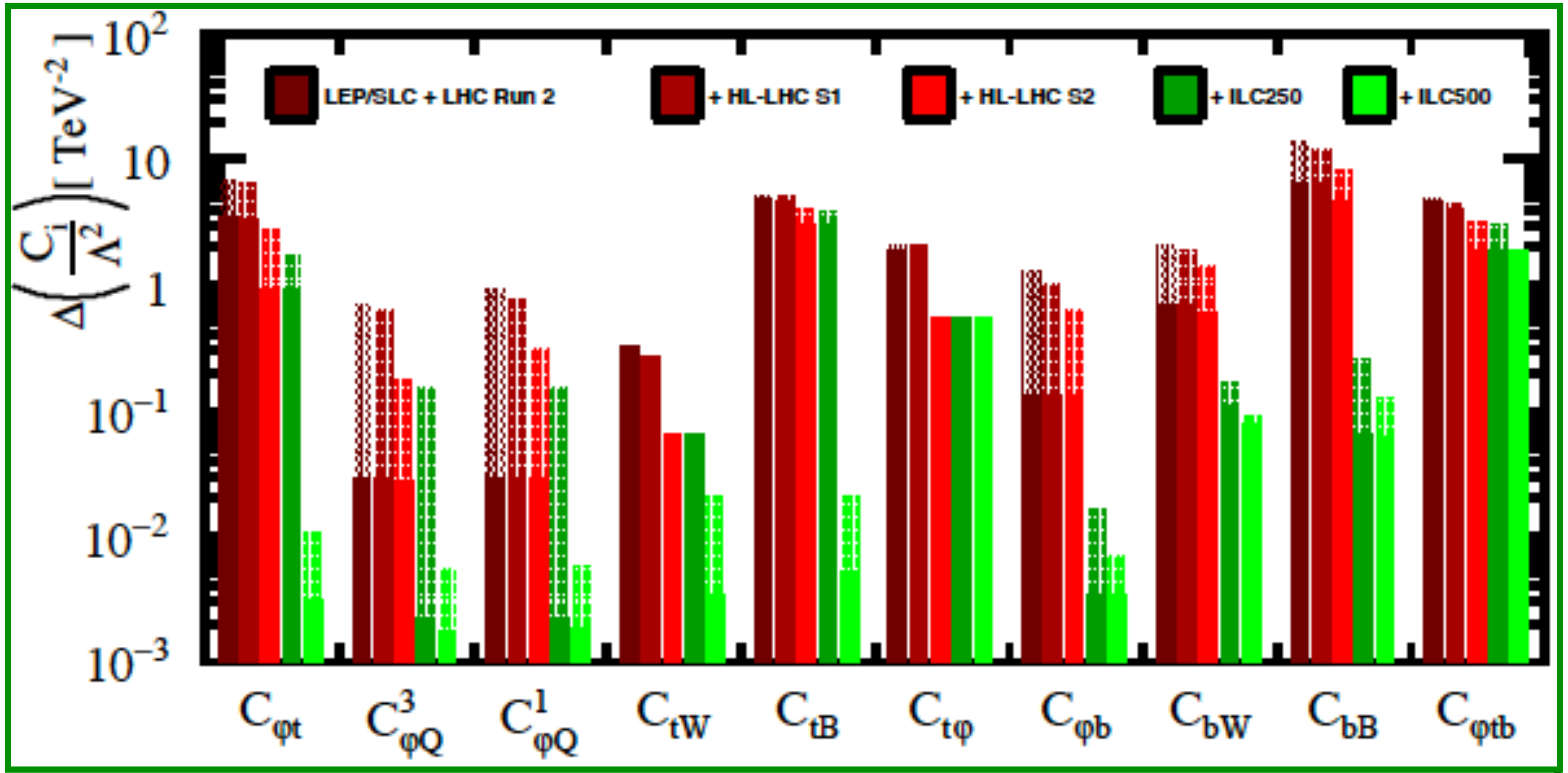


Outlook to higher energies: top / bottom EFT

- Fit of 10 Wilson coefficients of SMEFT that modify top and bottom production

arXiv:1907.10619

- Already e^+e^- -> bb at ILC250 helps a lot
- ILC500 with e^+e^- -> tt even more so!



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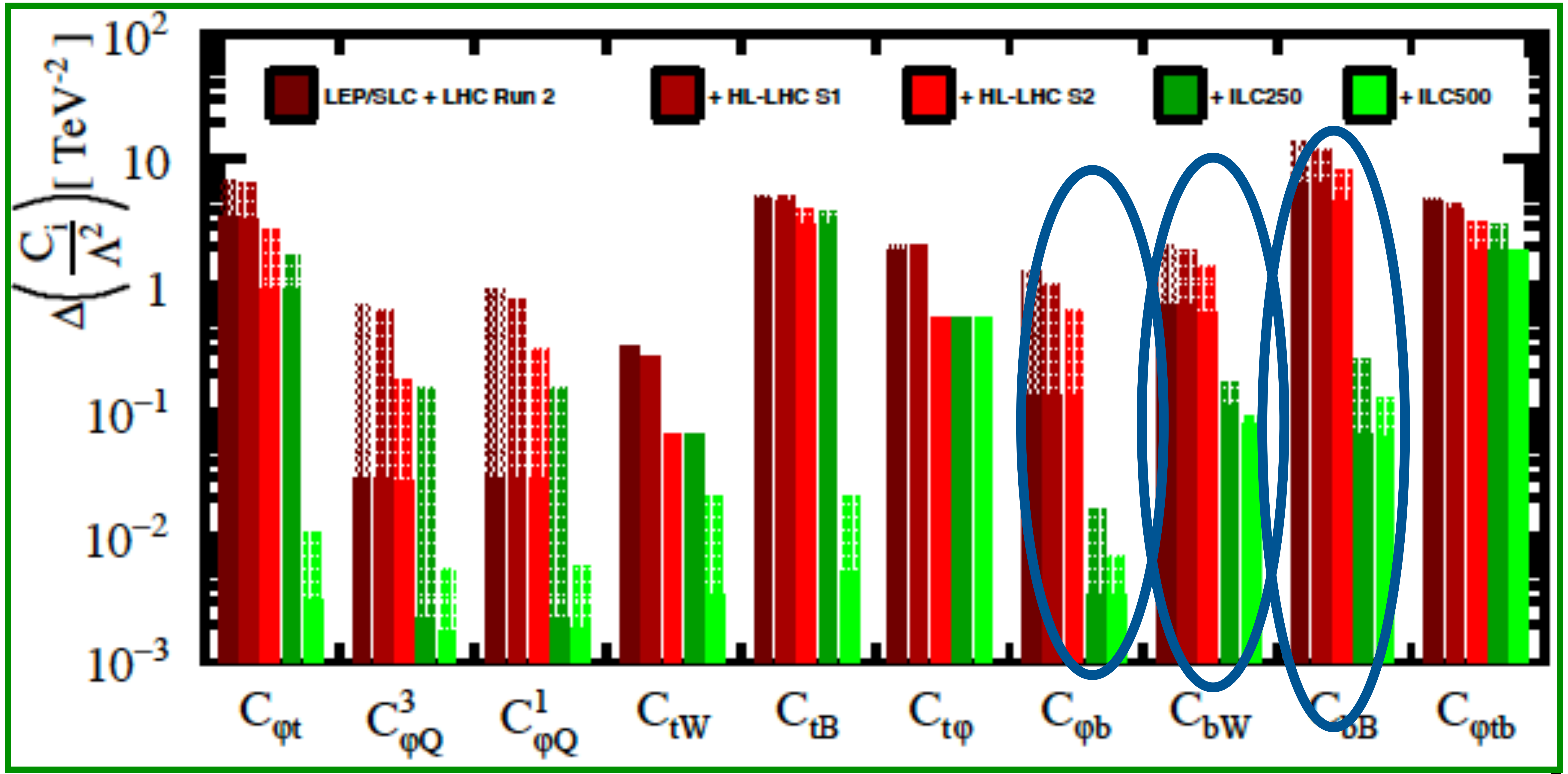

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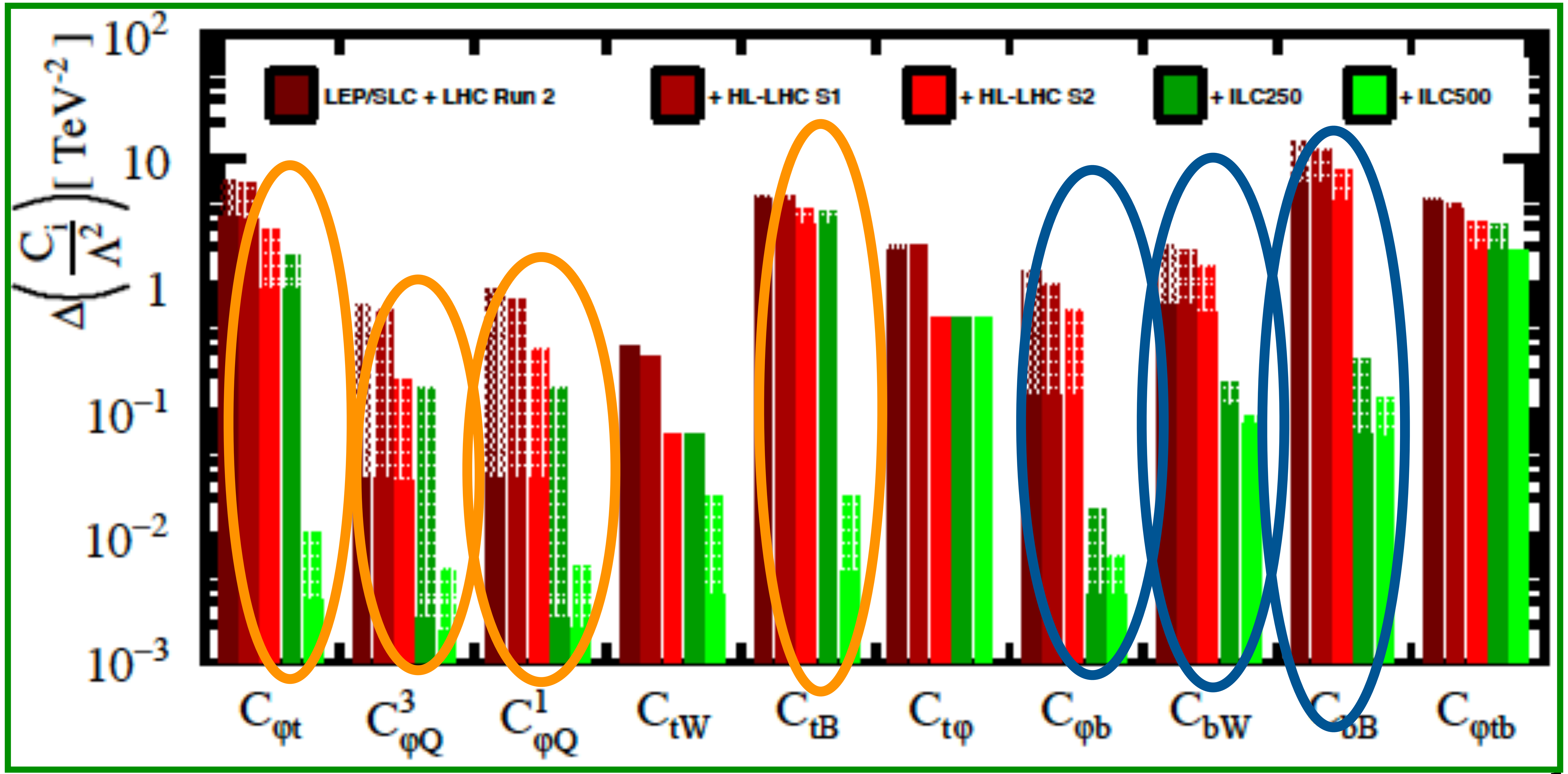
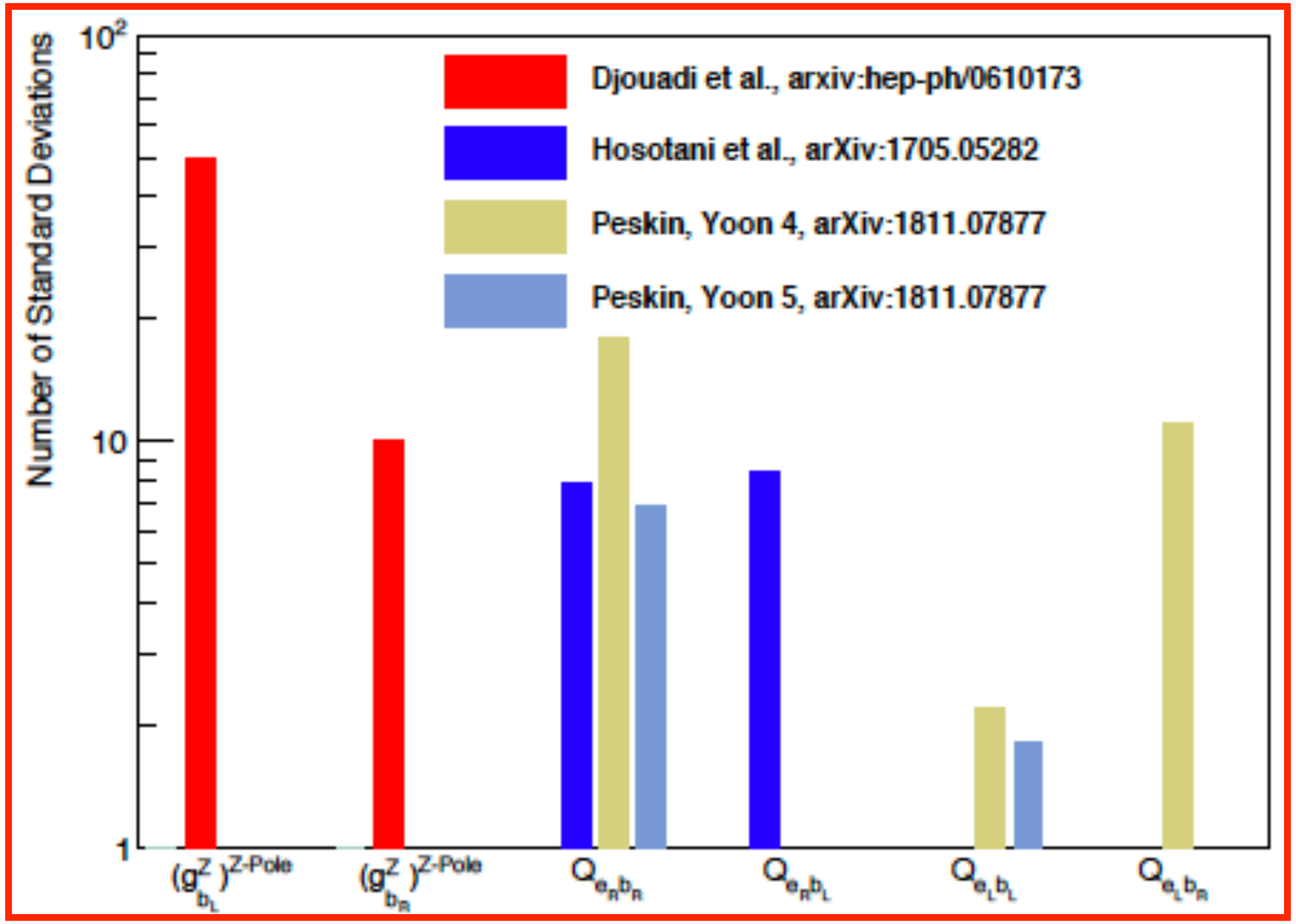


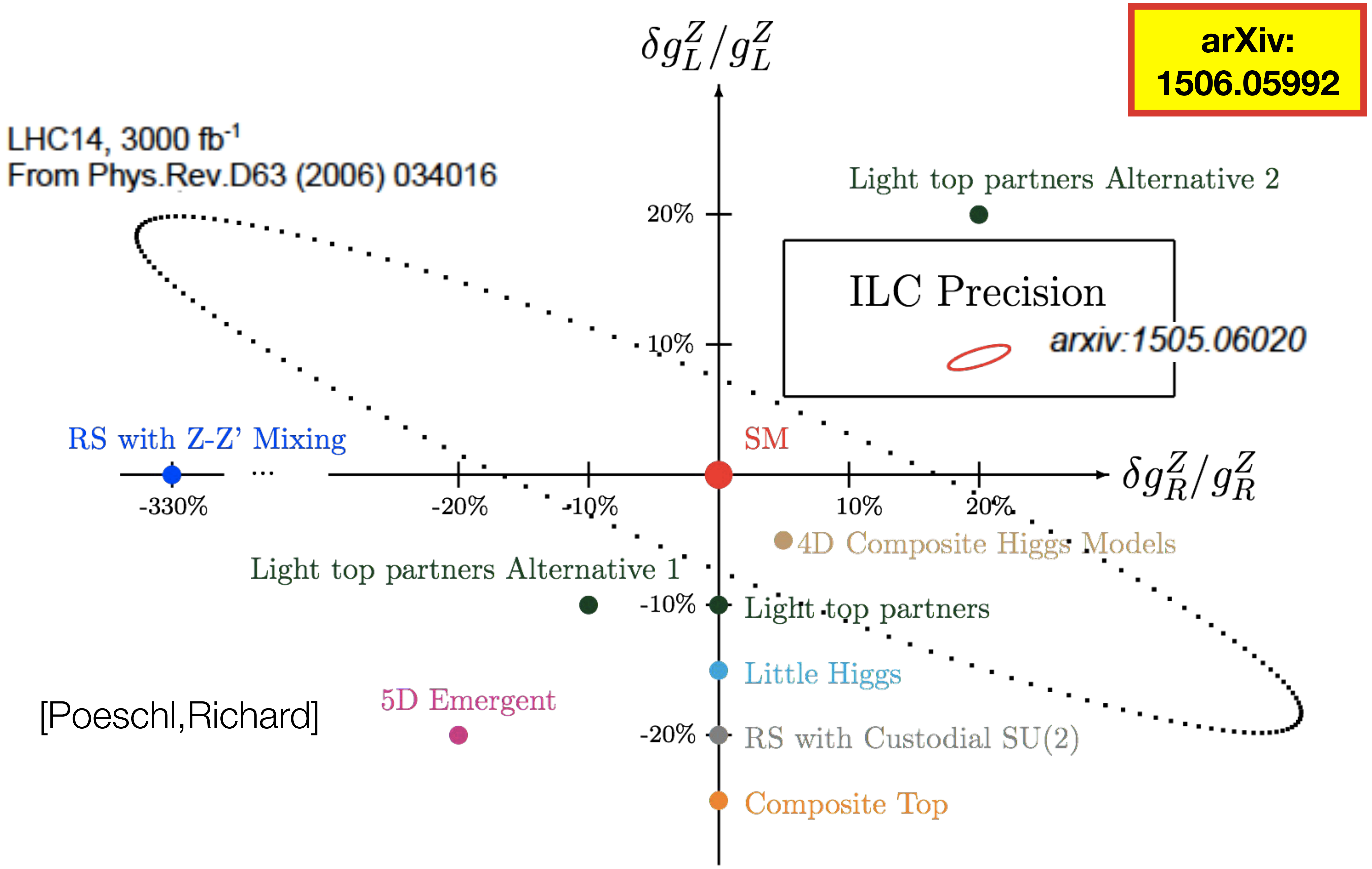
BSM significances



Measurements of the beam parameters

- Beam polarisation
- Beam energy
- Luminosity

New Properties of the Top Quark



Sensitivity to huge variety of models with **compositeness and/or extra-dimensions** complementary to resonance searches

- **ILC precision allows model discrimination**
- **sensitivity in g^Z_L, g^Z_R plane complementary to LHC**

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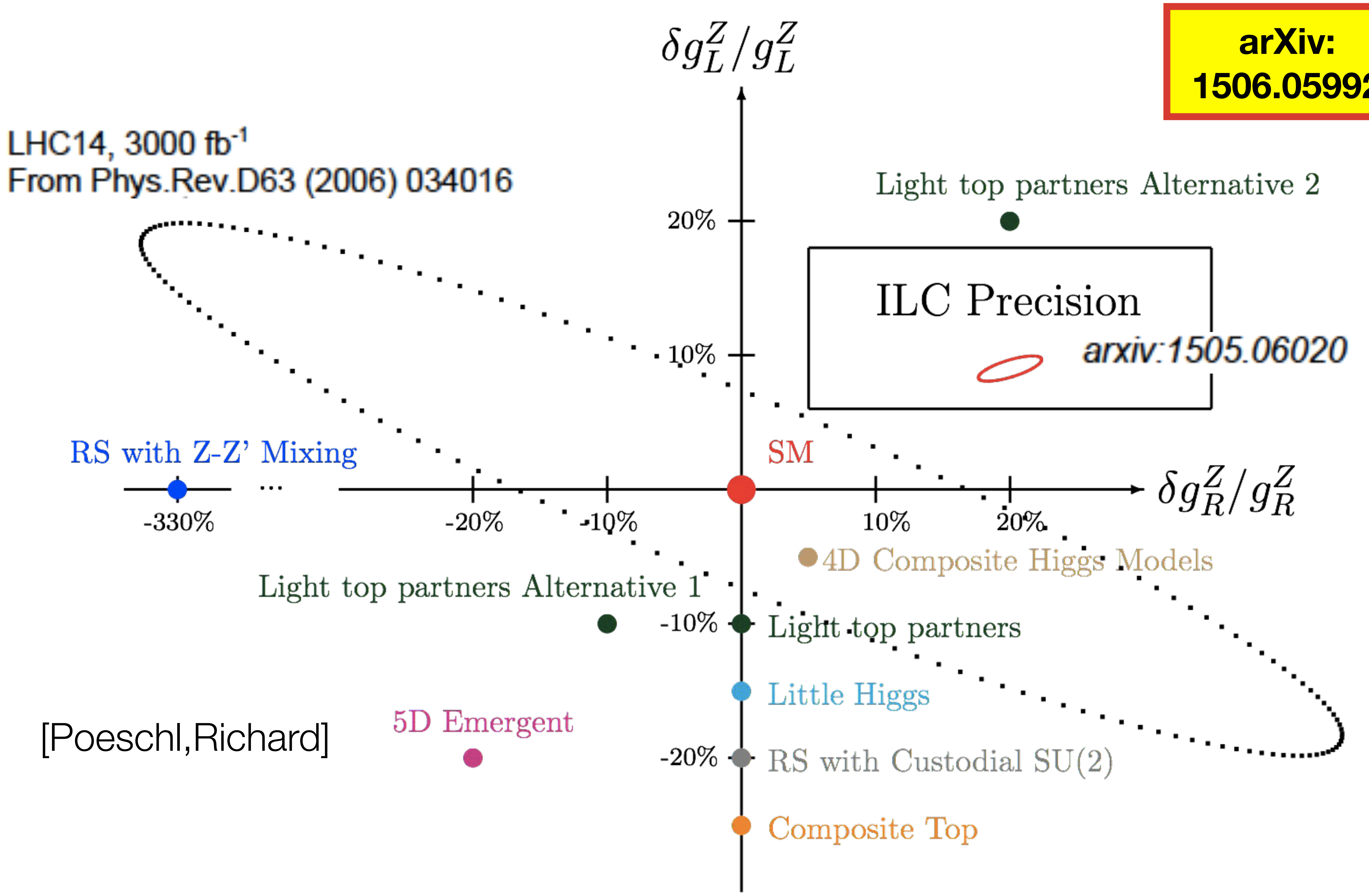

arXiv: 1506.05992

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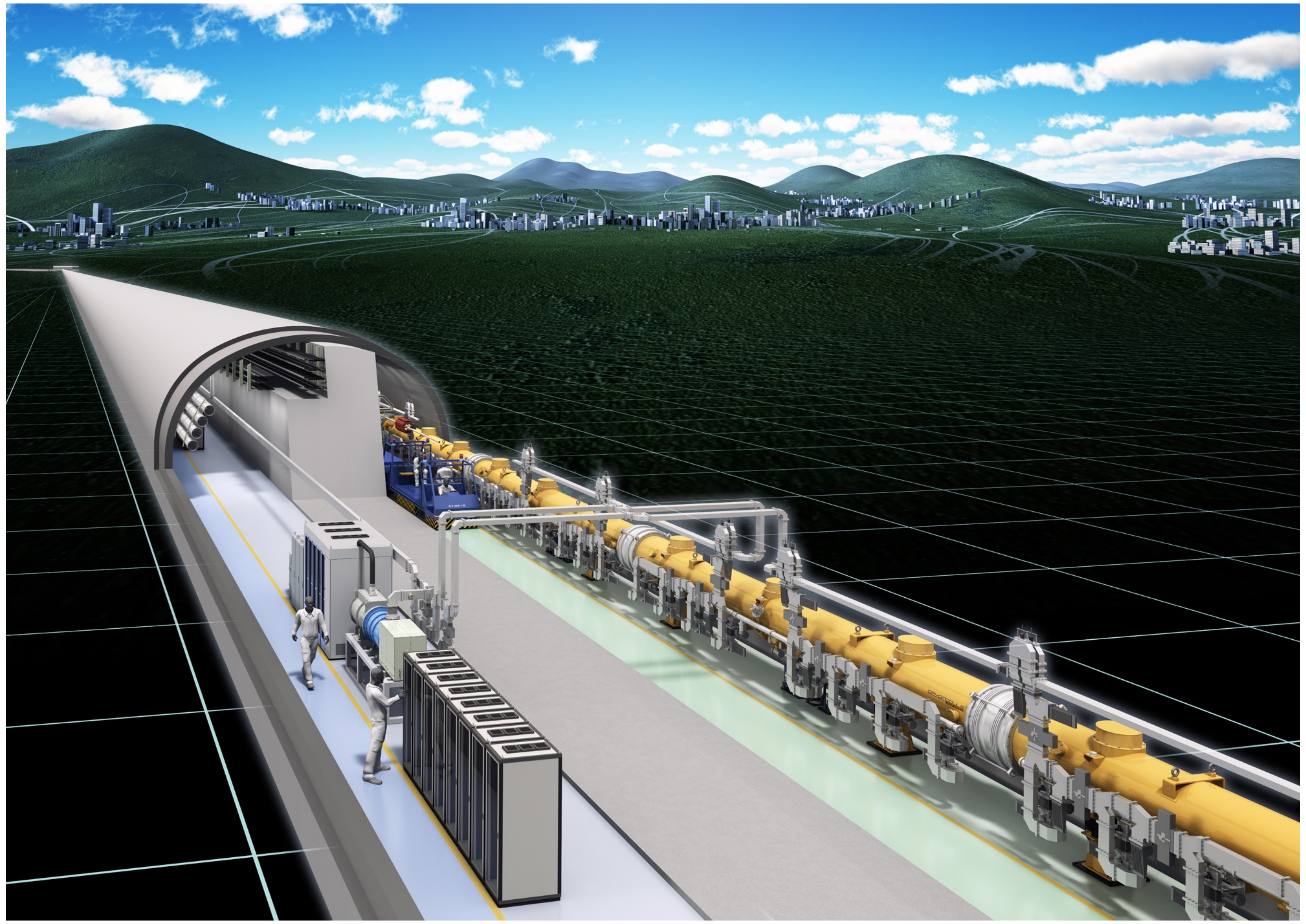
Also from other e^+e^- -> ff:

- probe Z' up to ~10 TeV 500fb^{-1} @ 500 GeV (initial run)
- up to ~17 TeV for 1ab^{-1} at 1 TeV
- polarised beams gain ~ 2TeV in reach

The International Linear Collider

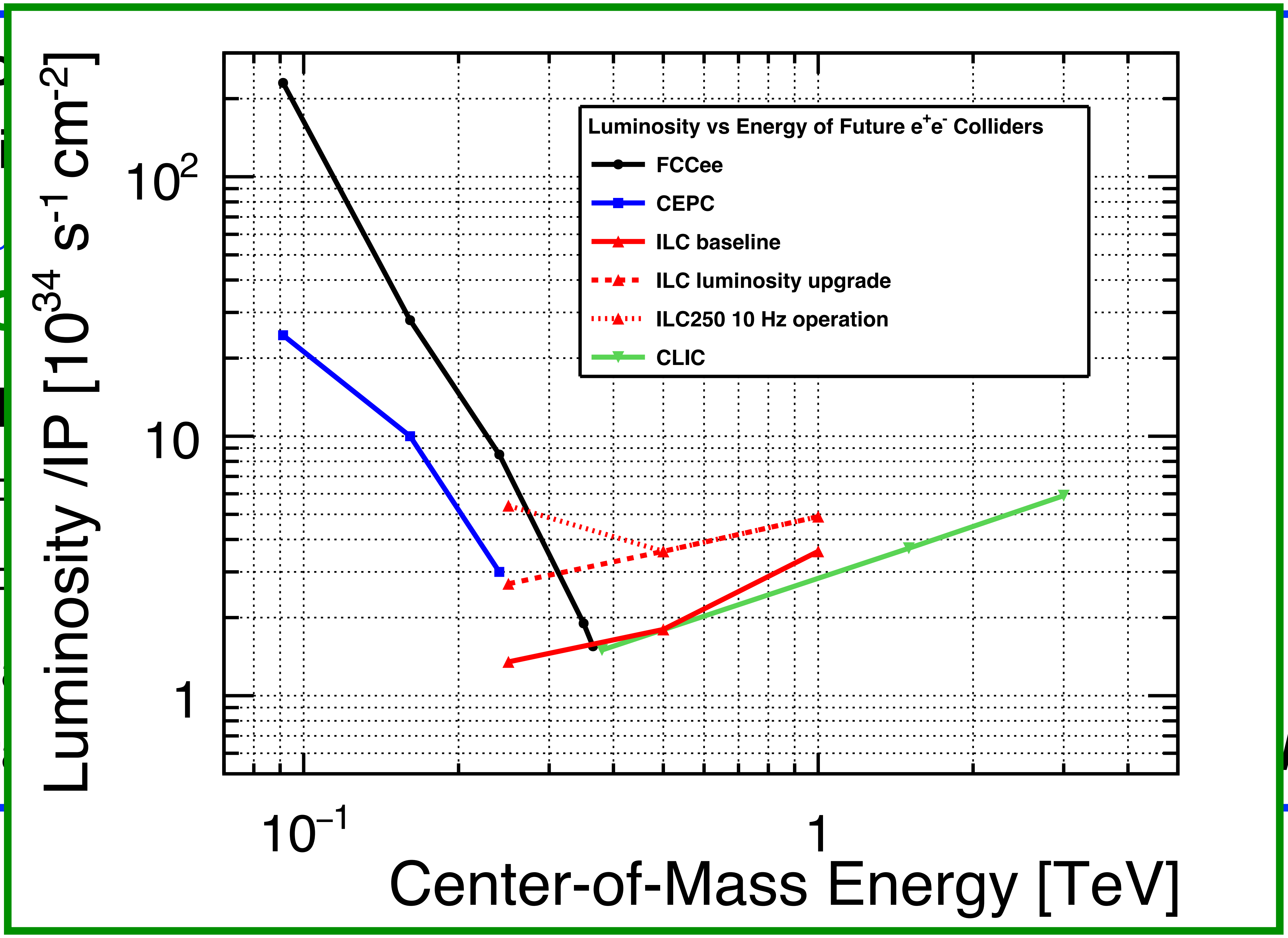
- **proposed e^+e^- collider**
  - first stage: 250 GeV
  - upgrades: 500 GeV, 1 TeV
  - **GigaZ & WW threshold possible**
- **polarised beams**
  - $P(e^-) \geq \pm 80\%$,
  - $P(e^+) = \pm 30\%$, at 500 GeV upgradable to 60%
- **total length (250**/500/1000 **GeV): 20.5**/34/50 **km**
- **total site power (250**/500/1000 **GeV): 130**/160/300 **MW**

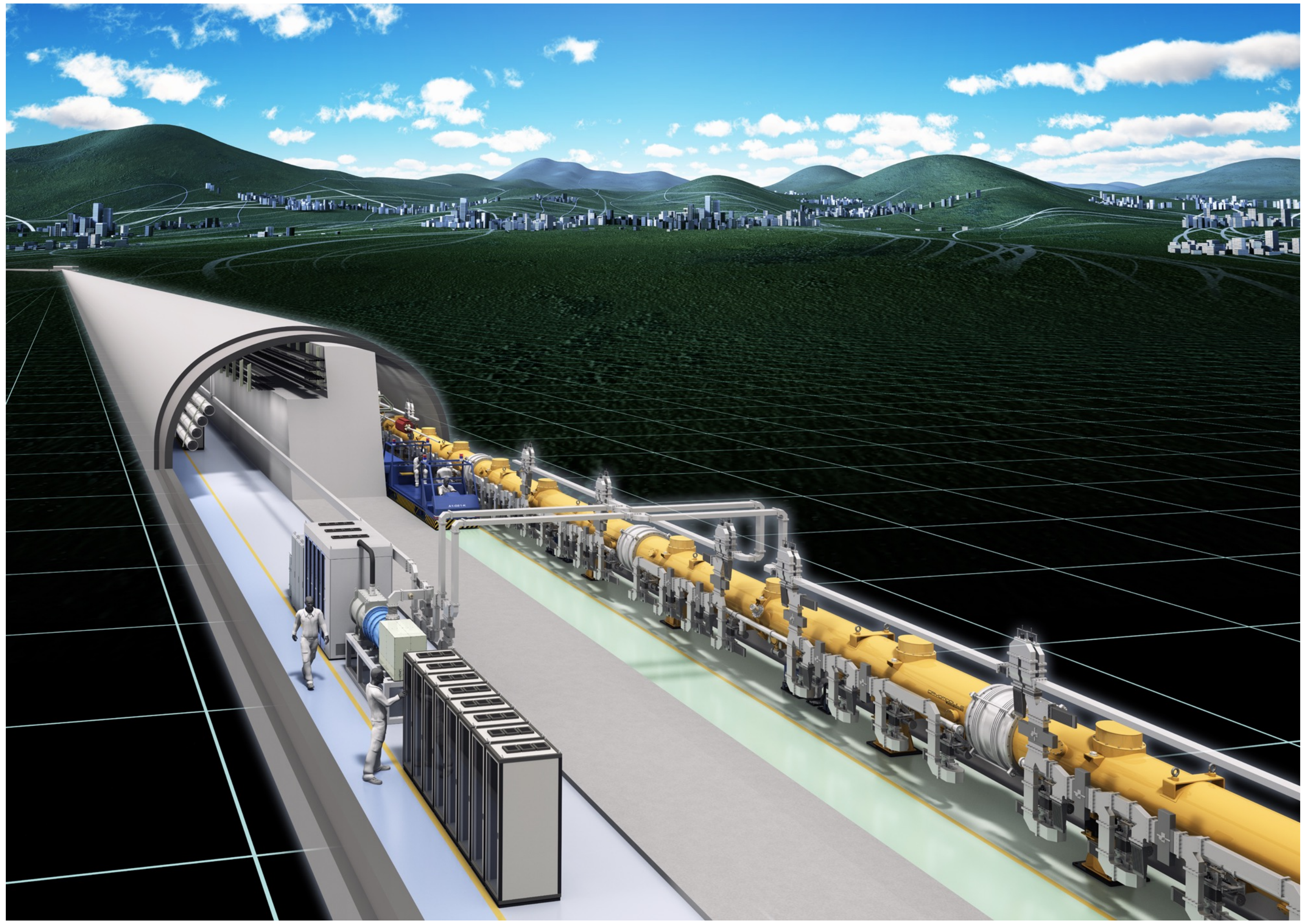


TDR published in 2012
Ready to be built
ILC250 under *political* consideration in Japan

The International Linear Collider

- **pro**
  - fi
  - u
  - C
- **pol**
  - P
  - P
- **tot**
- **tot**





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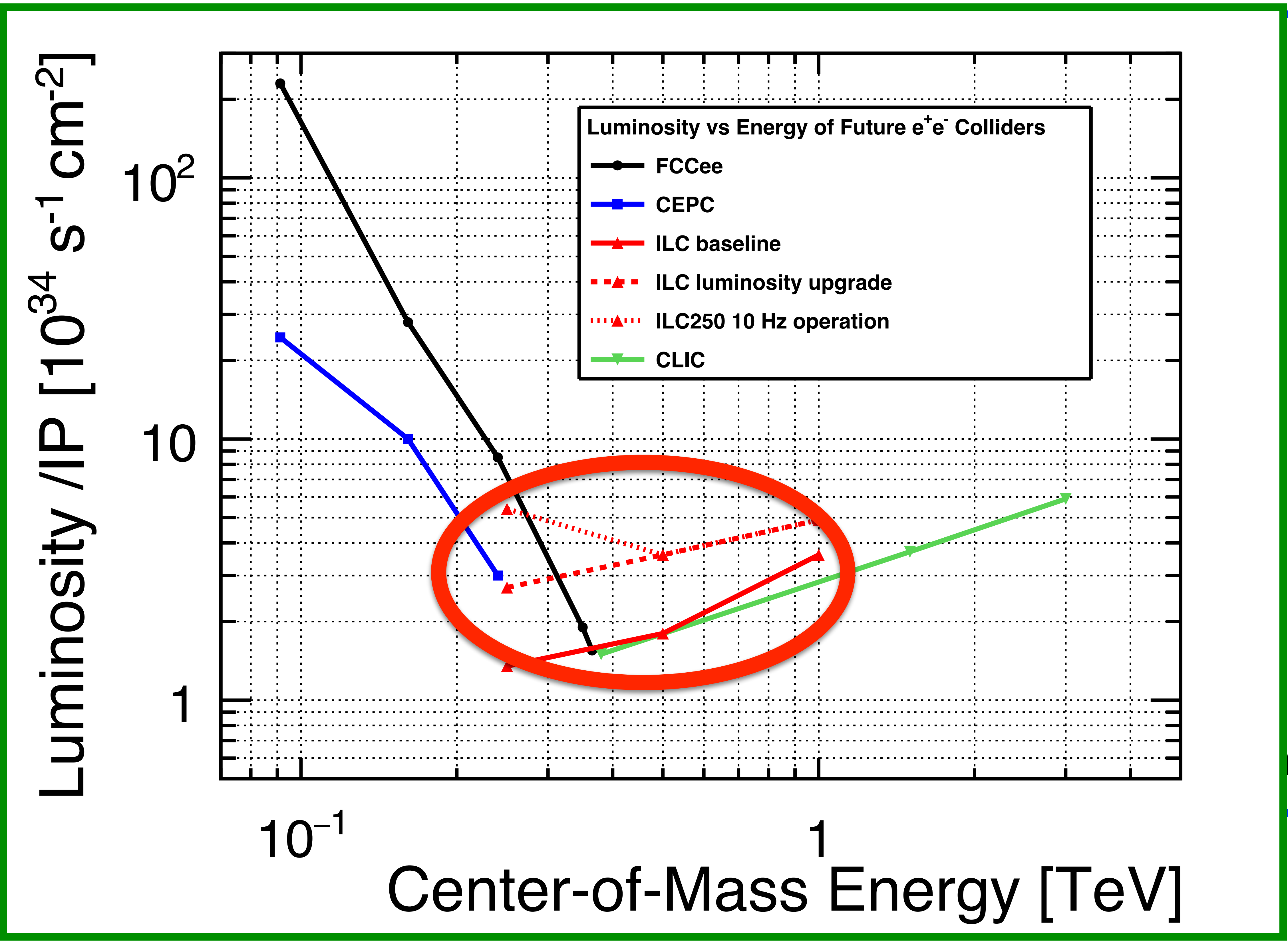
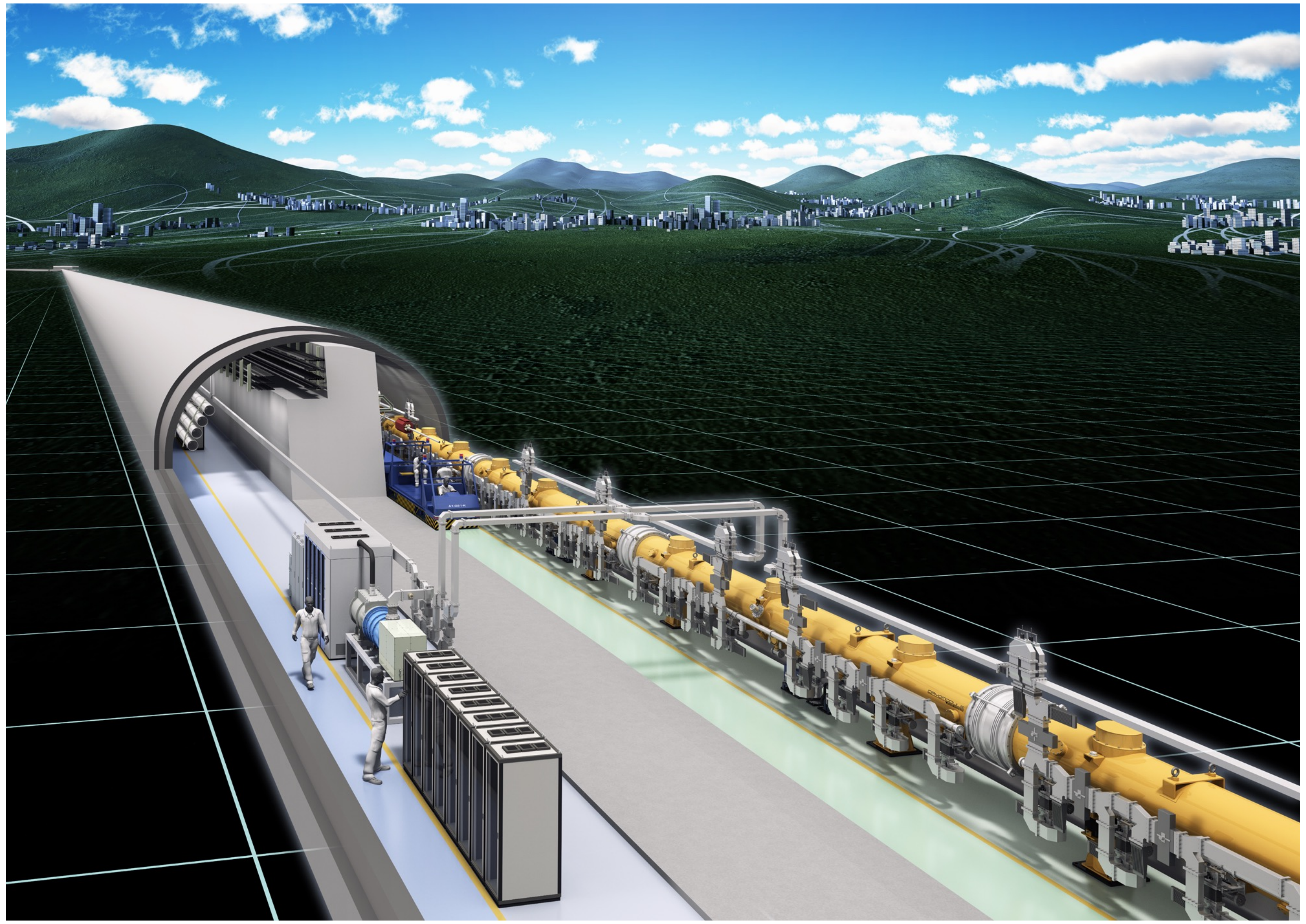
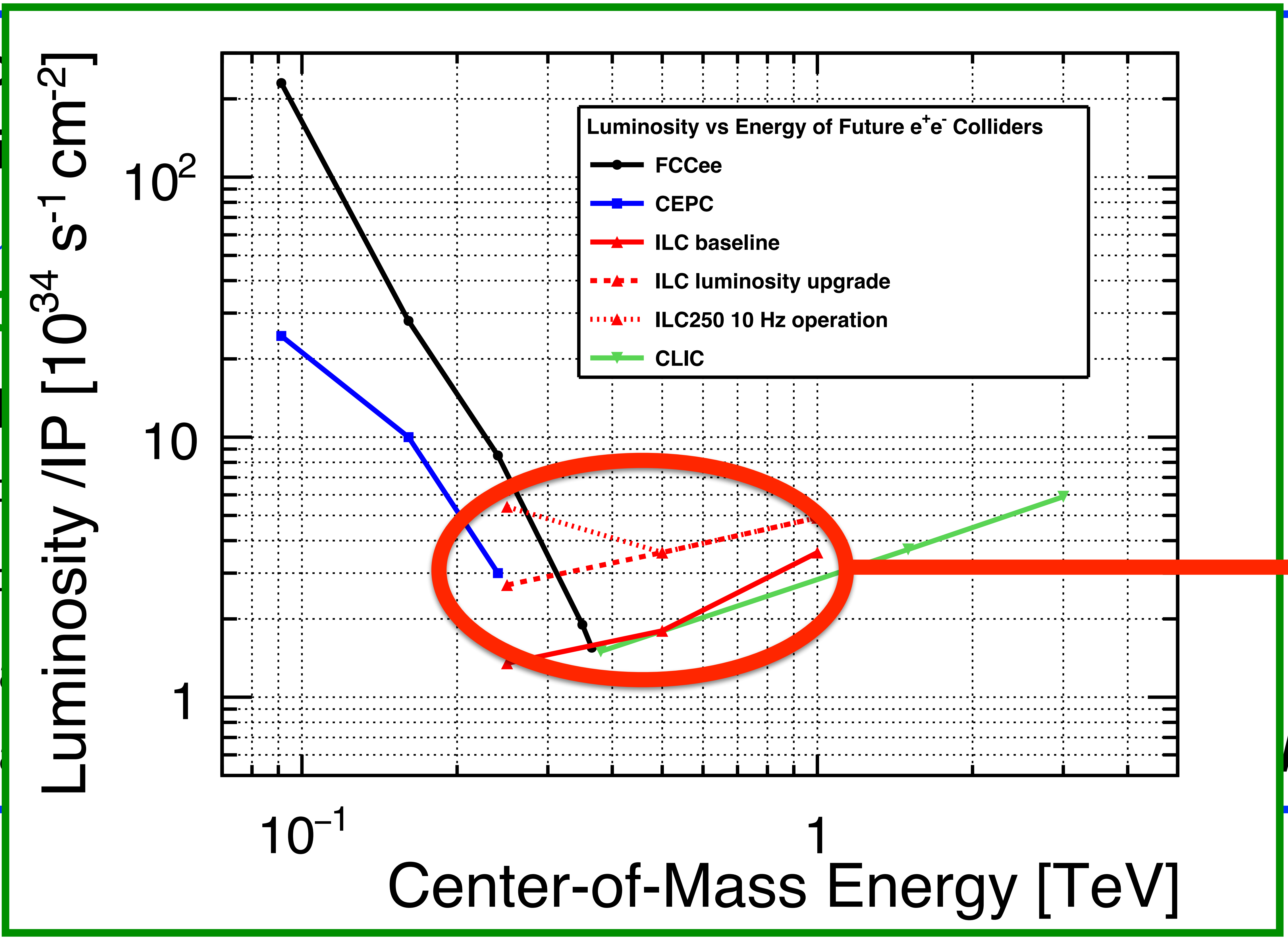
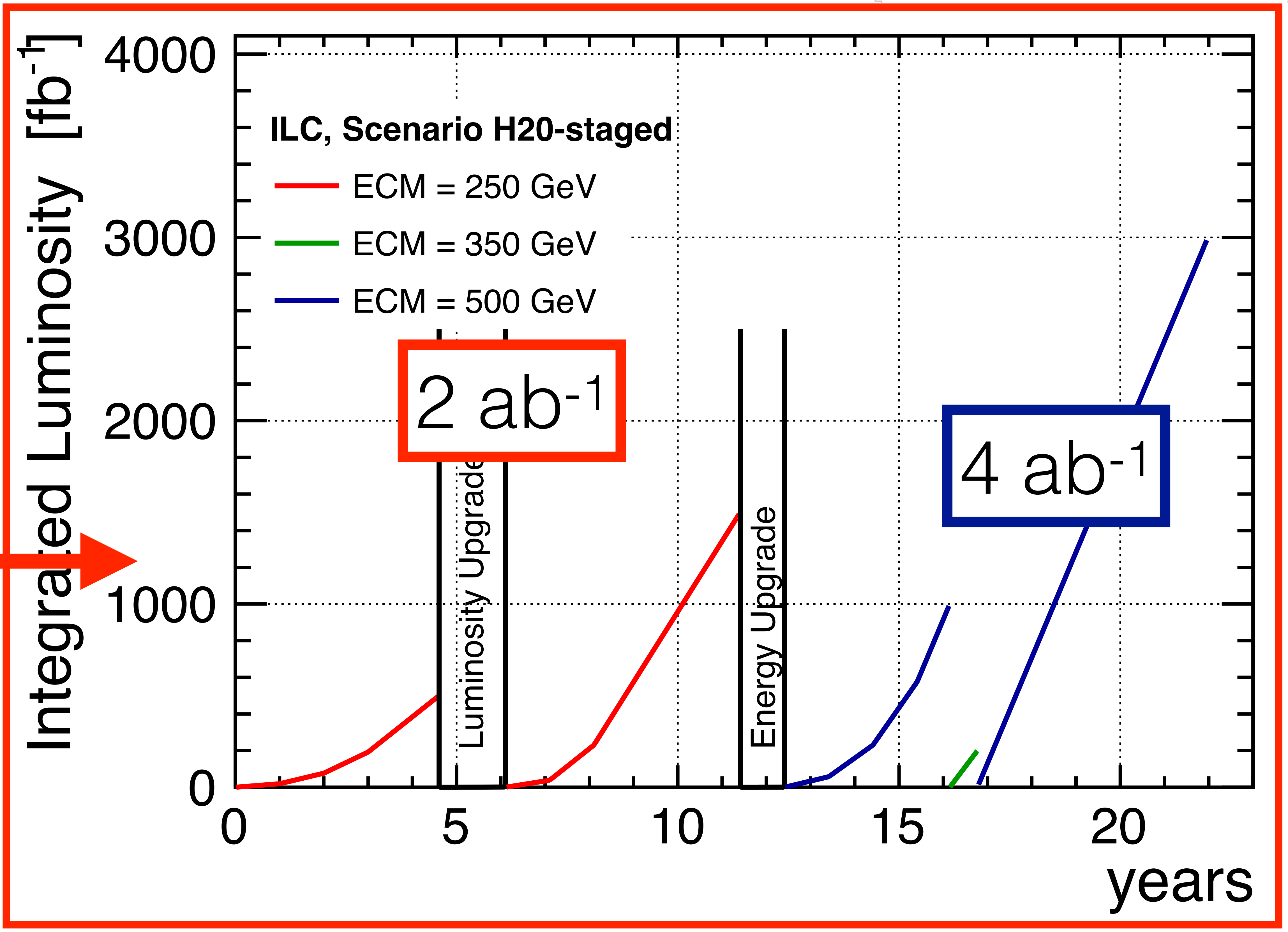




<u>TDR</u> published in 2012
Ready to be built
ILC250 under *political* consideration in Japan

The International Linear Collider





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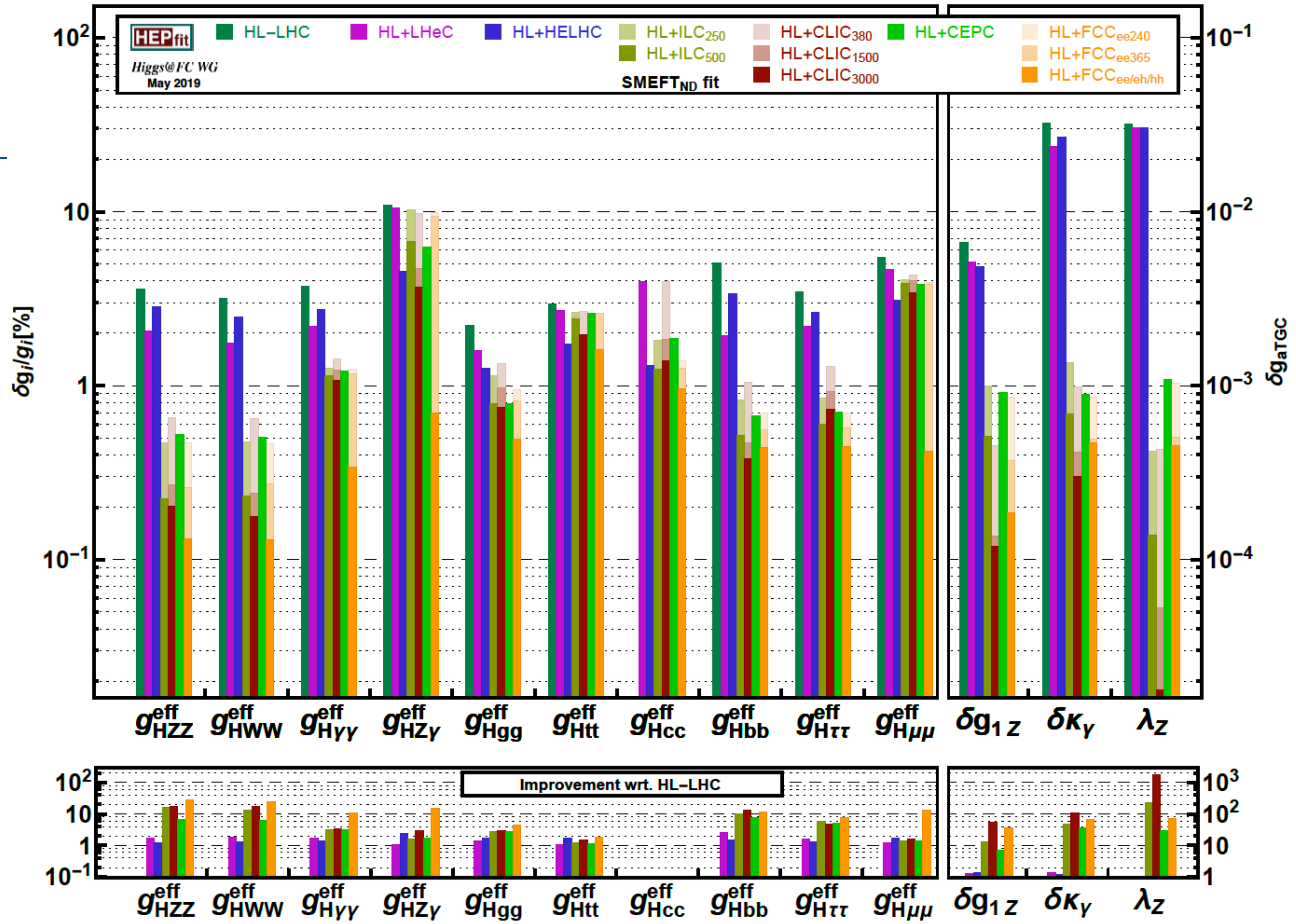
GigaZ events

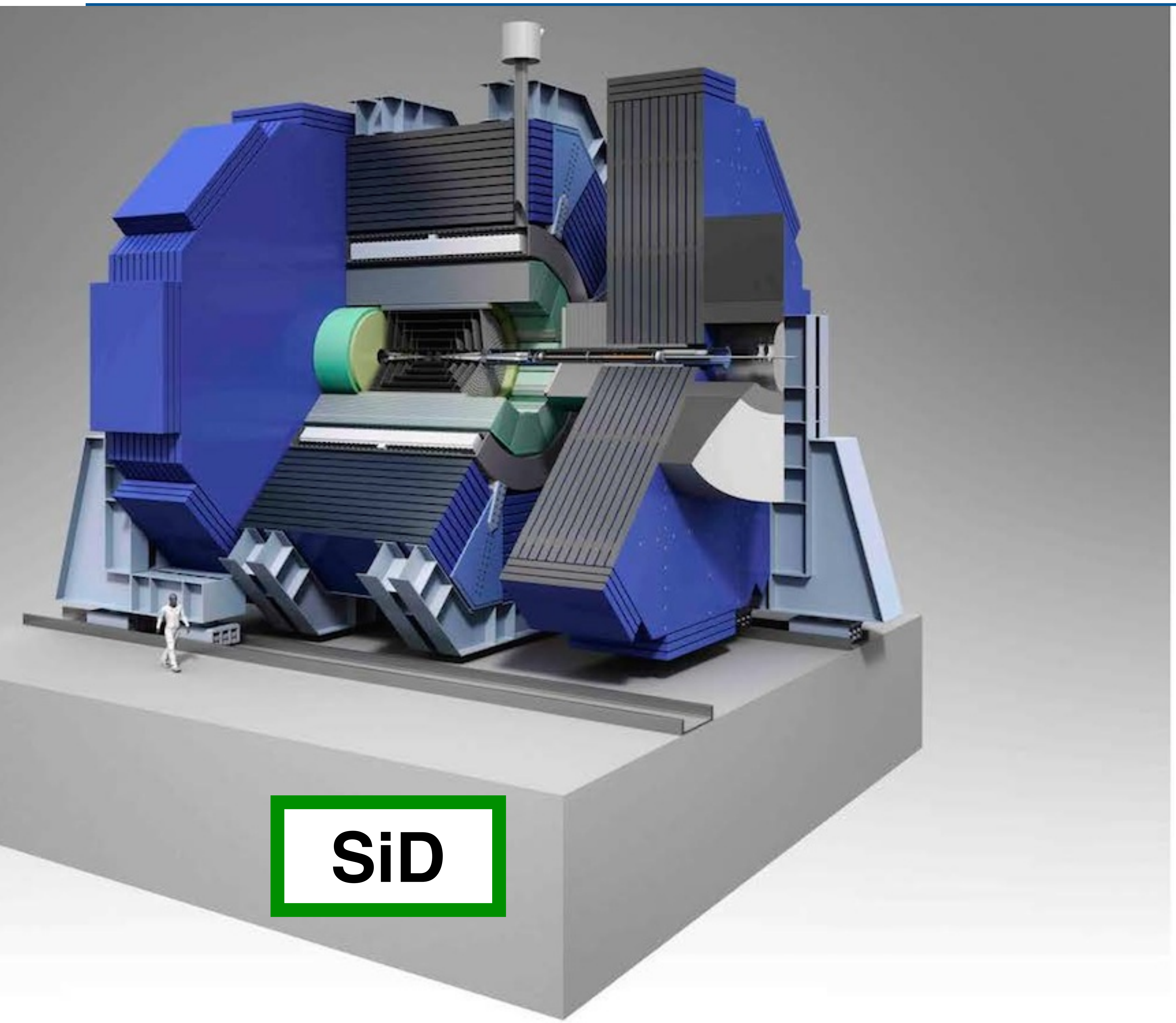
	sign($P(e^-), P(e^+)$) =				
	$(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	sum
luminosity [fb^{-1}]	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	60.4	46.1	35.9	29.4	
Z events [10^9]	2.4	1.8	0.36	0.29	4.9
hadronic Z events [10^9]	1.7	1.3	0.25	0.21	3.4

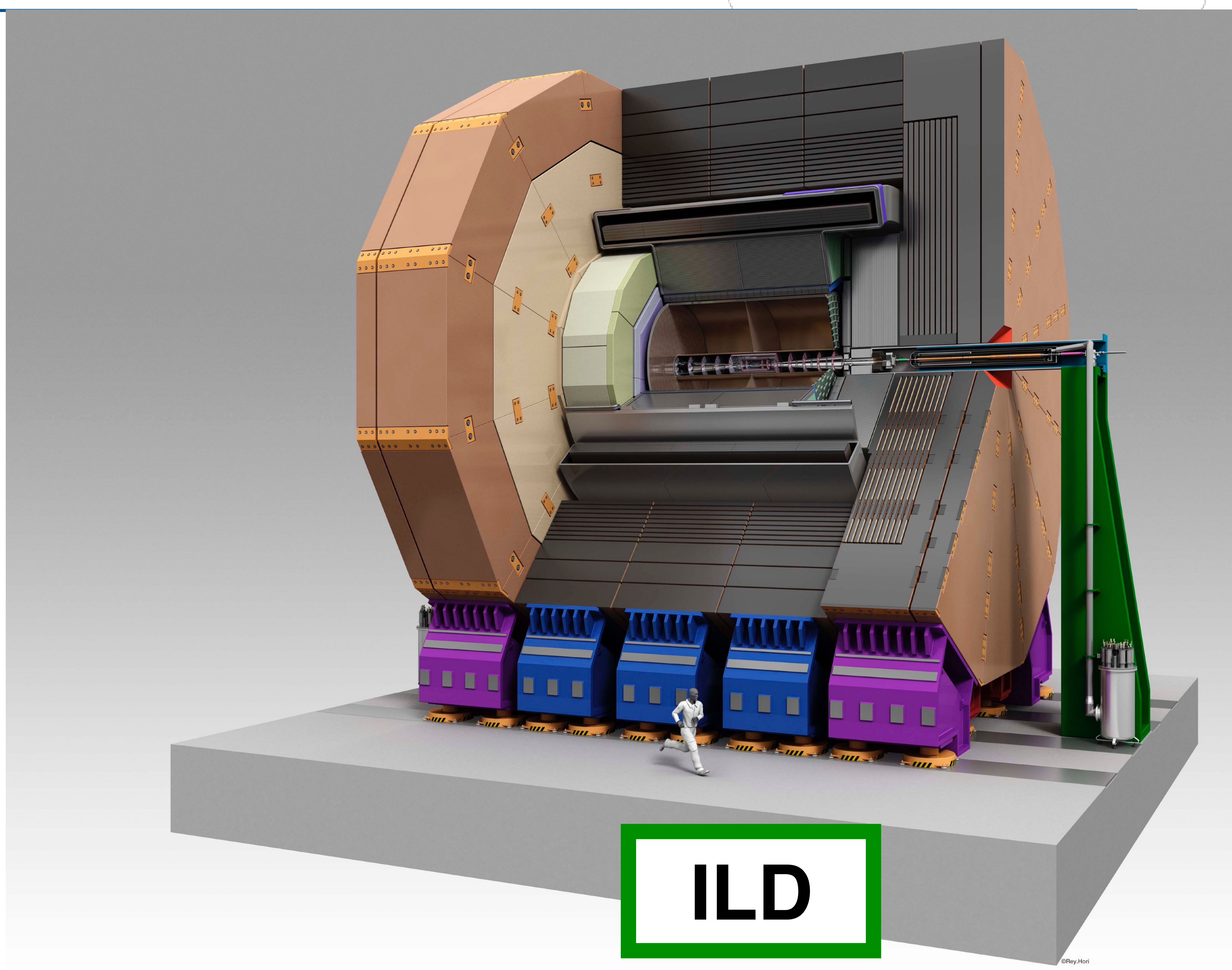
TGCs



HEPfit
Higgs@FC WG
May 2019
HL−LHC
HL+LHeC
HL+HELHC
HL+ILC250
HL+ILC500
HL+CLIC380
HL+CLIC1500
HL+CLIC3000
HL+CEPC
HL+FCCee240
HL+FCCee365
HL+FCCee/eh/hh
SMEFTND fit
δgi/gi[%]
δgaTGC
Improvement wrt. HL−LHC

The Detector Concepts





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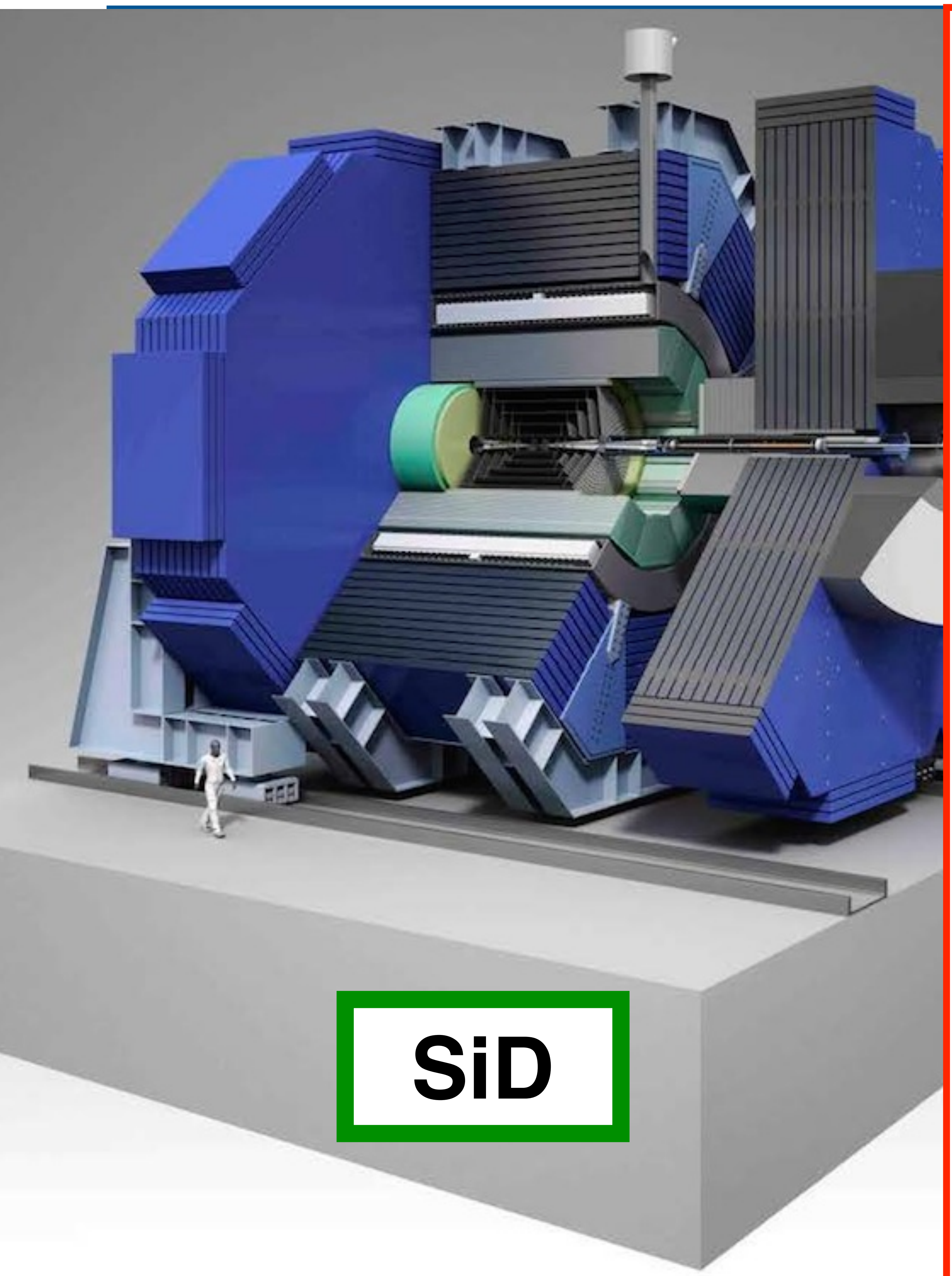

From key requirements from physics:

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

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

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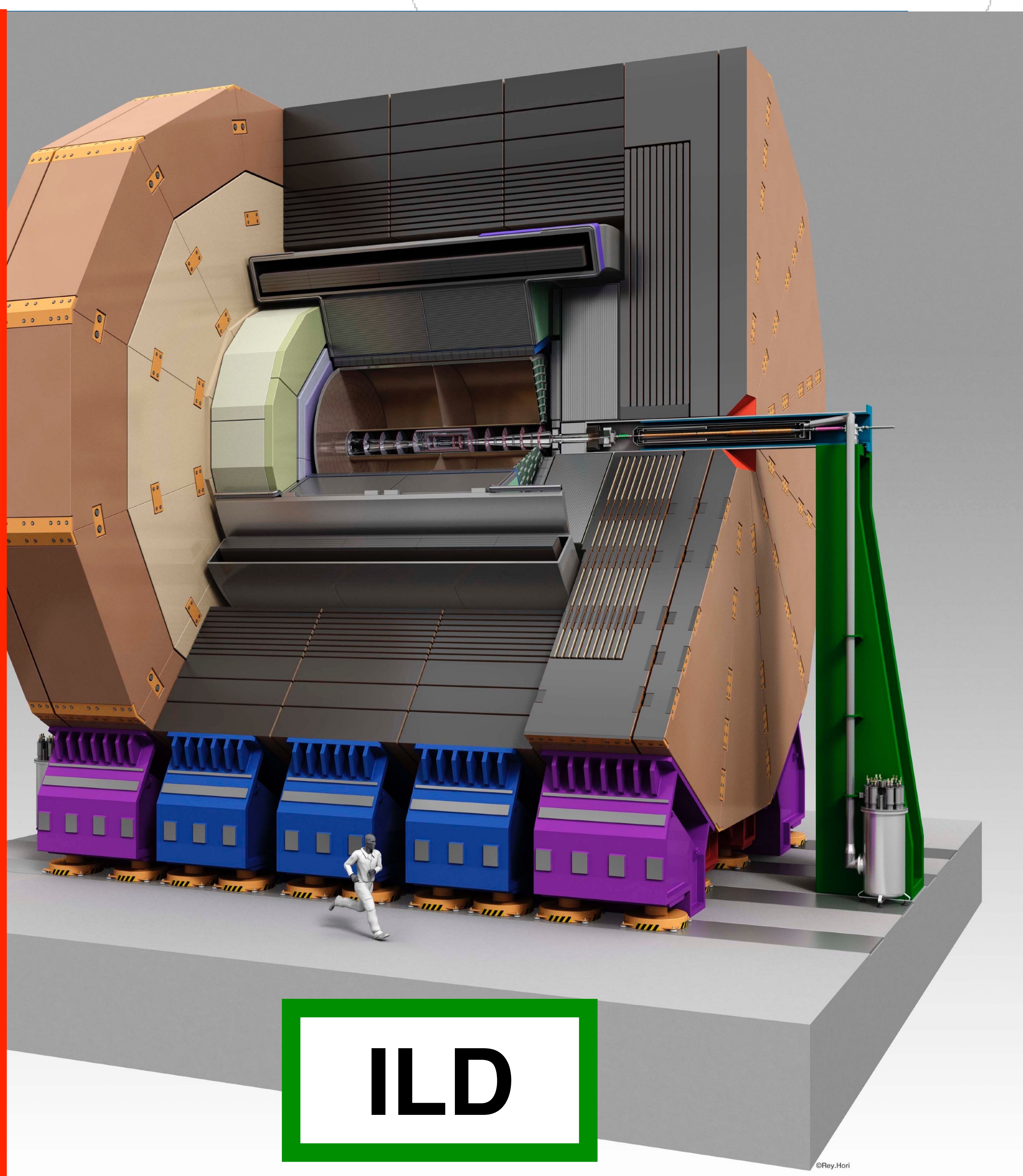

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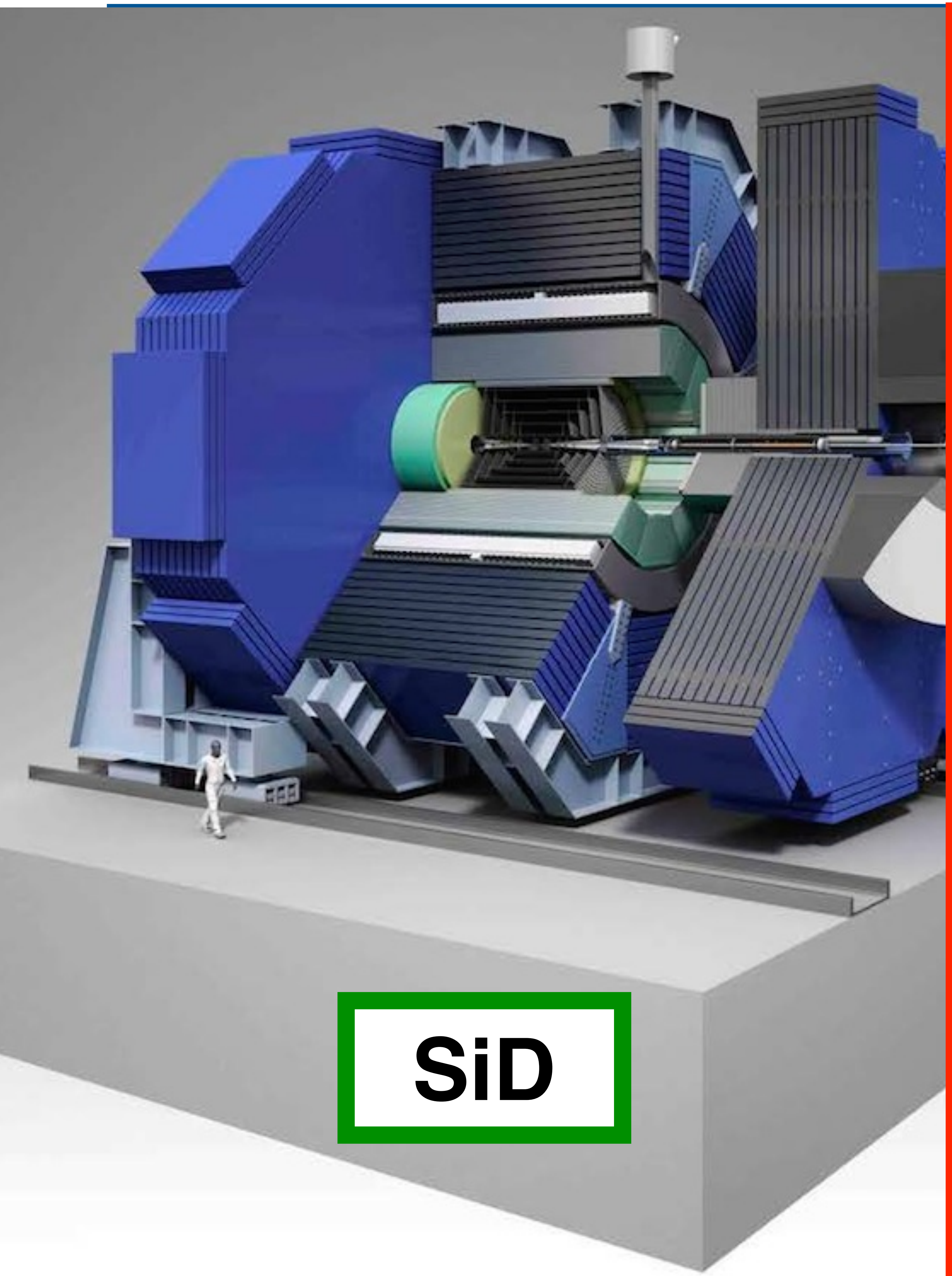

