Physics Summary I:

Higgs, Top/QCD, Loops (incl. $\gamma\gamma$, $e\gamma$, e^-e^-)

Sven Heinemeyer, Zaragoza

Bangalore, 03/2006

20 minutes (minus discussion time) $\Rightarrow$ the usual apologies

- Physics at the ILC
- Higgs
- Top/QCD
- LoopVerein
- Outlook

1. Physics at the ILC

(ILC always includes $\gamma\gamma$, $e\gamma$, e^-e^-)

Reality: ILC will start after the LHC

Q: What will the ILC add to the LHC?

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The ILC can make discoveries $\Rightarrow$ What can the ILC detect/discover?

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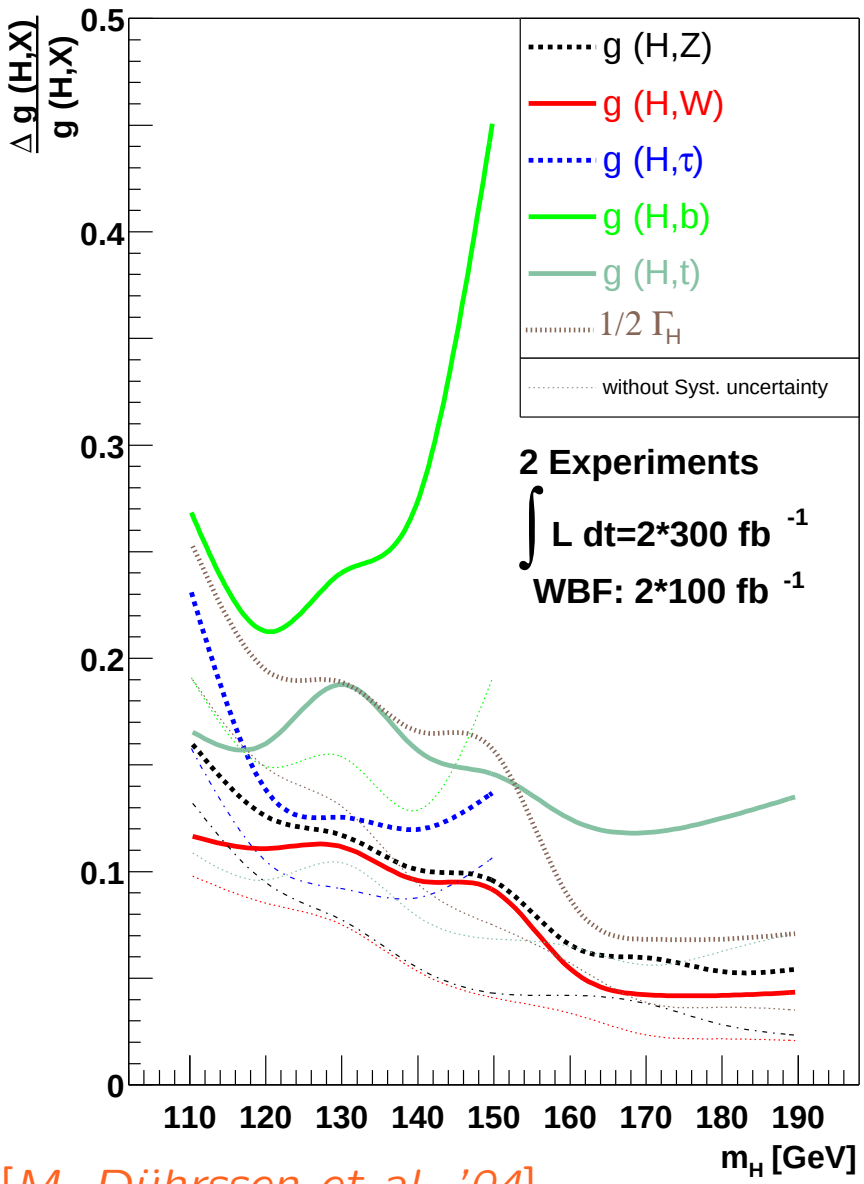
Where are we in this respect? (Status? What is needed? Achievement?)

- Higgs
- Top/QCD
- LoopVerein $\Rightarrow$ relevant for all other topics!
- SUSY
- New Physics at TeV, precision electroweak
- Cosmological connections

2. Higgs — The LHC will find a Higgs and measure its characteristics:



[*M. Dührssen et al. '04*]

- mass: $\delta M_h \approx 200$ MeV
- couplings: $(2 * 300 + 2 * 100)$ fb^{-1} :

  typical accuracies of 20-30%
  for $m_H \leq 150$ GeV

  10% accuracies for HVV couplings
  above WW threshold

Assumption:

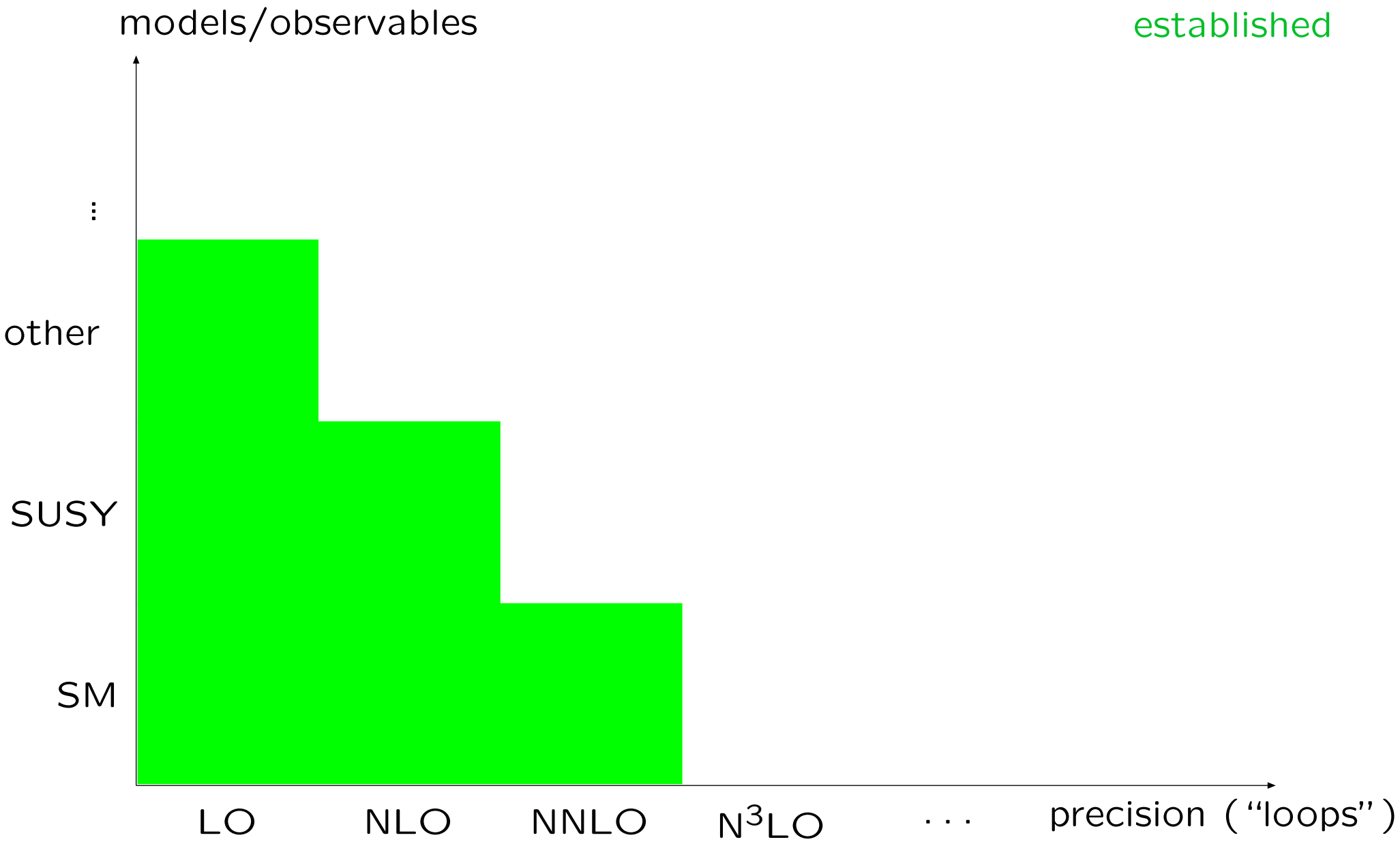
- $g^2_{HVV} \leq g^2_{HVV,\mathrm{SM}} \times 1.05$
- SM rates for the Higgs

Problems:

- valid in weakly interacting models
- rates much lower than in SM ??
- physics can/will hide in 5% margin
- self-couplings out of reach

$\Rightarrow$ ILC comes in

Higgs: theory situation



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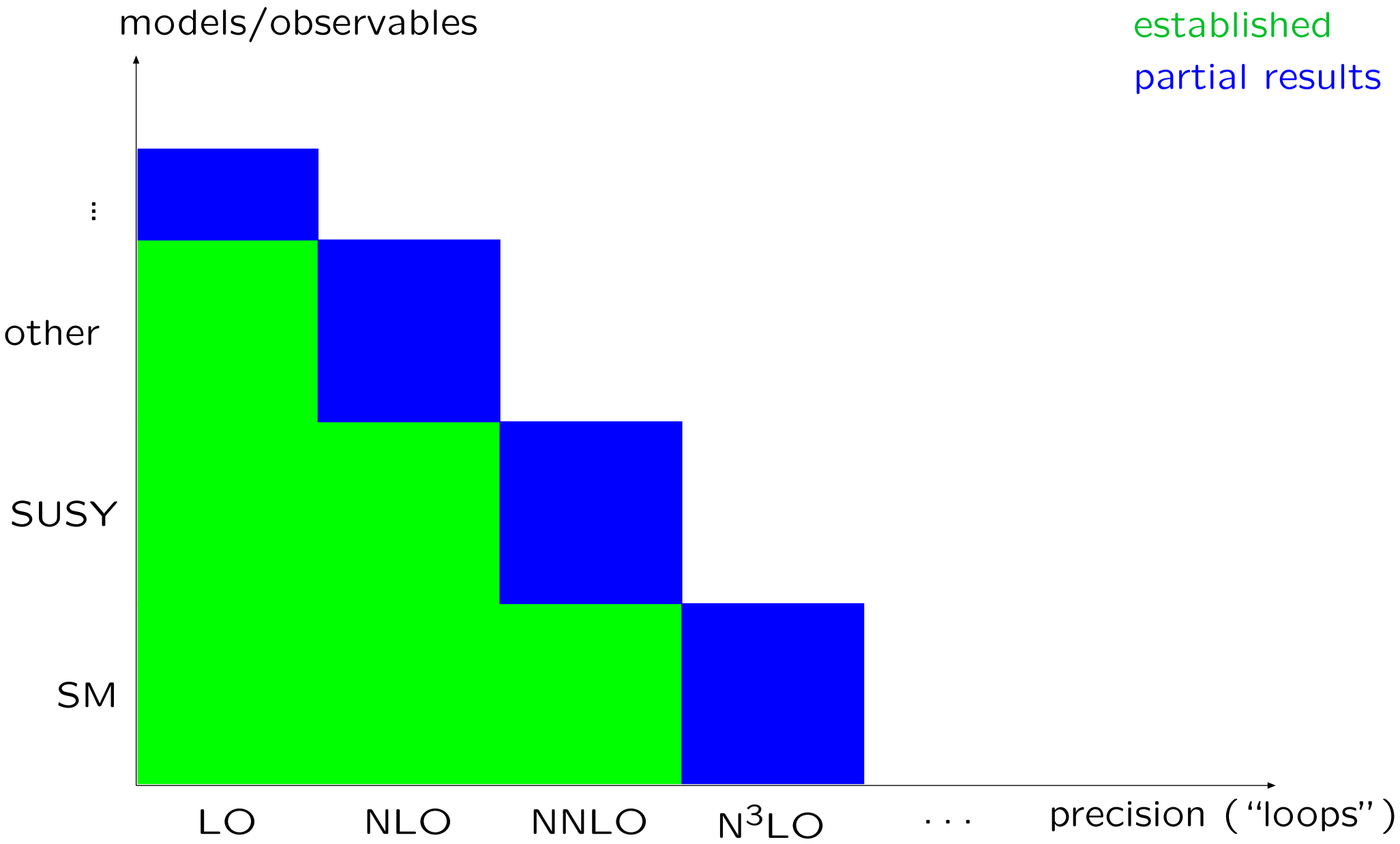

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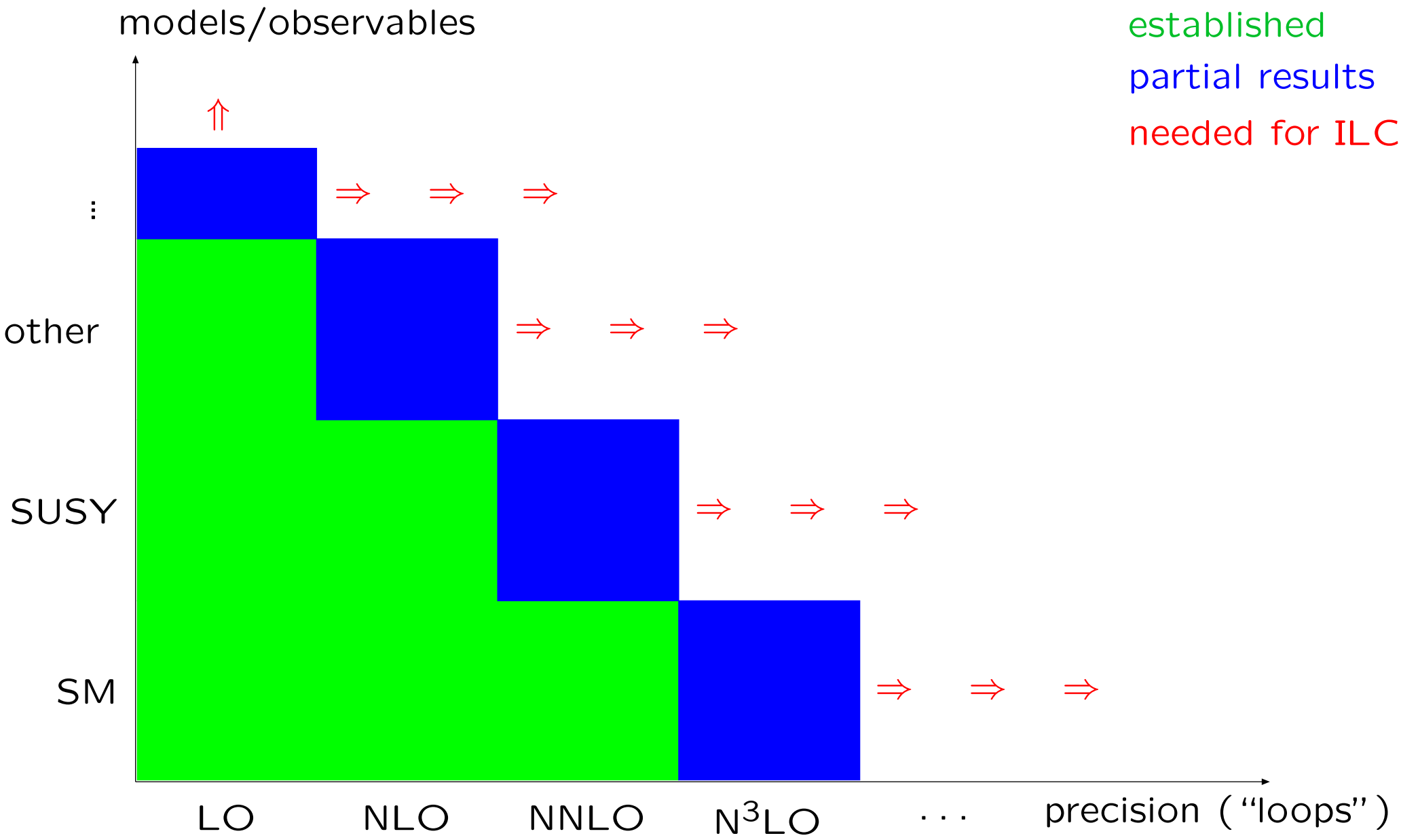

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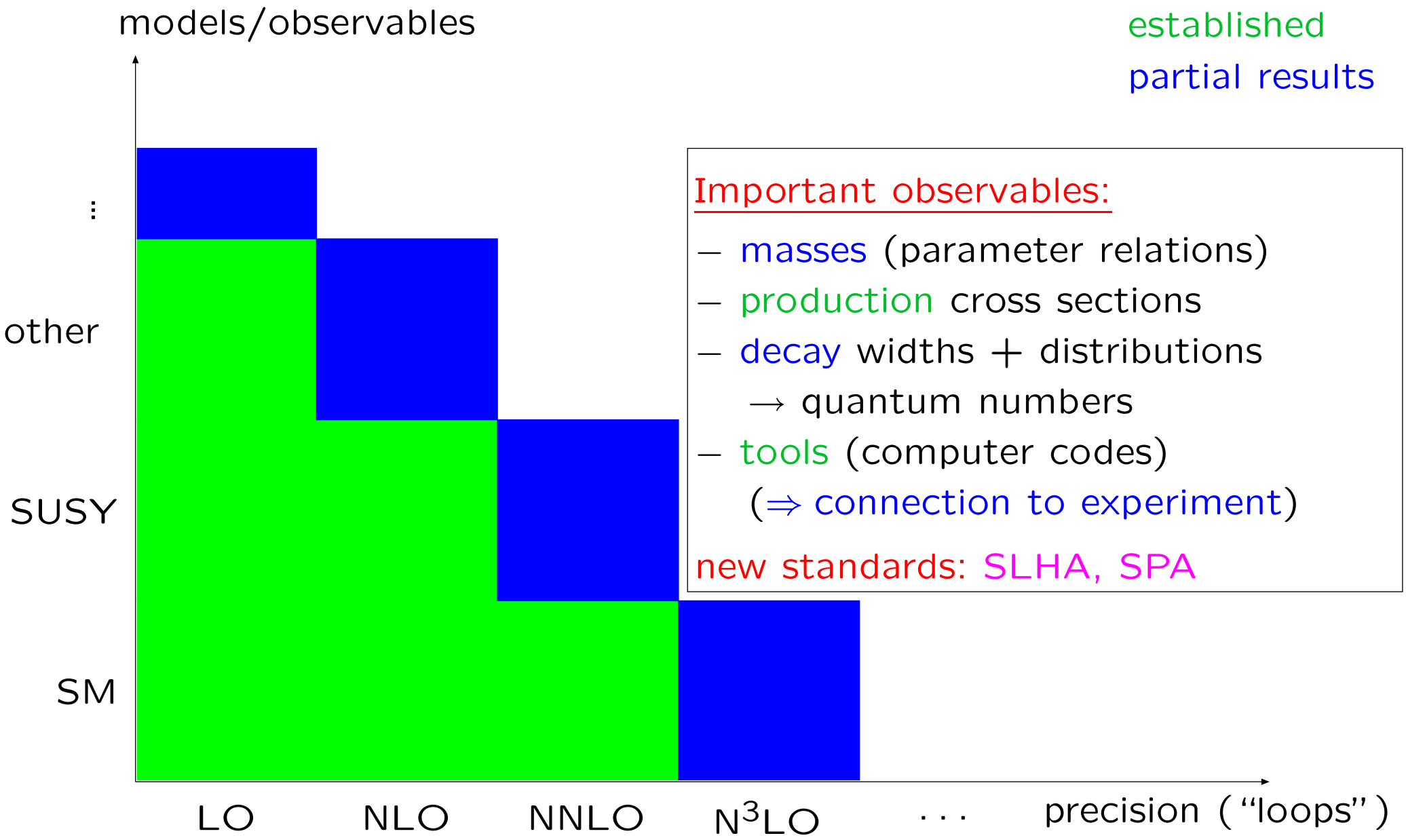
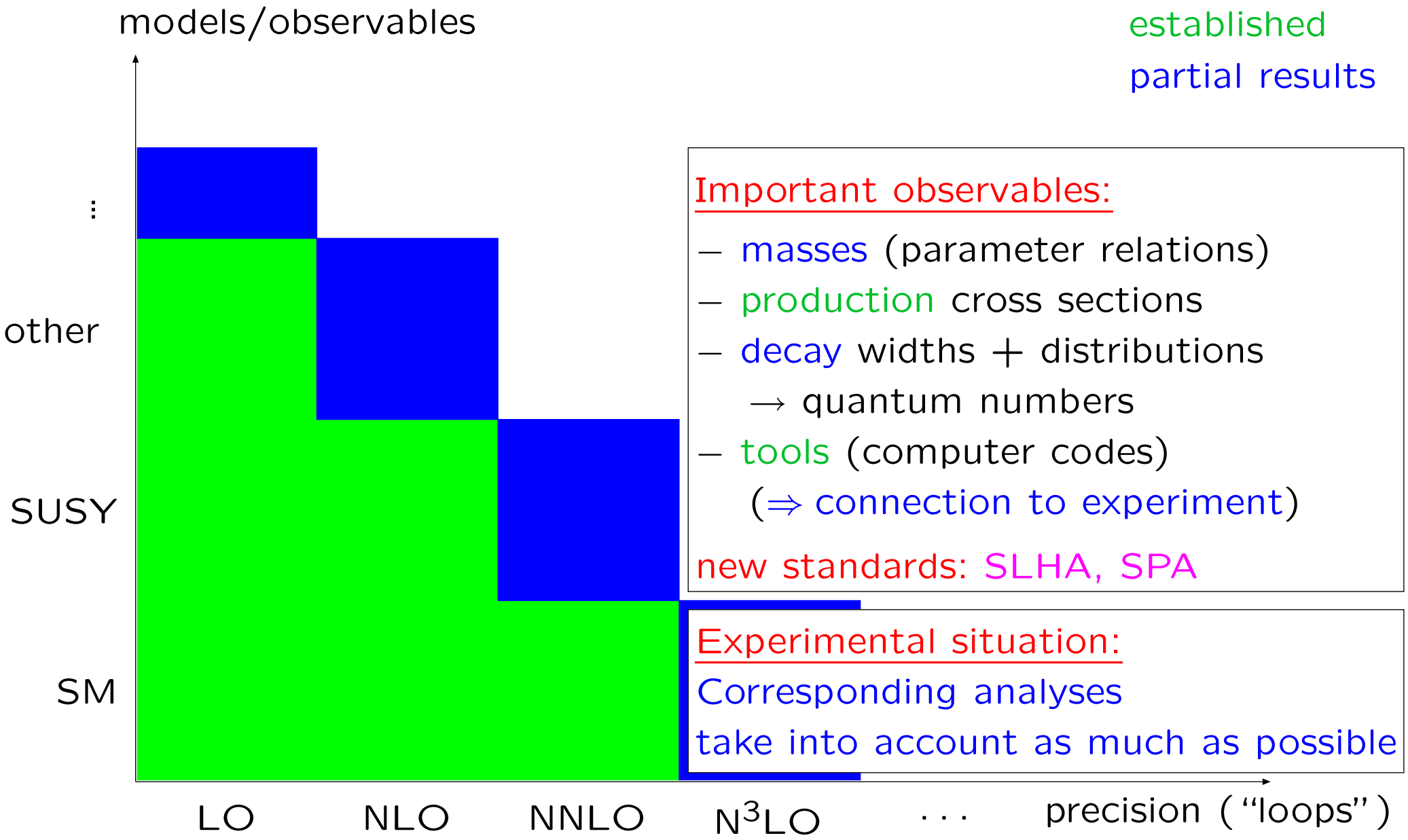


Important observables:

- masses (parameter relations)
- production cross sections
- decay widths + distributions
  → quantum numbers
- tools (computer codes)
  (⇒ connection to experiment)

