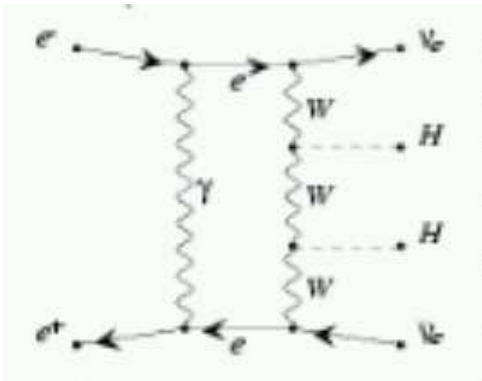
Preparing for the ILC

Sven Heinemeyer, IFCA (CSIC-UC)

Fermilab, 04/2007



1. Physics at the ILC
2. Higgs and Loops
3. Loops everywhere
4. Outlook

Worldwide Study of
the Physics and Detectors
for Future Linear
e+ e- Colliders

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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A: The ILC will add precision $\Rightarrow$ The ILC delivers $\oplus$ needs precision!

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

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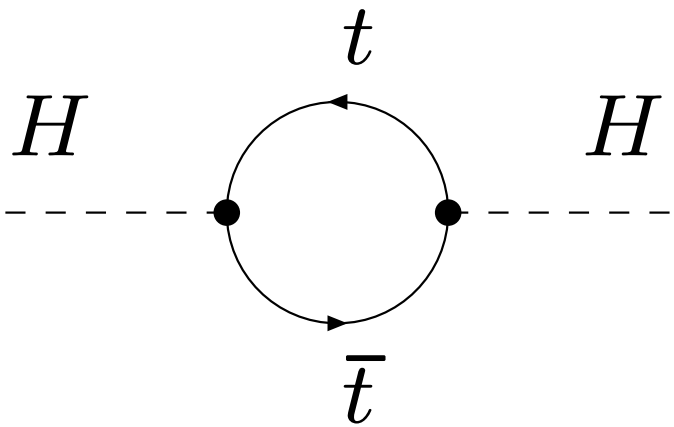
Where are we in this respect? (Status? What is needed? Achievement?)

- Higgs
- Top/QCD ($\rightarrow$ see e.g. talk by Andre Hoang)
- SUSY
- New Physics at TeV, precision electroweak
- Cosmological connections
- LoopVerein $\Rightarrow$ relevant for all other topics!

Everything is connected:

Nearly any model: large coupling of the Higgs to the top quark:



$\Rightarrow$ one-loop corrections $\Delta m_h^2 \sim G_\mu m_t^4$ $\quad (\rightarrow \mathcal{O}(\alpha_t))$

$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

SUSY as an example: $\Delta m_t \approx \pm 2$ GeV $\Rightarrow$ $\Delta m_h \approx \pm 2$ GeV

$\mathcal{O}\left(\alpha_t \alpha_s^2\right)$: $\Rightarrow$ $\Delta m_h \sim 1$ GeV

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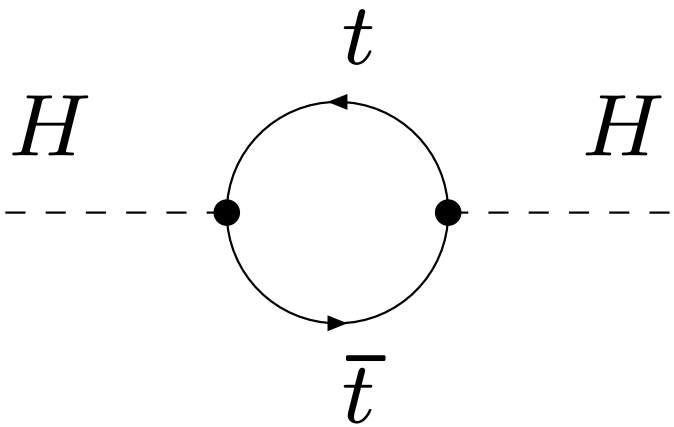

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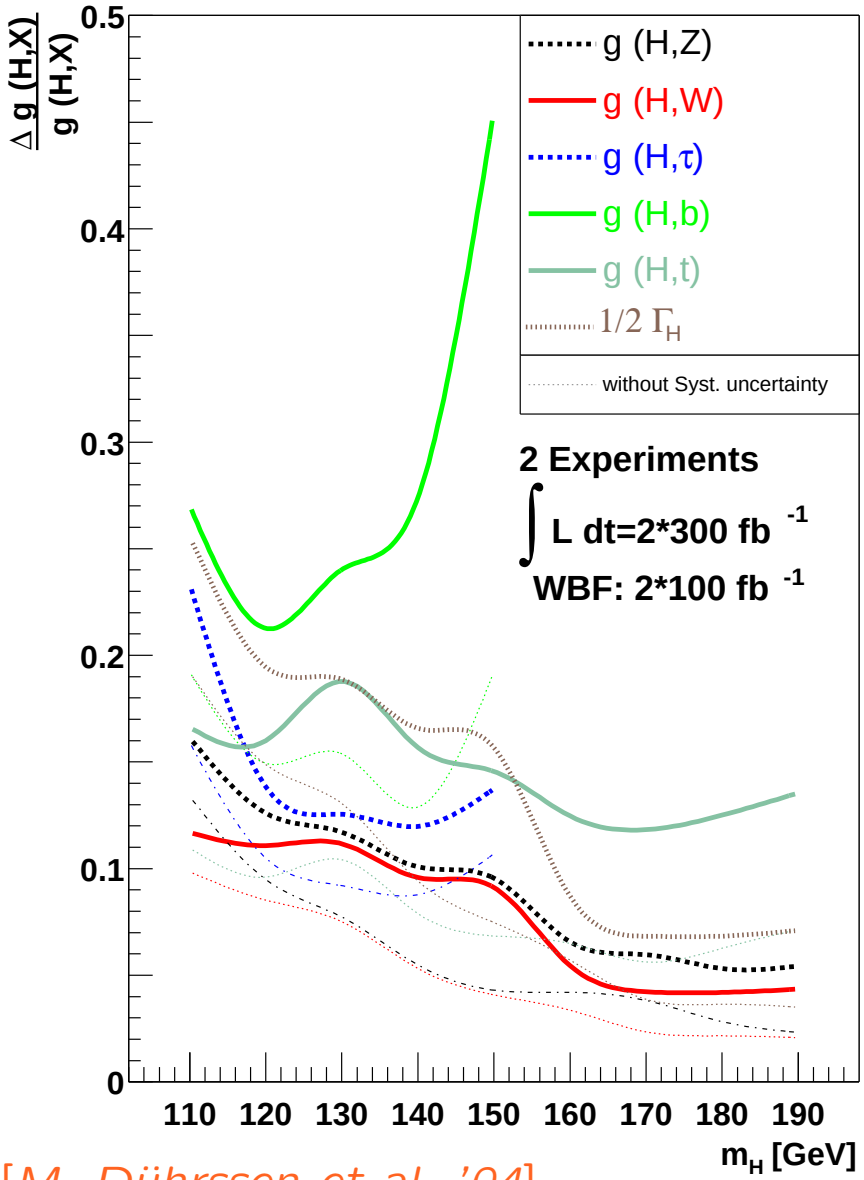
$\Rightarrow$ Precision Higgs physics needs loops + precision top physics

2. Higgs and Loops The LHC will find a Higgs, 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

Assumptions:

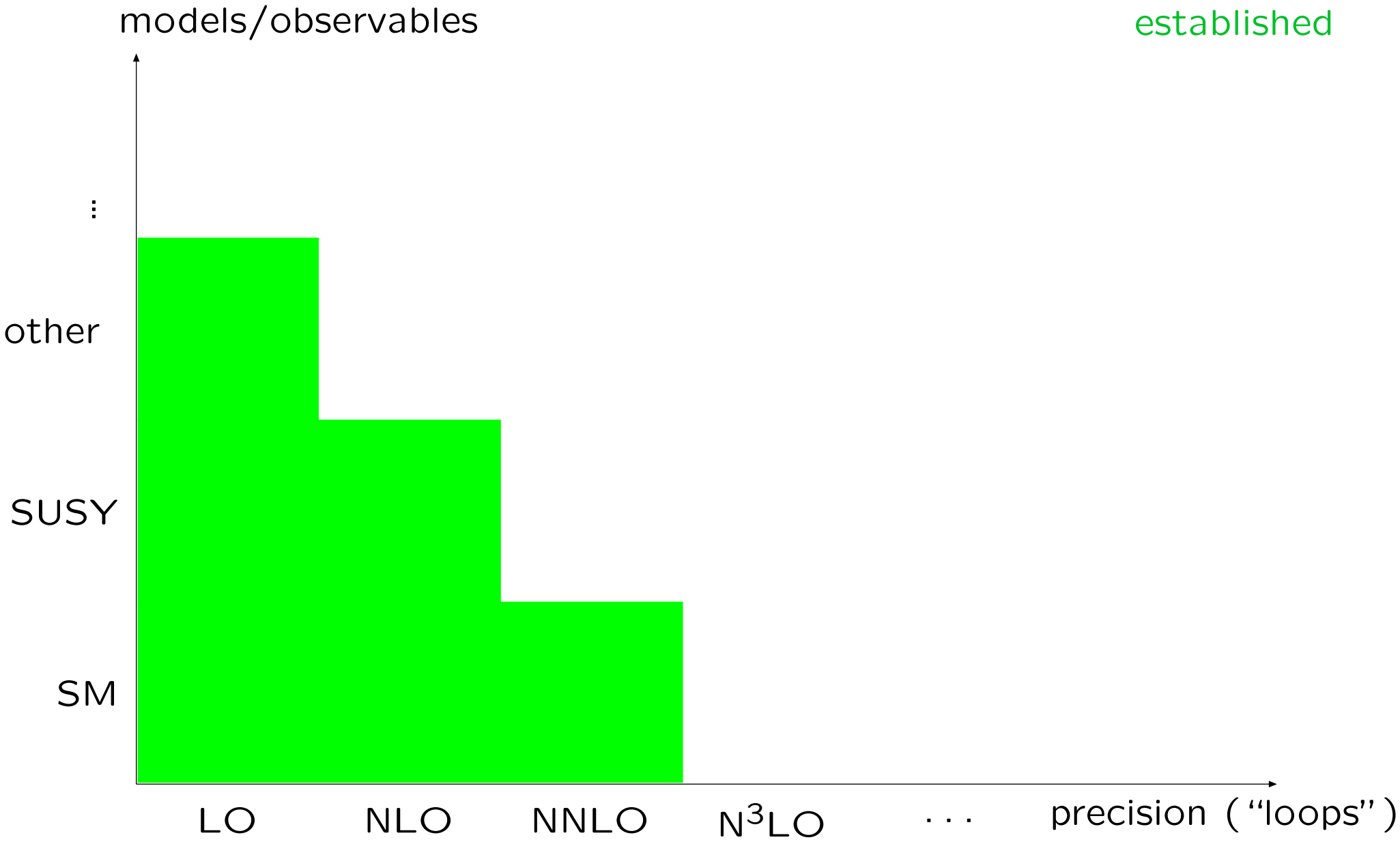
- $g^2_{HVV} \leq g^2_{HVV,\text{SM}} \times 1.05$
- SM rates for the Higgs

Problems:

- precision not good enough?
- 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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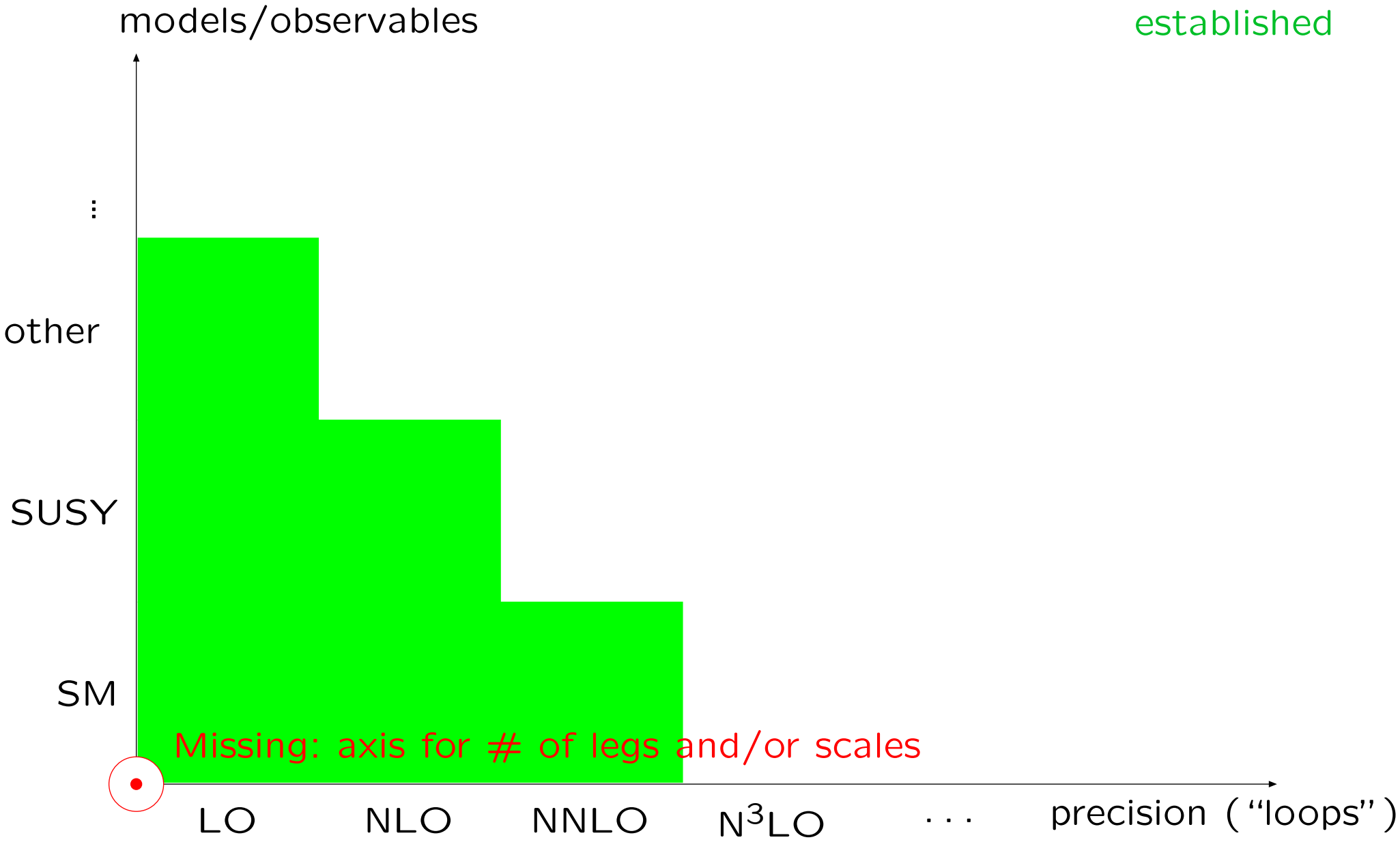

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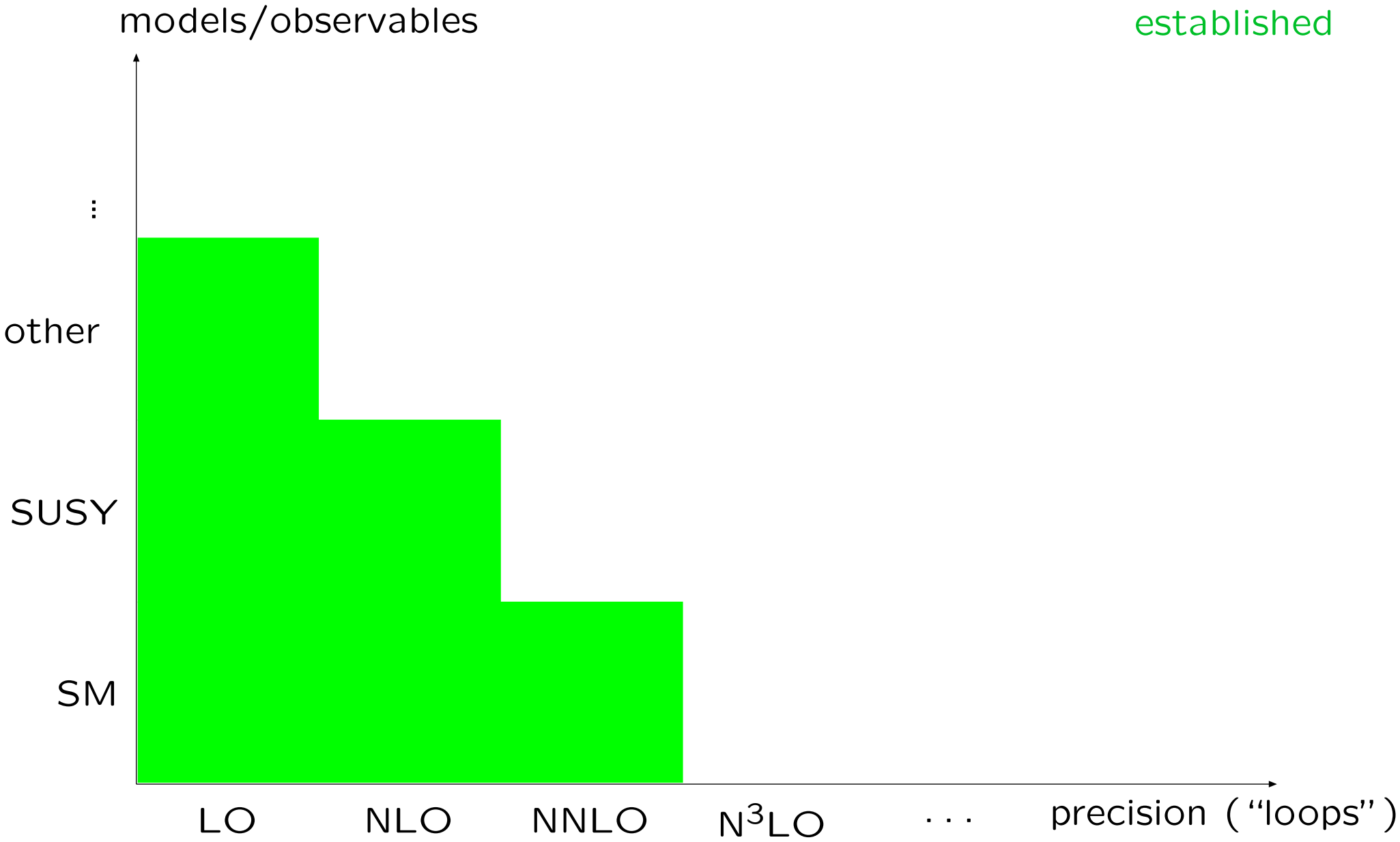