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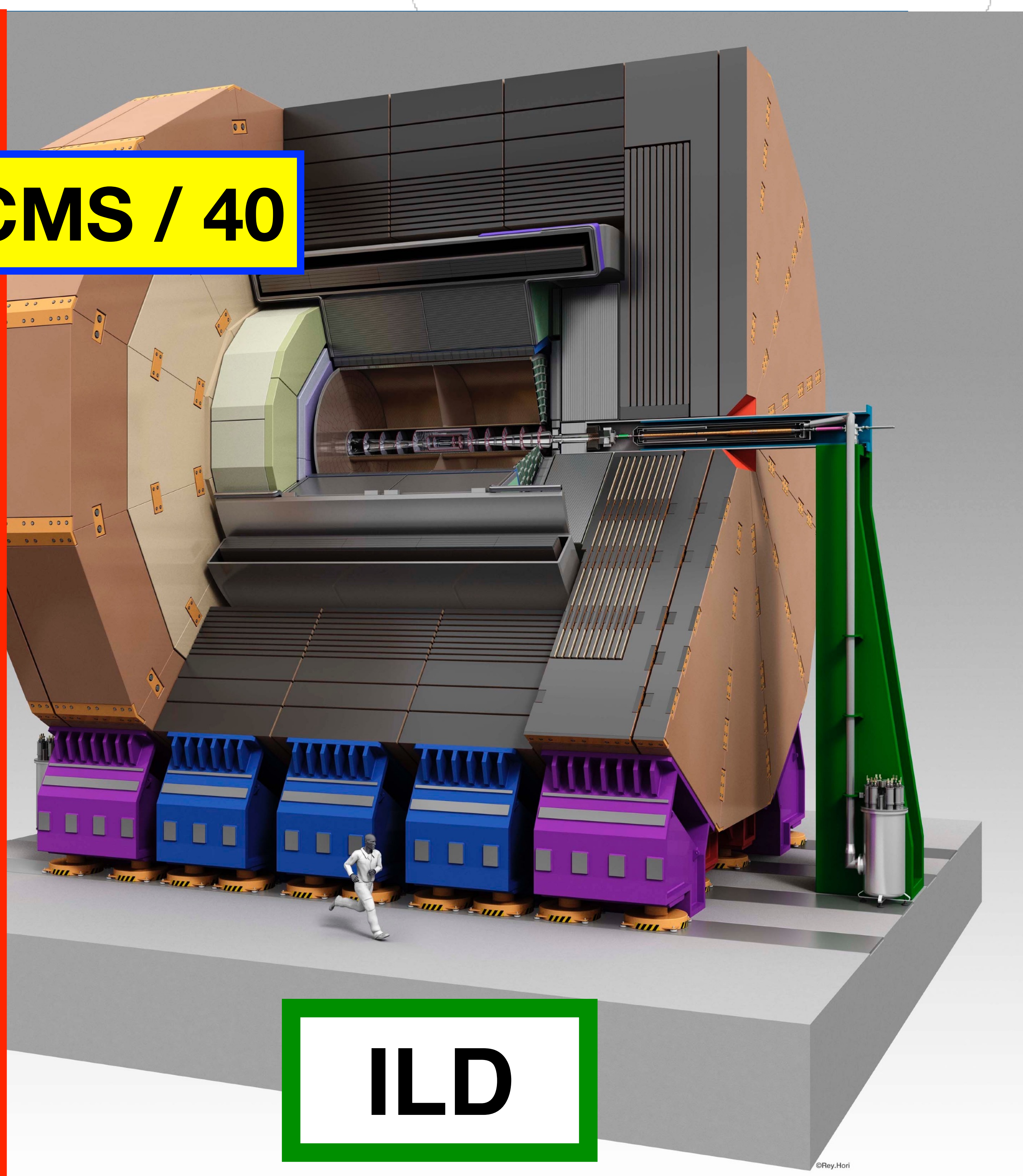

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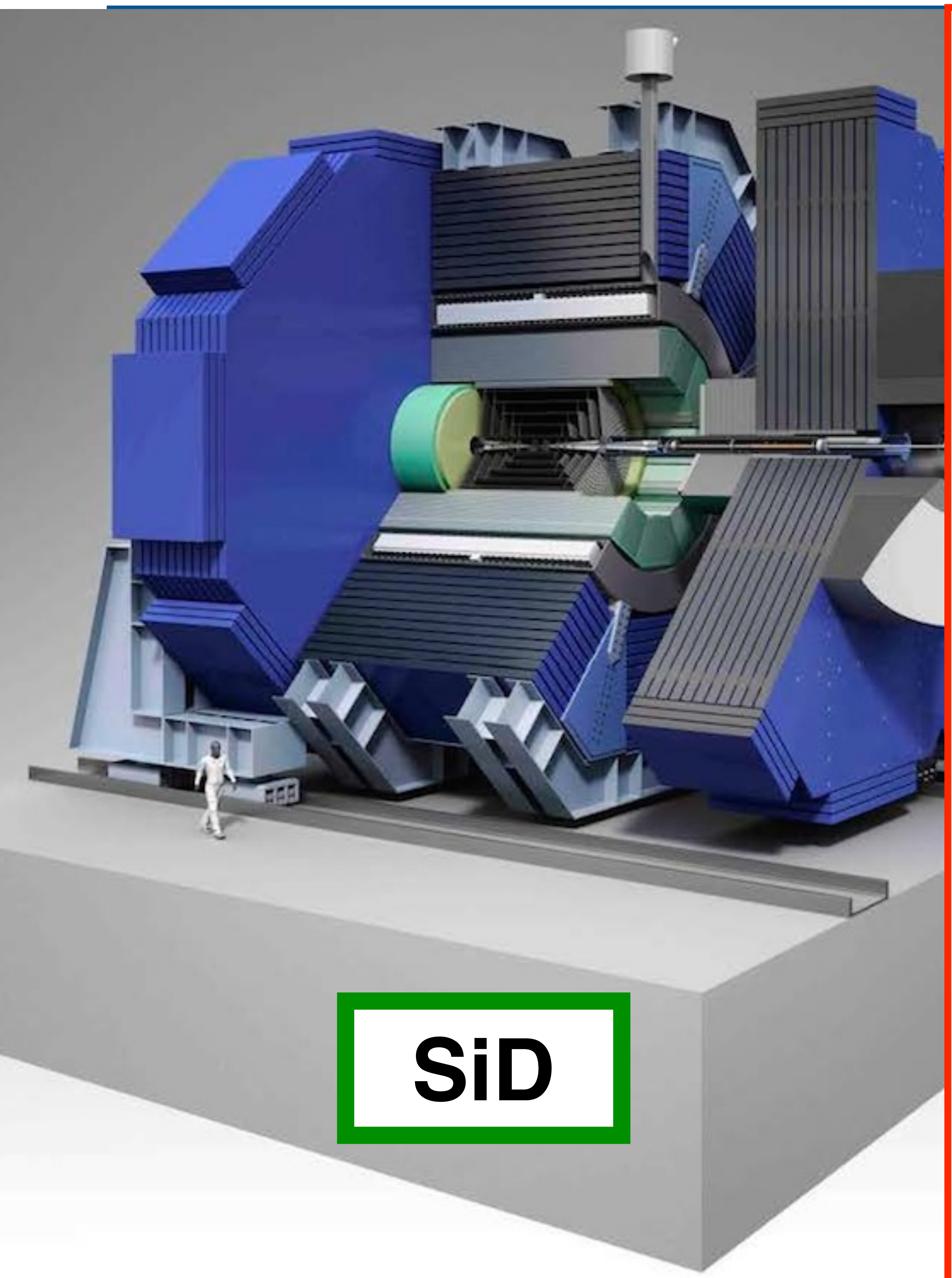

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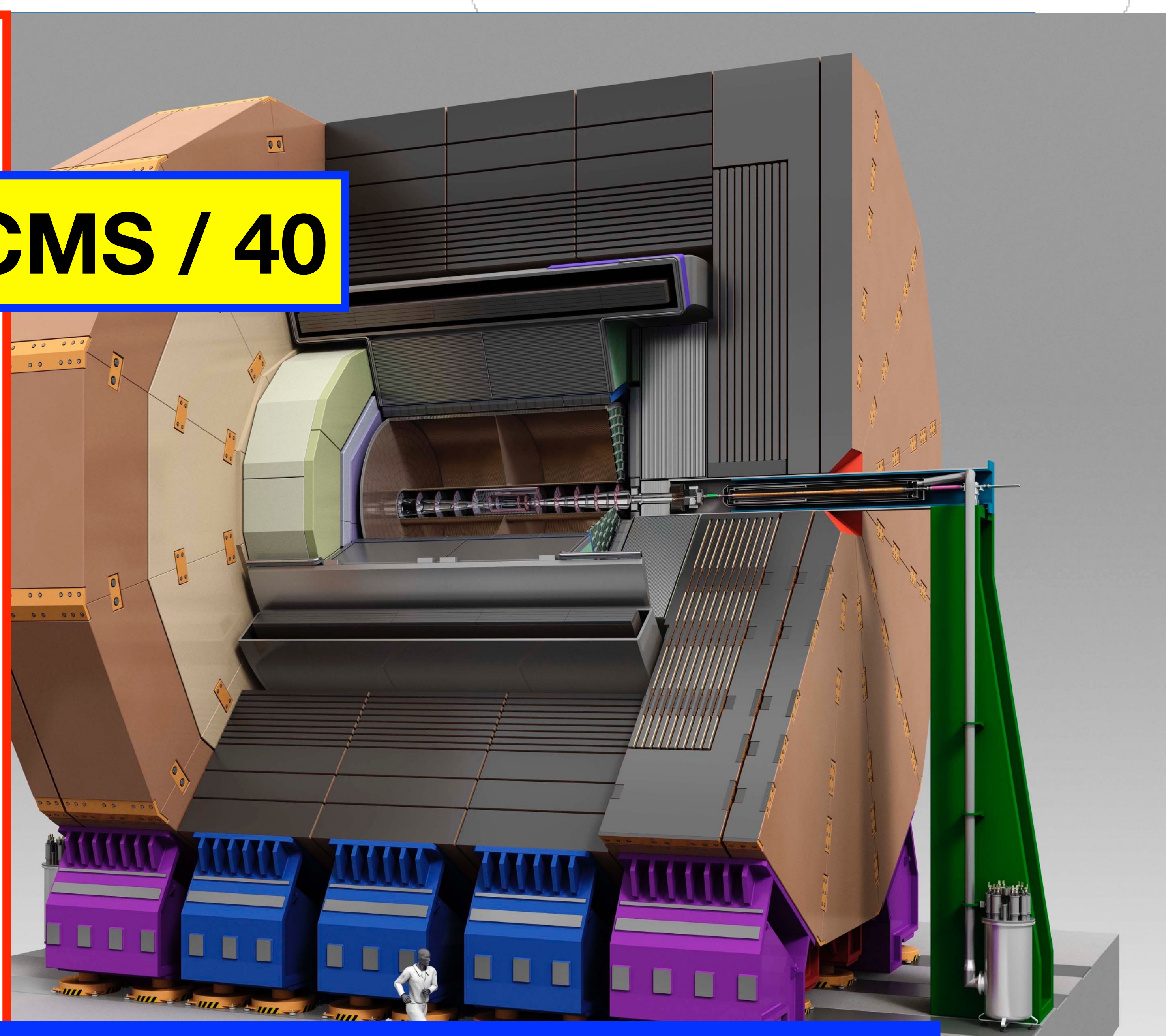

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- **much less radiation**
- **much lower collision rate**
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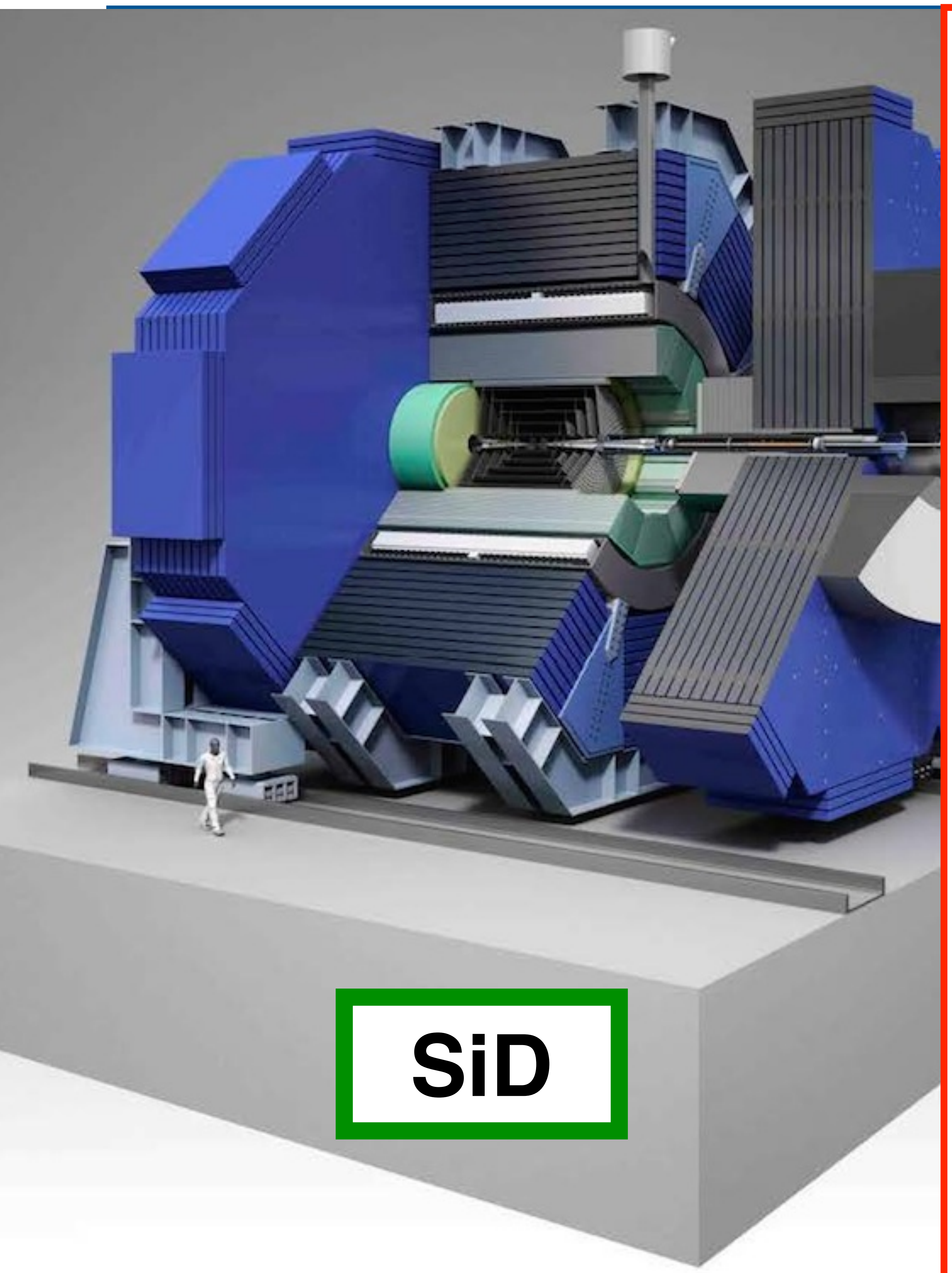

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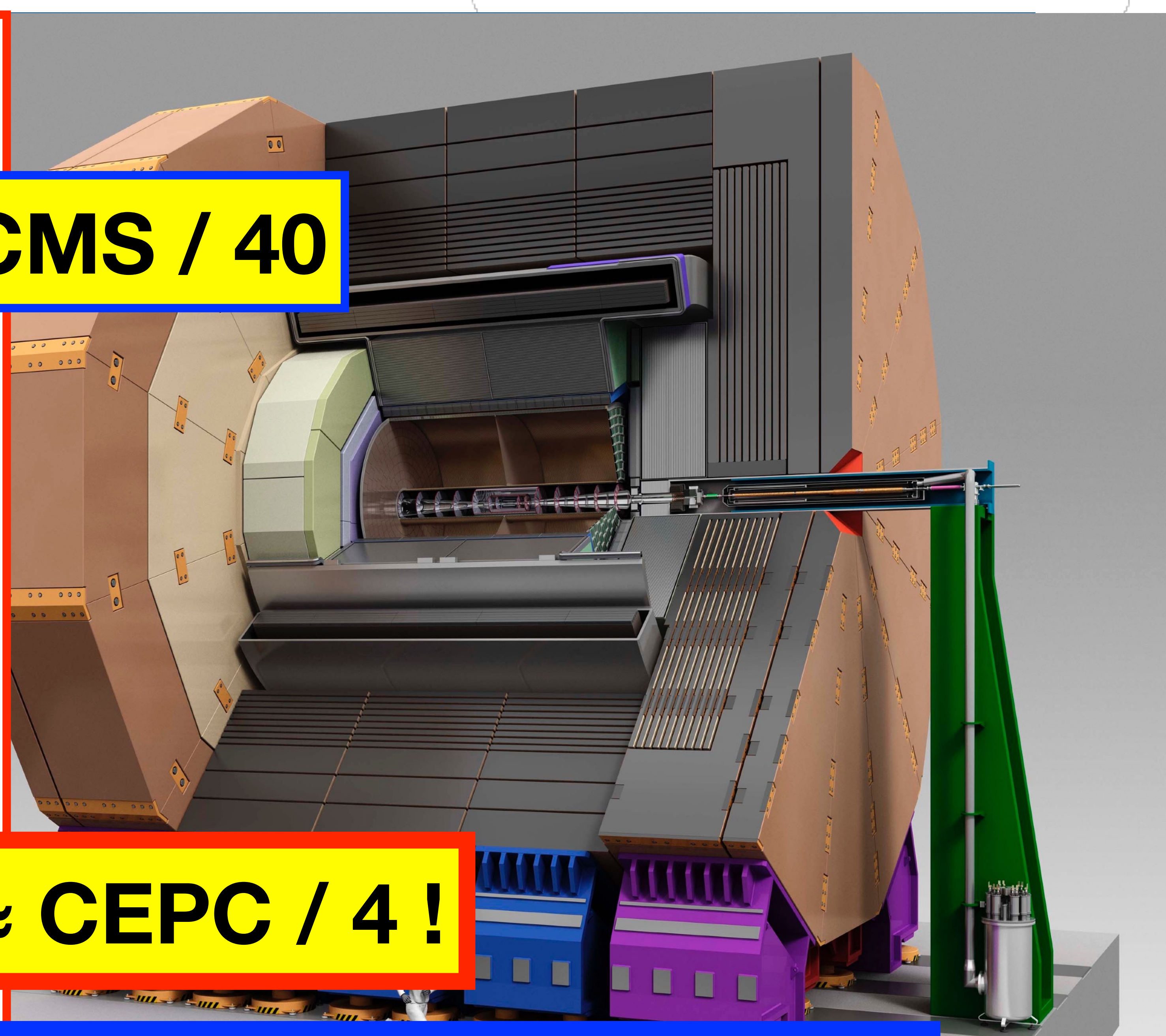

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Unique LC features for BSM physics

Triggerless operation	Hermeticity	Low-p_t tracking
=> soft / unexpected signatures	**=> missing 4-momentum**	**=> BSM states with small mass gaps**

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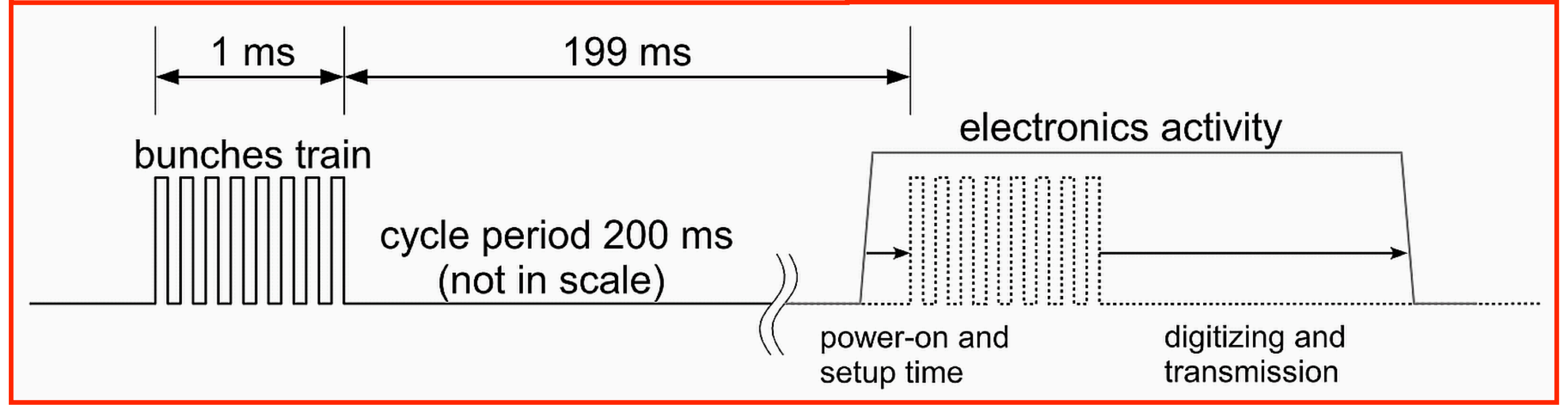

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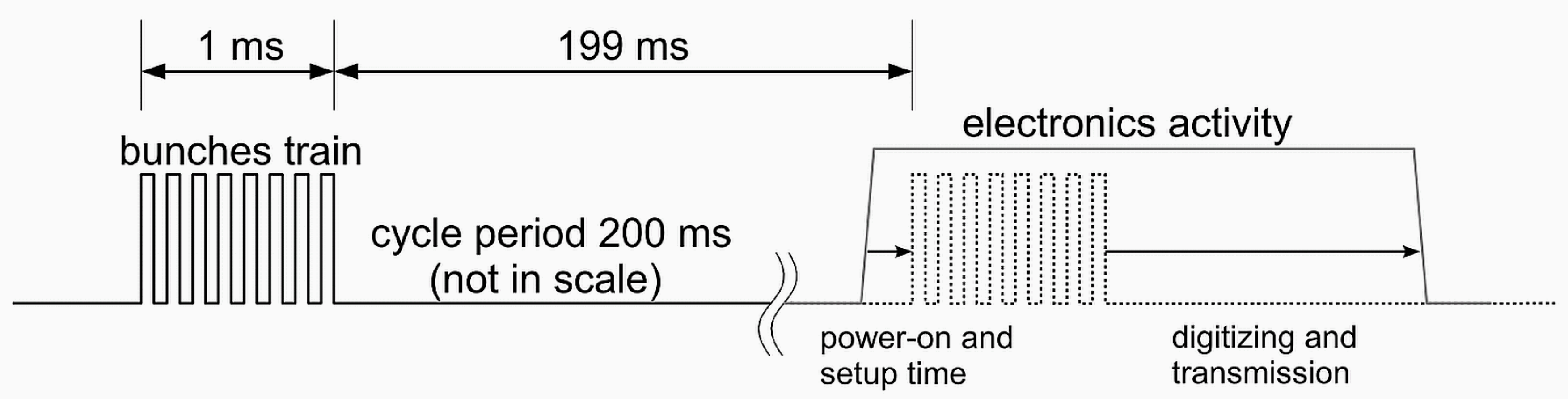

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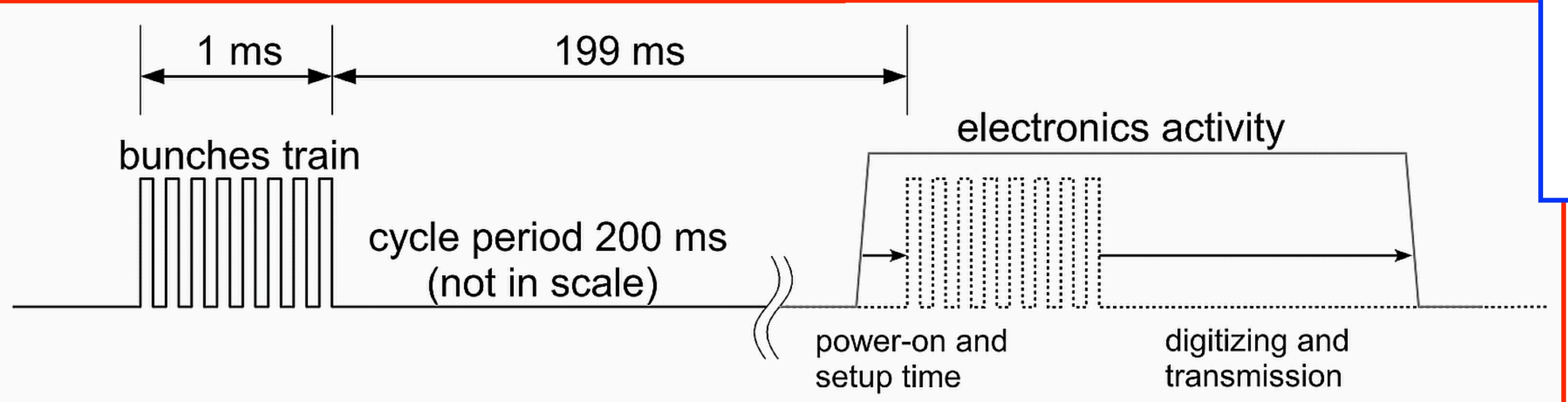

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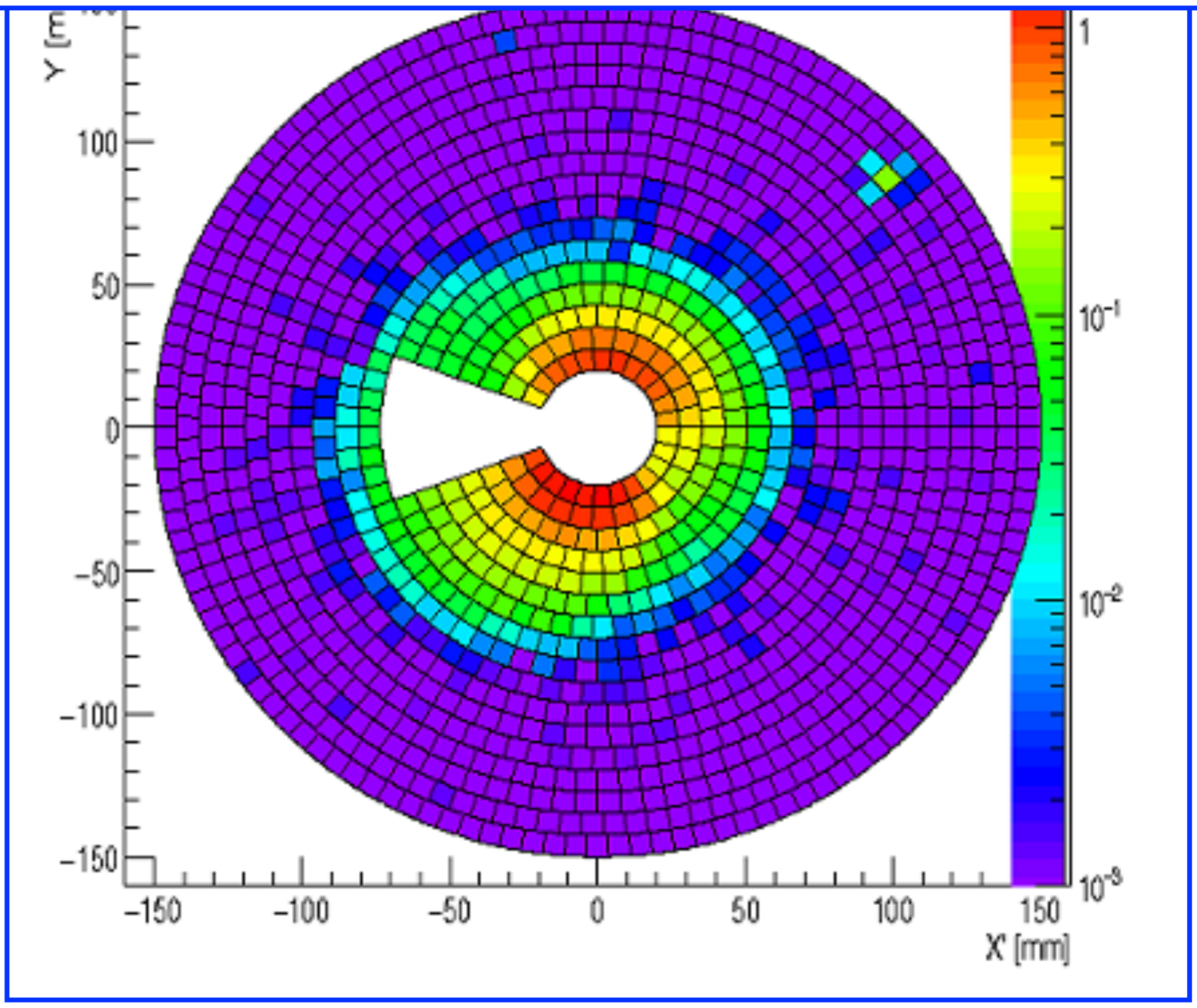

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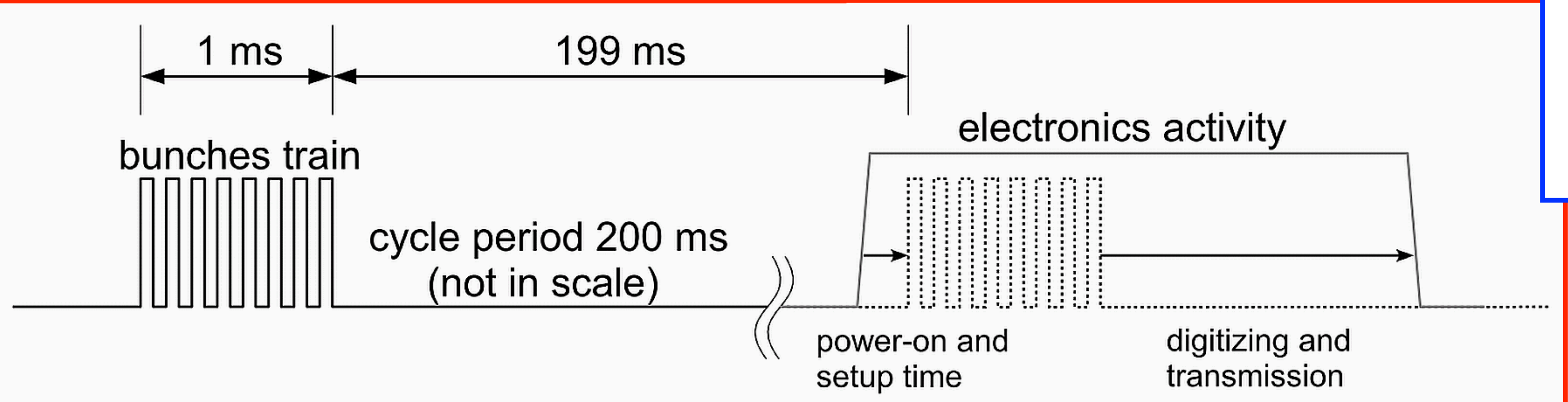

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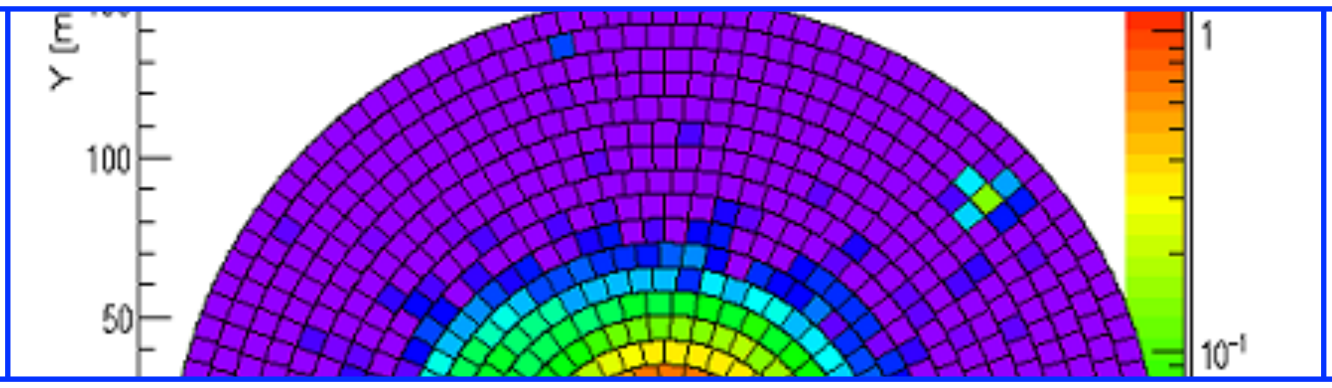

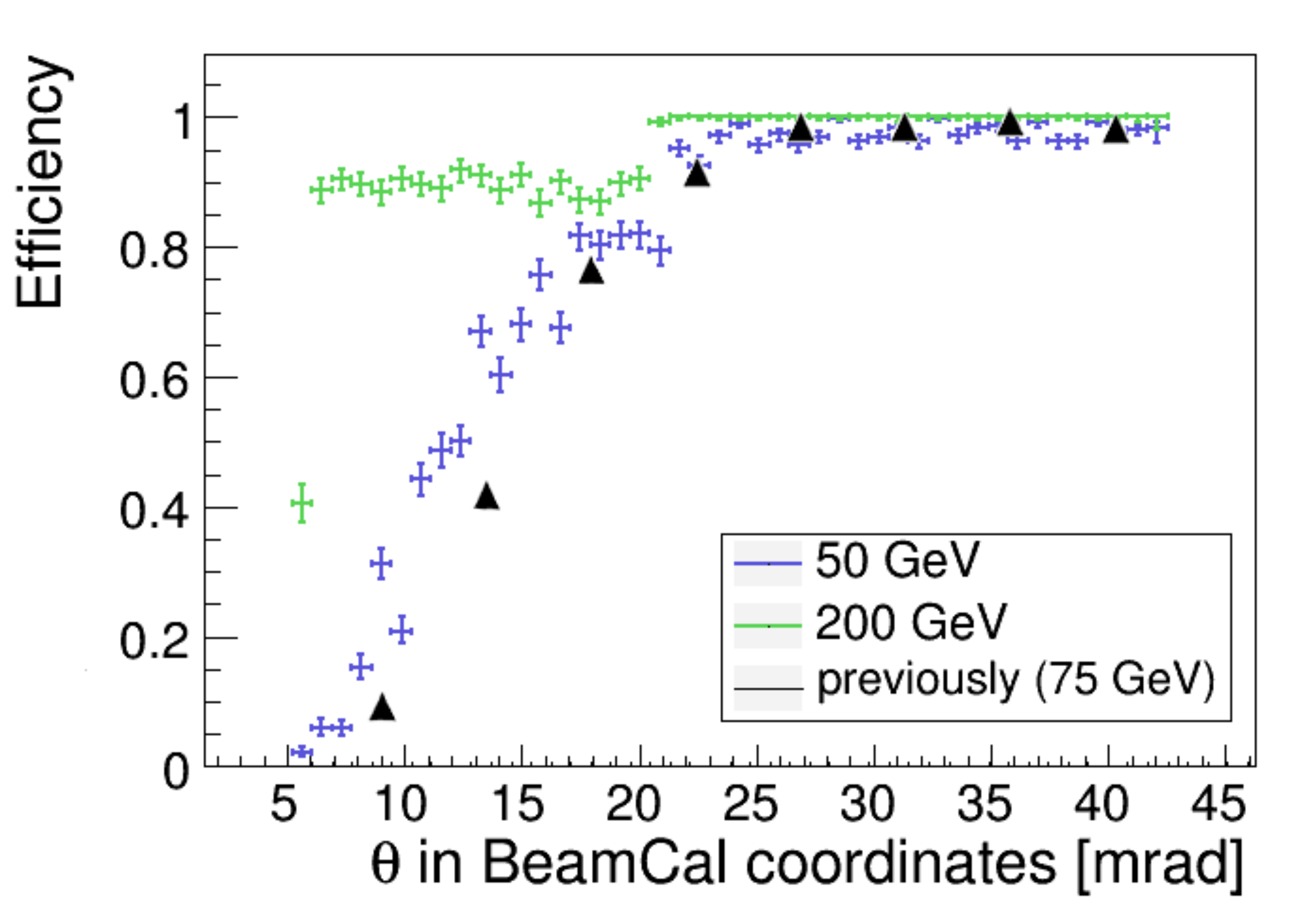

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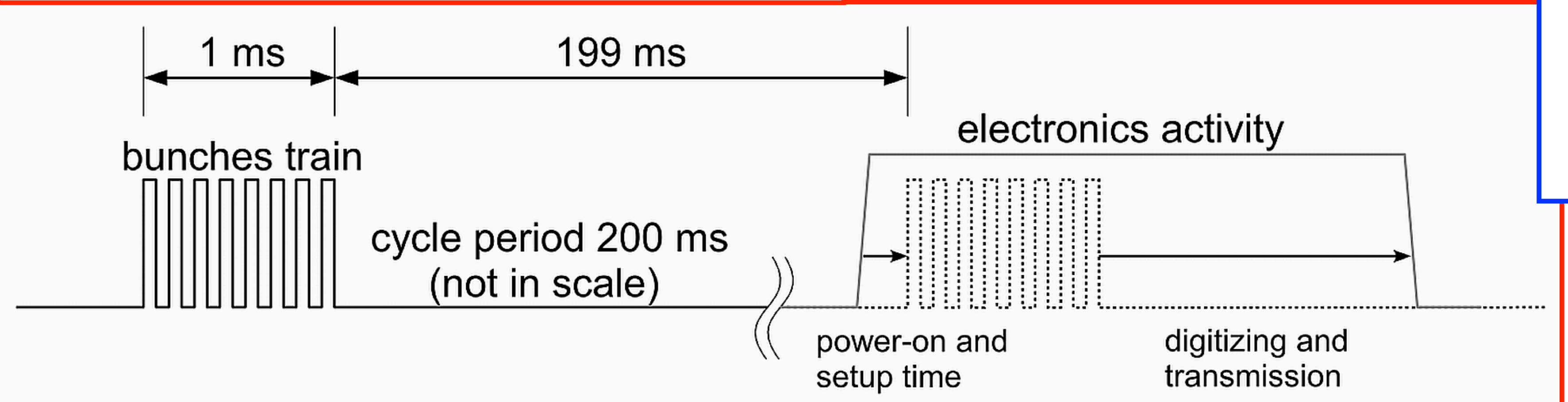

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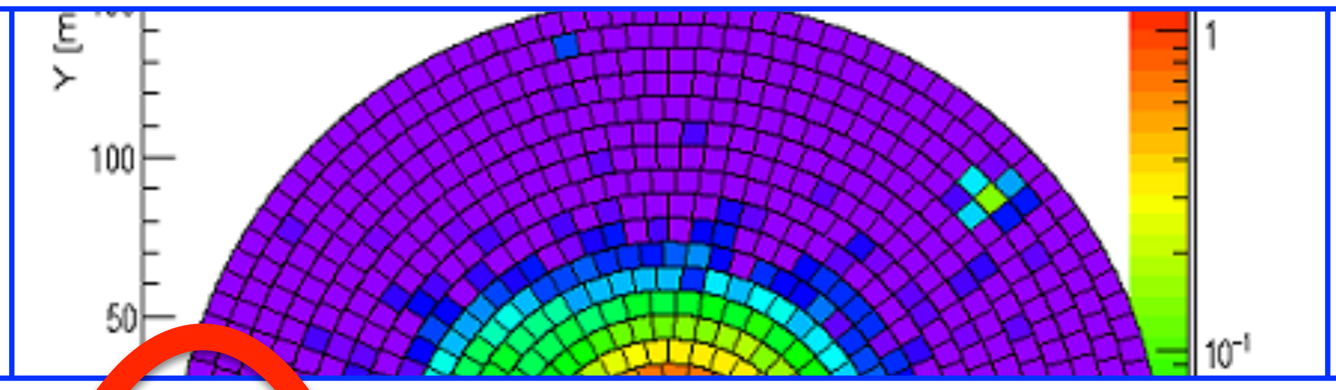

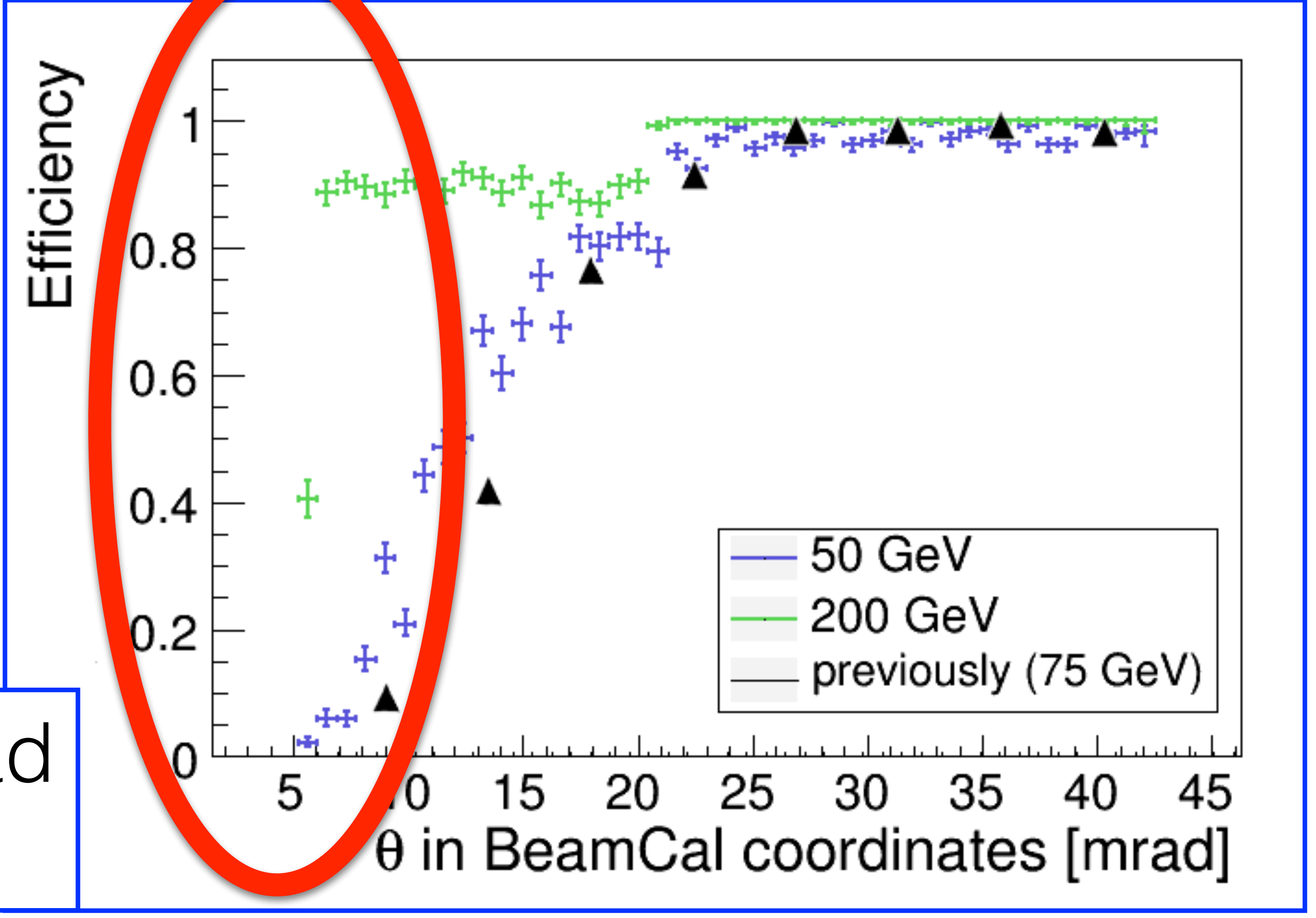

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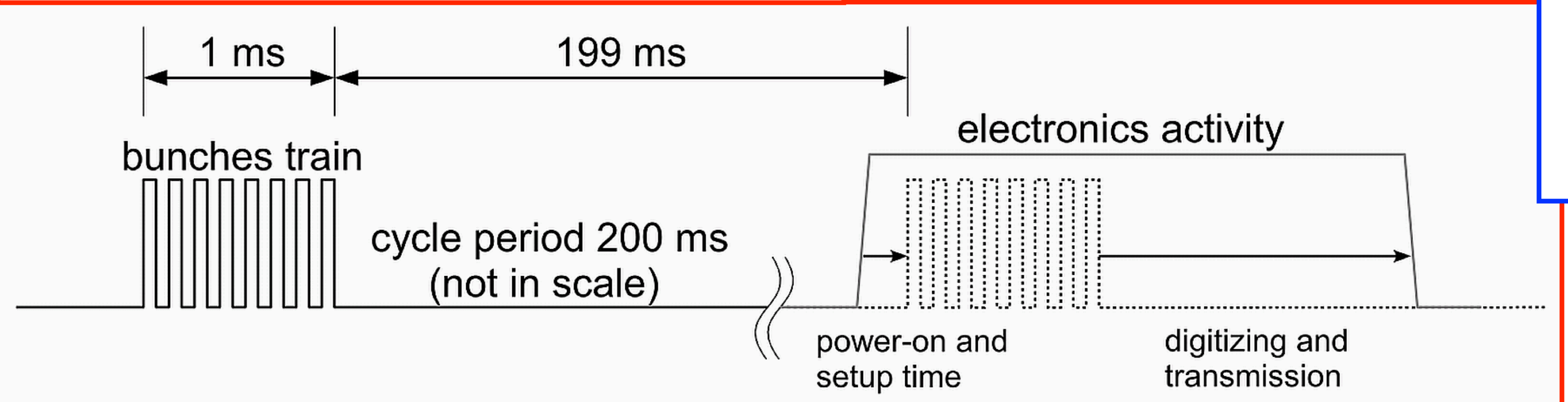

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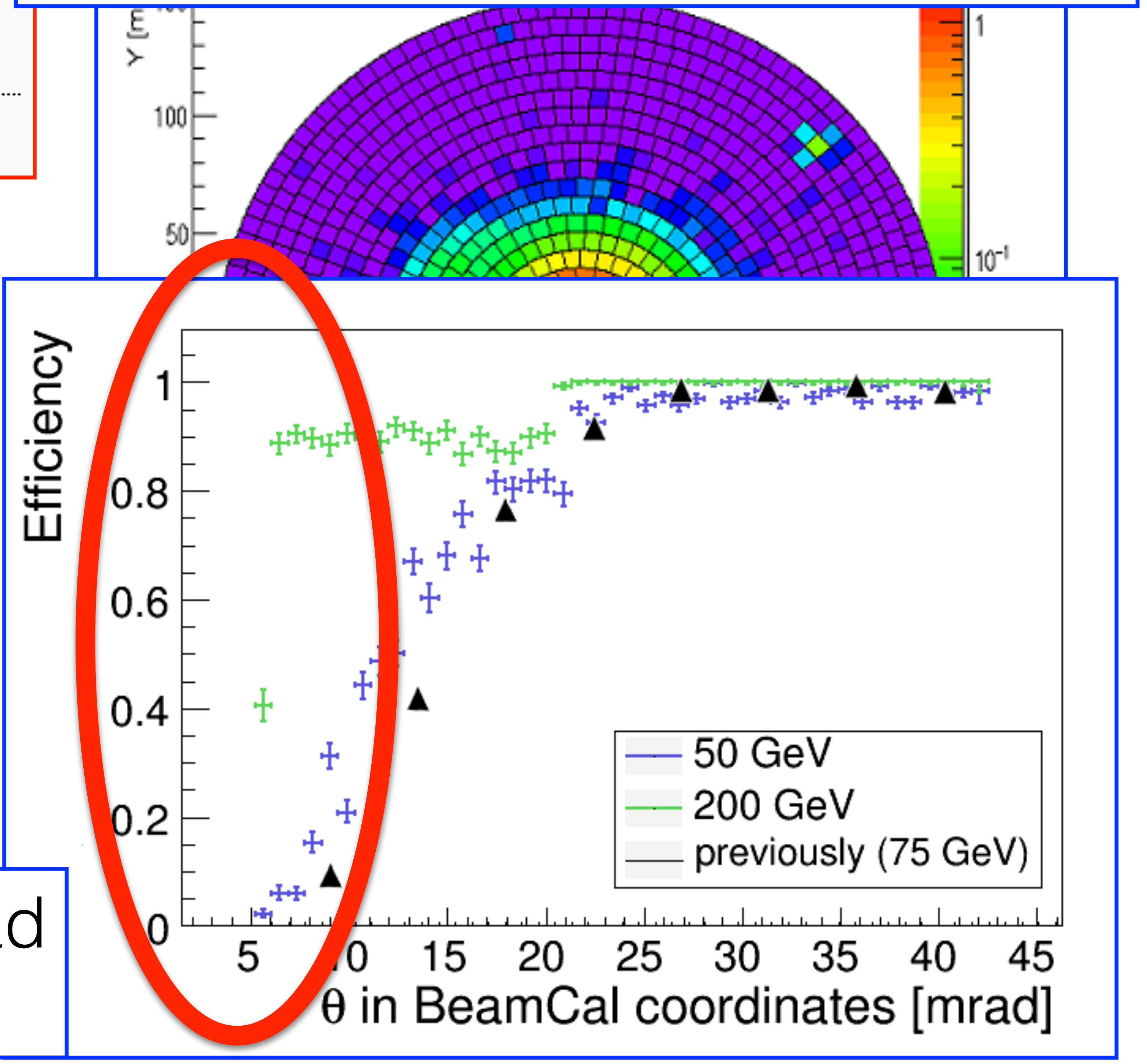

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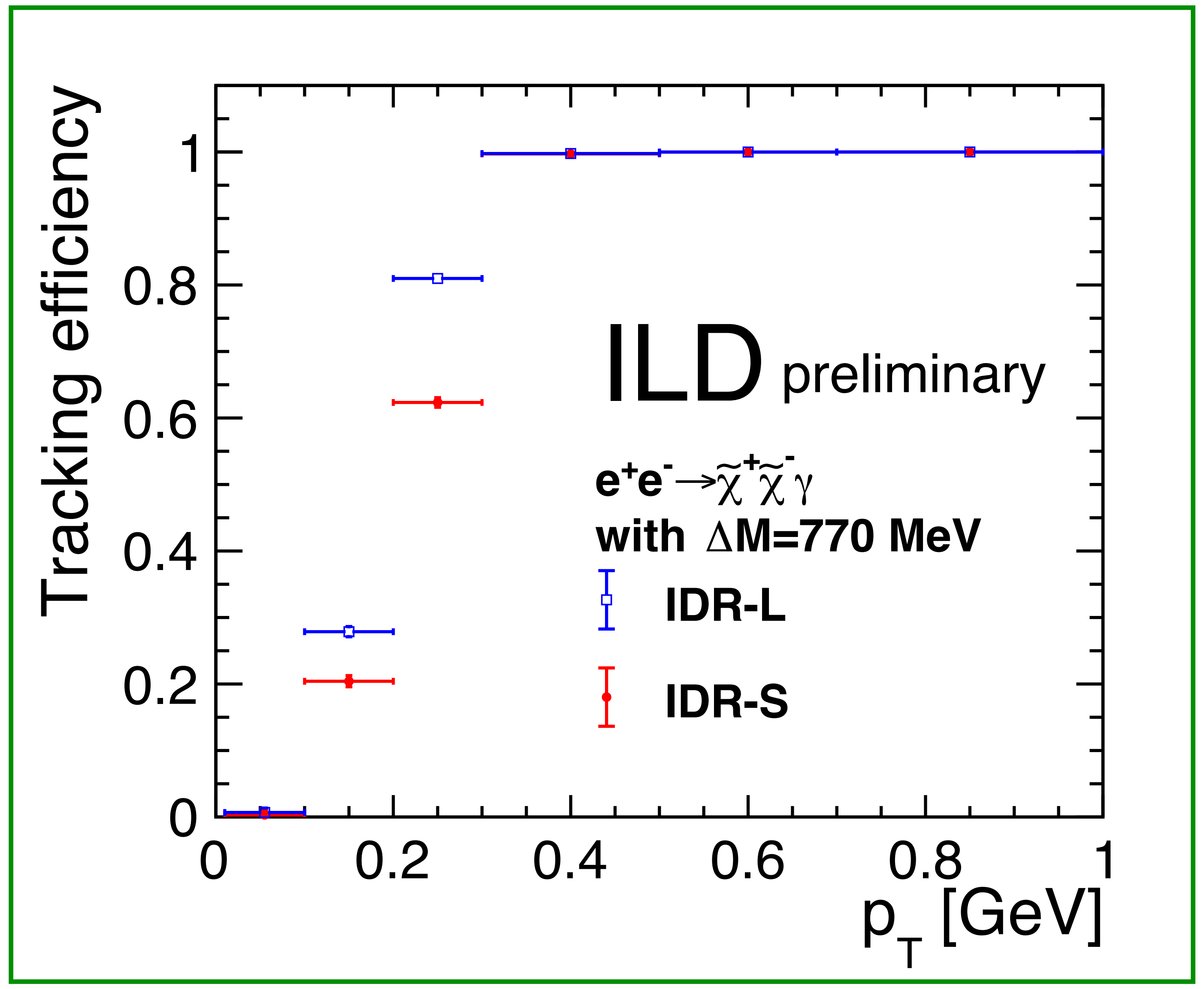

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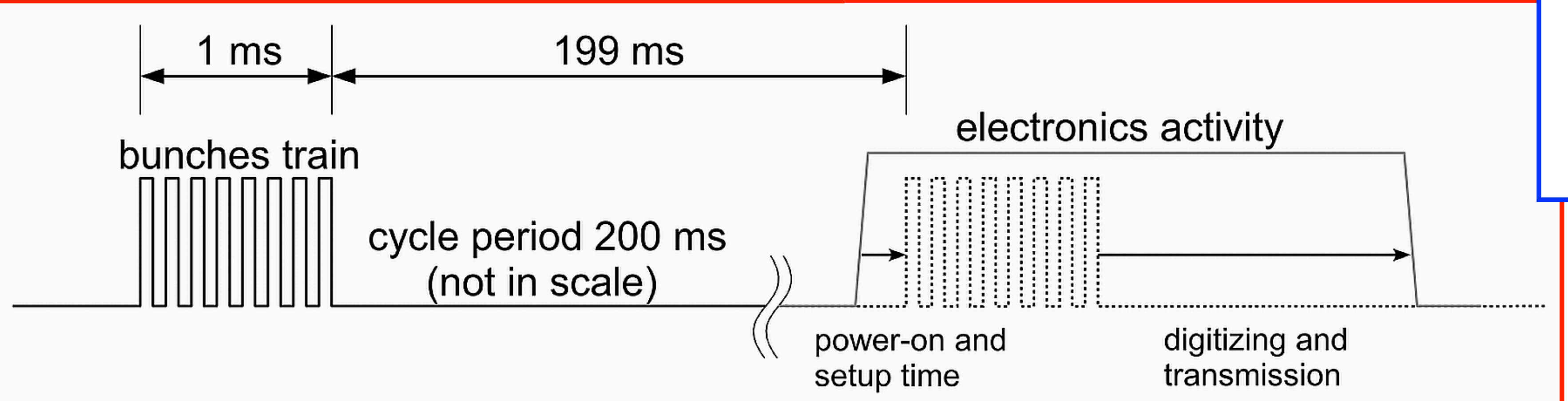

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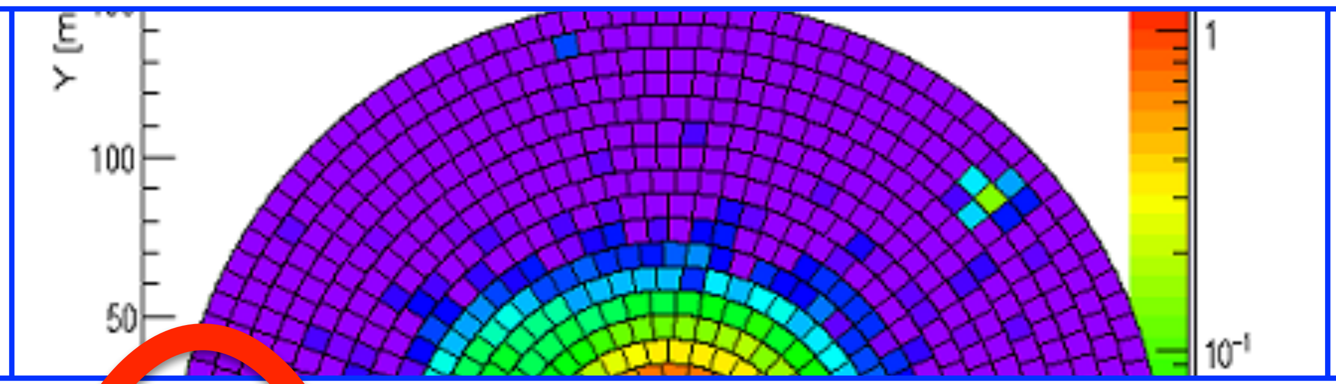

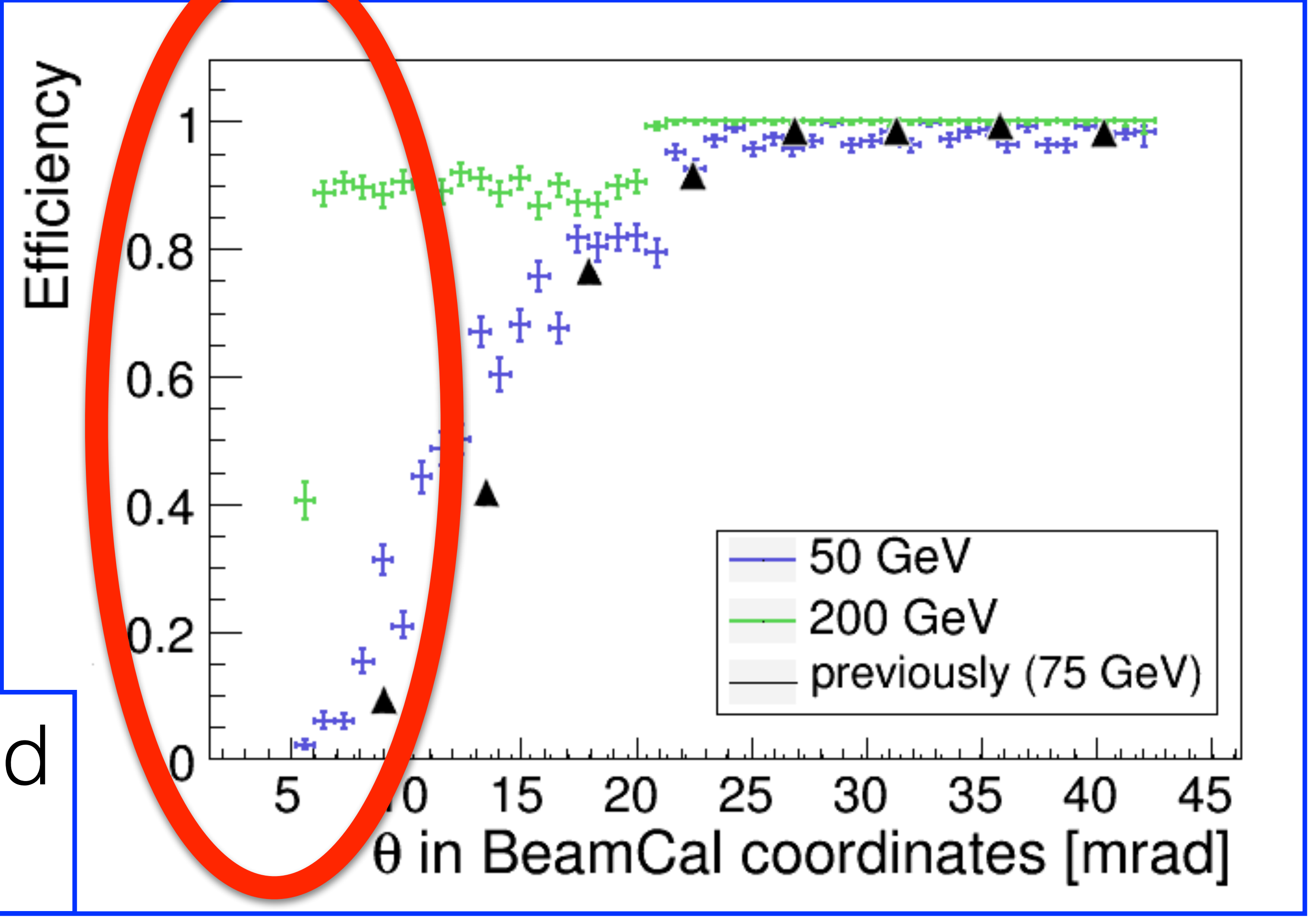

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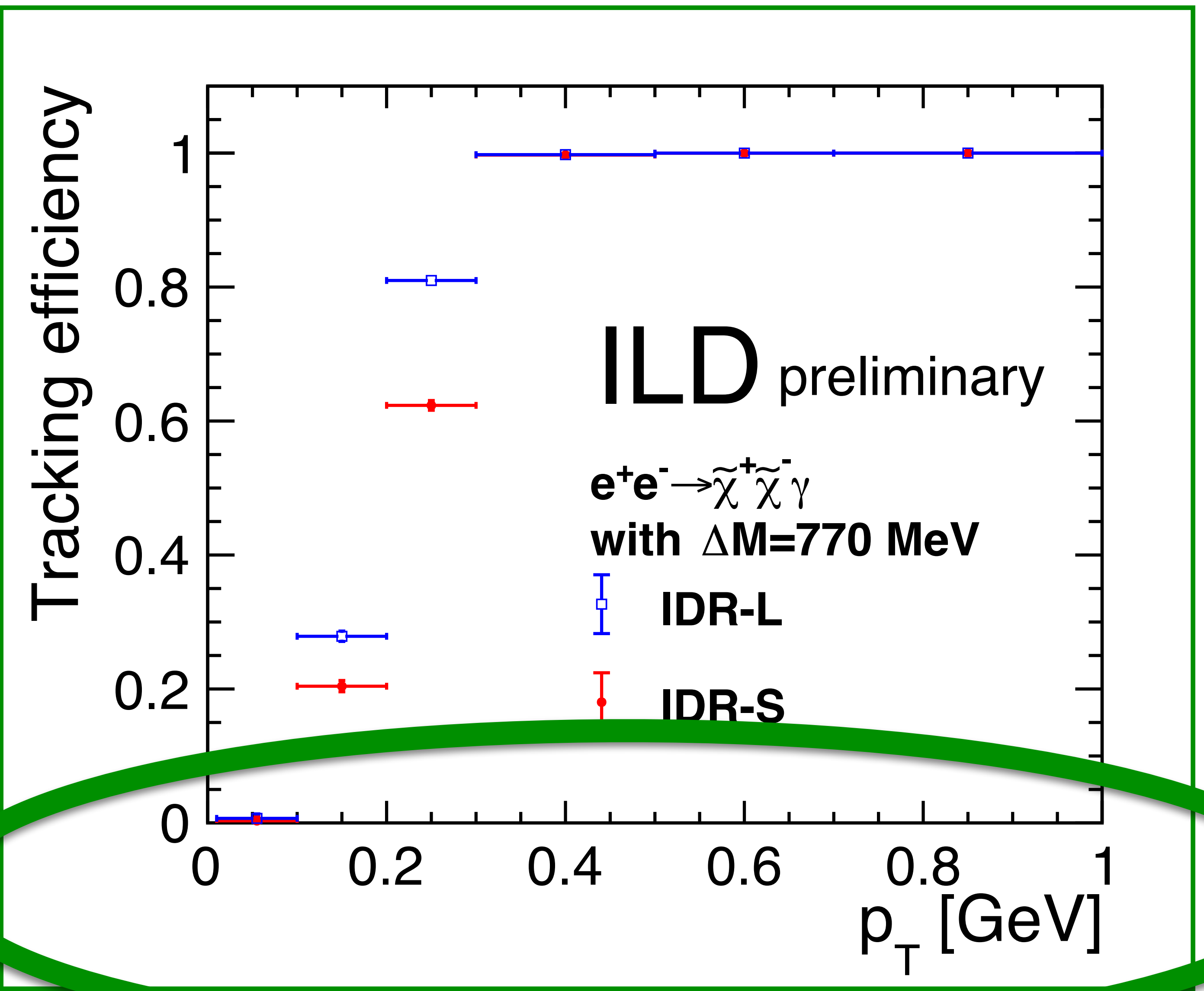

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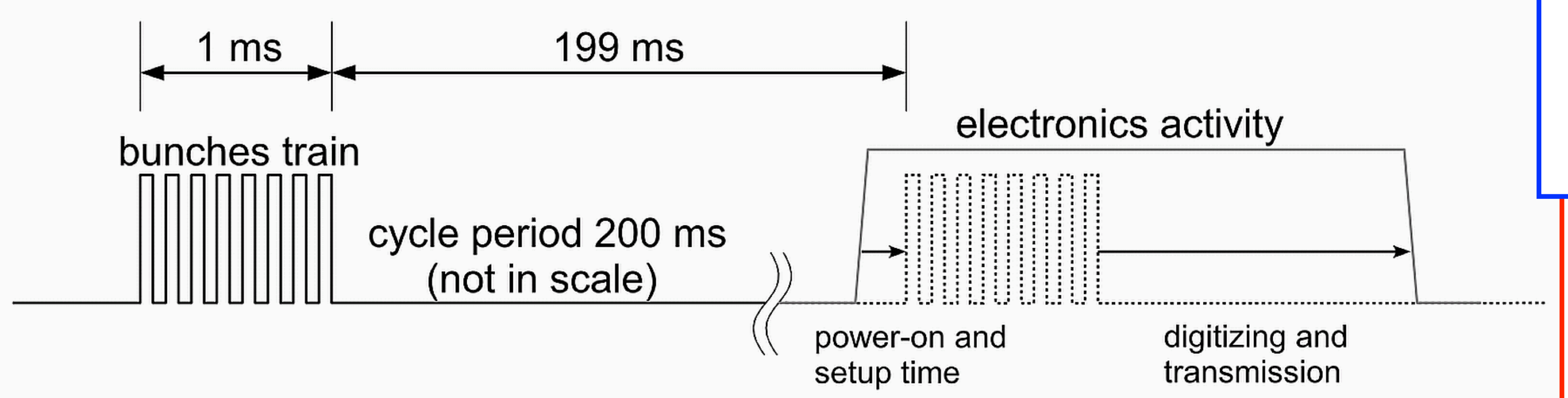

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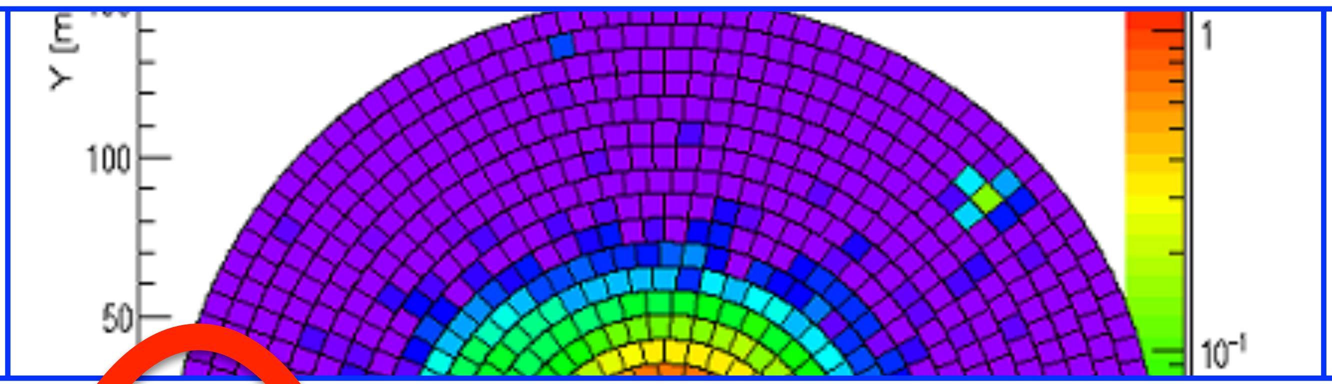

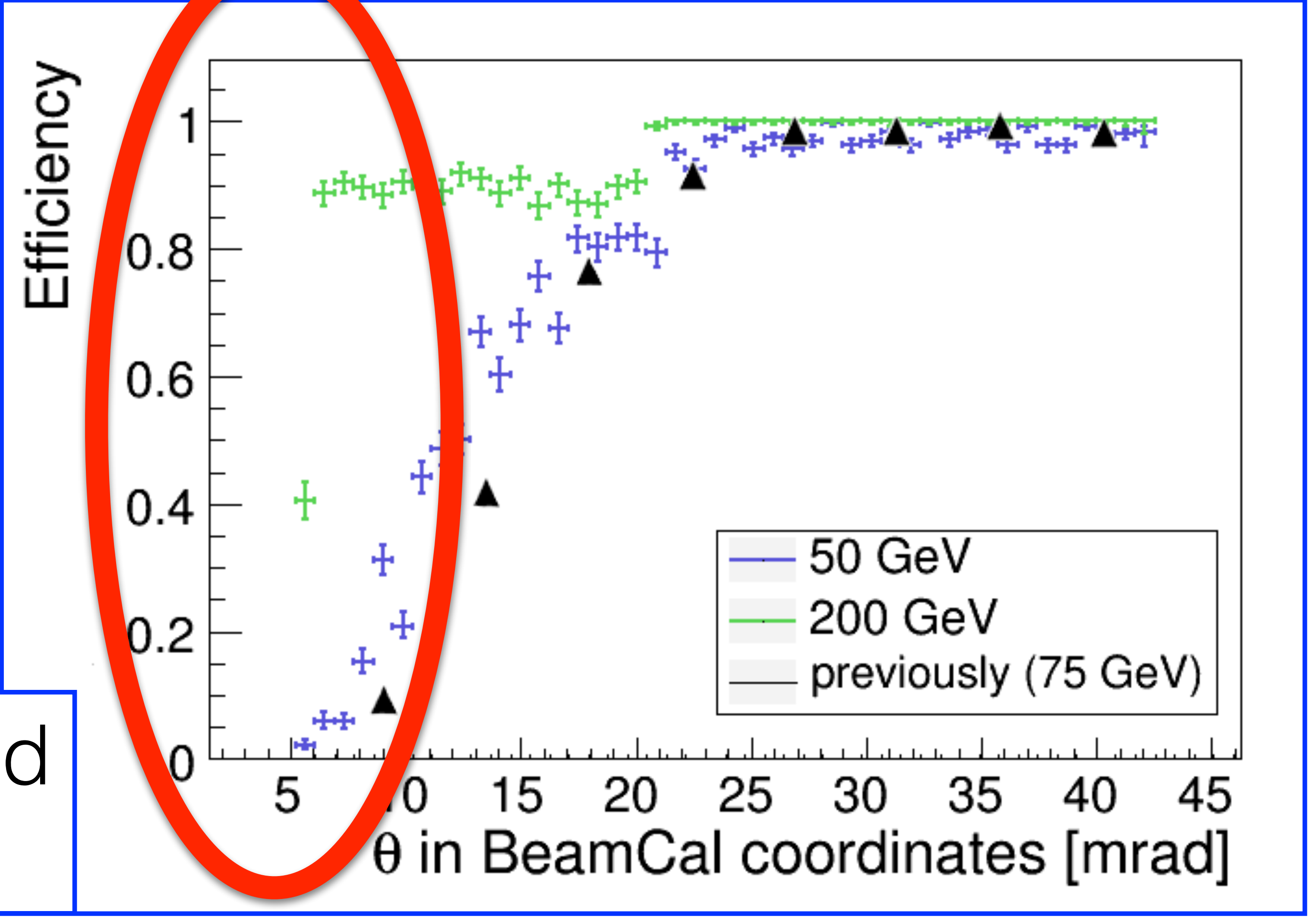

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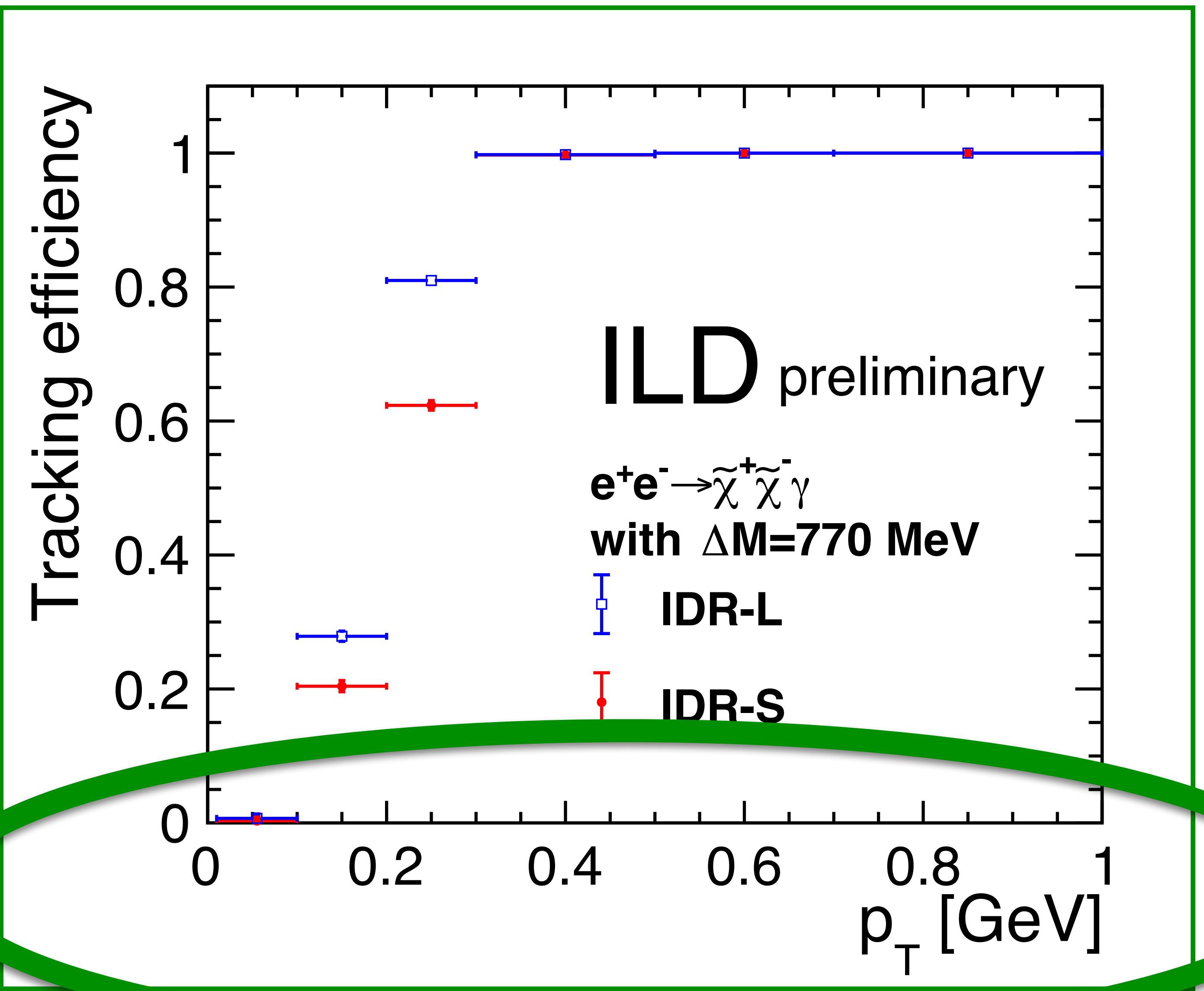
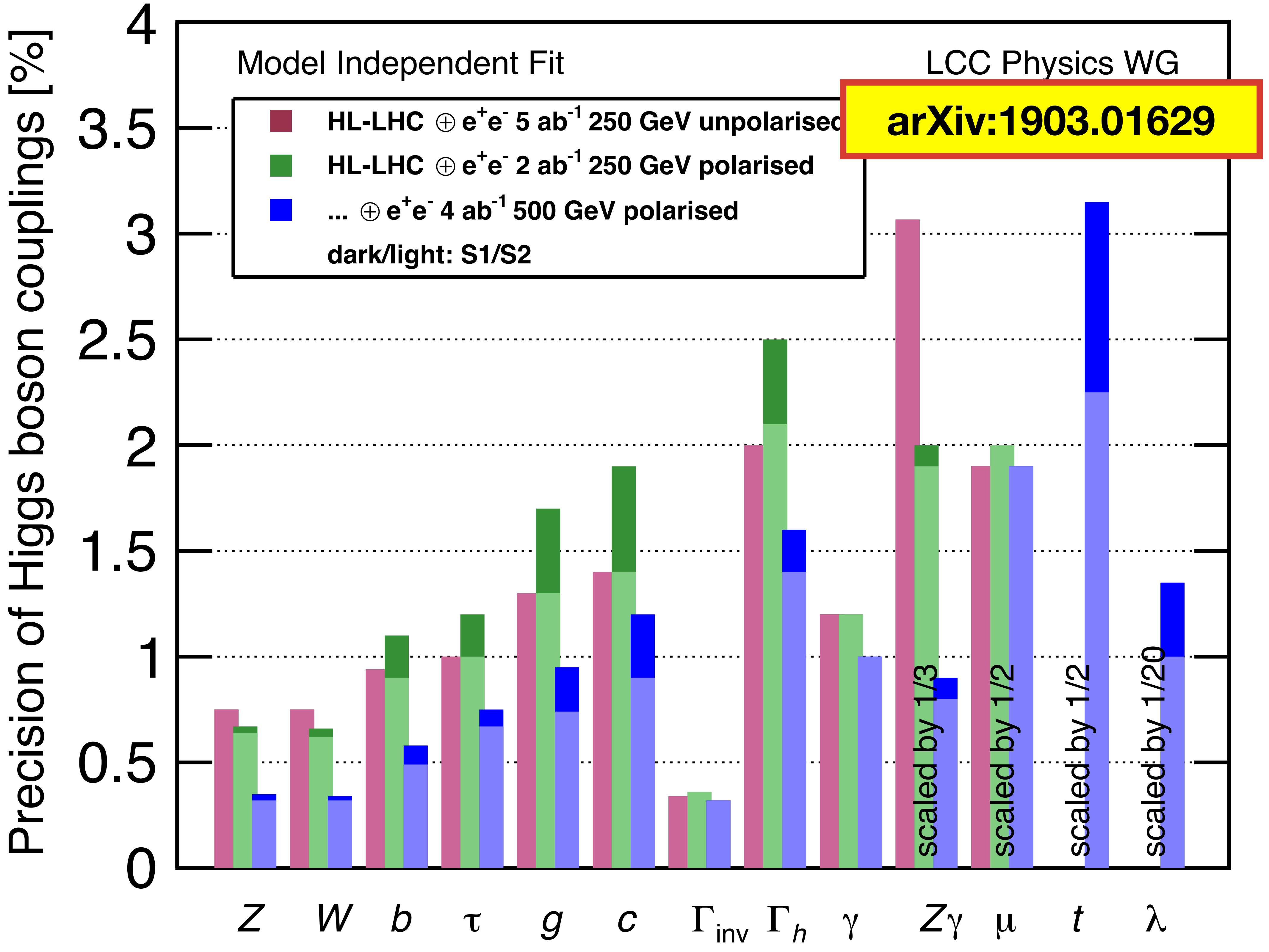


achieved by:

- r_{vtx} = 1.4 cm
- **stand-alone pattern recognition in vertex detector** (3 double layers)
- further improvement under study!