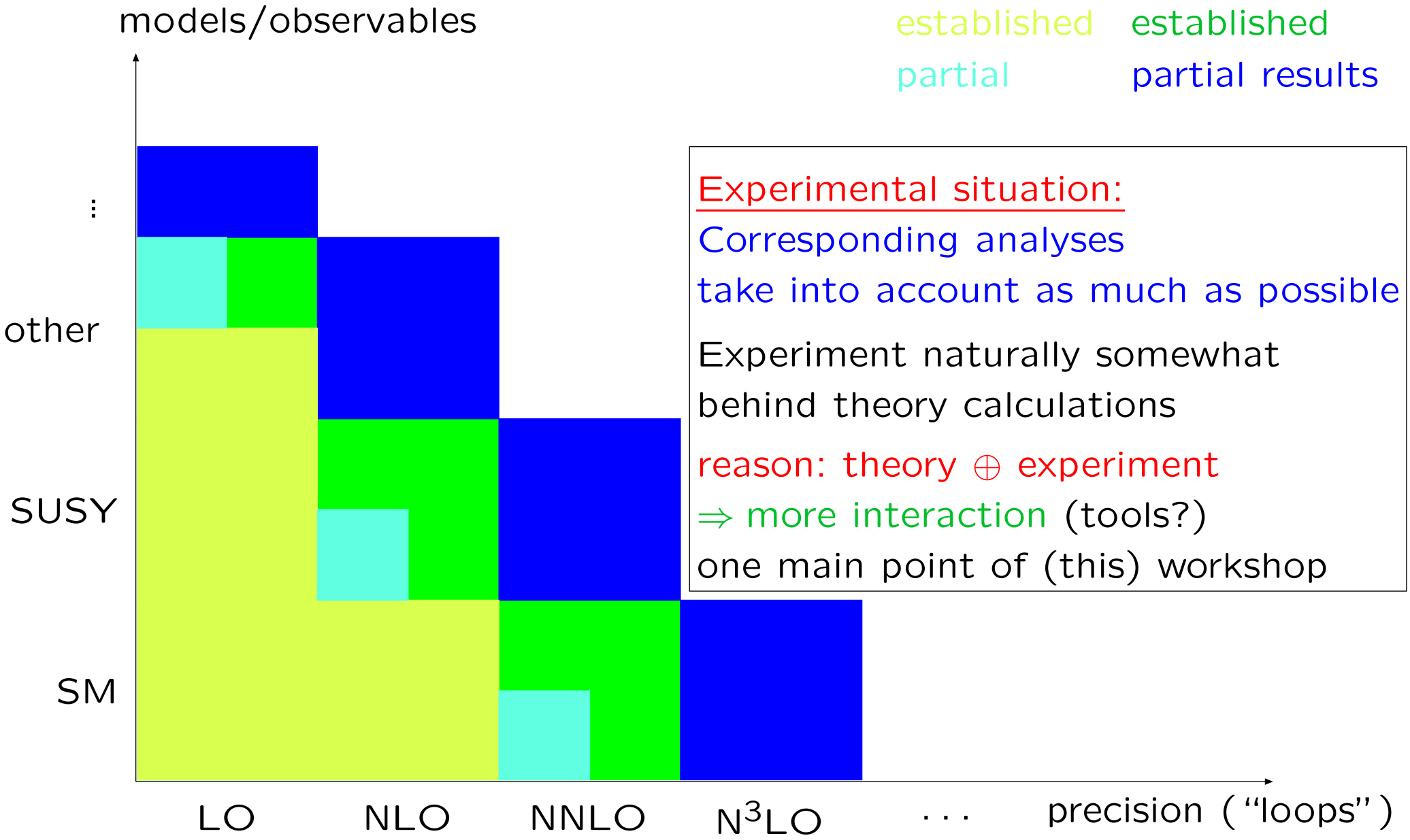
new standards: SLHA, SPA

Higgs: experimental situation



Higgs: experimental situation

experiment	theory
established	established
partial	partial results



Experimental situation:

Corresponding analyses

take into account as much as possible

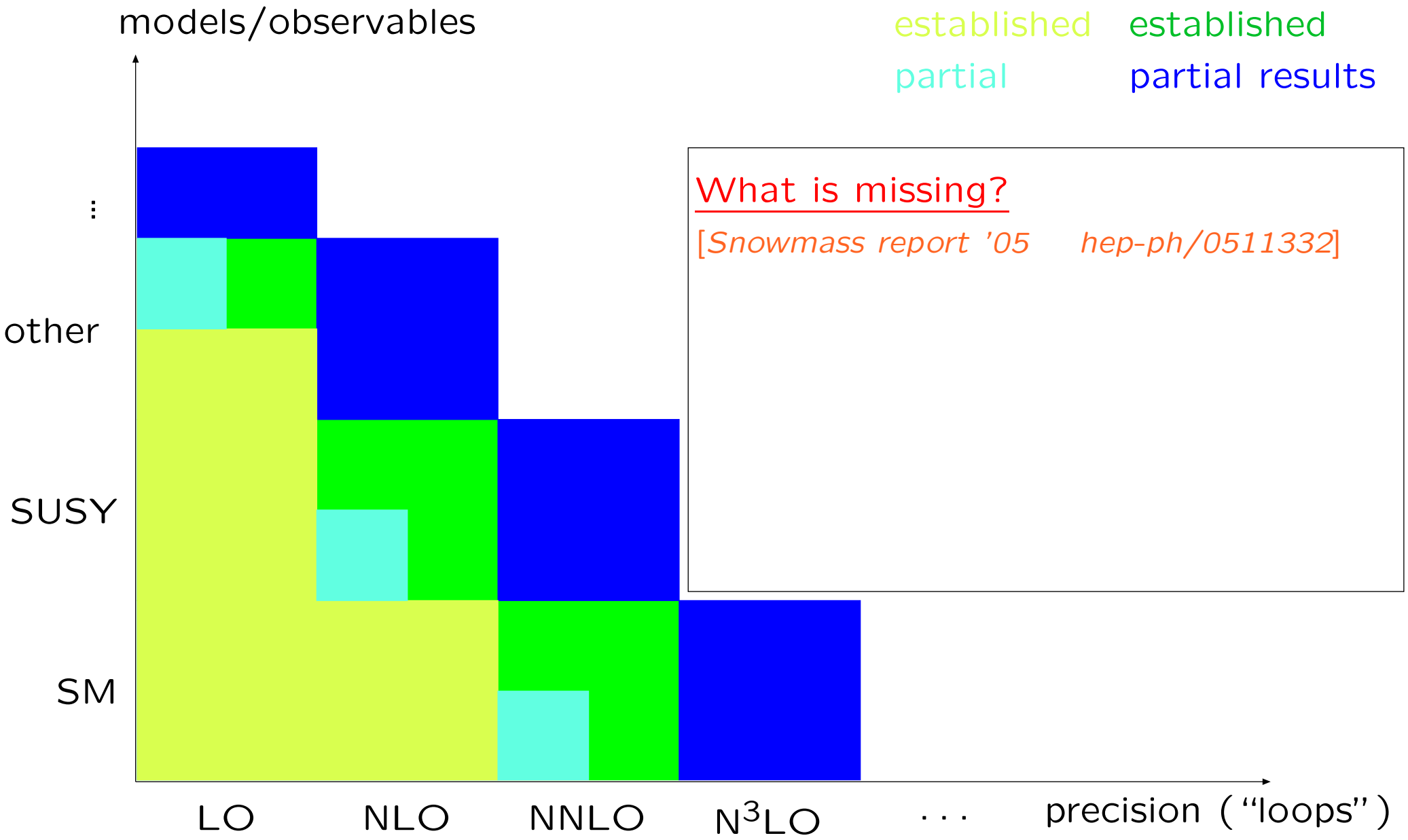
Experiment naturally somewhat behind theory calculations

reason: theory $\oplus$ experiment

$\Rightarrow$ more interaction (tools?)

one main point of (this) workshop

Higgs: experimental situation



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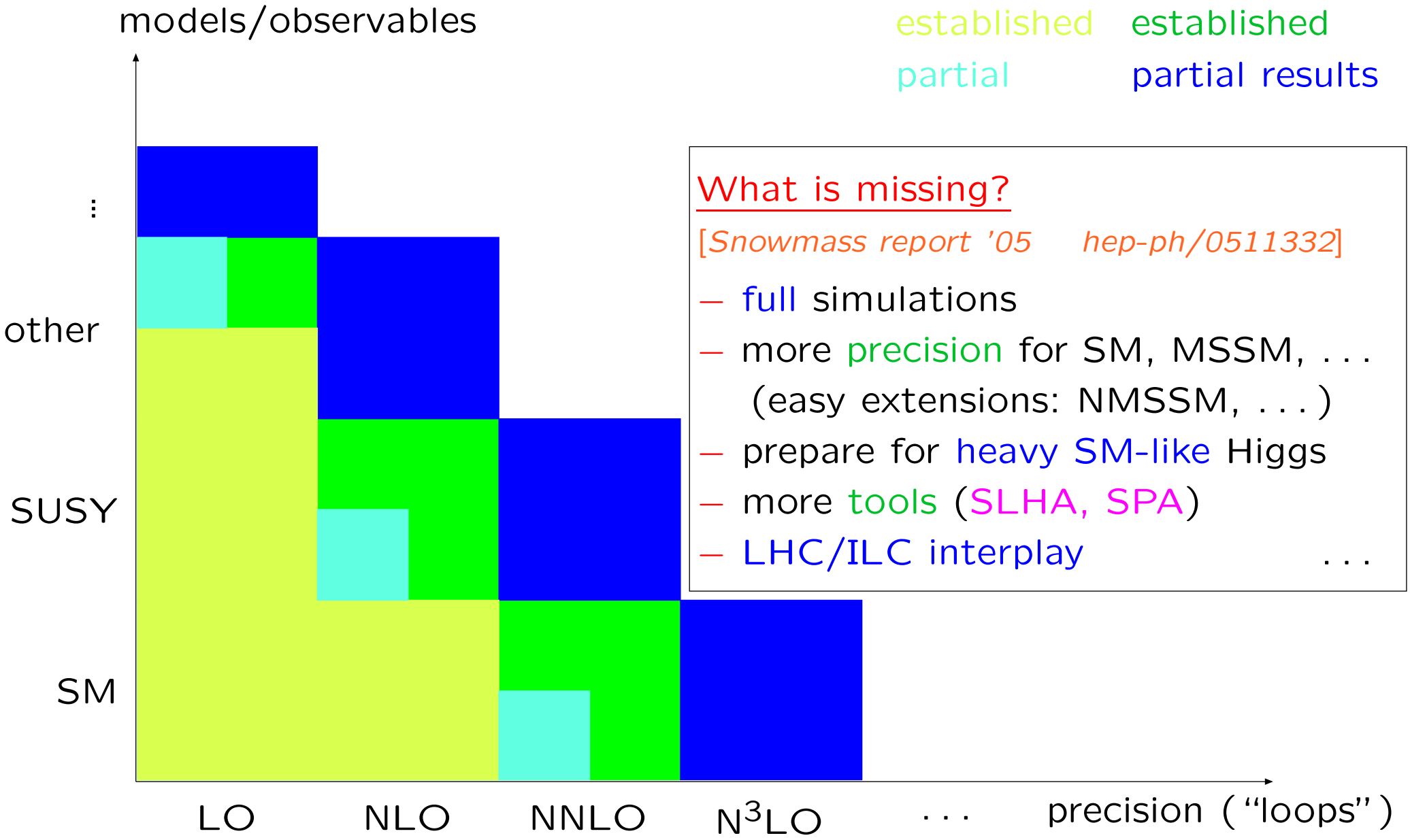
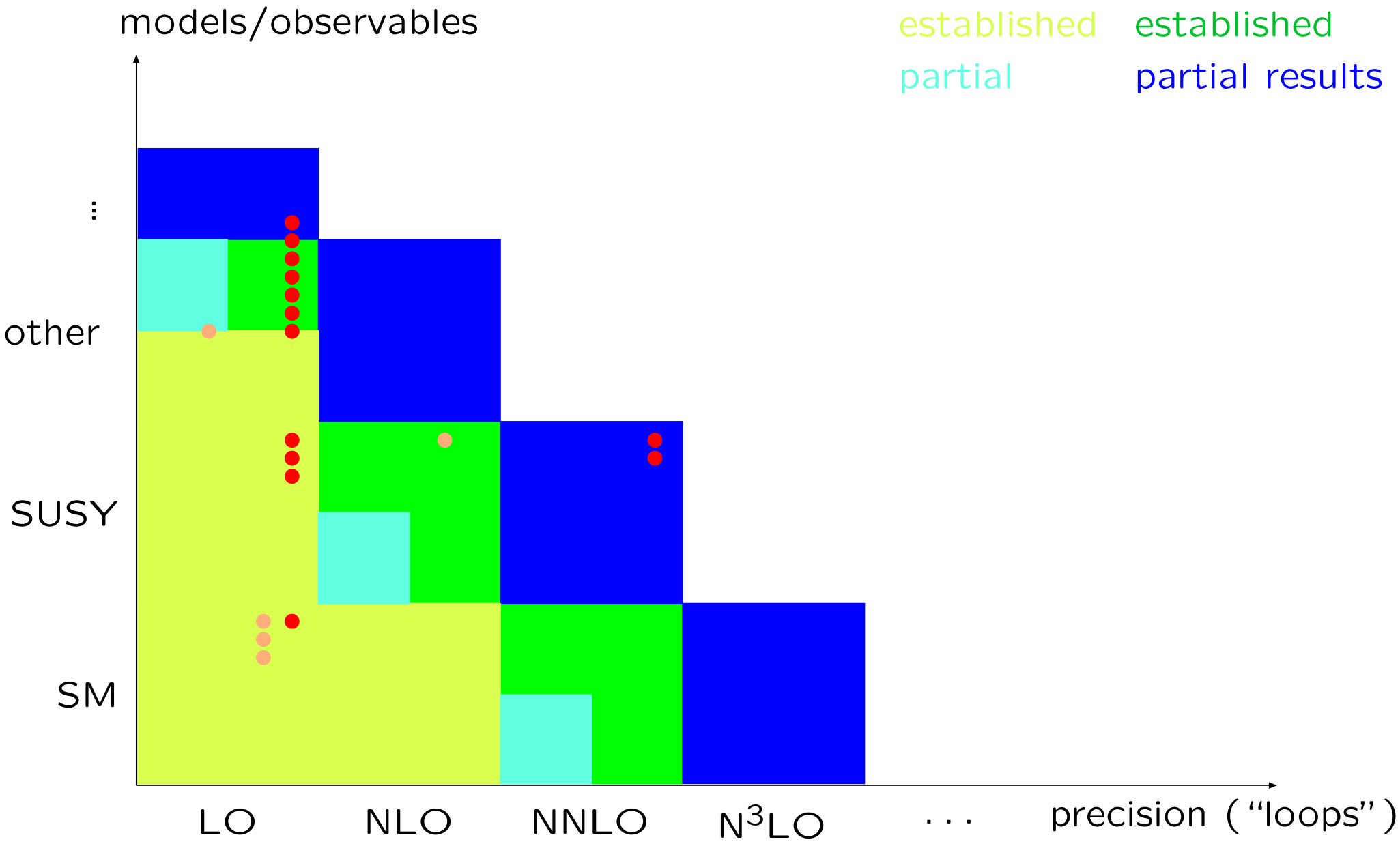


What is missing?

[*Snowmass report '05 hep-ph/0511332*]

- full simulations
- more precision for SM, MSSM, . . .
  (easy extensions: NMSSM, . . .)
- prepare for heavy SM-like Higgs
- more tools (SLHA, SPA)
- LHC/ILC interplay . . .

Higgs: **contributions in Bangalore**



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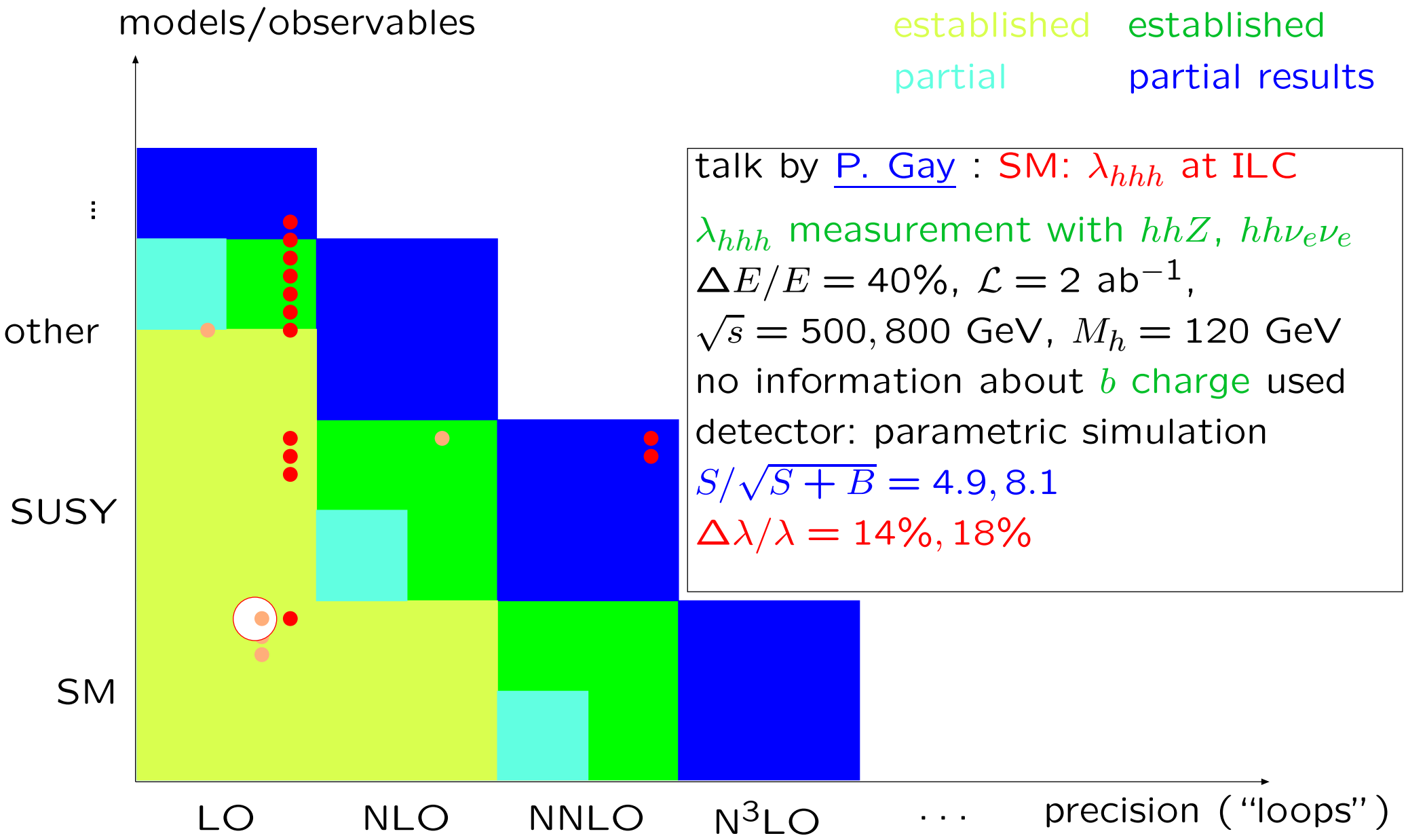

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partial	partial results

models/observables

⋮

other

SUSY

SM

talk by P. Gay : SM: λ_{hhh} at ILC

λ_{hhh} measurement with hhZ, $hh\nu_e\nu_e$

$E = 40\%$, $\mathcal{L} = 2$ ab^{-1},

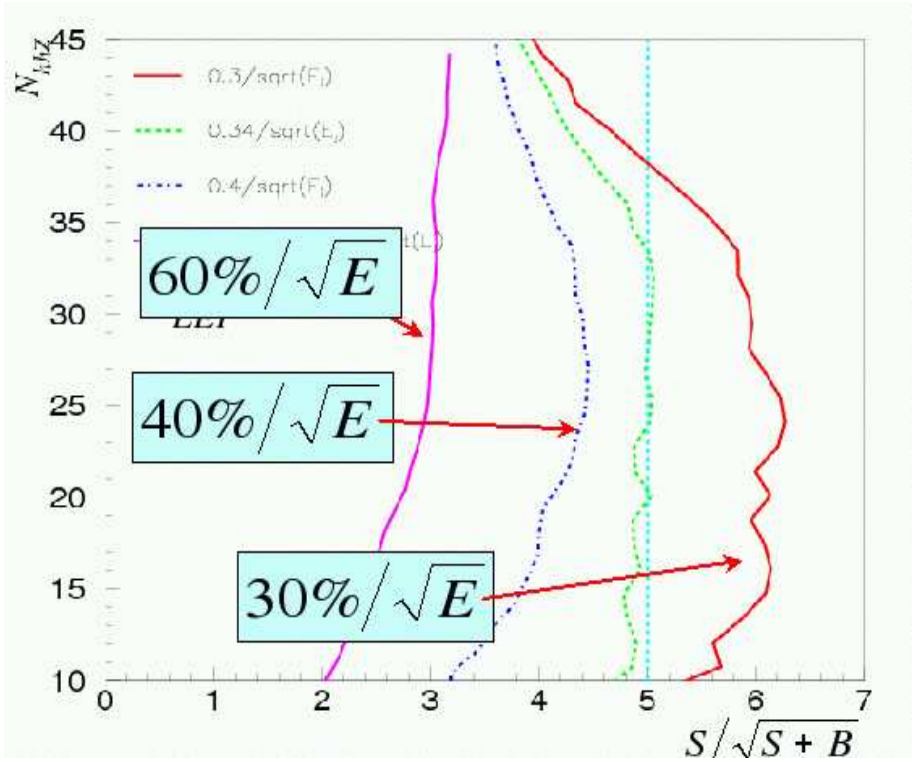
500, 800 GeV, $M_h = 120$ GeV

formation about b charge used

ctor: parametric simulation

$\sqrt{S+B} = 4.9, 8.1$

$\lambda = 14\%, 18\%$



LO NLO NNLO N^{3}LO ... precision ("loops")

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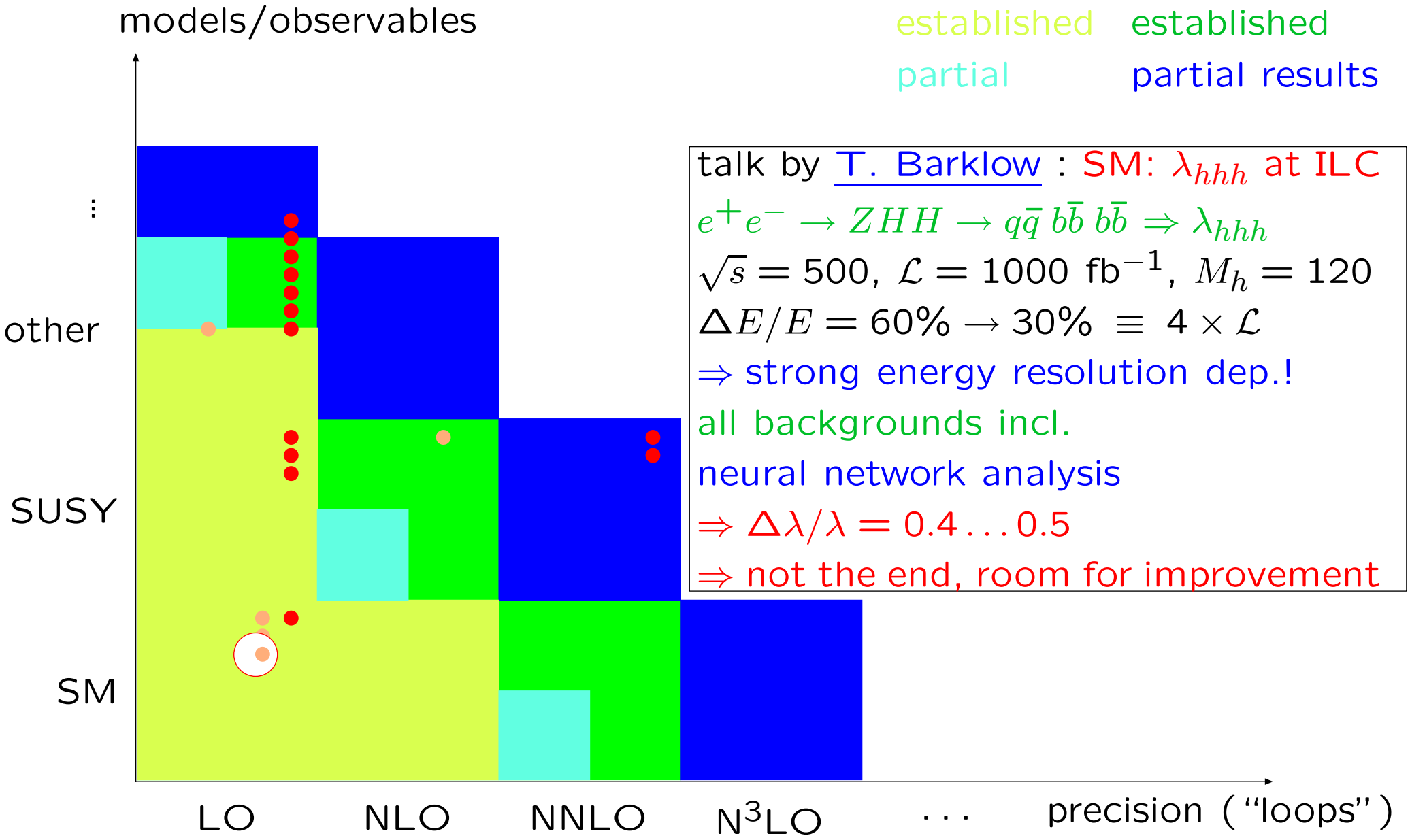

talk by T. Barklow : SM: λ_{hhh} at ILC

$e^+e^- \to ZHH \to q\bar{q}\, b\bar{b}\, b\bar{b} \Rightarrow \lambda_{hhh}$

$\sqrt{s} = 500$, $\mathcal{L} = 1000$ fb^{-1}, $M_h = 120$

$\Delta E/E = 60\% \to 30\% \equiv 4 \times \mathcal{L}$

$\Rightarrow$ strong energy resolution dep.!

all backgrounds incl.