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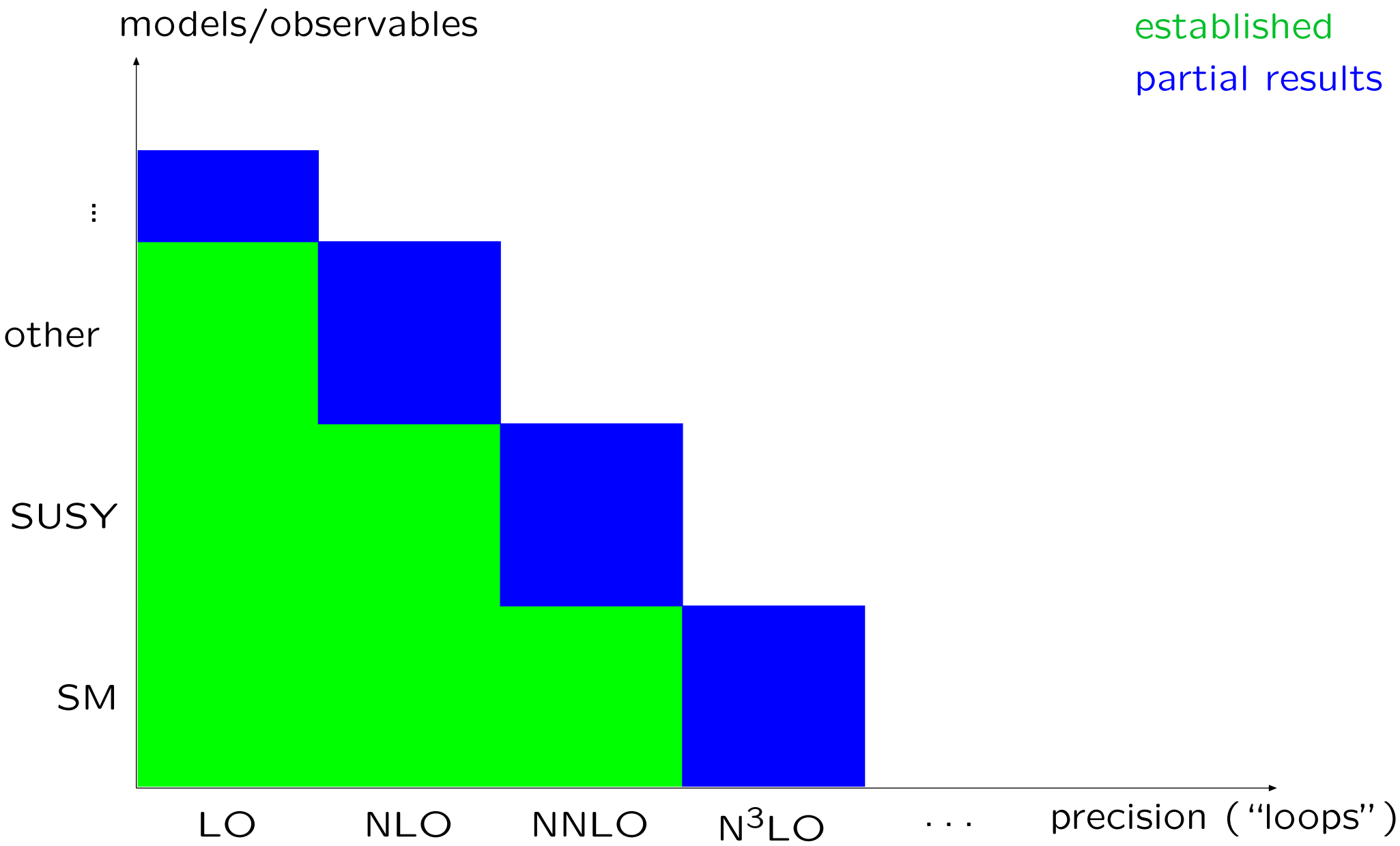

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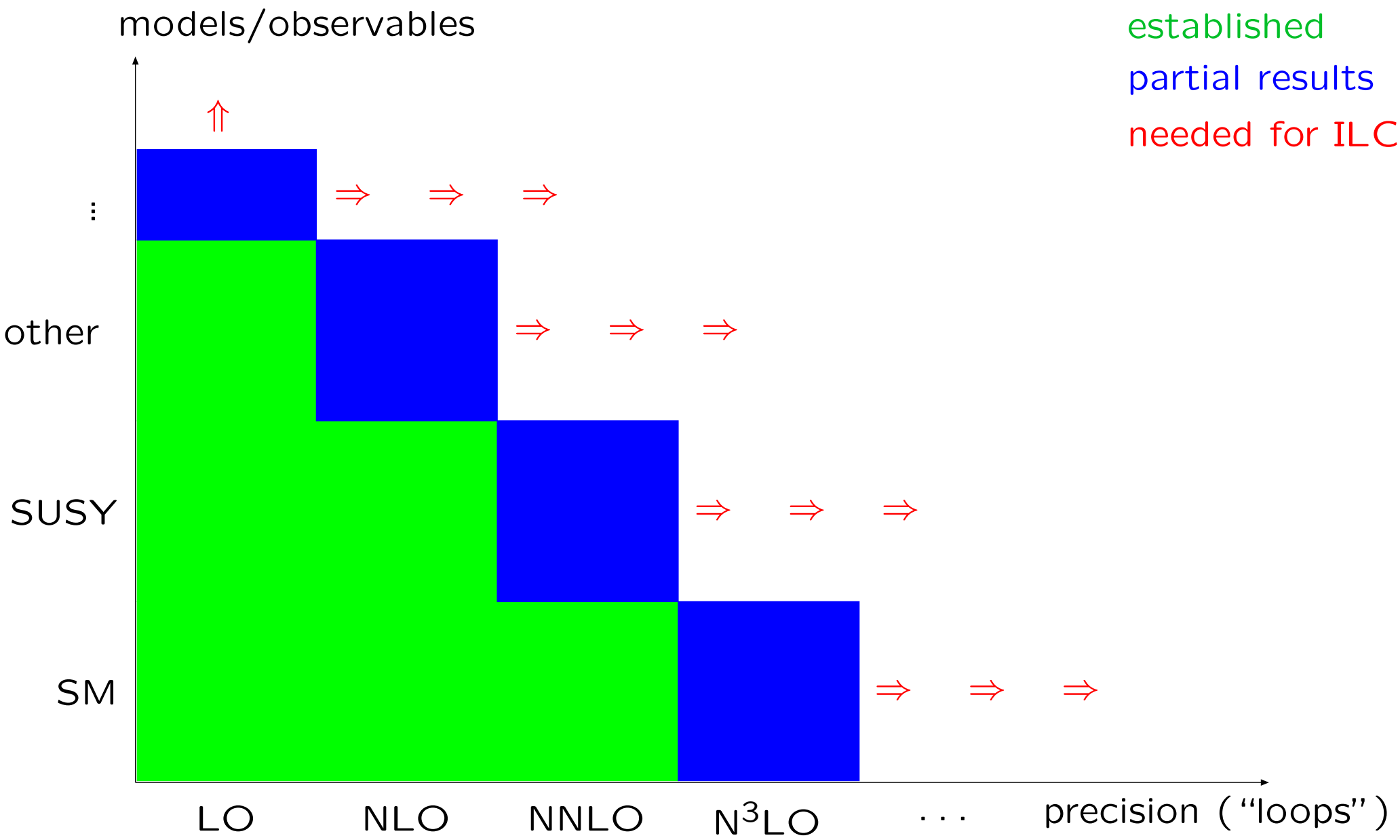