New Properties of the Higgs Boson



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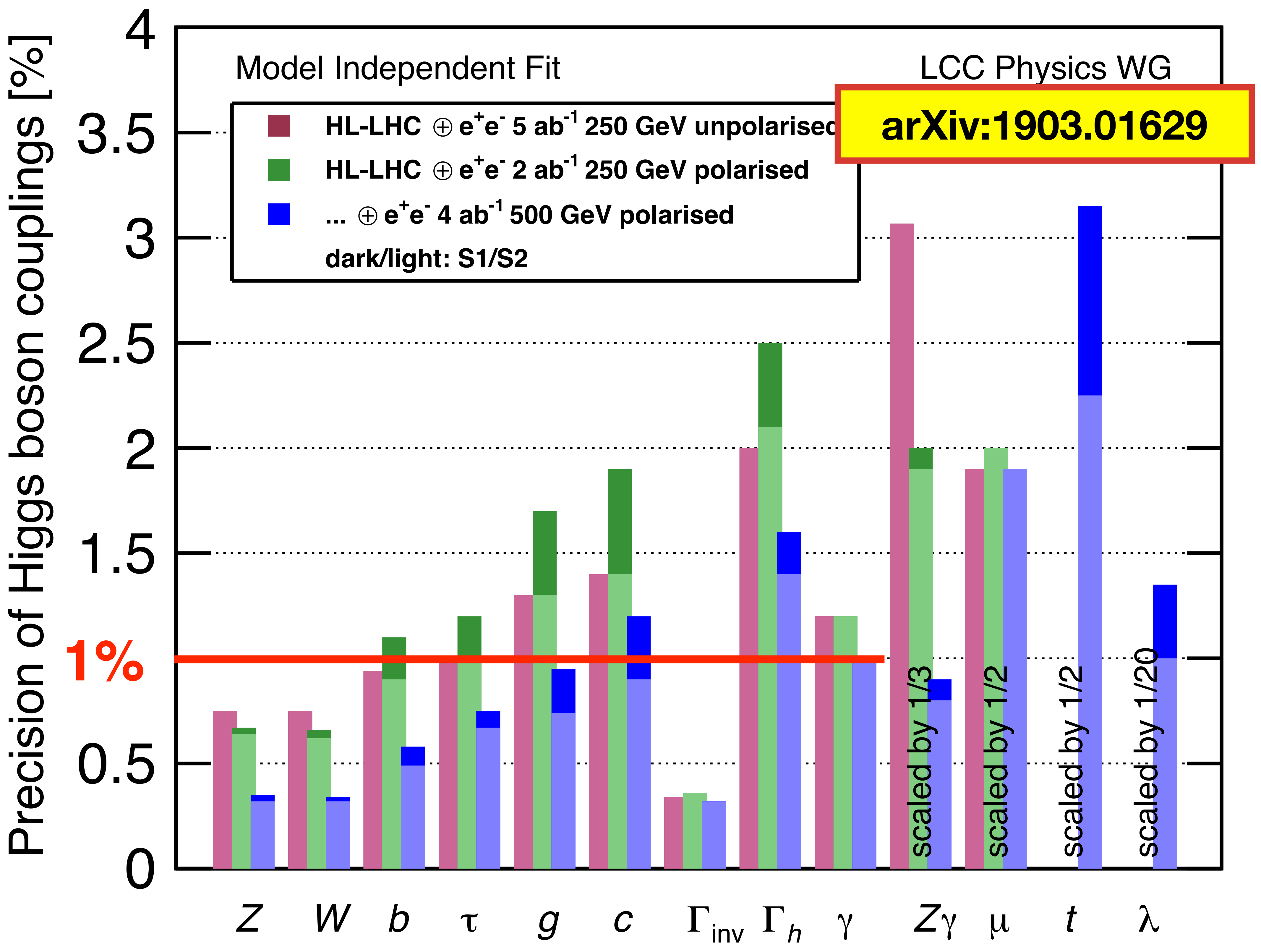

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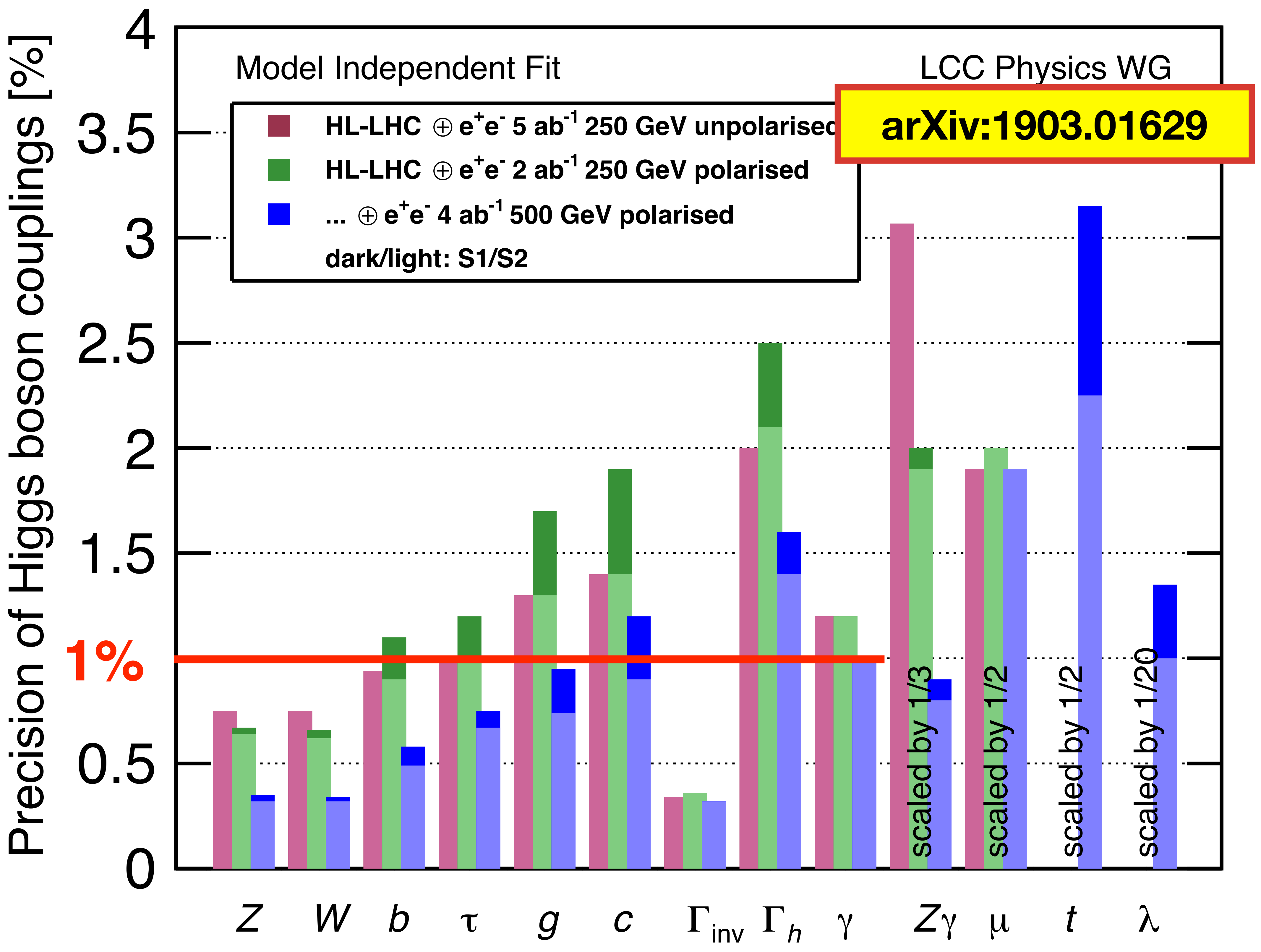

more information on poster by J.Tian (Mon/Tue)

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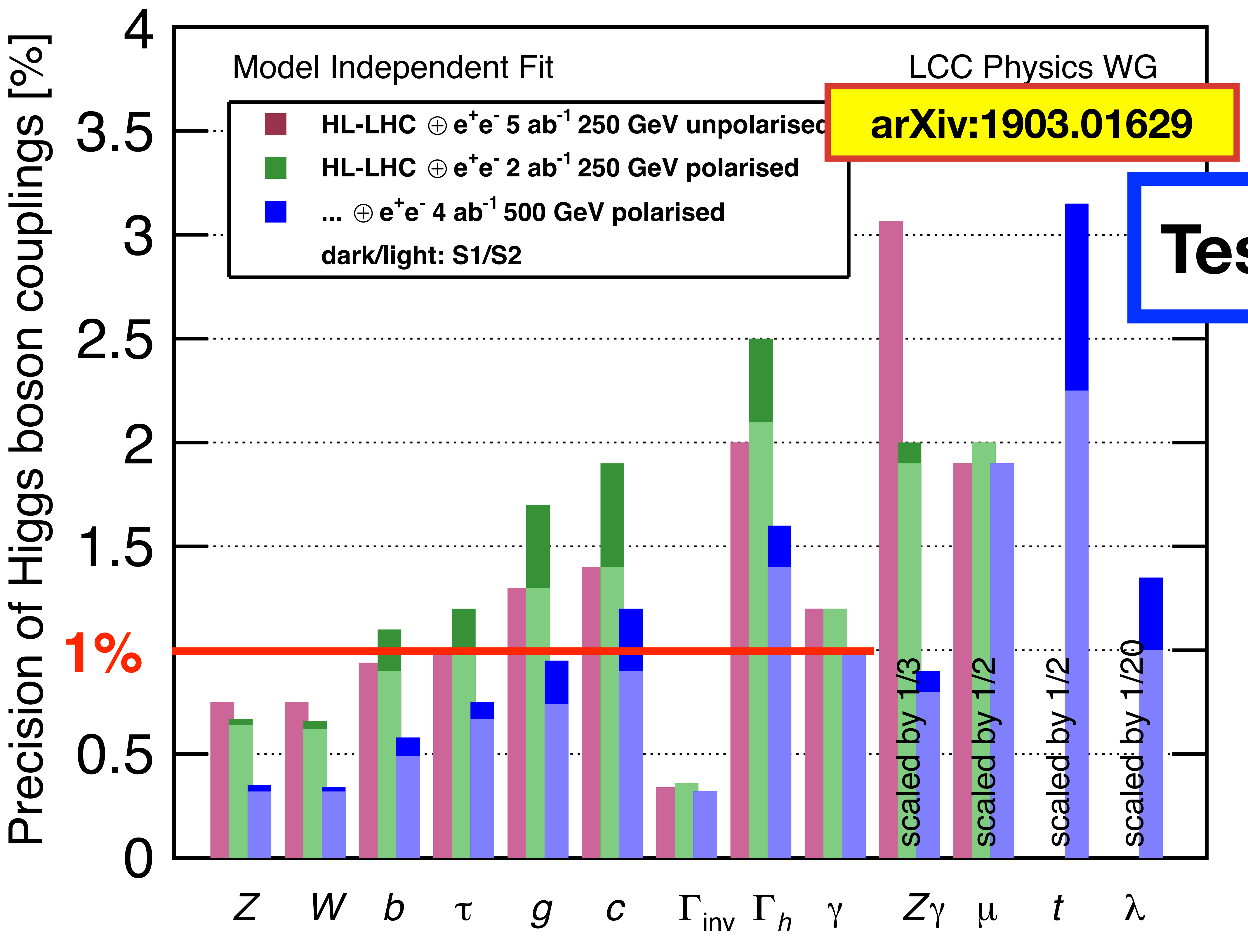

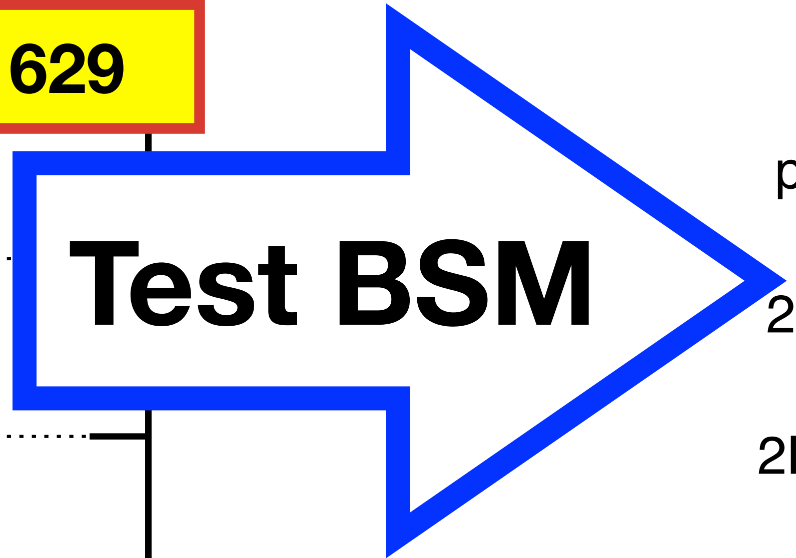

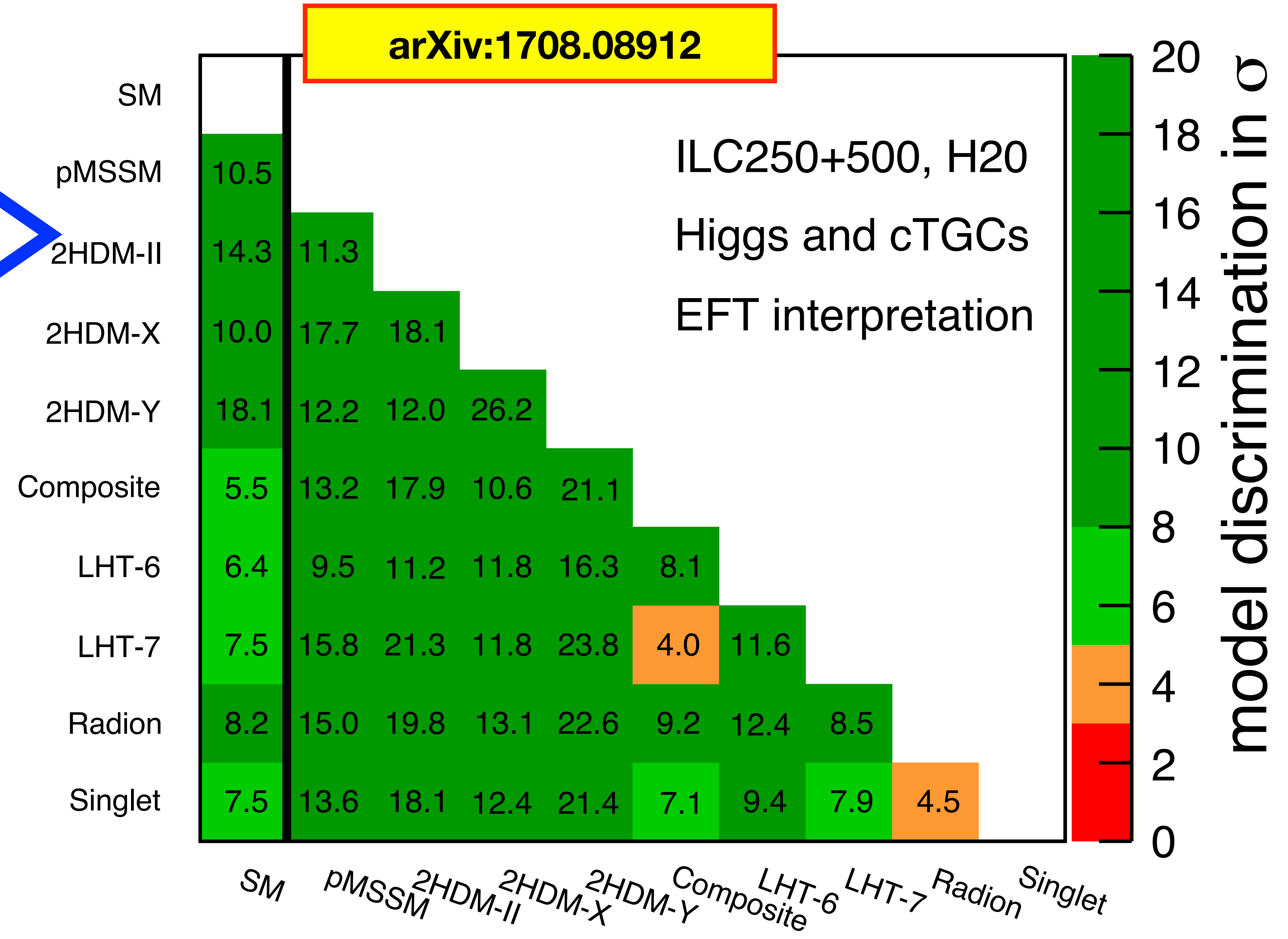

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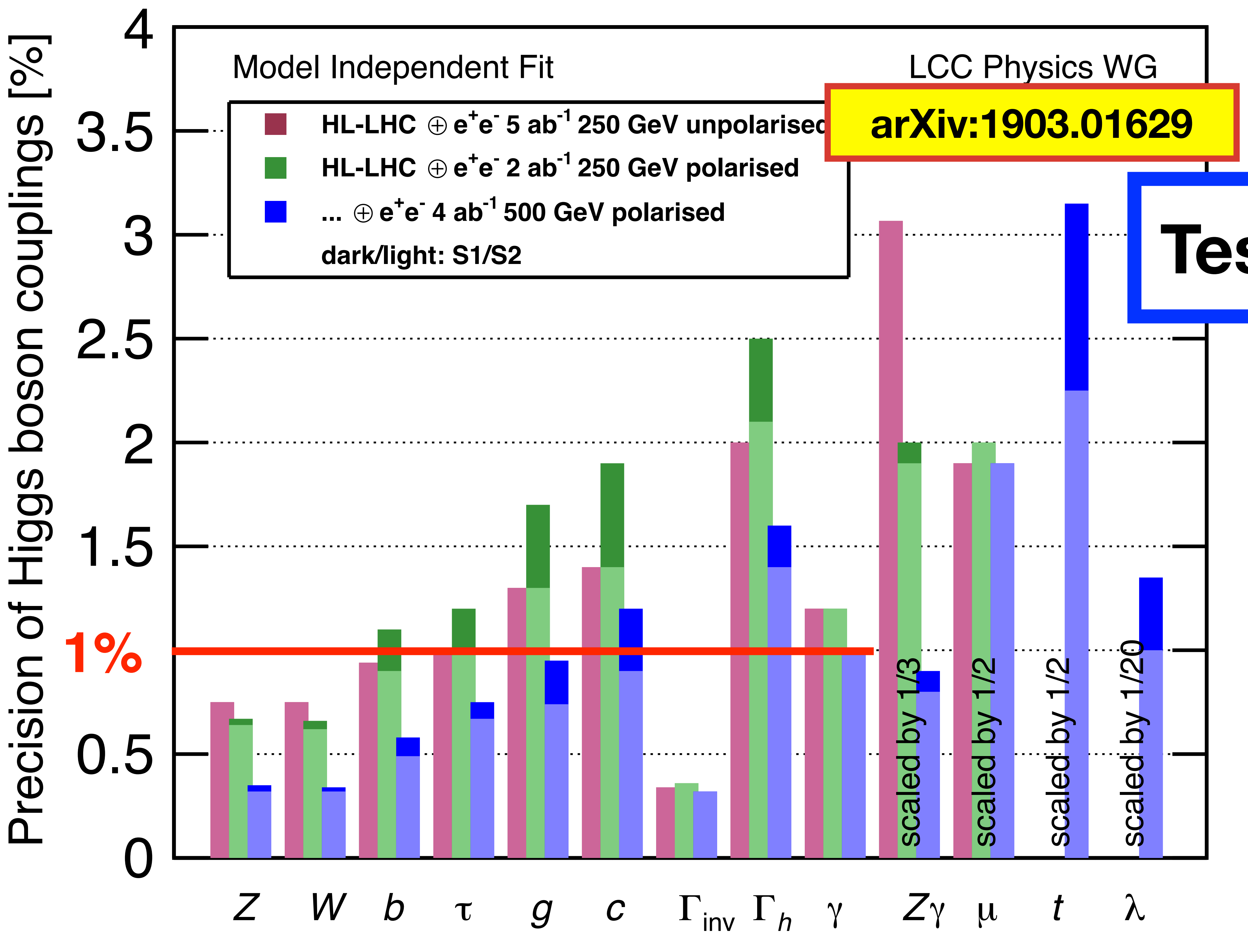
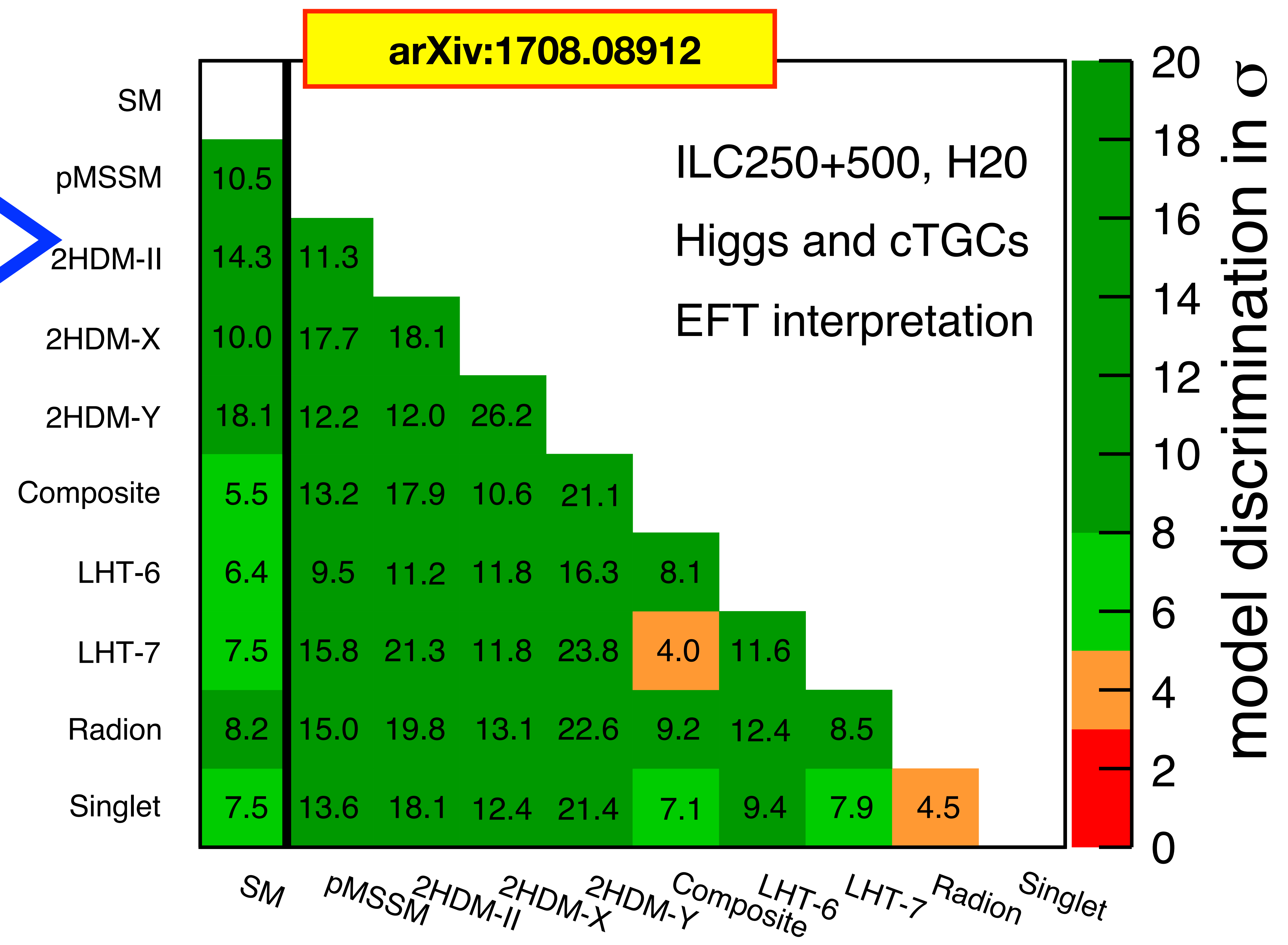


Test BSM



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discovery and identification of various BSM benchmark models (not observable at LHC)

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- e.g. from 2HDMs or additional singlets (as in NMSSM)
- Can be searched for with various techniques

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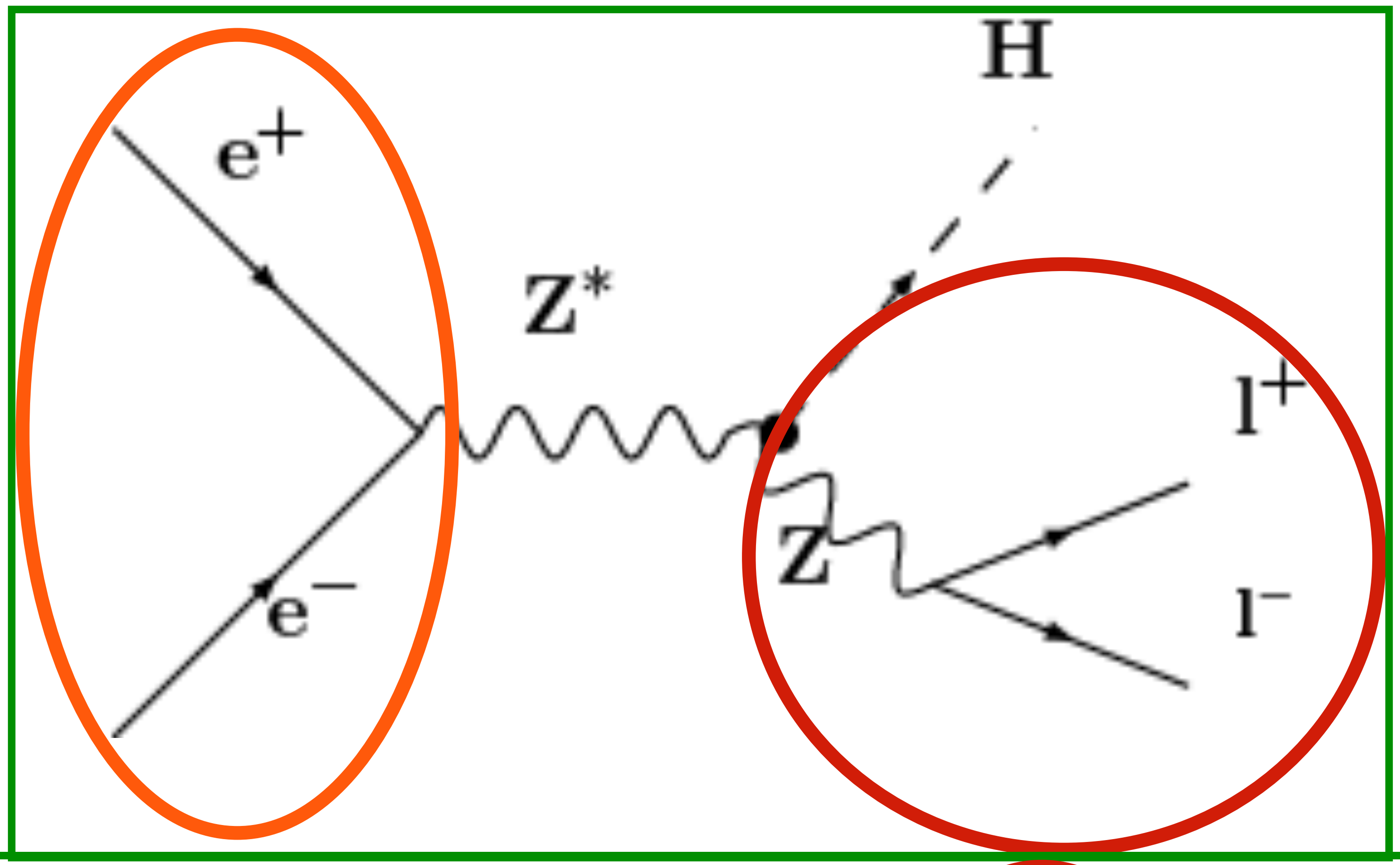

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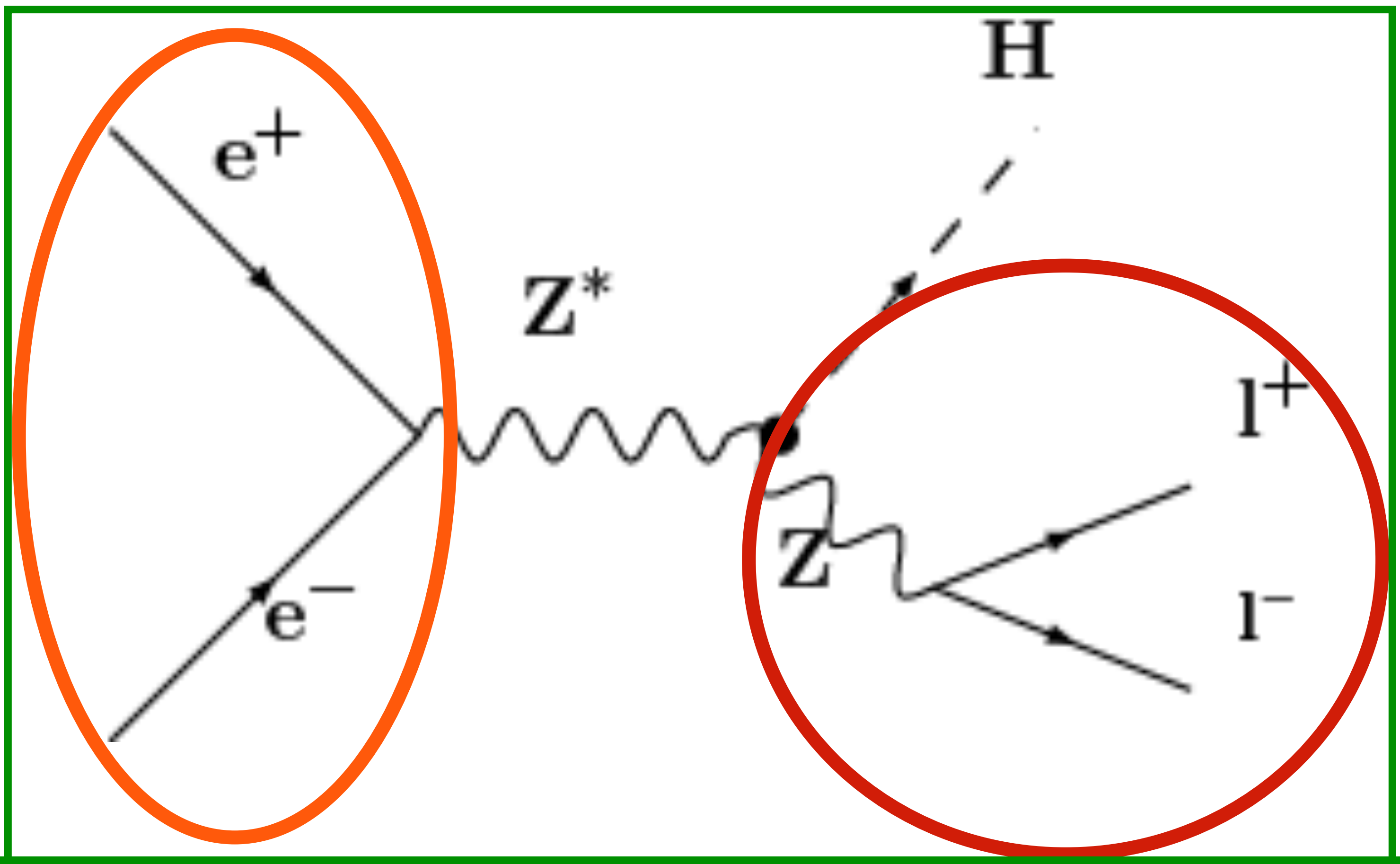

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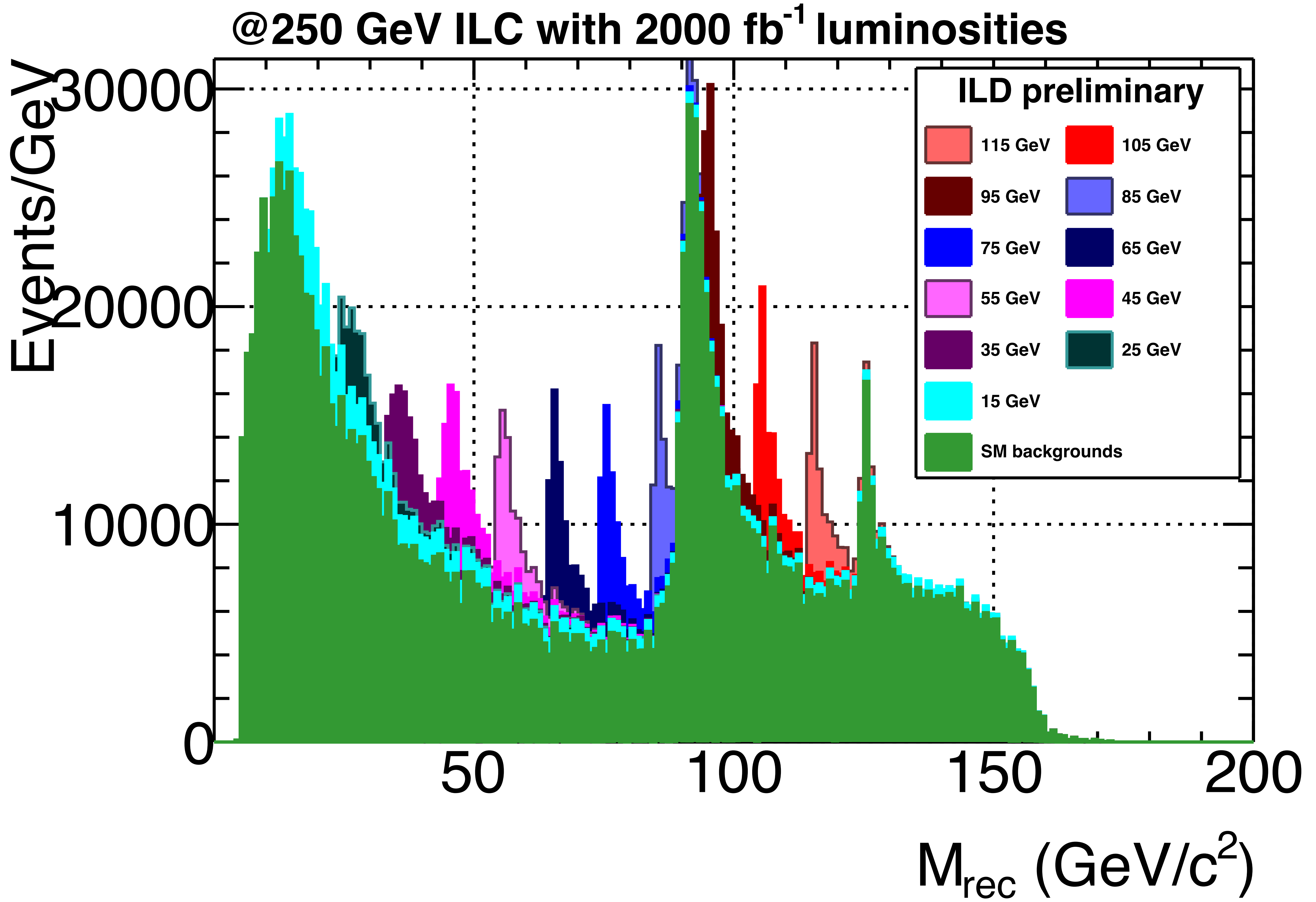

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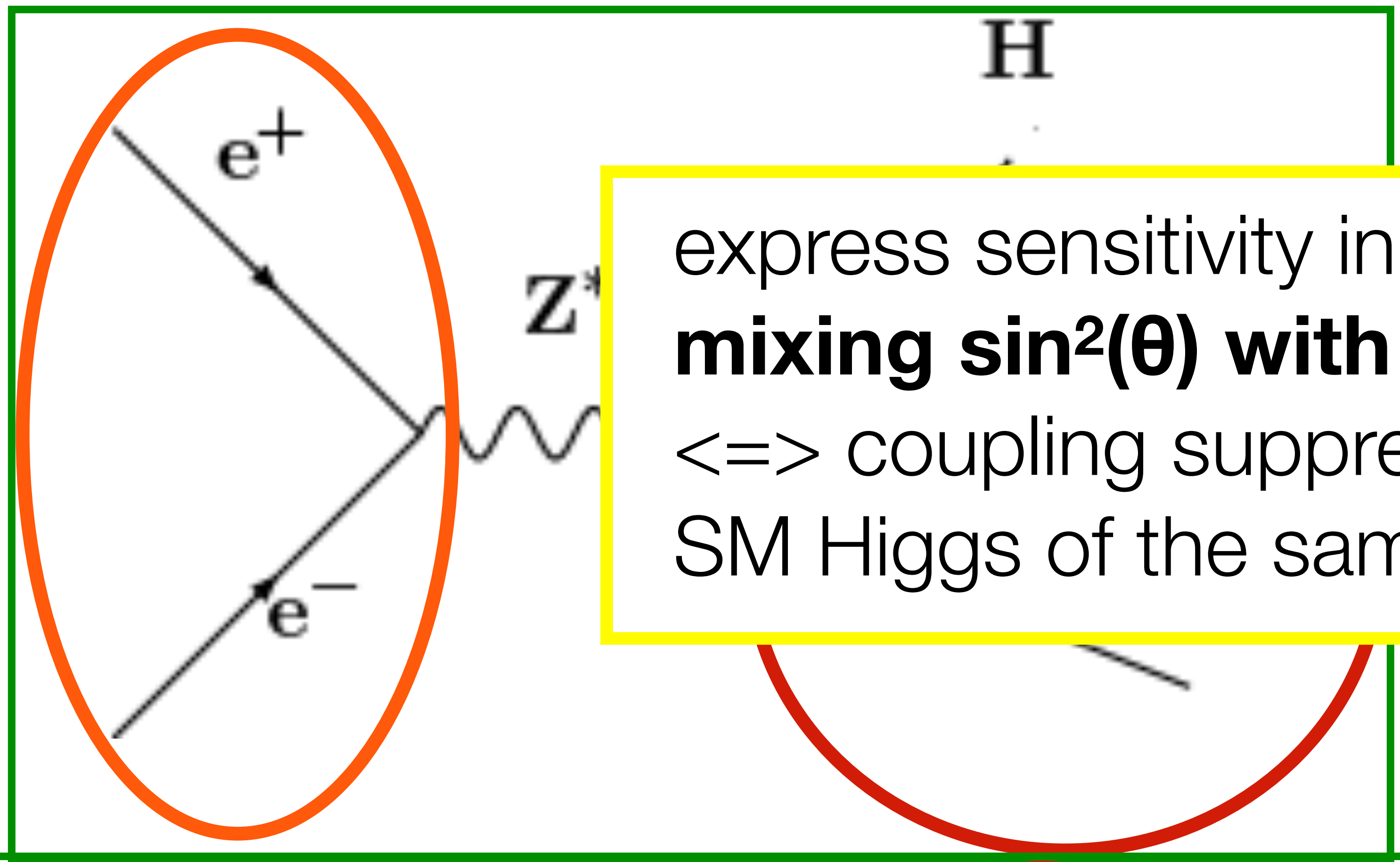
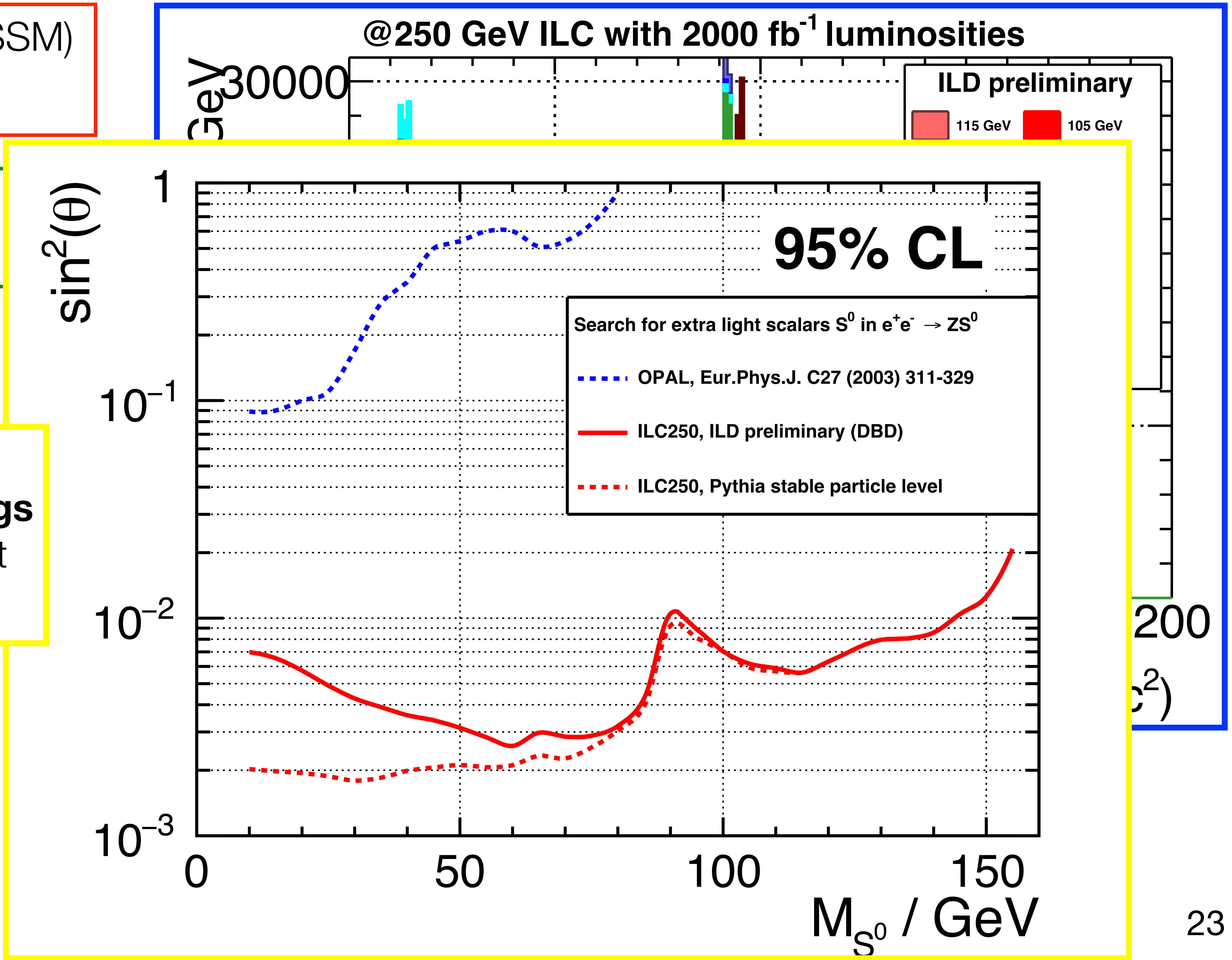


express sensitivity in terms of **mixing $\sin^2(\theta)$ with SM Higgs** <=> coupling suppression wrt SM Higgs of the same mass

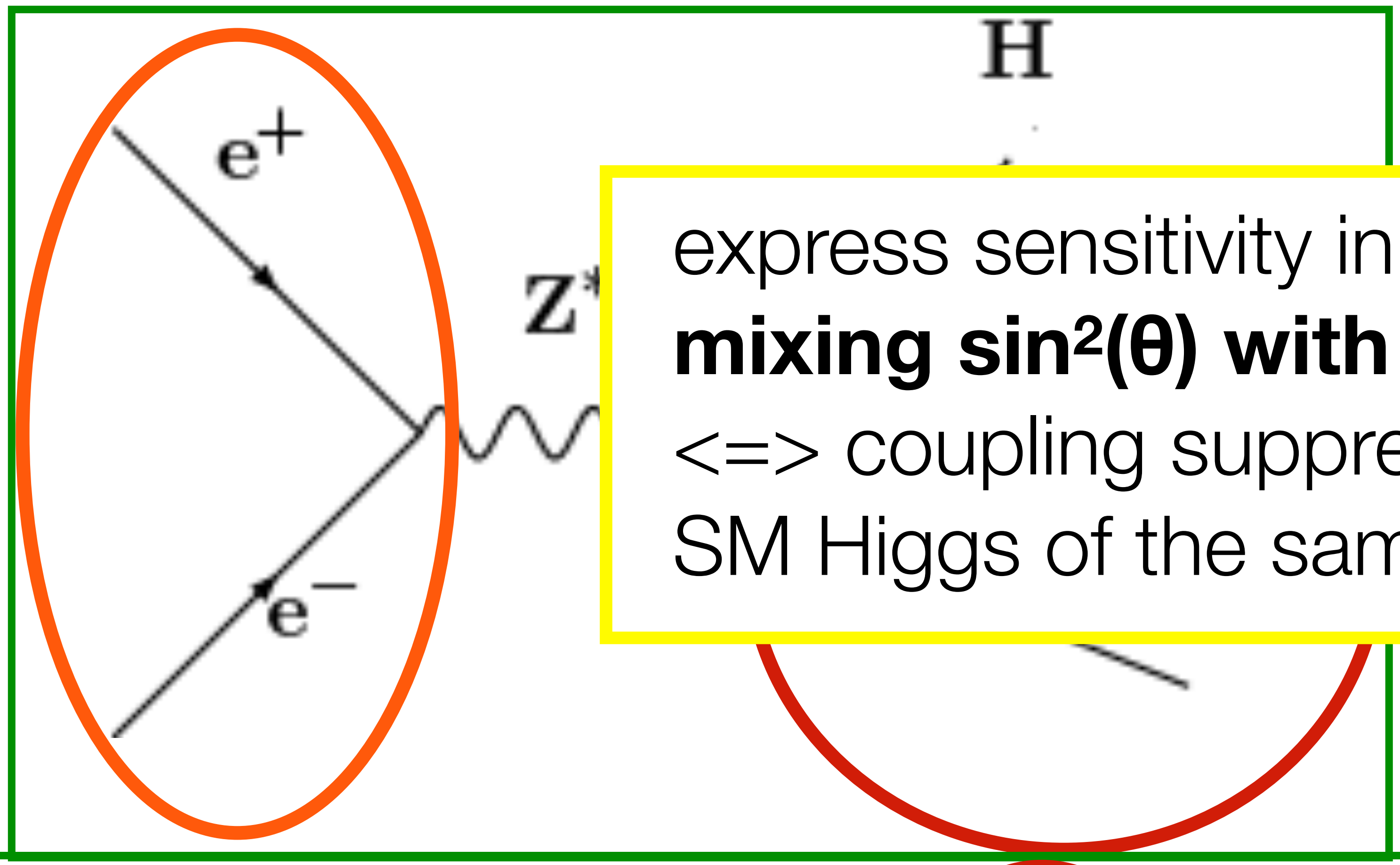
$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$



Additional Scalar(Higgs) Bosons

- e.g. from 2HDMs or additional singlets (as in NMSSM)
- Can be searched for with various techniques

- **Here: recoil against Z ->μ⁺μ⁻ @250 GeV**
  - analogous to SM Higgs recoil



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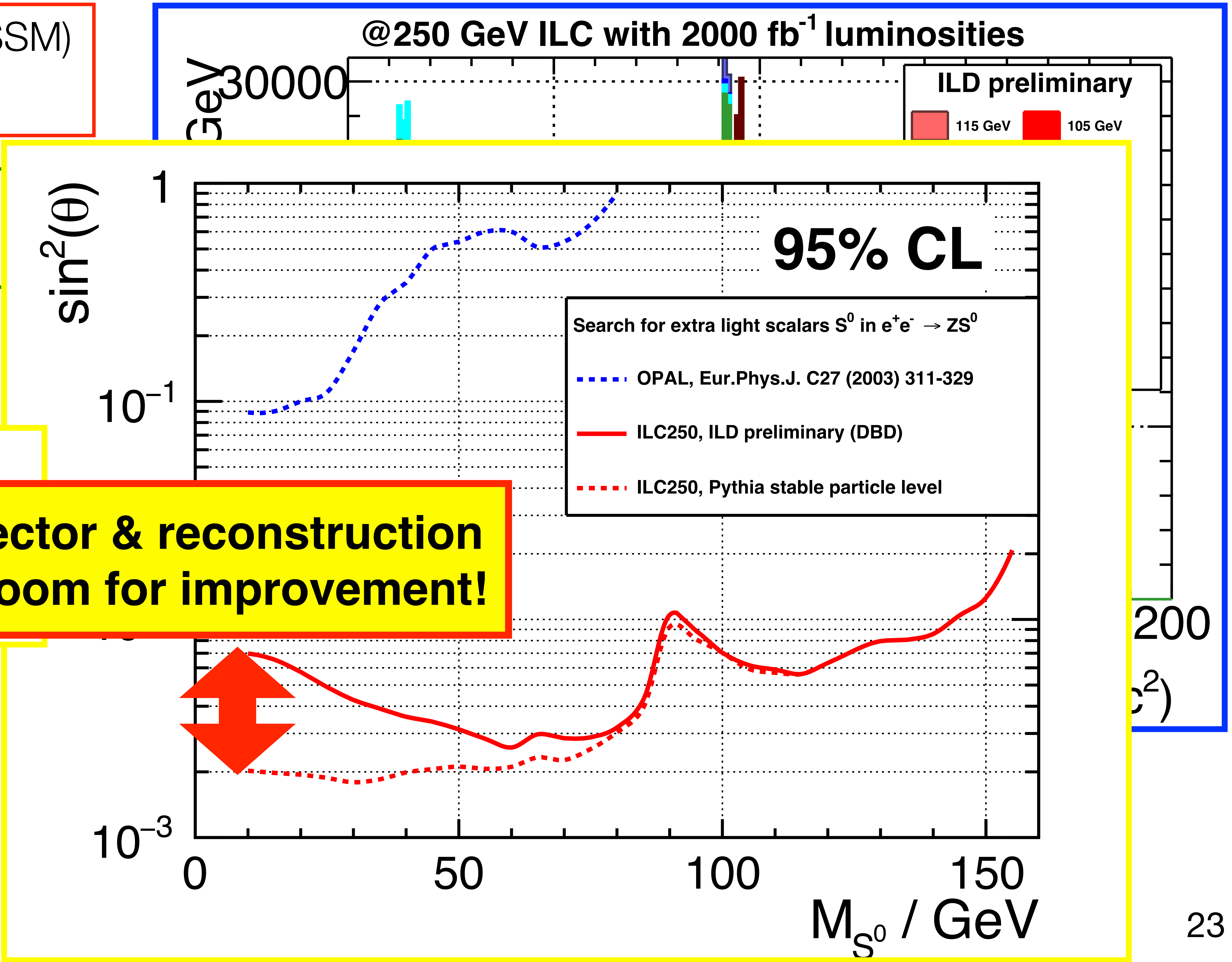
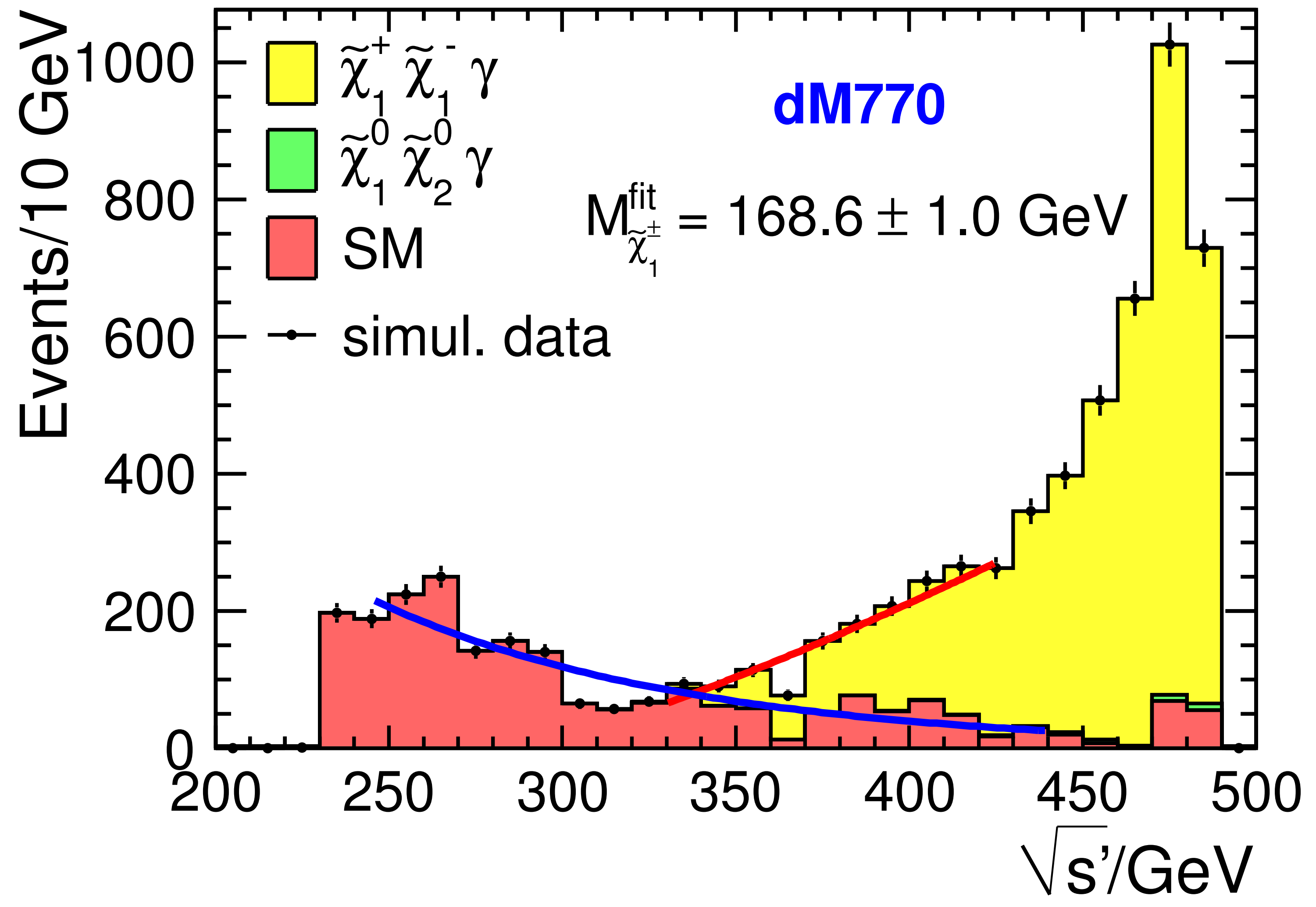


detector & reconstruction => room for improvement!

Supersymmetric Partners of the Higgs Boson

higgsinos with sub-GeV mass splitting Eur.Phys.J. C73 (2013) no.12, 2660



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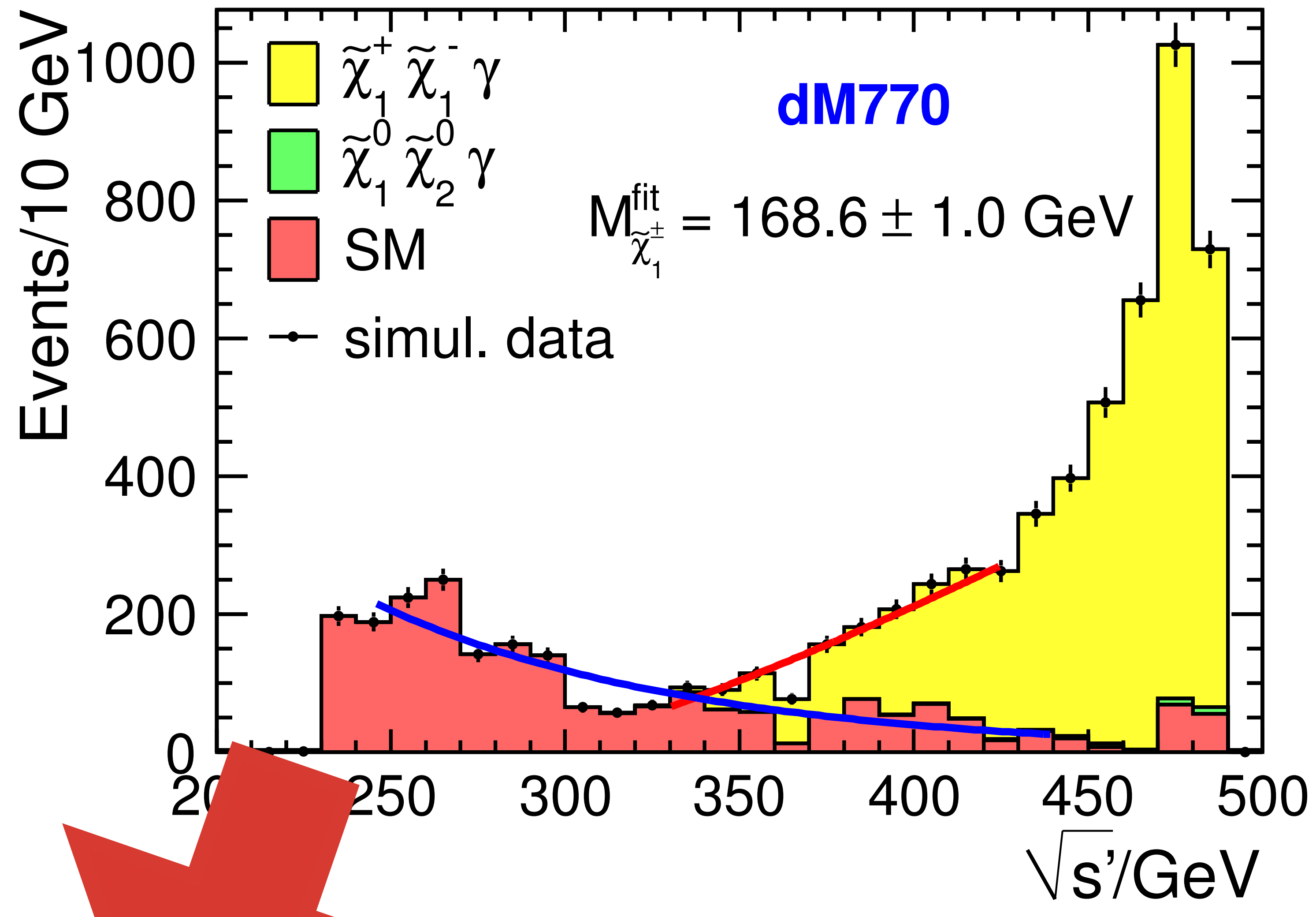

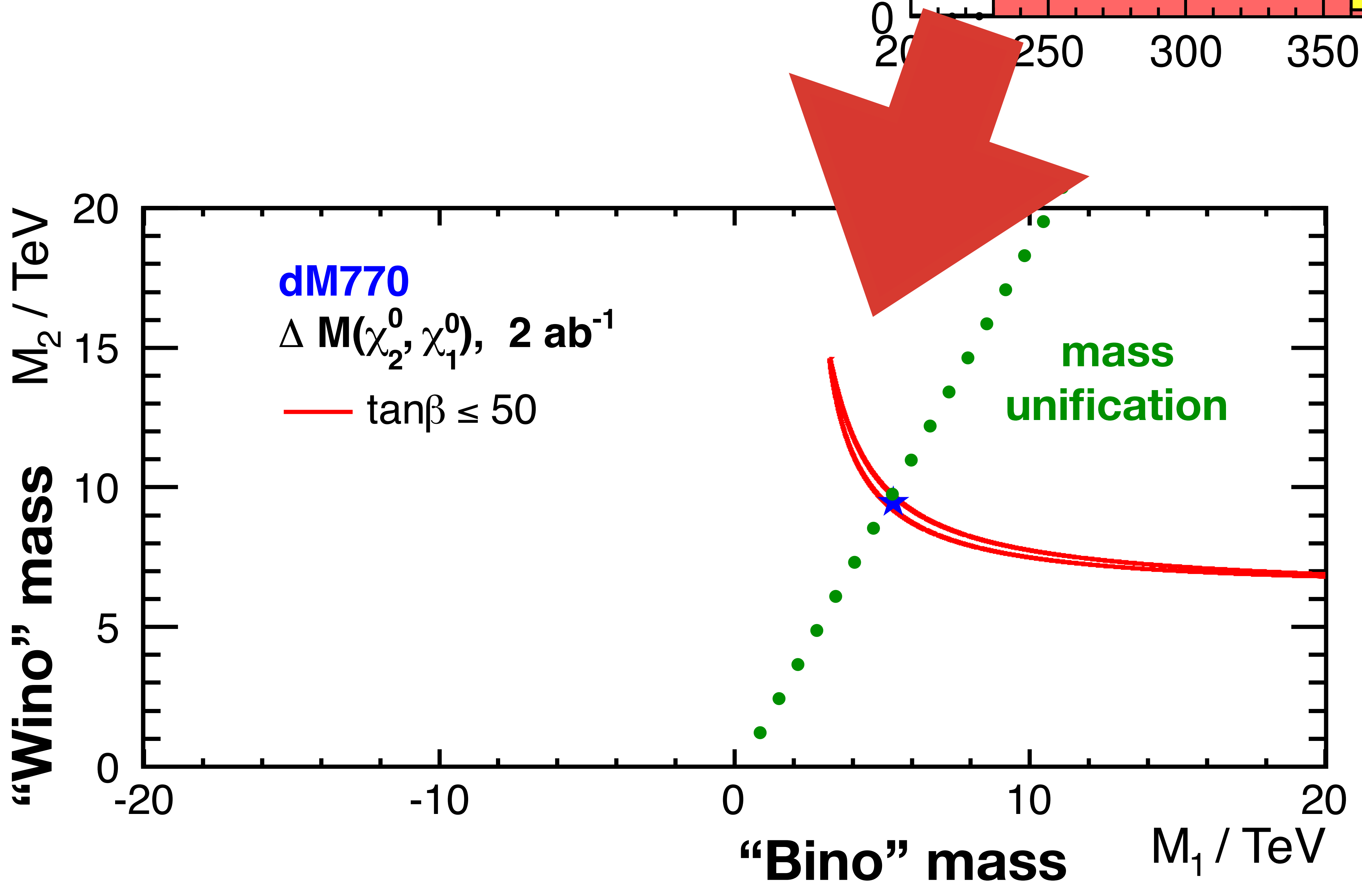

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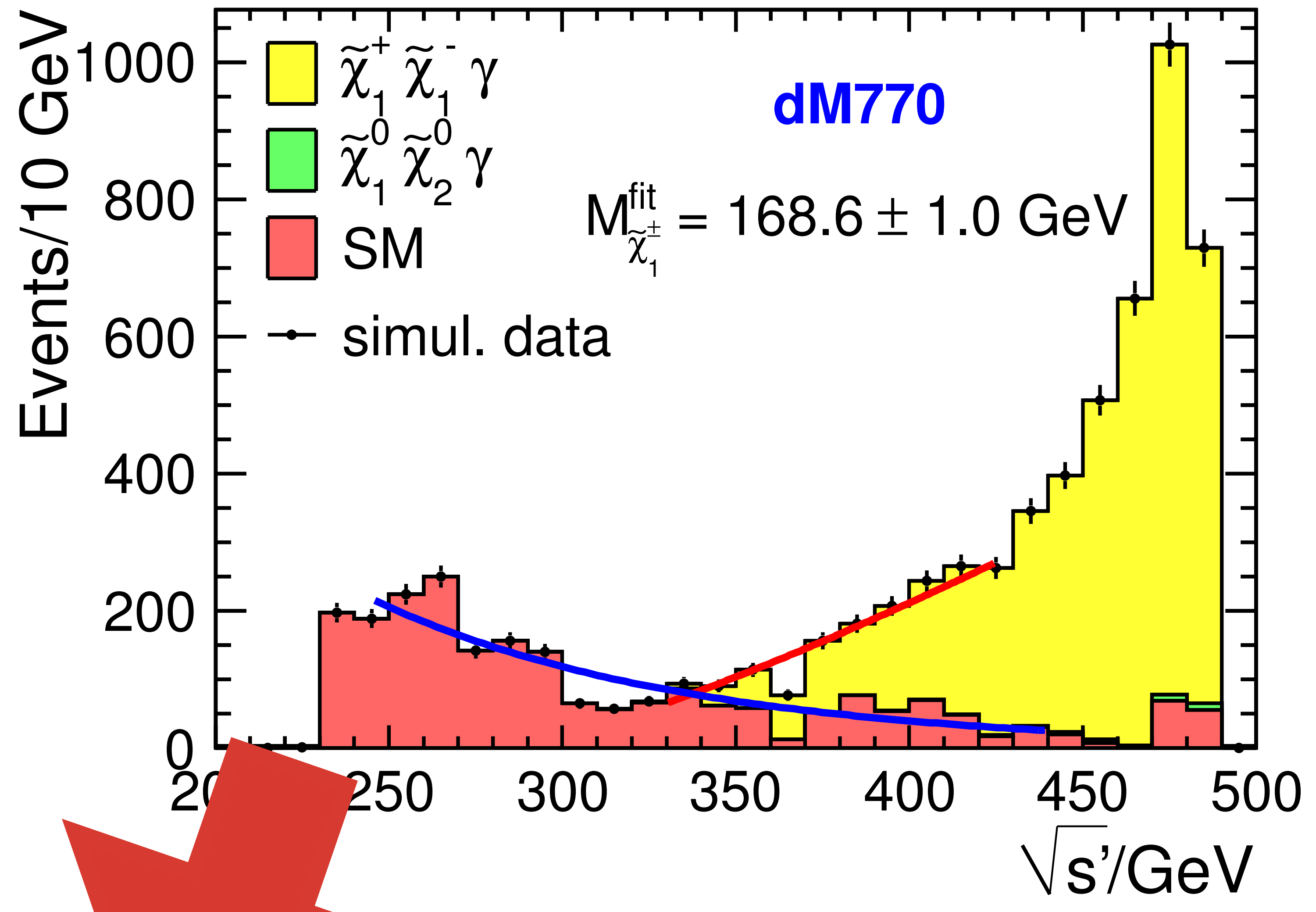