neural network analysis

$\Rightarrow \Delta\lambda/\lambda = 0.4 \ldots 0.5$

$\Rightarrow$ not the end, room for improvement

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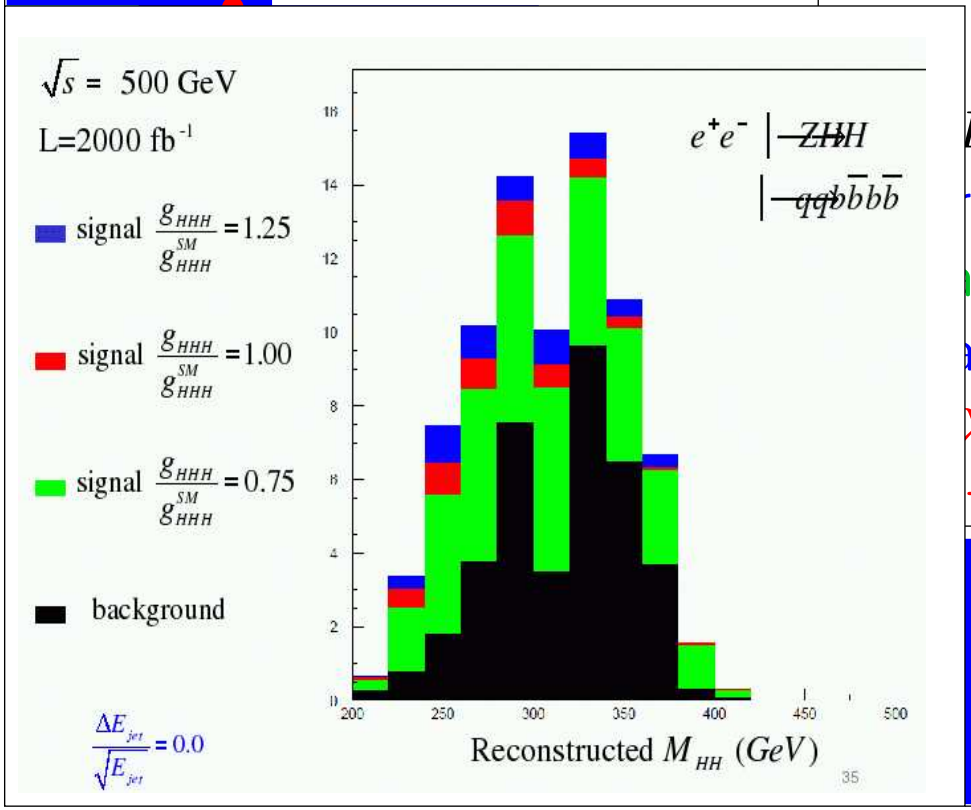

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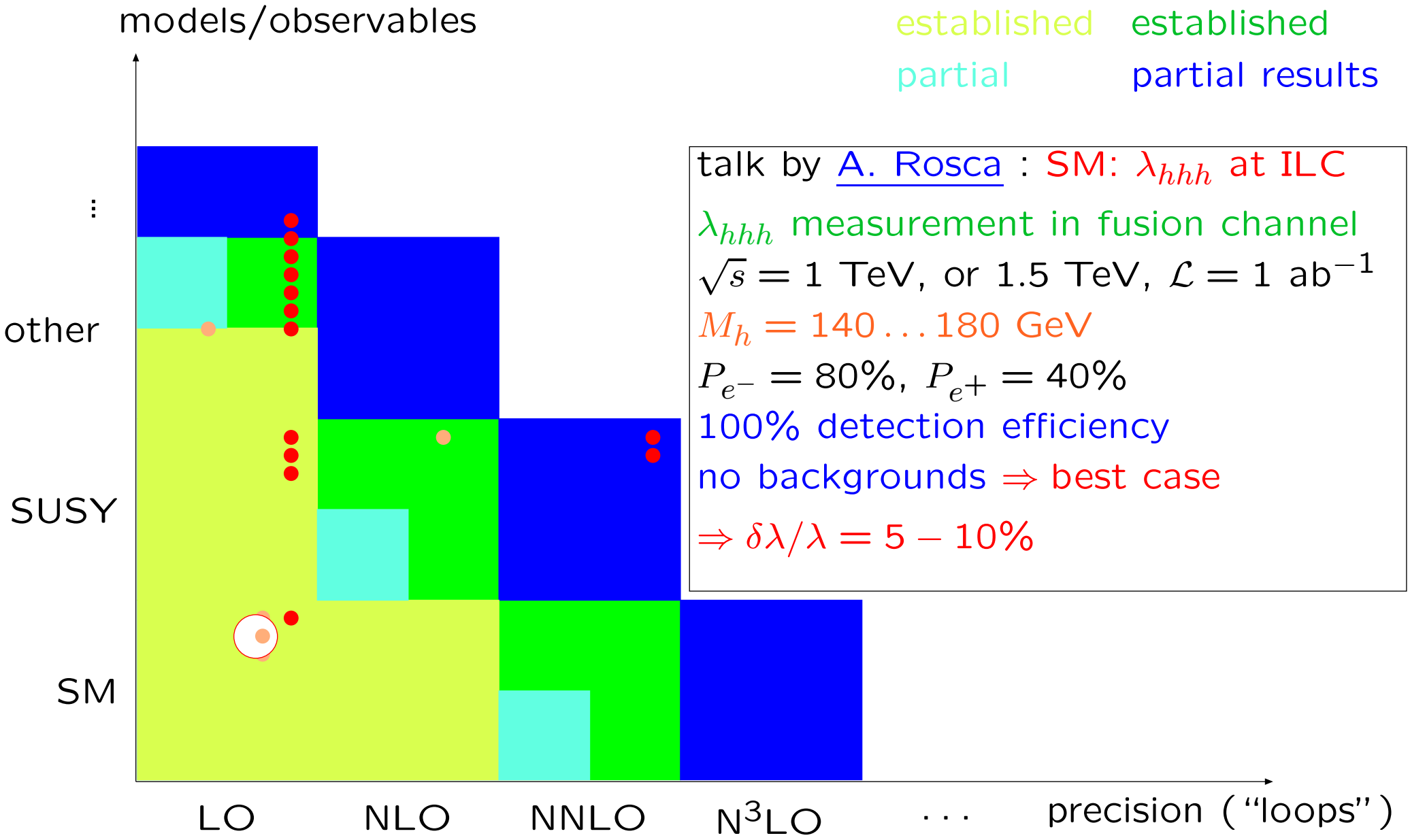

talk by A. Rosca : SM: λ_{hhh} at ILC

λ_{hhh} measurement in fusion channel

$\sqrt{s} = 1$ TeV, or 1.5 TeV, $\mathcal{L} = 1$ ab^{-1}

$M_h = 140 \ldots 180$ GeV

$P_{e^-} = 80\%$, $P_{e^+} = 40\%$

100% detection efficiency

no backgrounds $\Rightarrow$ best case

$\Rightarrow \delta\lambda/\lambda = 5 - 10\%$

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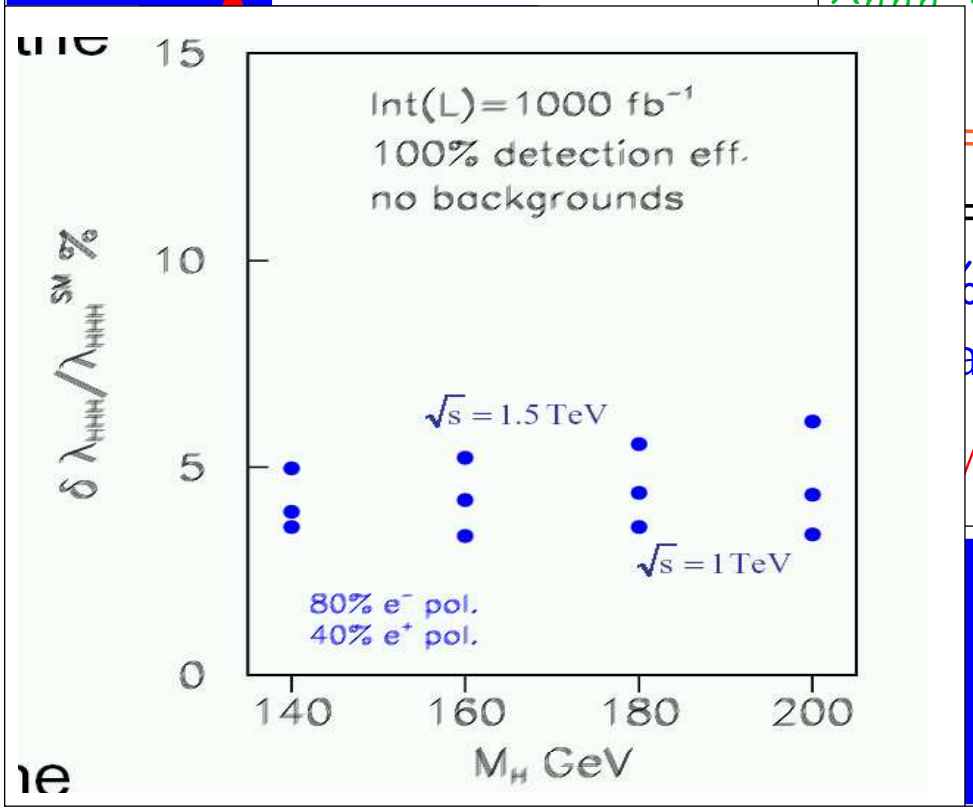

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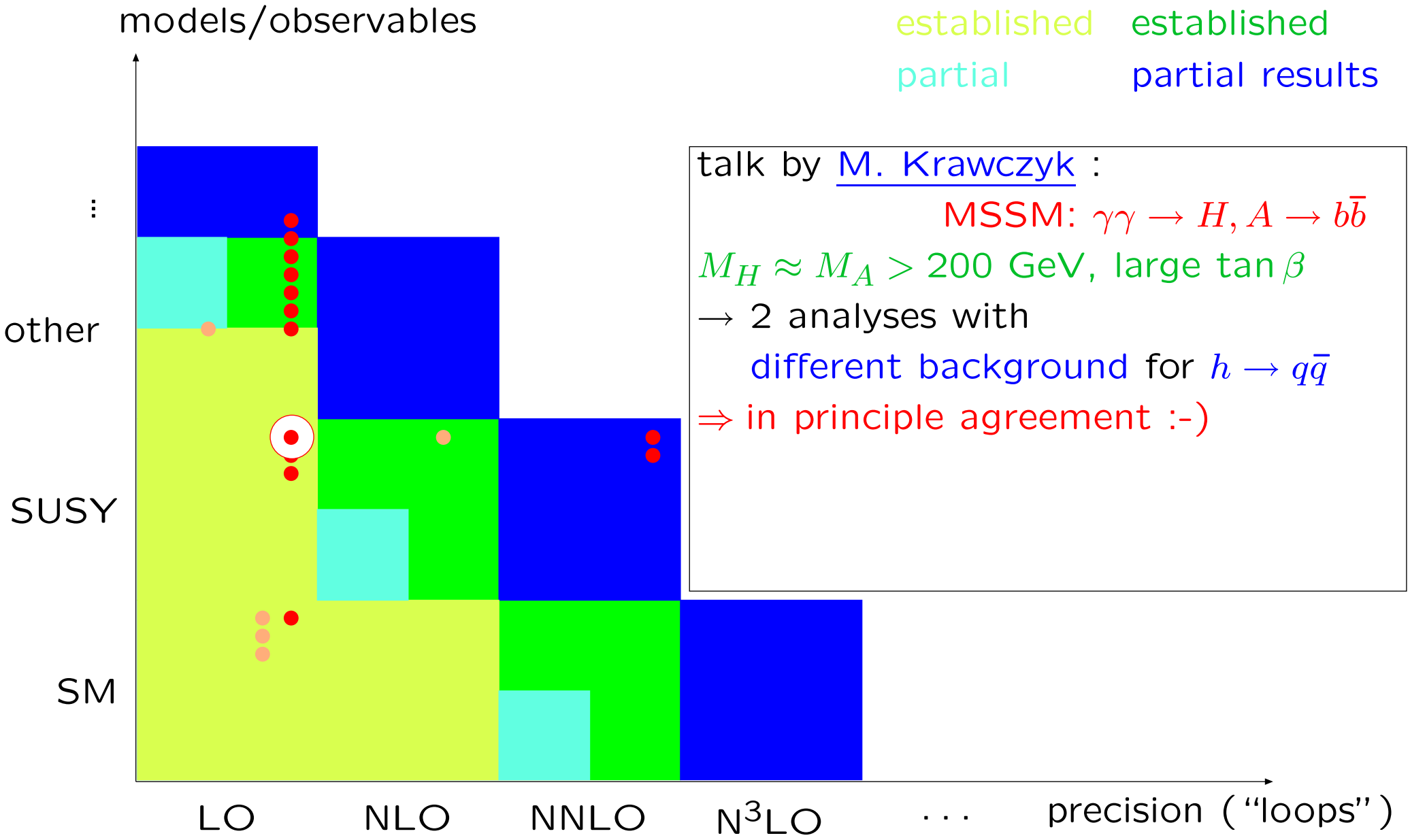

talk by M. Krawczyk :

MSSM: $\gamma\gamma \to H, A \to b\bar{b}$

$M_H \approx M_A > 200$ GeV, large $\tan\beta$

$\to$ 2 analyses with

different background for $h \to q\bar{q}$

$\Rightarrow$ in principle agreement :-)

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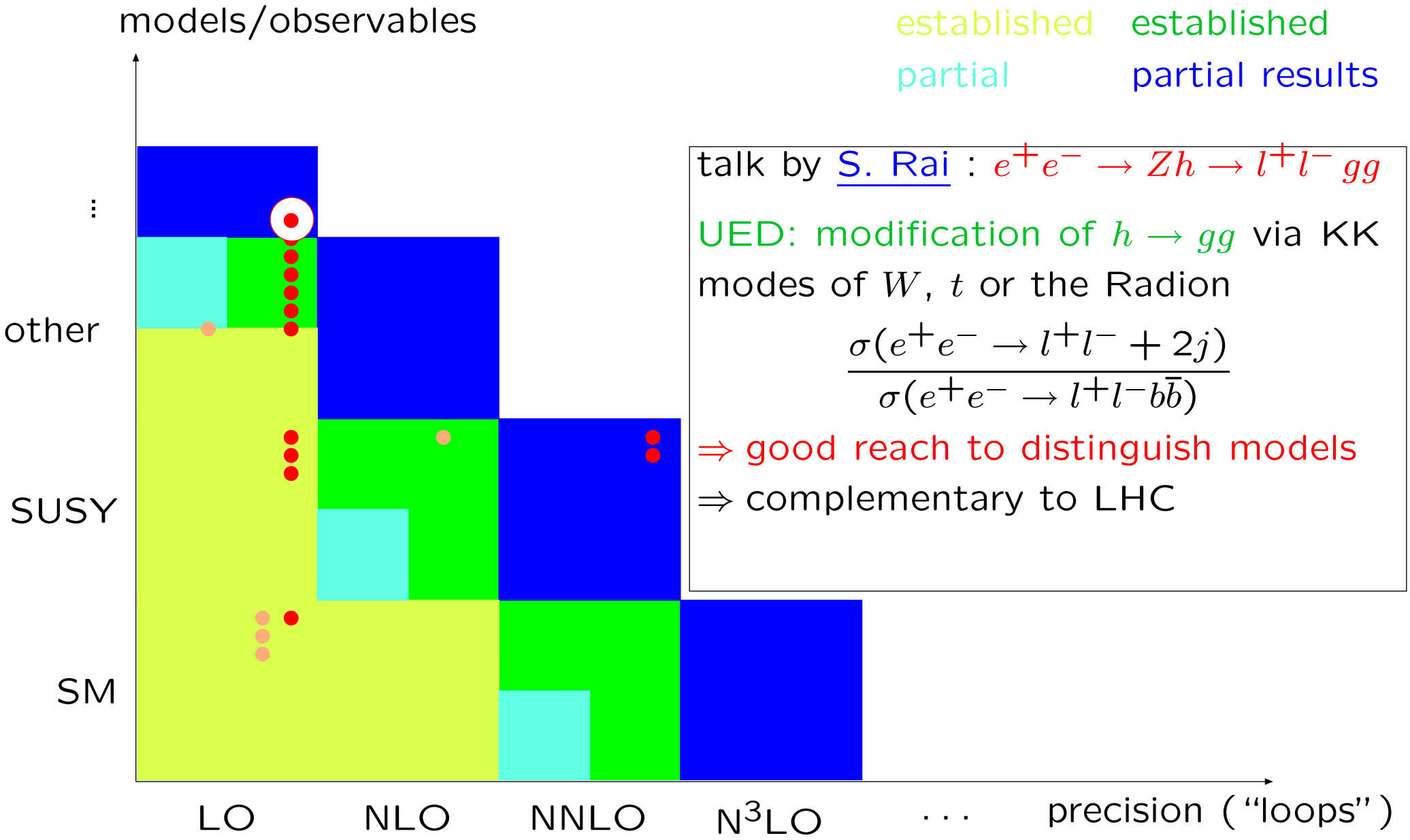

talk by S. Rai : $e^+e^- \to Zh \to l^+l^- gg$

UED: modification of $h \to gg$ via KK modes of W, t or the Radion

$$\frac{\sigma(e^+e^- \to l^+l^- + 2j)}{\sigma(e^+e^- \to l^+l^- b\bar{b})}$$

$\Rightarrow$ good reach to distinguish models

$\Rightarrow$ complementary to LHC

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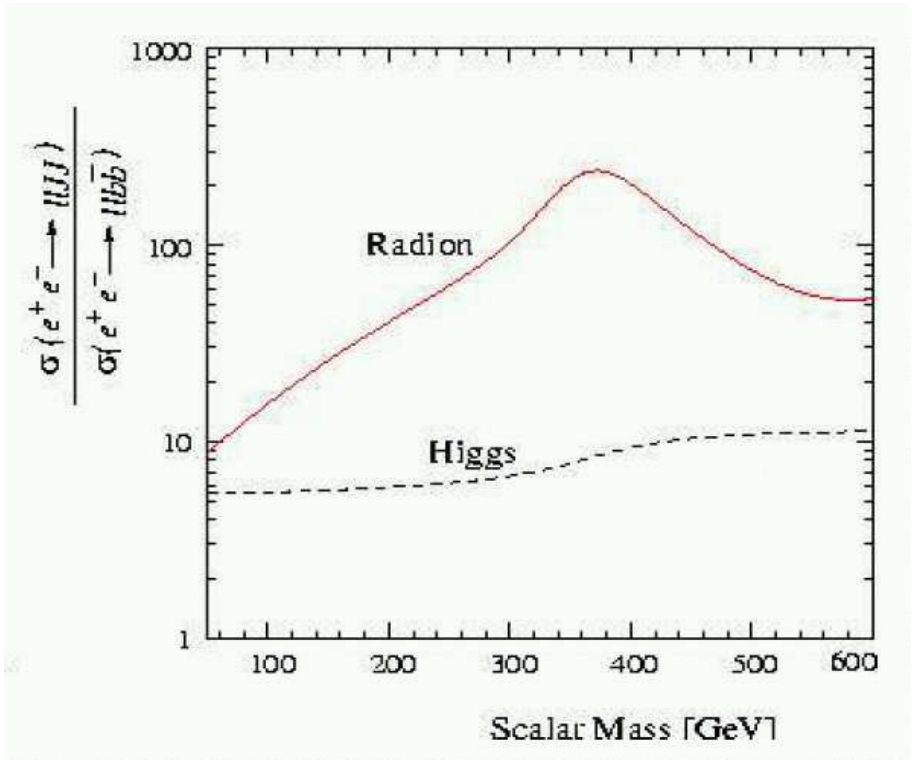

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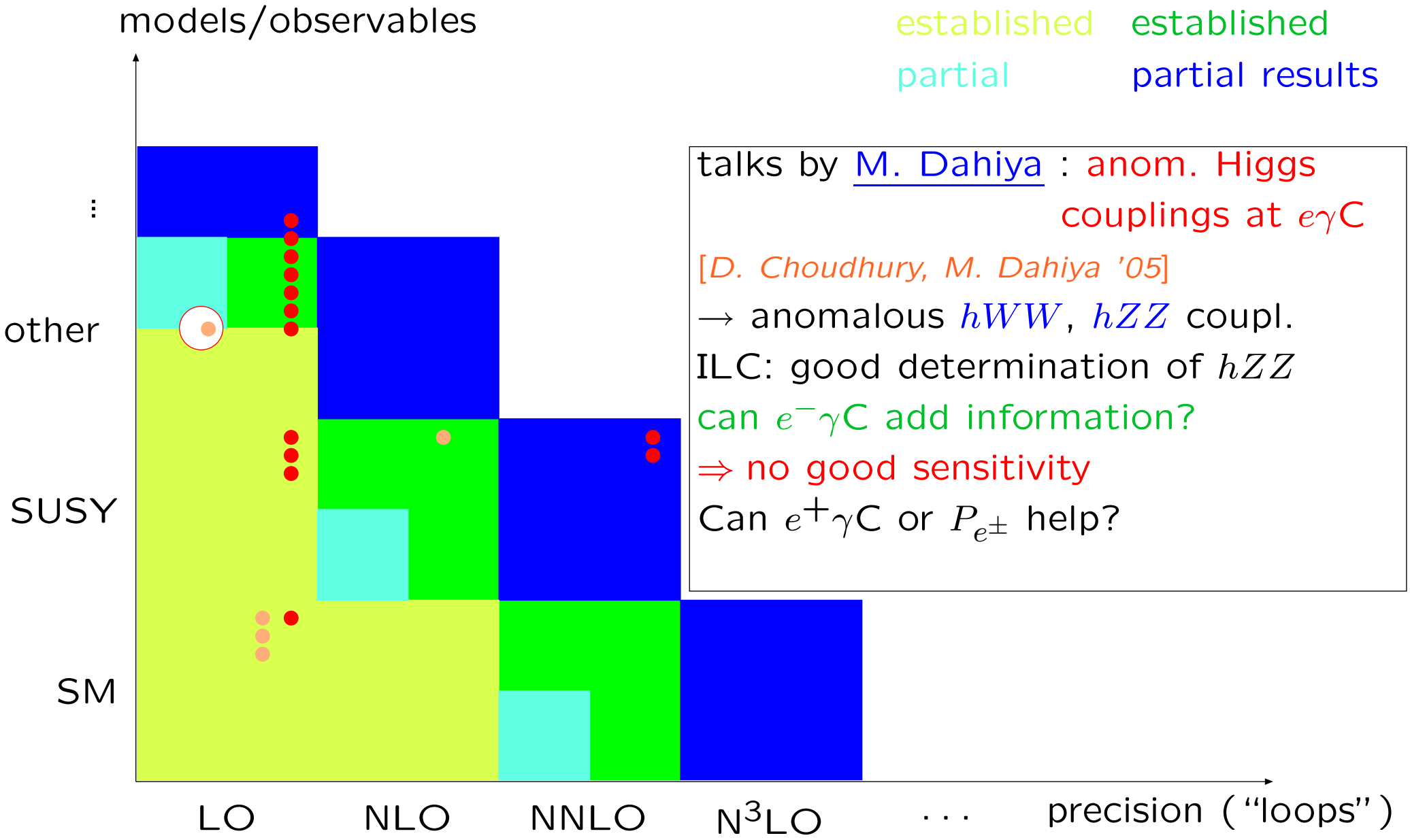

talks by M. Dahiya : anom. Higgs couplings at $e\gamma$C

[*D. Choudhury, M. Dahiya '05*]

$\rightarrow$ anomalous hWW, hZZ coupl.

ILC: good determination of hZZ

can $e^-\gamma$C add information?

$\Rightarrow$ no good sensitivity

Can $e^+\gamma$C or $P_{e^\pm}$ help?