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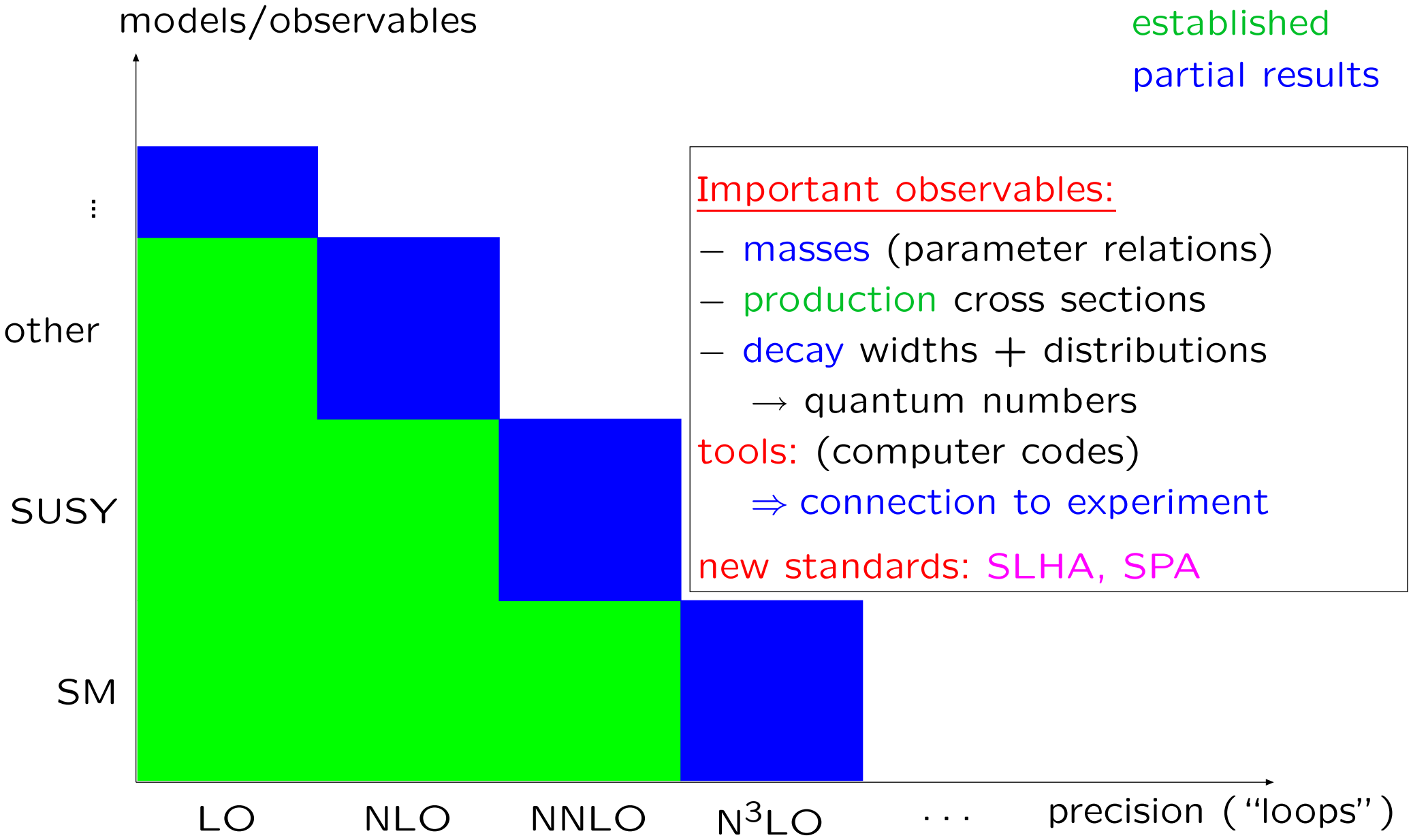


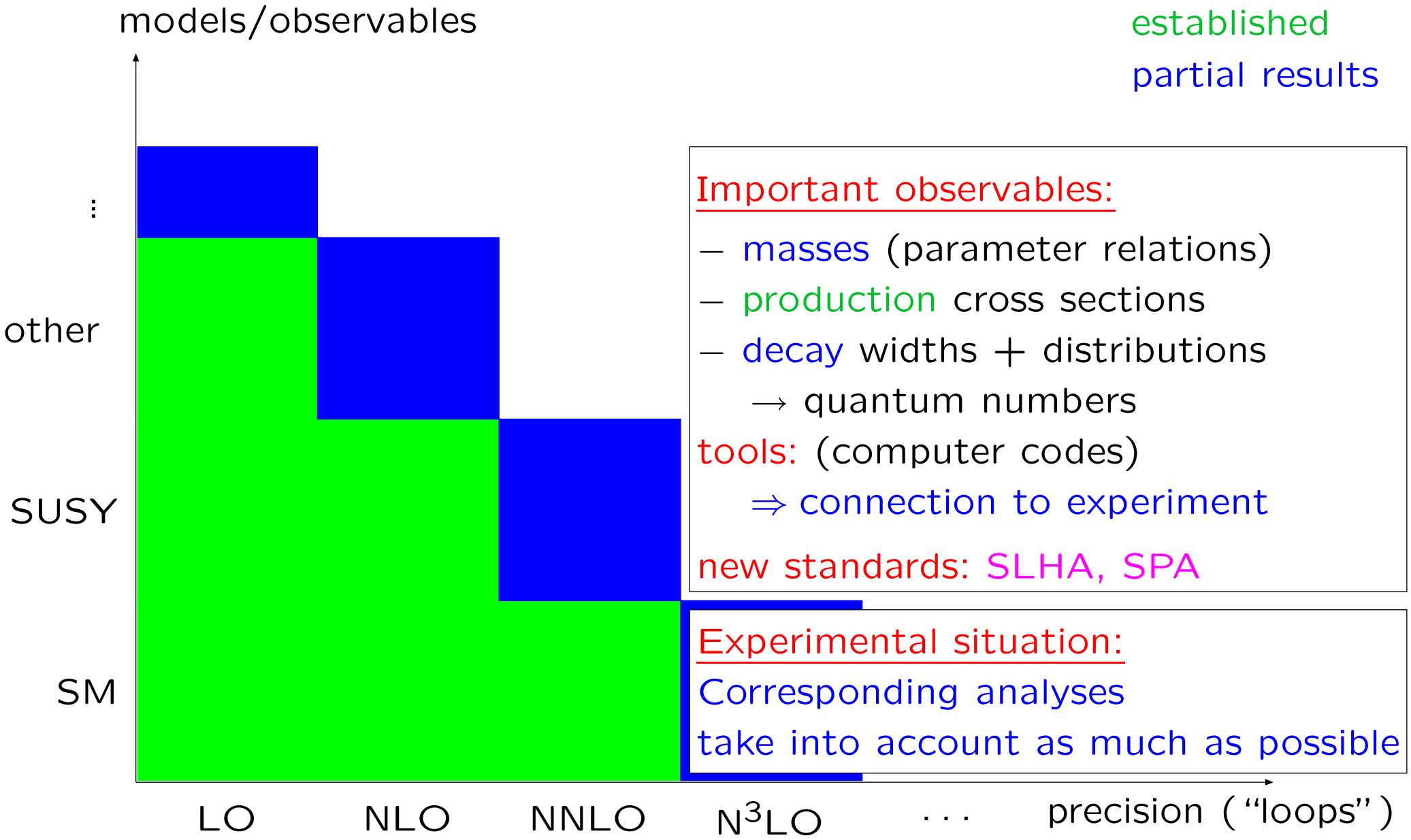
Important observables:

– masses (parameter relations)
– production cross sections
– decay widths + distributions
  → quantum numbers

tools: (computer codes)
  ⇒ connection to experiment

new standards: SLHA, SPA

Higgs: experimental situation



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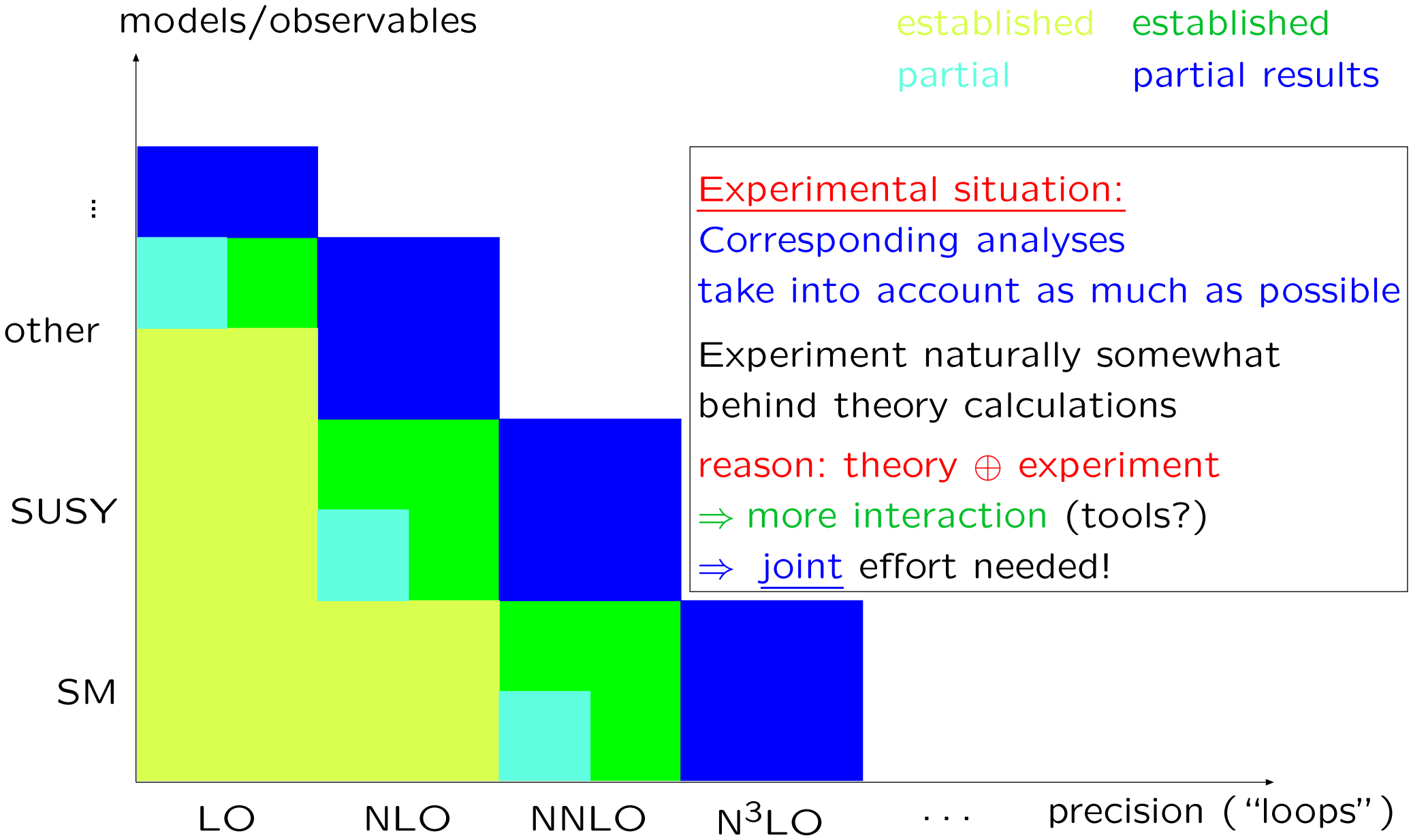
Experimental situation:

Corresponding analyses
take into account as much as possible

Higgs: experimental situation

experiment	theory
established	established
partial	partial results



Experimental situation:

Corresponding analyses take into account as much as possible

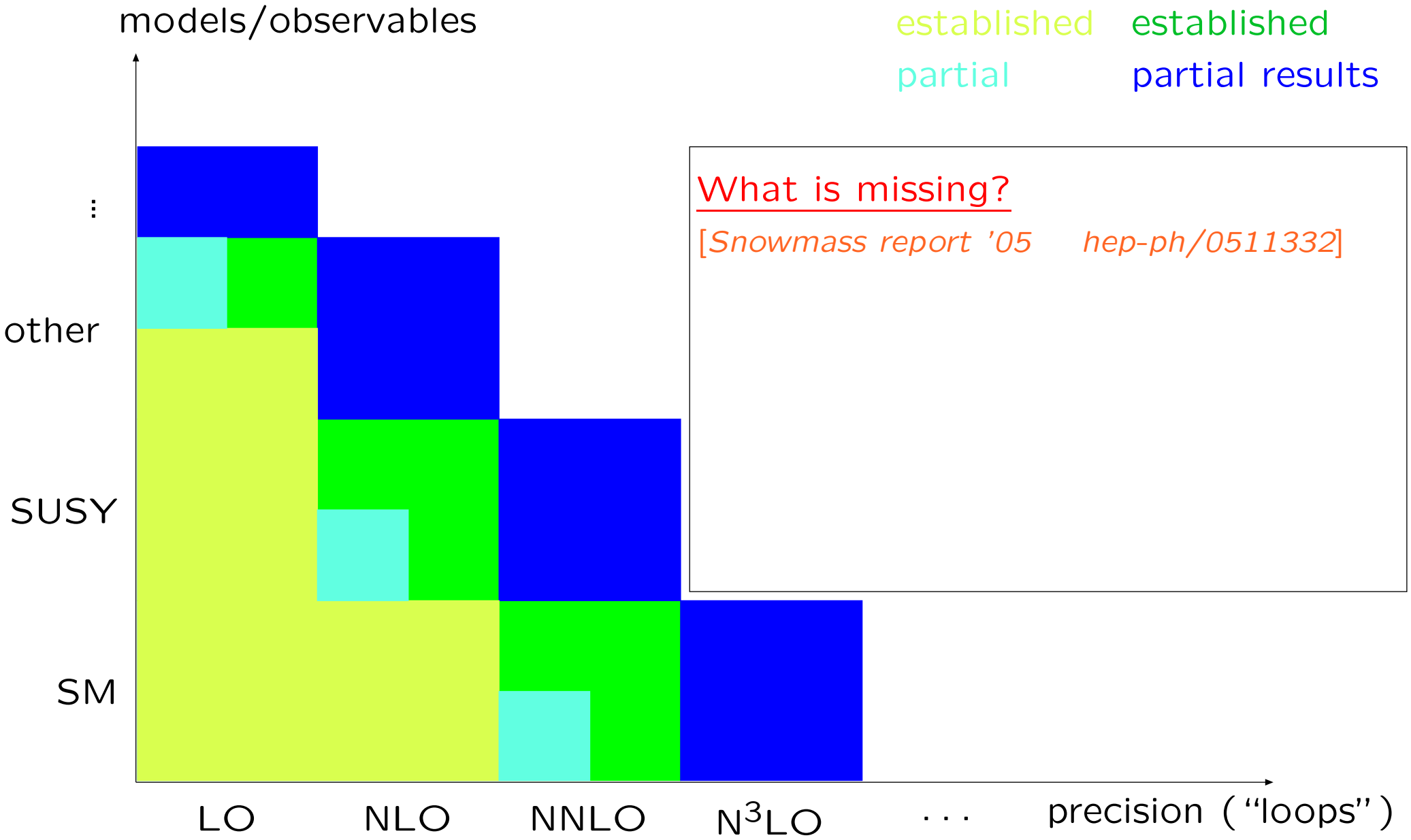
Experiment naturally somewhat behind theory calculations

reason: theory $\oplus$ experiment

$\Rightarrow$ more interaction (tools?)

$\Rightarrow$ joint effort needed!

Higgs: experimental situation



What is missing?

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

Higgs: experimental situation

experiment	theory
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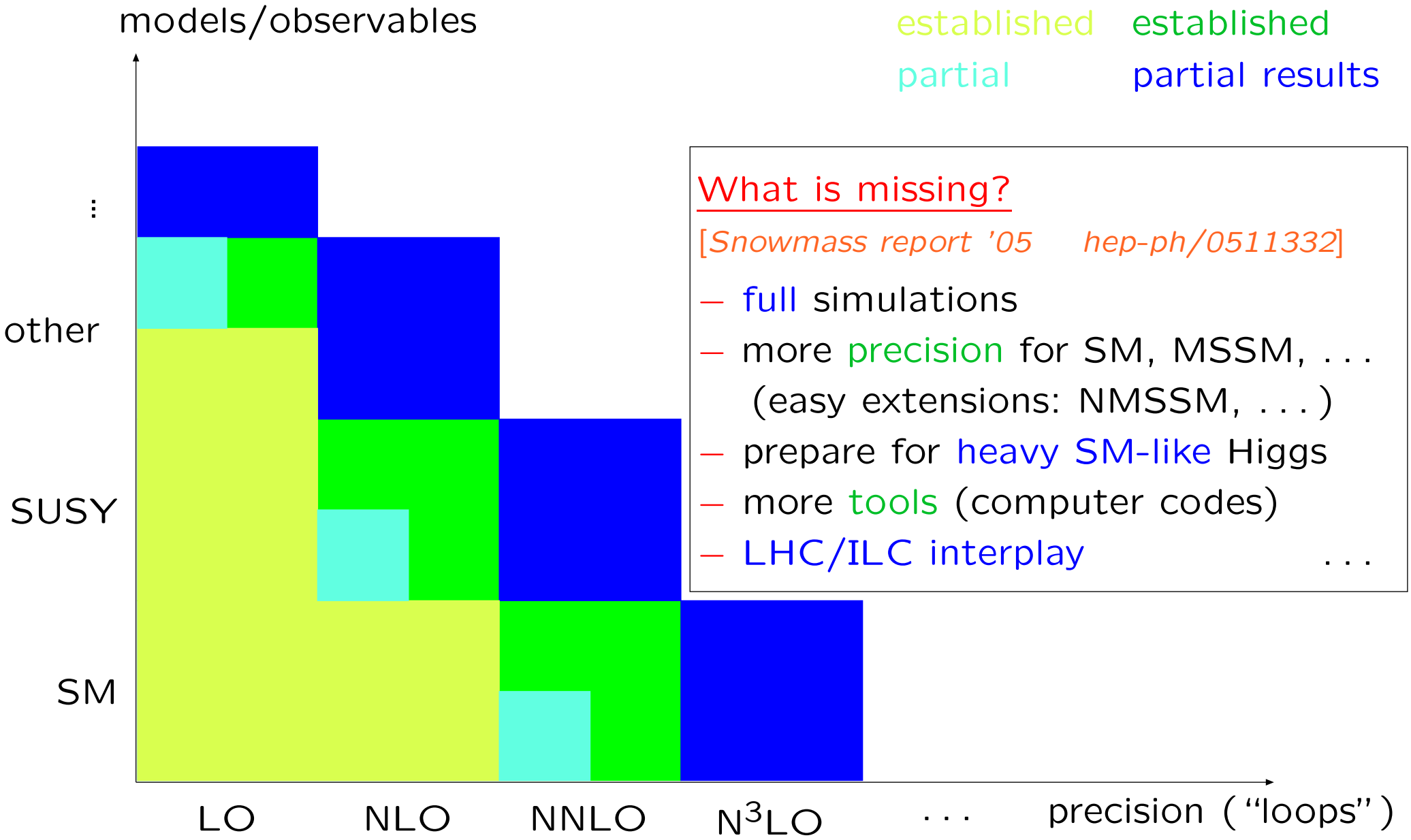
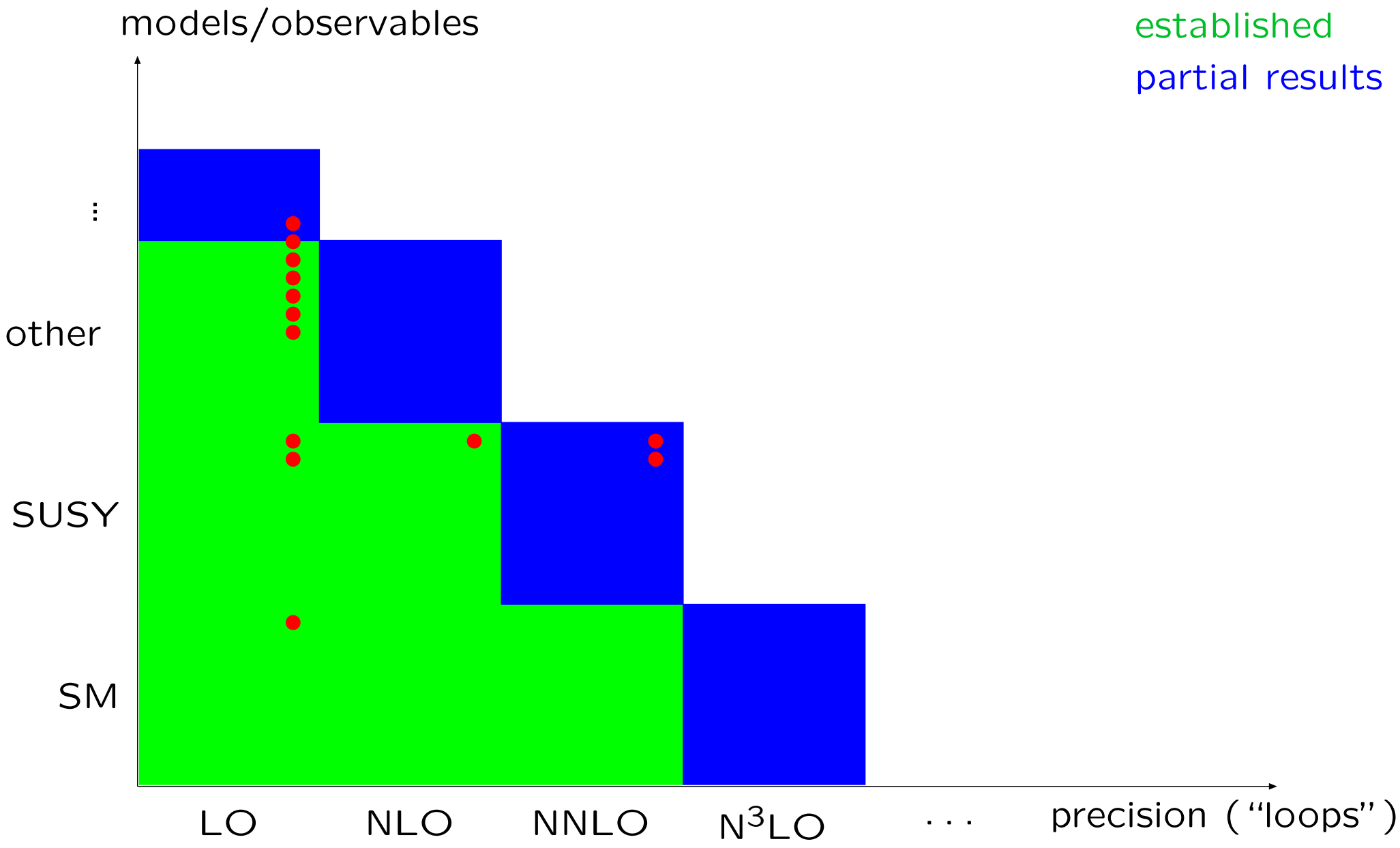