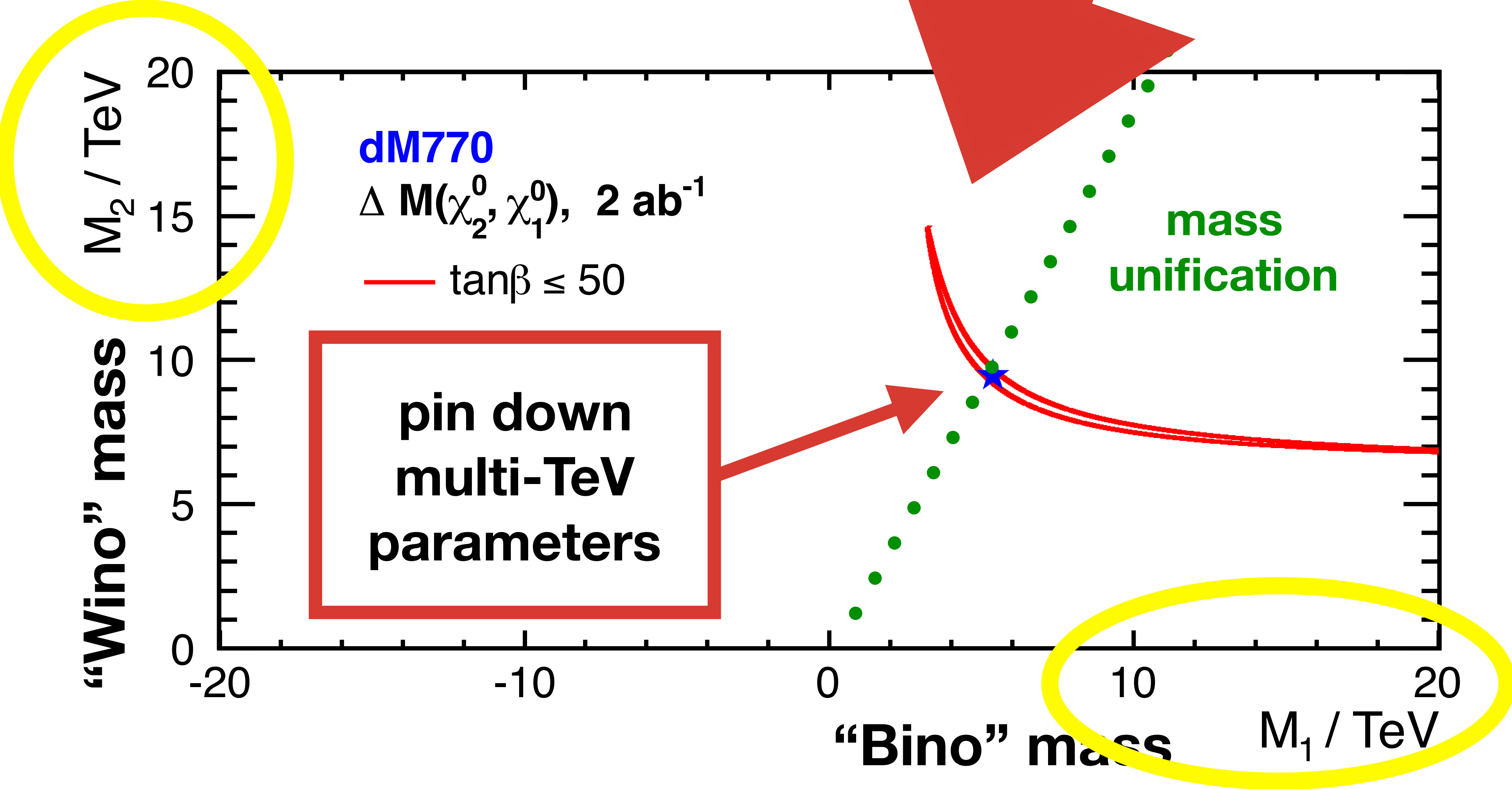

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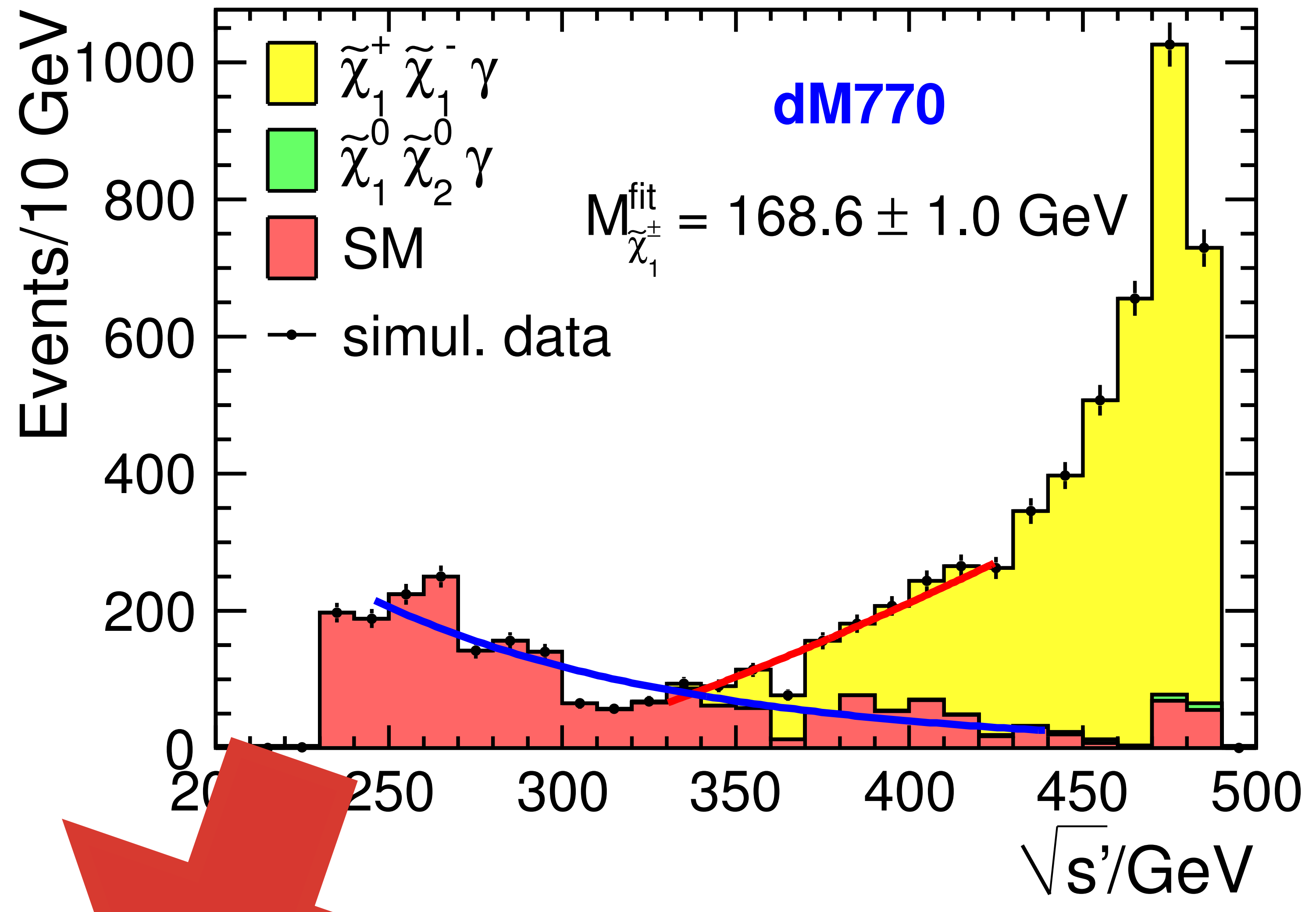
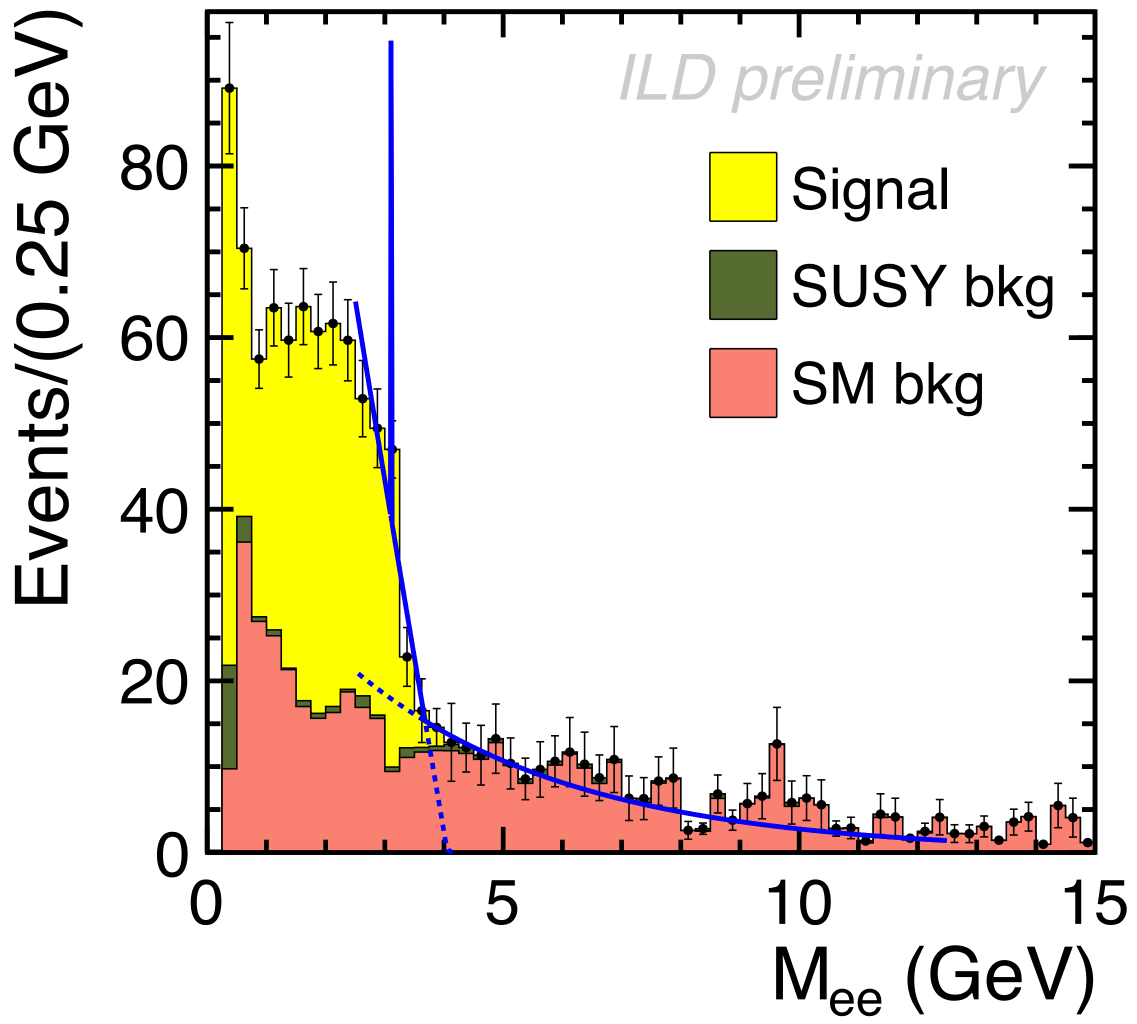
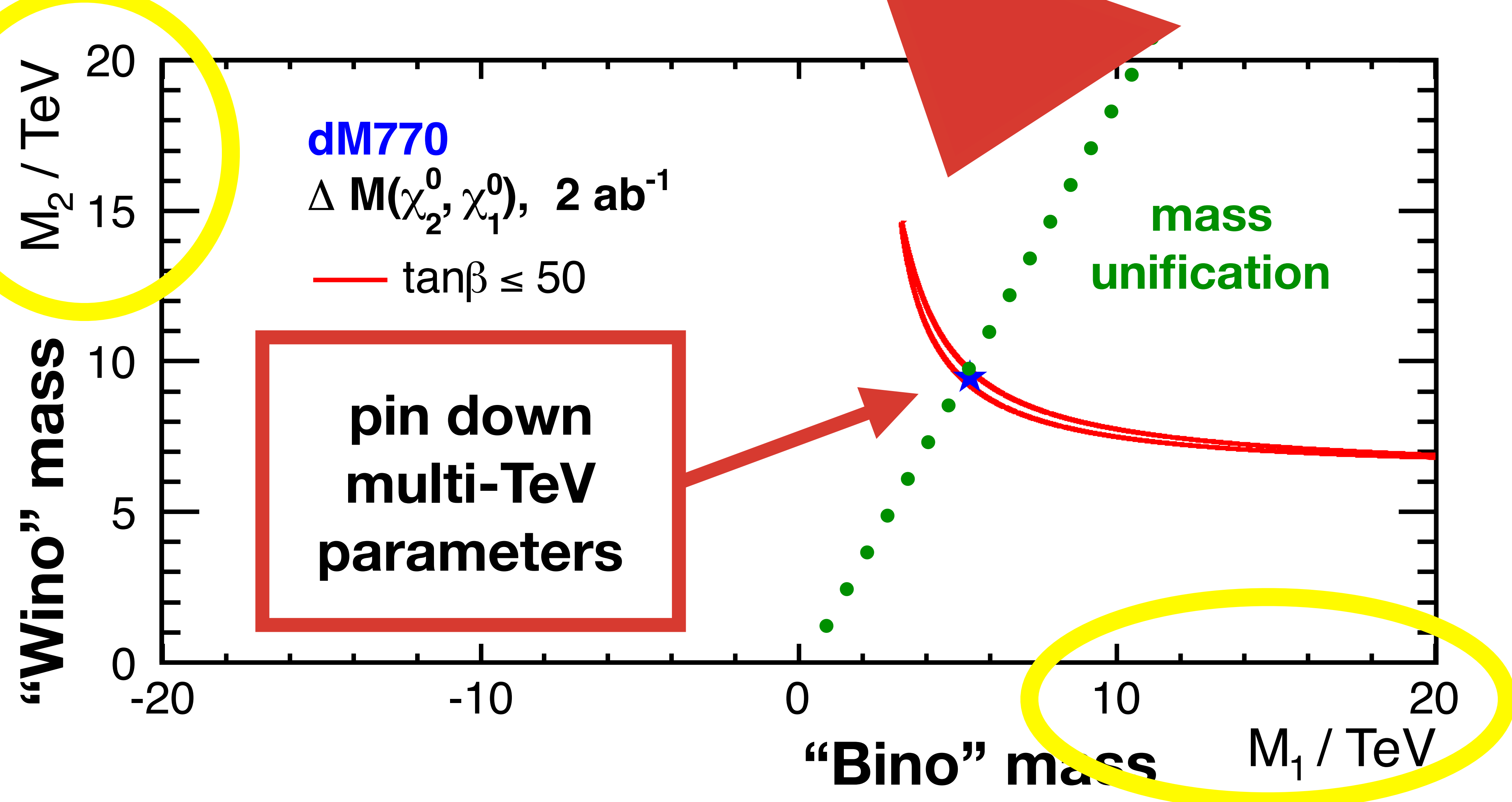




higgsinos with few GeV mass splitting DESY-THESIS-2018-035



pin down multi-TeV parameters

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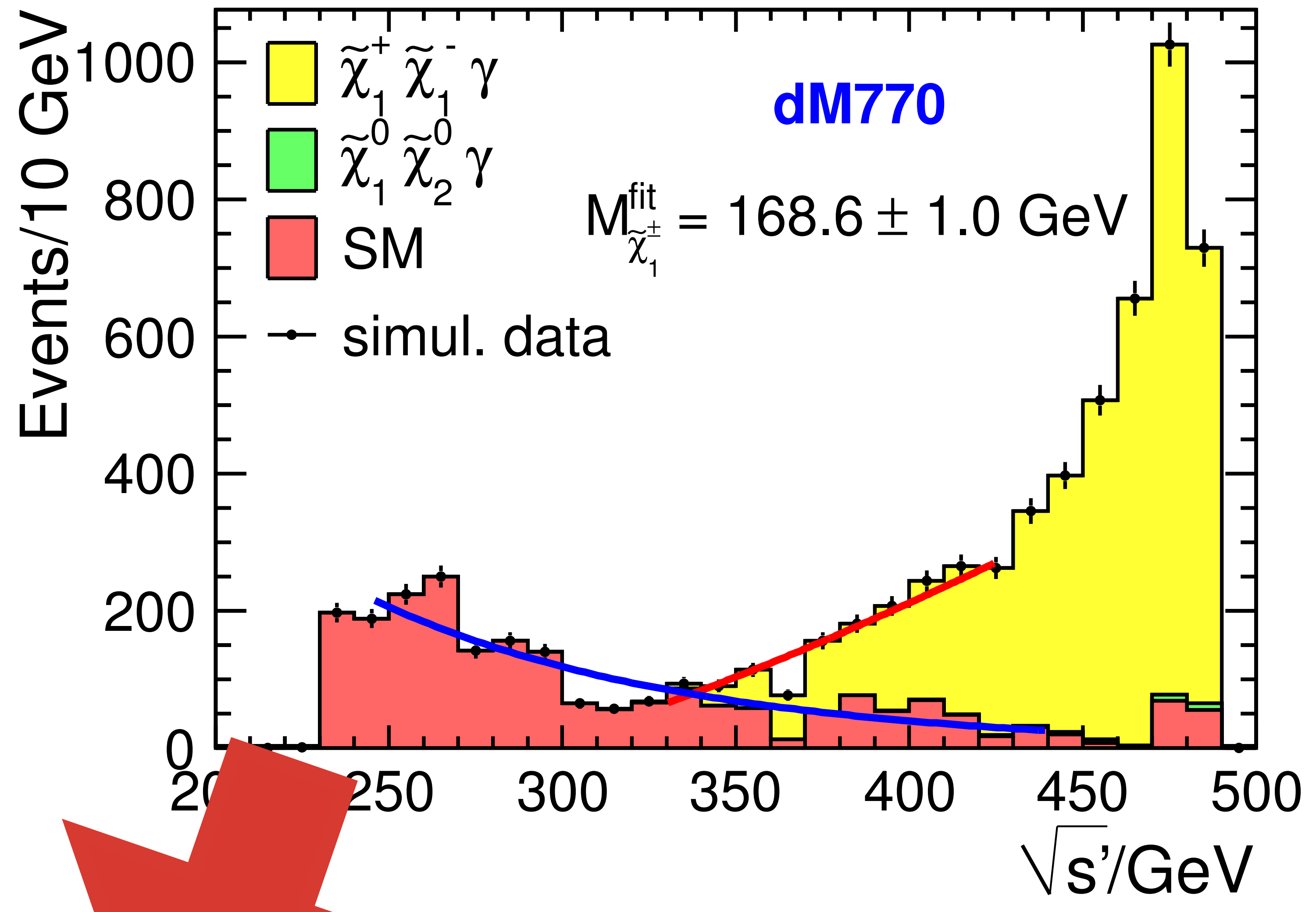

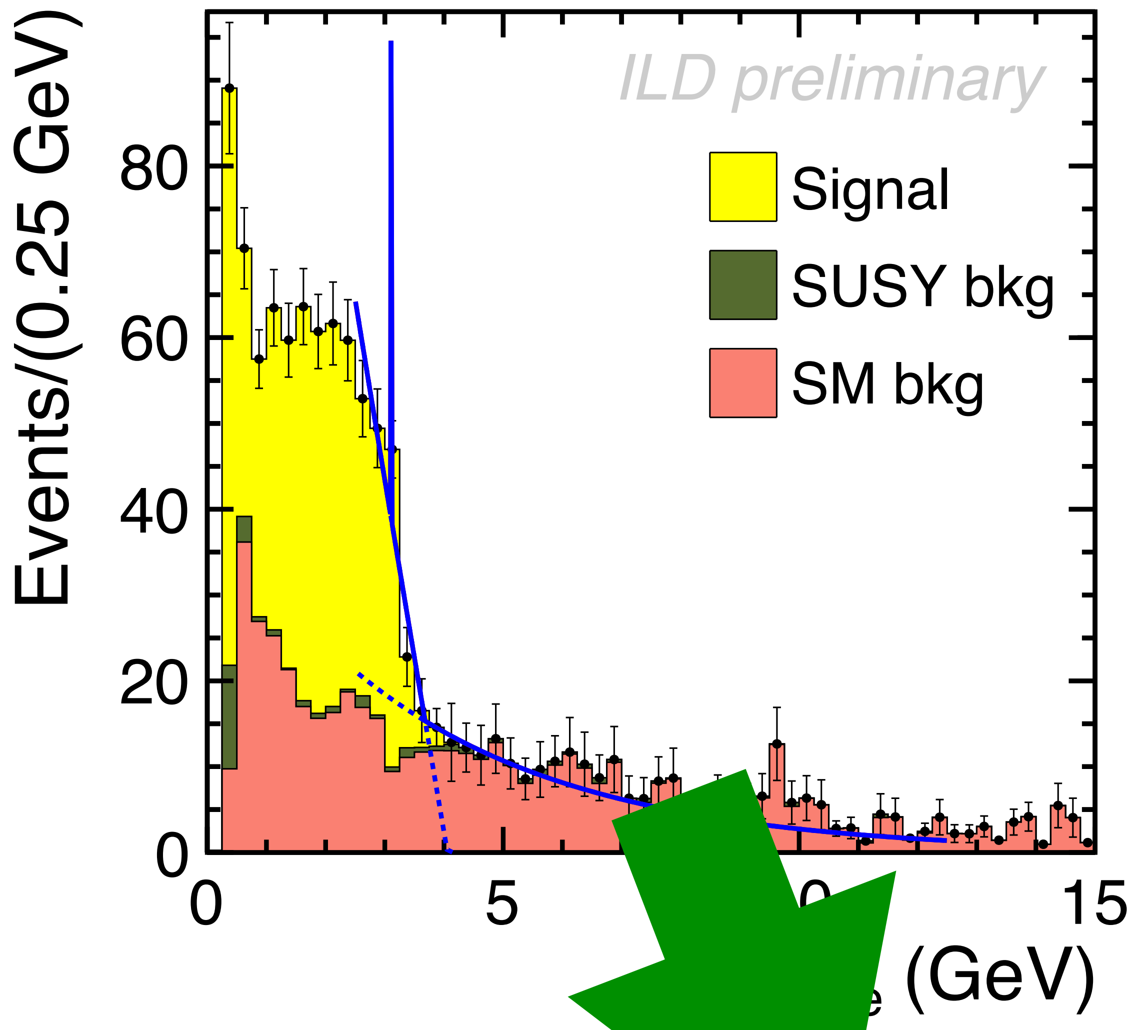

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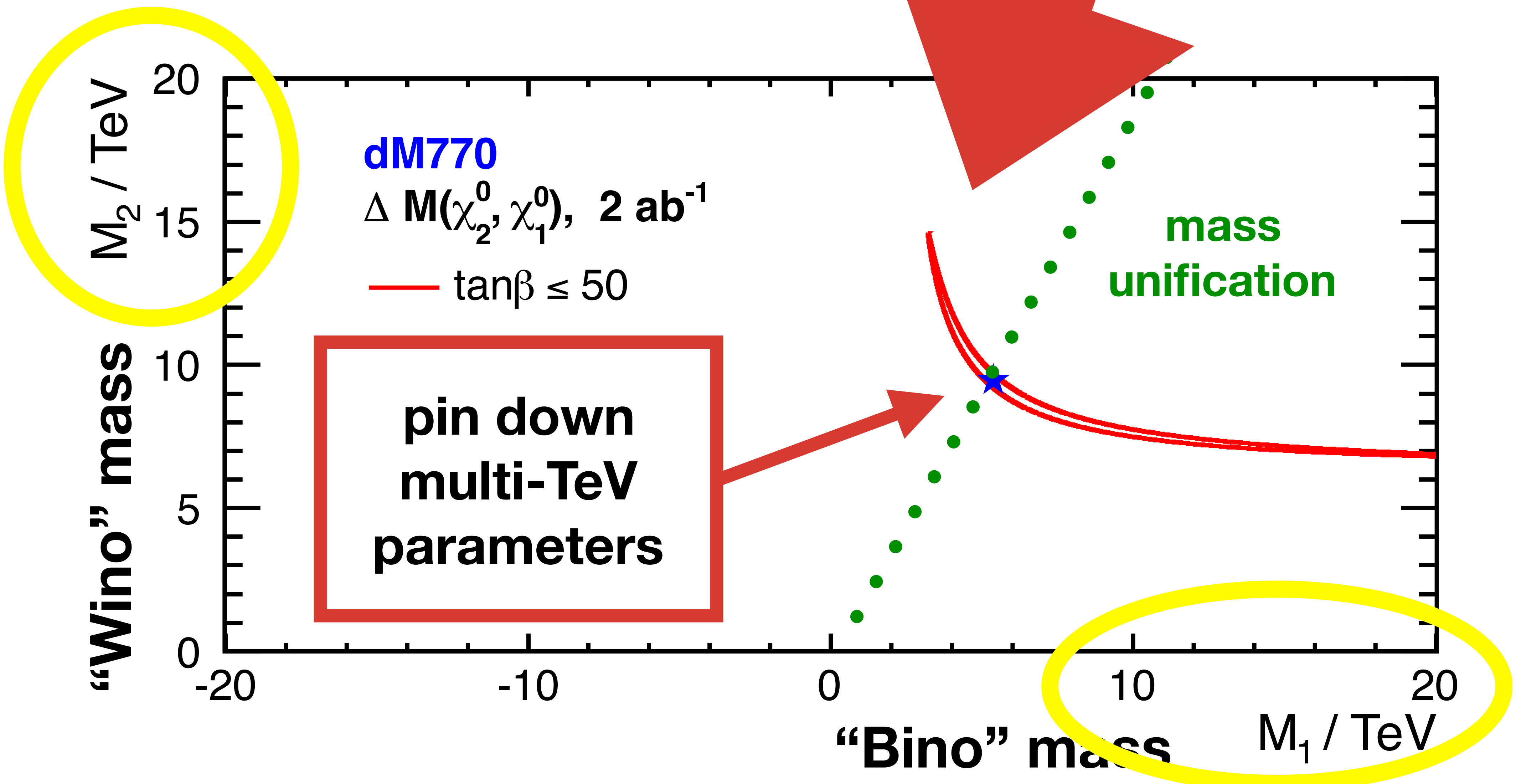

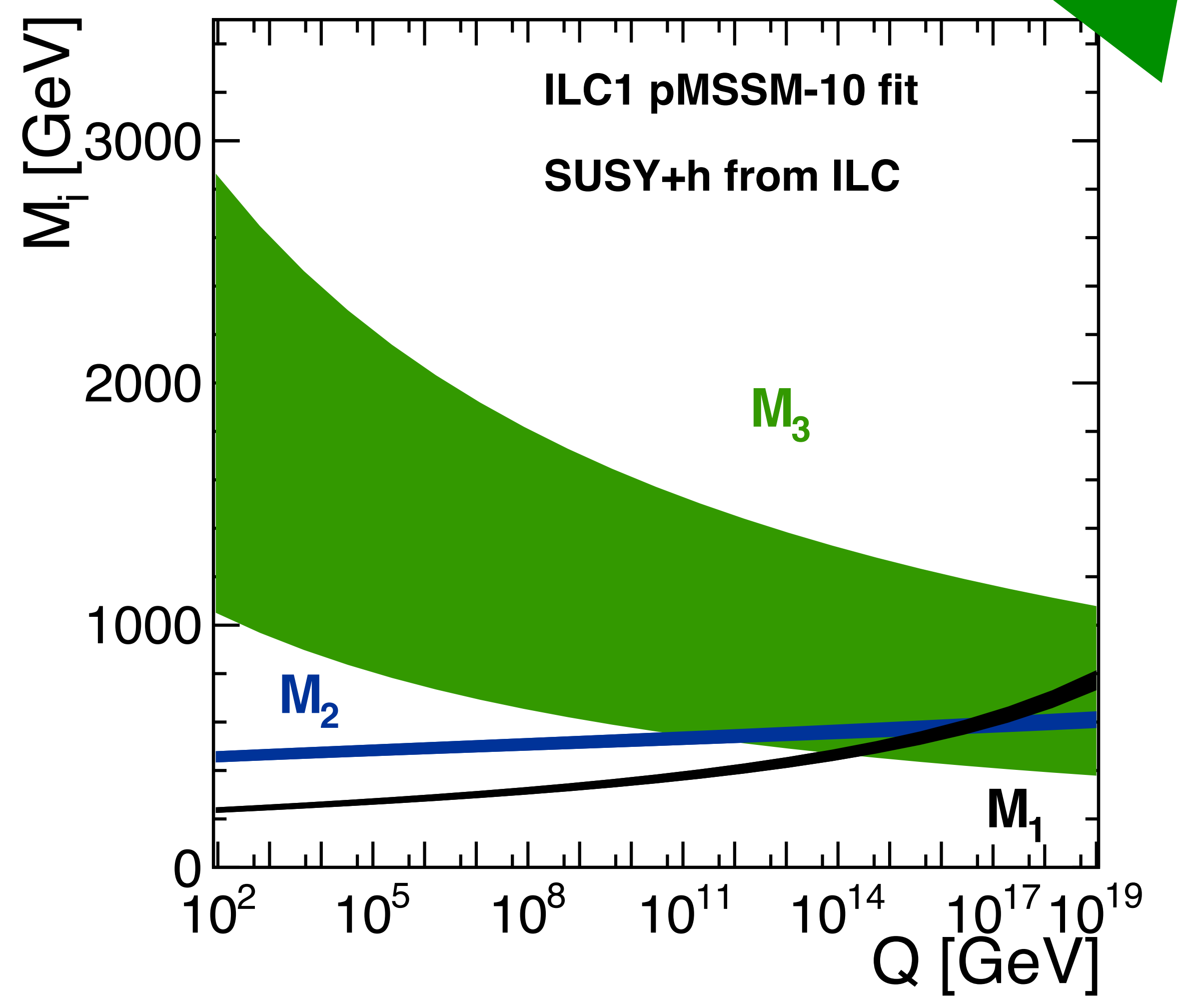

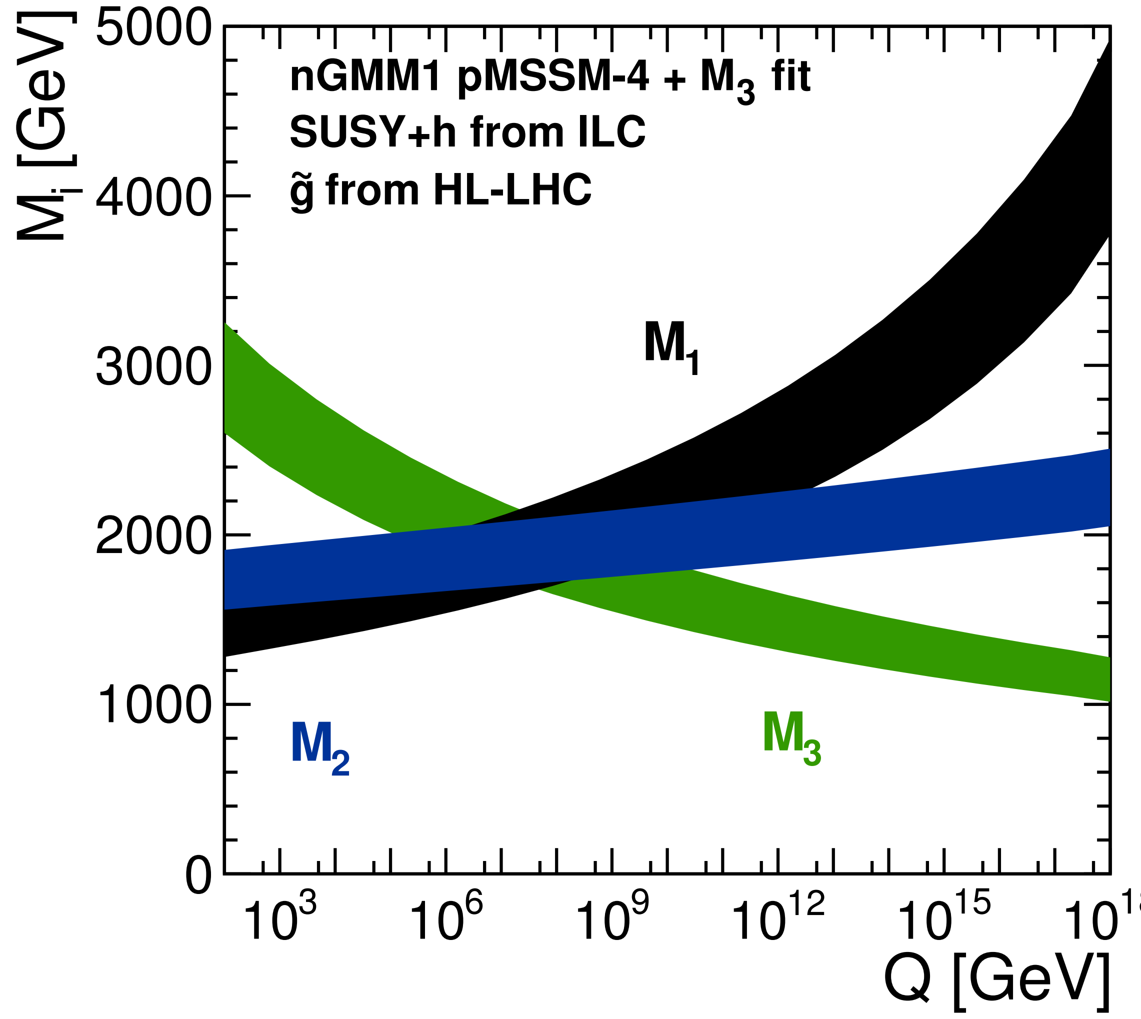

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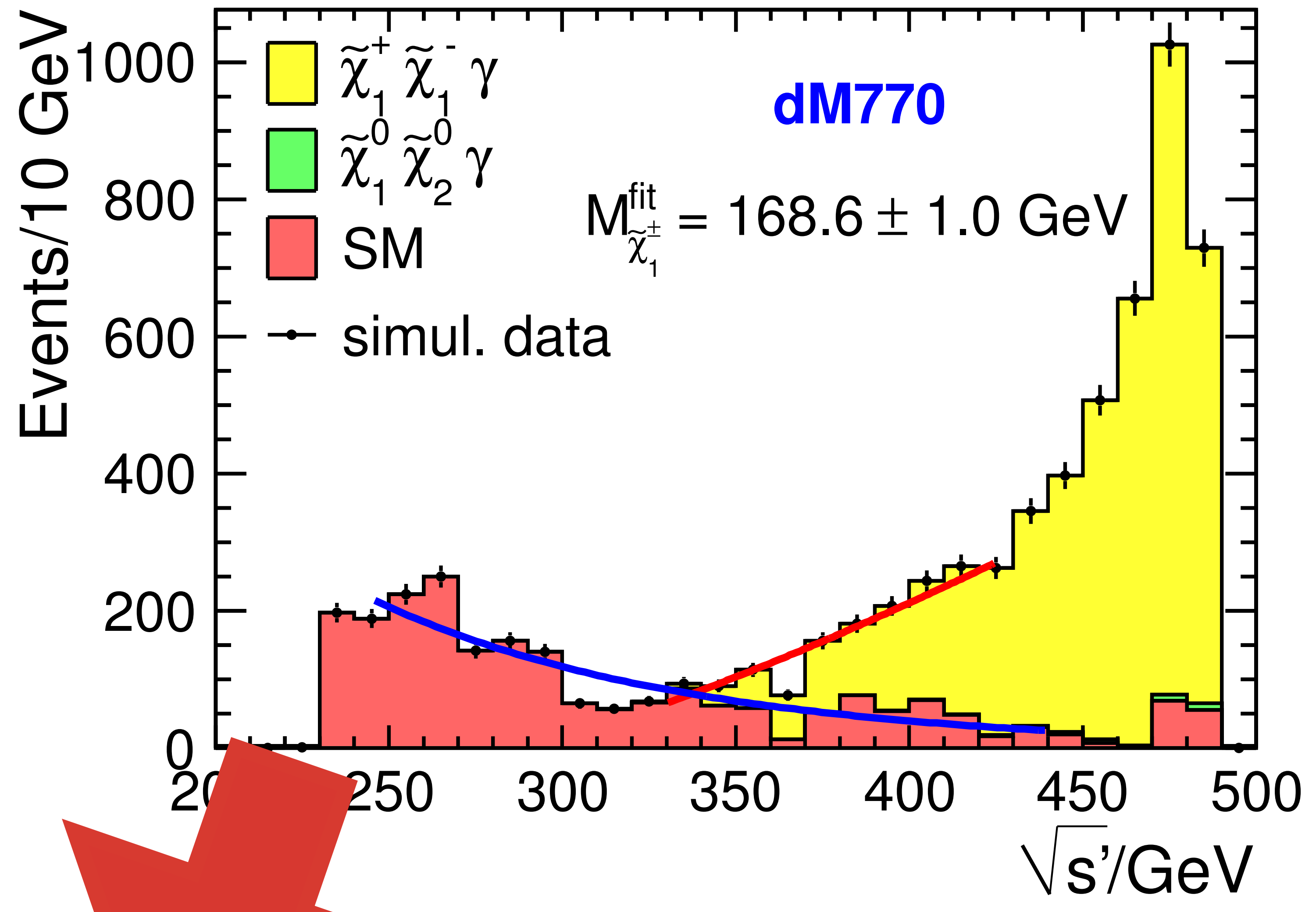

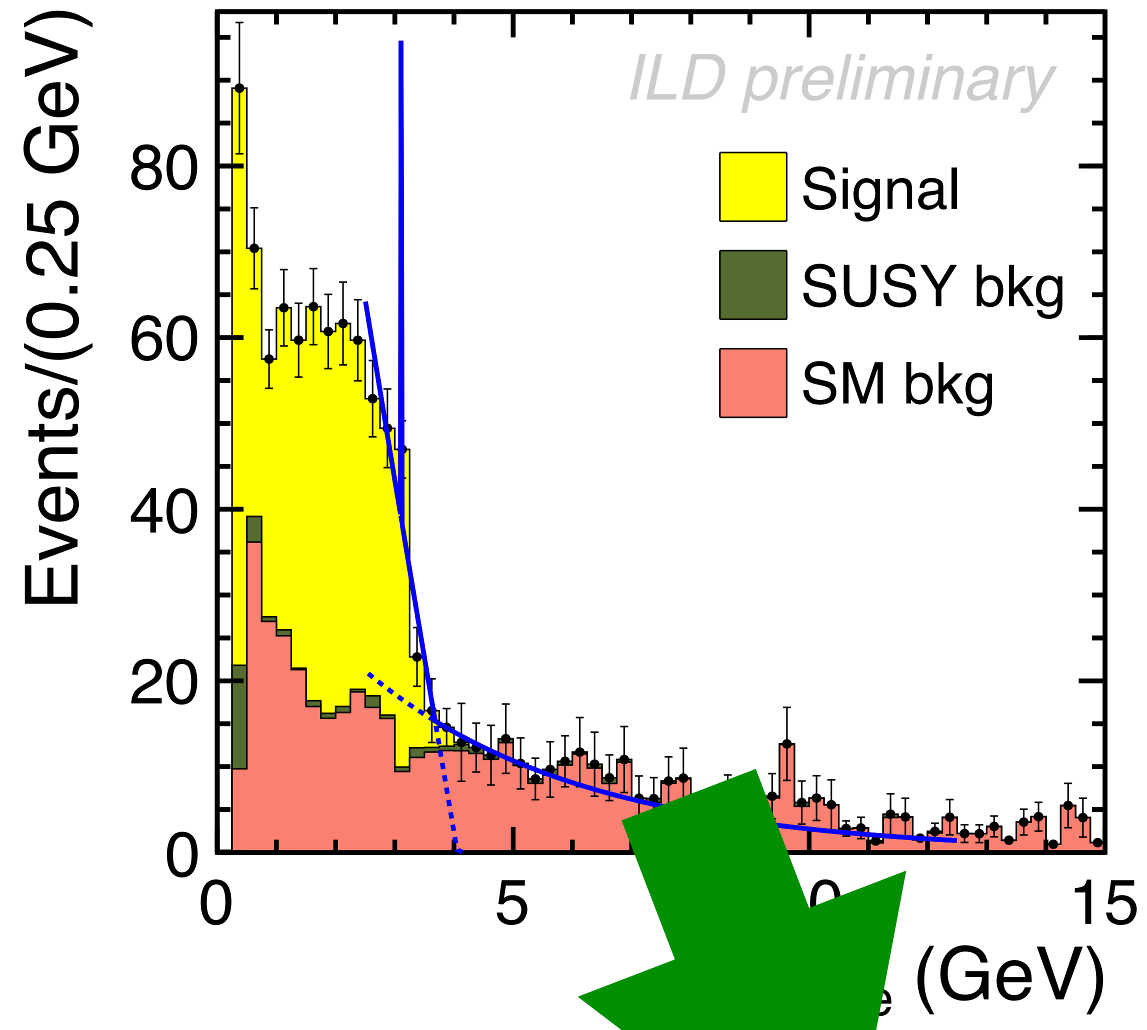

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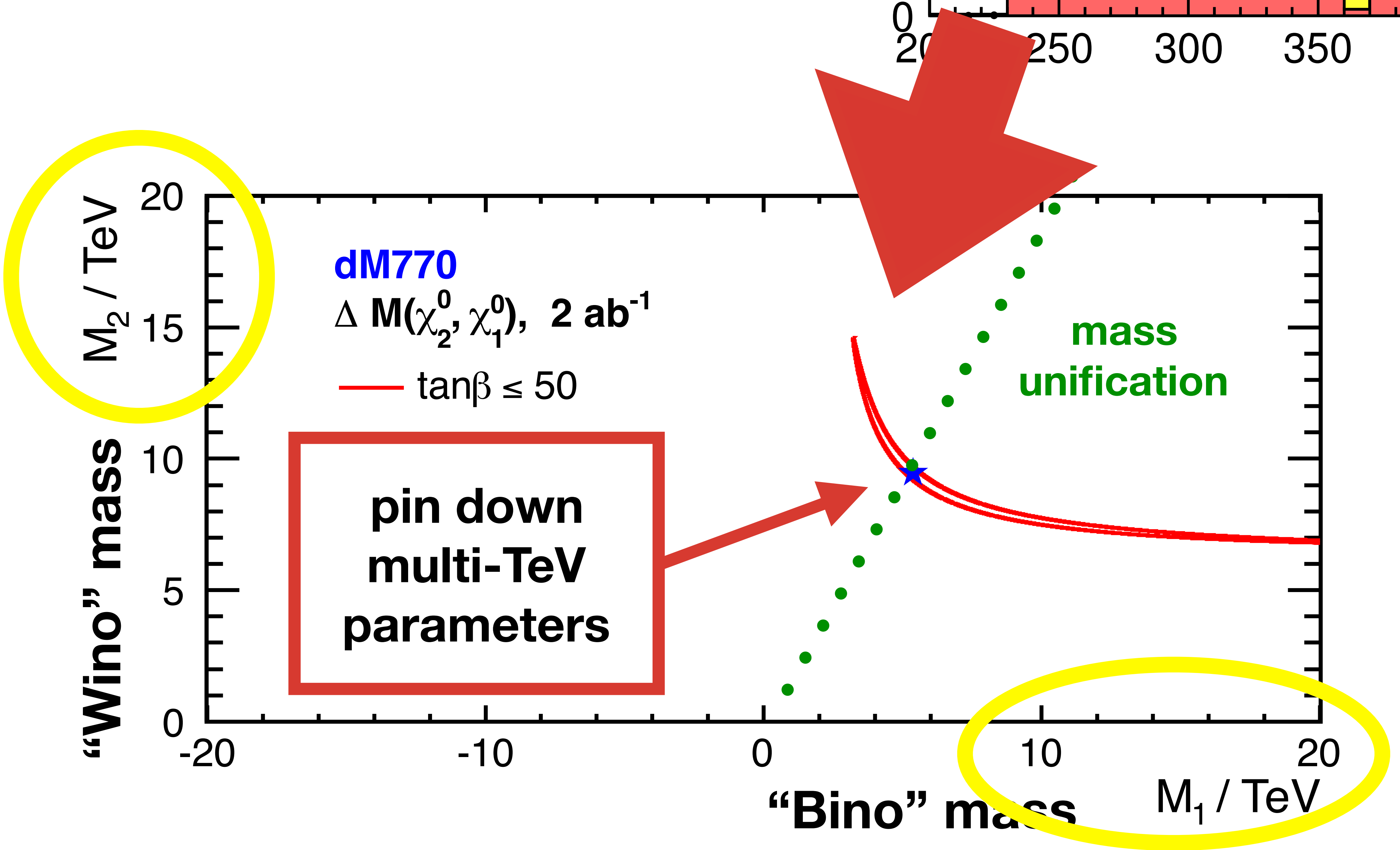

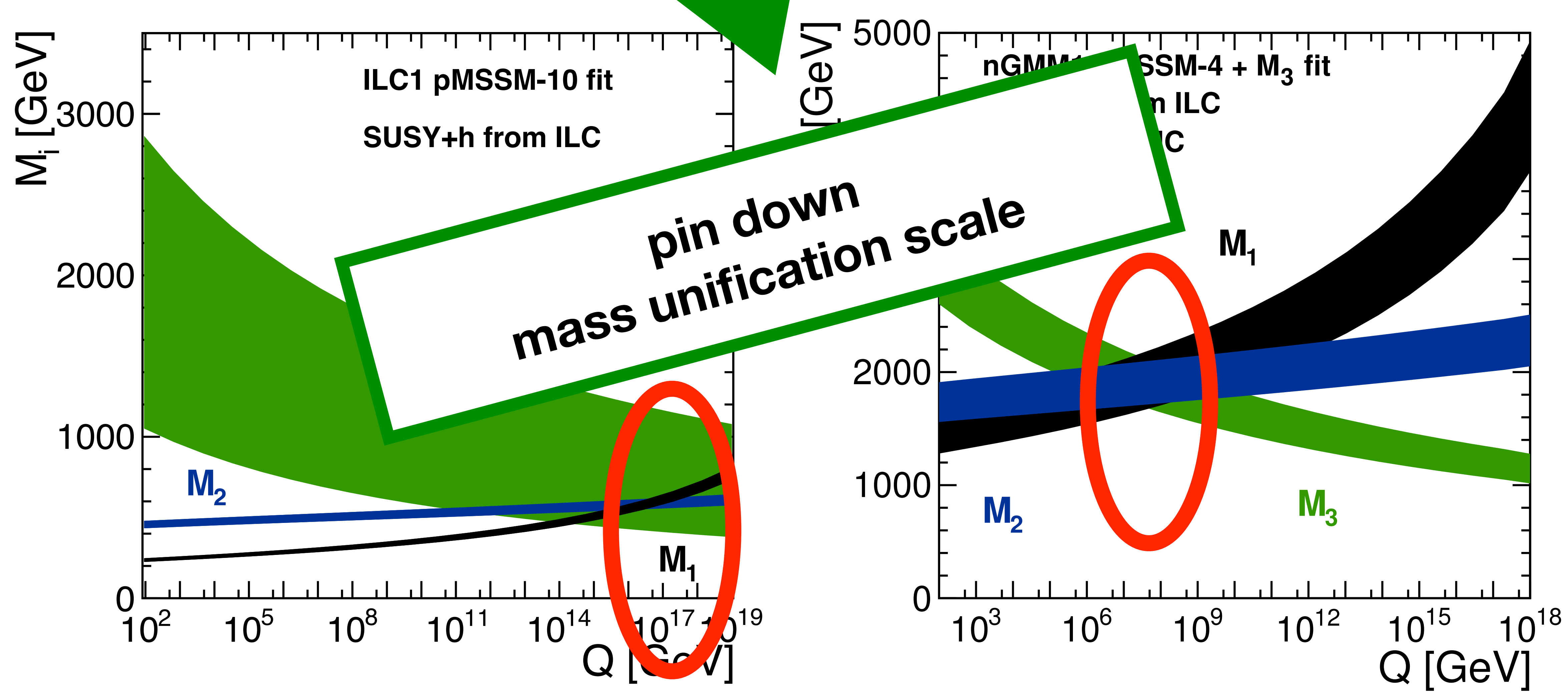

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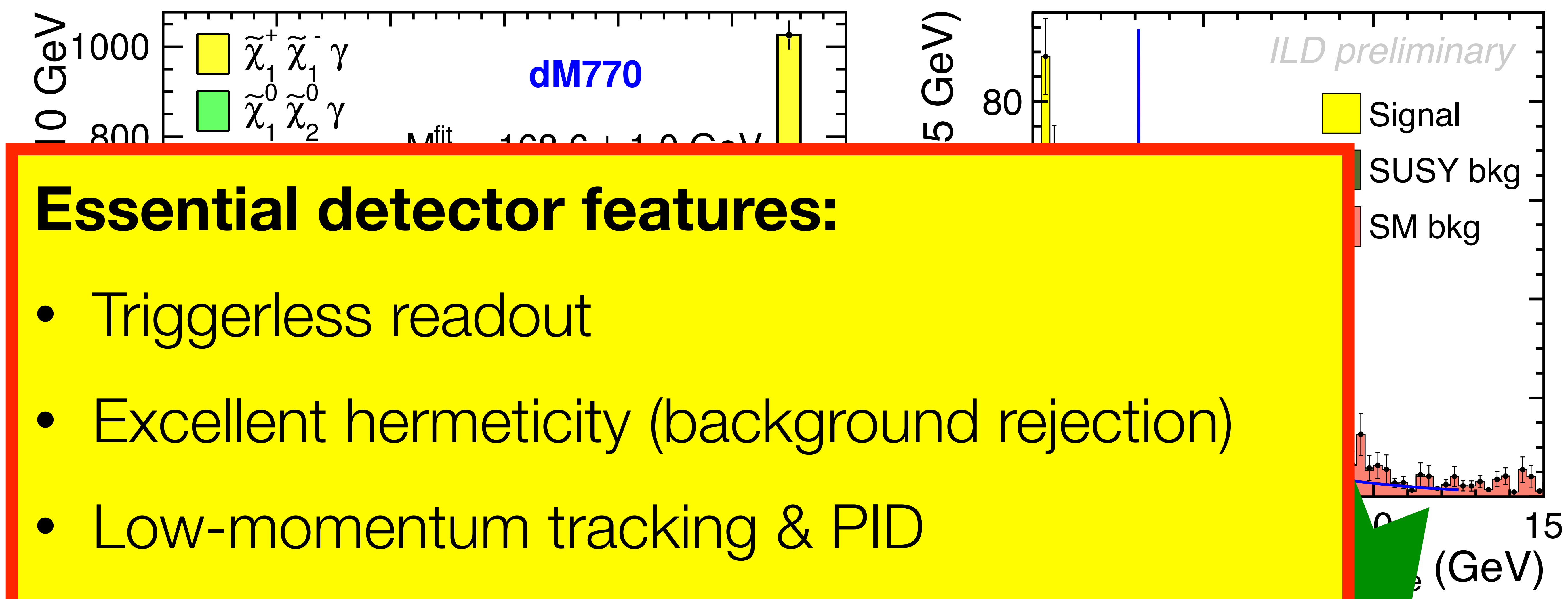
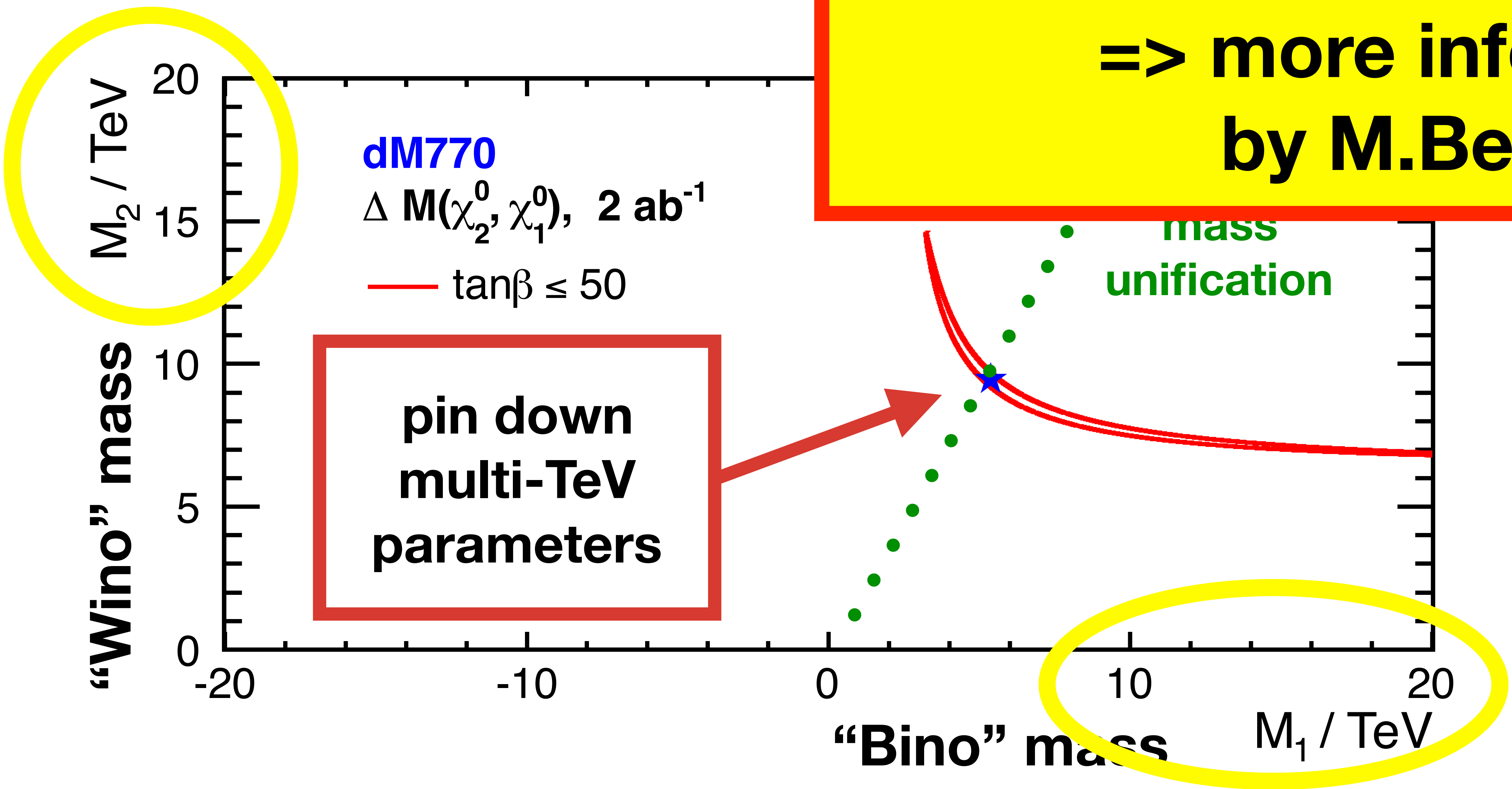


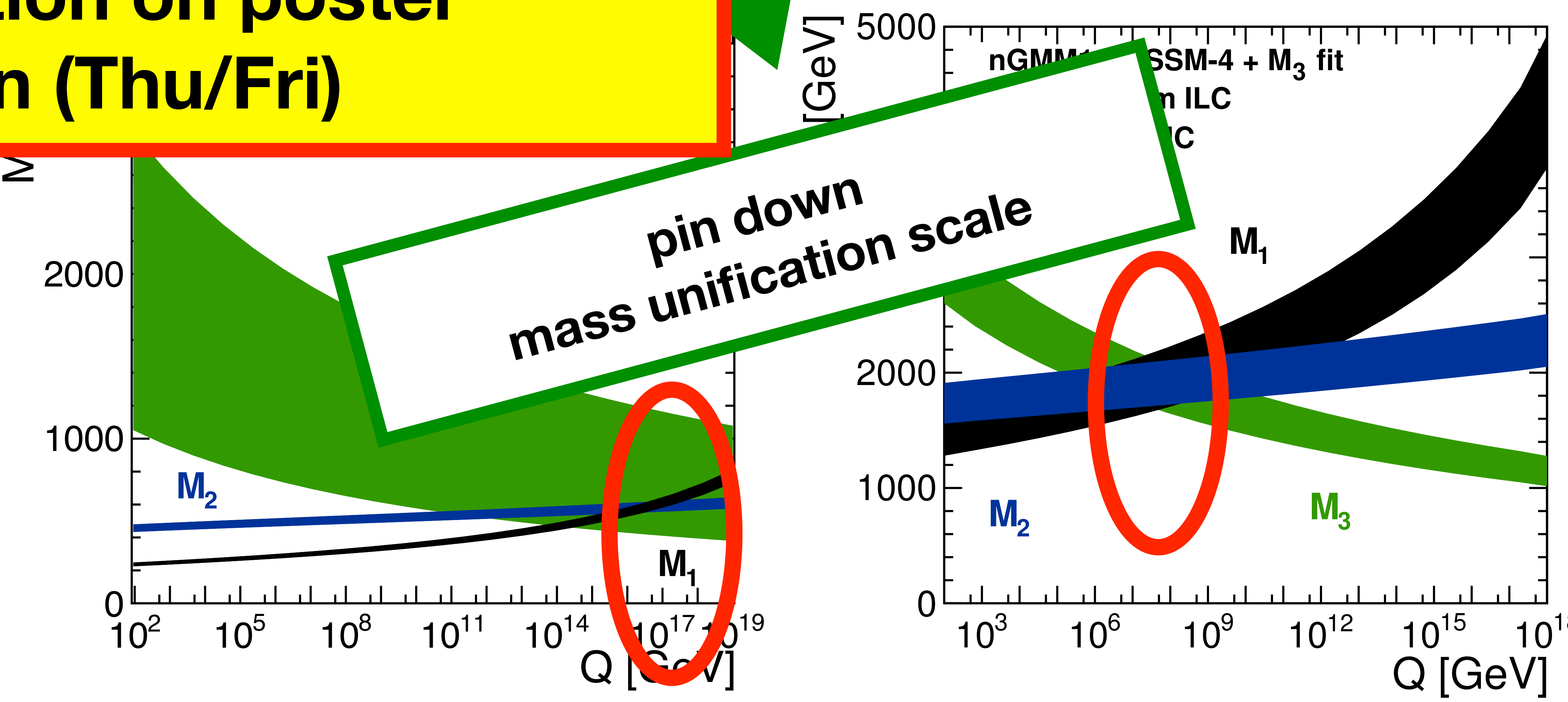
higgsinos with few GeV mass splitting DESY-THESIS-2018-035

Essential detector features:

- Triggerless readout
- Excellent hermeticity (background rejection)
- Low-momentum tracking & PID

=> more information on poster by M.Berggren (Thu/Fri)





SUSY without Loop-Holes

- **pair production of new, weakly coupled particles**
- special case SUSY: couplings are known
- R partity conservation: NSLP -> SM partner + LSP
- assume e.g. “worst case” mixing

=> loop-hole free search for NLSP pair production up to ~$\sqrt{s}$ / 2

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Most challenging case: stau !

- **current limit** (any mixing, any mass difference to LSP) still from **LEP** (Delphi): **M > 28 GeV**
- **no stau mass limit so far from LHC**
- **ILC** will cover **M < ~√s/2**

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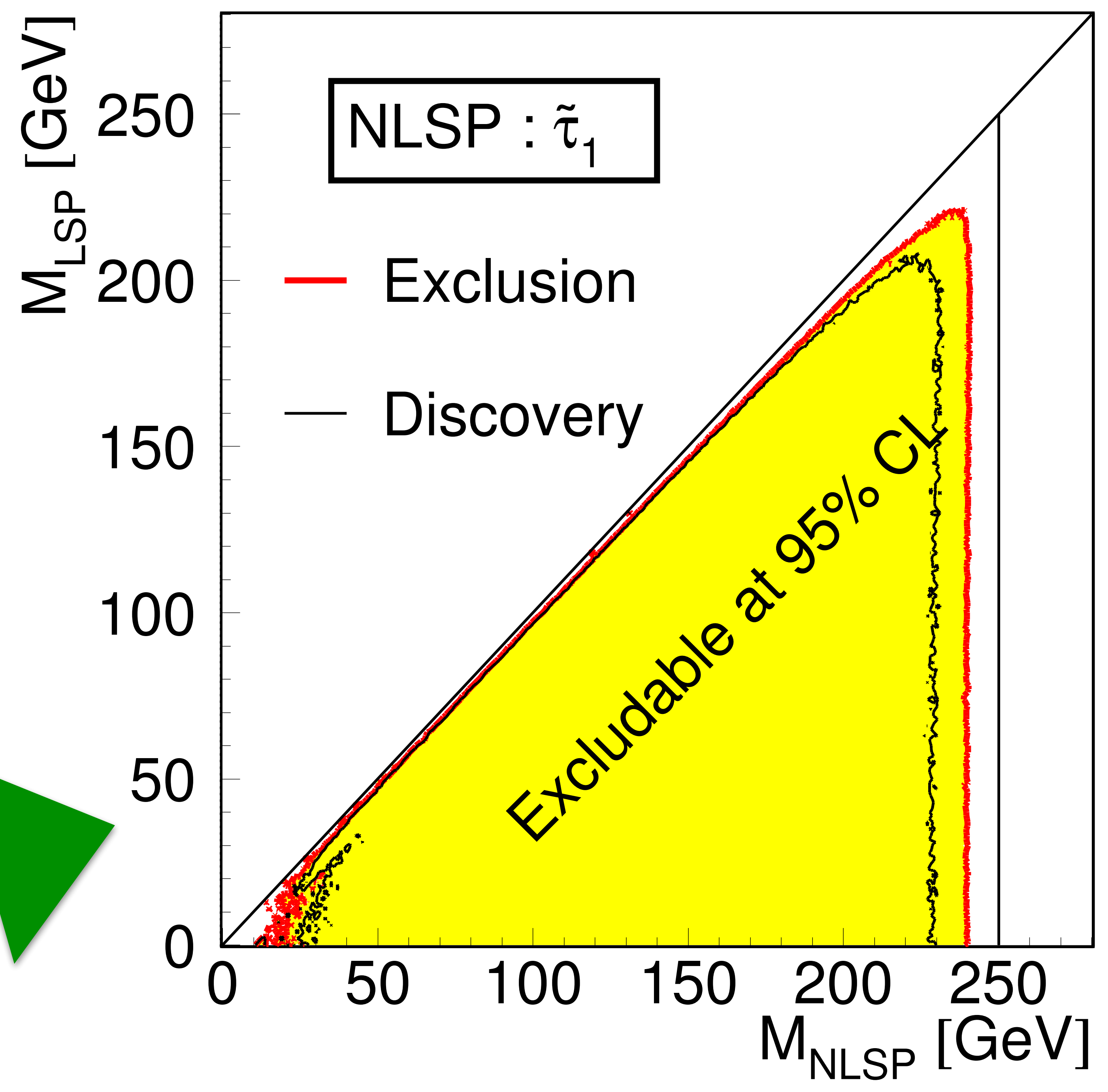

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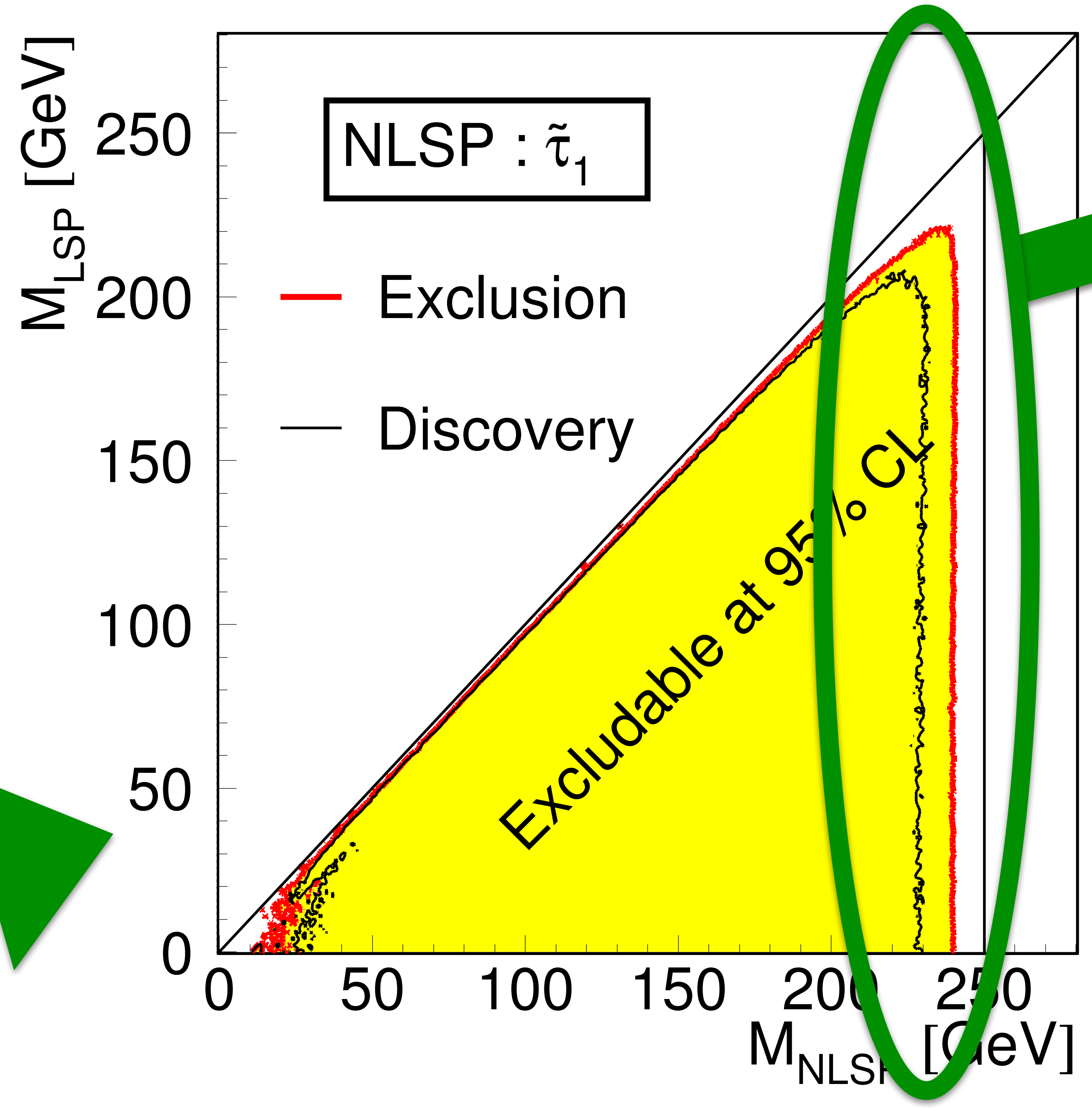

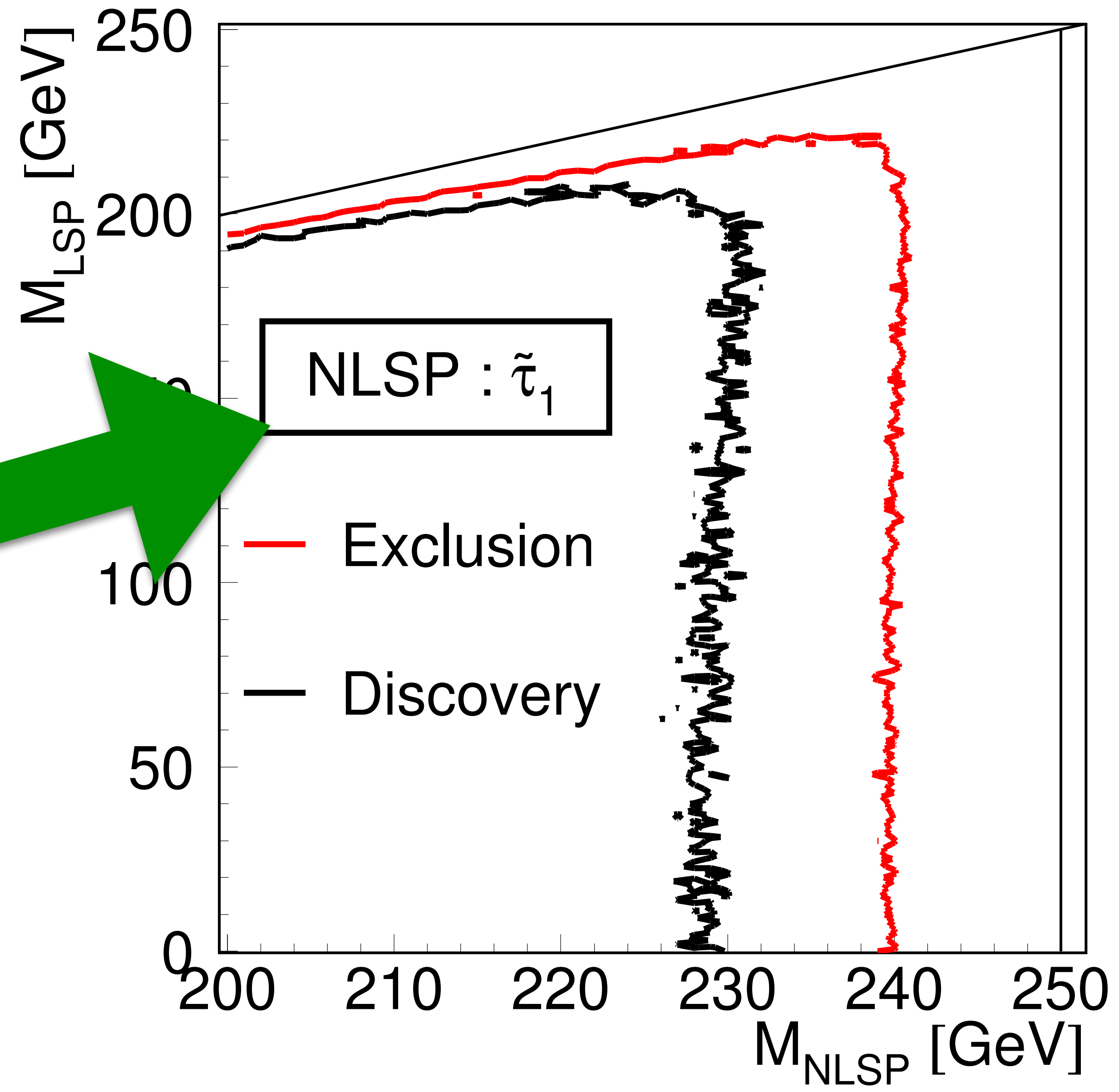

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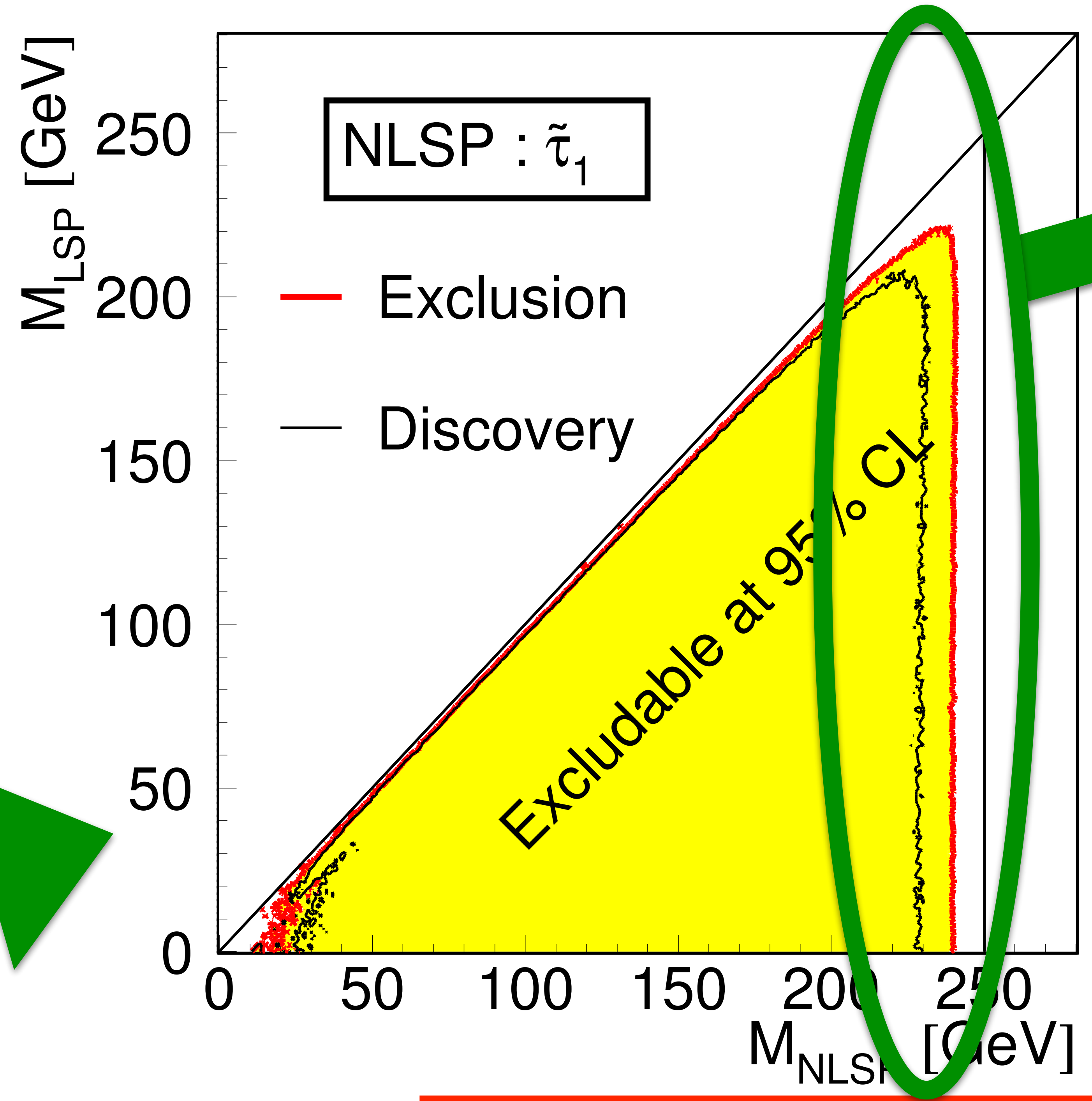