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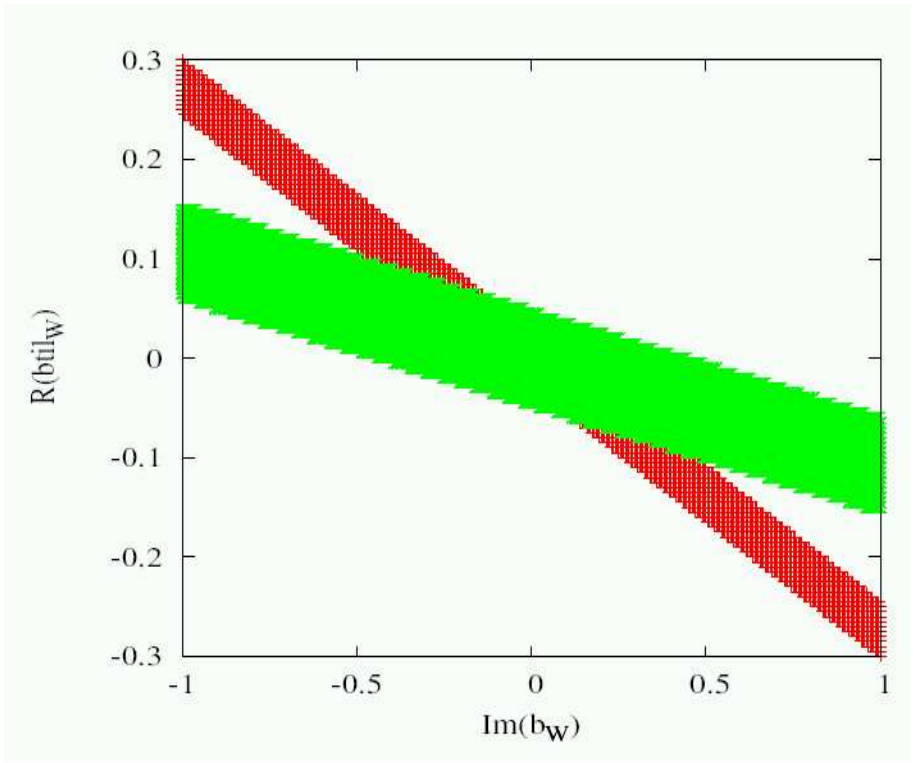

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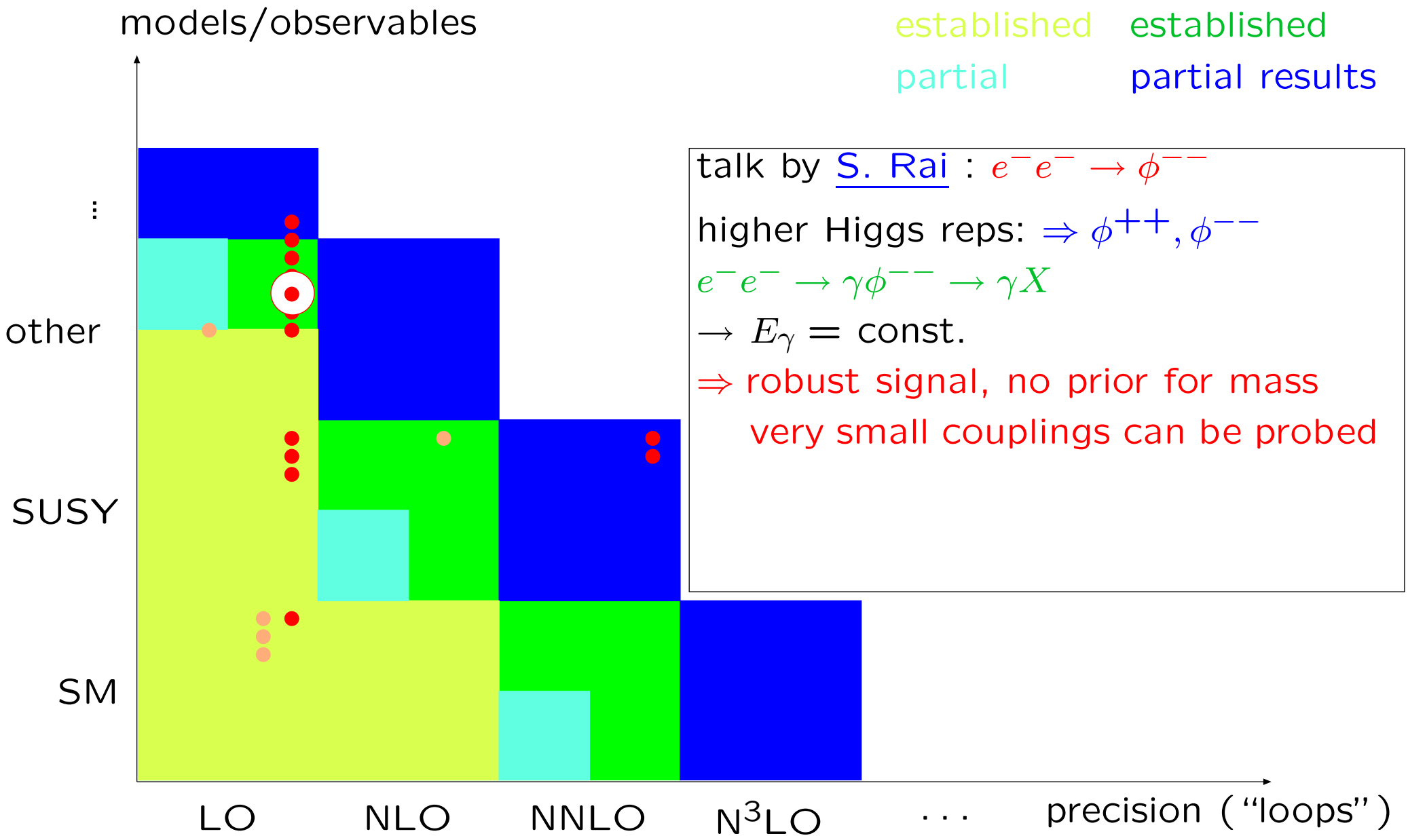

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talk by S. Rai : $e^-e^- \to \phi^{--}$

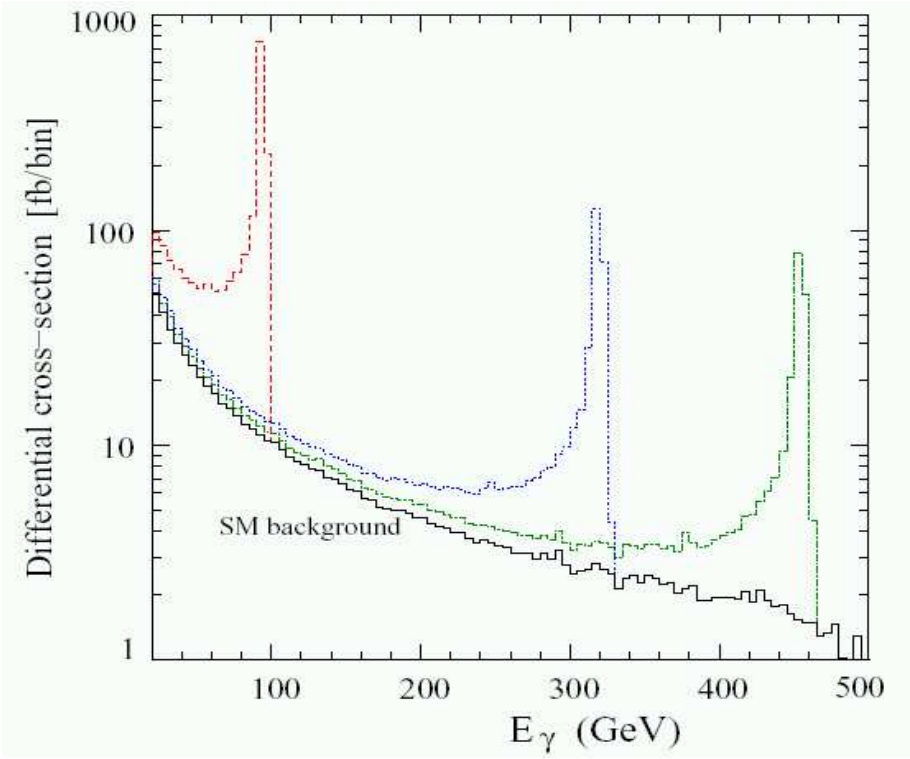
higher Higgs reps: $\Rightarrow \phi^{++}, \phi^{--}$

$\to \gamma\phi^{--} \to \gamma X$

$= \text{const.}$

bust signal, no prior for mass

ry small couplings can be probed



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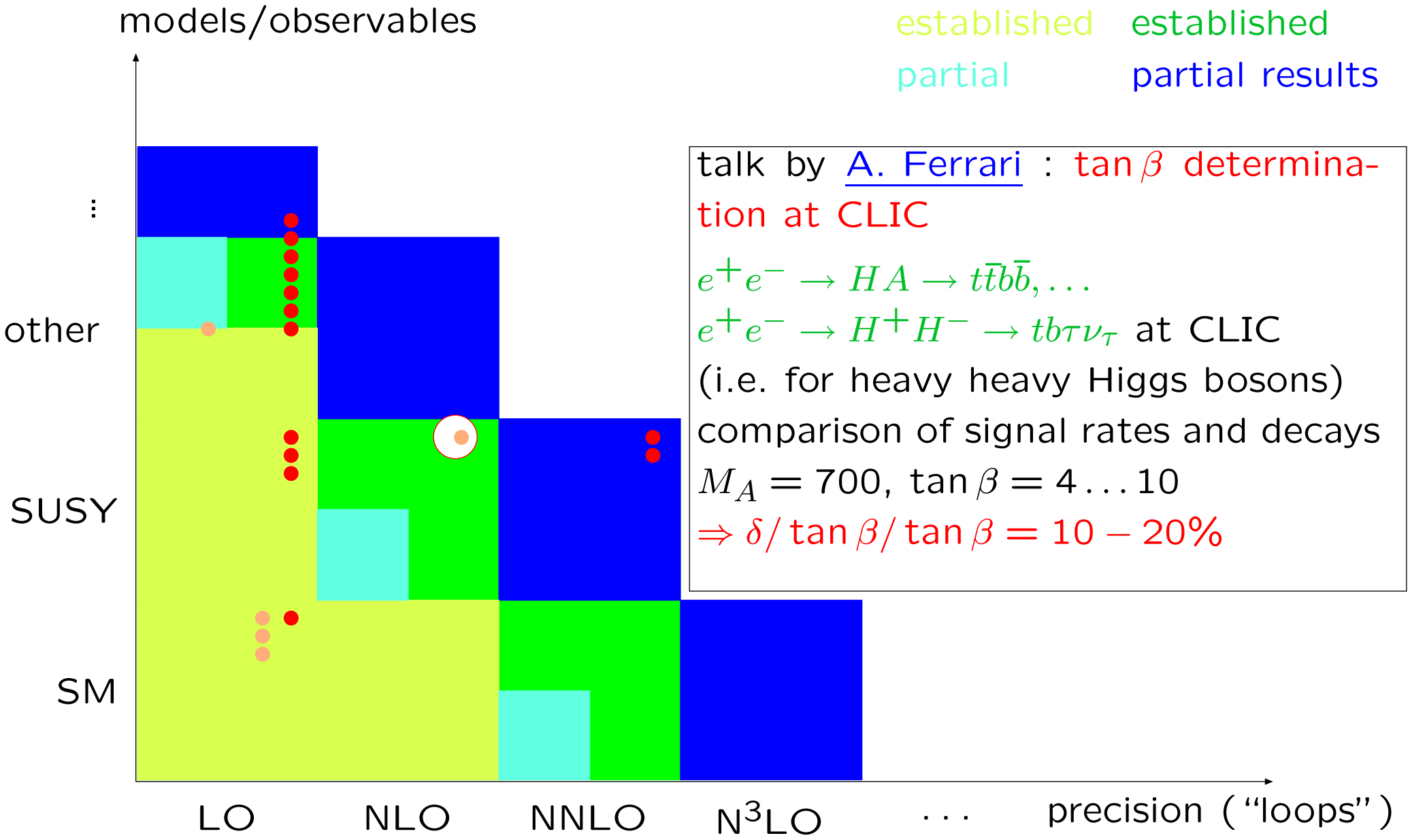

talk by A. Ferrari : $\tan\beta$ determination at CLIC

$e^+e^- \to HA \to t\bar{t}b\bar{b}, \ldots$

$e^+e^- \to H^+H^- \to tb\tau\nu_\tau$ at CLIC

(i.e. for heavy heavy Higgs bosons)

comparison of signal rates and decays

$M_A = 700$, $\tan\beta = 4 \ldots 10$

$\Rightarrow \delta/\tan\beta/\tan\beta = 10 - 20\%$

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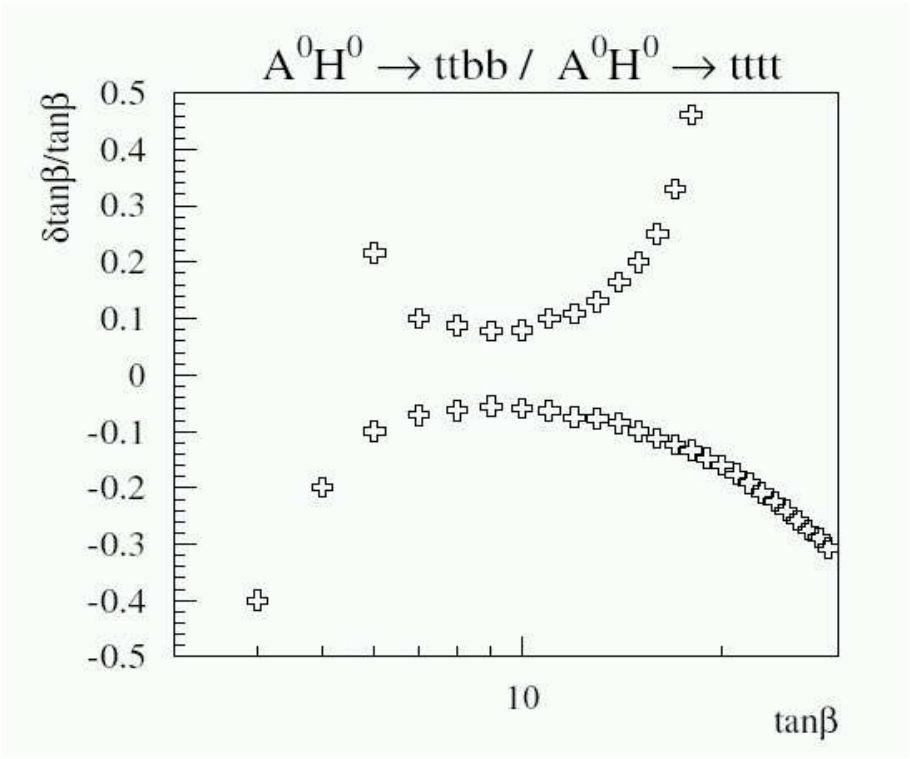

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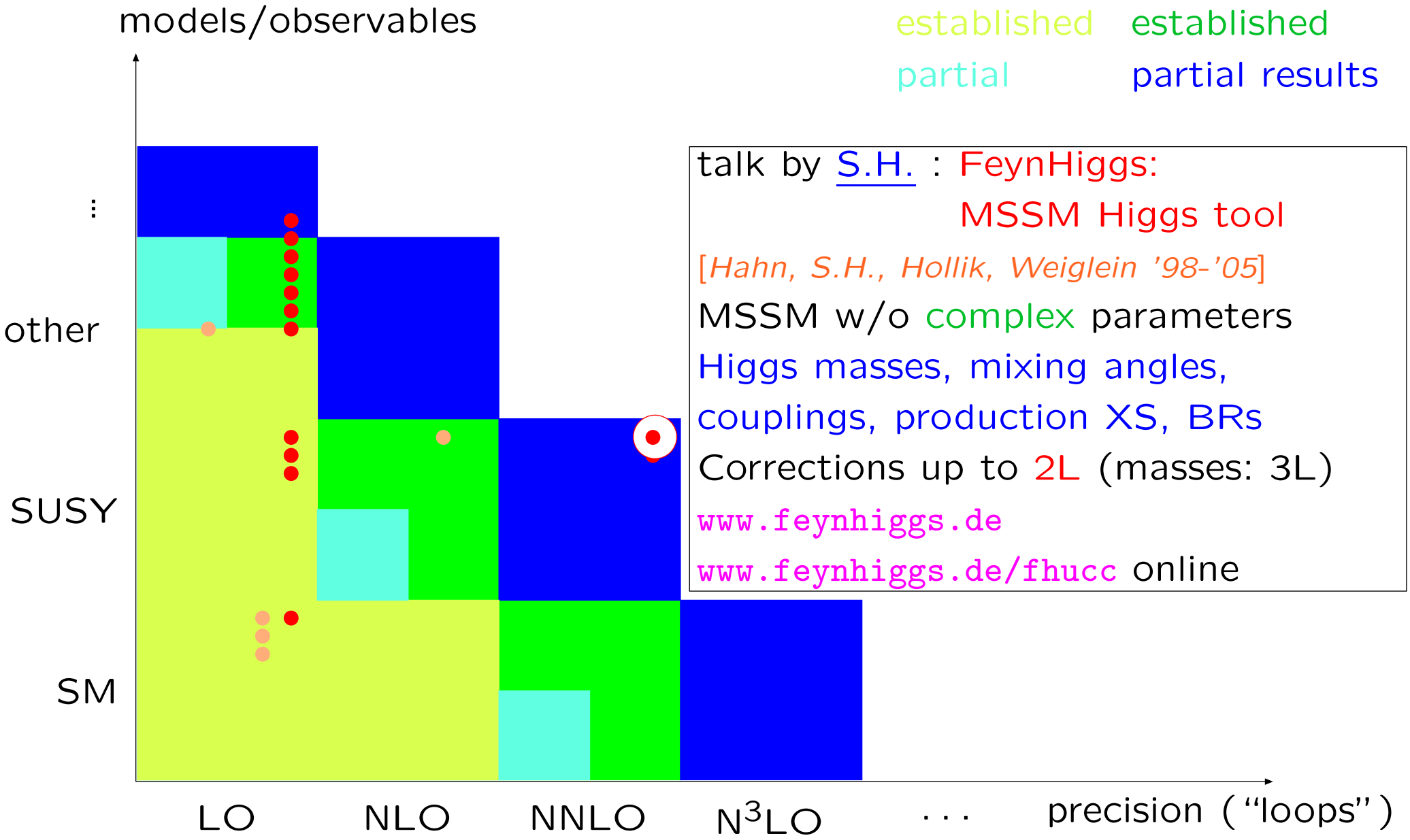


talk by S.H. : FeynHiggs:
MSSM Higgs tool

[*Hahn, S.H., Hollik, Weiglein '98-'05*]

MSSM w/o complex parameters

Higgs masses, mixing angles,
couplings, production XS, BRs

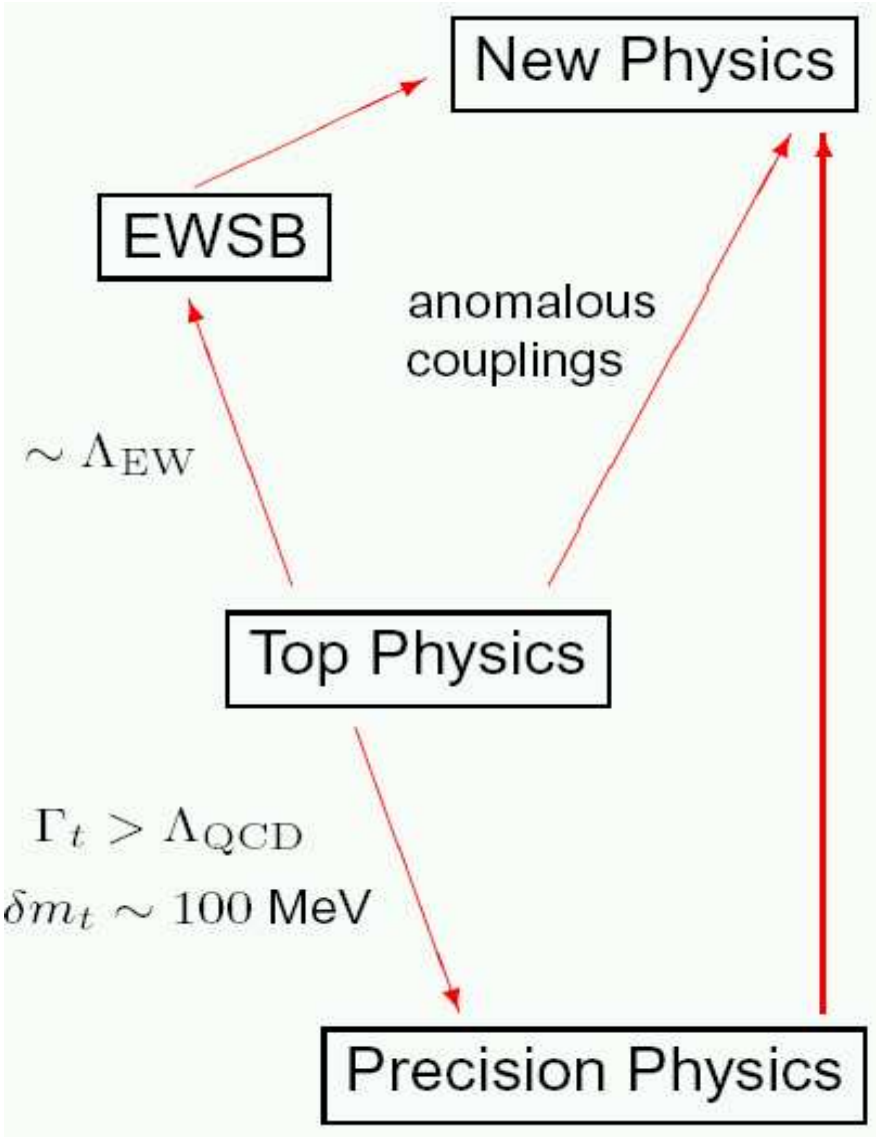
Corrections up to 2L (masses: 3L)

`www.feynhiggs.de`

`www.feynhiggs.de/fhucc` online

3. Top/QCD (few QCD, more top)

The top is guaranteed at the ILC ⇒ sure physics case!



EWSB: just a heavy quark?
special role for t in EWSB?
strong constraint on any model

Precision physics:
$\delta m_t^{\rm exp}$ leading parametric uncertainty
$\rightarrow$ could obscure new physics

SUSY: m_t crucial input parameter
drives SSB/unification

Little Higgs: heavier top

Tevatron/LHC: "rough" measurements
of mass, couplings, BRs

ILC: high precision of everything
. . . if we are ready

Few QCD: ⇒ one talk :-)

Most important top observables:

- top quark mass: m_t (most important input parameter)
  measurement from production peak position
  experiment: ok – theory: not yet ($m_t^{\text{shortdistance}} \longrightarrow m_t^{\overline{\text{MS}}}$)
  ⇒ no news here :-(
- top quark width: Γ_t ⇒ no news here :-(
- top quark production cross section: σ_{tt}
  precise prediction needed for m_t
  new physics contributions? experiment: ok – theory: nearly...?
  ⇒ no news here :-(
- top quark branching ratios
  → anomalous couplings → $\mathcal{O}(\%)$ at ILC, polarization crucial
  ToDo: fully exploit polarization ⇒ one talk :-)
  vary more than 1 coupling
  QCD corrections to SM
  tools for $e^+e^- \to 6f,\ 8f$ at $\mathcal{O}(\alpha_s)$ ($6f$: Lusifer)
- top Yukawa coupling: Y_t
  → connection to Higgs sector ⇒ two talks :-)

Few QCD: ⇒ one talk :-)

Most important top observables:

QCD talk by R. Godbole: $\sigma(\gamma\gamma \to \text{ had})$

→ use data from $p\bar{p} \to \gamma\gamma$
model with 3 free parameters
⇒ predict $\sigma(\gamma\gamma \to \text{ had})$
⇒ new (preliminary) results similar
to old results (but more solid now)

input parameter)
osition
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tt

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talk by R. Singh: lepton characteristics in t decay

⇒ new physics probe

angular distribution of secondary lepton insensitive to anomalous Wtb coupling

E_l dist. for anomalous Wtb coupling

use of polarization advantageous

- top quark branching ratios
  → anomalous couplings → $\mathcal{O}(\%)$ at ILC, polarization crucial
  ToDo: fully exploit polarization
  vary more than 1 coupling
  QCD corrections to SM
  tools for $e^+e^- \rightarrow 6f,\ 8f$ at $\mathcal{O}(\alpha_s)$ ($6f$: Lusifer)

  ⇒ one talk :-)

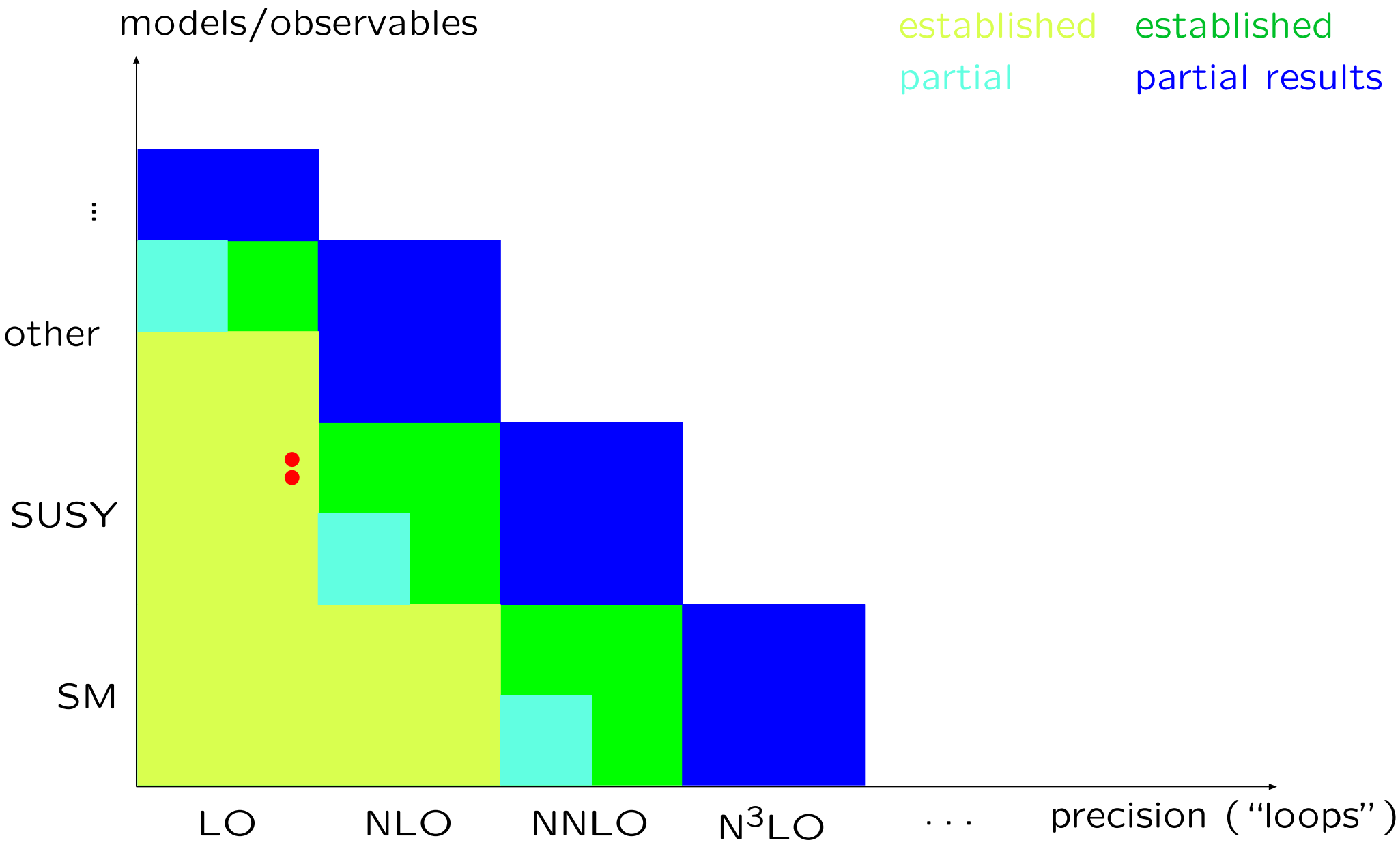
- top Yukawa coupling: Y_t
  → connection to Higgs sector ⇒ two talks :-)