What is missing?

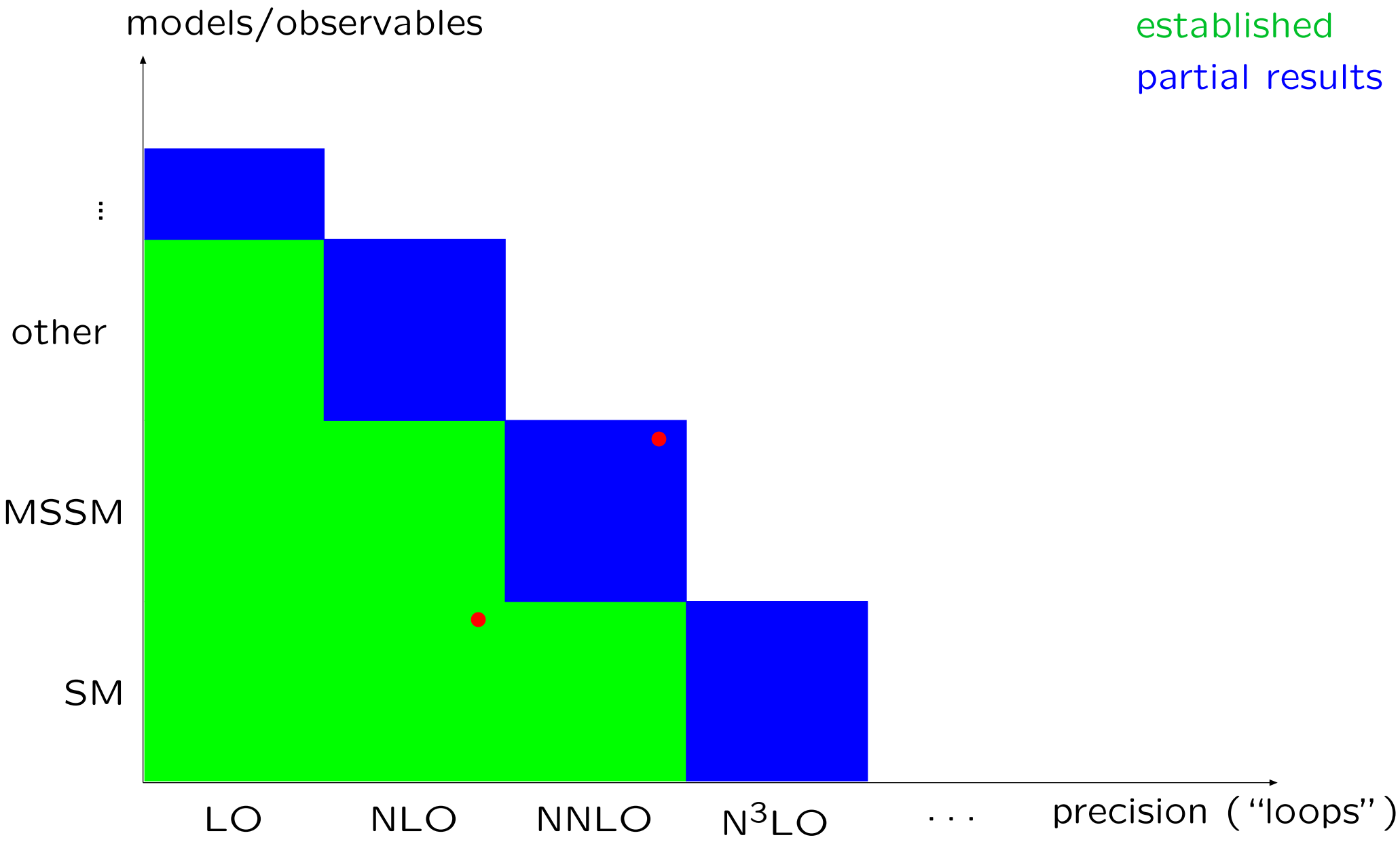
[*Snowmass report '05 hep-ph/0511332*]