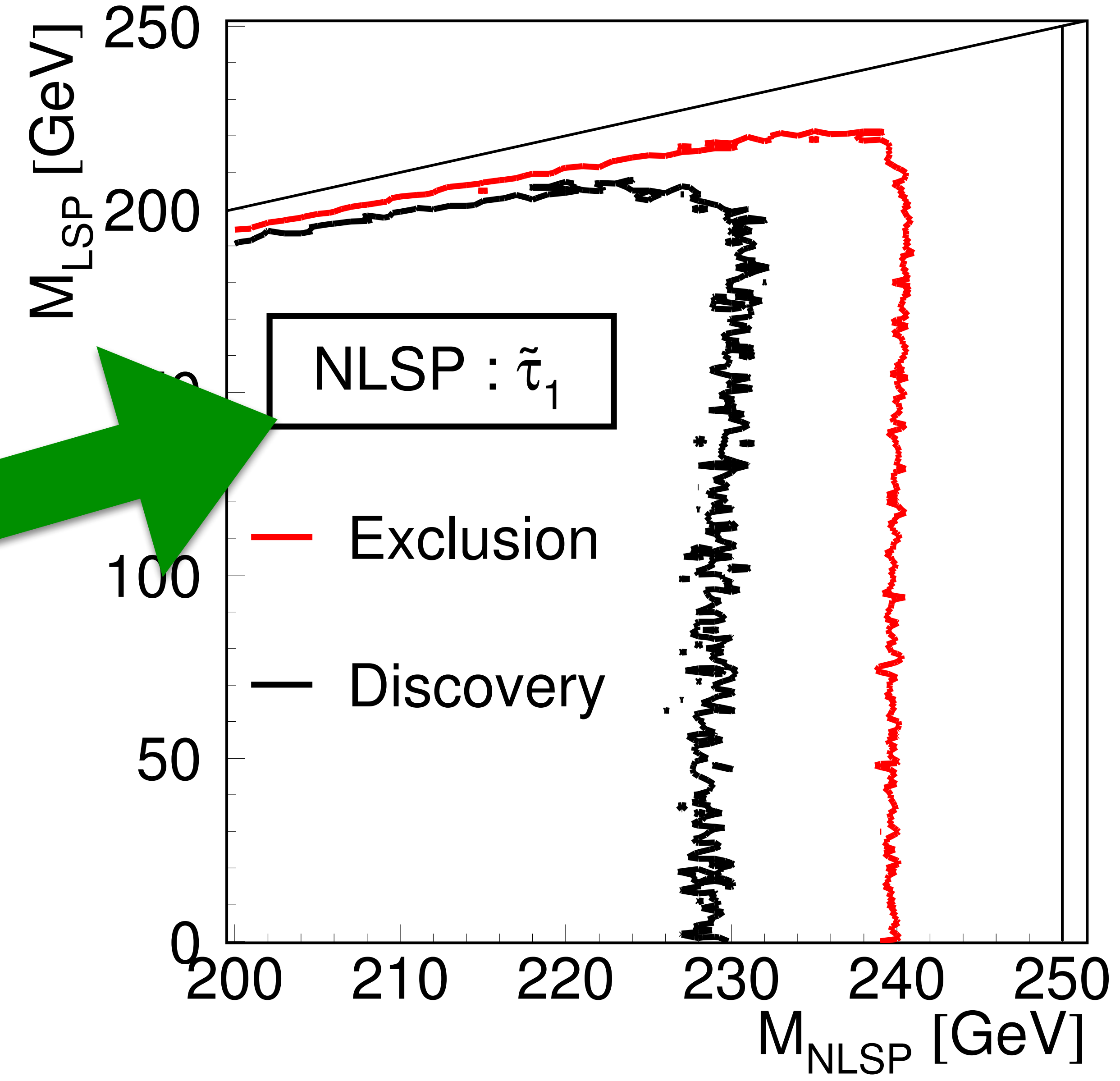

Plots for only 500 fb^{-1} @ 500 GeV
=> ~2 years of operation
(full 500 GeV run 4 ab^{-1})

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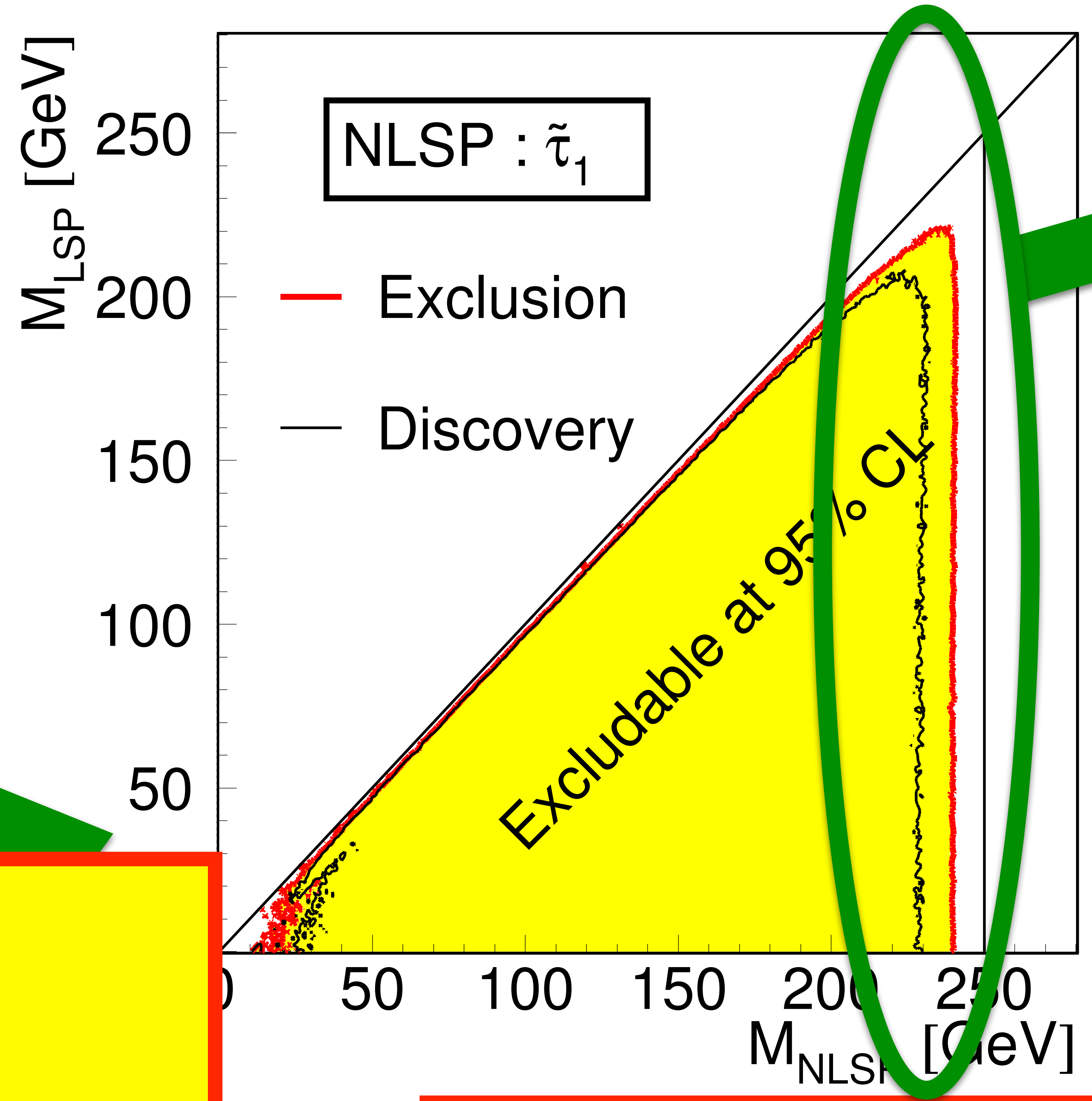

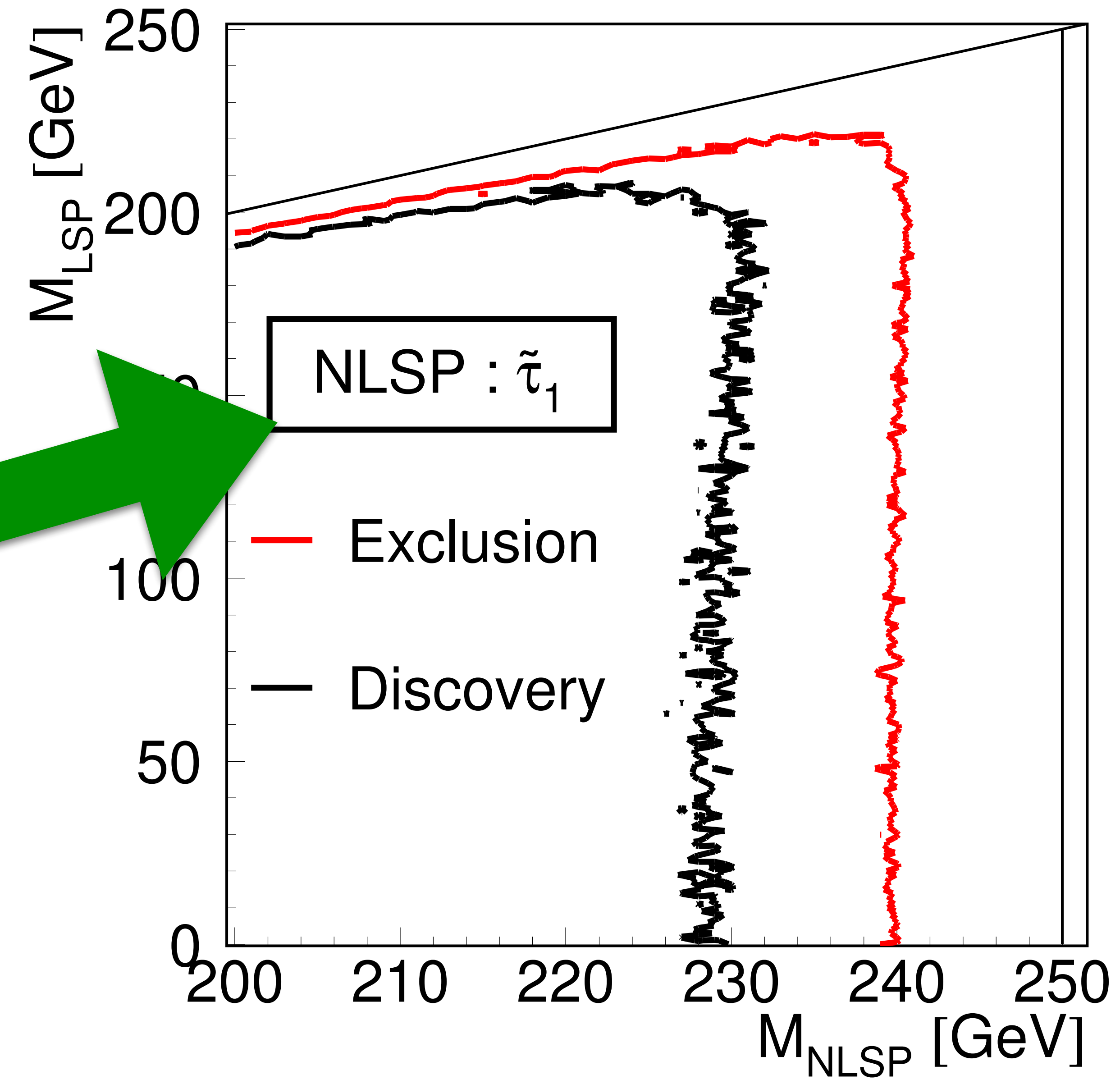

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essential ILC features:

- **triggerless operation**
- **tiny beam spot**
- **polarisation for parameter determination**

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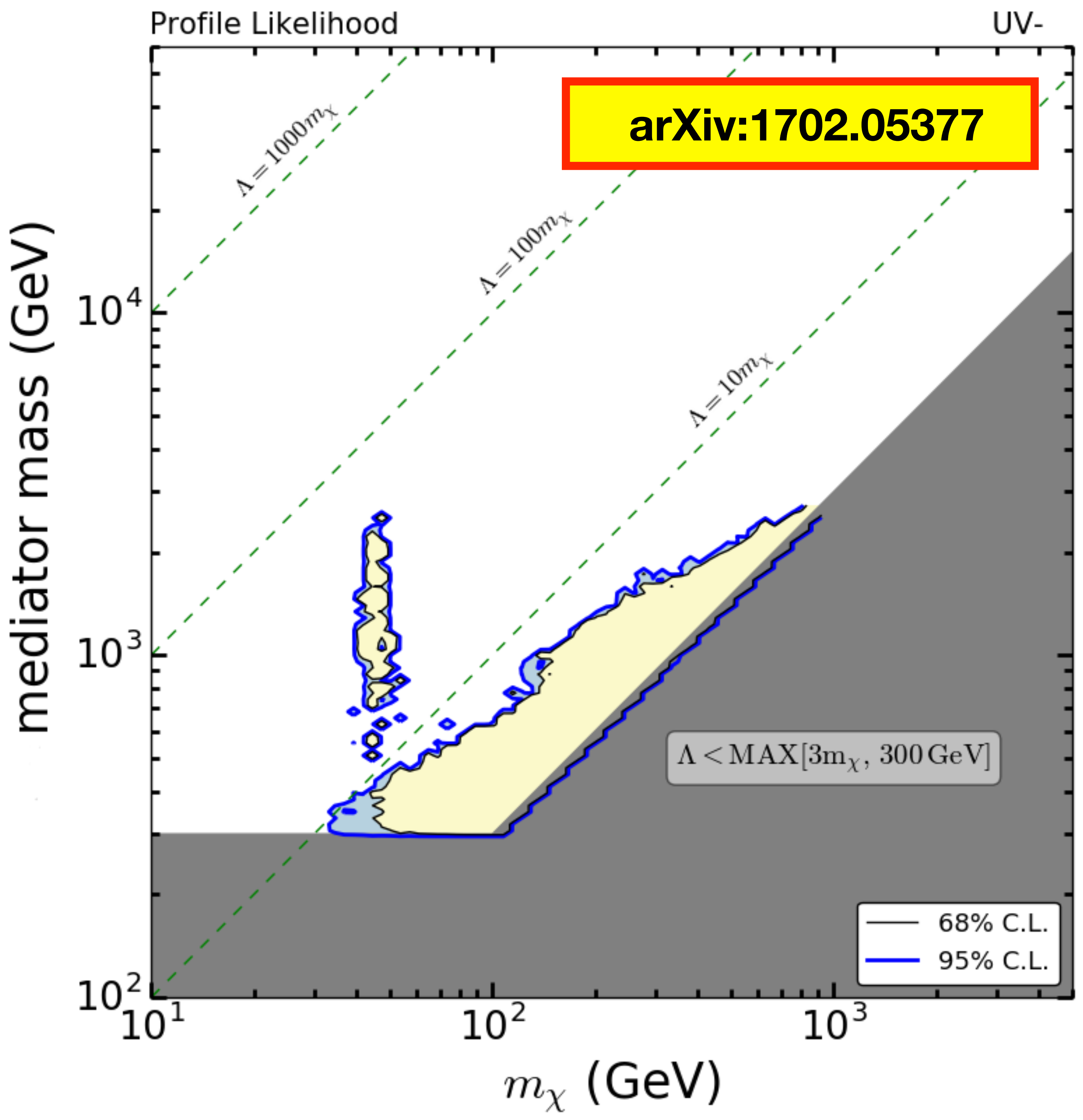
Discovering Dark Matter Particles



- likelihood scan over WIMP parameter space including existing and future direct, indirect and collider experiments (apart from ILC)
- e.g. here: singlet like fermion WIMP

=> significant unexplored regions below M=120 GeV !!!

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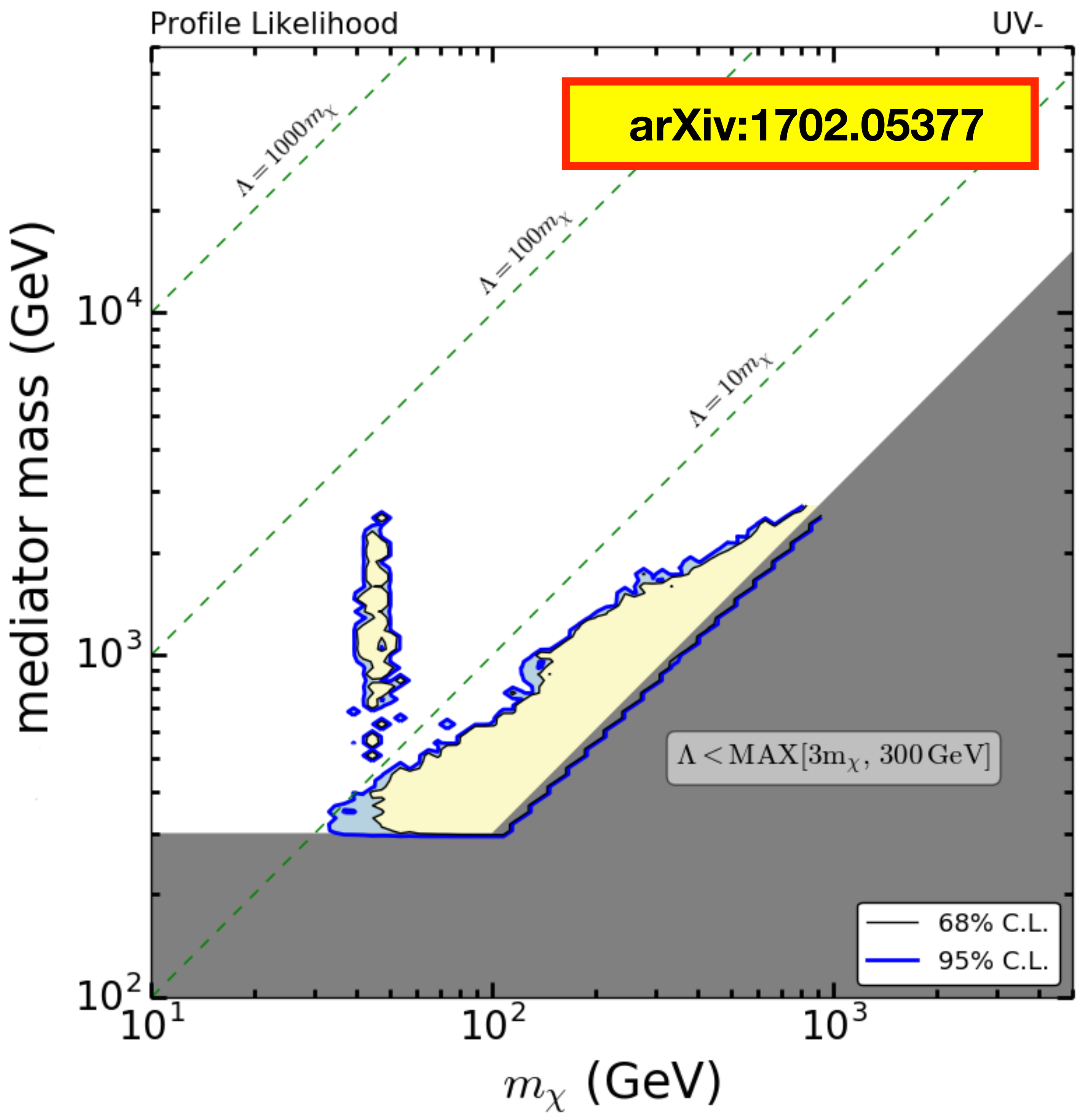

- **$e^+e^- \to \chi\chi\gamma$** "mono-photons"
- **Effective operator interpretation**
  [nota bene: valid in e+e- collider sensitivity range]

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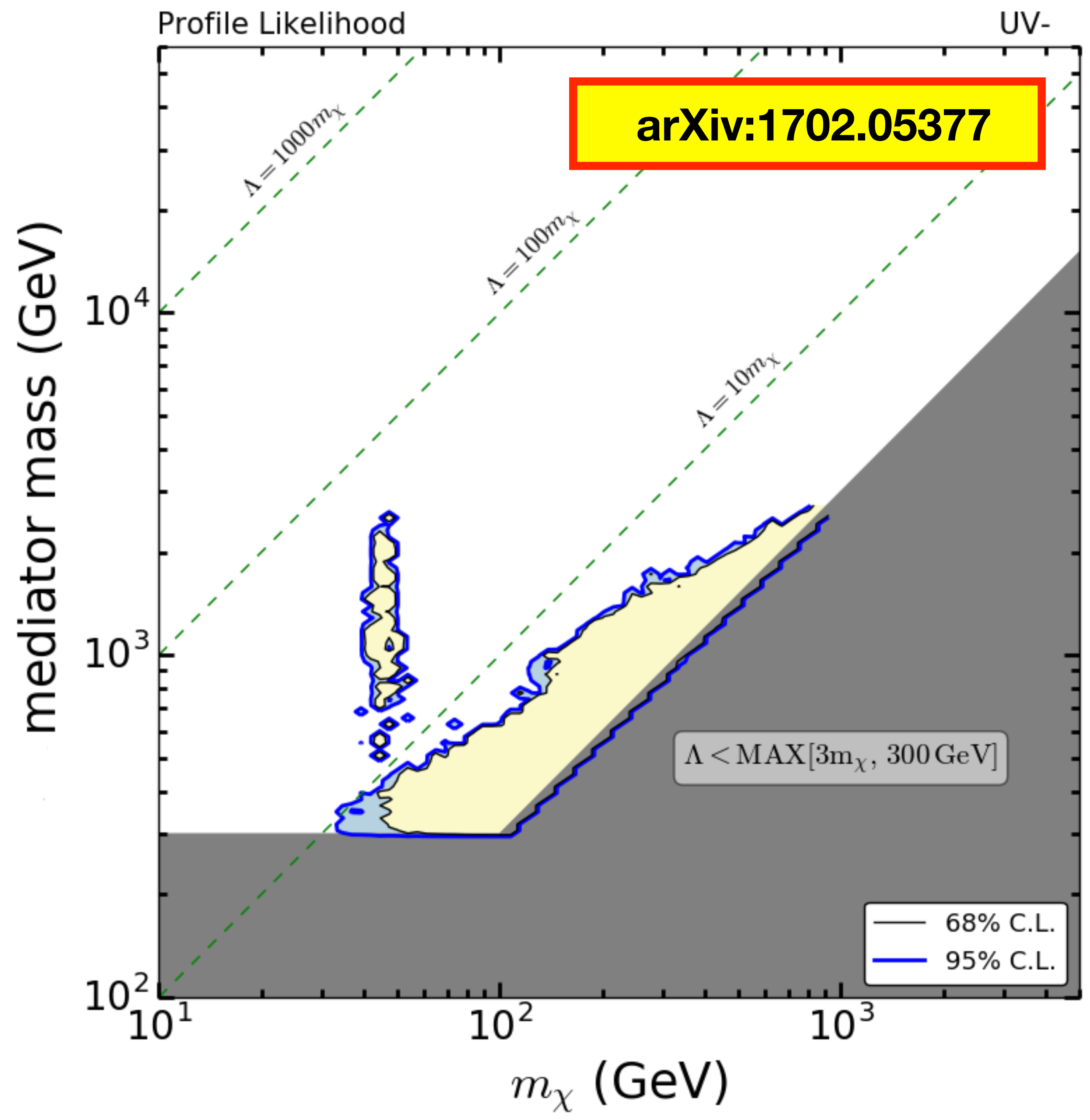

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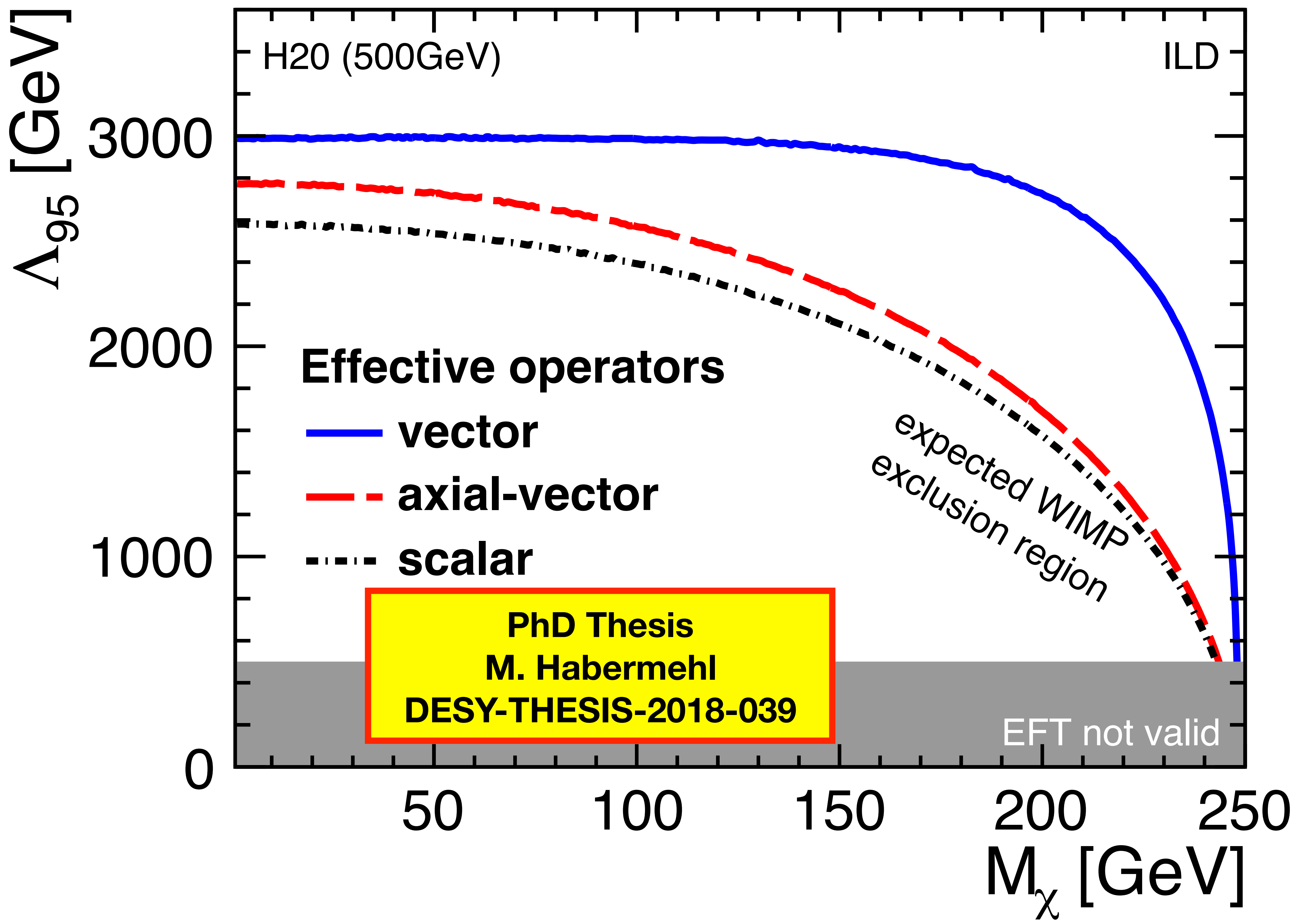

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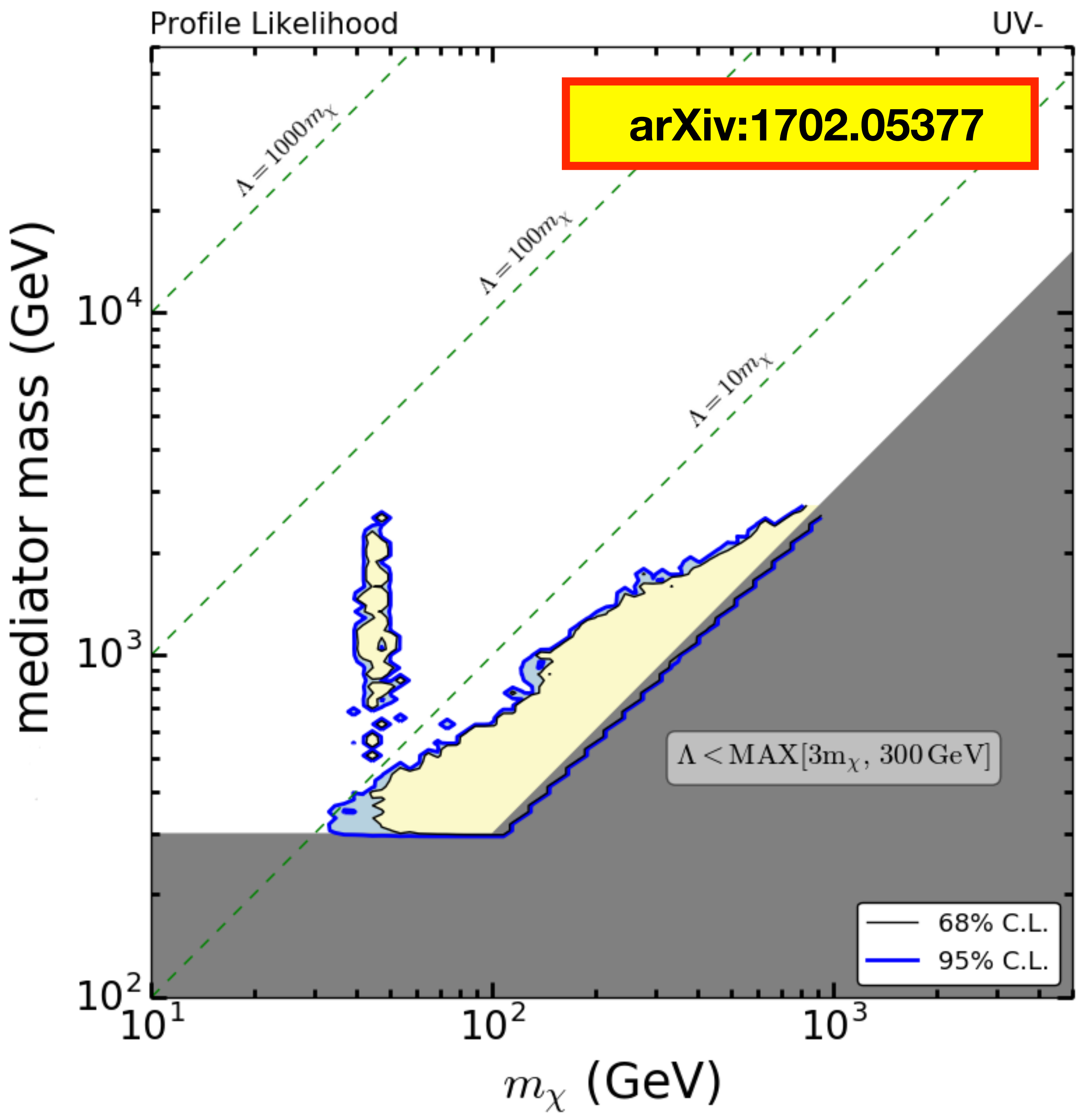

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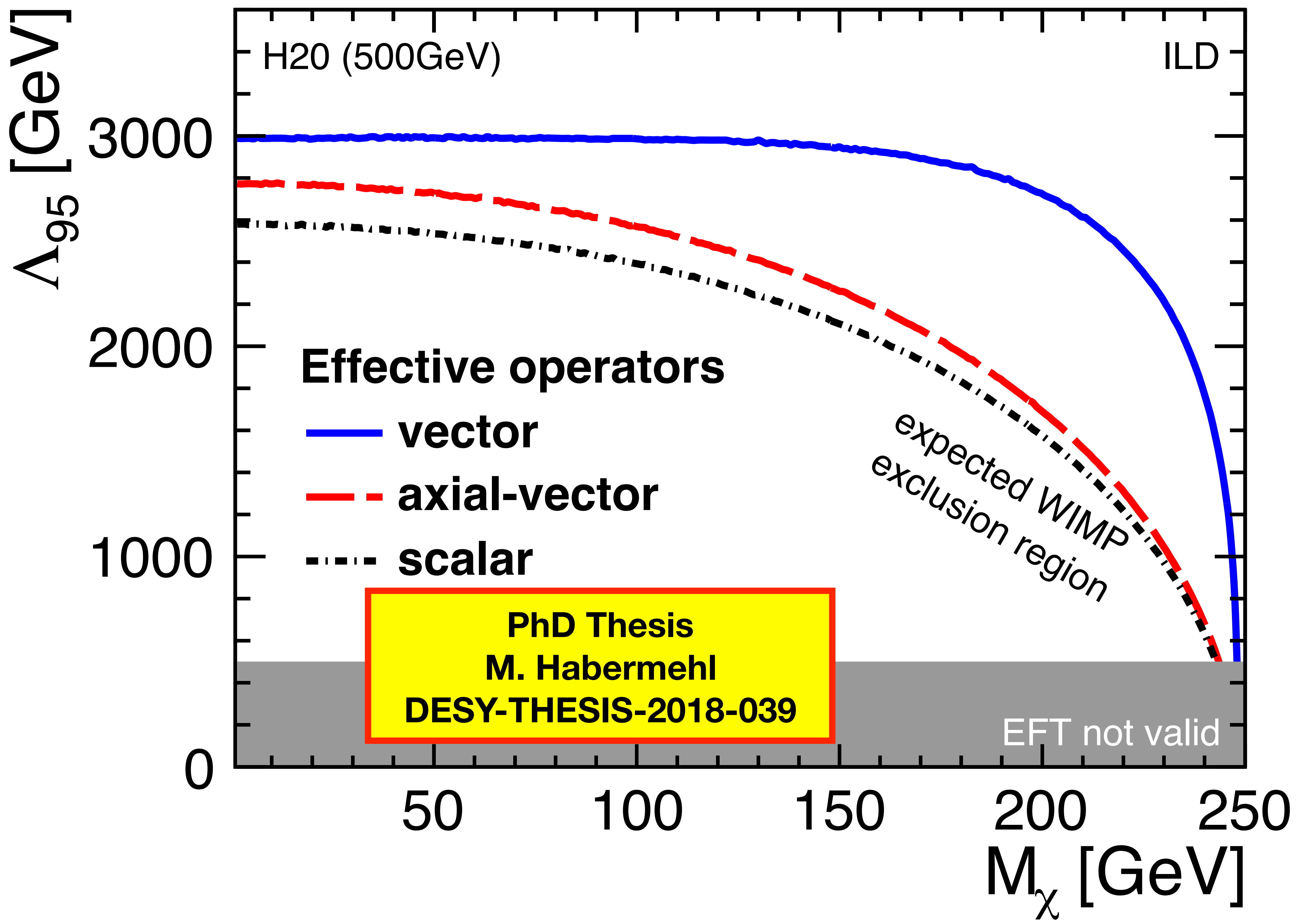
for M_χ < 100 GeV ILC probes Λ (95% CL)

- **up to ~3 TeV @ 500 GeV**
- **up to ~1.4 TeV @ 250 GeV**



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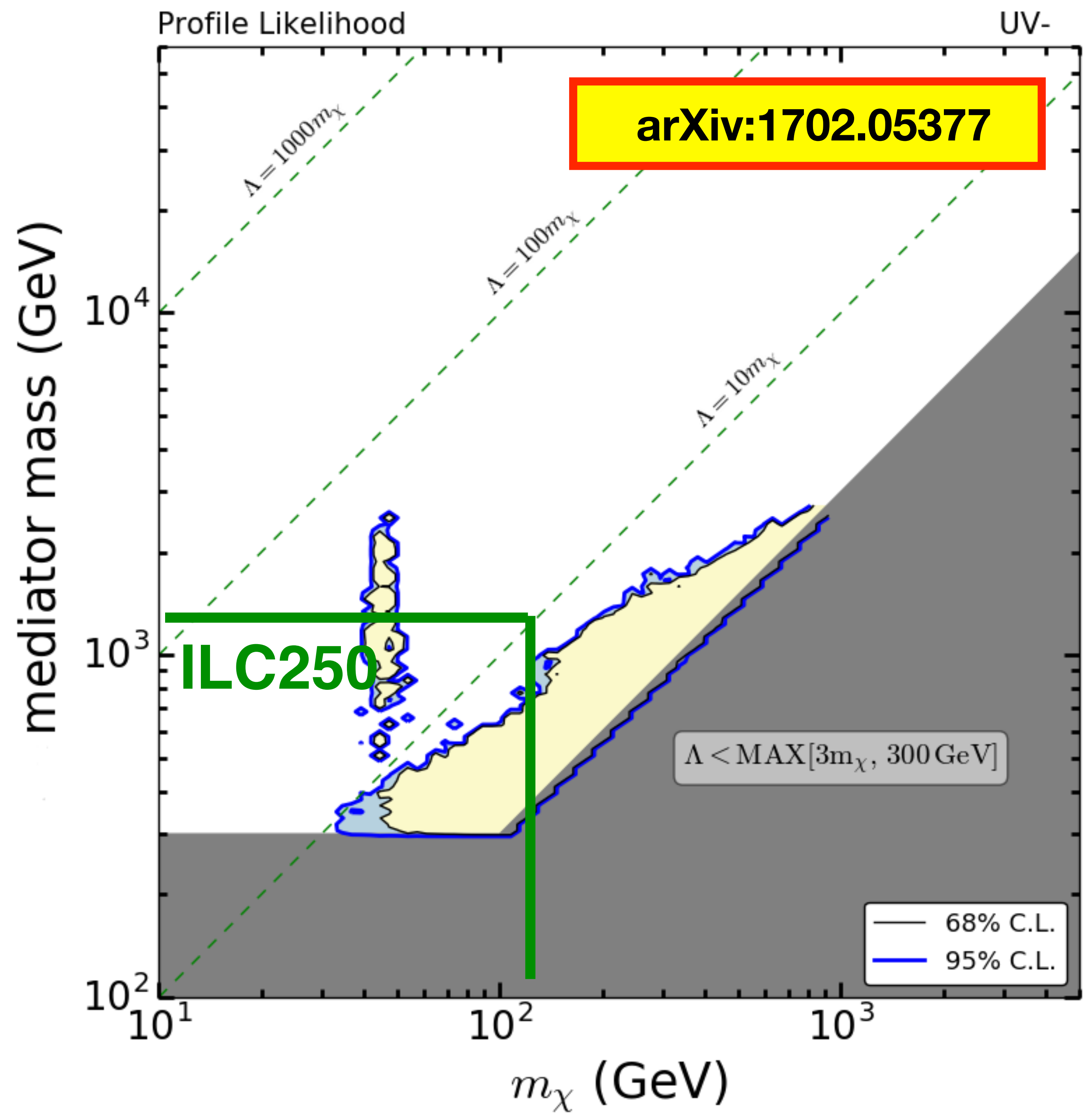

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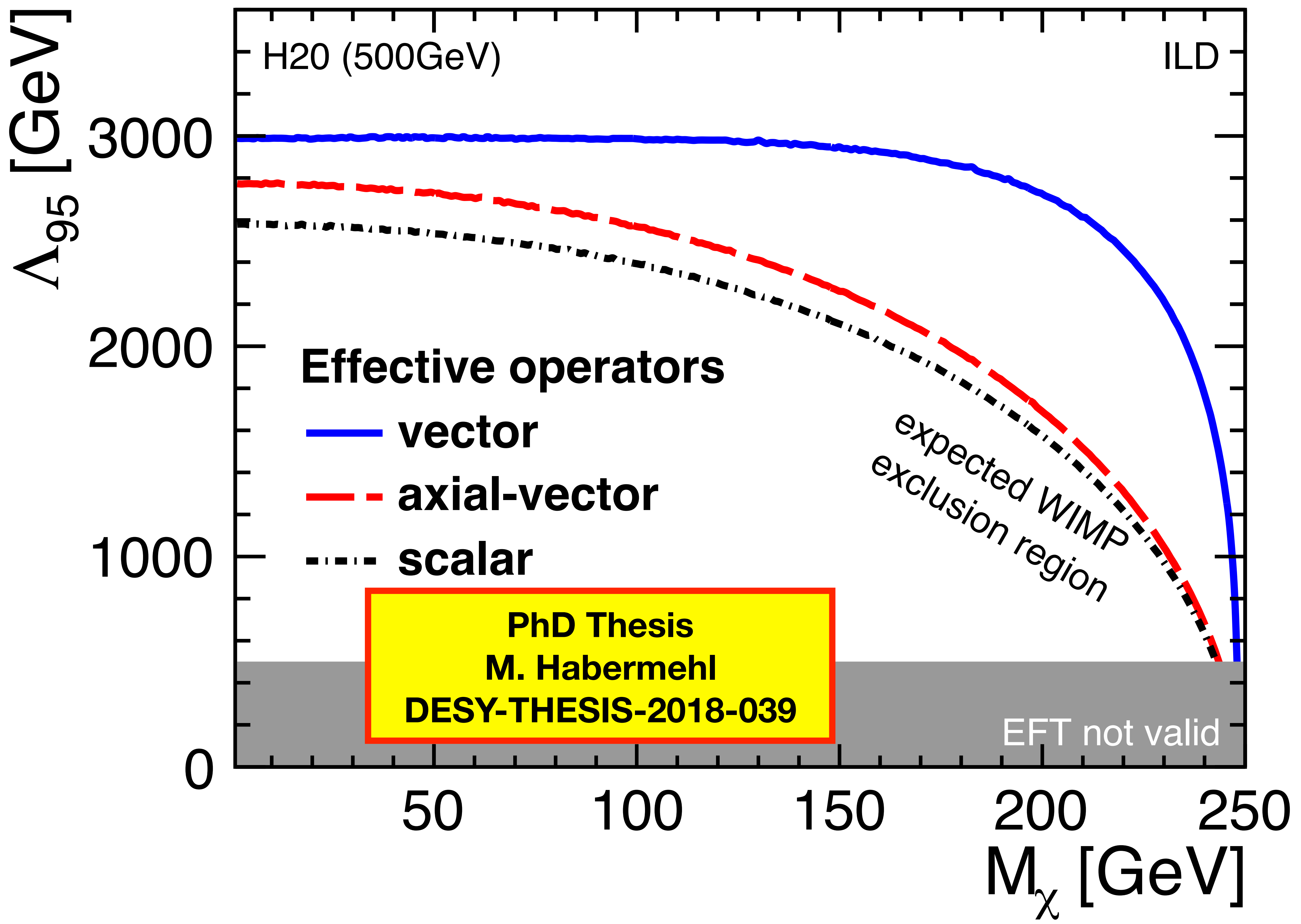

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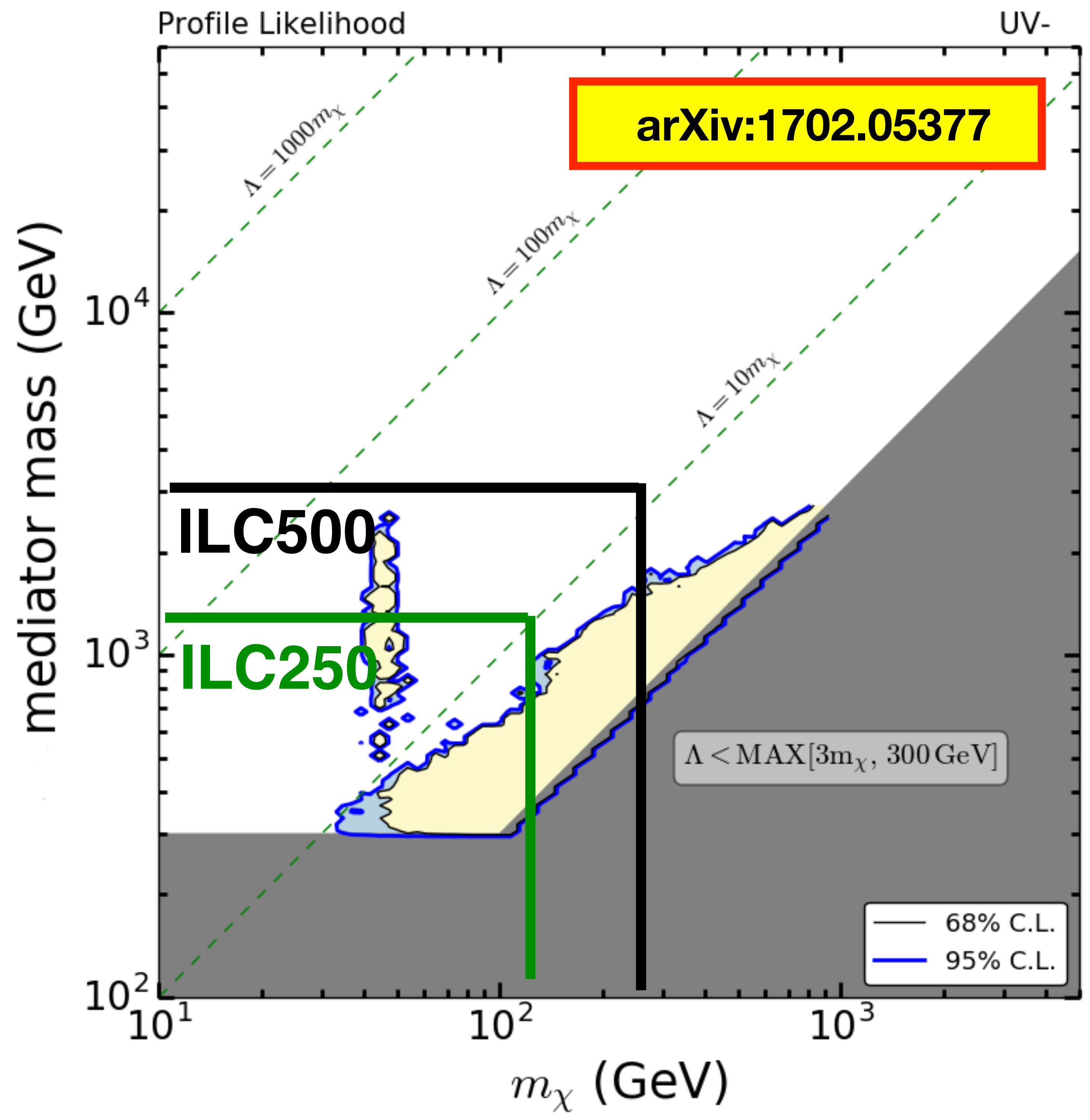

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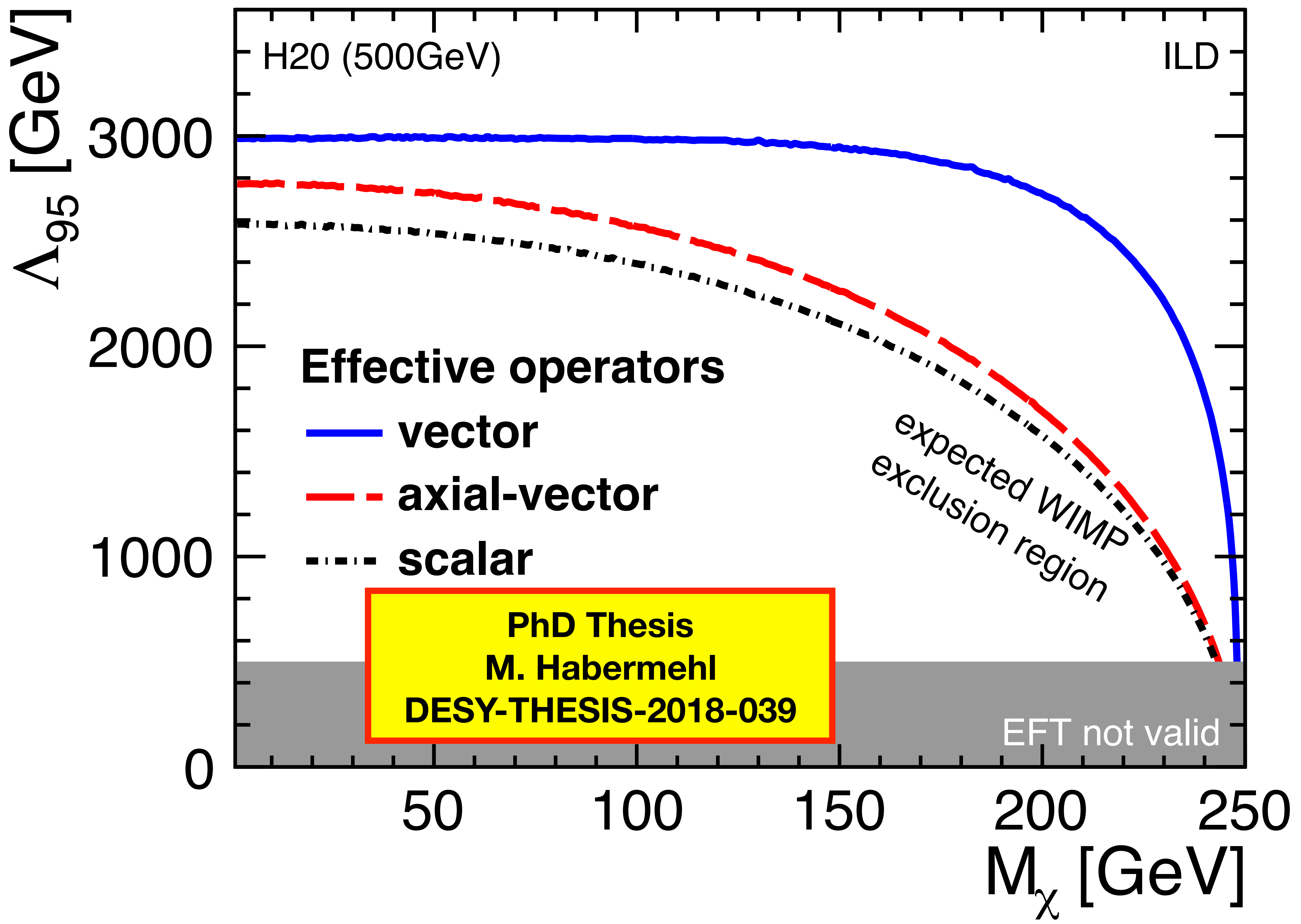

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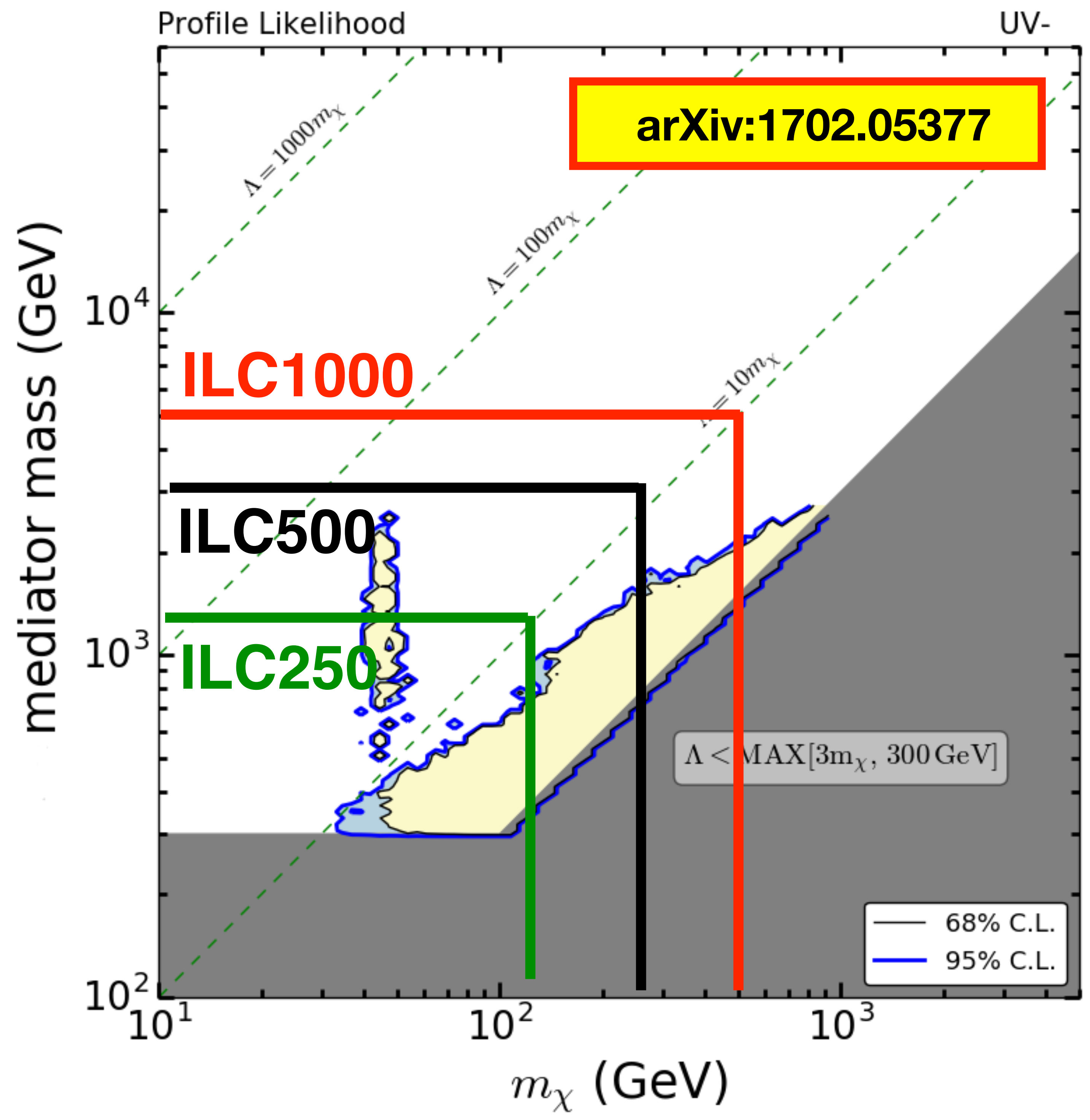

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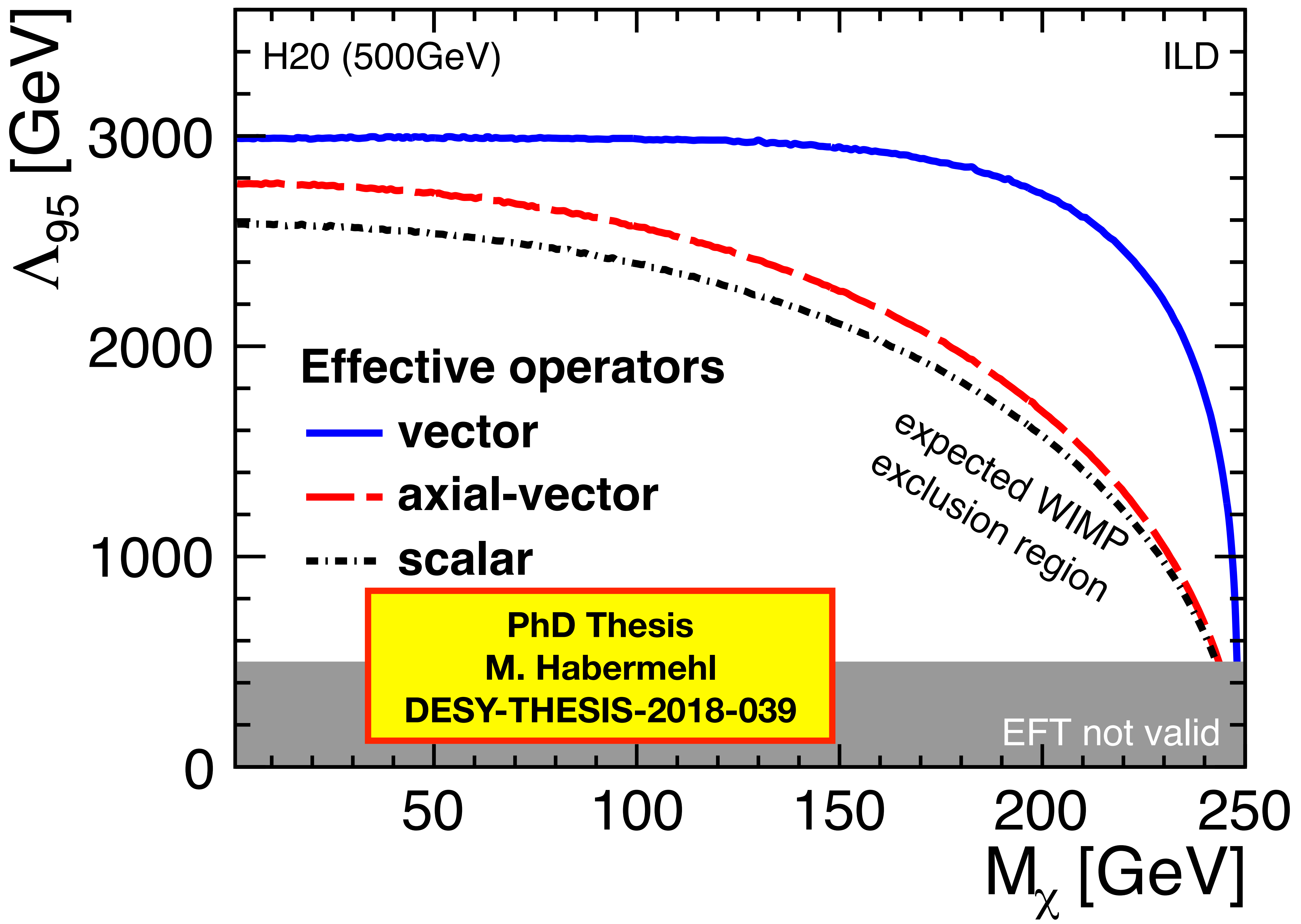

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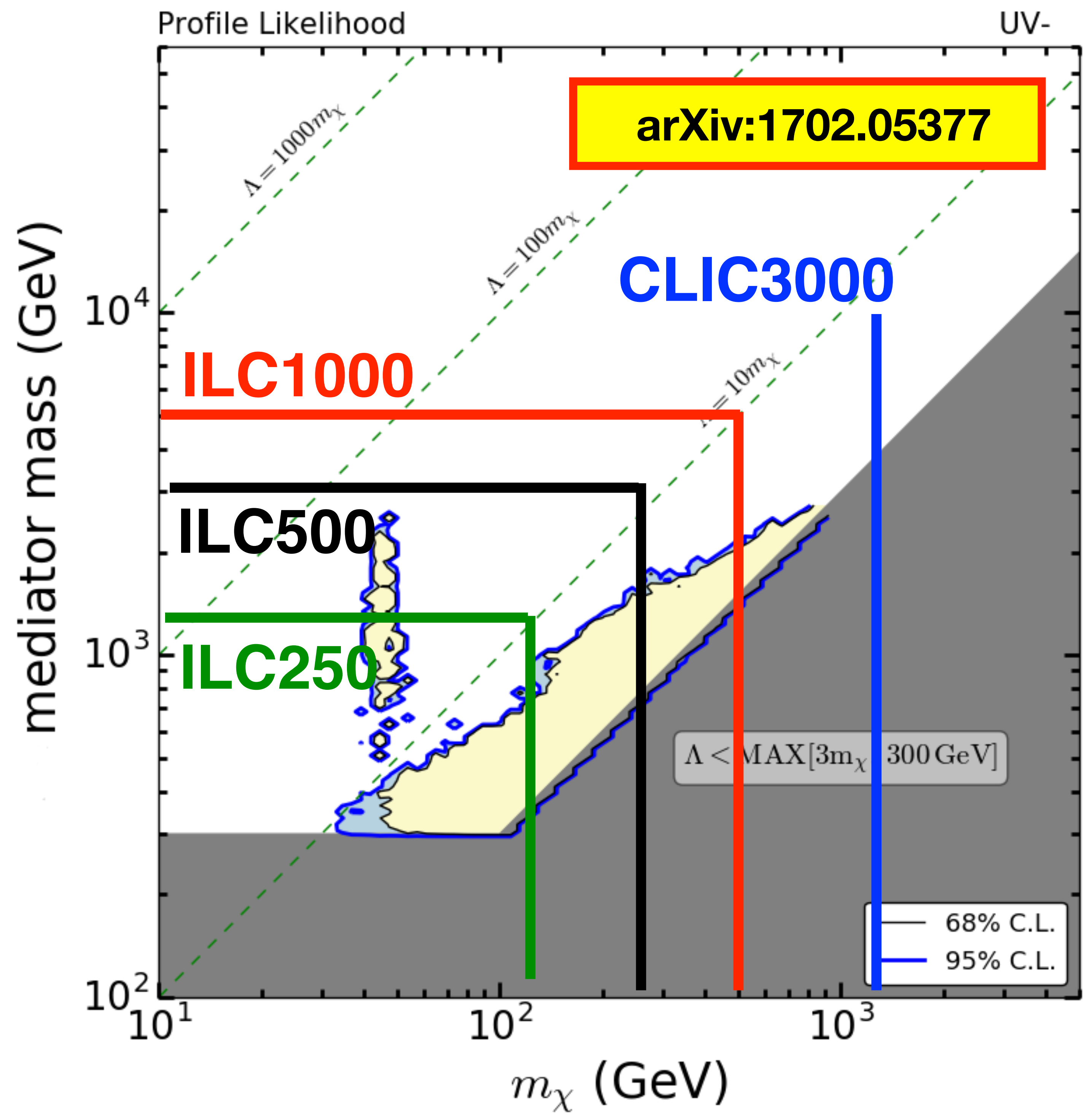

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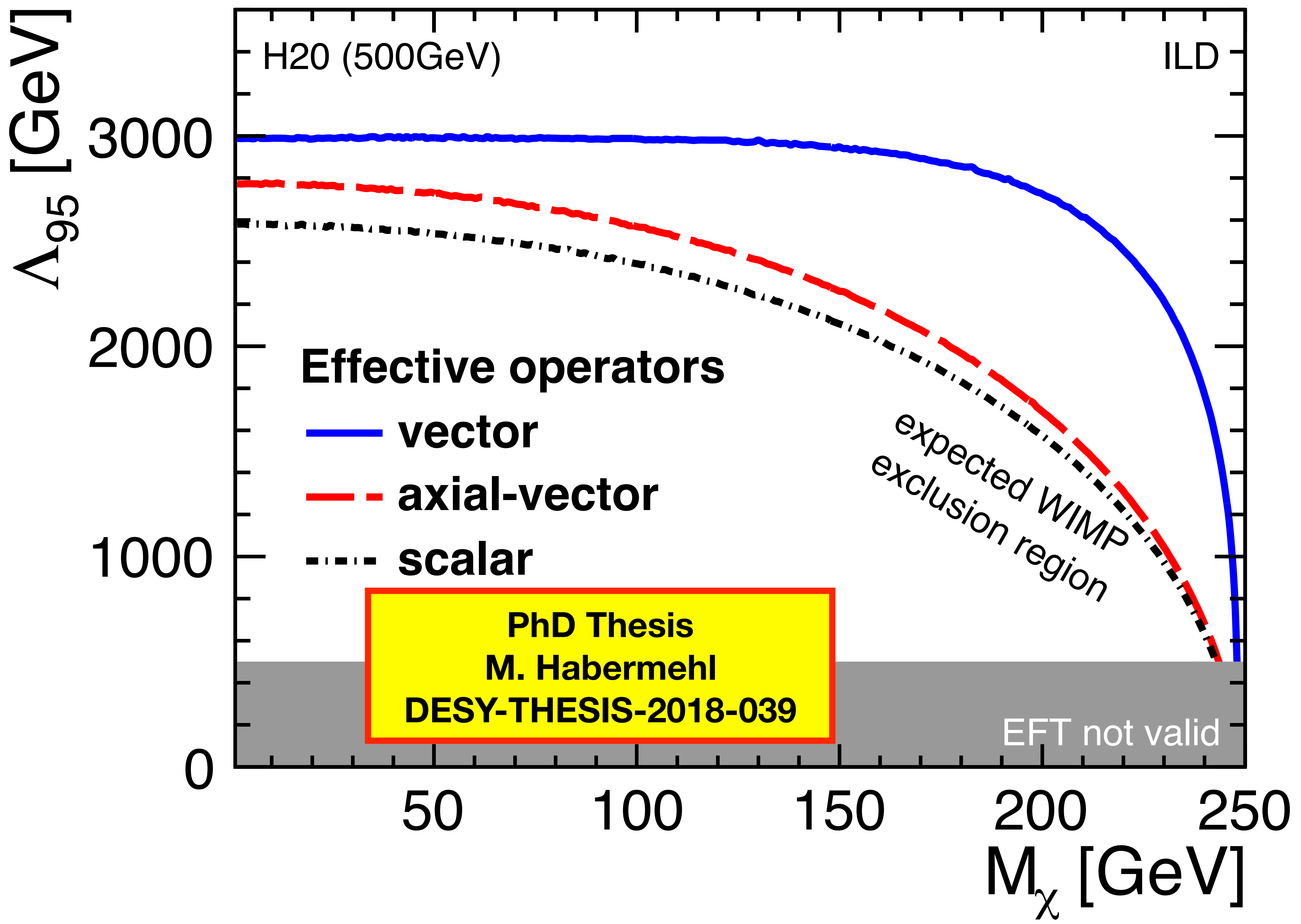

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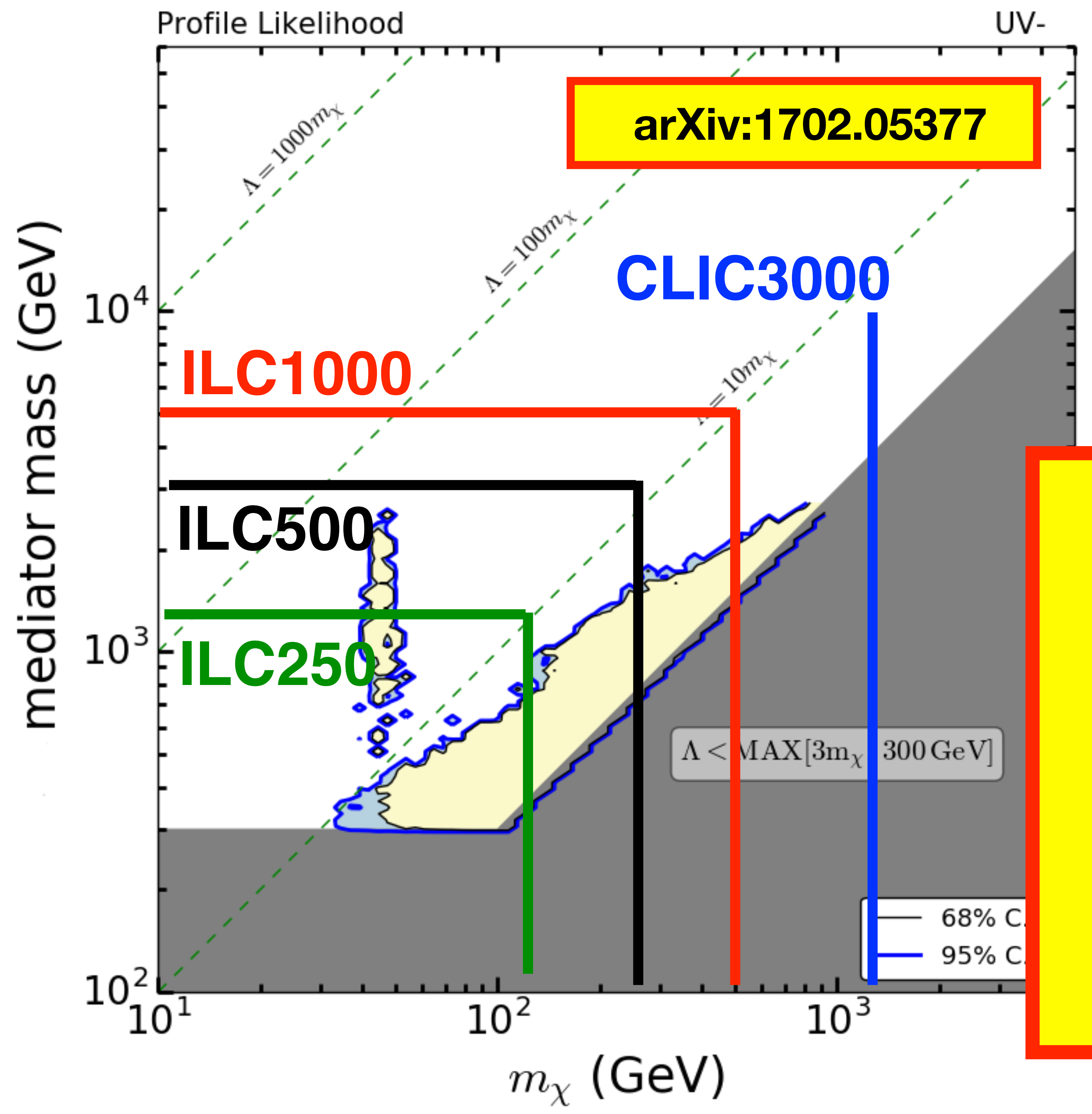

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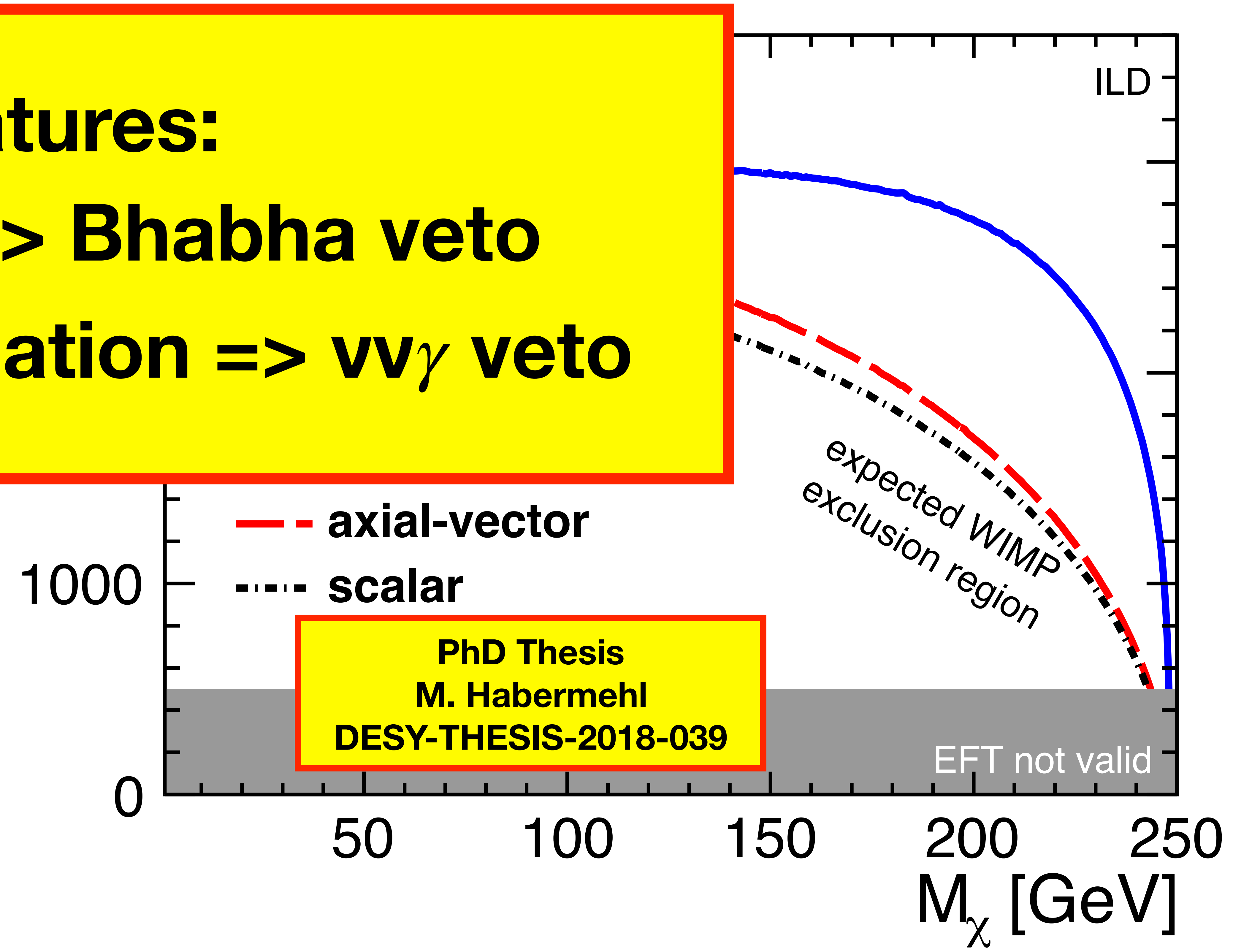
essential ILC features:

- **hermeticity => Bhabha veto**
- **Beam polarisation => $\nu\nu\gamma$ veto**



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Dark Matter: **hermeticity** and **beam polarisation**

PhD Thesis
M. Habermehl
DESY-THESIS-2018-039

- **hermeticity: vetoing Bhabha events**
- **θ_{eff}: angle above which veto is effective**
- **Λ_{95} for M_χ = 1 GeV vector op as benchmark**

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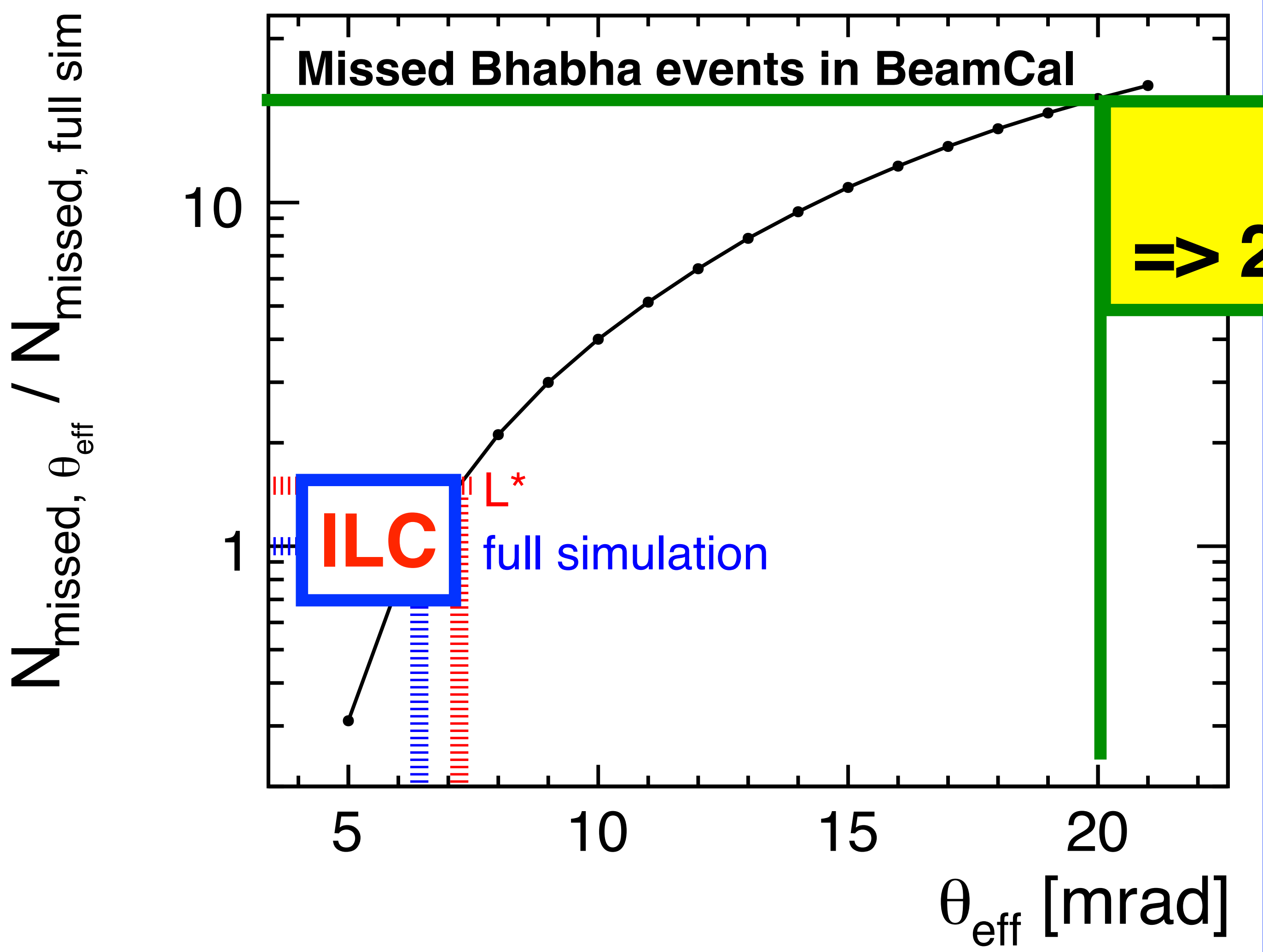
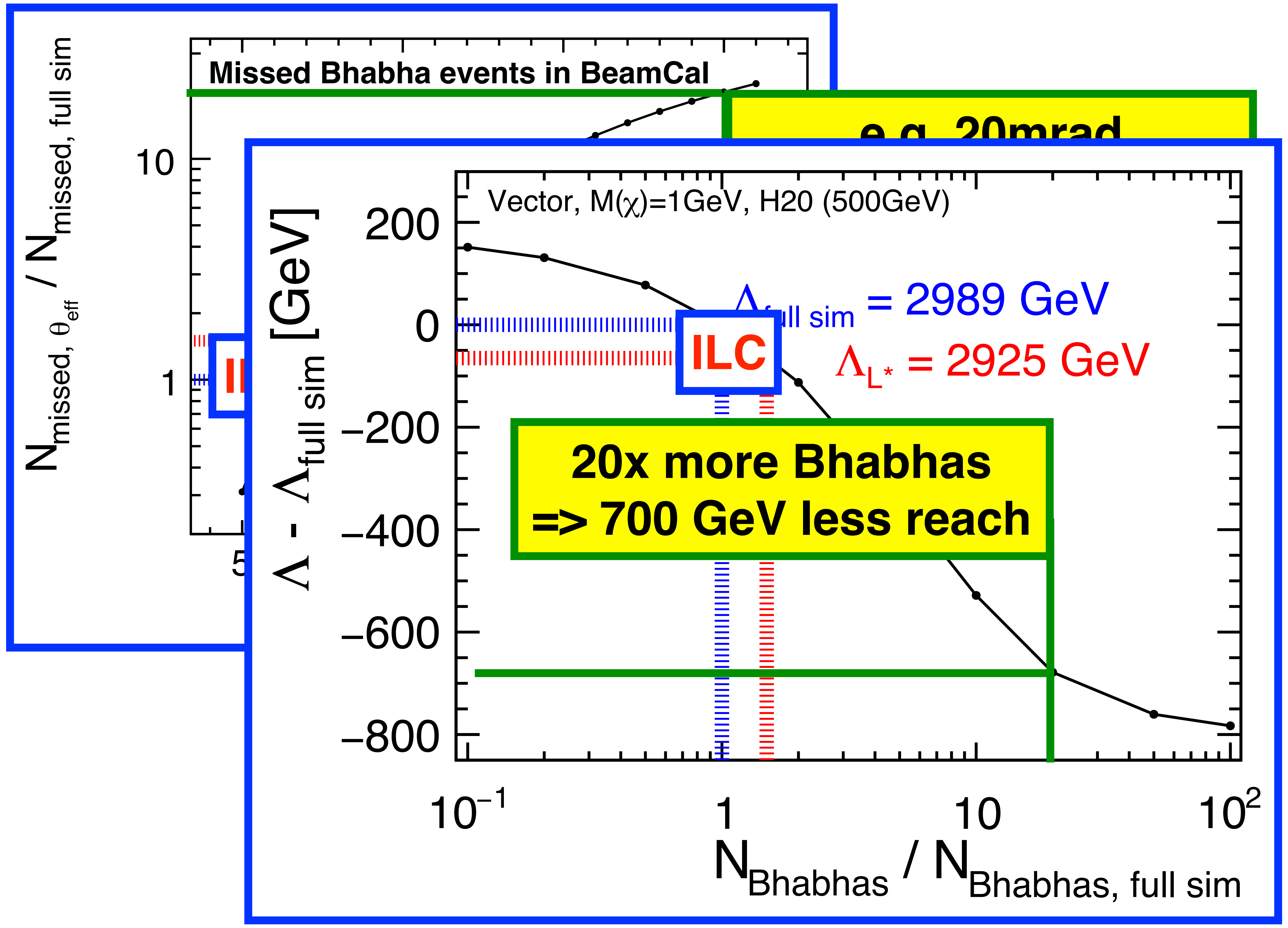


e.g. 20mrad
=> 20x more Bhabhas

Dark Matter: **hermeticity** and **beam polarisation**

PhD Thesis
M. Habermehl
DESY-THESIS-2018-039

- **hermeticity: vetoing Bhabha events**
- **θ_{eff}: angle above which veto is effective**
- **Λ_{95} for M_χ = 1 GeV vector op as benchmark**



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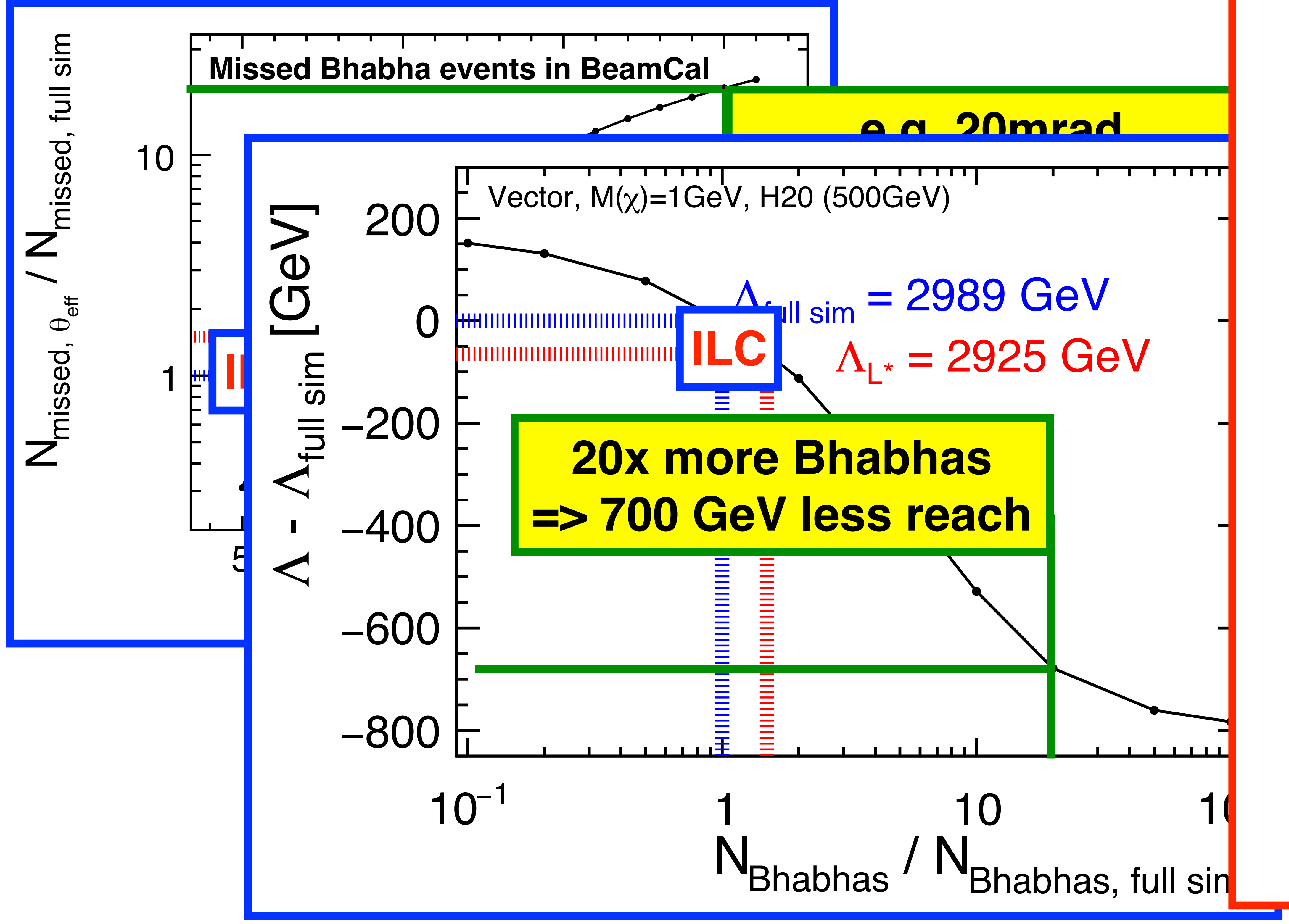

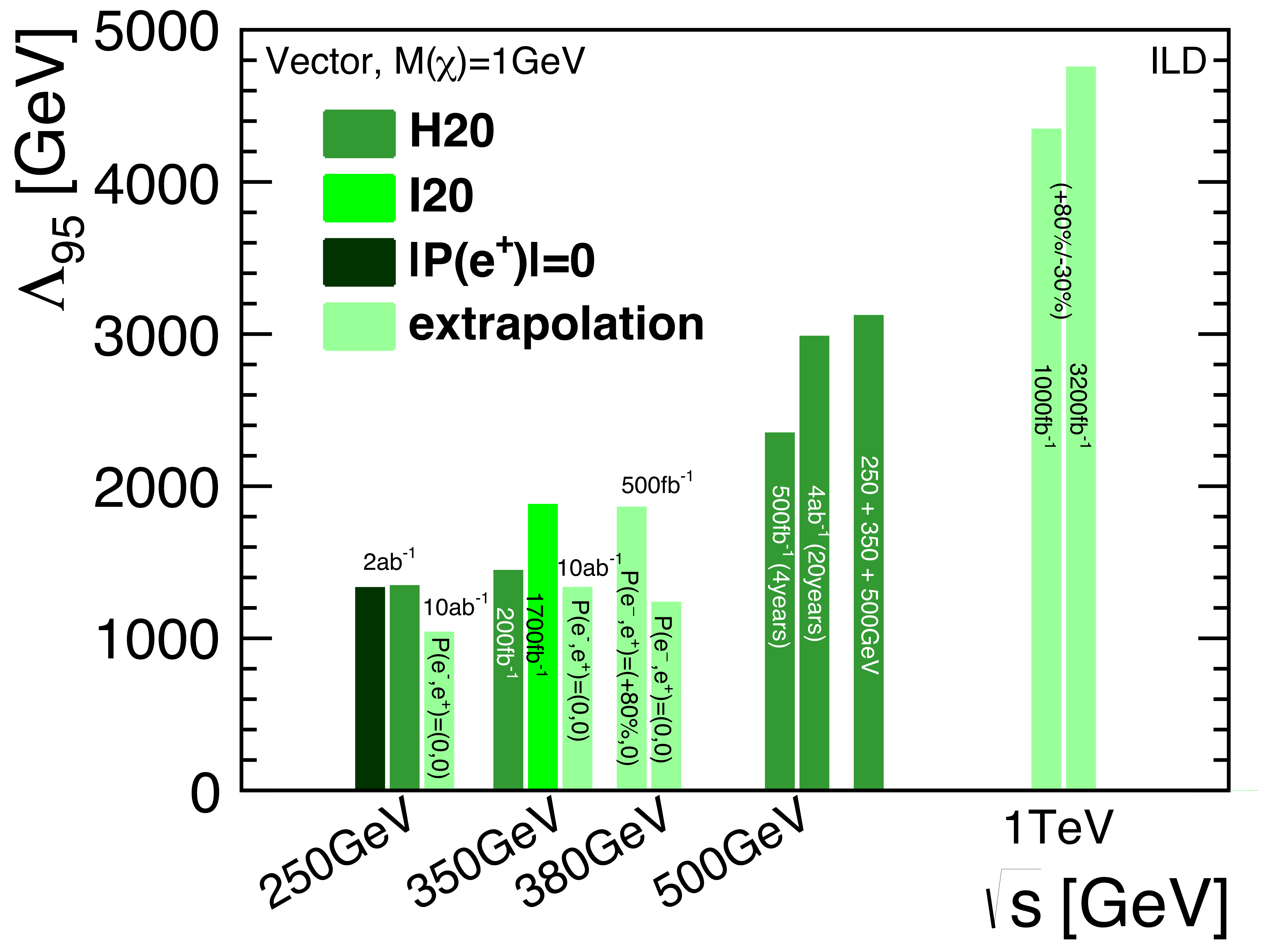

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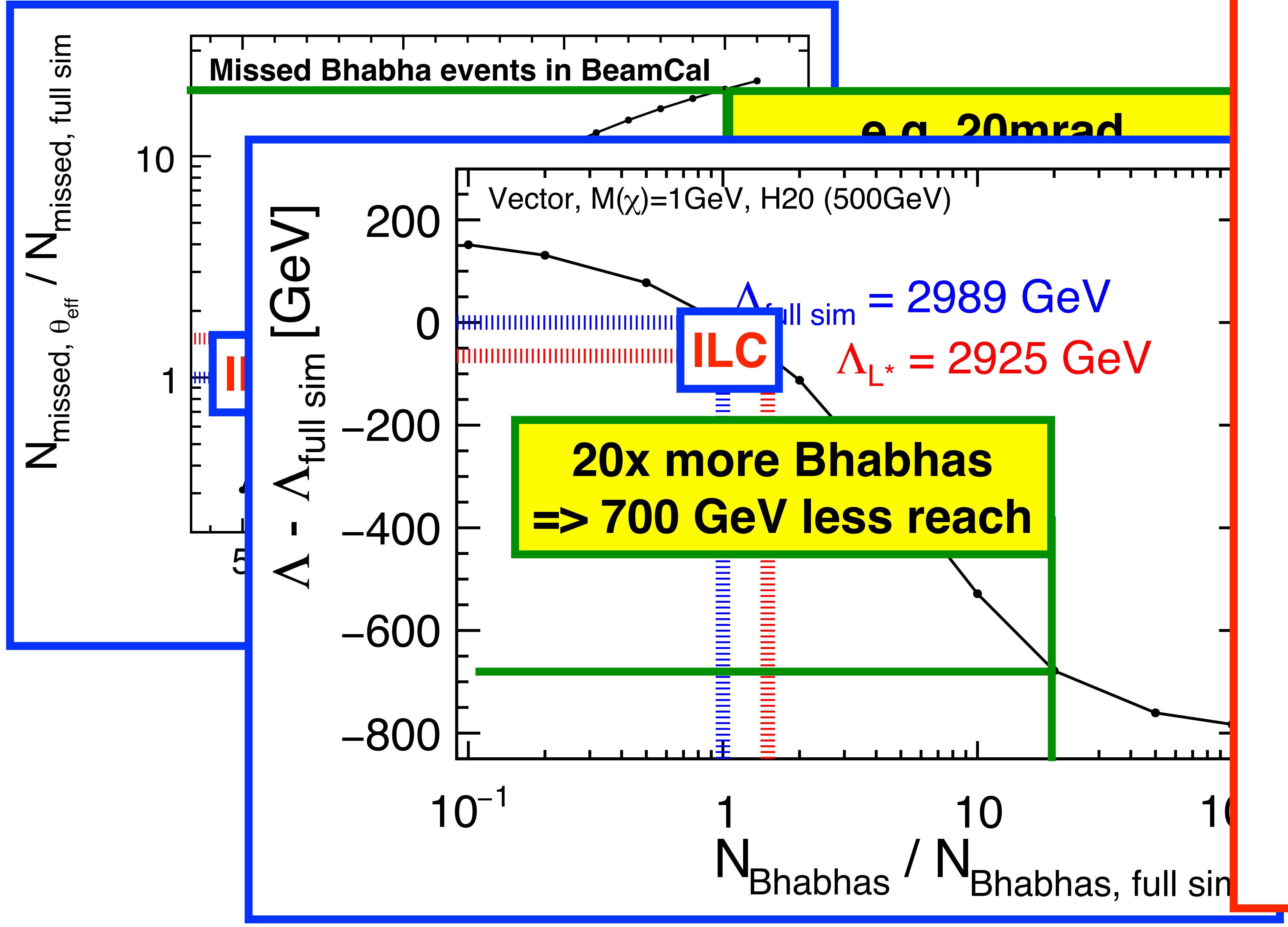

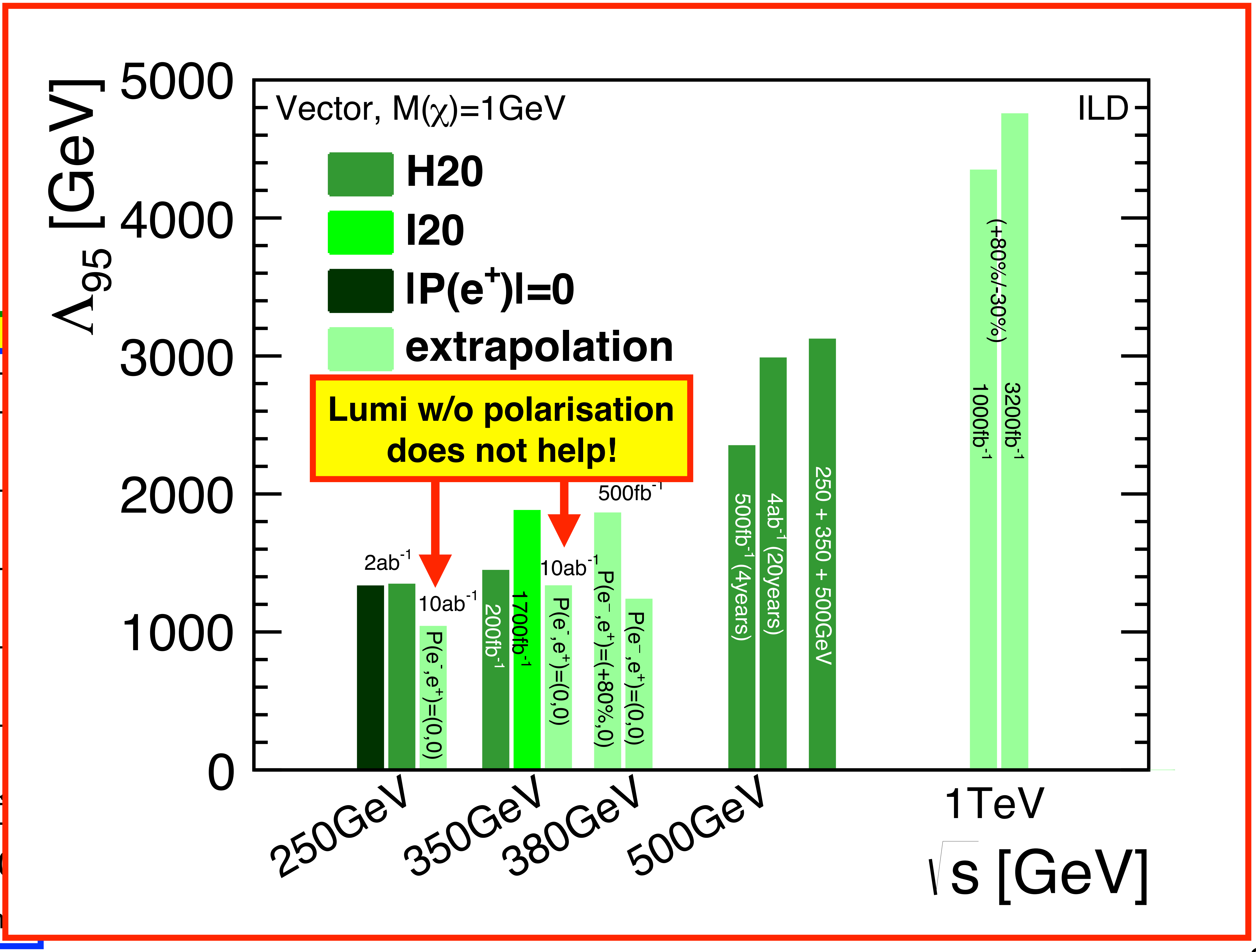

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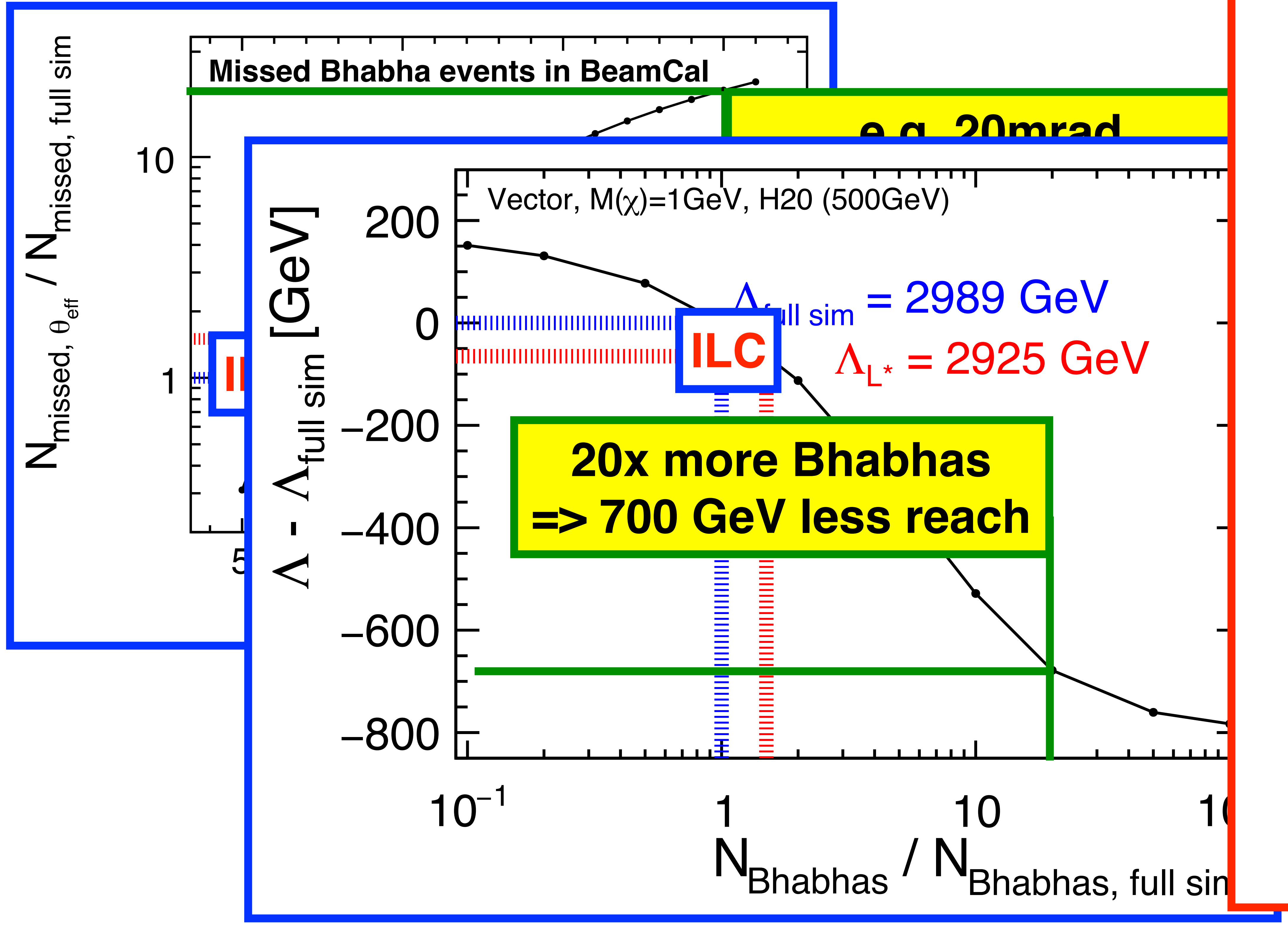
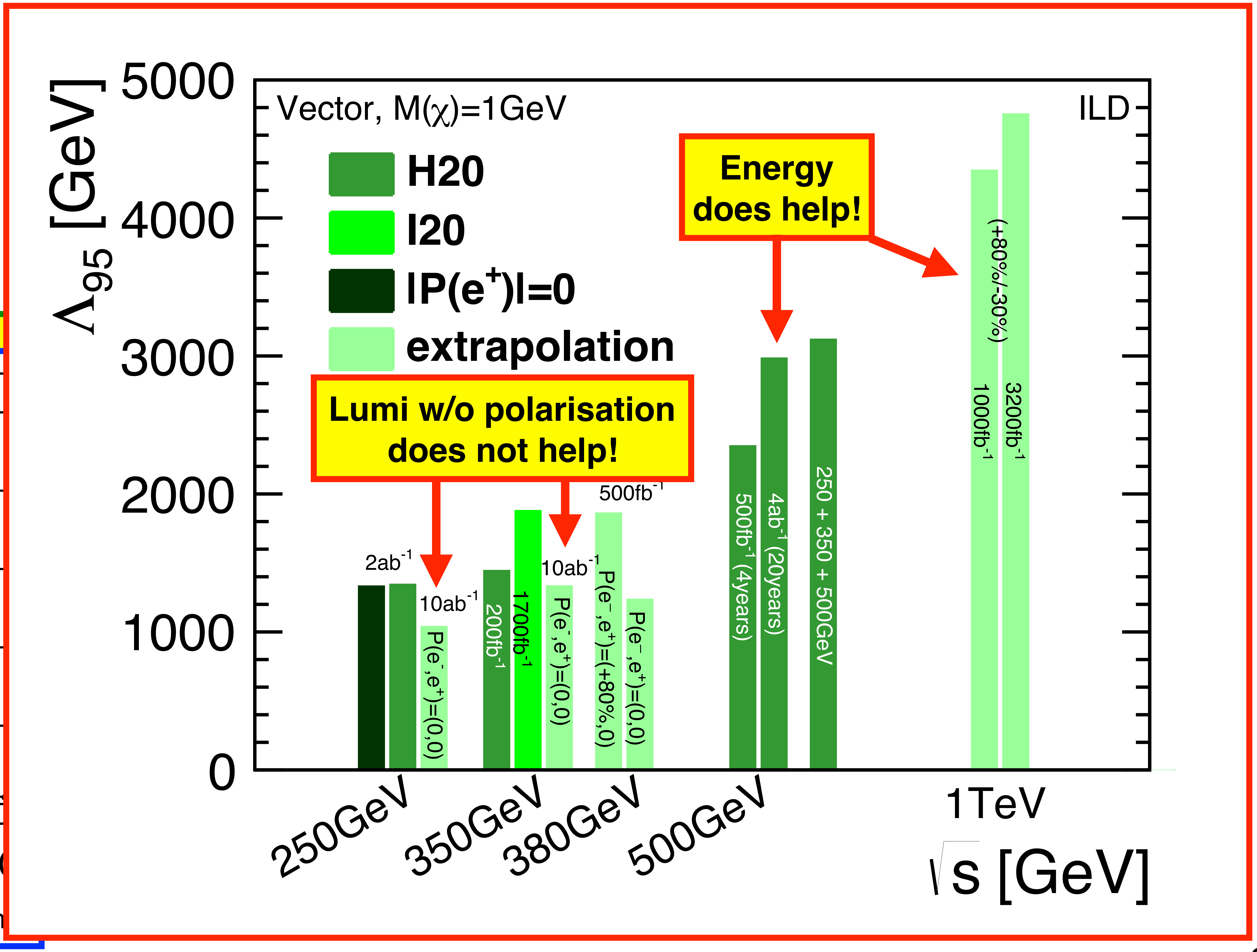




Conclusions

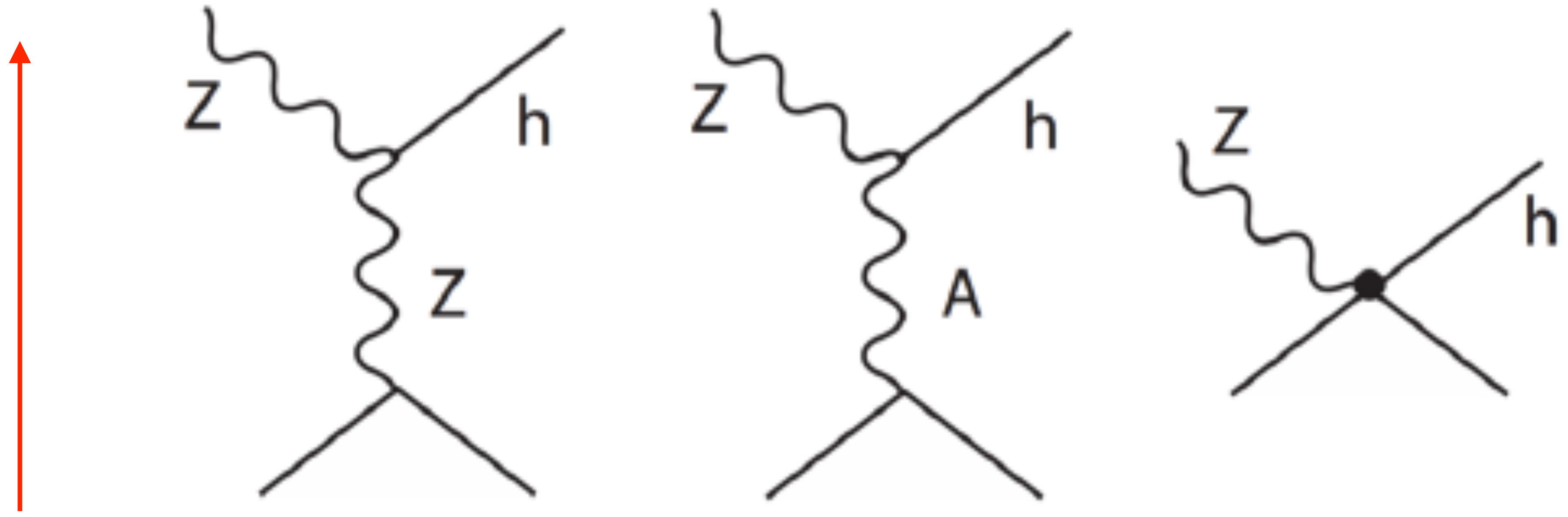
- **ILC offers significant discovery potential - both via indirect and direct searches**
- Rely strongly on the well-appreciated properties of **electron-positron colliders**:
  - **well defined initial state**
  - **clean environment, electroweak rates**
  - **democratic production of particles with electroweak charges**
- …and on the ***particular Linear Collider*** assets:
  - **extendability in energy & polarised beams**
  - **trigger-less operation of detectors**
  - **excellent hermeticity due to large L***
  - **tiny beam spot**
- **ILC's discovery potential is highly complementary to the LHC**

more details on ILC, detectors, physics: arXiv:1903.01629

more details on BSM at ILC arXiv:1702.05333

Why is A_{LR}(ZH) so important in EFT fit ?

Diagrams contributing to ee→Zh:



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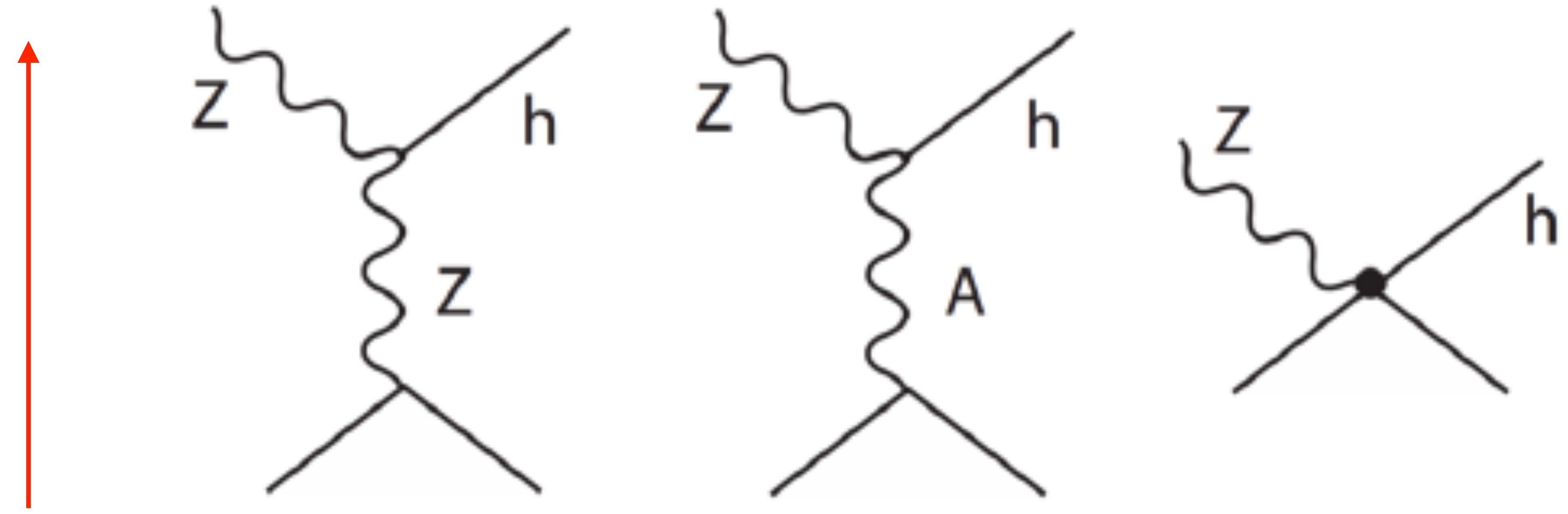

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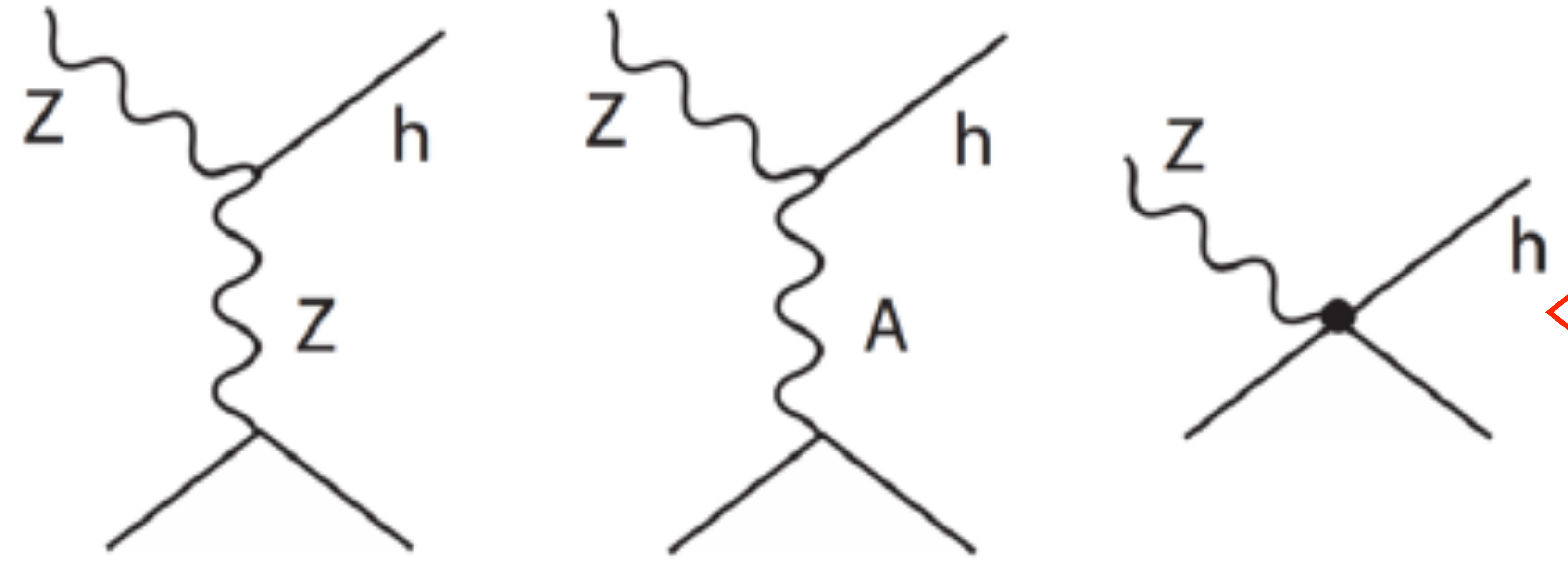

constrained by EWPOs (*)

only diagram allowed in SM

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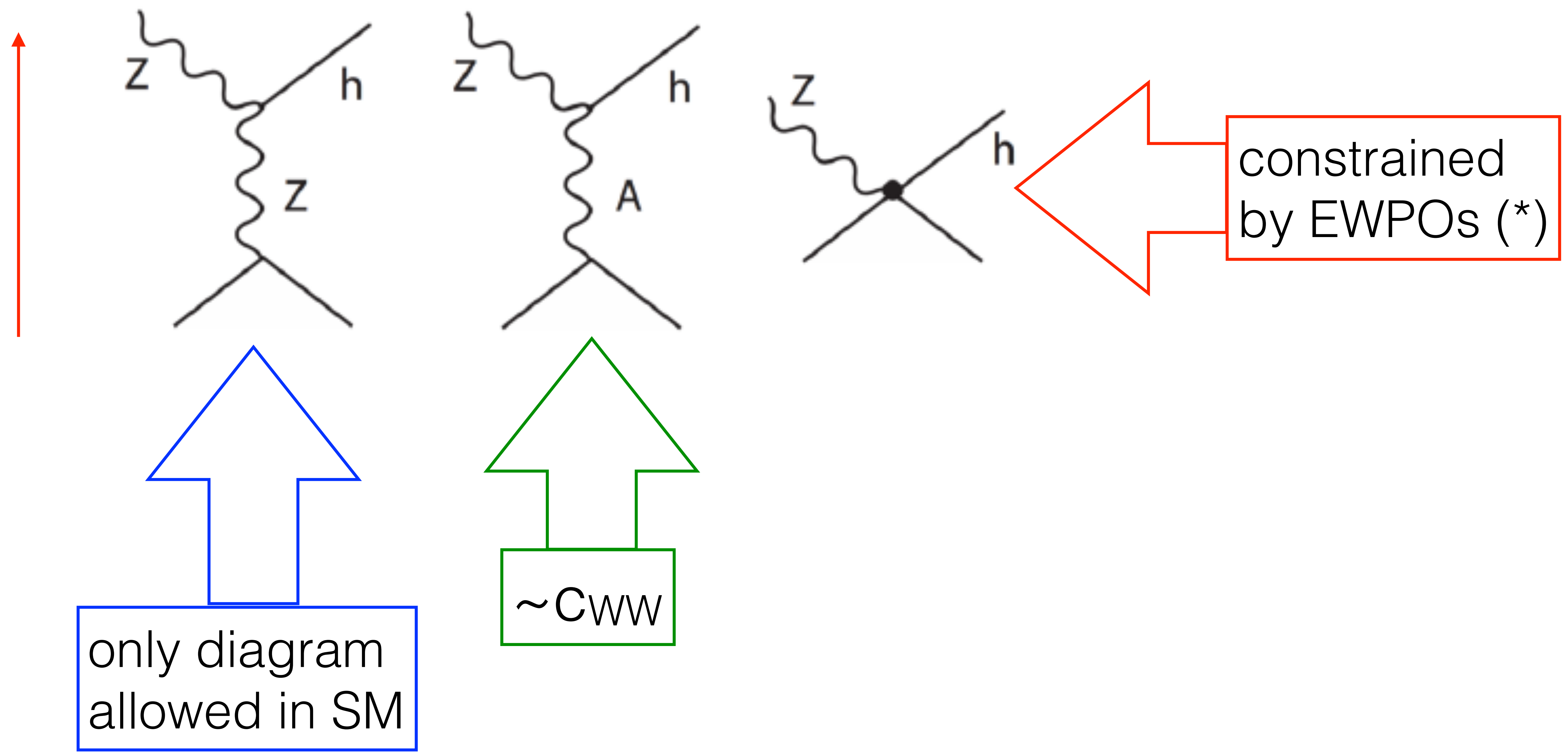

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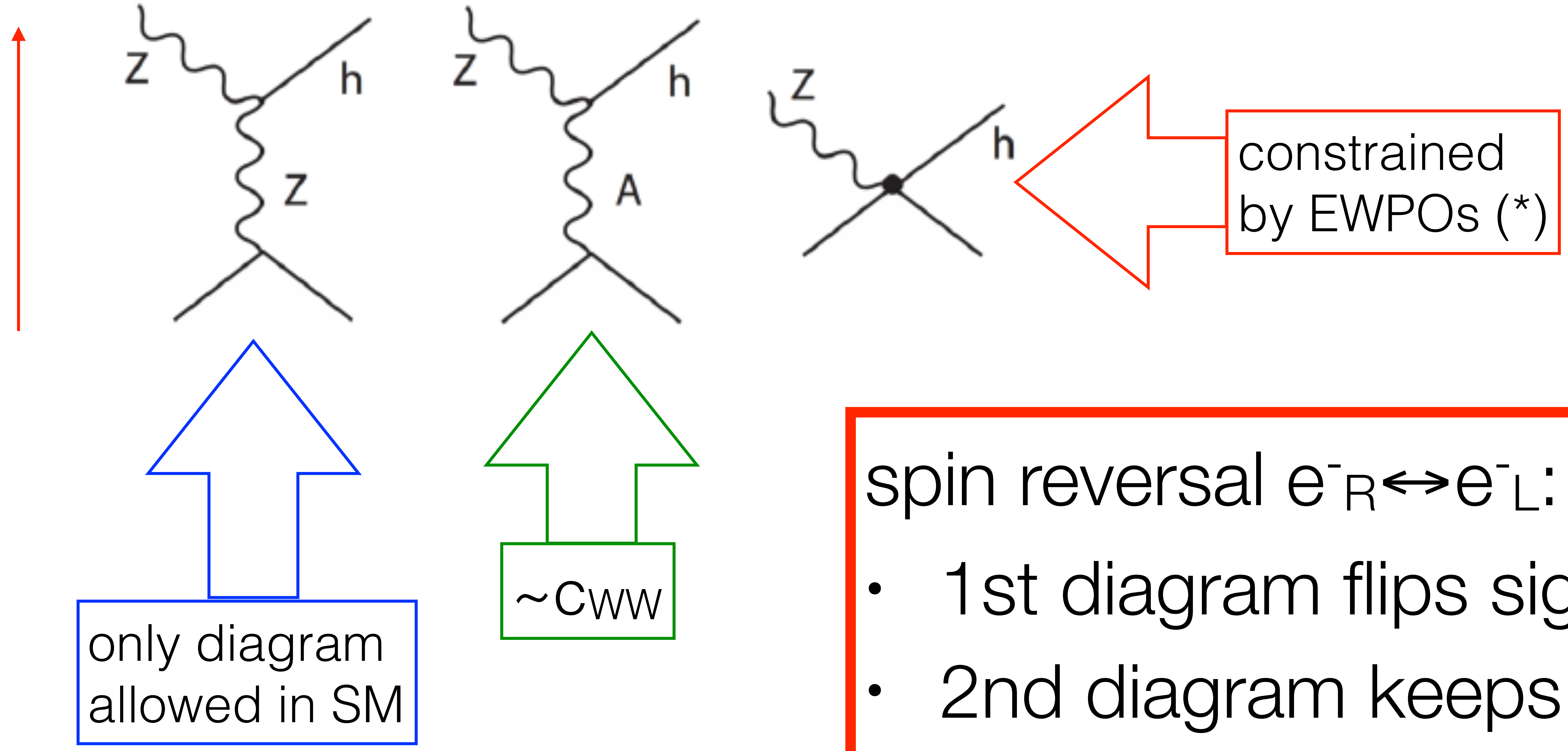

spin reversal $e^-_R \leftrightarrow e^-_L$:

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

⇒ **A_{LR} directly measures c_{WW} !**

New Properties of the Higgs Boson

New Properties of the Higgs Boson

No a priori constraint
on total width,
nor on $k_V < 1$,
nor on Γ_{BSM};
different tensor structure
of HVV couplings included

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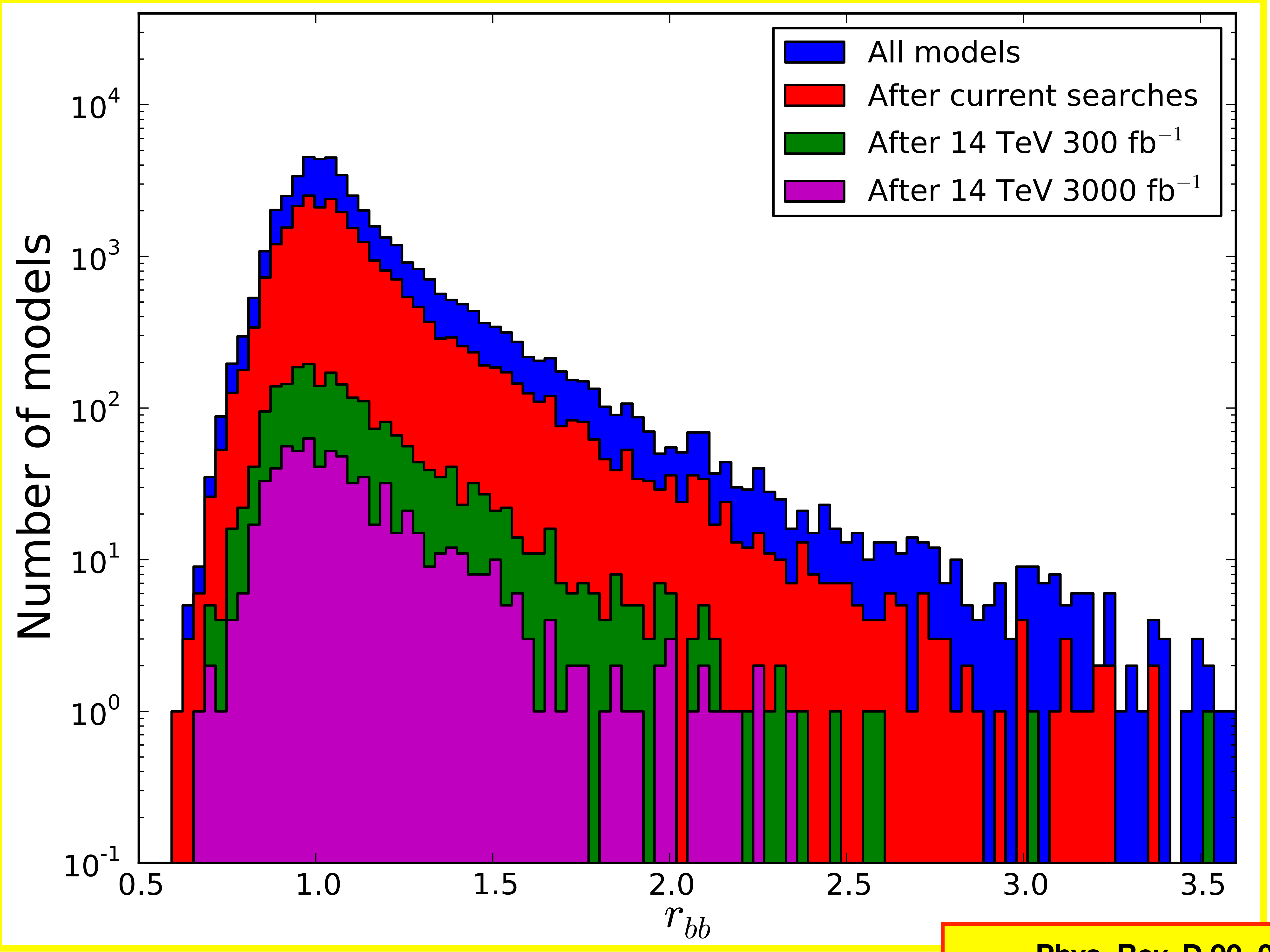

Phys. Rev. D 90, 095017 (2014)

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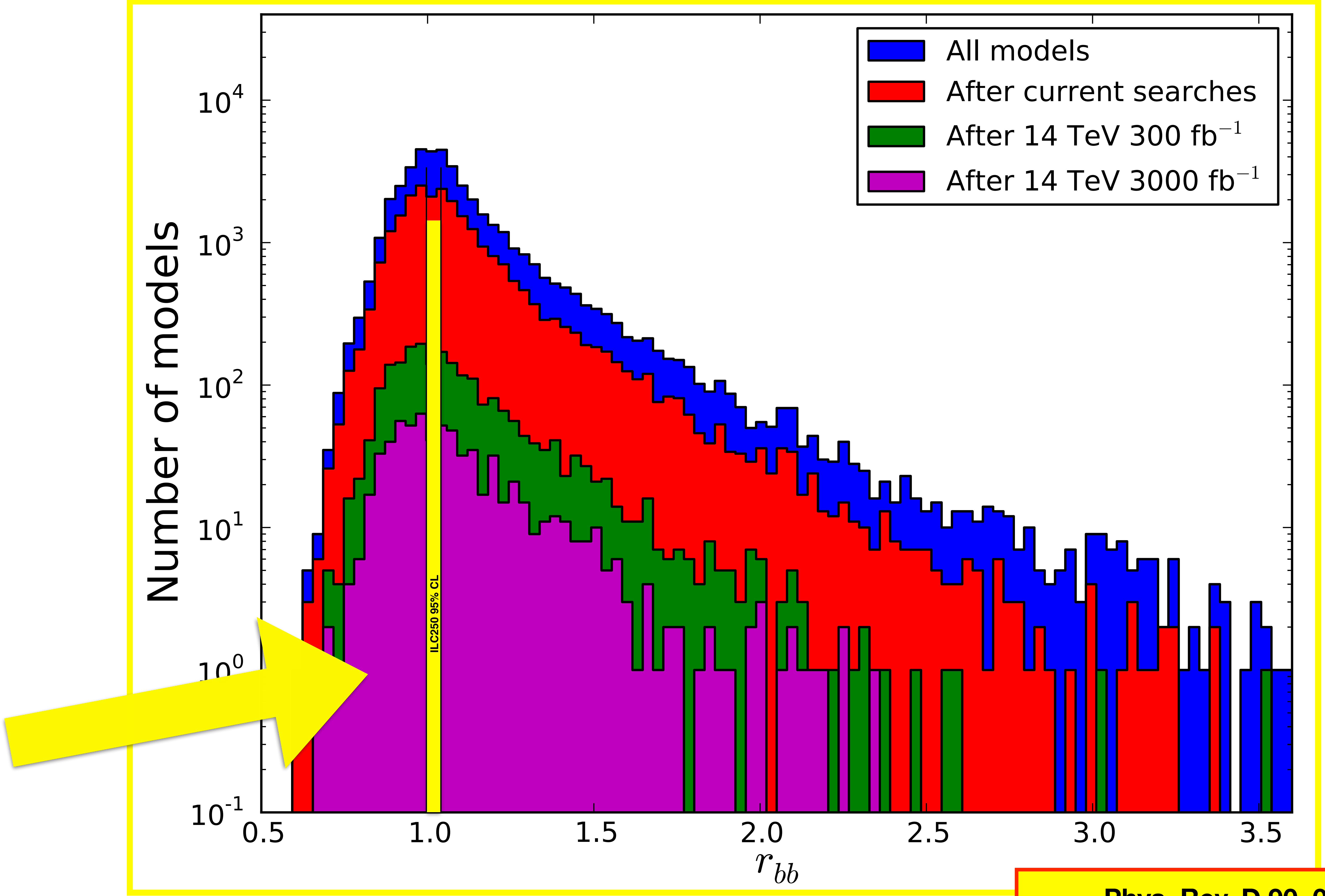

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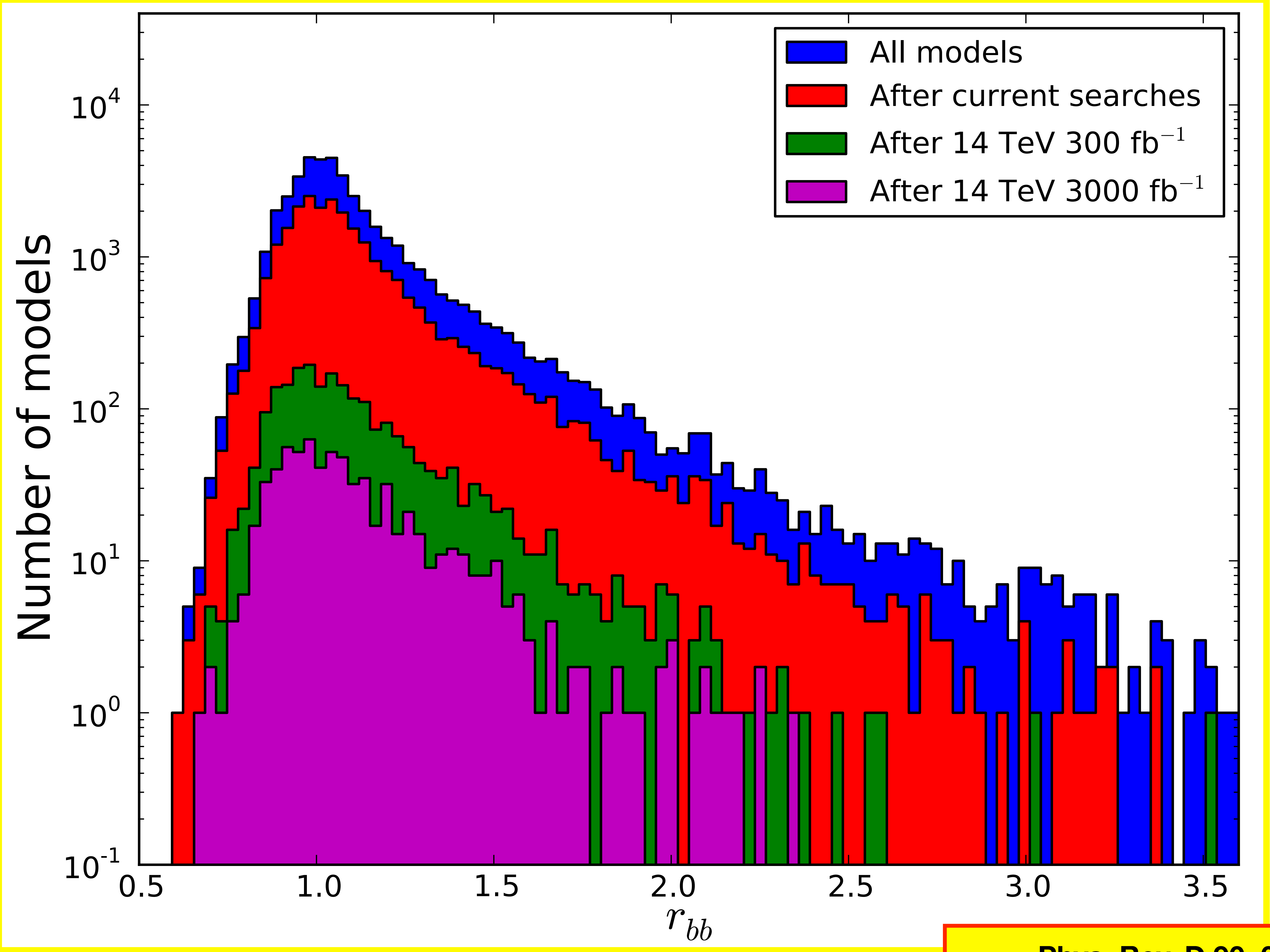

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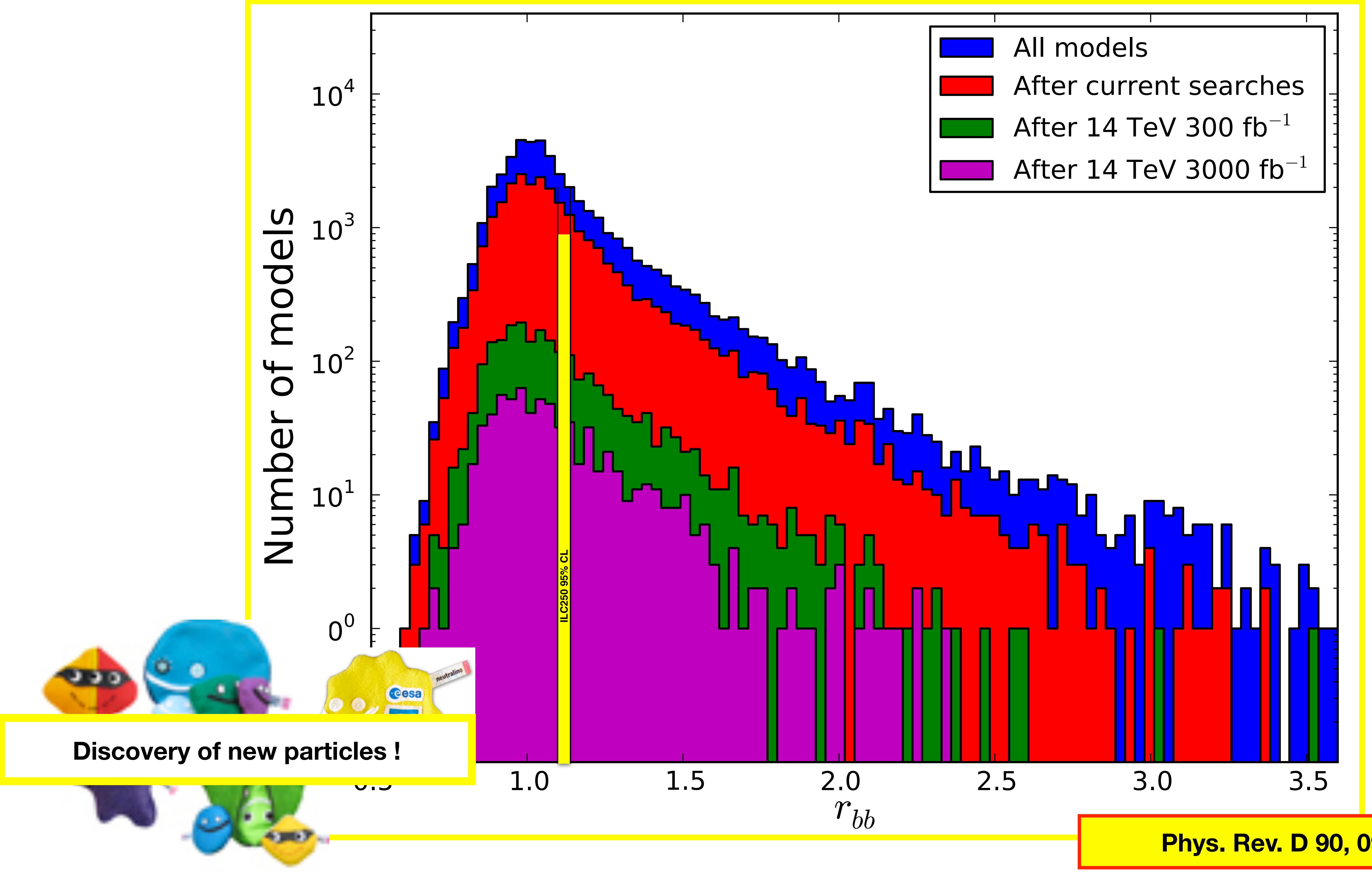

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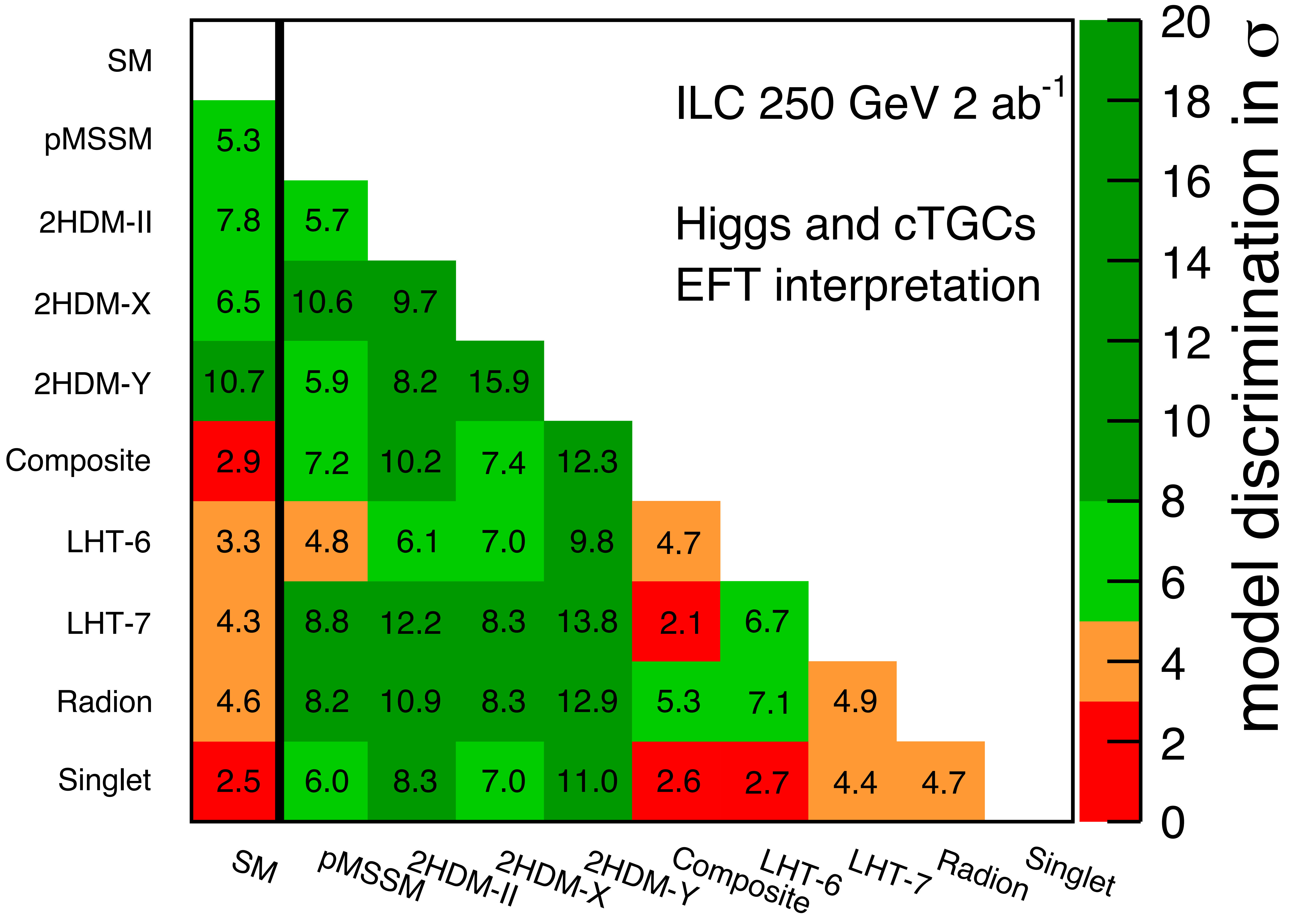
Test BSM



Identifying the Nature of Dark Matter

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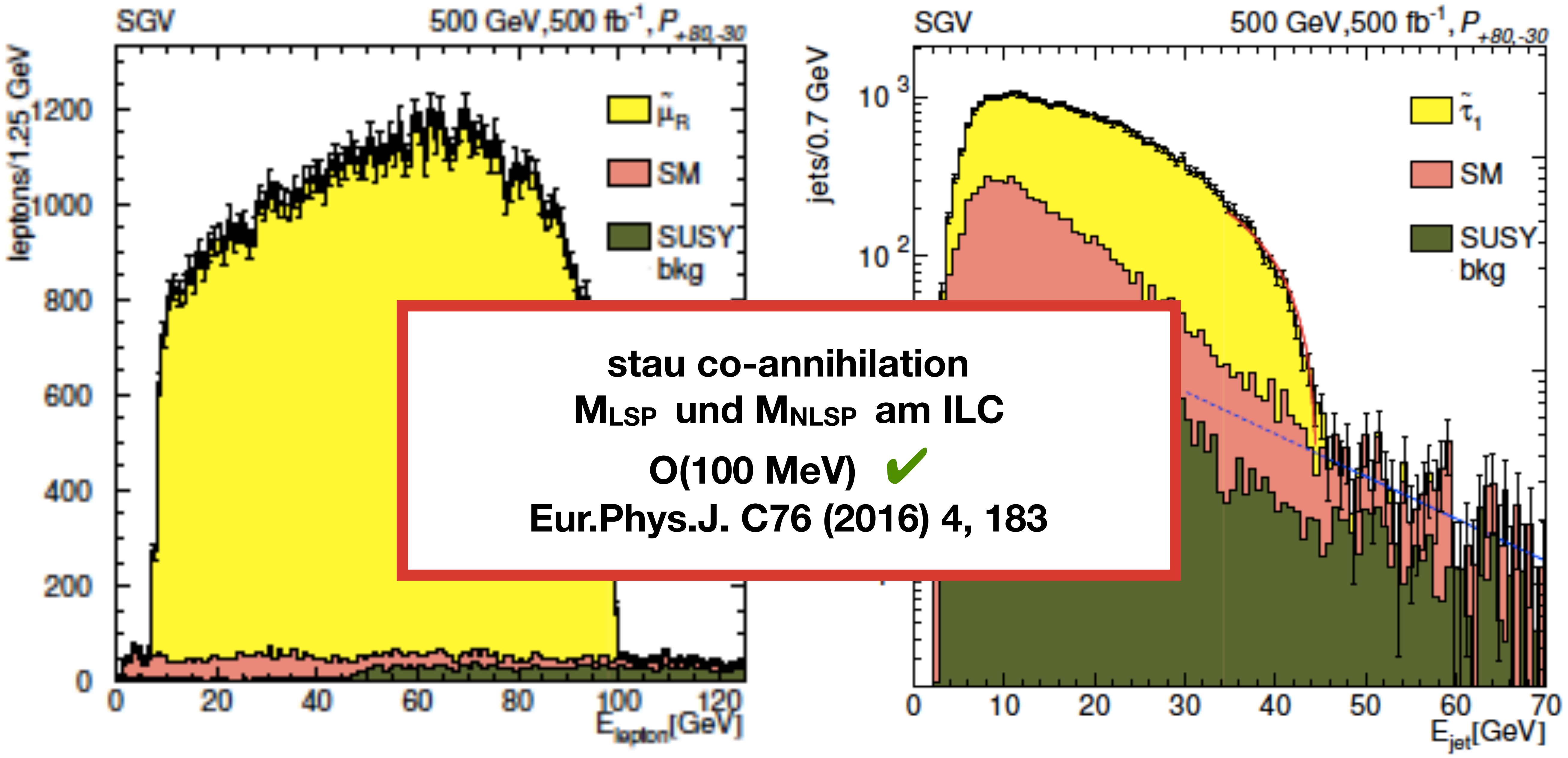

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M_{LSP} und M_{NLSP} am ILC
O(100 MeV) ✔
Eur.Phys.J. C76 (2016) 4, 183