Few QCD: ⇒ one talk :-)

Most important top observables:

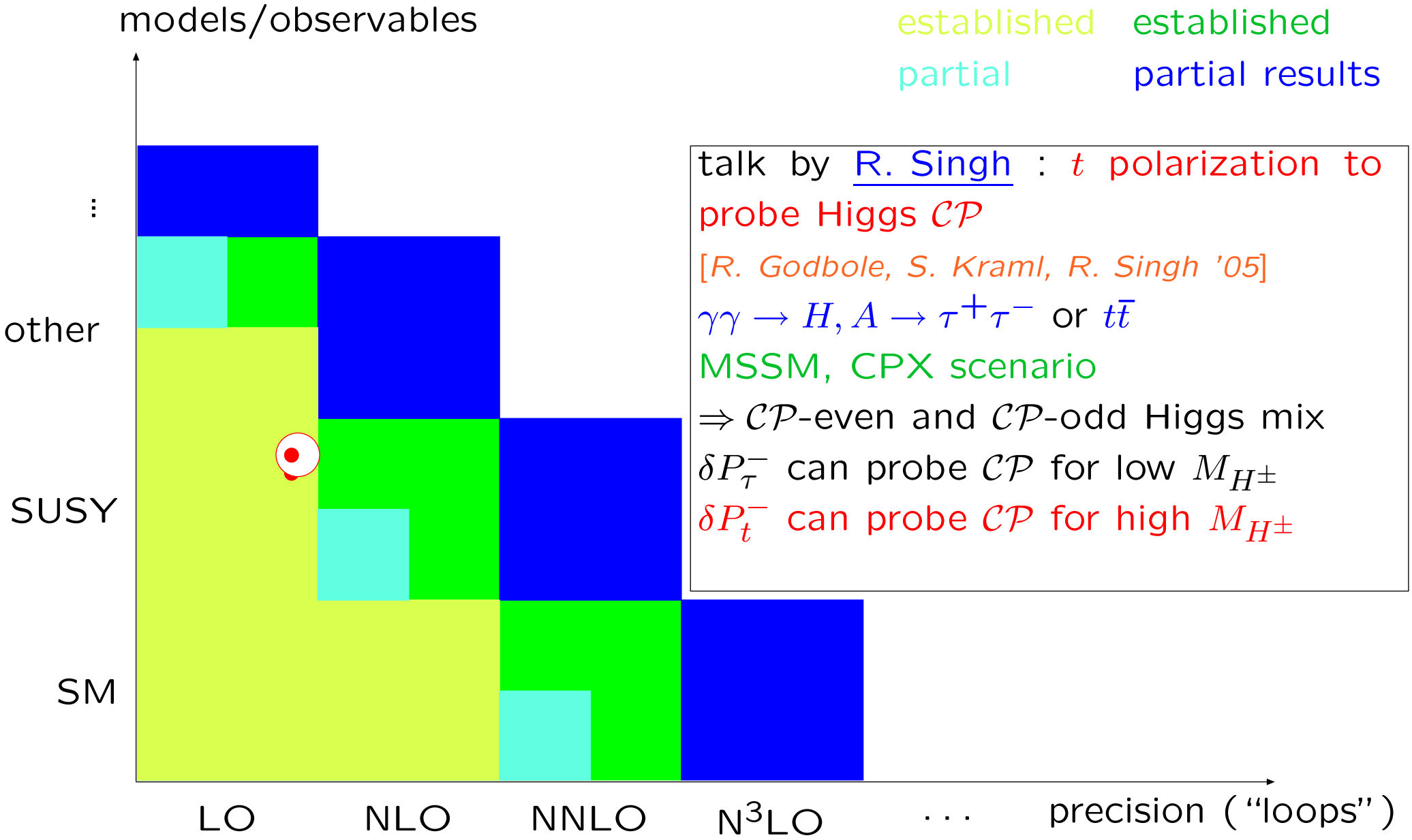
- top quark mass: m_t (most important input parameter)
  measurement from production peak position
  experiment: ok – theory: not yet ($m_t^{\text{shortdistance}} \longrightarrow m_t^{\overline{\text{MS}}}$)
  ⇒ no news here :-(
- top quark width: Γ_t ⇒ no news here :-(
- top quark production cross section: σ_{tt}
  precise prediction needed for m_t
  new physics contributions? experiment: ok – theory: nearly...?
  ⇒ no news here :-(
- top quark branching ratios
  → anomalous couplings → $\mathcal{O}(\%)$ at ILC, polarization crucial
  ToDo: fully exploit polarization ⇒ one talk :-)
  vary more than 1 coupling
  QCD corrections to SM
  tools for $e^+e^- \to 6f,\ 8f$ at $\mathcal{O}(\alpha_s)$ ($6f$: Lusifer)
- top Yukawa coupling: Y_t
  → connection to Higgs sector ⇒ two talks :-)

top/Higgs: **contributions in Bangalore**



top/Higgs: **contributions in Bangalore**

experiment	theory
established	established
partial	partial results



talk by R. Singh : t polarization to probe Higgs $\mathcal{CP}$

[*R. Godbole, S. Kraml, R. Singh '05*]

$\gamma\gamma \to H, A \to \tau^+\tau^-$ or $t\bar{t}$

MSSM, CPX scenario

$\Rightarrow \mathcal{CP}$-even and $\mathcal{CP}$-odd Higgs mix

δP_τ^- can probe $\mathcal{CP}$ for low $M_{H^\pm}$

δP_t^- can probe $\mathcal{CP}$ for high $M_{H^\pm}$

top/Higgs: **contributions in Bangalore**

experiment	theory
established	established
partial	partial results

models/observables

⋮

other

SUSY

SM

talk by R. Singh : t polarization to probe Higgs $\mathcal{CP}$

…odbole, S. Kraml, R. Singh '05]

$H, A \to \tau^+\tau^-$ or $t\bar{t}$

M, CPX scenario

-even and $\mathcal{CP}$-odd Higgs mix

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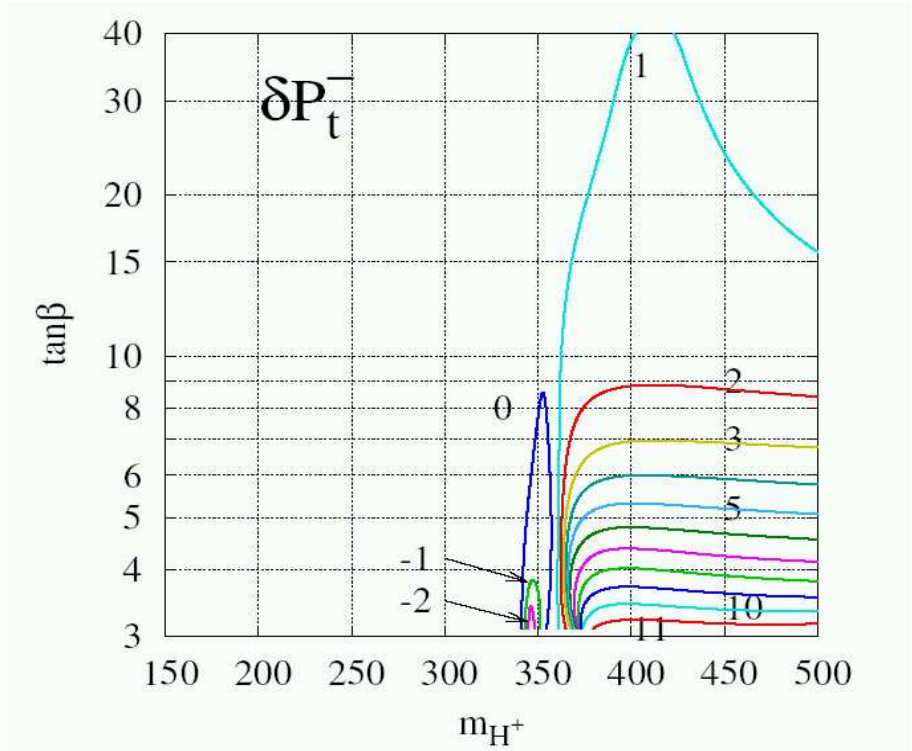
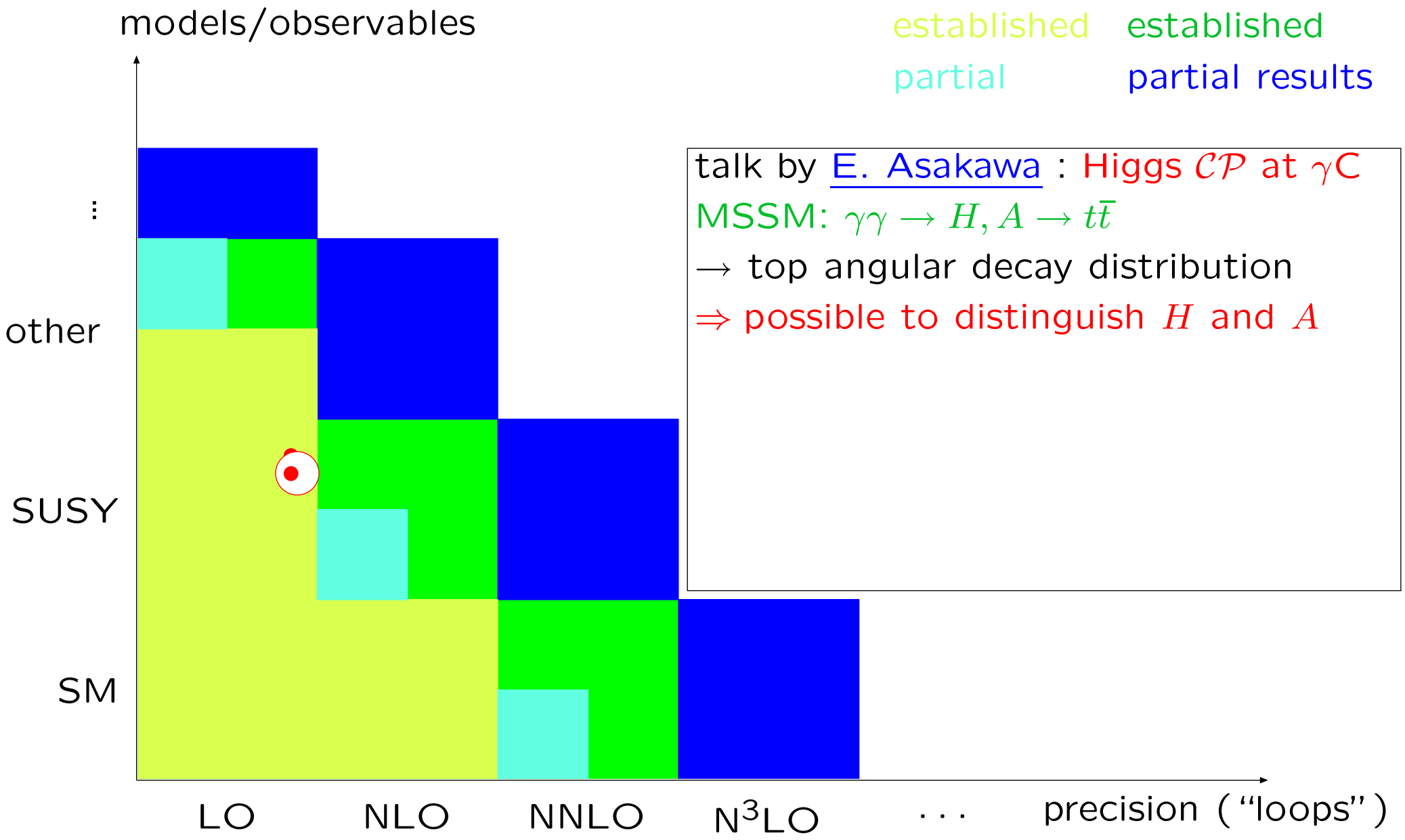


LO NLO NNLO N^3LO ··· precision ("loops")

top/Higgs: **contributions in Bangalore**



4. LoopVerein

Why is it necessary to include all those loop corrections?

4. LoopVerein

Why is it necessary to include all those loop corrections?

Experimental situation:

ILC $\rightarrow$ provide high accuracy measurements !

Theory situation:

measured observables have to be compared with theoretical predictions
(of your favorite model)

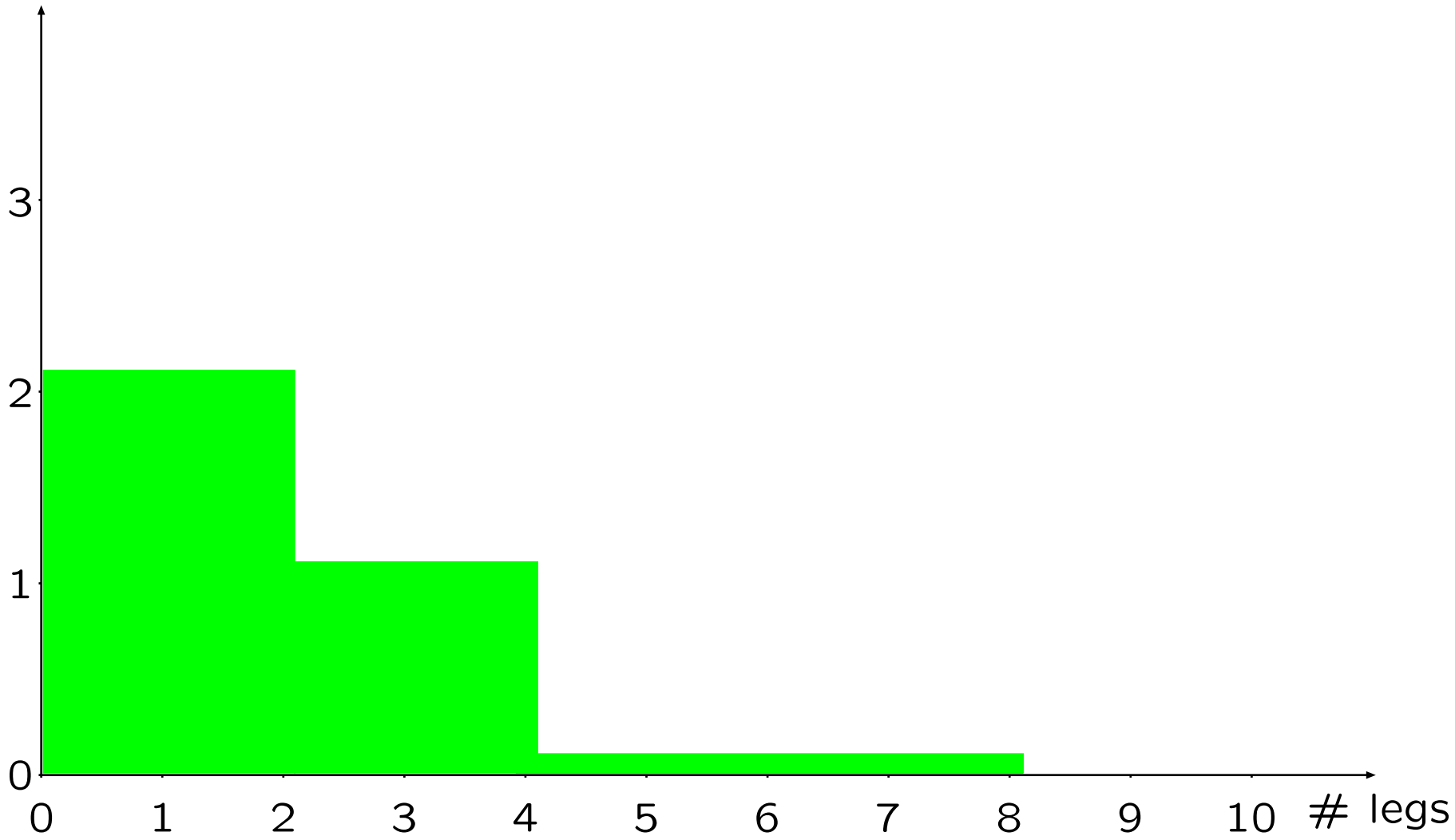
High precision of data can only fully be exploited if it is matched with theoretical calculations at the same level of accuracy

We could not make full use of the great ILC precision
without corresponding loop calculations

We have to work **NOW** to achieve necessary accuracy in time

Theory/Loop calculations should be viewed as an essential part of the ILC Physics program

Technique well established

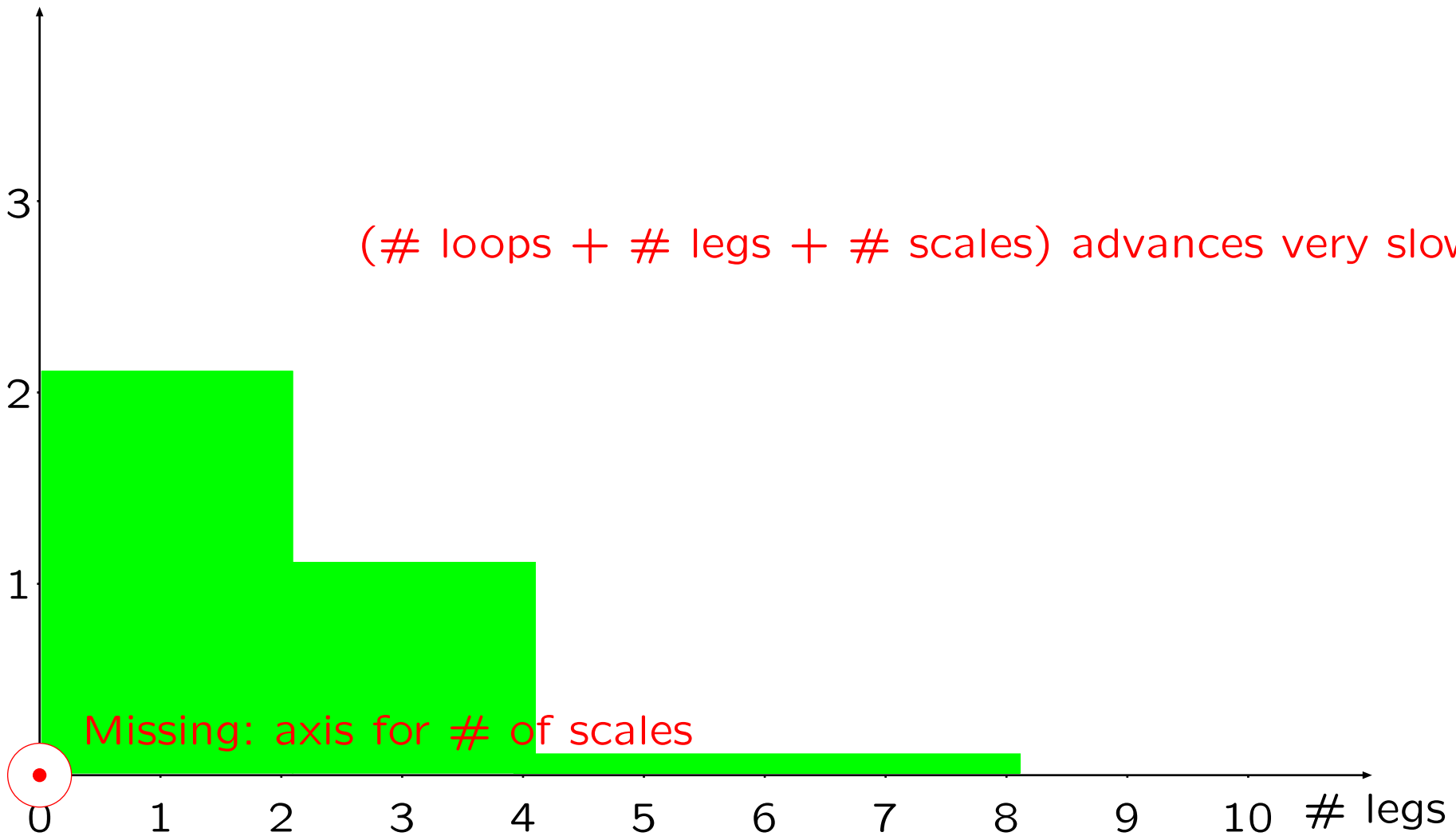


vacuum graphs self-energies $2 \to 2$, $1 \to 3$ $ee \to 4f$ $ee \to 6f$

$\Delta\rho$ Δr, masses Bhabha $ee \to 4f + \gamma$

$1 \to 2$, $\sin^2\theta_{\text{eff}}$ $2 \to 3$

Technique well established



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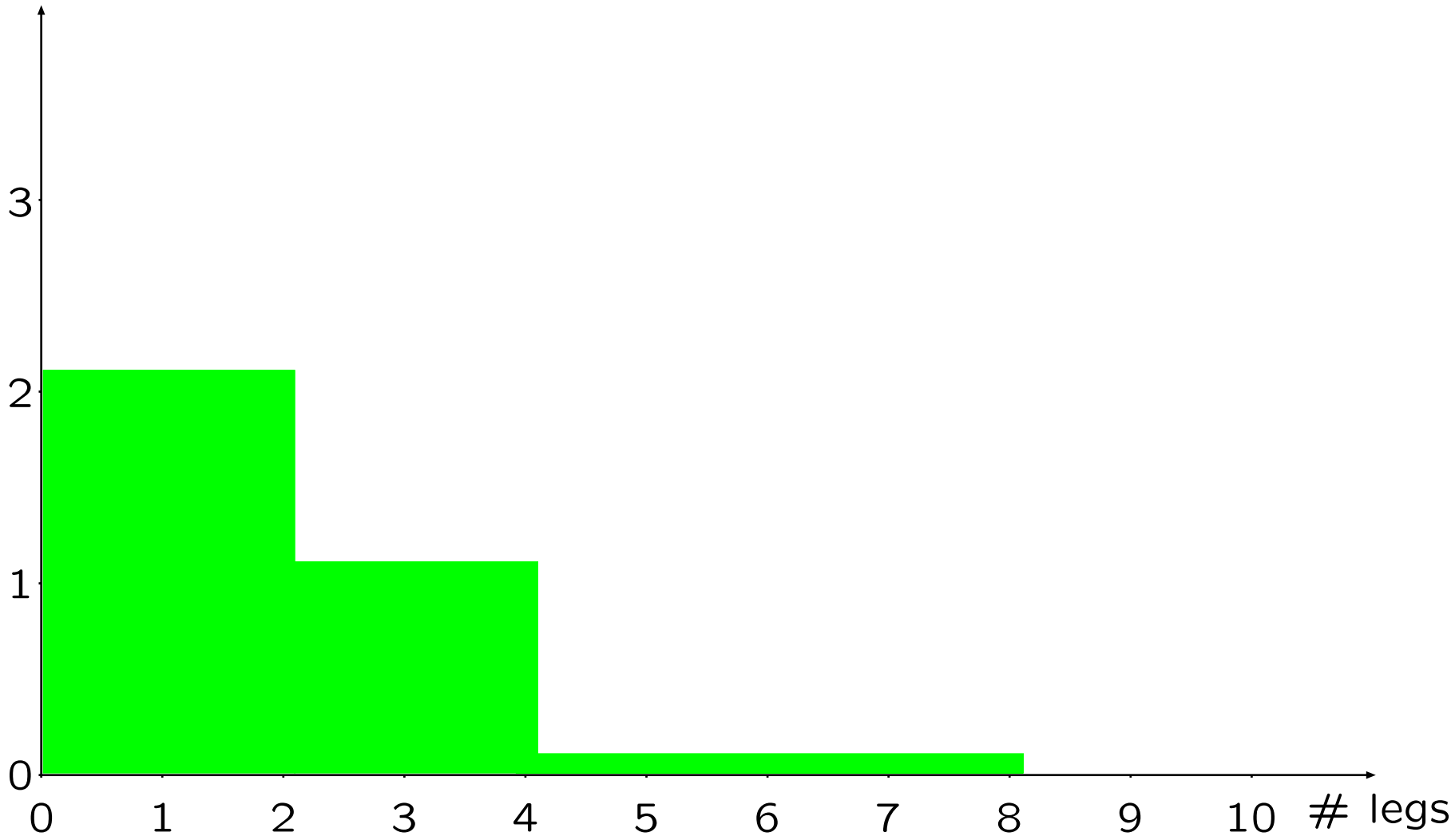
Technique well established