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

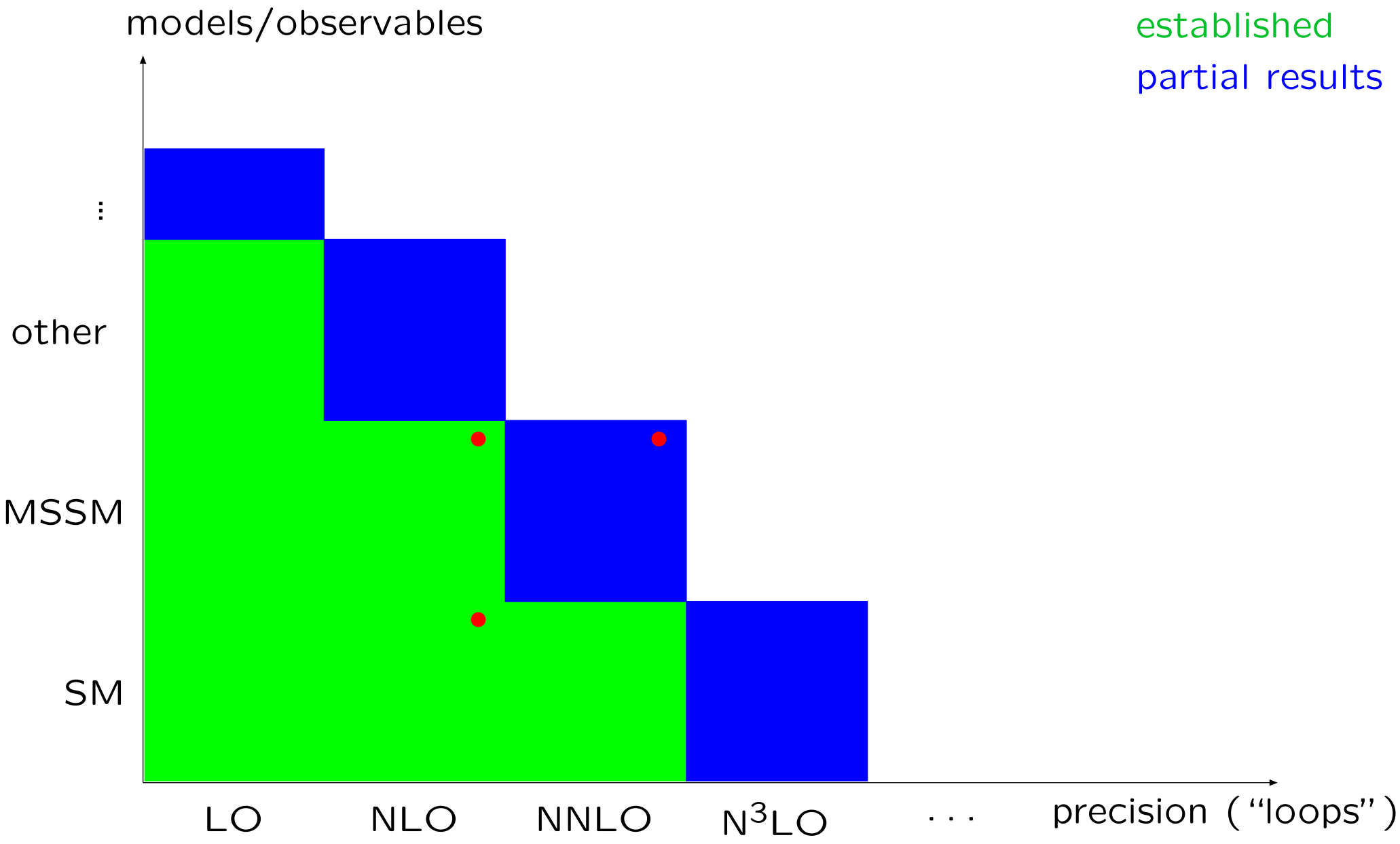
Higgs/theory: ILC world conference '06 (Bangalore)



Higgs/theory: ILC european conference '06 (Valencia)



Higgs/theory: two examples

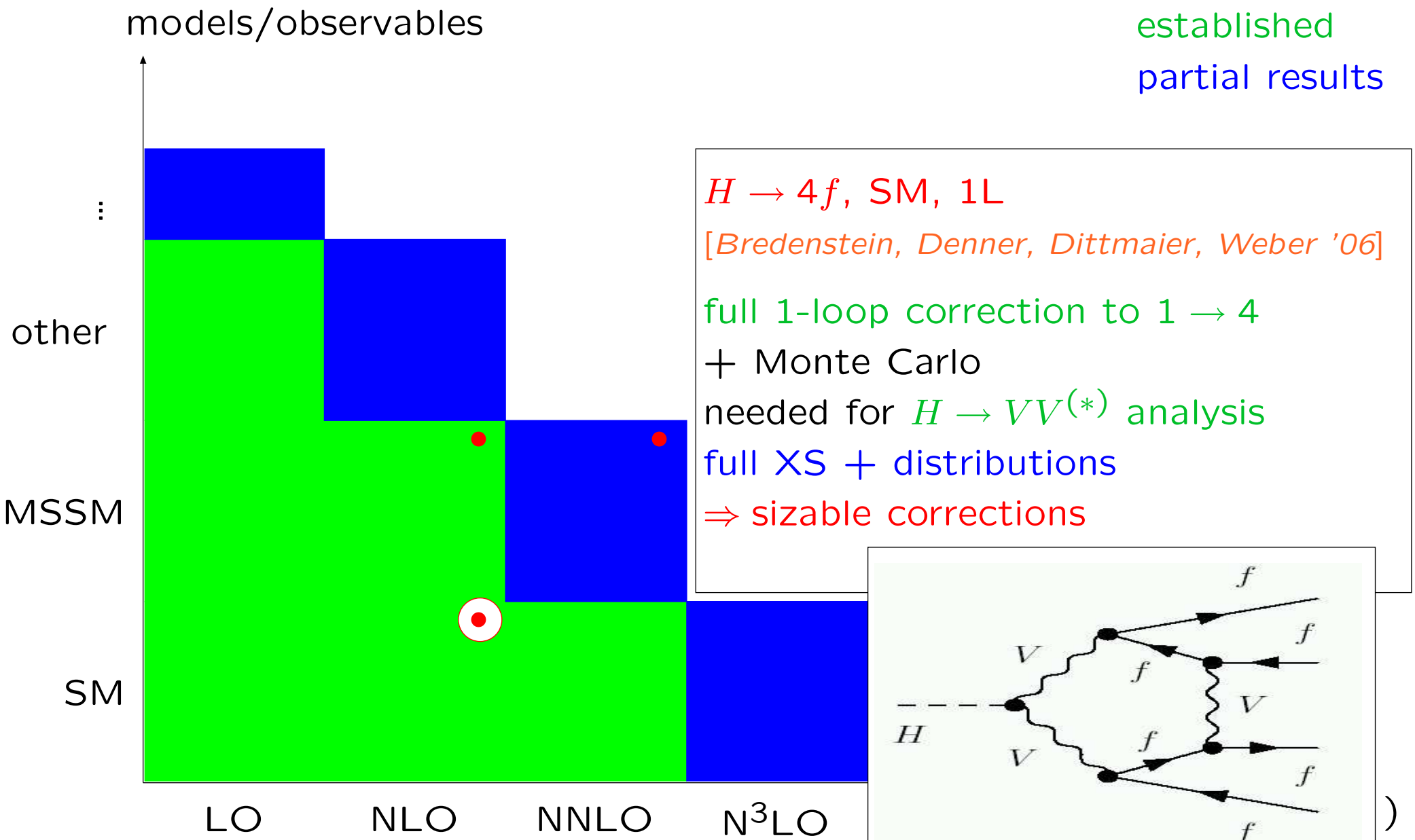


Higgs/theory: two examples

theory

established

partial results



$H \to 4f$, SM, 1L

[*Bredenstein, Denner, Dittmaier, Weber '06*]

full 1-loop correction to $1 \to 4$

+ Monte Carlo

needed for $H \to VV^{(*)}$ analysis

full XS + distributions

$\Rightarrow$ sizable corrections

Higgs/theory: two examples

theory

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partial results

models/observables

$H \to 4f$, SM, 1L

denstein, Denner, Dittmaier, Weber '06]

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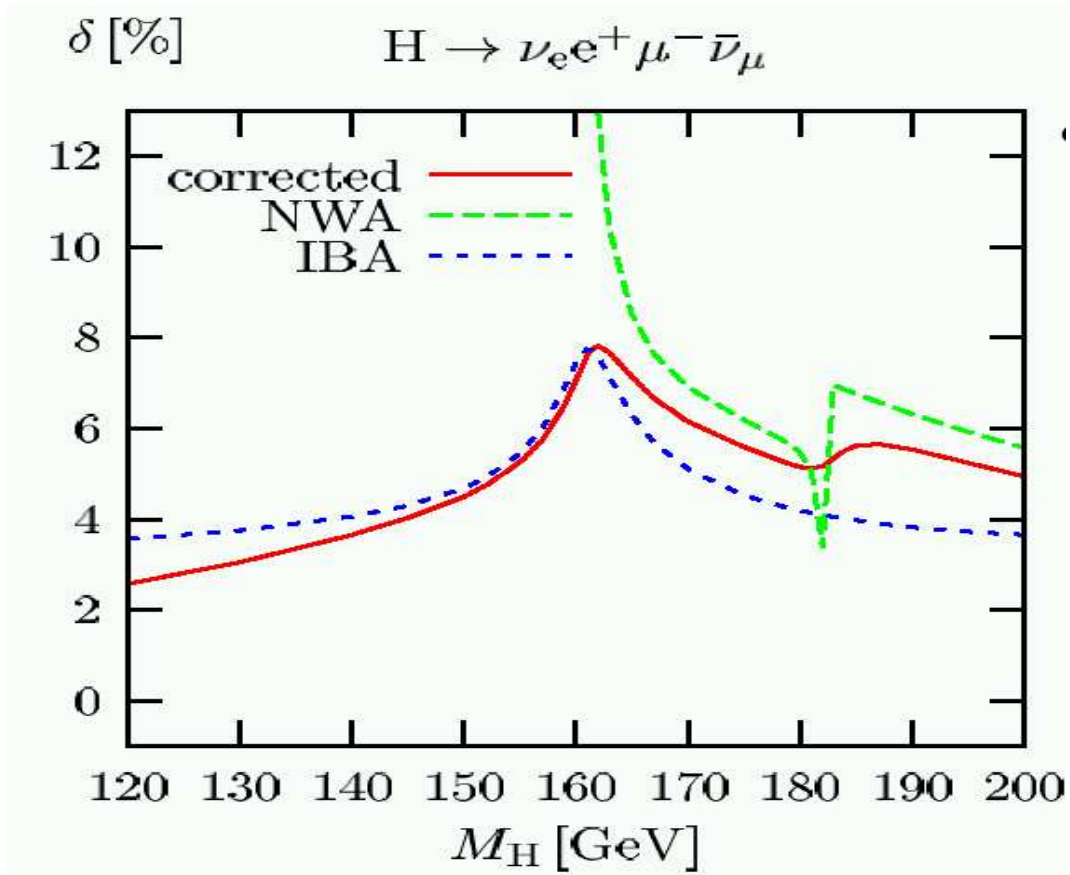