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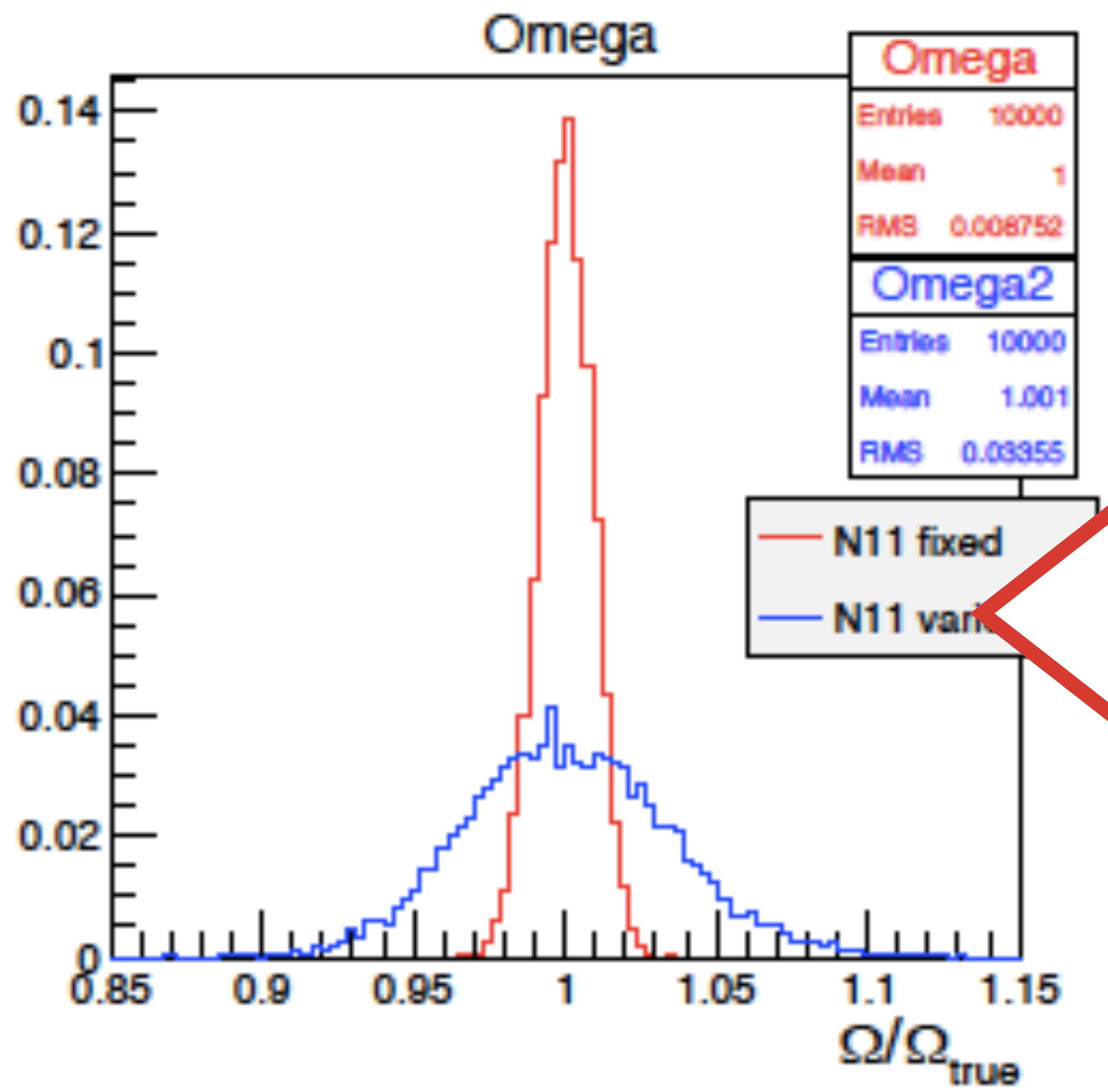
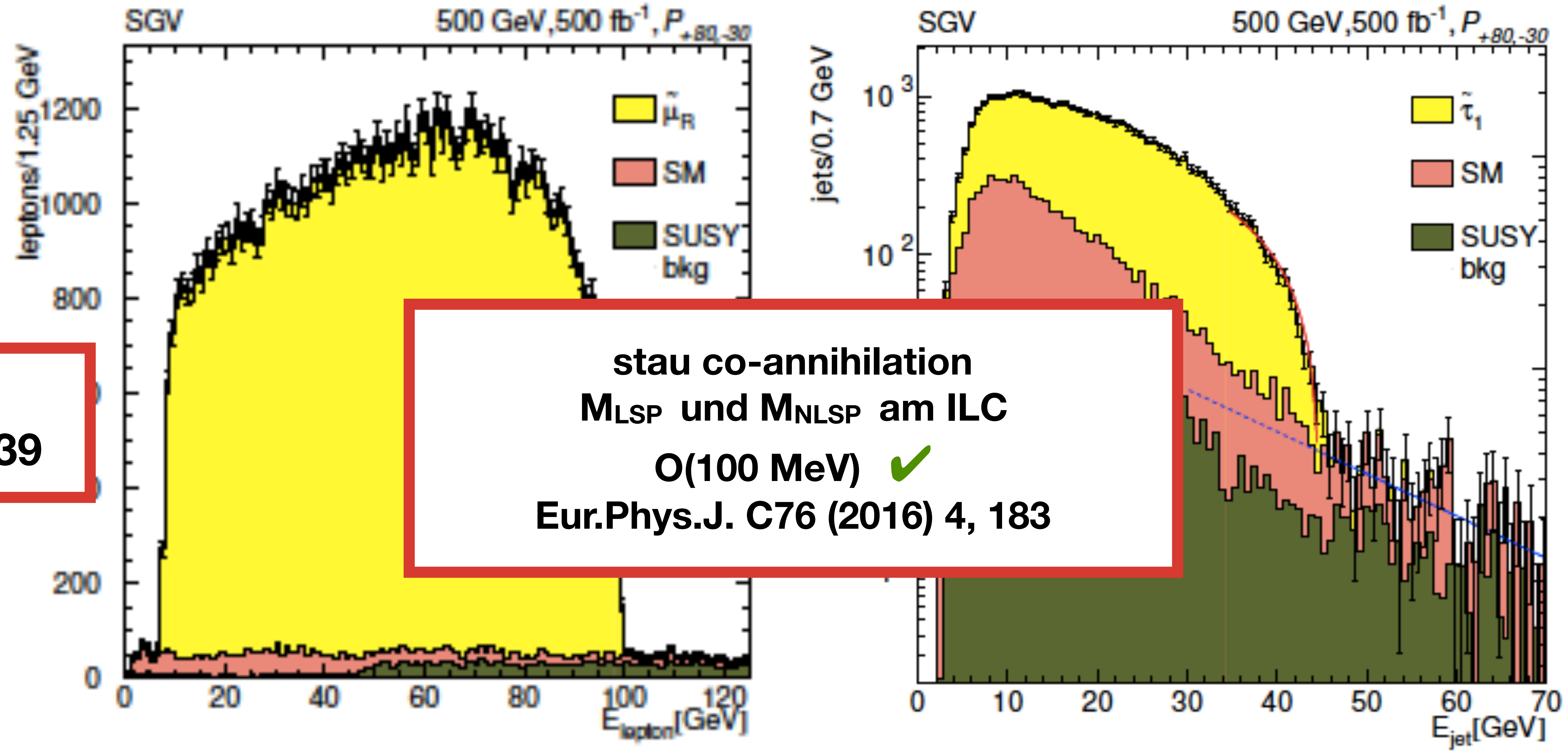


arXiv: 1602.08439



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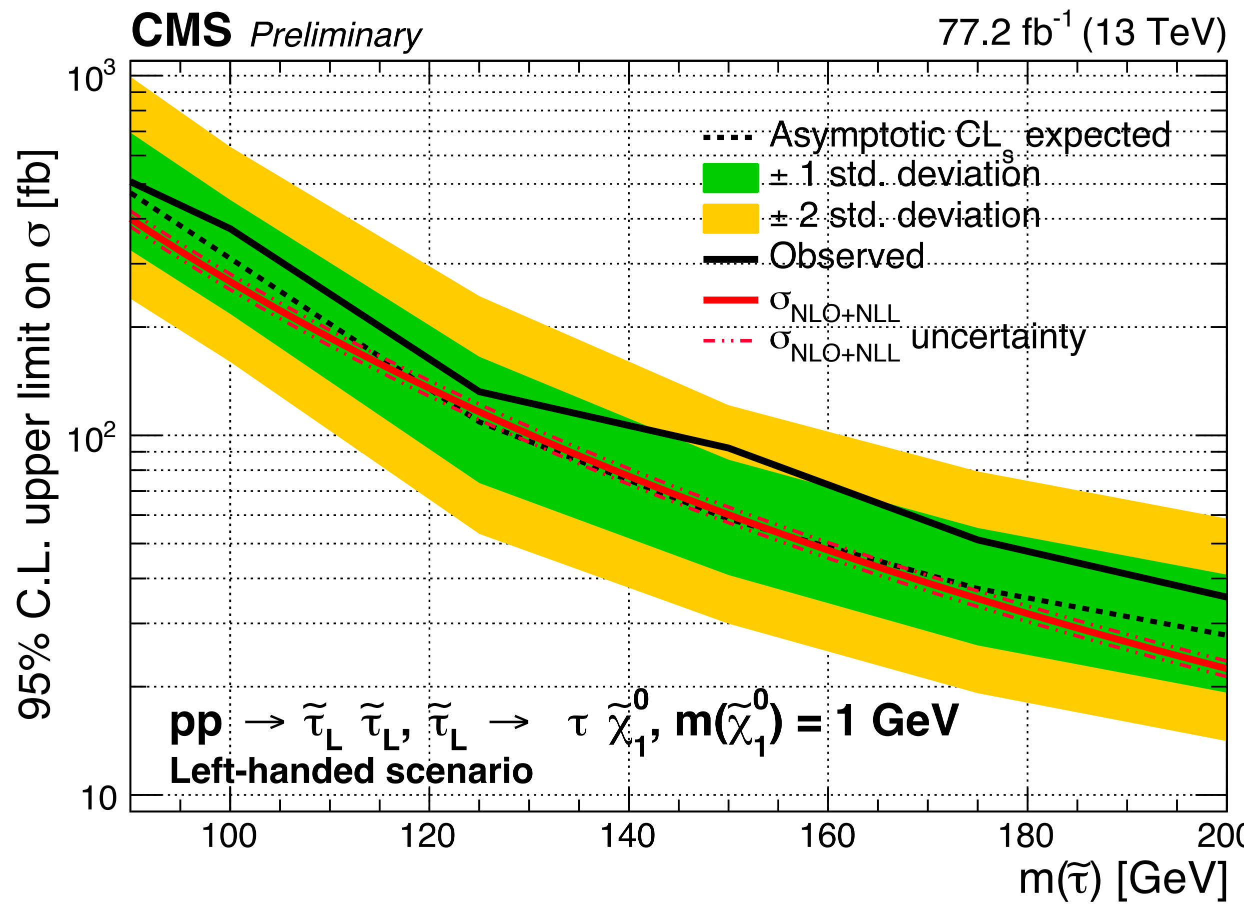
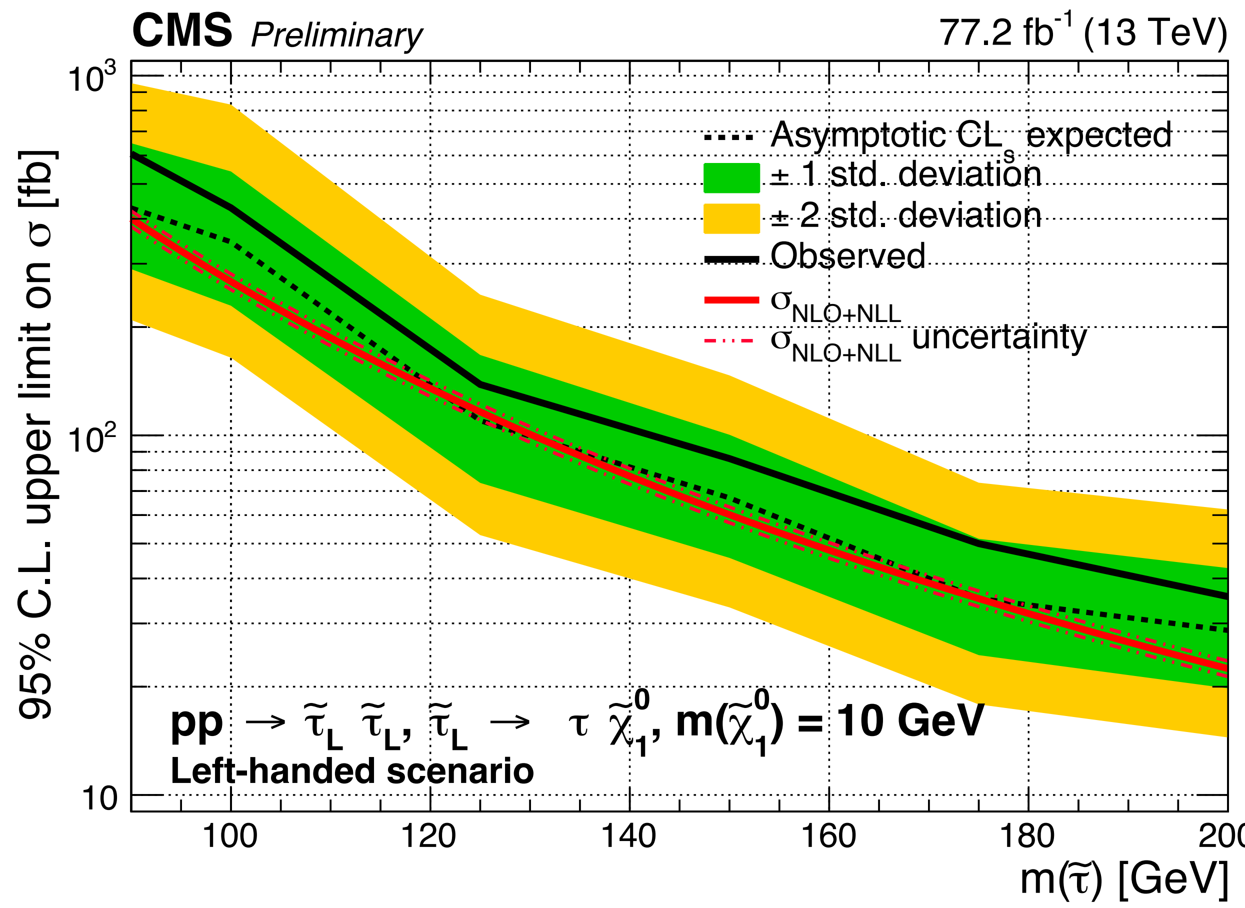
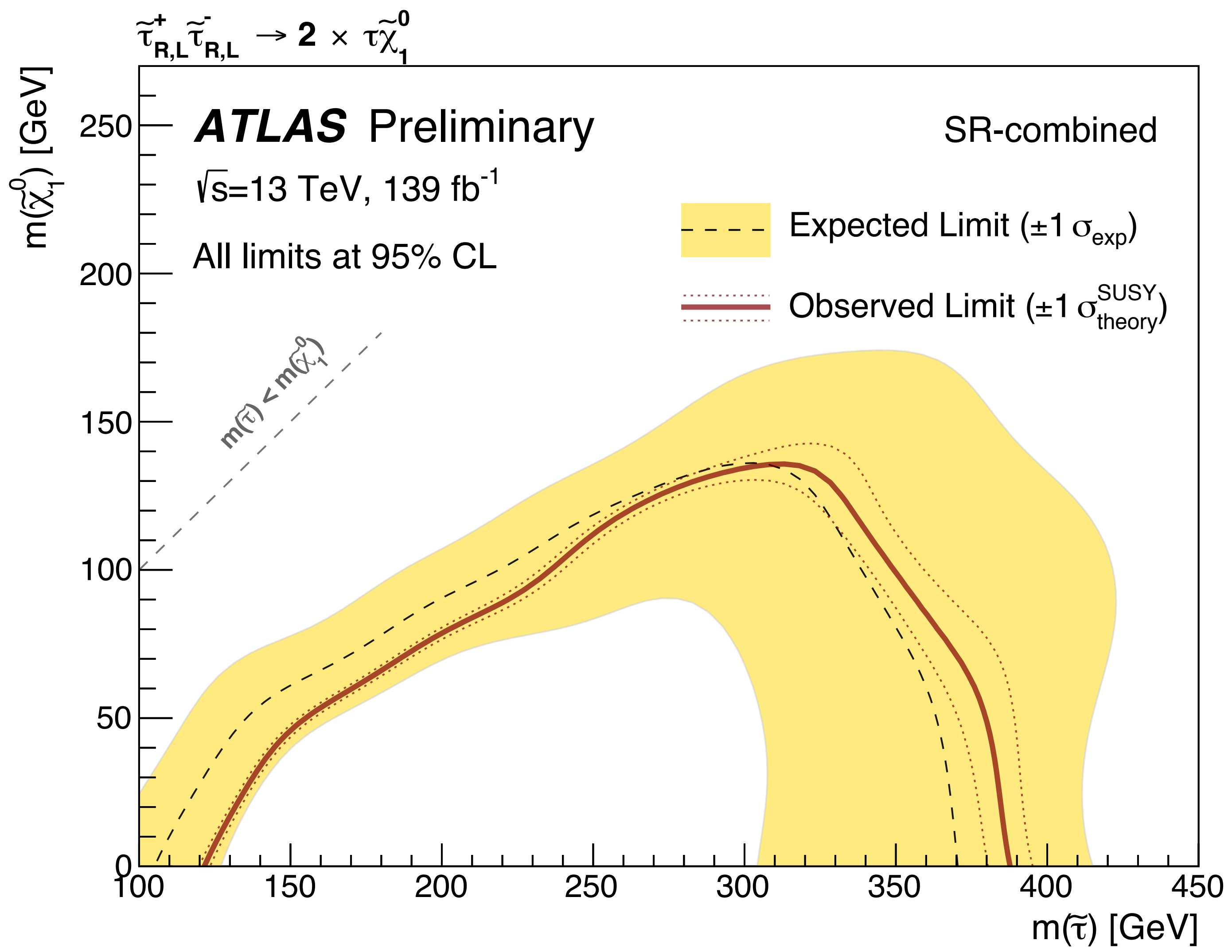
LHC stau limits

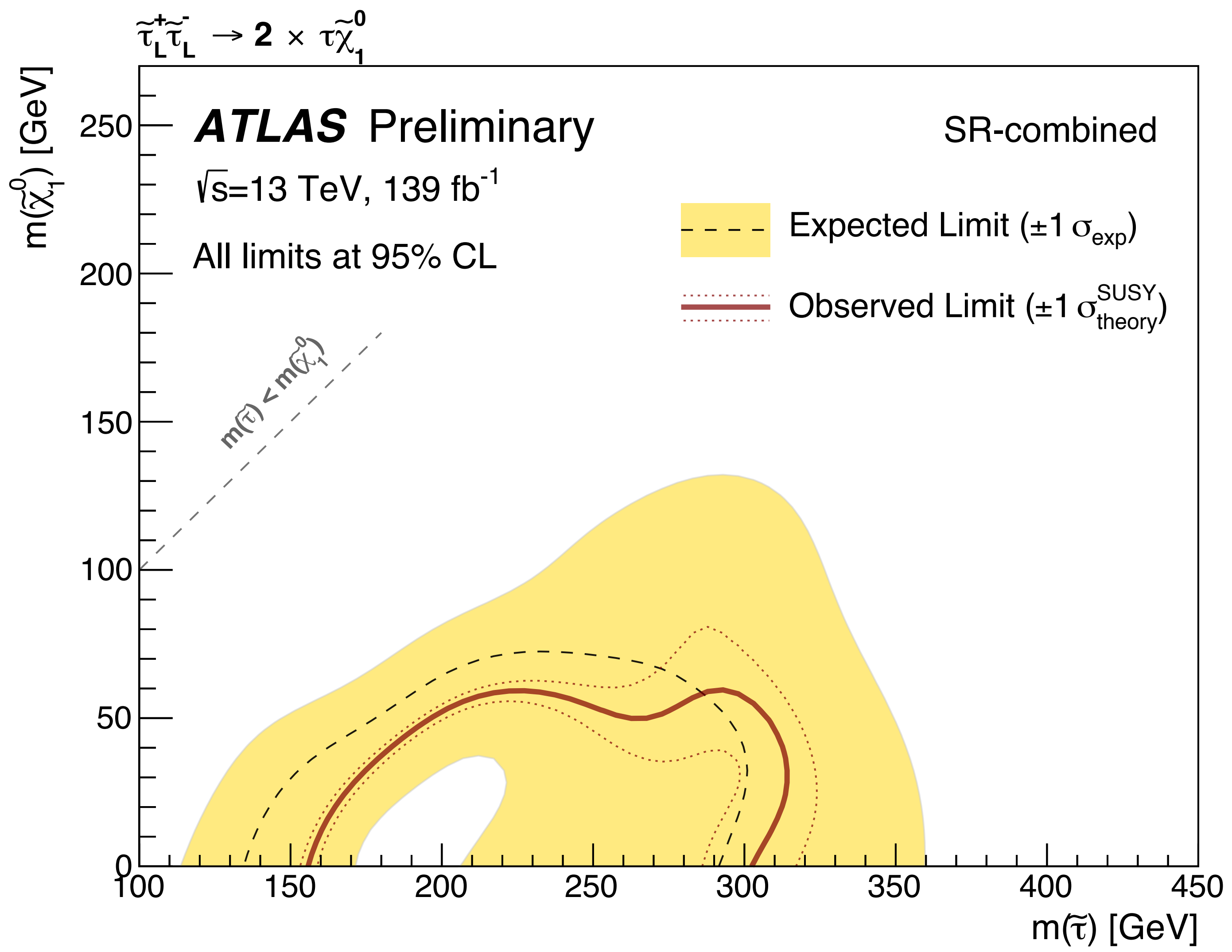
CMS PAS SUS-18-006

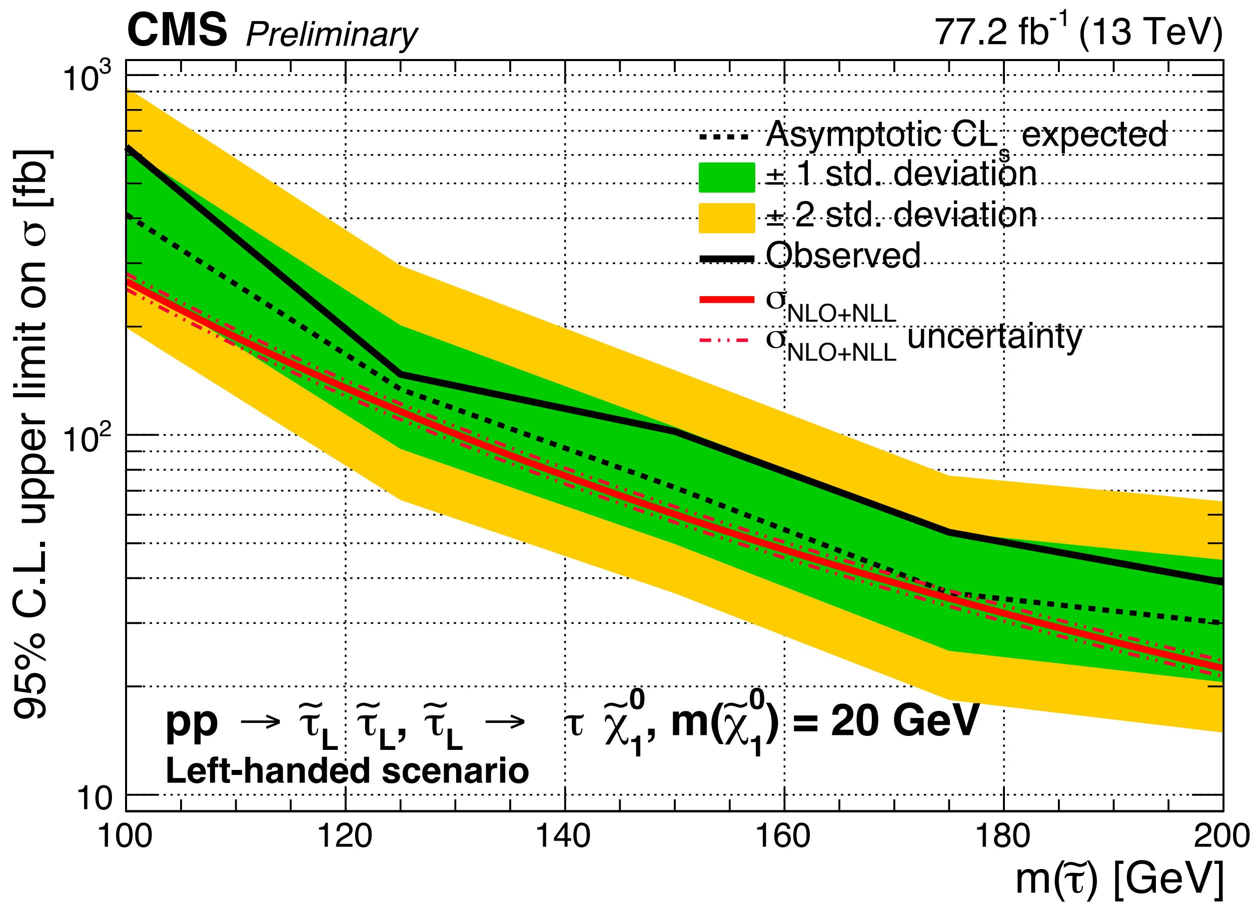




ATLAS-CONF-2019-018







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- scale of neutrino mass generation still unknown
- some models testable at colliders
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bRPV: ILD full simulation Eur.Phys.J. C74 (2014) 2720

- **LSP pair production discoverable for selectron masses up to ~ 2 TeV**
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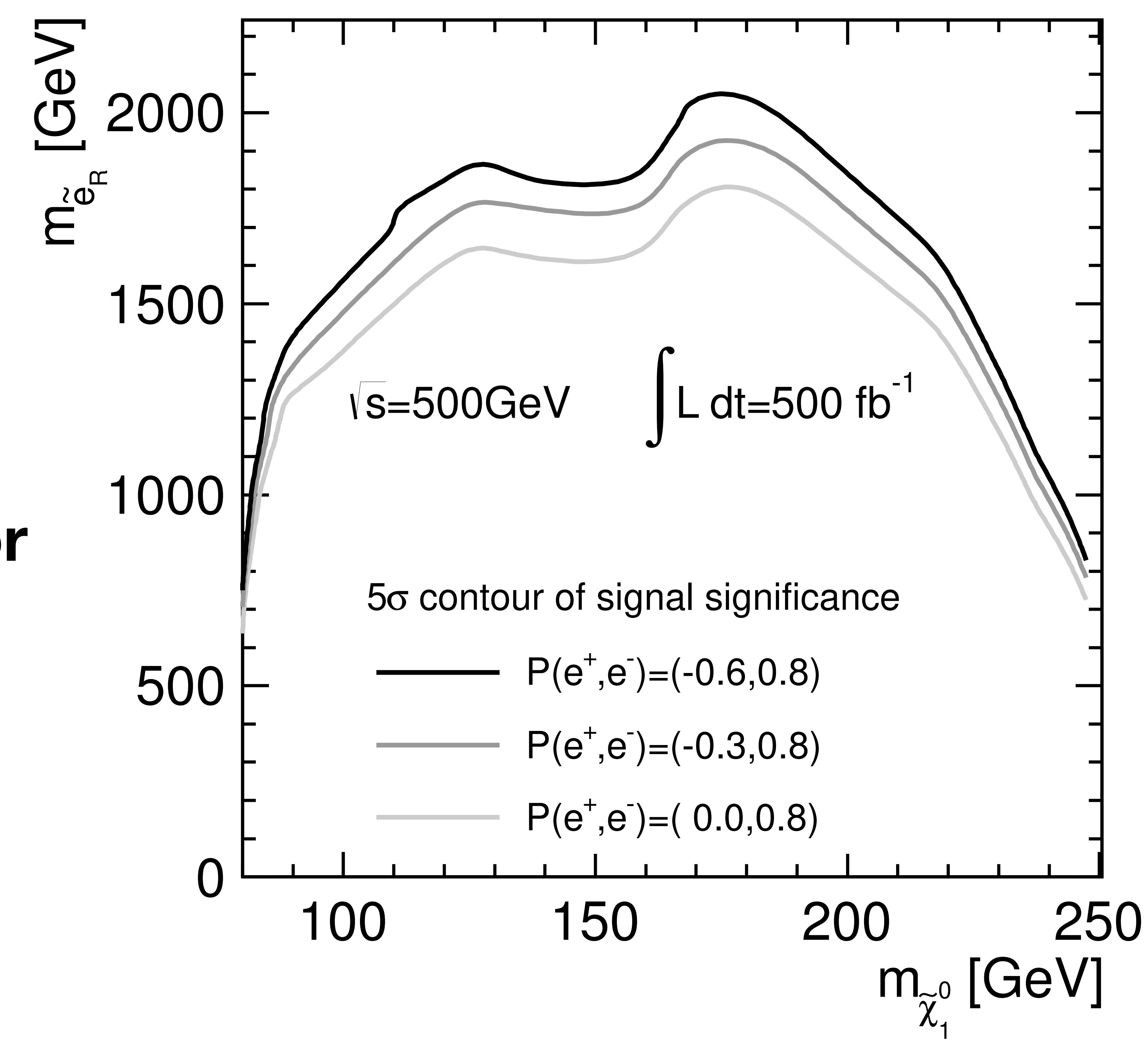
- compare of collider measurement with neutrino oscillation data **=> verify or falsify bRPV as mechanism of neutrino mass generation**

μμ channel



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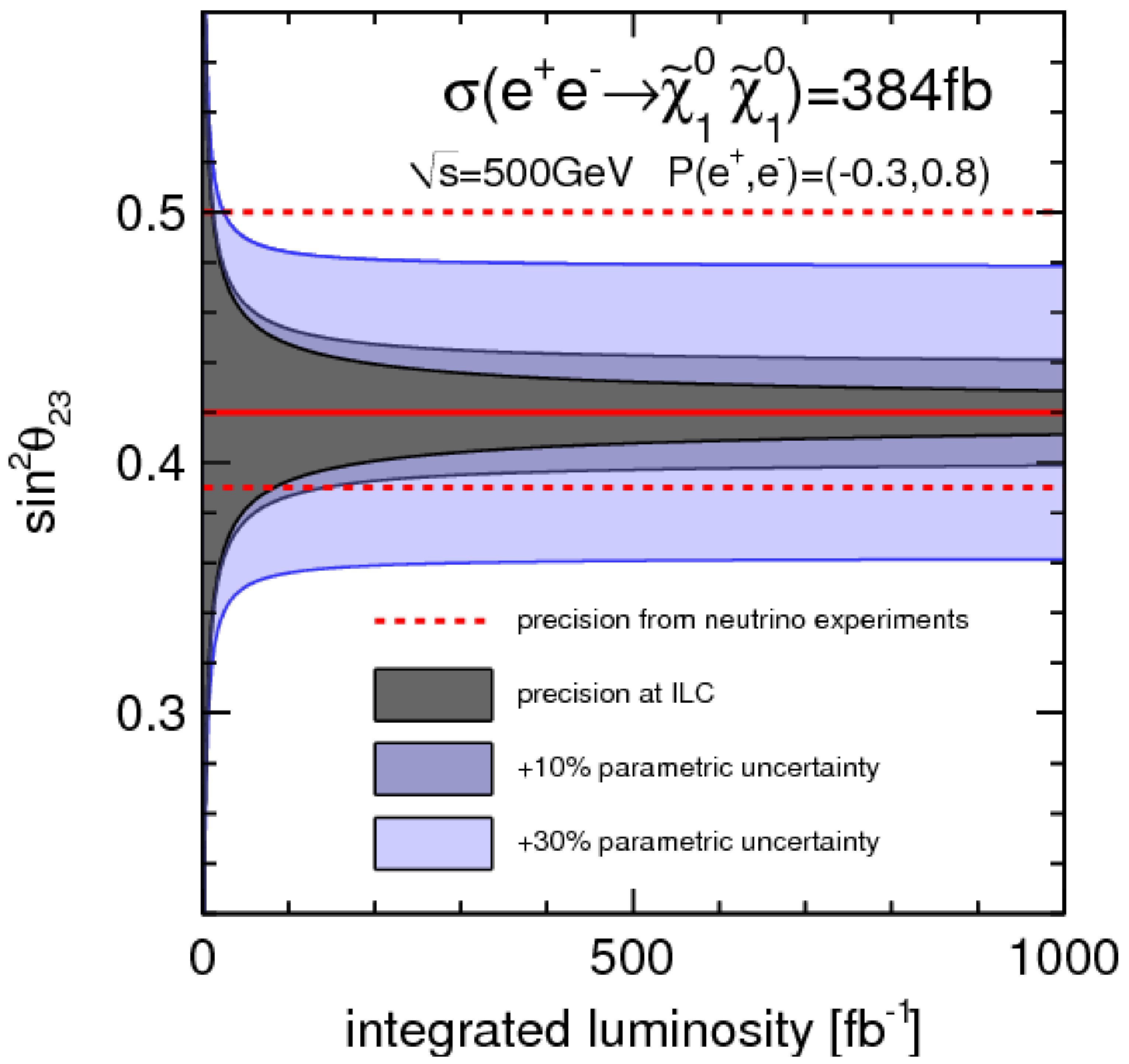

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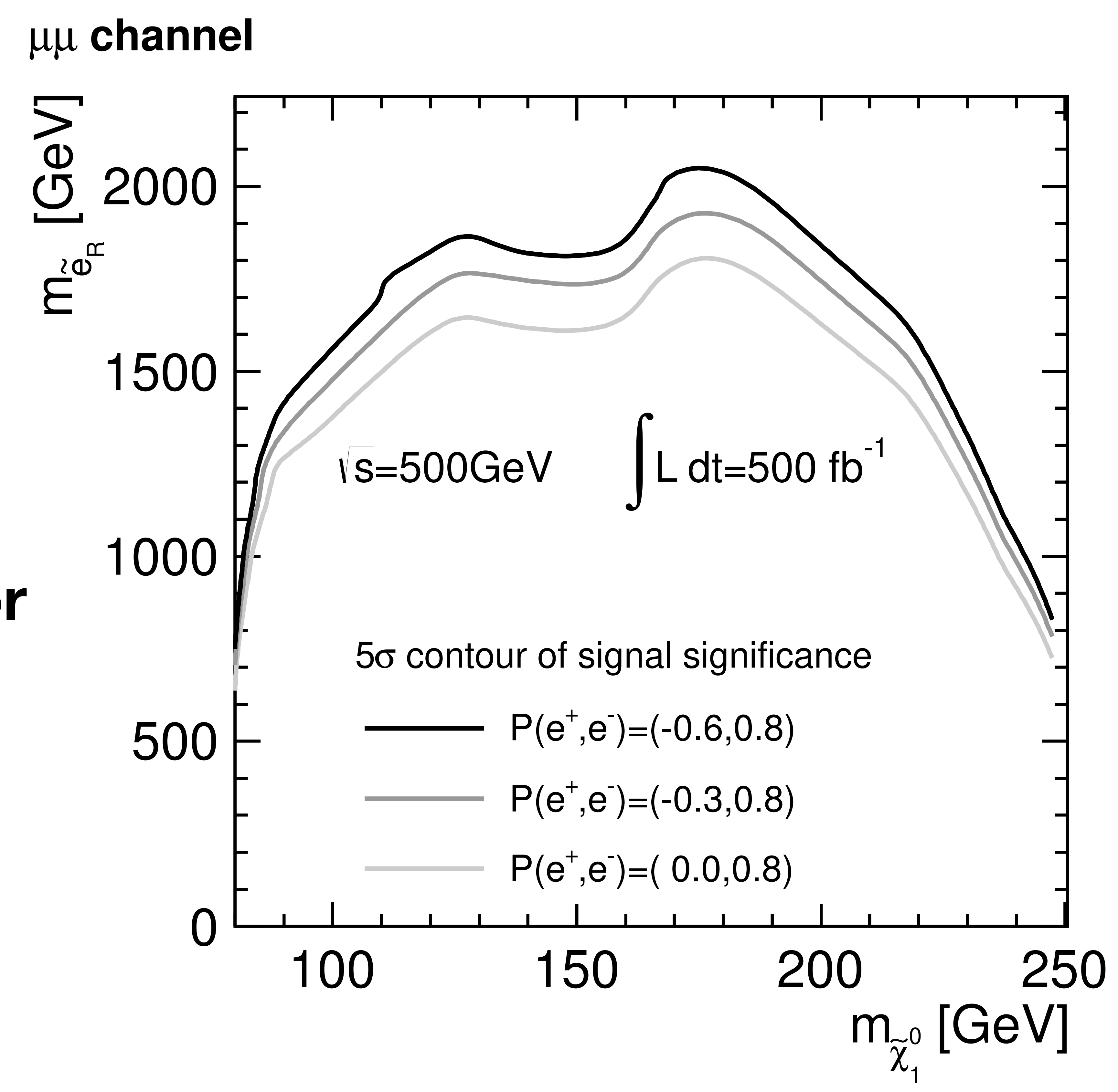
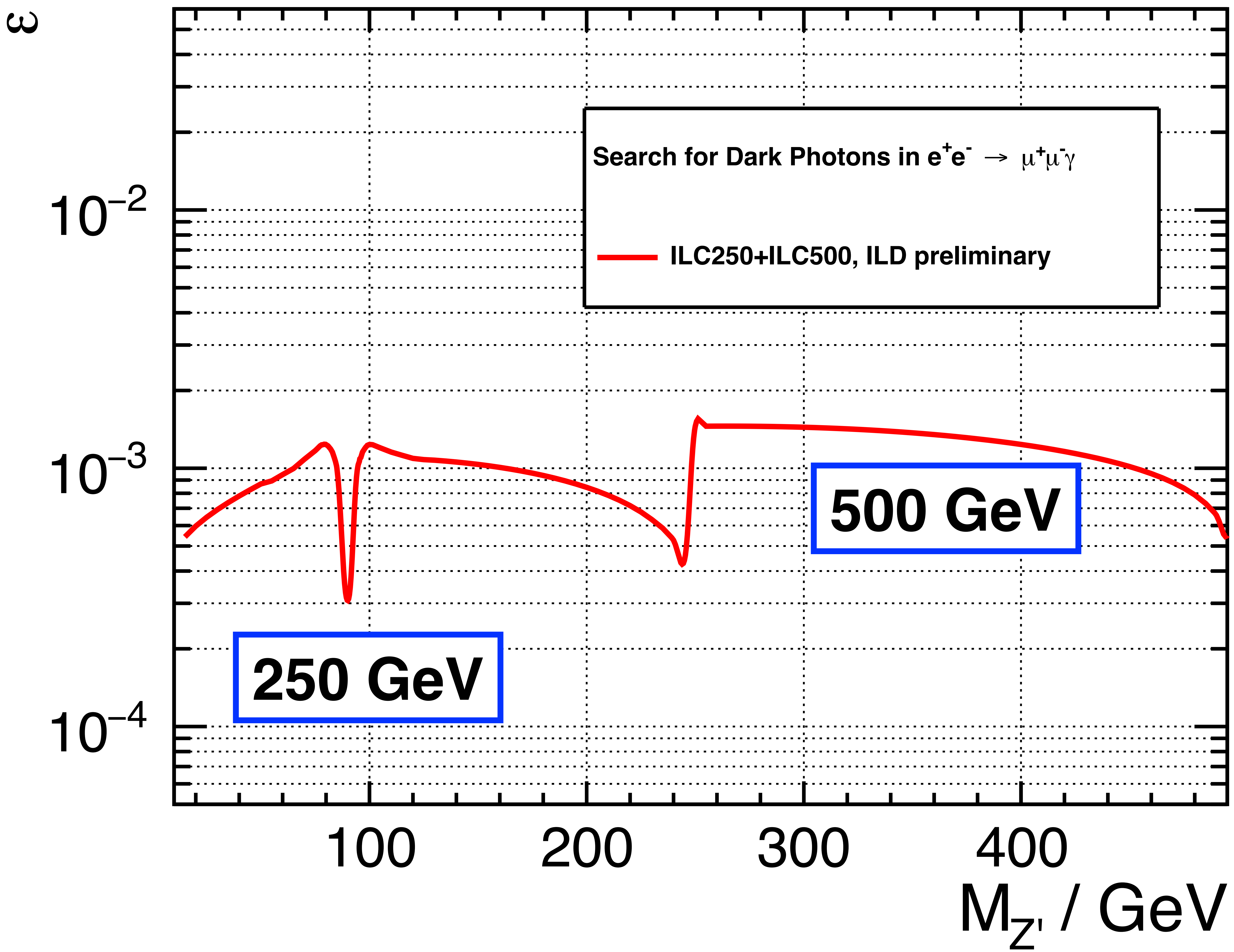
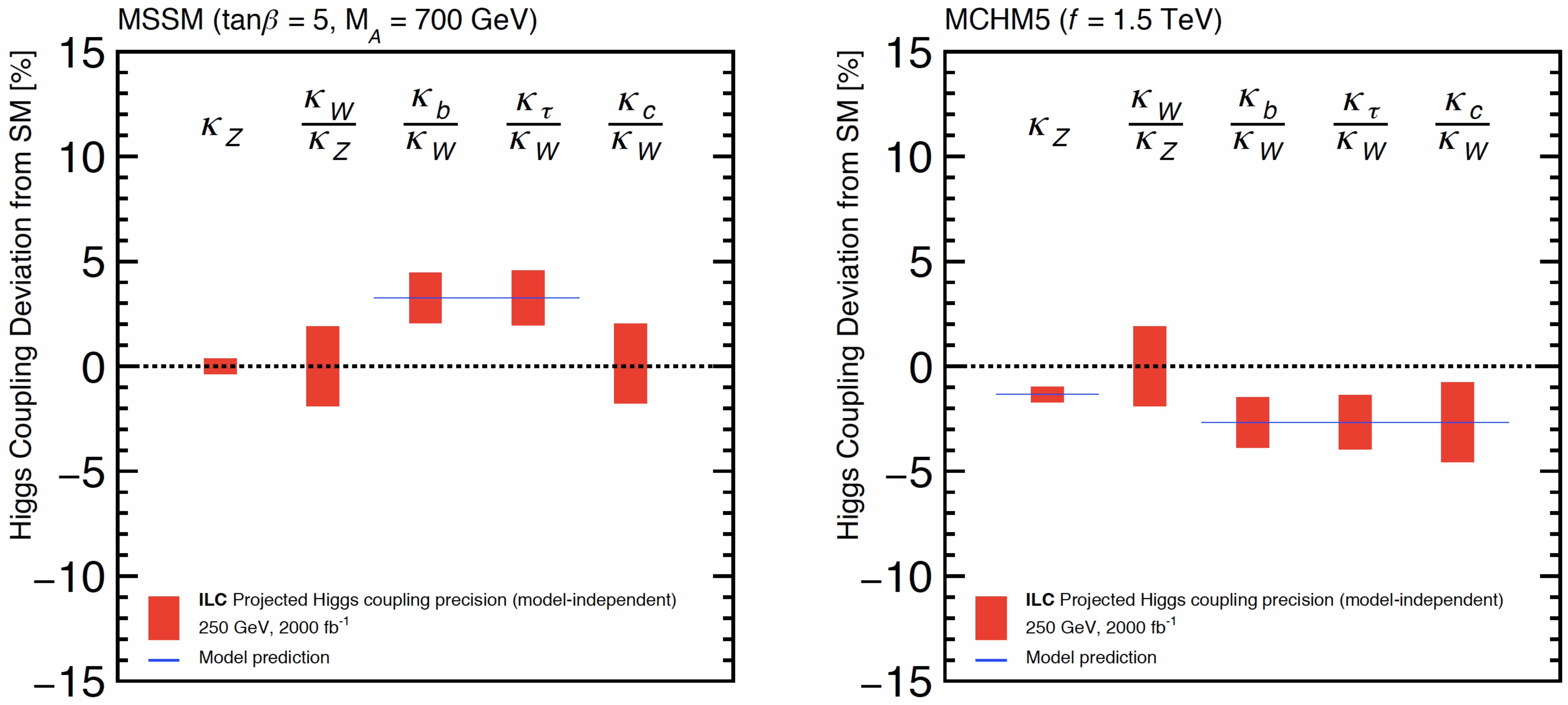


Vector Portal Dark Matter: Dark Photon



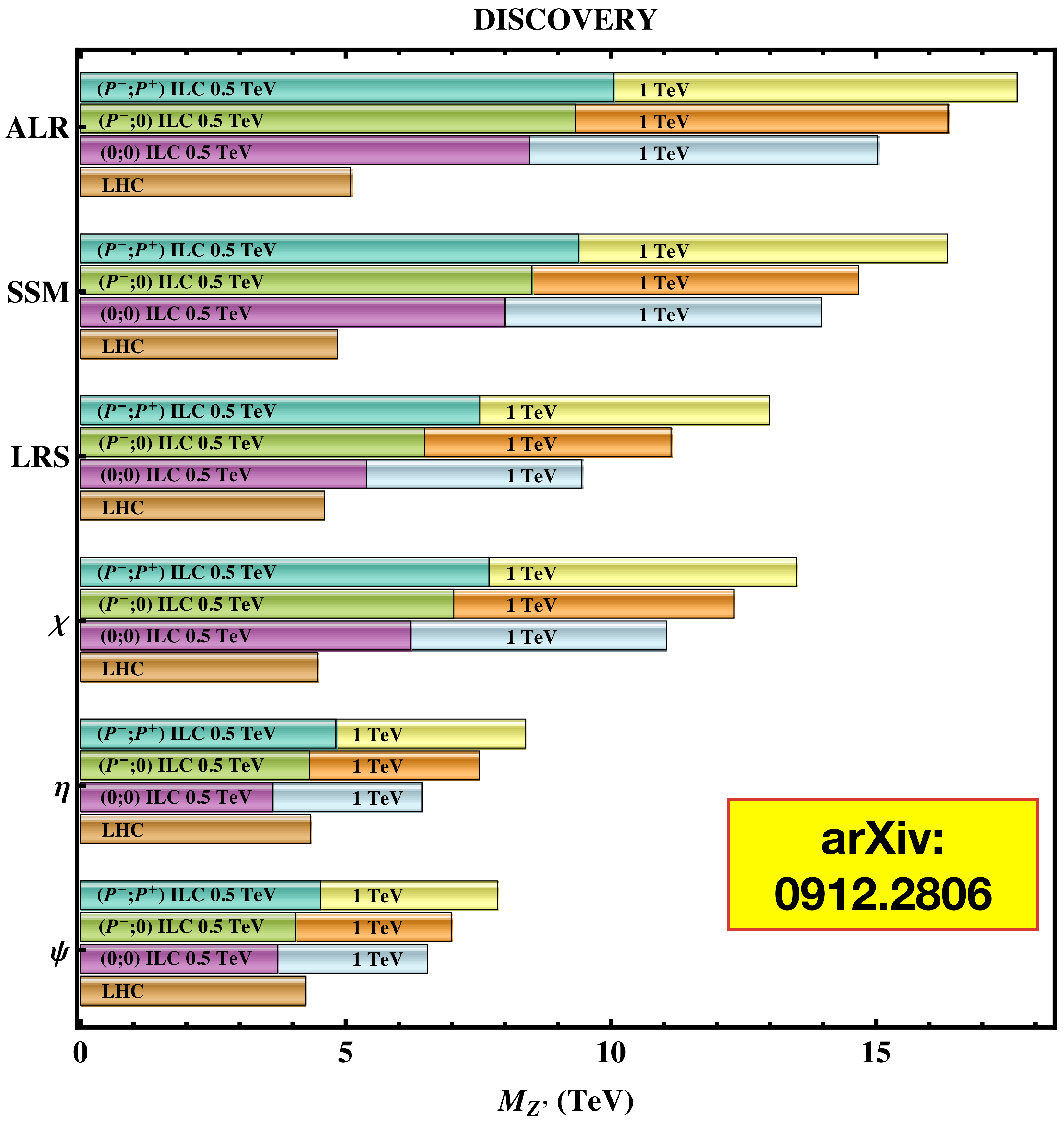
Finger-printing the Higgs: SUSY or Composite?



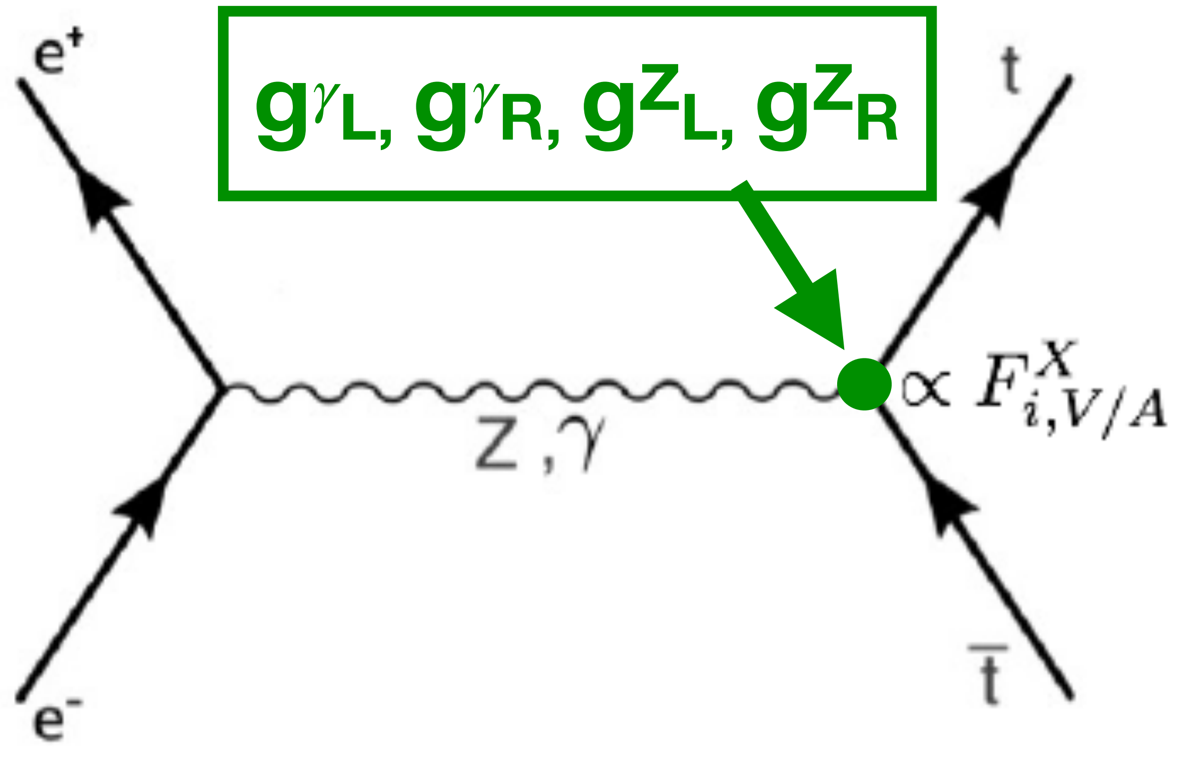
The full ILC250 stage gives significant BSM discrimination power

New Force Carriers

- via e^+e^- -> ff: sensitivity to Z' up to ~10 TeV
- already for 500fb^{-1} @ 500 GeV (initial run)
- increases to up to ~17 TeV for 1ab^{-1} at 1 TeV
- polarised beams typically gain ~2 TeV in reach



Electroweak Couplings of the Top Quark



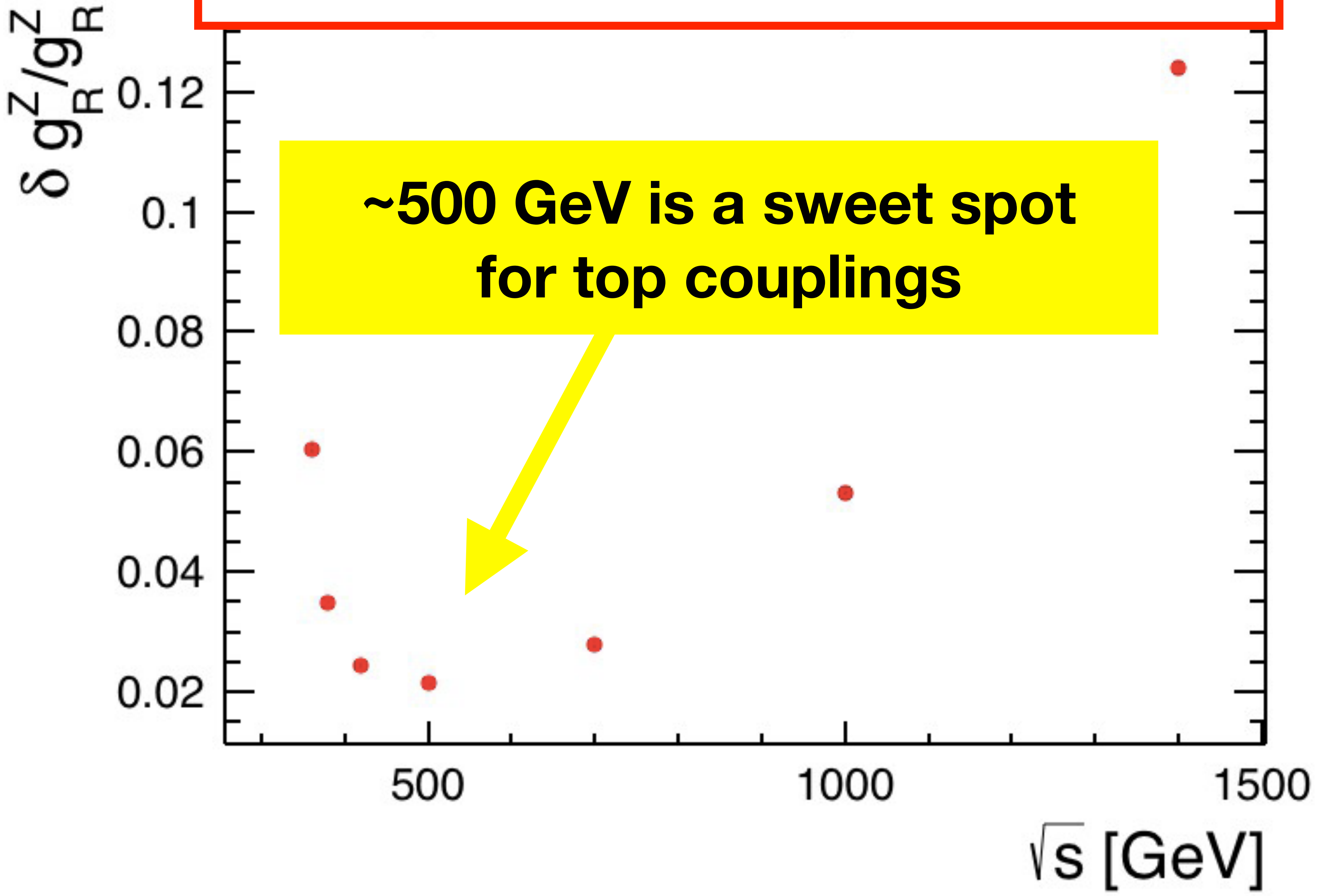
Pure γ or pure Z^0 : $\sigma \backsim (F_i)^2 \Rightarrow$ No sensitivity to sign of Form Factors

Z^0/γ interference : $\sigma \backsim (F_i) \Rightarrow$ Sensitivity to sign of Form Factors

ILC 'provides' two beam polarisations

$P(e^-) = \pm 80\%$ $P(e^+) = \mp 30\%$

√s dependency: top physics is *not* done at threshold!



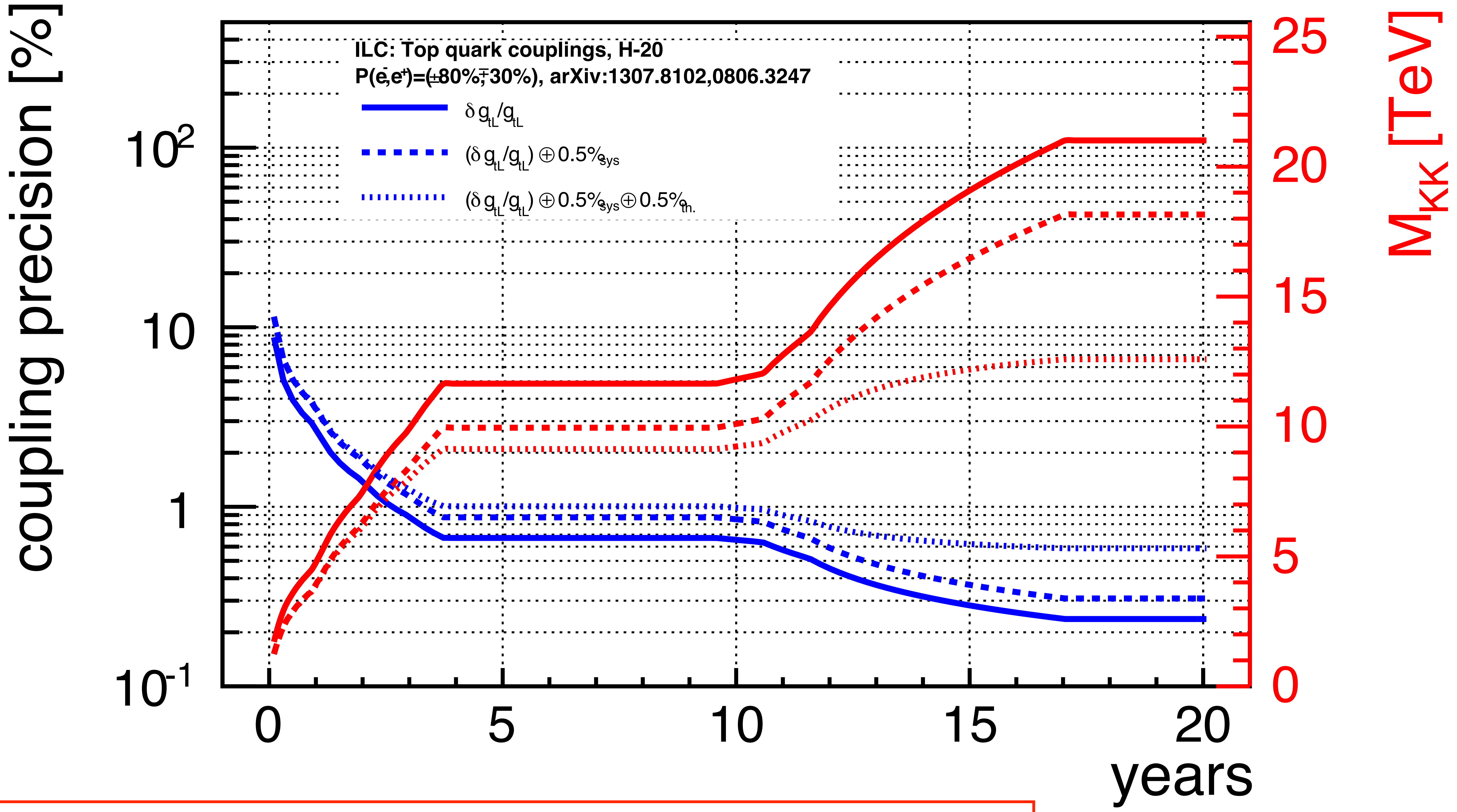
Polarised beams

- allow to disentangle g^{γ} vs g^Z
- provide robustness against systematic uncertainties
- minimise higher-order corrections

500 GeV

New Physics Reach of full ILC500 Program

….for typical BSM scenarios with **composite Higgs/Top and/or extra dimensions**
based on phenomenology described in Pomerol et al. arXiv:0806.3247



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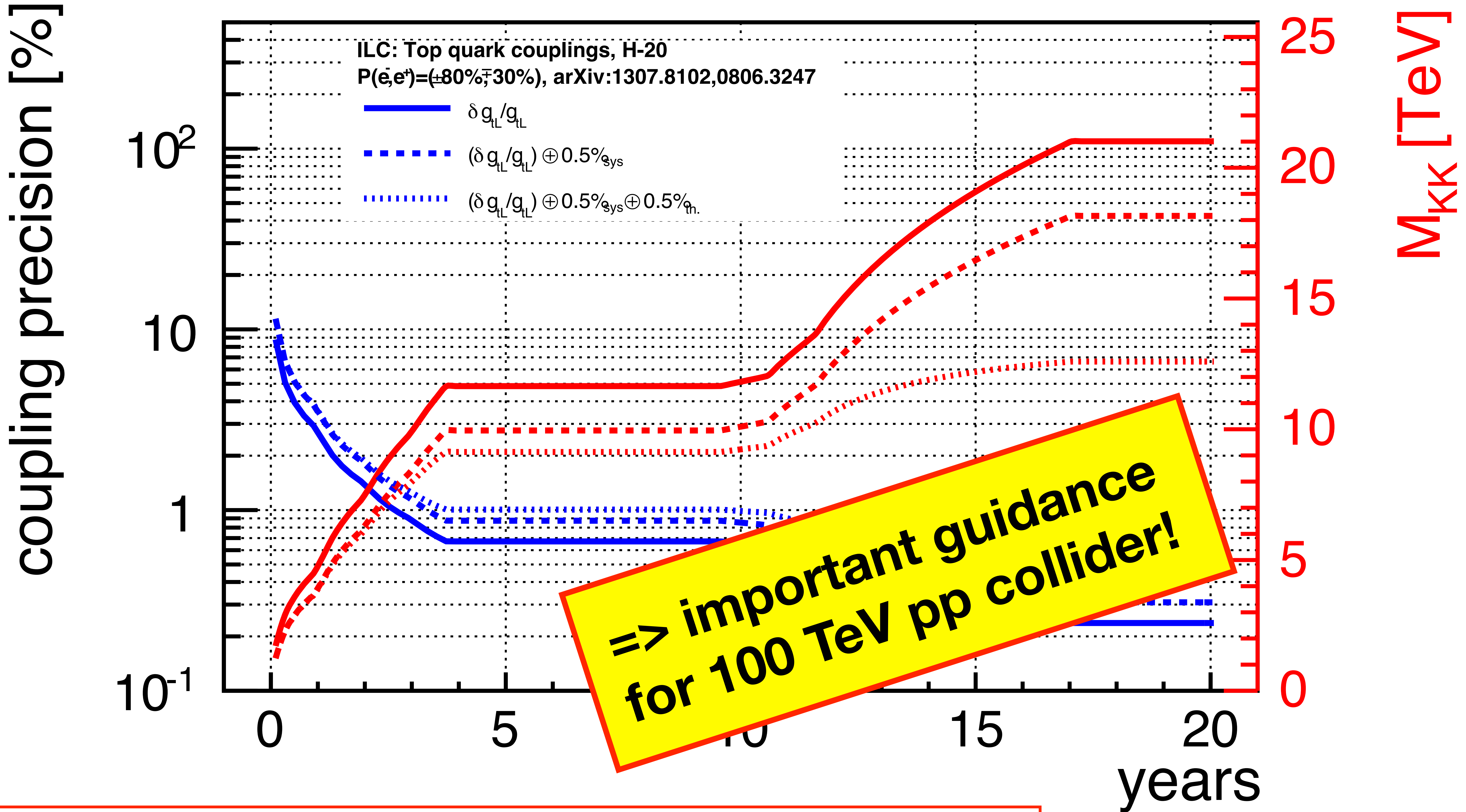

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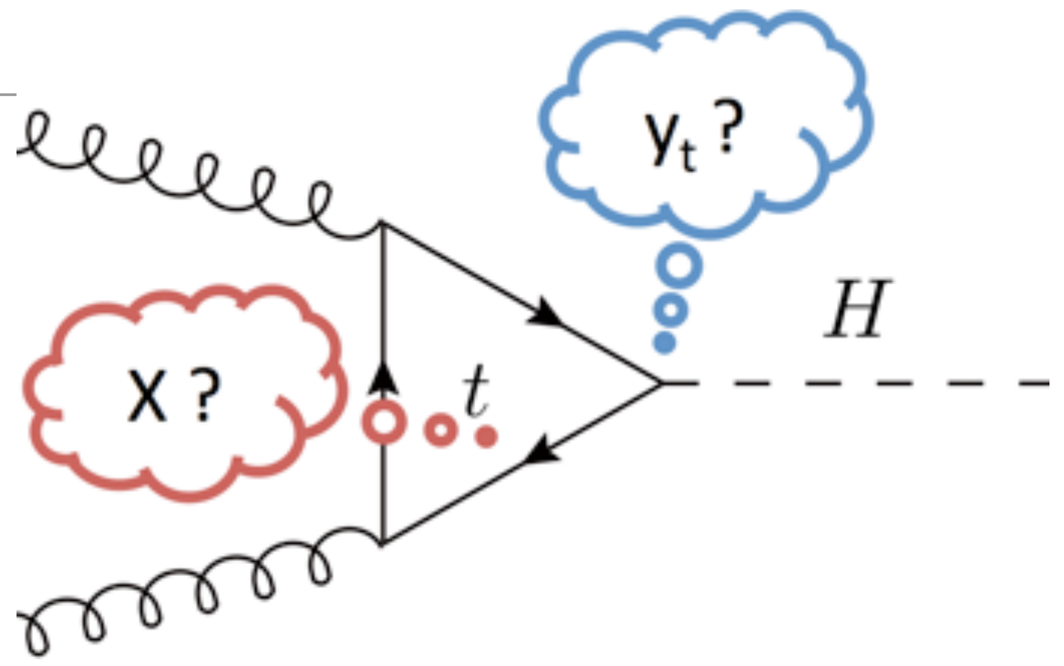
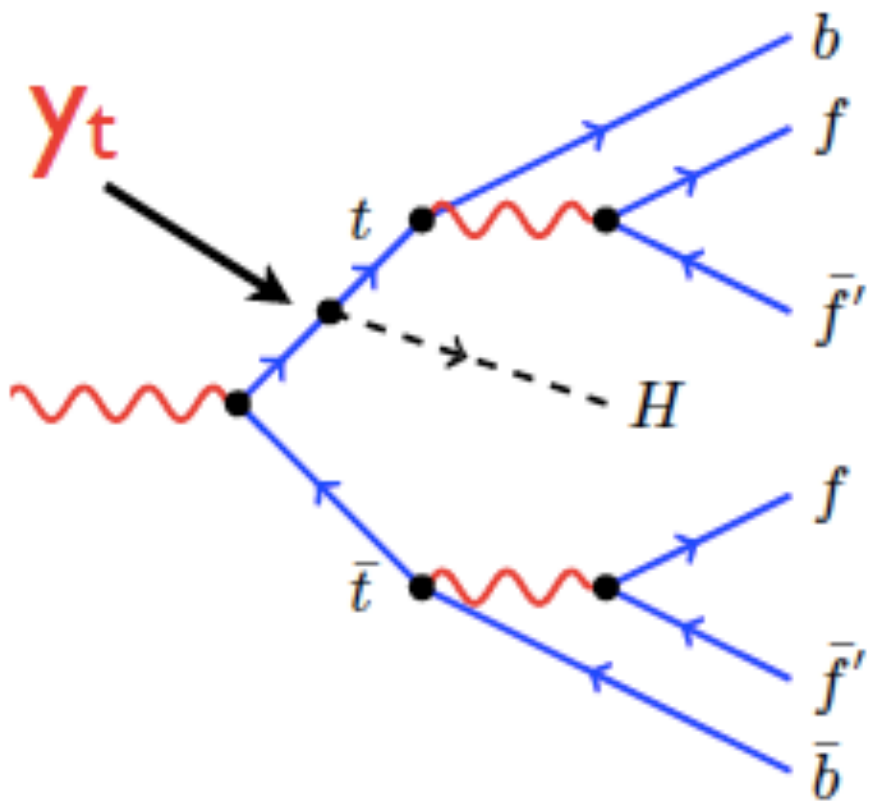
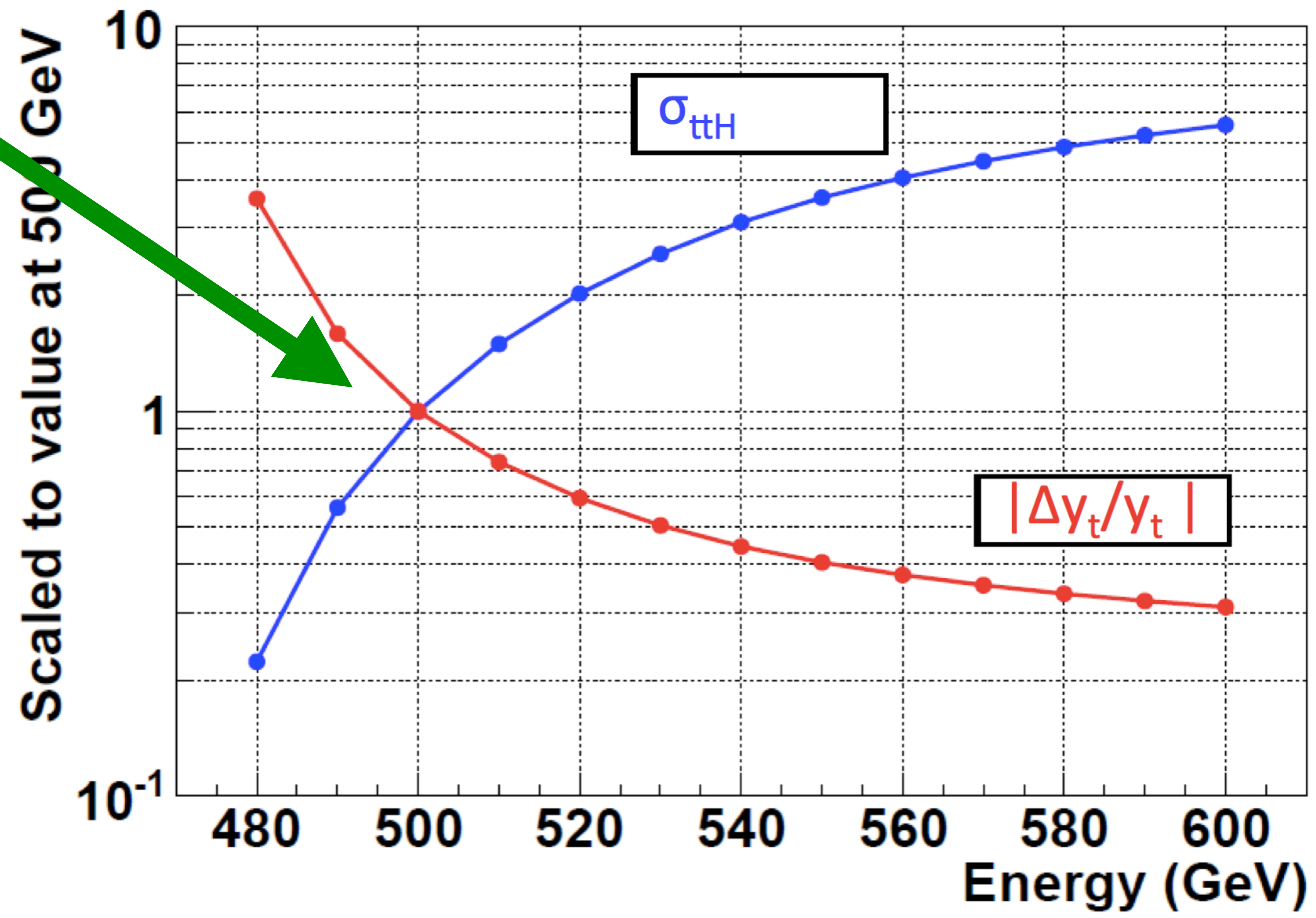
500 GeV

Top Yukawa Coupling

- **Indirect**: loop couplings, top threshold scan …
  => is it *really* y_t ?
- **Direct**: tth production
  => possible for $\sqrt{s} \geq 500$ GeV
- SM **σ(ttH) = 0.45fb** @ 500 GeV
  => ILC500 full running scenario, geant4-based detector simulation:
  δy_t = 6.3%
- ILC tunnel length contains 1.5 km reserve space on each side (at the moment "empty"…)
- δy_t could be **2.5% if $\sqrt{s}$ = 550 GeV**

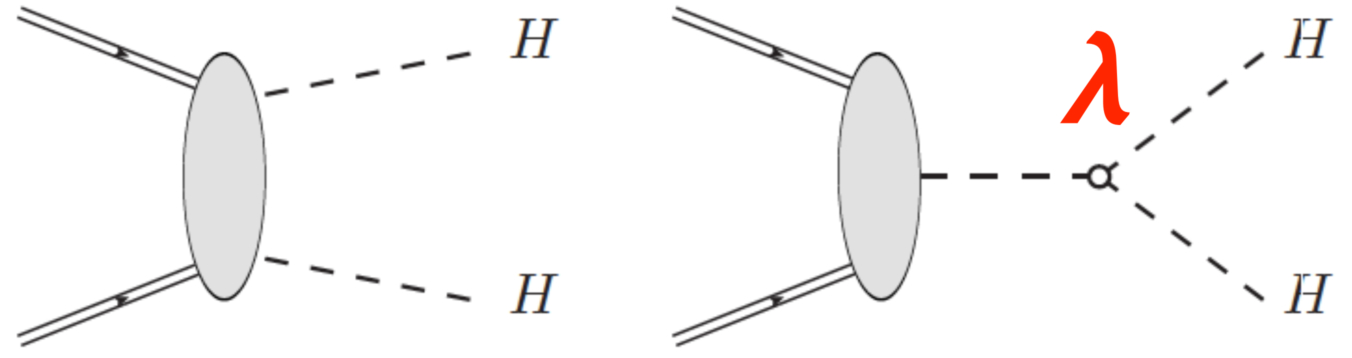






500 GeV

Double Higgs Production & Higgs Self-Coupling



two **complementary** production processes:

- **ZHH @ ~500 GeV**
  - **unique feature: *increases* if $\lambda > \lambda_{SM}$**
  - **$\delta\sigma/\sigma$ = 16% : > 5 sigma discovery**
  - **$\delta\lambda/\lambda$ = 27% : 3 sigma observation**
- **vvH (VBF) @ ECM > 1 TeV**
  - **$\delta\sigma/\sigma$ = 13%**
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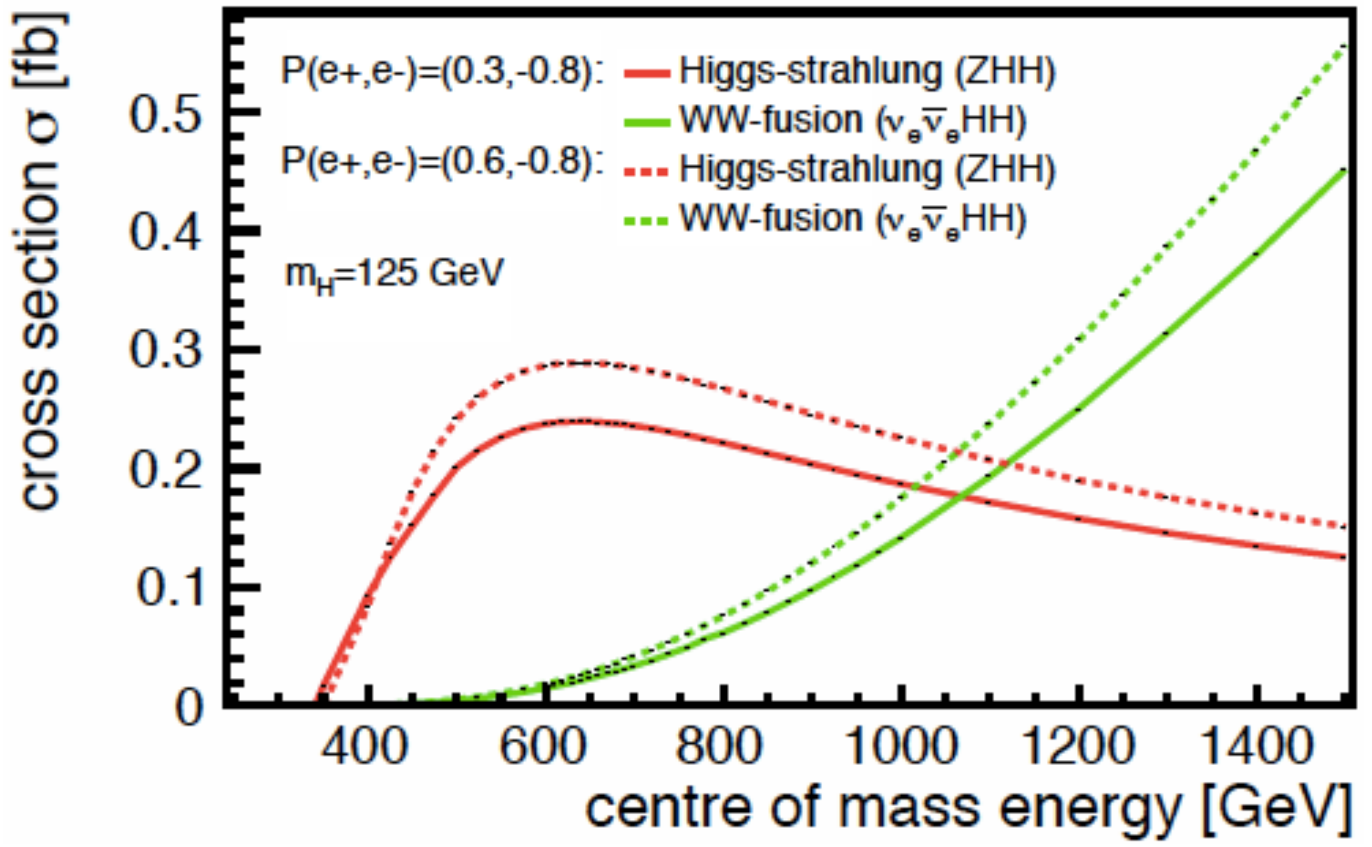
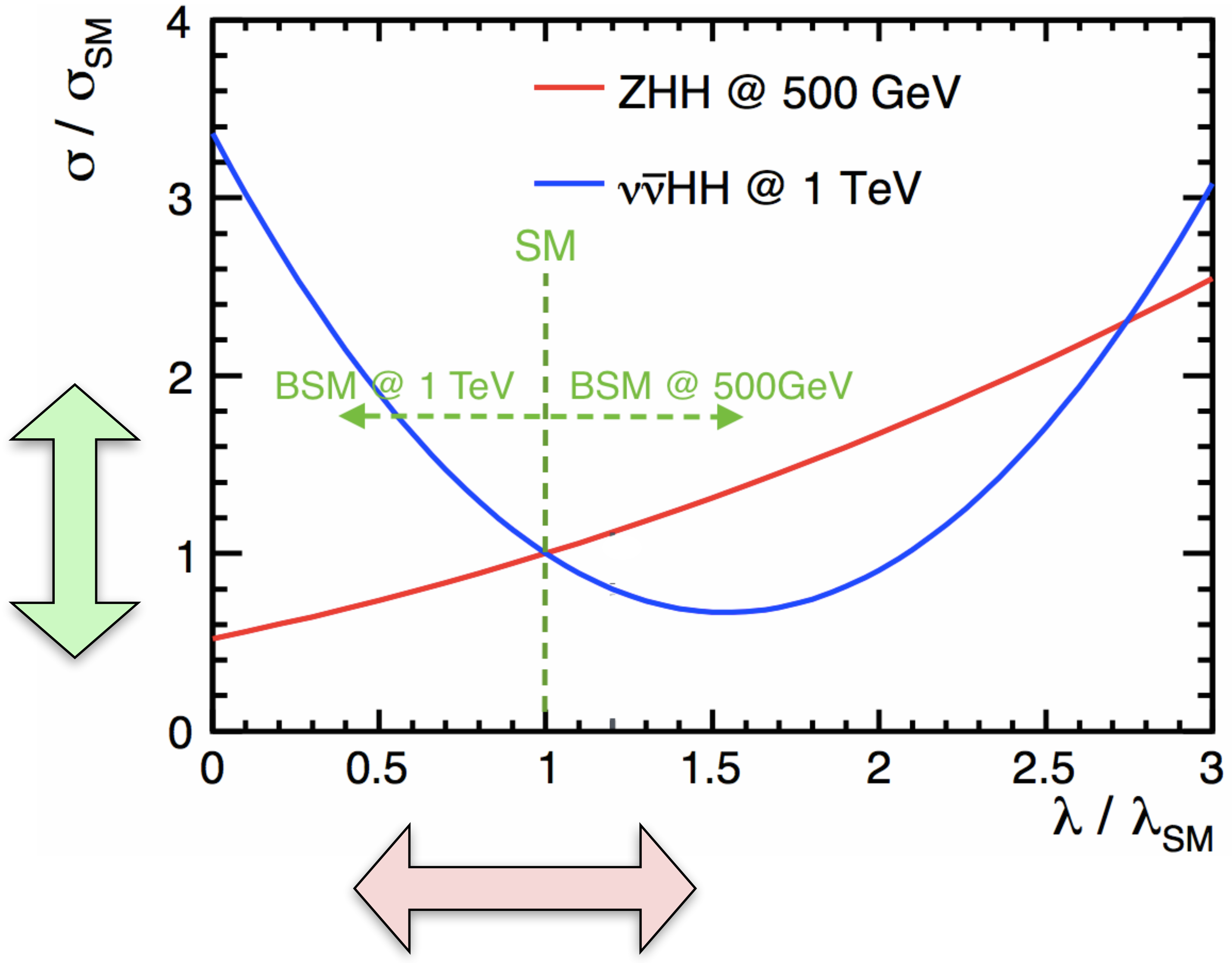
BSM changes the picture: e.g. λ = **1.5** λ_{SM}

500GeV: $\delta\lambda/\lambda$ = 20%, 1TeV: $\delta\lambda/\lambda \to \infty$

=> with combination of 500 GeV and 1 TeV we're always on the safe side!