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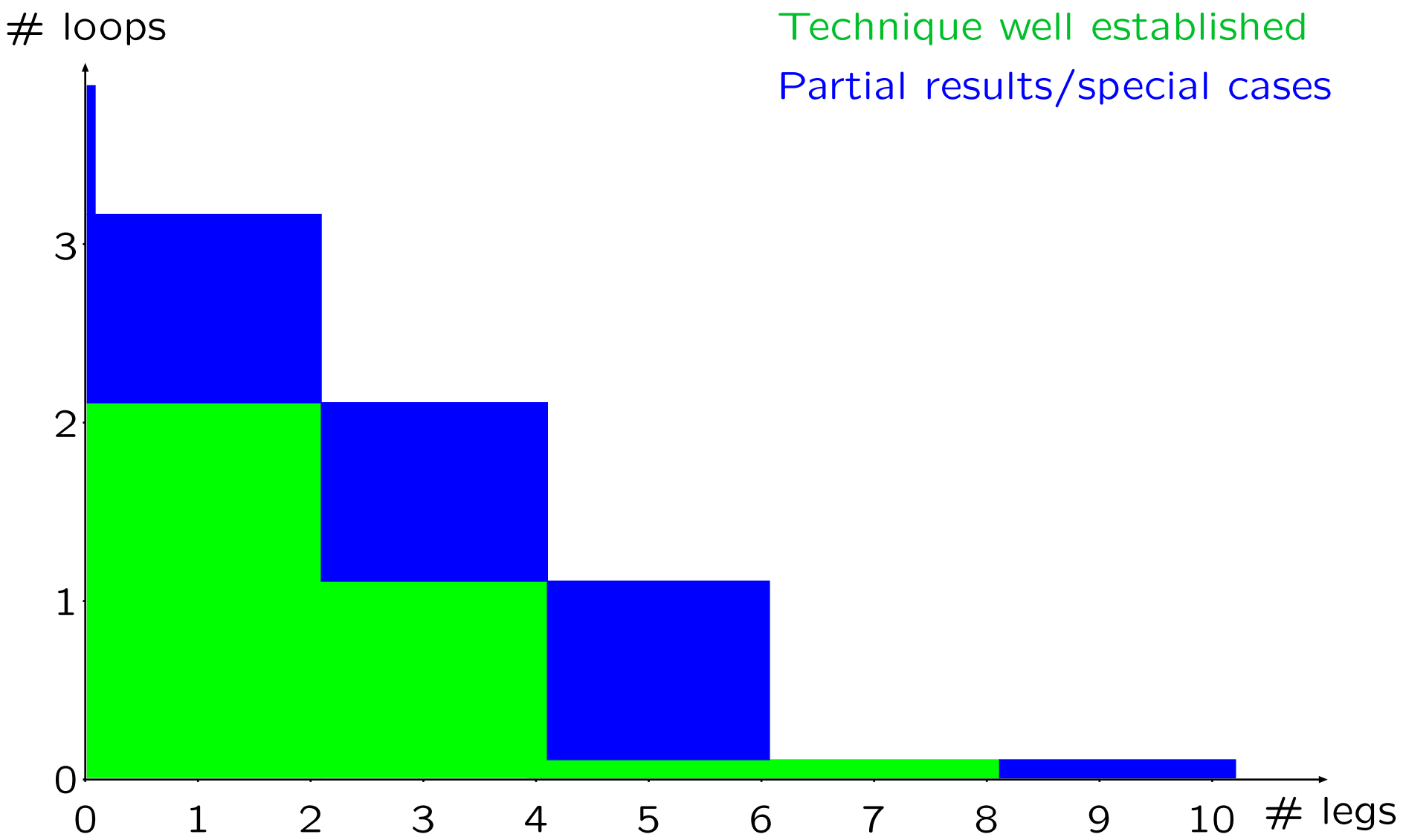
$1 \to 2$, $\sin^2\theta_{\text{eff}}$ $2 \to 3$


loops
Technique well established
Partial results/special cases
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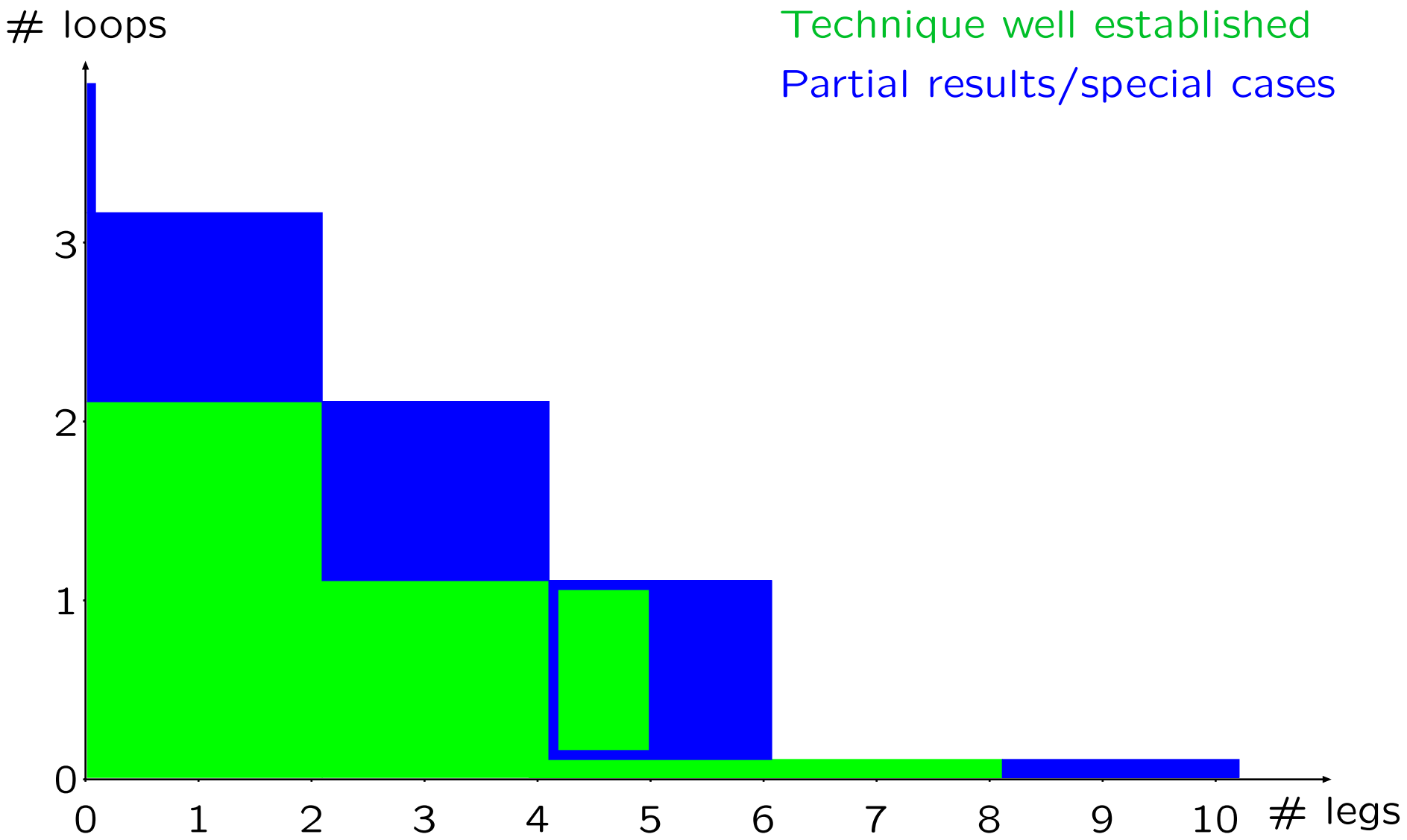
legs
vacuum graphs
self-energies $2 \to 2$, $1 \to 3$
$ee \to 4f$
$ee \to 6f$
$\Delta\rho$
Δr, masses
Bhabha
$ee \to 4f + \gamma$
$1 \to 2$, $\sin^2\theta_{\text{eff}}$
$2 \to 3$


loops
Technique well established
Partial results/special cases
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legs
vacuum graphs
self-energies
$2 \to 2$, $1 \to 3$
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Bhabha
$ee \to 4f + \gamma$
$1 \to 2$, $\sin^2\theta_{\text{eff}}$
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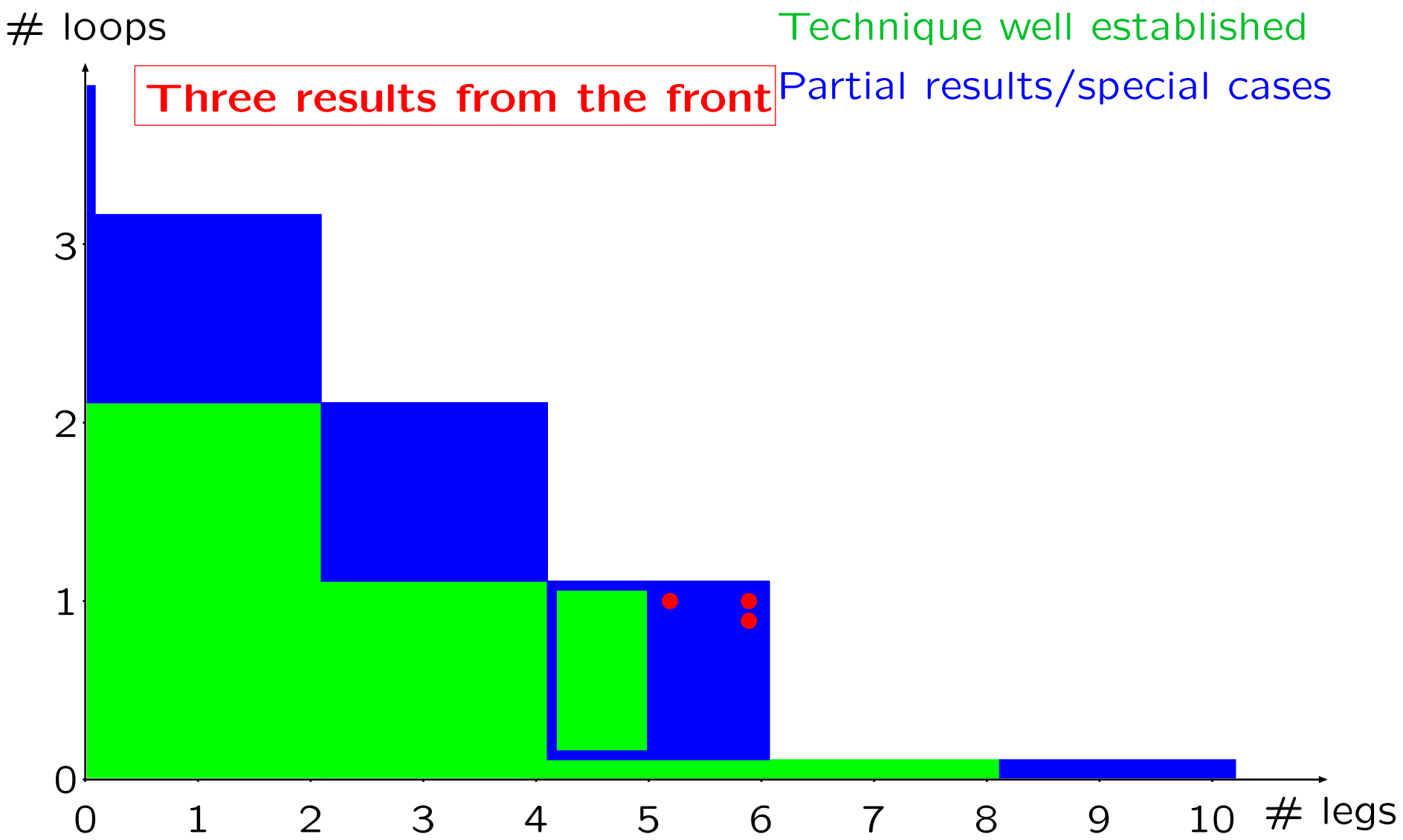
loops
Technique well established
Partial results/special cases
Three results from the front
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legs
vacuum graphs
self-energies $2 \to 2$, $1 \to 3$
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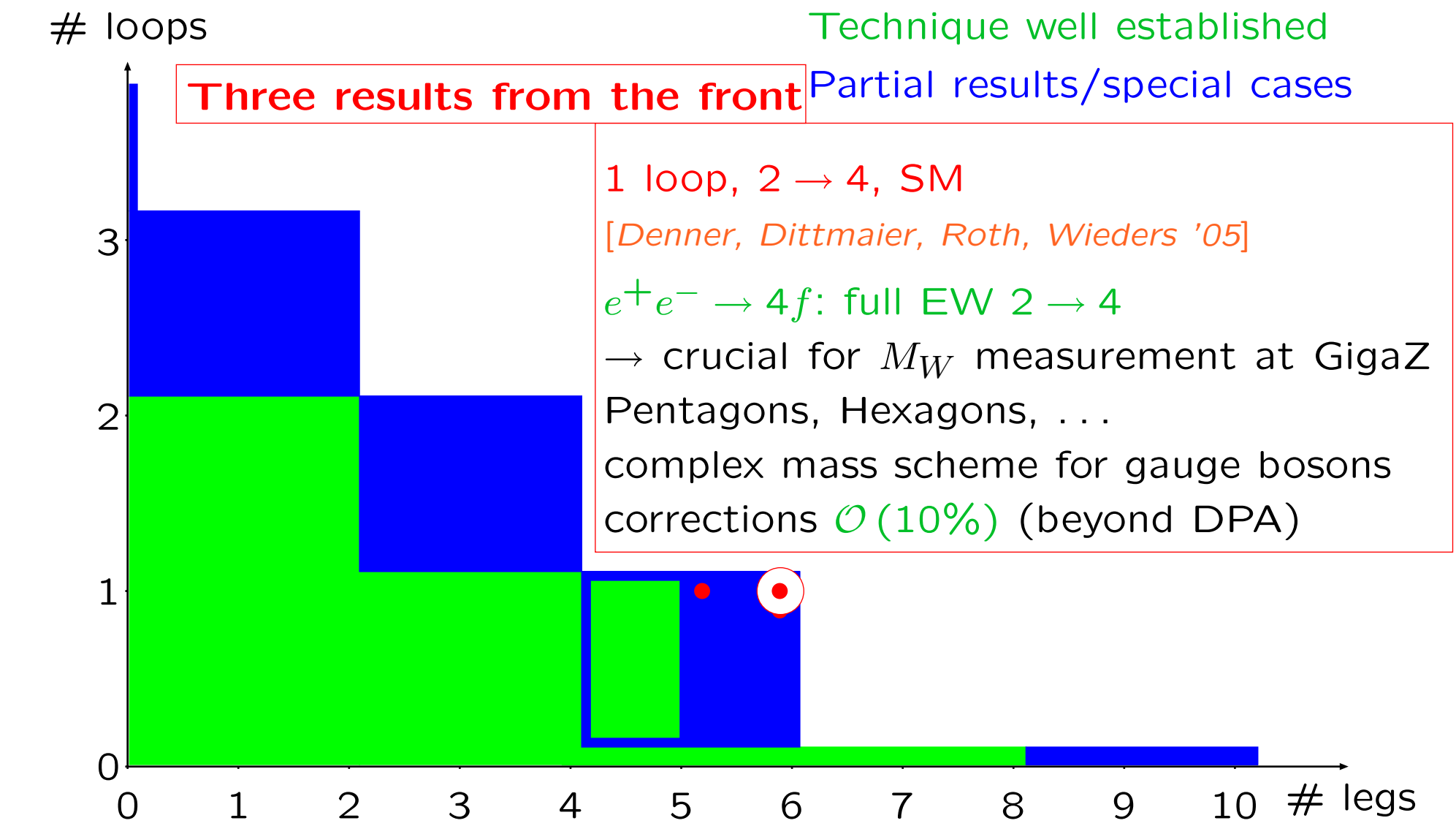
loops
Technique well established
Partial results/special cases
Three results from the front
1 loop, $2 \to 4$, SM
[Denner, Dittmaier, Roth, Wieders '05]
$e^+e^- \to 4f$: full EW $2 \to 4$
$\to$ crucial for M_W measurement at GigaZ
Pentagons, Hexagons, . . .
complex mass scheme for gauge bosons
corrections $\mathcal{O}(10\%)$ (beyond DPA)
0
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0 1 2 3 4 5 6 7 8 9 10
legs
vacuum graphs
self-energies $2 \to 2$, $1 \to 3$
$ee \to 4f$
$ee \to 6f$
$\Delta\rho$
Δr, masses
Bhabha
$ee \to 4f + \gamma$
$1 \to 2$, $\sin^2\theta_{\text{eff}}$
$2 \to 3$

loops

Technique well established

Partial results/special cases

Two results from the front

1 loop, $2 \to 4$, SM

[*Denner, Dittmaier, Roth, Wieders '05*]

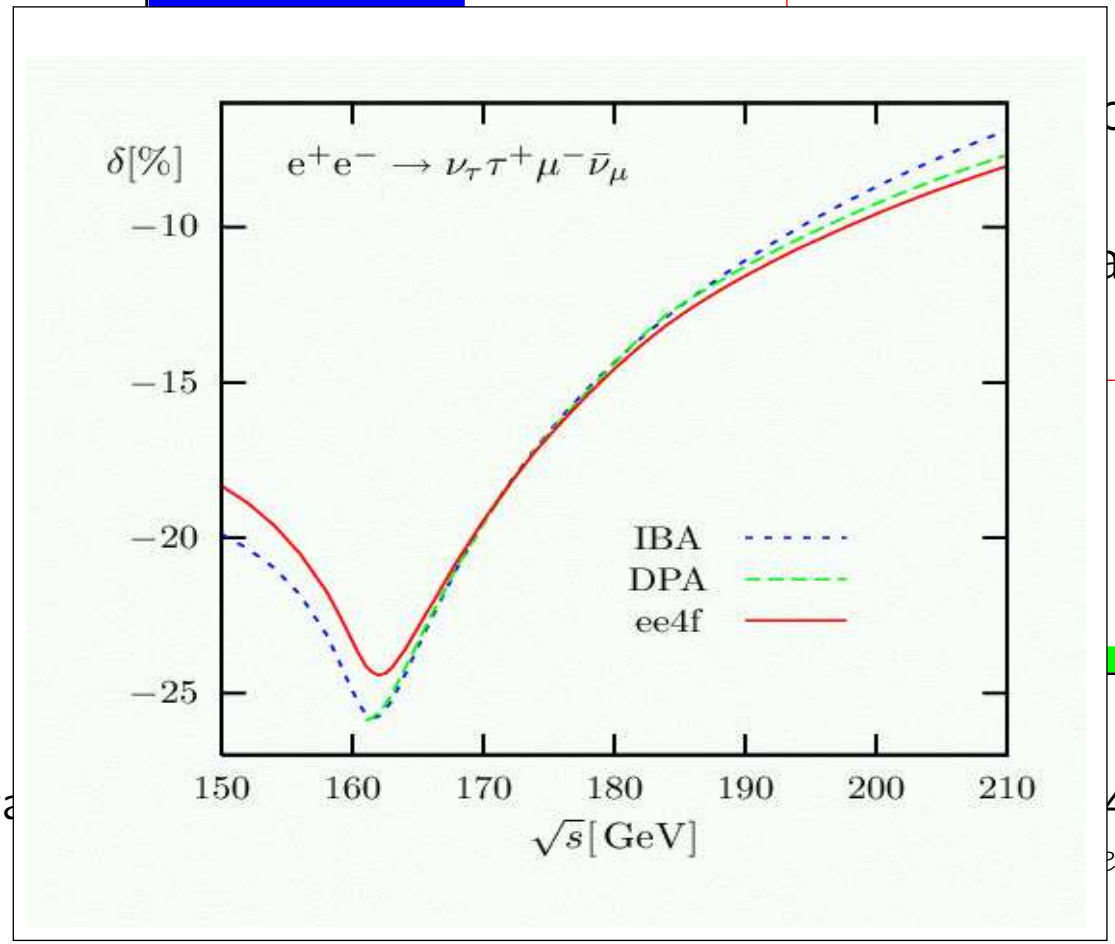
full EW $2 \to 4$

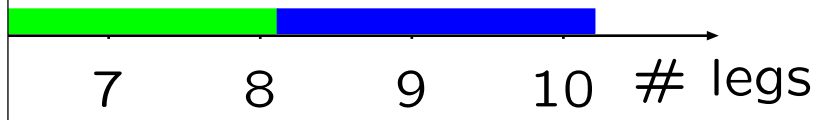
or M_W measurement at GigaZ

Hexagons, . . .

ass scheme for gauge bosons

$\mathcal{O}(10\%)$ (beyond DPA)





va

$4f$ $ee \to 6f$

$ee \to 4f + \gamma$

loops

Technique well established

Partial results/special cases

Three results from the front

1 loop, $2 \to 4$, SM

[*GRACE '05*]

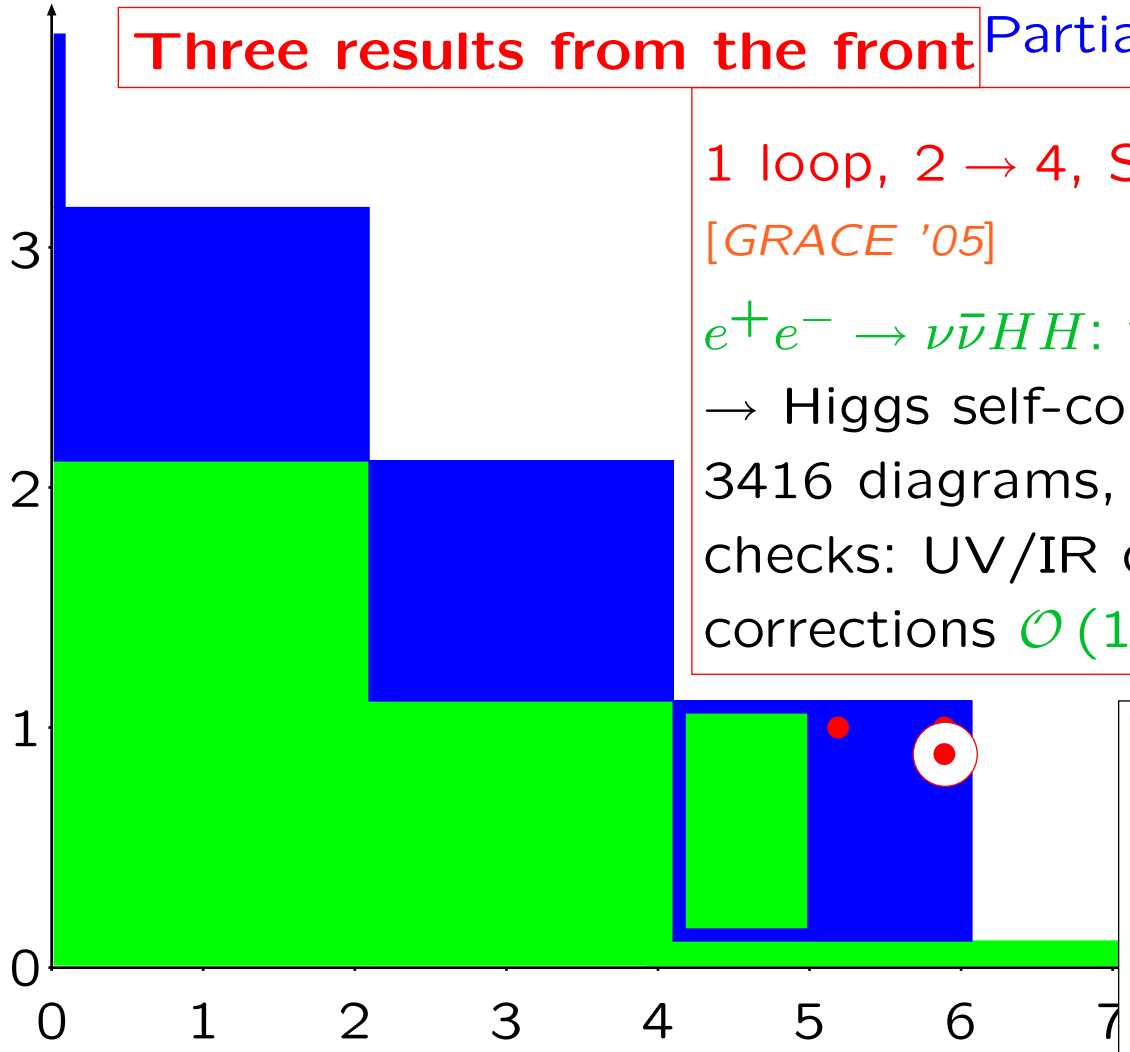
$e^+e^- \to \nu\bar{\nu}HH$: first full EW $2 \to 4$

$\to$ Higgs self-coupling measurement

3416 diagrams, 218 Pent. 74 Hex.

checks: UV/IR div., gauge par. independ.

corrections $\mathcal{O}(10\%)$ (top-loop in HHH)



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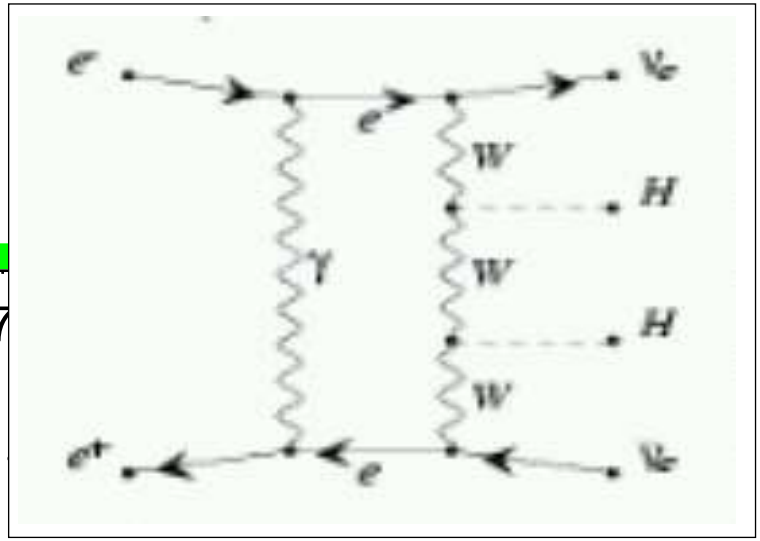
$\Delta\rho$ Δr, masses Bhabha $ee \to$

$1 \to 2$, $\sin^2\theta_{\text{eff}}$ $2 \to 3$



loops

Technique well established

Partial results/special cases

Two results from the front

1 loop, $2 \to 4$, SM

[*GRACE '05*]

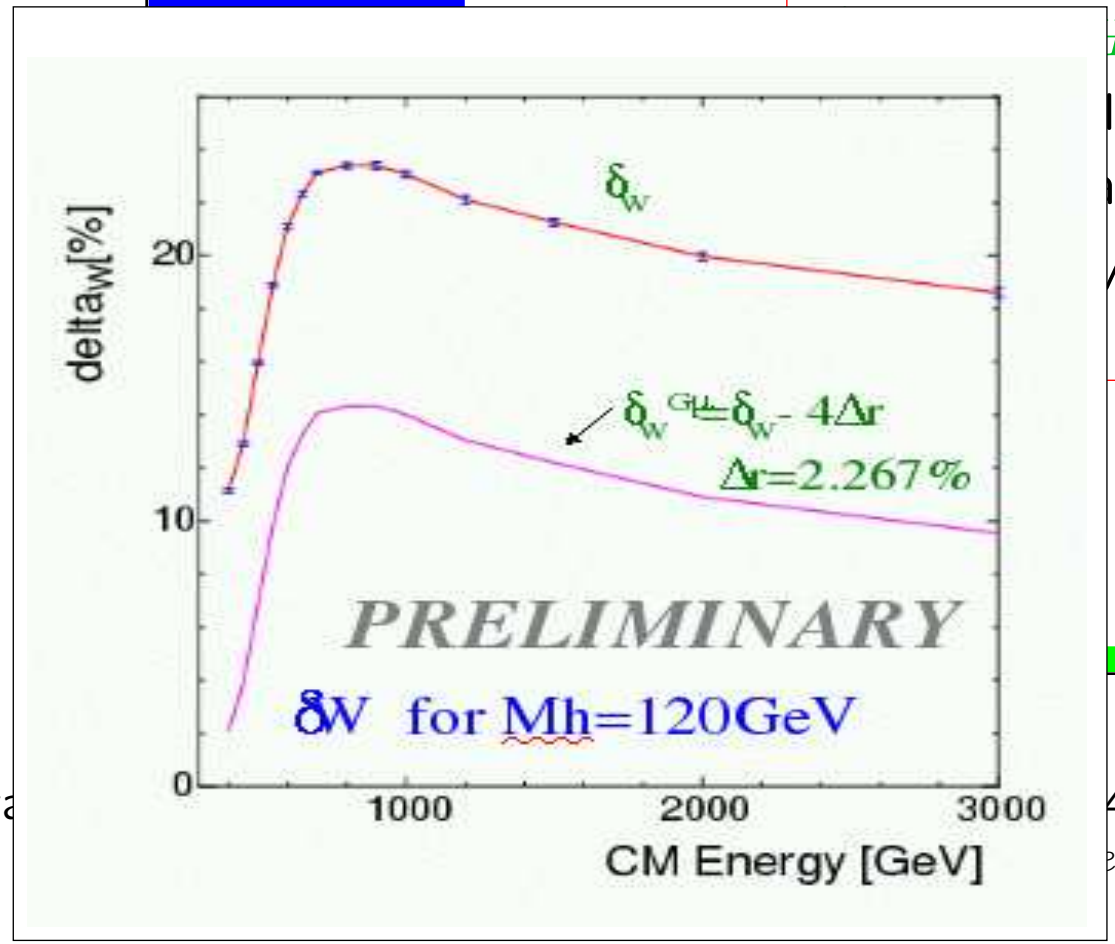
HH: first full EW $2 \to 4$

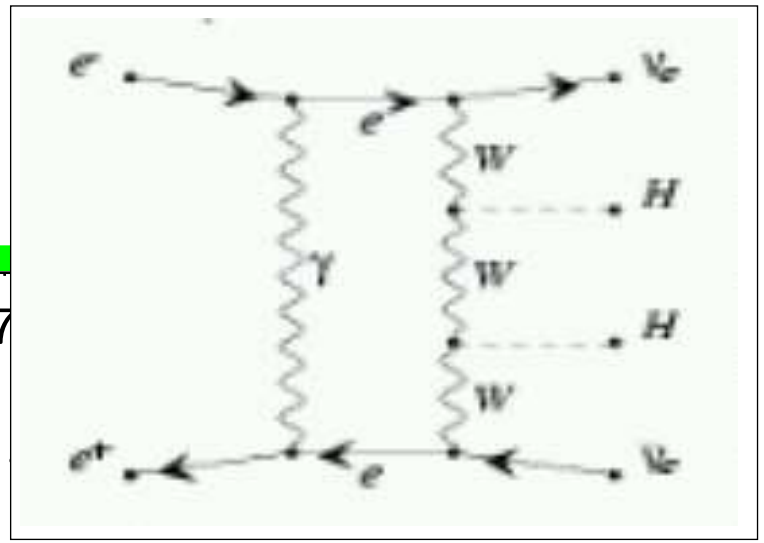
lf-coupling measurement

ms, 218 Pent. 74 Hex.

/IR div., gauge par. independ.

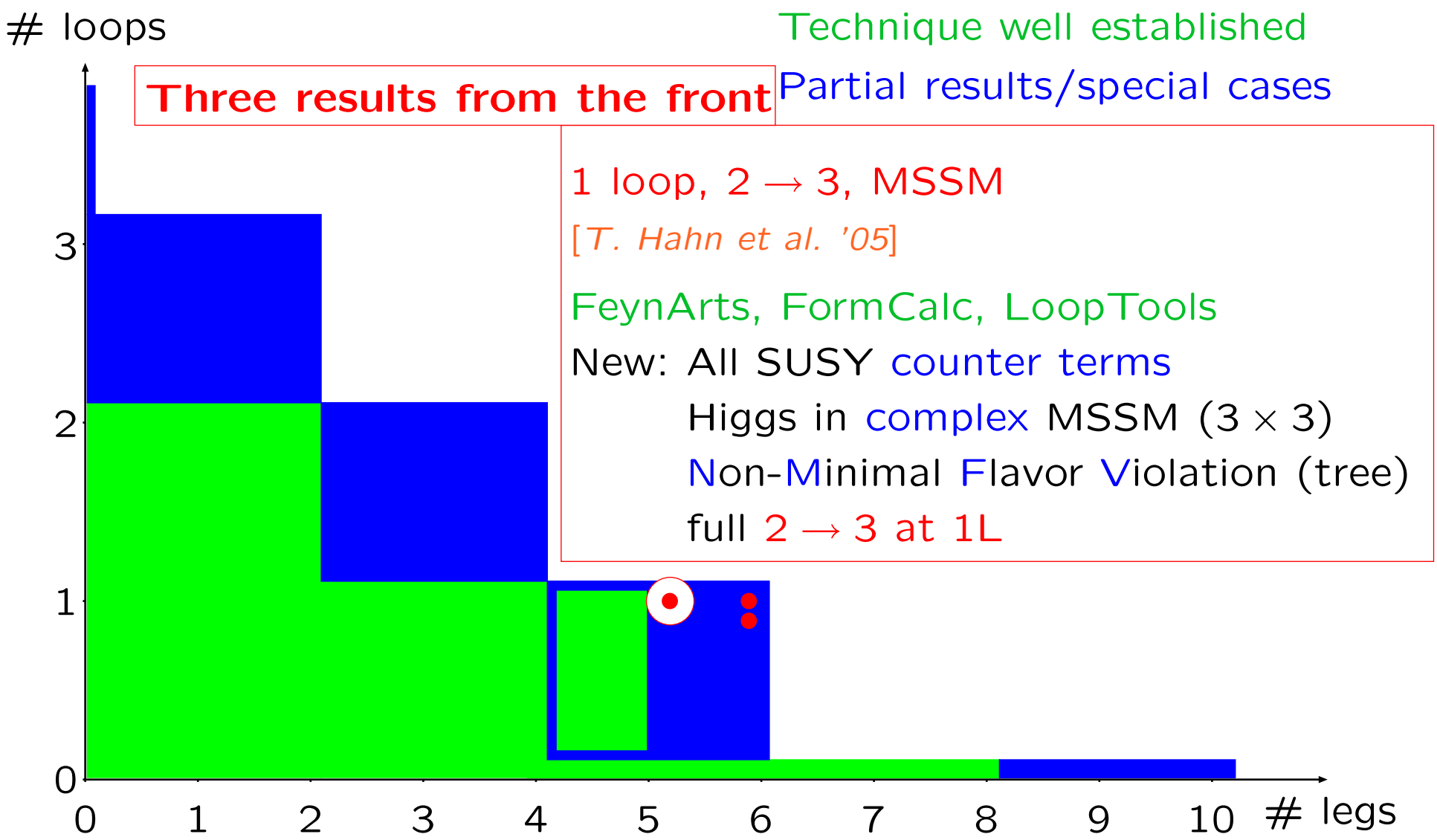
$\mathcal{O}(10\%)$ (top-loop in HHH)





$4f$

$ee \to$


loops
Technique well established
Partial results/special cases
Three results from the front
1 loop, 2 → 3, MSSM
[T. Hahn et al. '05]
FeynArts, FormCalc, LoopTools
New: All SUSY counter terms
Higgs in complex MSSM (3 × 3)
Non-Minimal Flavor Violation (tree)
full 2 → 3 at 1L
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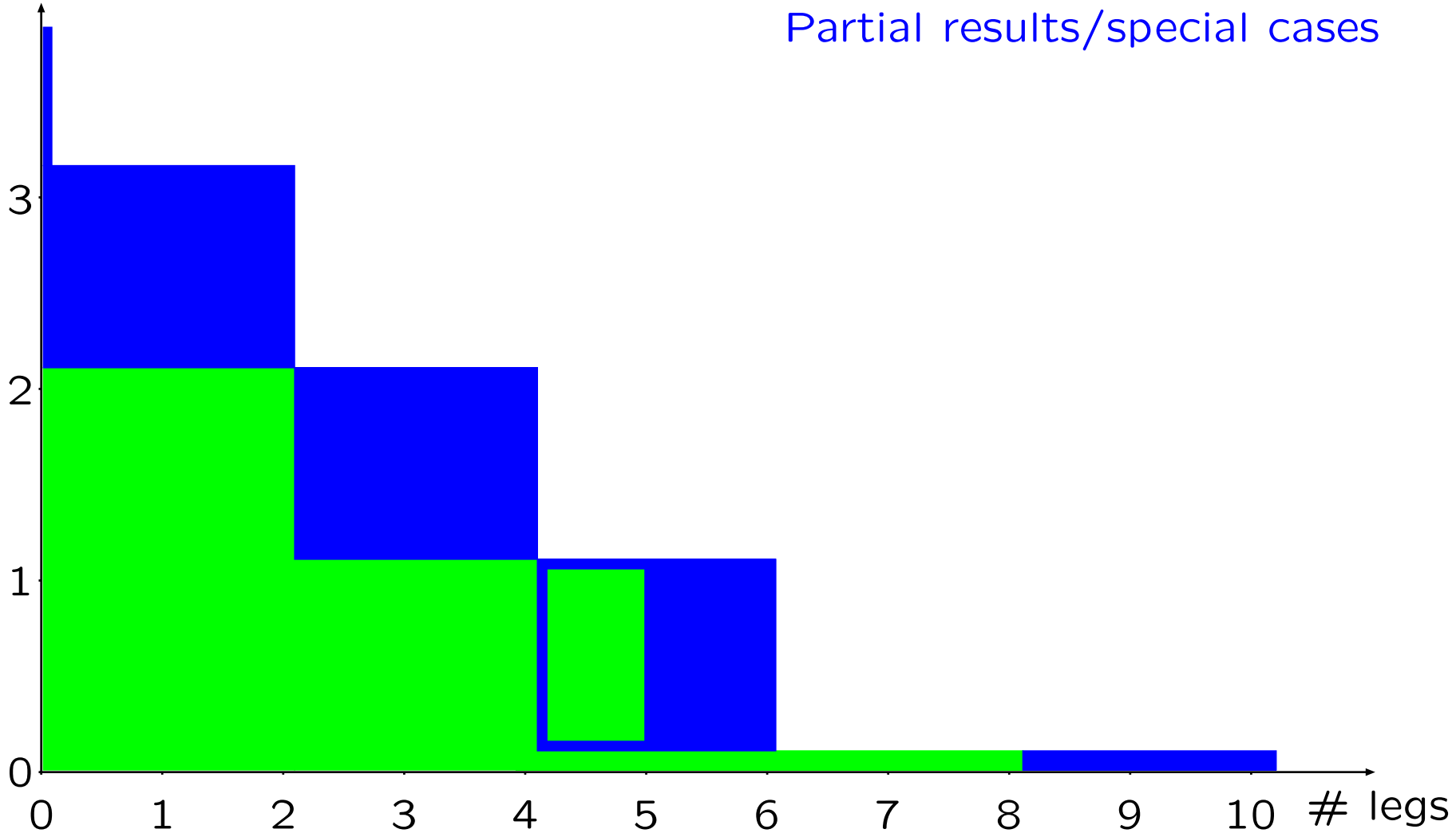
legs
vacuum graphs
self-energies
2 → 2, 1 → 3
ee → 4f
ee → 6f
Δρ
Δr, masses
Bhabha
ee → 4f + γ
1 → 2, sin² θeff
2 → 3

Technique well established

Partial results/special cases



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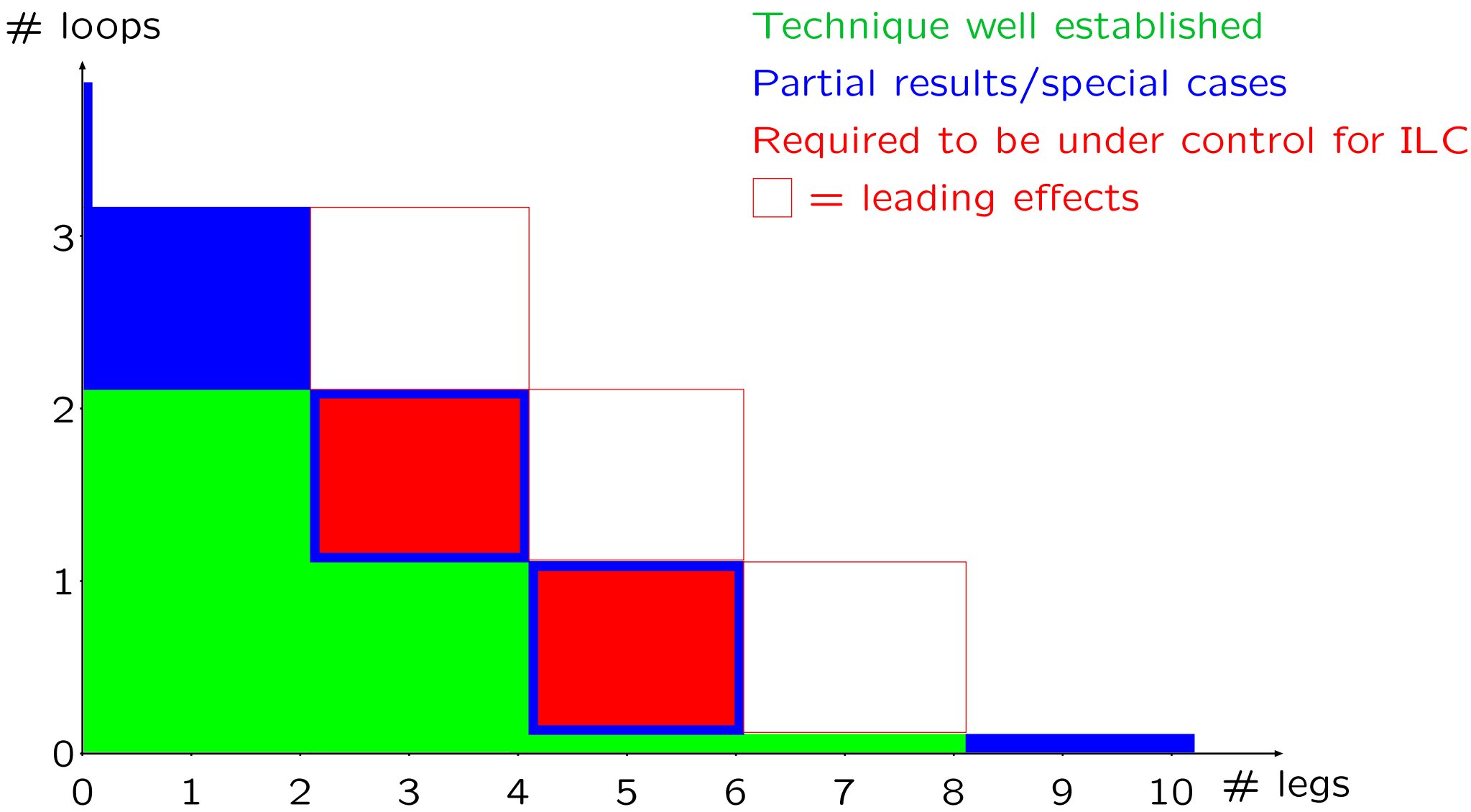
$1 \to 2$, $\sin^2\theta_{\text{eff}}$ $2 \to 3$


loops
Technique well established
Partial results/special cases
Required to be under control for ILC
= leading effects
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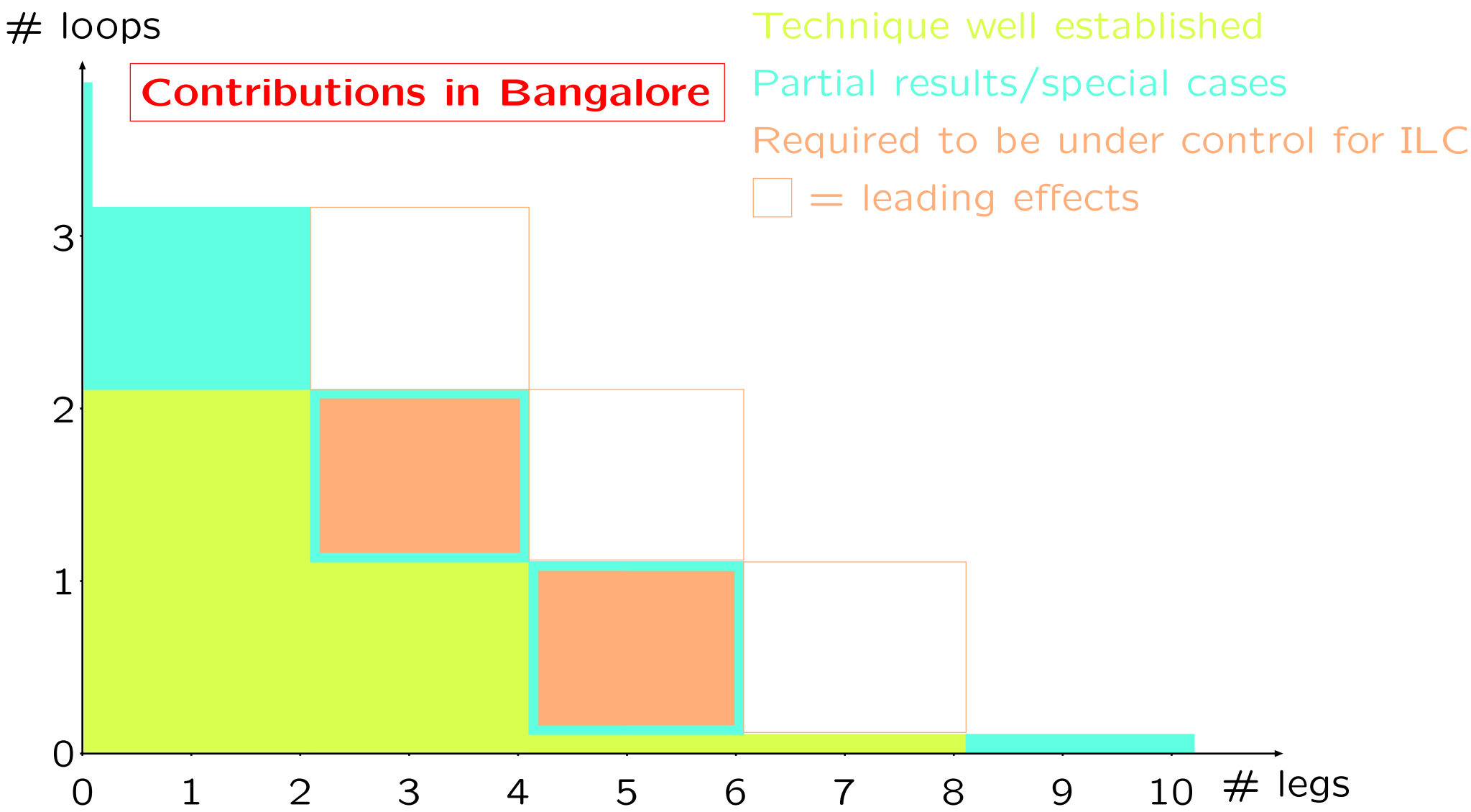
loops
Contributions in Bangalore
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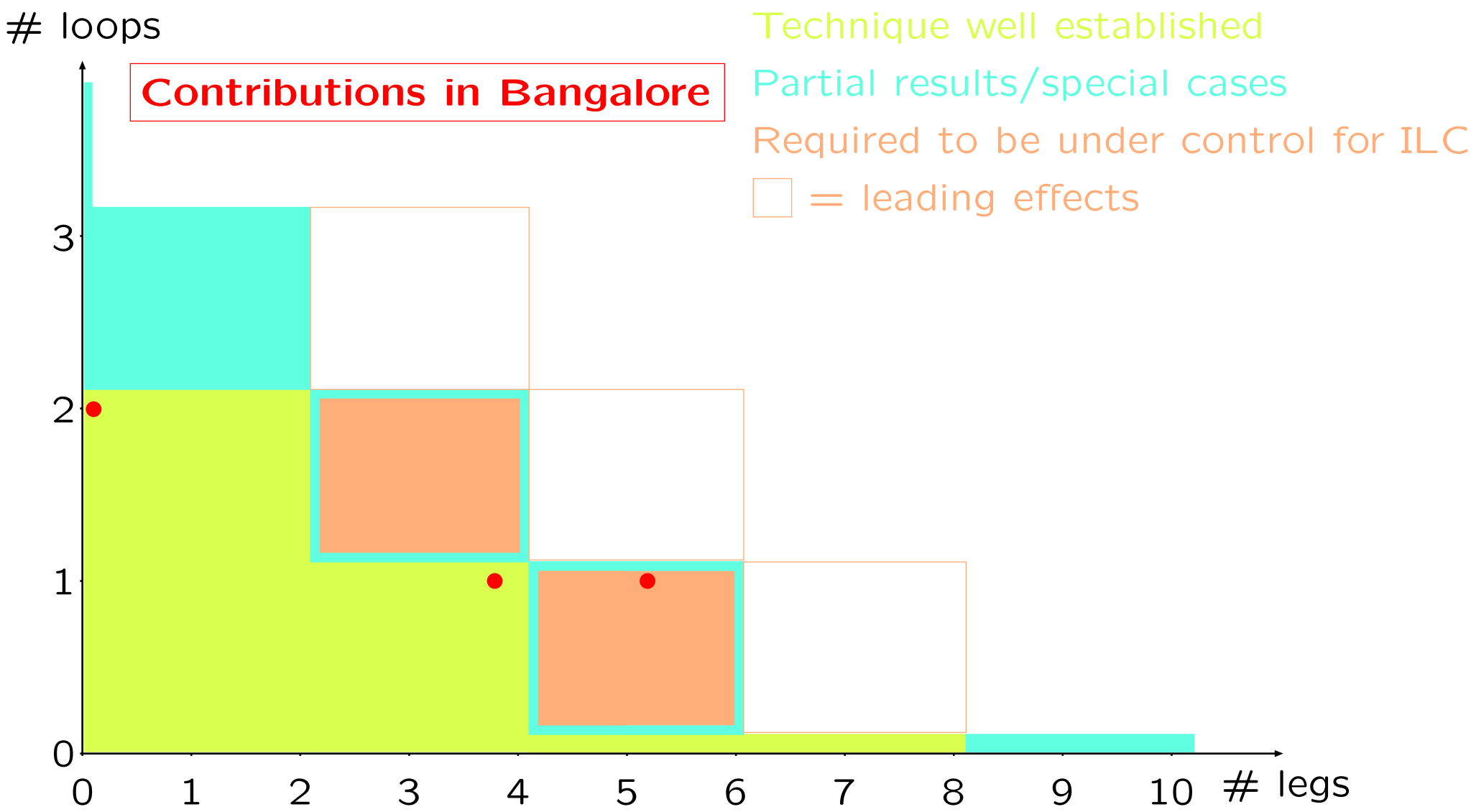
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Contributions in Bangalore