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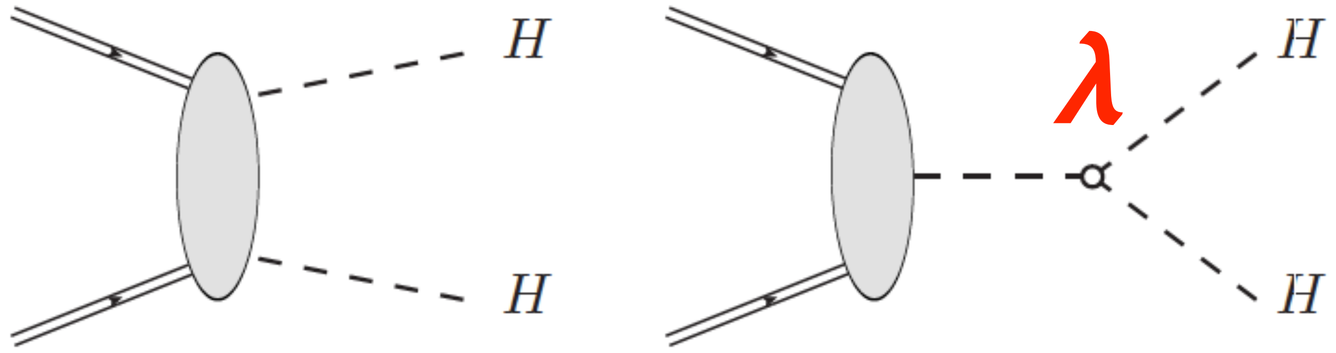

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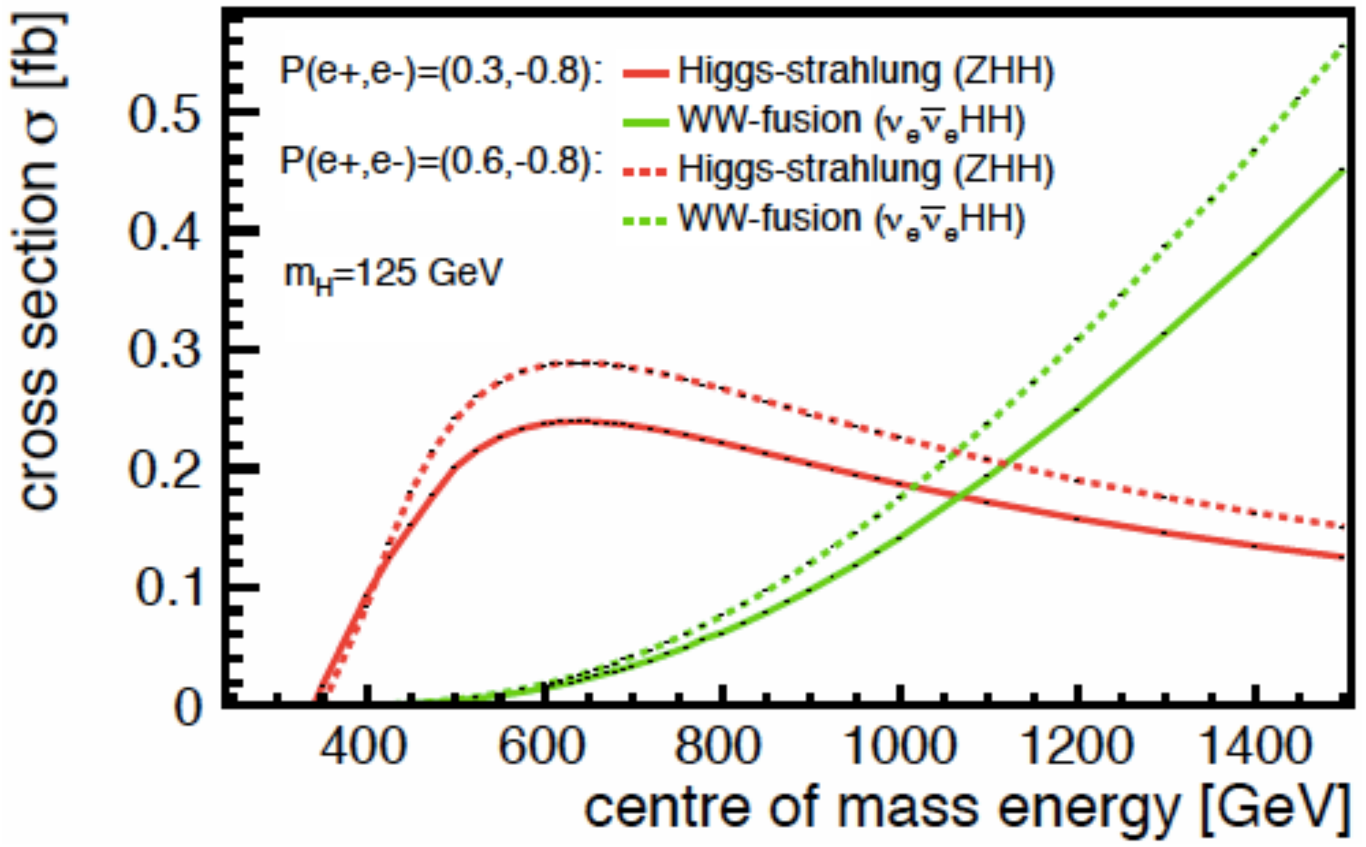

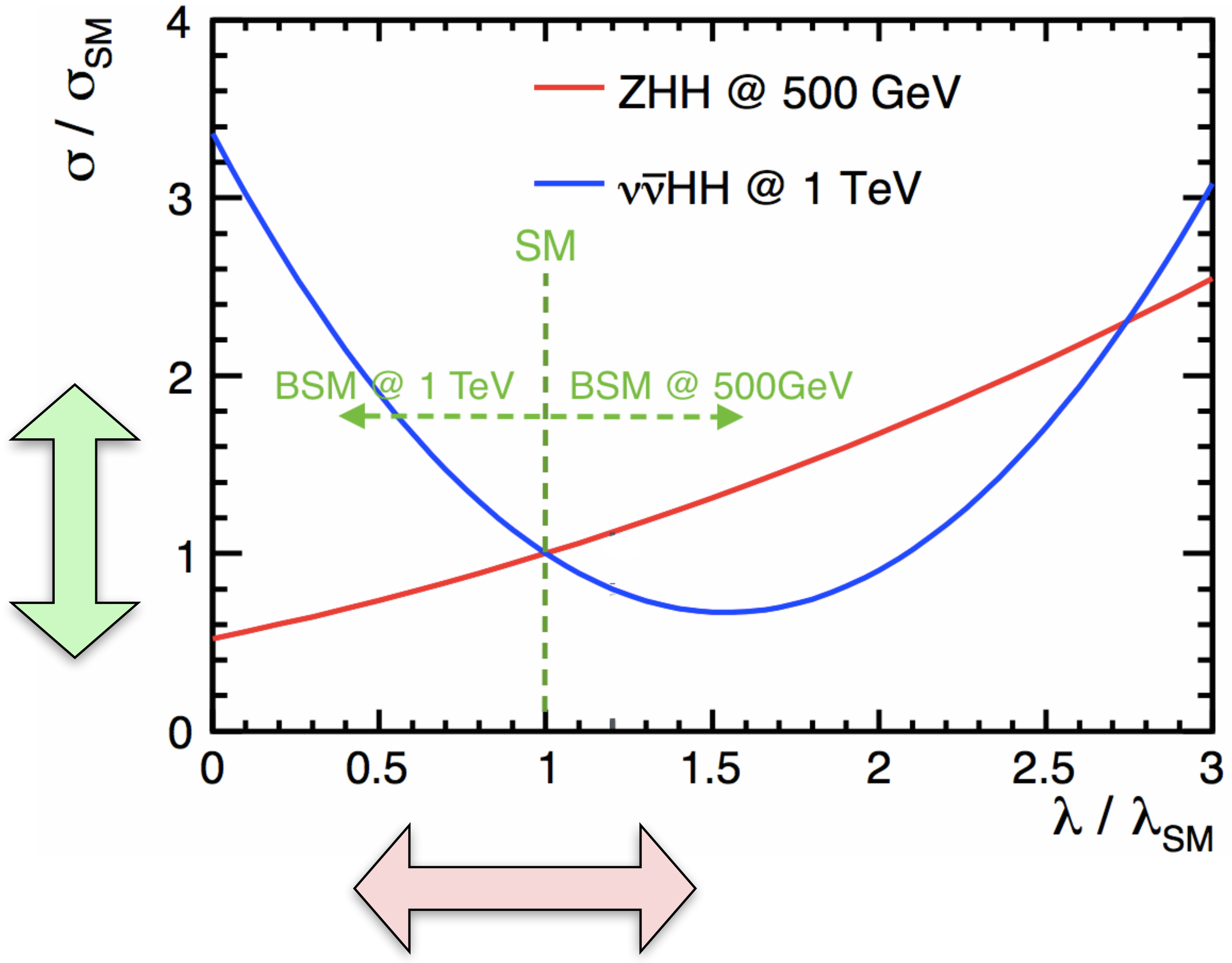

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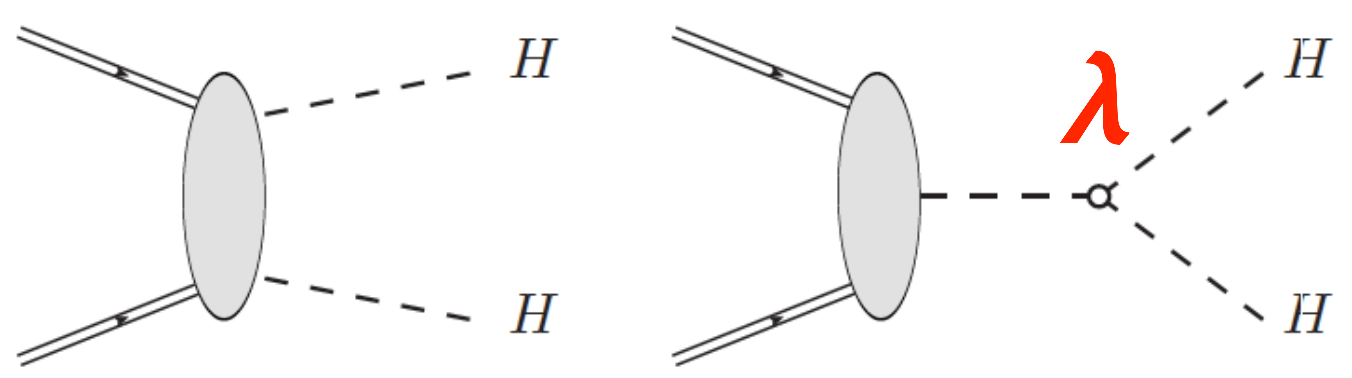

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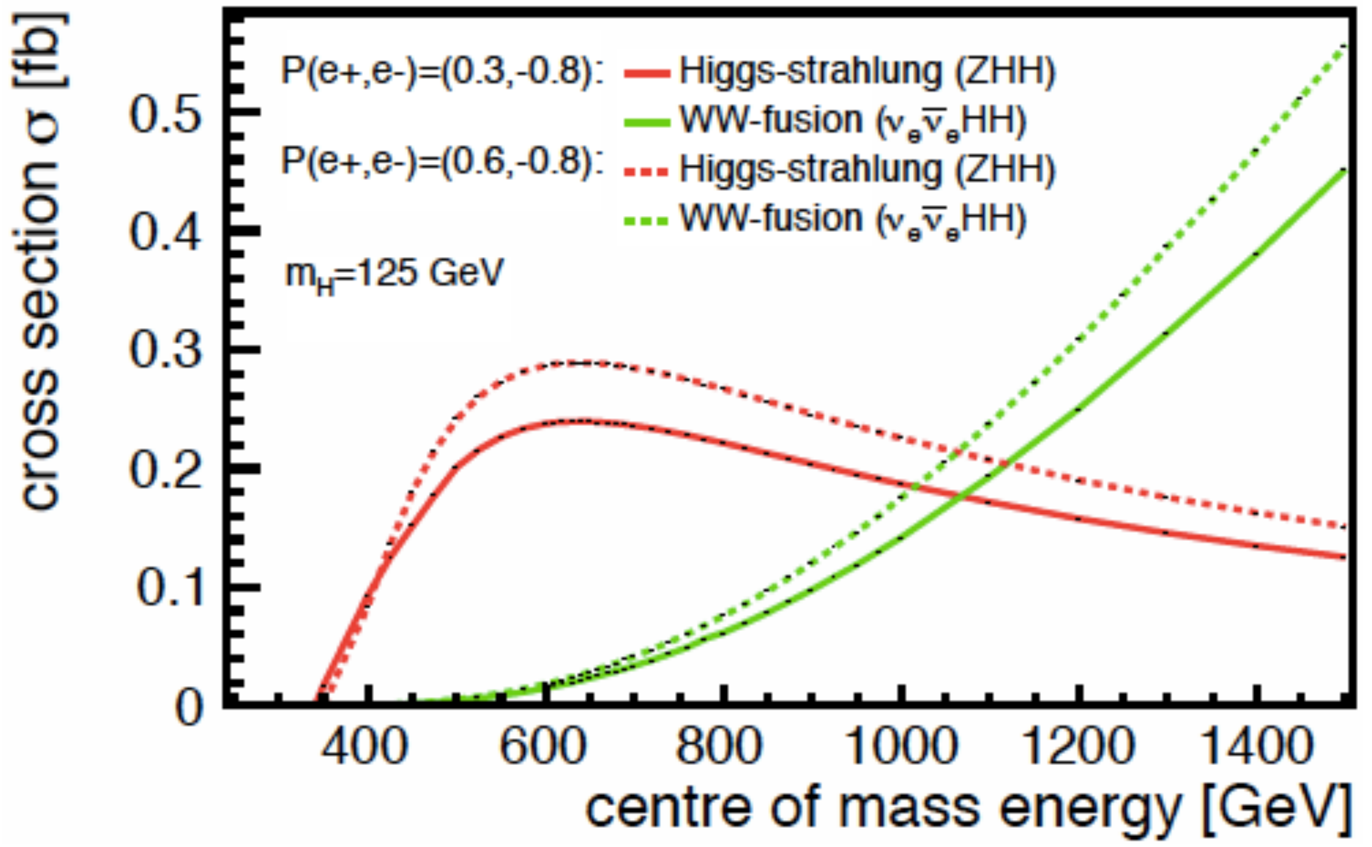
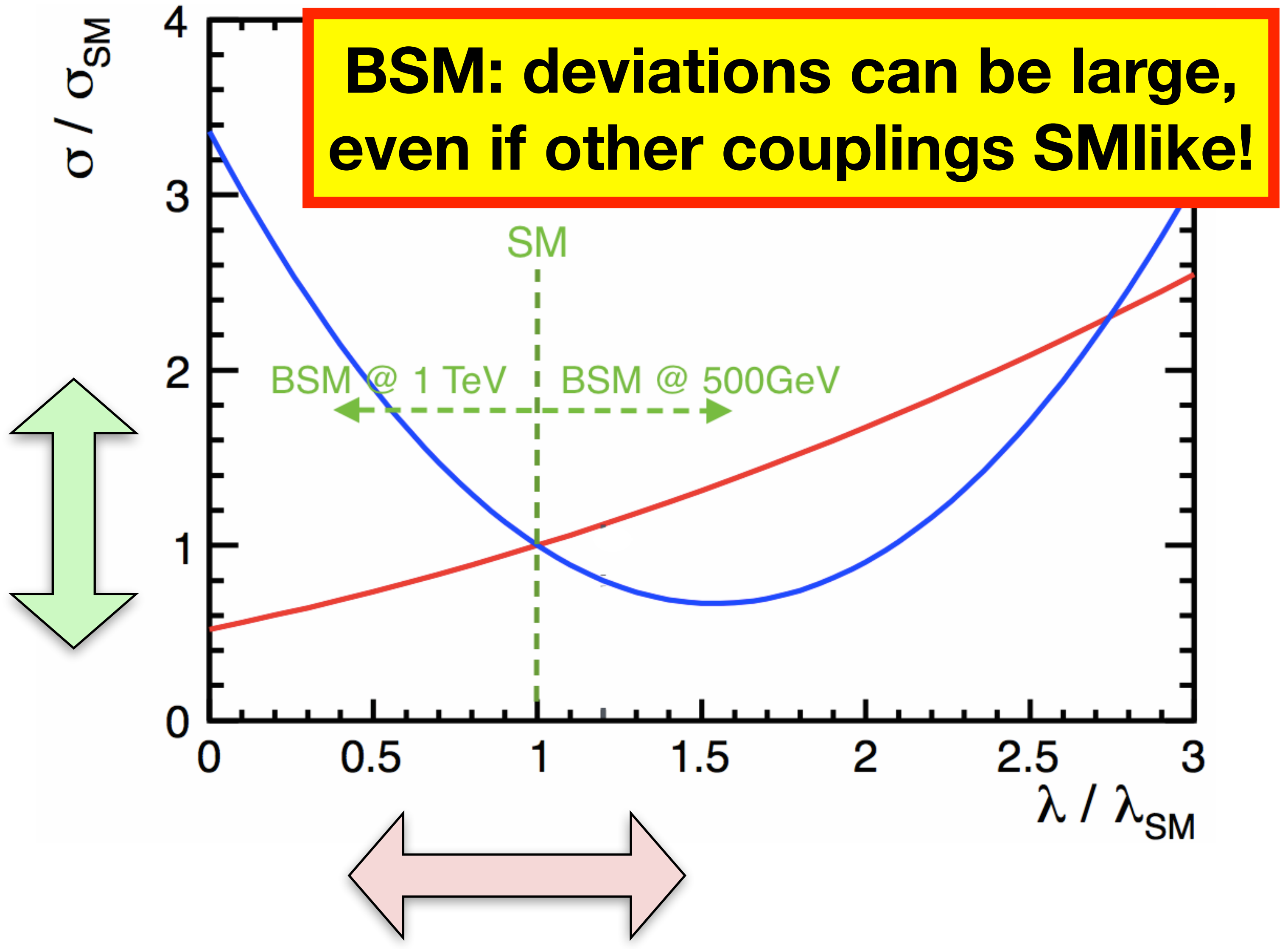
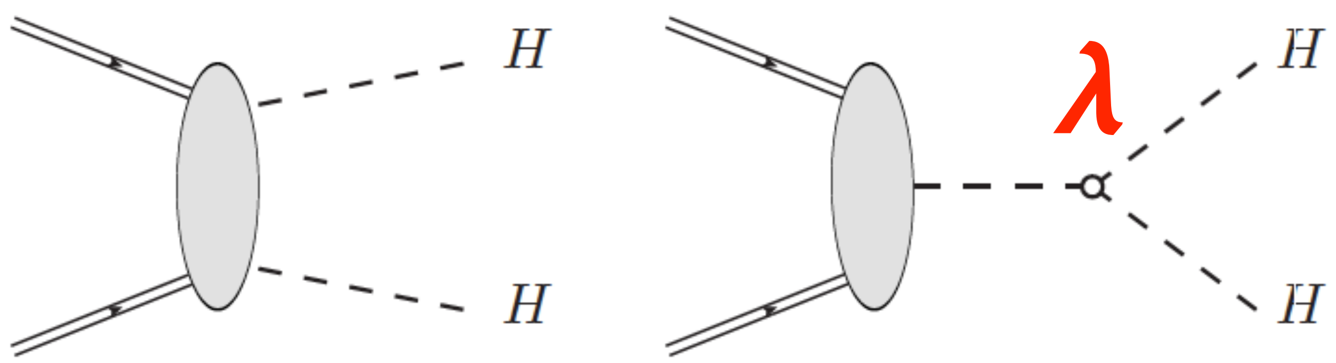
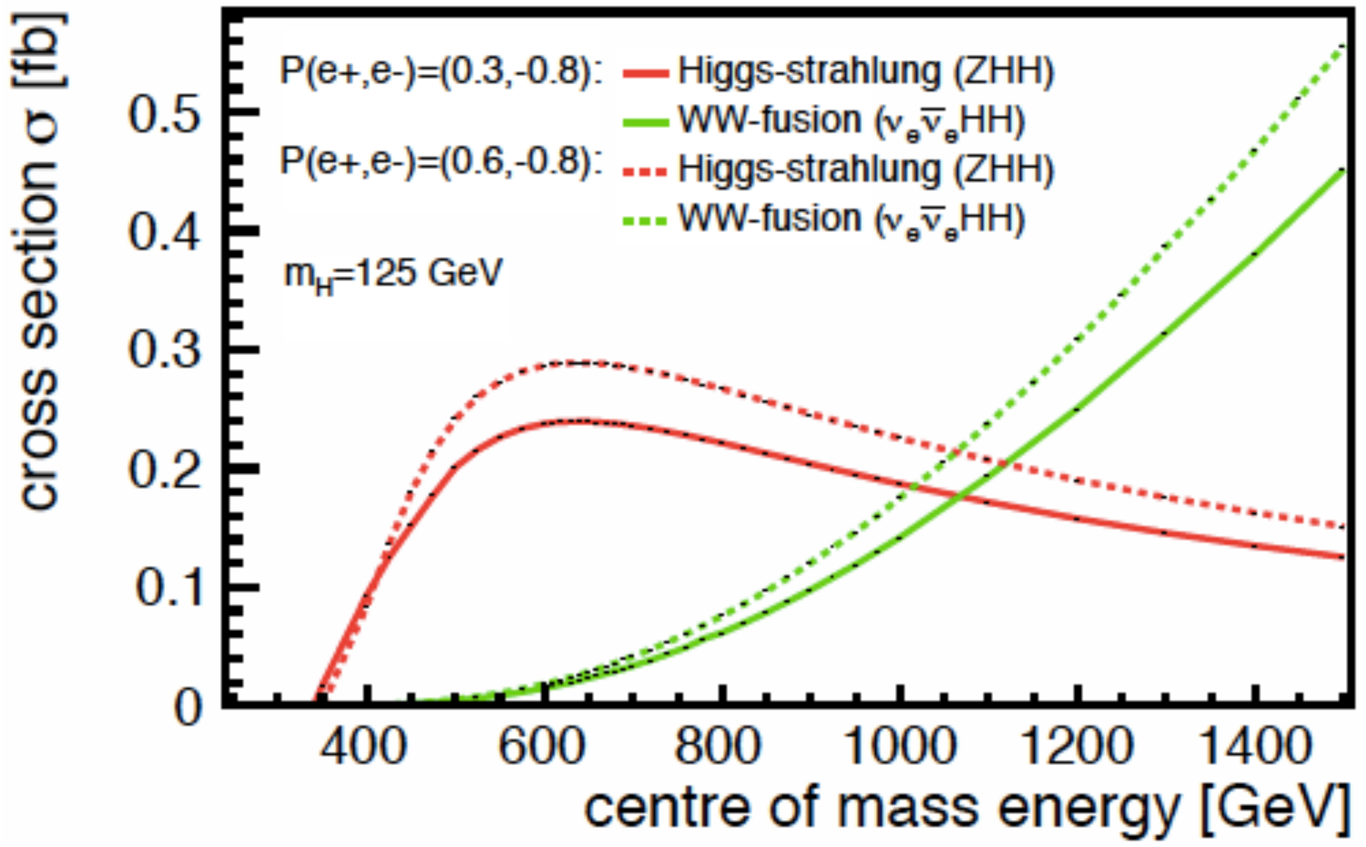




BSM: deviations can be large, even if other couplings SMlike!

Double Higgs Production & Higgs Self-Coupling





two **complementary** production processes:

- **ZHH @ ~500 GeV**
  - **unique feature: *increases* if $\lambda > \lambda_{SM}$**
  - **$\delta\sigma/\sigma$ = 16% : > 5 sigma discovery**
  - **$\delta\lambda/\lambda$ = 27% : 3 sigma observation**

SFB-B1 (PhD Th. C.Dürig)

- **vvH (VBF) @ ECM > 1 TeV**
  - **$\delta\sigma/\sigma$ = 13%**
  - **$\delta\lambda/\lambda$ = 10%**

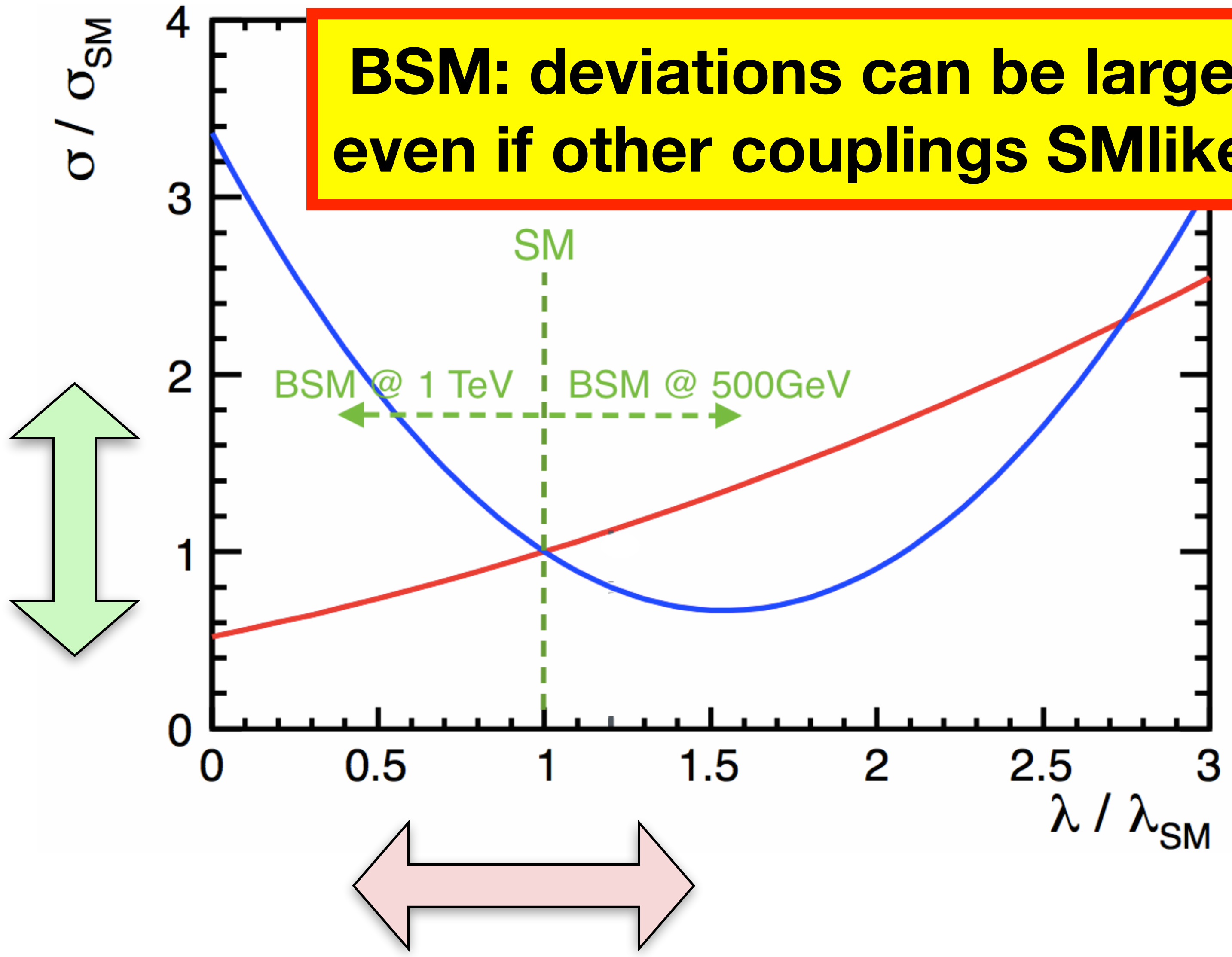
1 TeV is sweet spot: sensitivity to λ largest near threshold!

BSM changes the picture: e.g. **$\lambda = 1.5\ \lambda_{SM}$**

500GeV: $\delta\lambda/\lambda$ = 20%, 1TeV: $\delta\lambda/\lambda \to \infty$

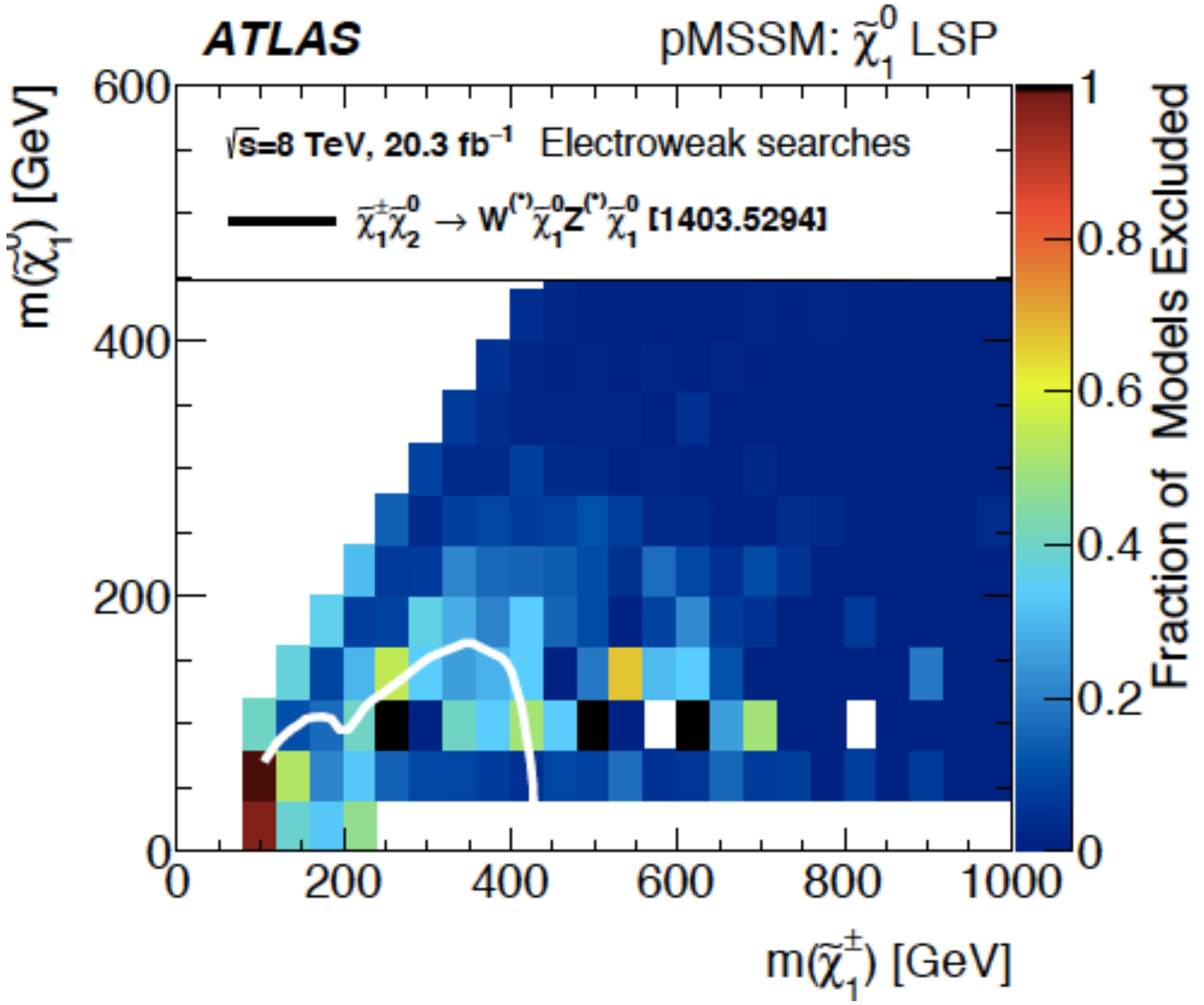
=> with combination of 500 GeV and 1 TeV we're always on the safe side!

BSM: deviations can be large, even if other couplings SMlike!



Plenty of room left for SUSY

simplified models don't give the full story
(e.g. 100% BR assumption rarely fulfilled)
-> c.f. pMSSM scan by ATLAS, arXiv:1508:06608



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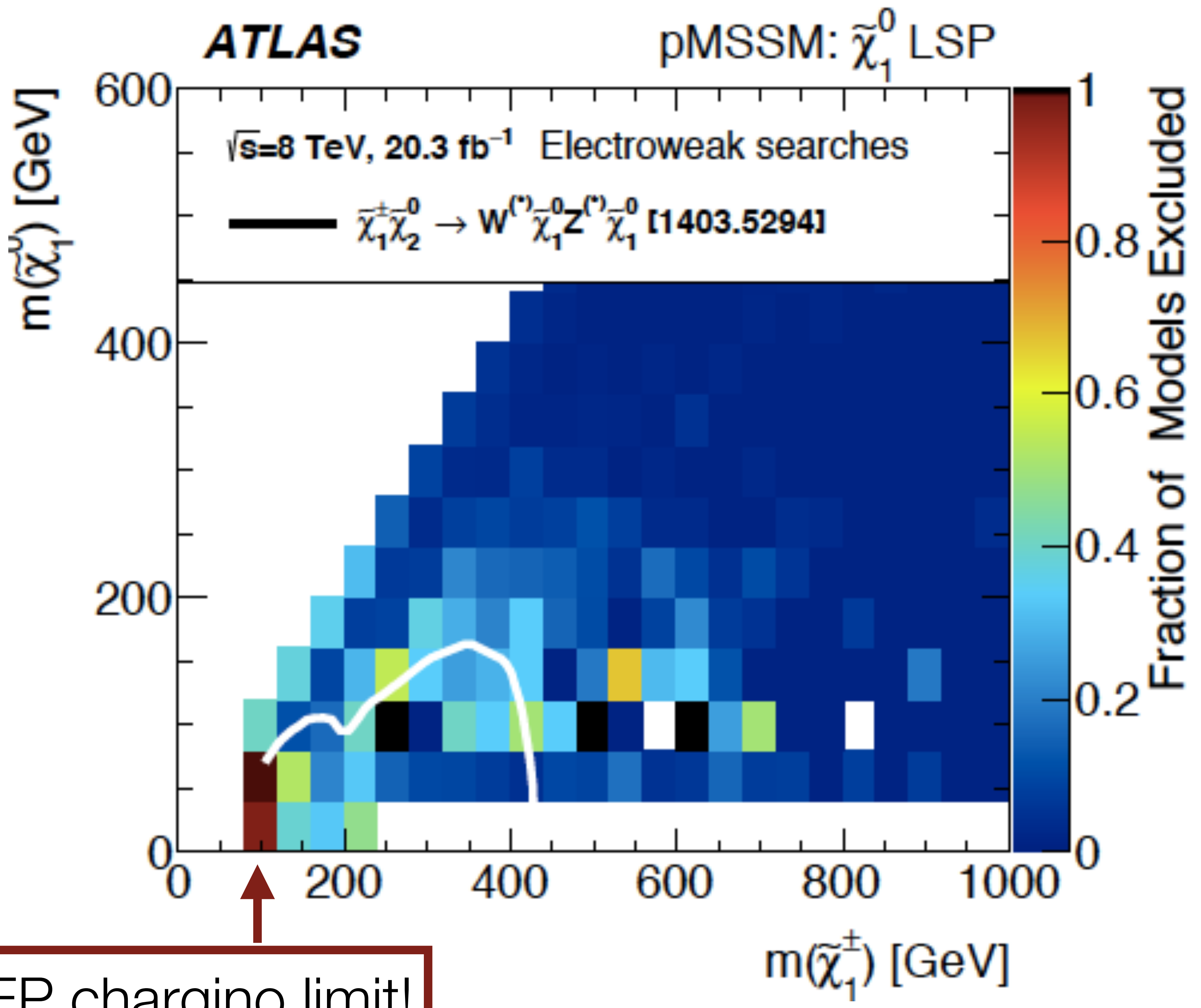

LEP chargino limit!

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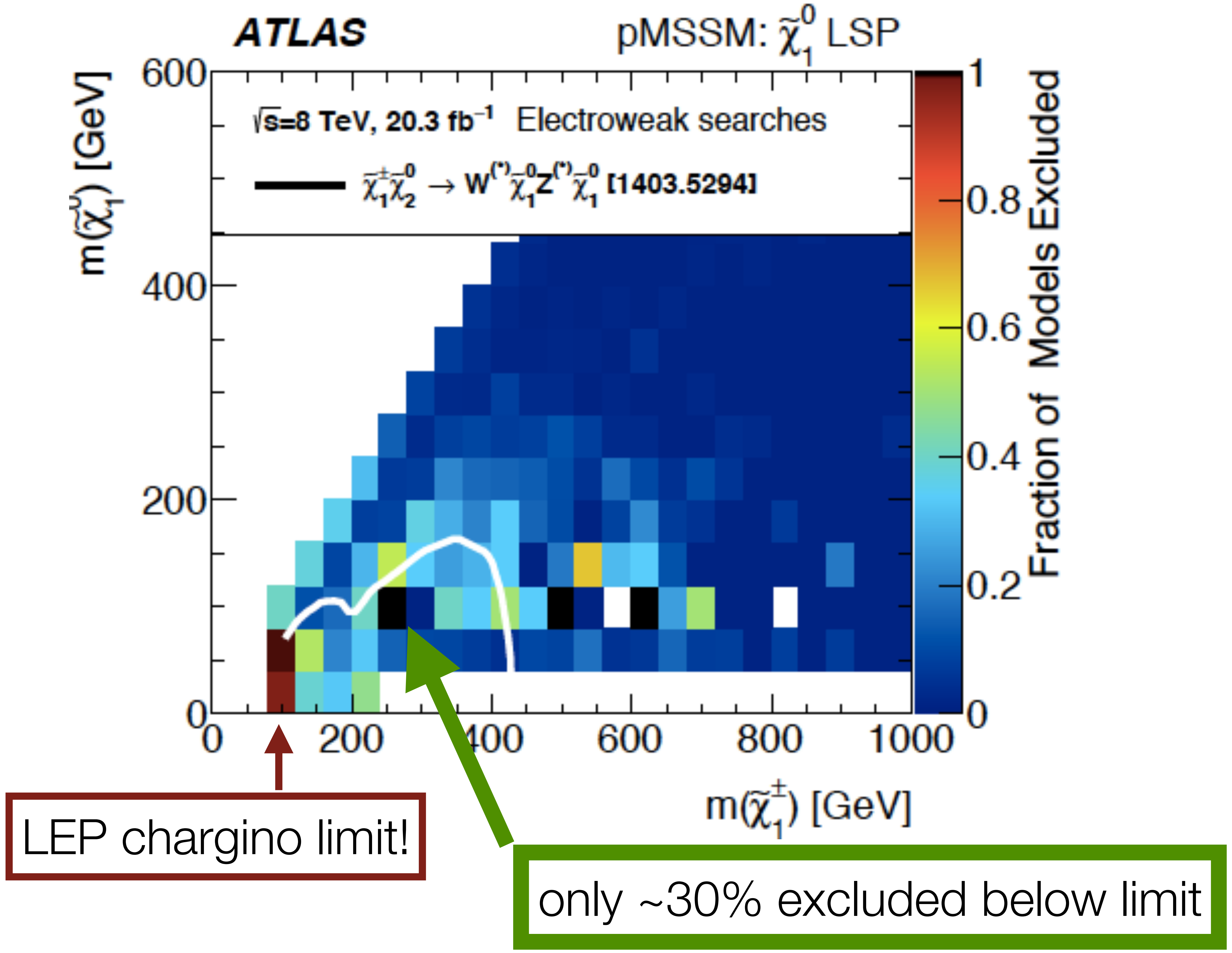

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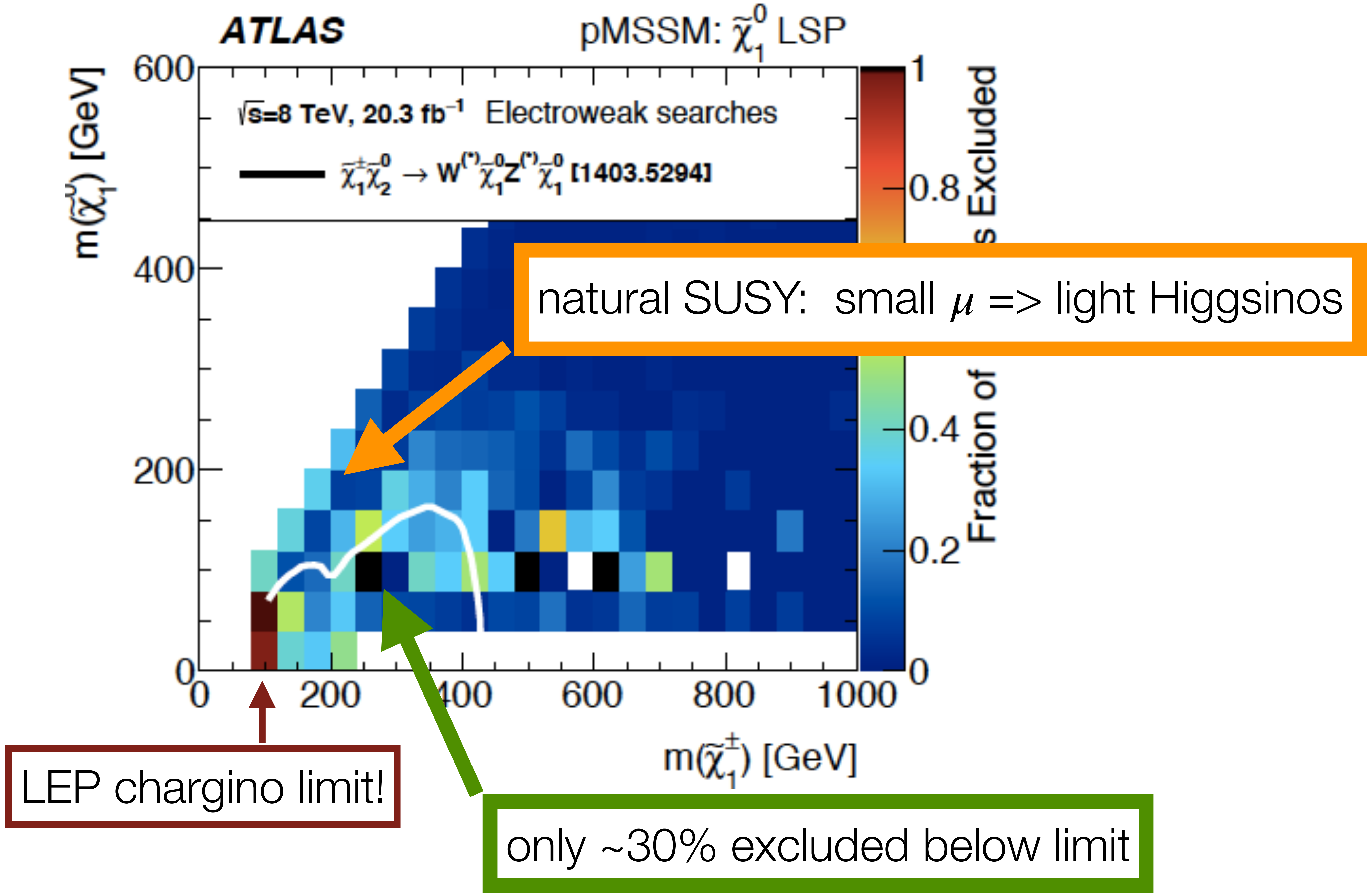

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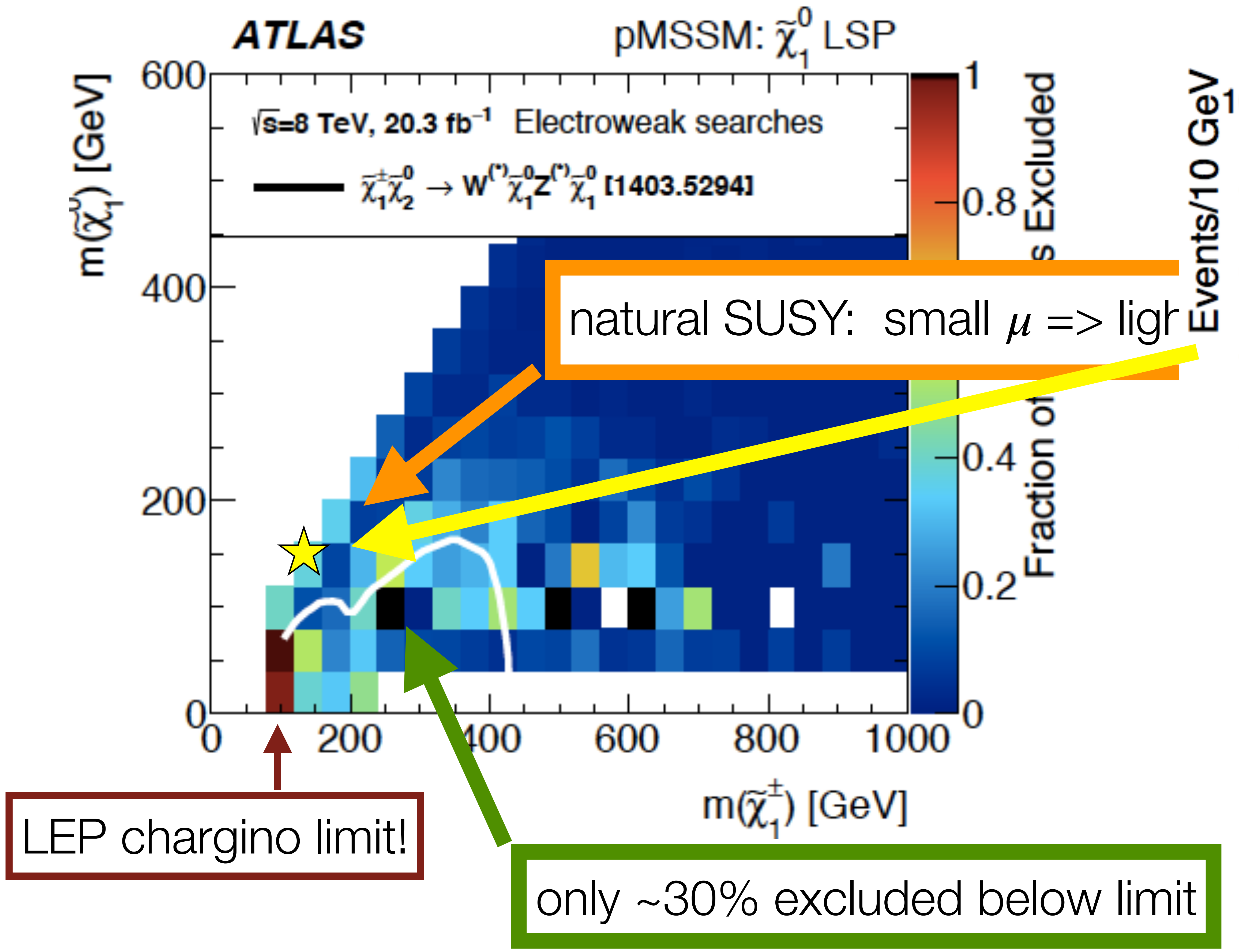
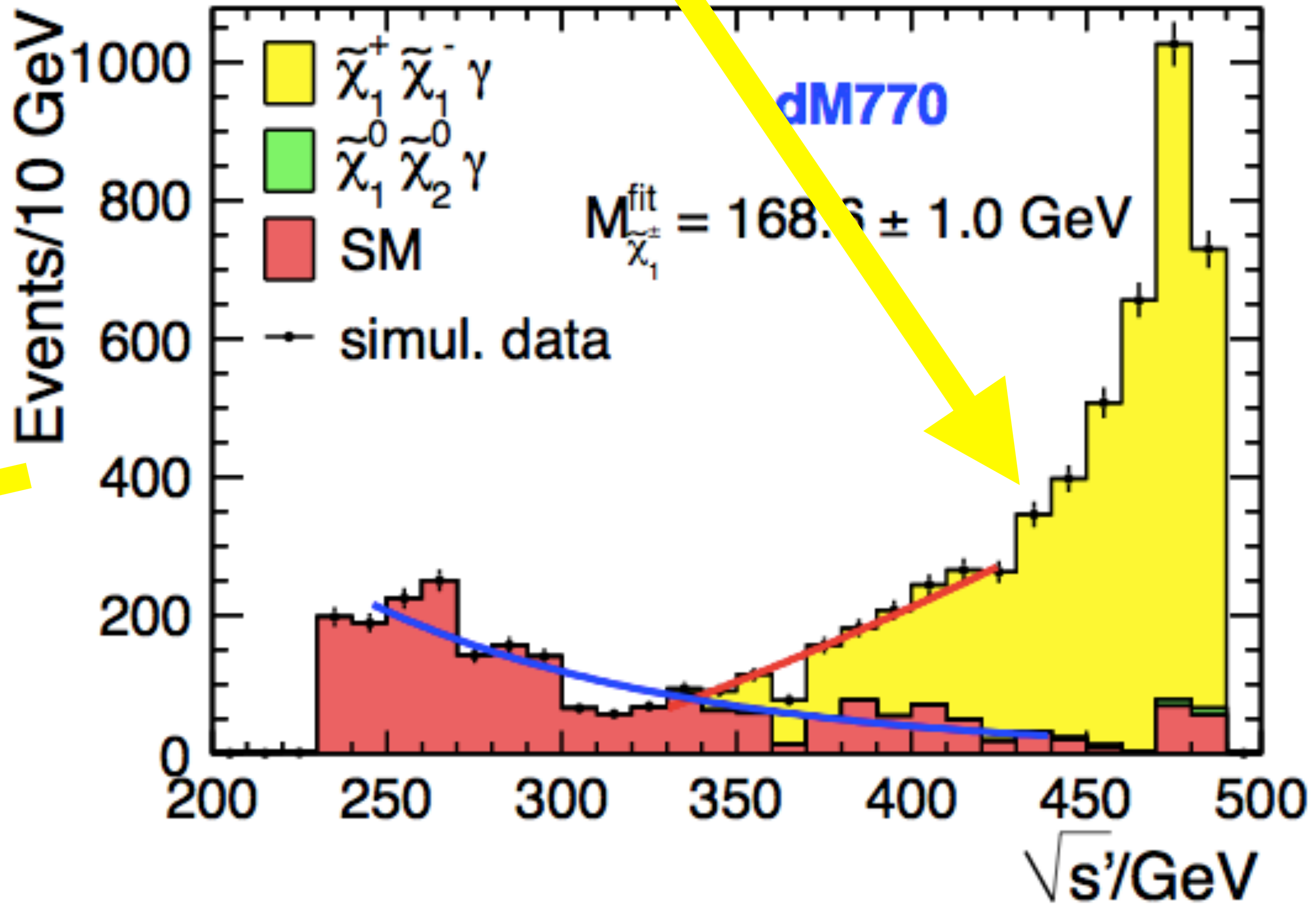


Light Higgsinos at ILC



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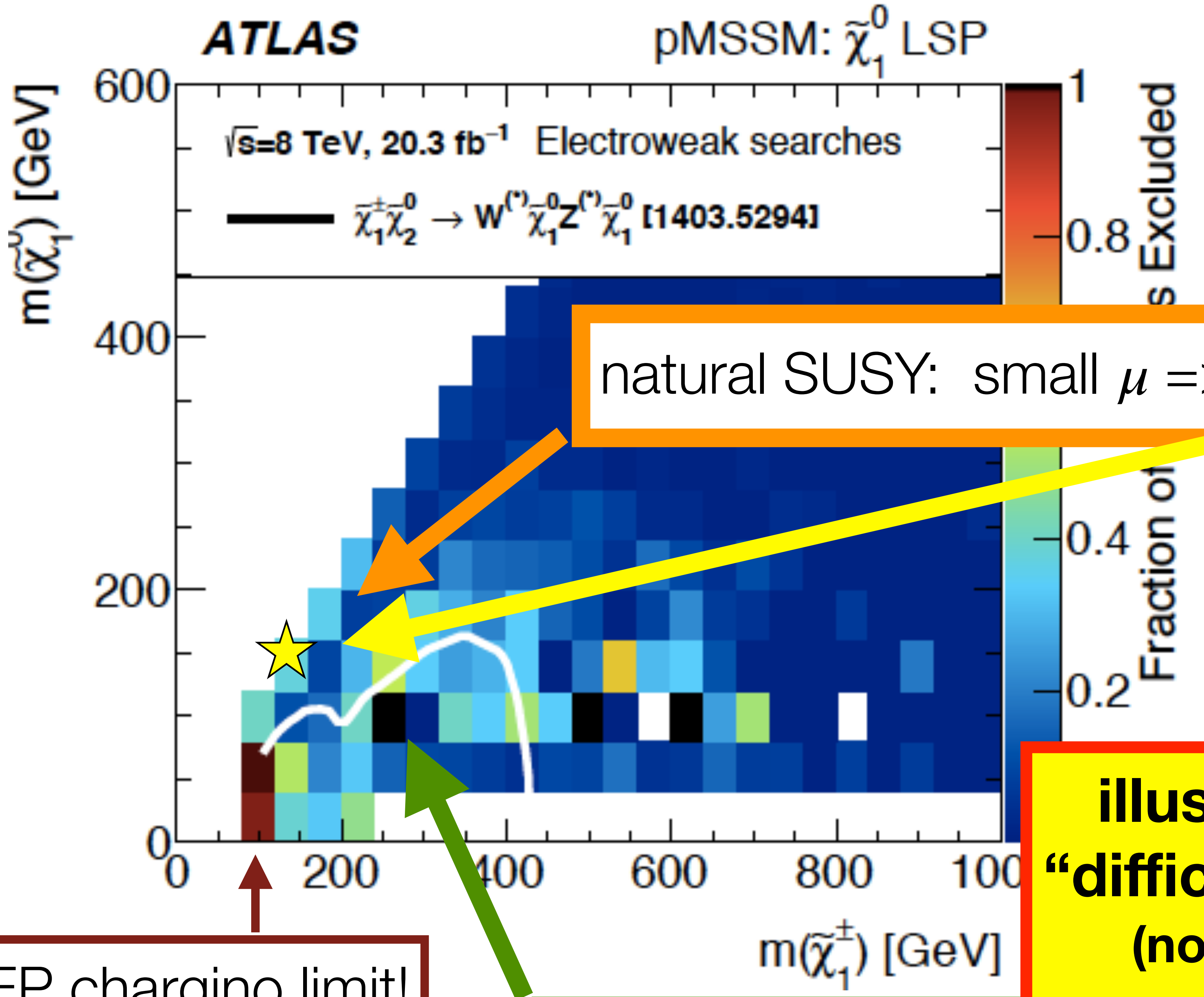

natural SUSY: small μ => light

LEP chargino limit!

only ~30% excluded below limit

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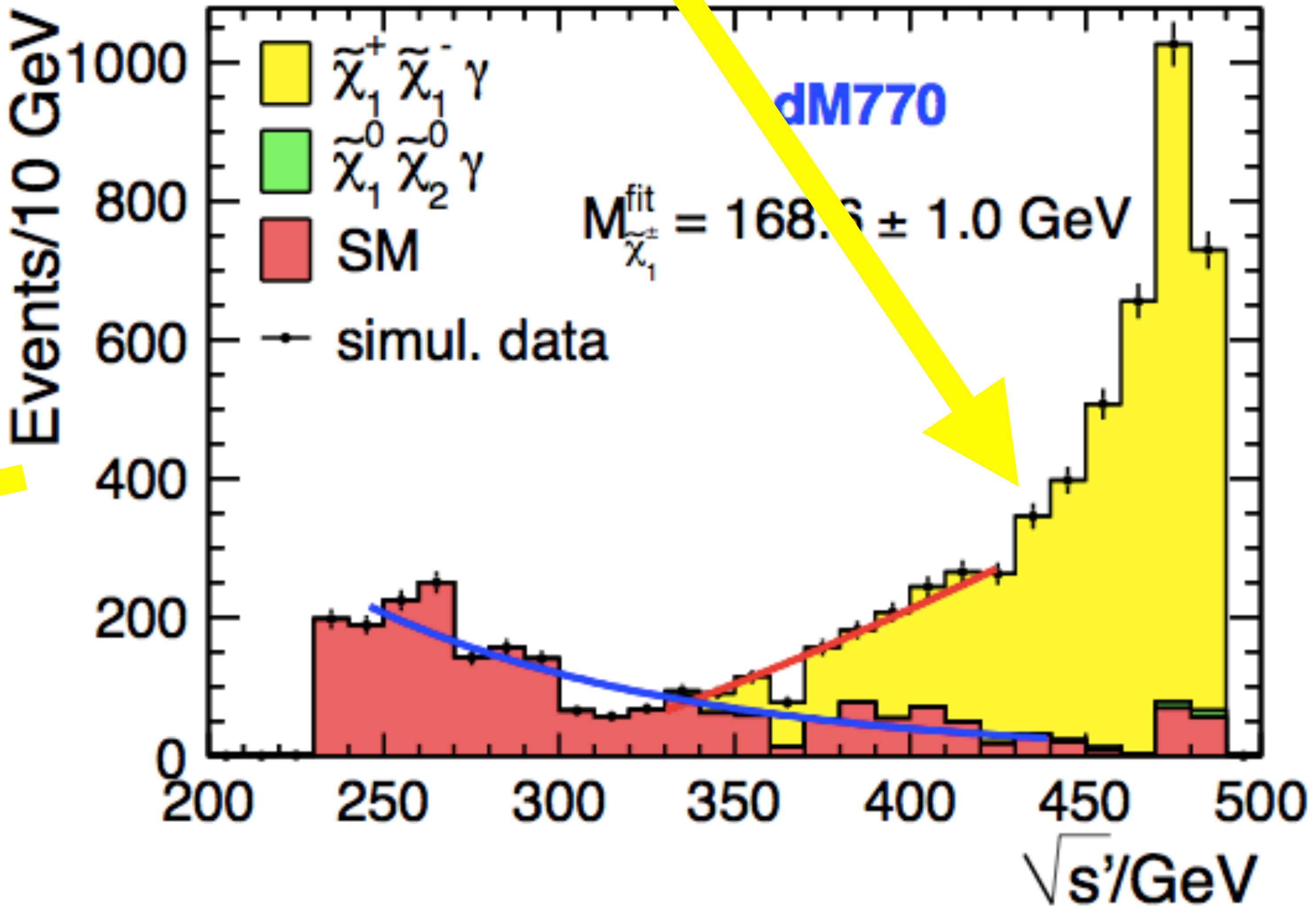
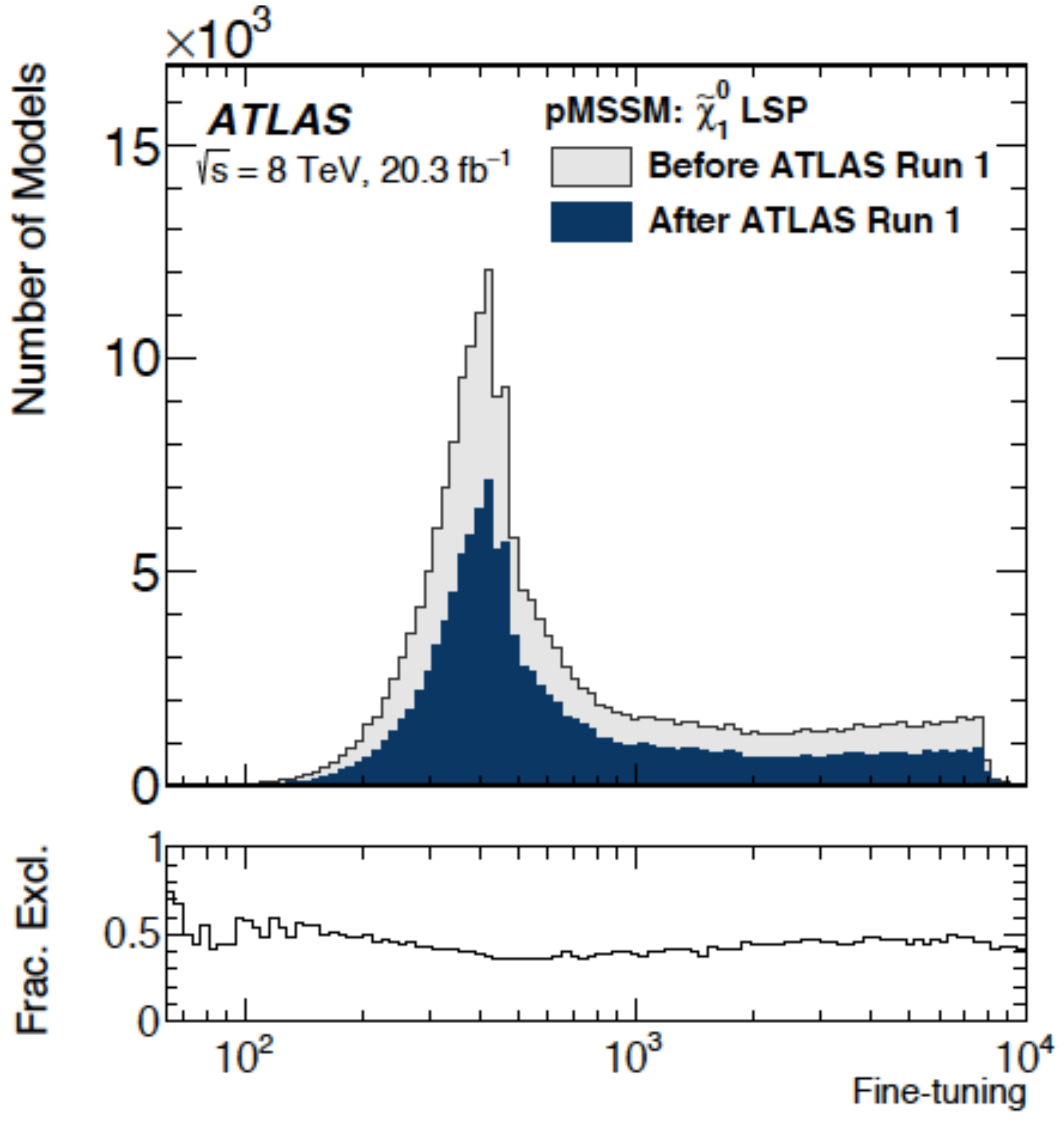


illustrates pp /e+e- complementarity:
"difficult" region at LHC is "easy" in e+e-
(note M_1 = 5 TeV, M_2 = 10 TeV in ILC study
ATLAS scan up to M = 4 TeV)

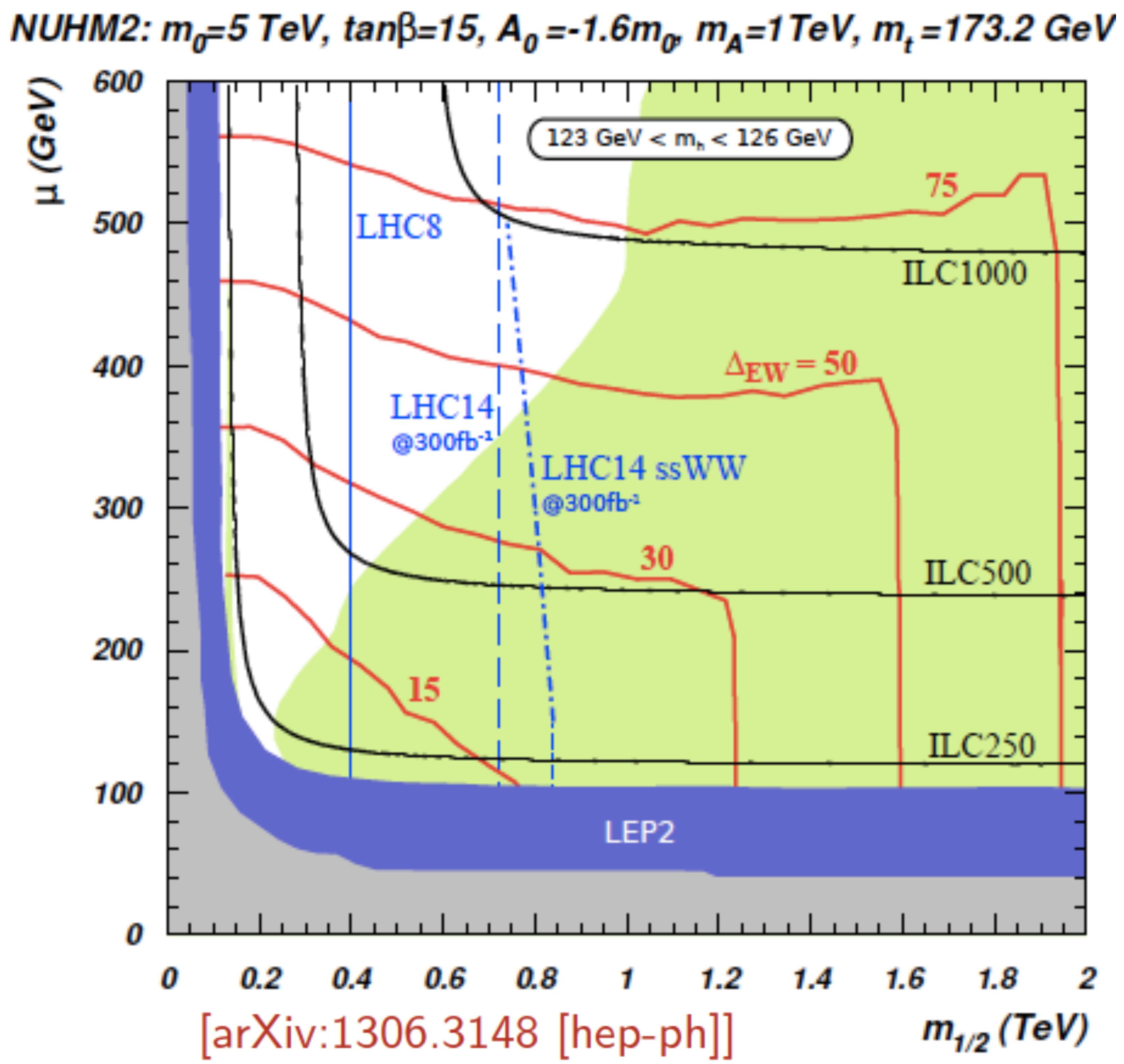
Is SUSY still natural?



=> no dramatic change in level of fine-tuning due to ATLAS exclusions (Barbieri-Giudice measure)

e^+e^- colliders:

directly & unambiguously probe naturalness by discovery or exclusion of Higgsinos up to ≲ √s / 2



[arXiv:1306.3148 [hep-ph]]