talk by Y. Yasui : 1 loop, $2 \to 2$, MSSM

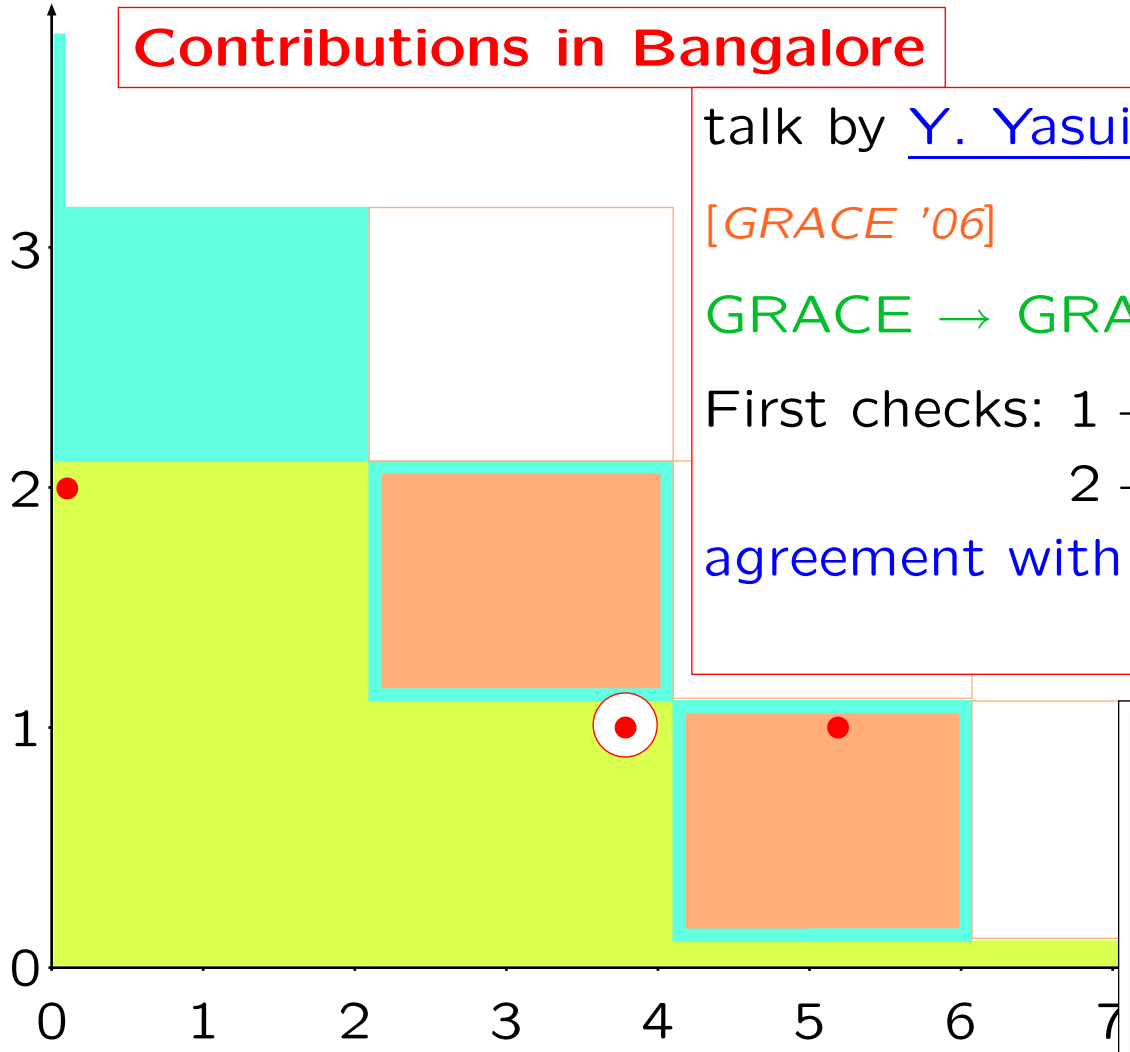
[*GRACE '06*]

GRACE $\to$ GRACE/SUSY

First checks: $1 \to 2$ (~ 10 procs)

$2 \to 2$: $e^+e^- \to \tilde{\chi}_i^\pm \tilde{\chi}_j^\pm$

agreement with older results



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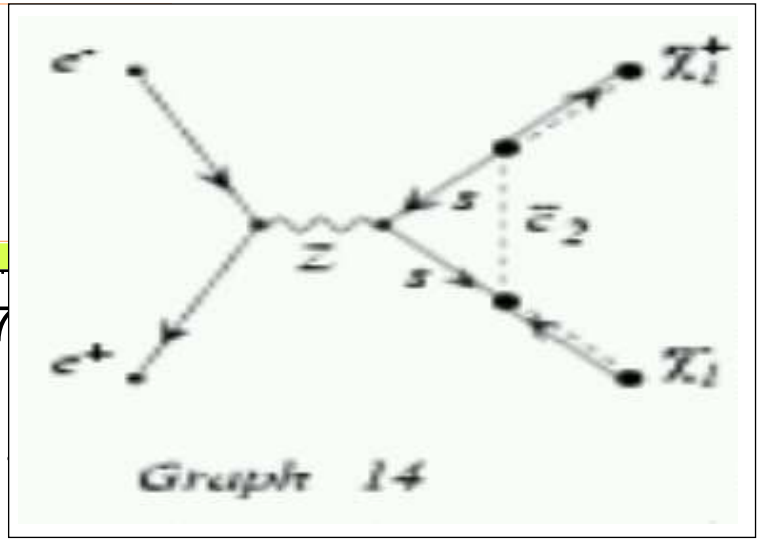


Contributions in Bangalore

talk by E. Berger : 1 loop: $2 \to 3$, SM

[*Balazs, Berger, Nadolski, Qiu, Yuan '06*]

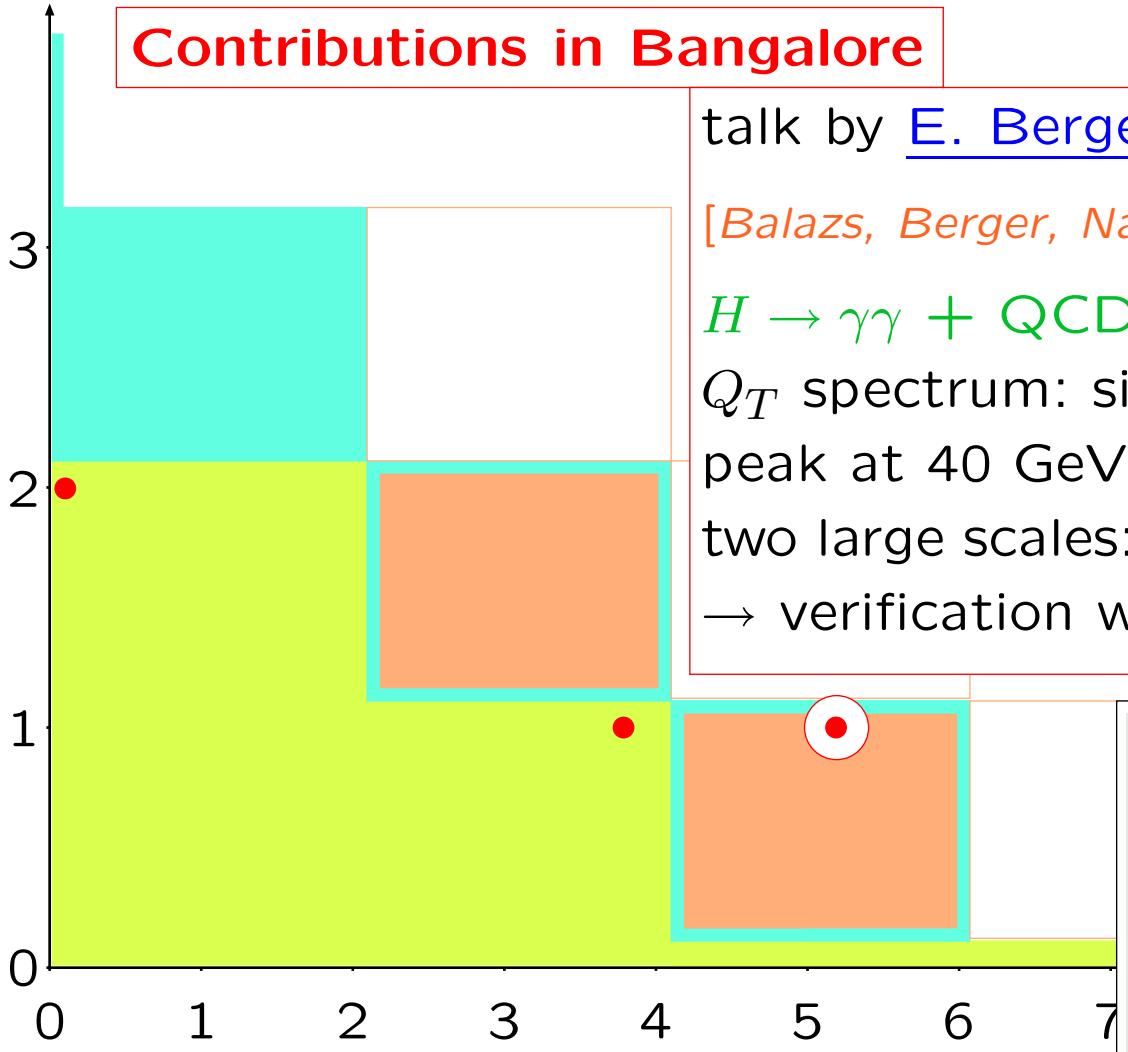
$H \to \gamma\gamma$ + QCD background

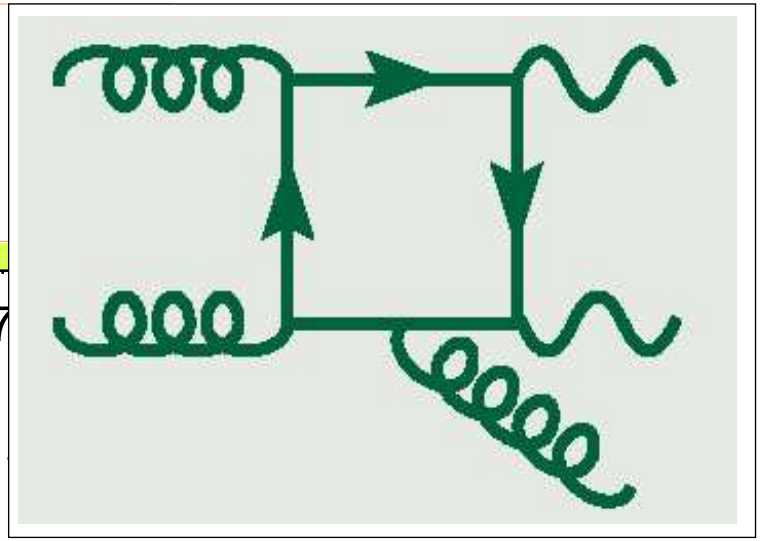
Q_T spectrum: signal vs. bgr:

peak at 40 GeV vs. 27 GeV

two large scales: $m_{\gamma\gamma}$ and Q_T $\Rightarrow$ LL resum.

$\to$ verification with CDF data





loops

Contributions in Bangalore

talk by S.H. : 2L vacuum, MSSM + Ren.

[S.H., W. Hollik, H. Rzehak, G. Weiglein '06]

2L top/stop corr. to M_h: $\mathcal{O}(\alpha_s\alpha_t)$ complex

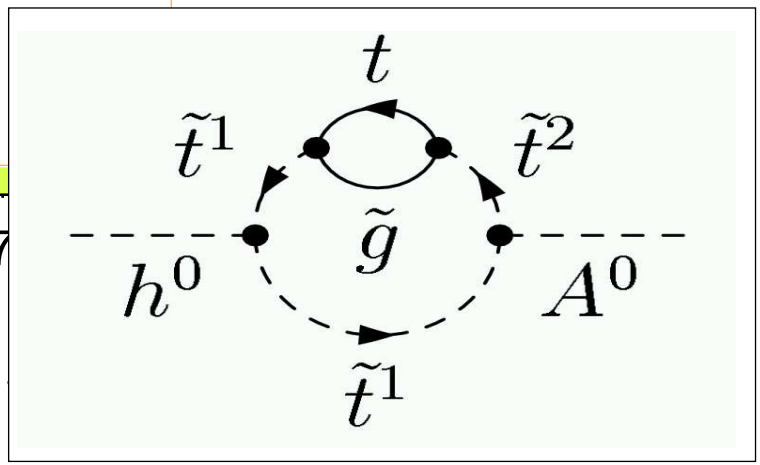
$\rightarrow$ renormalization at 2L/1L level

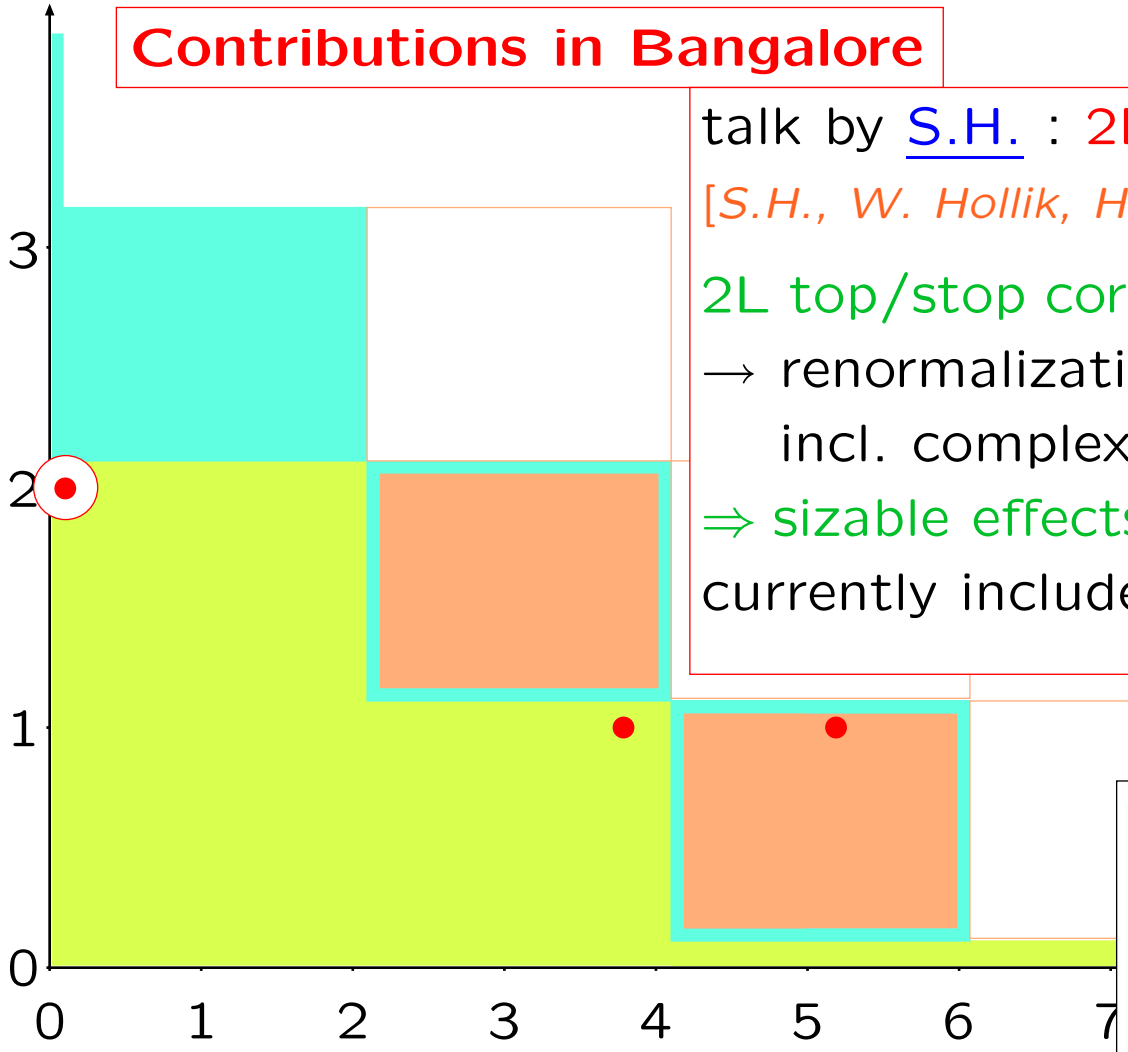
incl. complex phases

$\Rightarrow$ sizable effects for M_h

currently included in FeynHiggs

LC: $\delta M_h^{\rm exp} = 0.05$ GeV





vacuum graphs self-energies $2 \rightarrow 2$, $1 \rightarrow 3$ $ee \rightarrow 4f$

$\Delta\rho$ Δr, masses Bhabha $ee \rightarrow$

$1 \rightarrow 2$, $\sin^2\theta_{\rm eff}$ $2 \rightarrow 3$

loops

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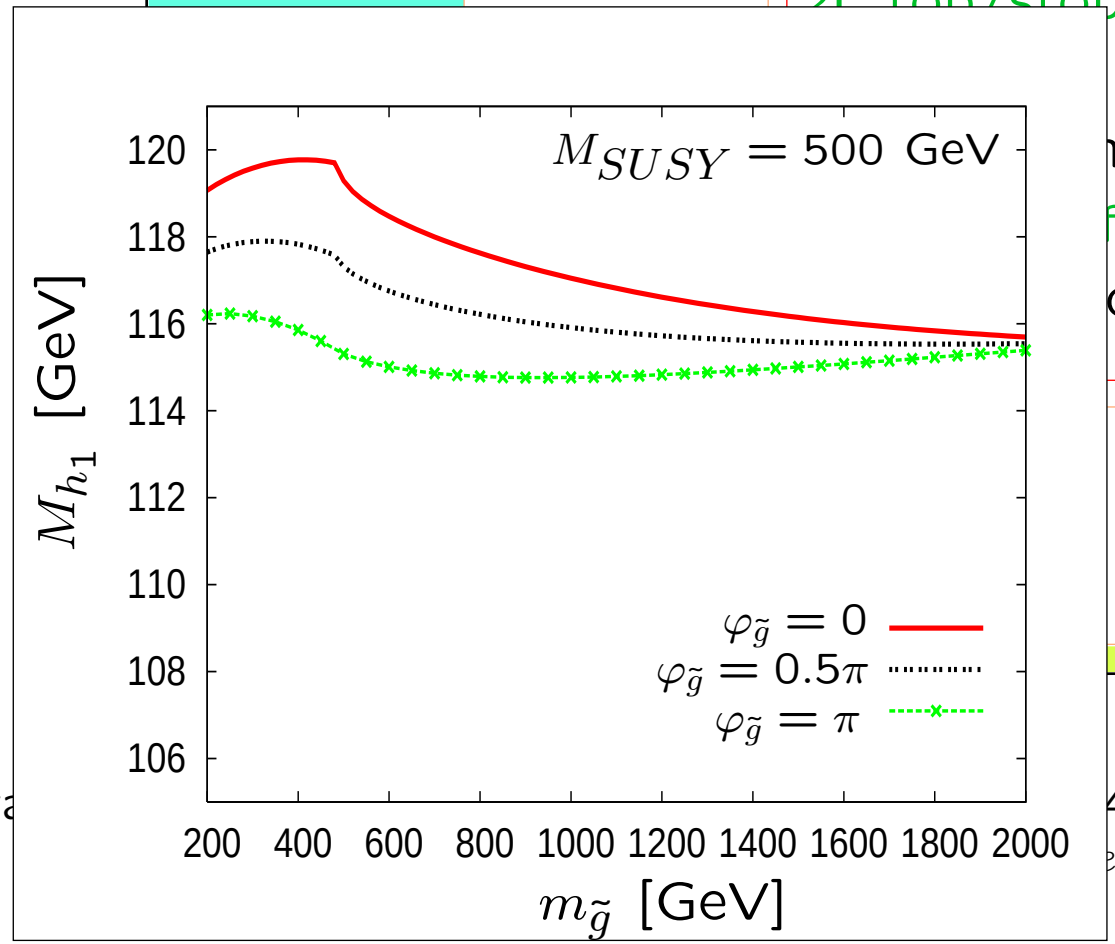
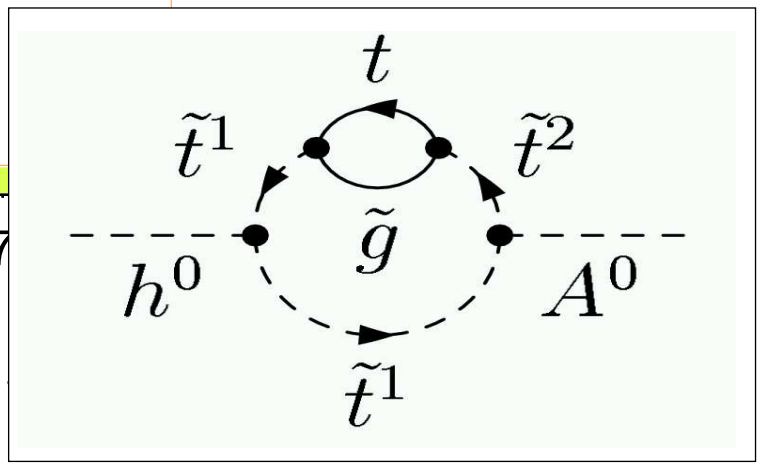
ffects for M_h

cluded in FeynHiggs



LC: $\delta M_h^{\text{exp}} = 0.05$ GeV



5. Outlook

. . . no time left . . .

There is progress in the right direction,
at least for Higgs, top/QCD, loops, . . .
(sometimes one might wish for more activities)

Some goals can be met without problems, other are harder (as usual)
and some are very difficult!

⇒ We must not stop in our efforts
⇒ We must support the people doing the really hard work

5. Outlook

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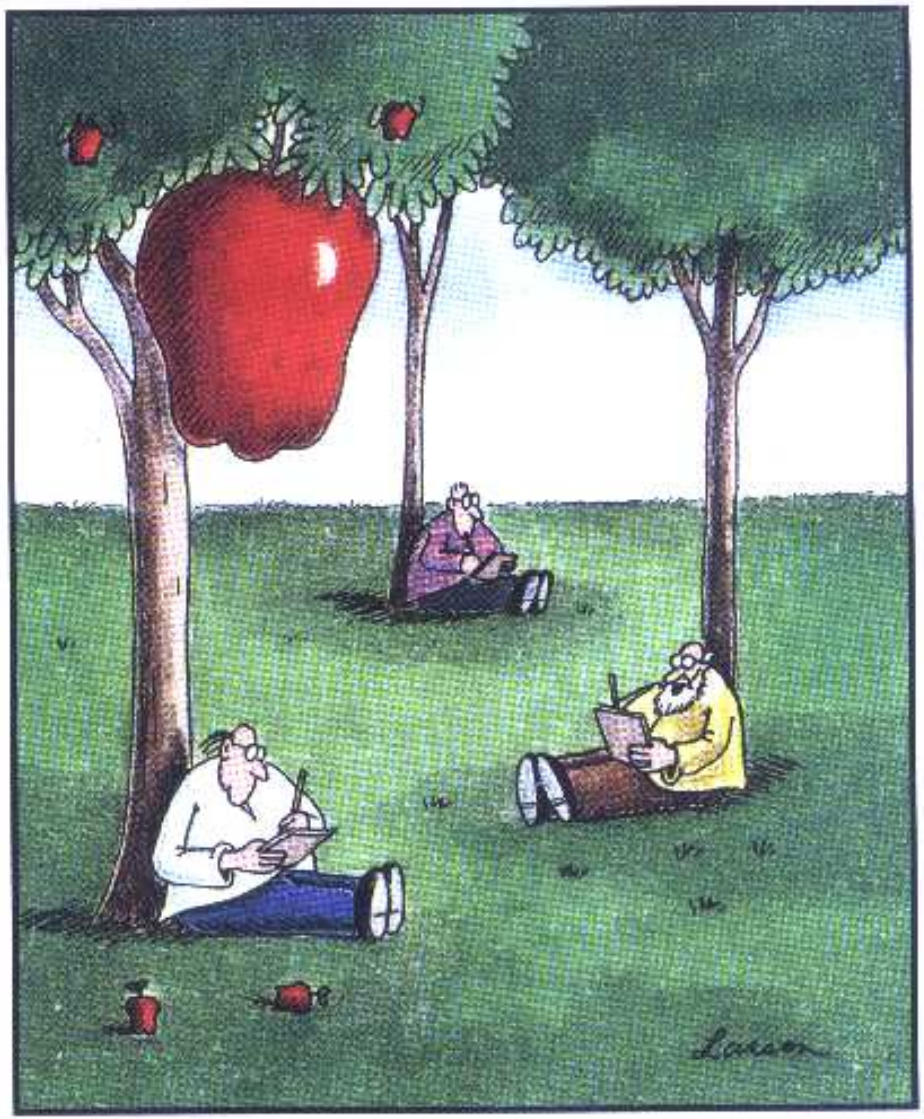
and some are very difficult!

⇒ We must not stop in our efforts
⇒ We must support the people doing the really hard work

If we continue with the hard work, physics will be ready for the ILC start

So let's work while we await the ILC:



"Nothing yet. ... How about you, Newton?"