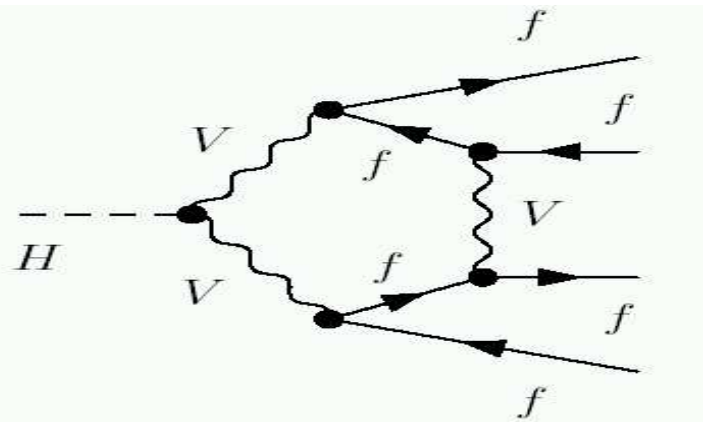

LO

Higgs/theory: two examples

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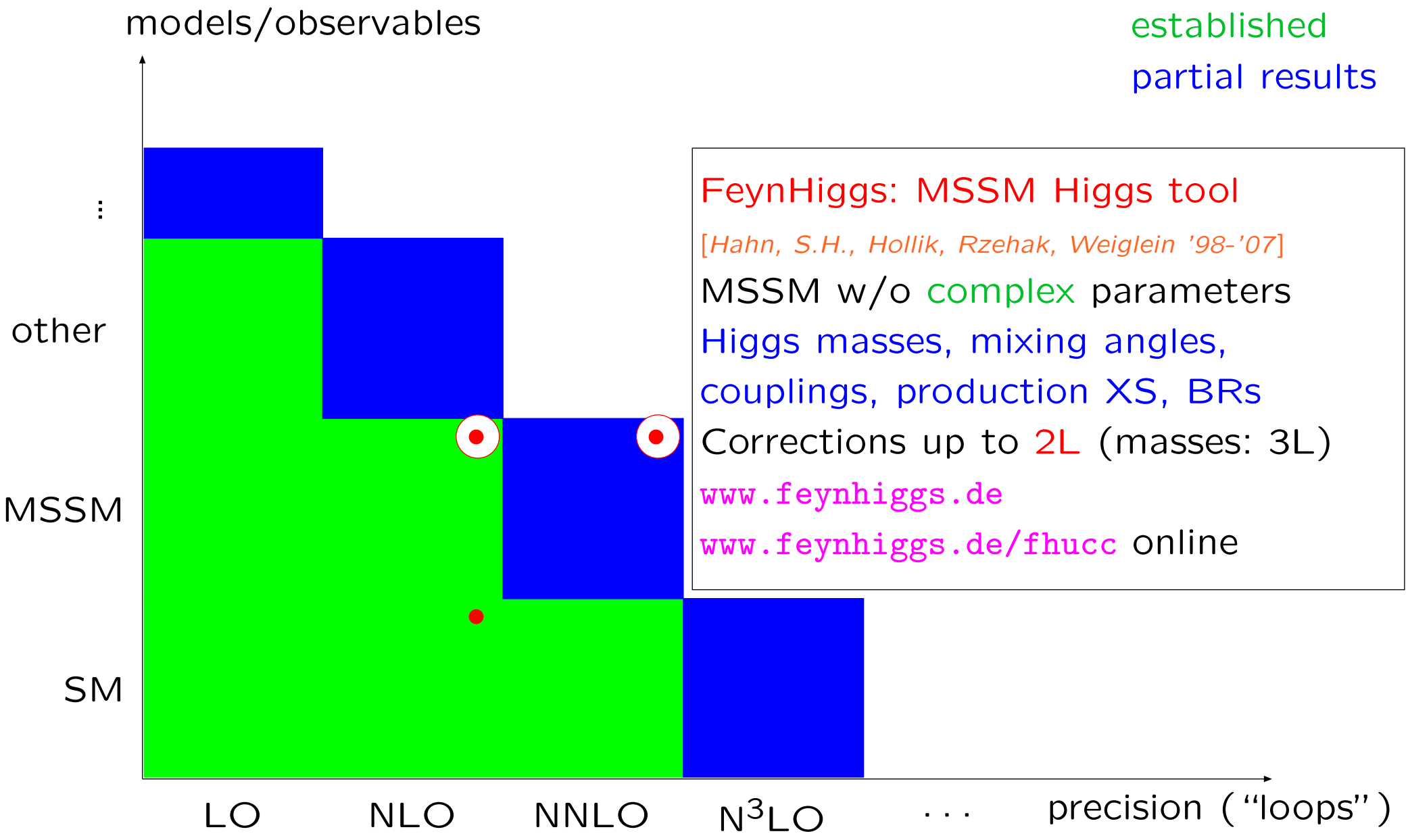
established

partial results



FeynHiggs: MSSM Higgs tool

[*Hahn, S.H., Hollik, Rzehak, Weiglein '98-'07*]

MSSM w/o complex parameters

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

Corrections up to 2L (masses: 3L)

`www.feynhiggs.de`

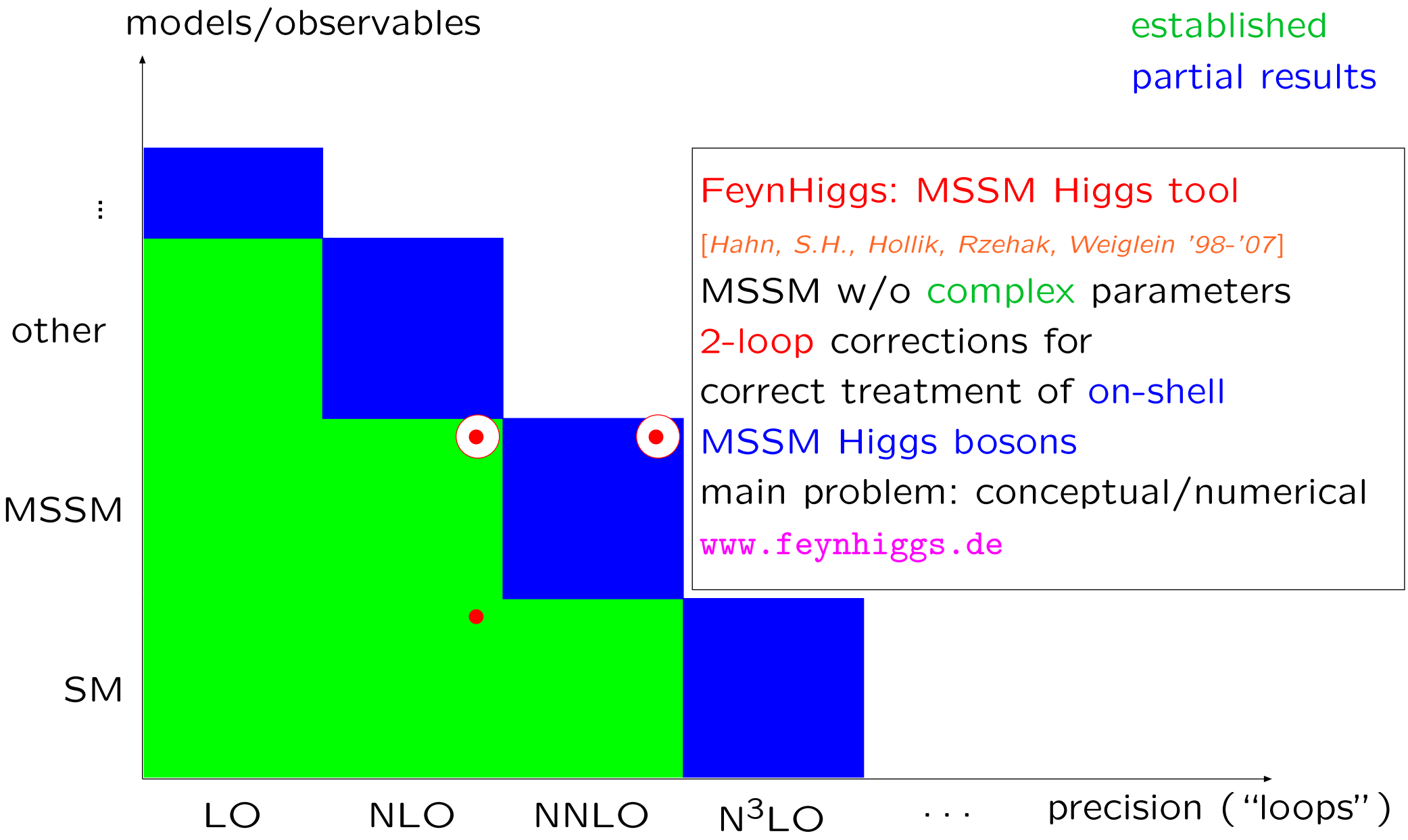
`www.feynhiggs.de/fhucc` online

Higgs/theory: two examples

theory

established

partial results



FeynHiggs: MSSM Higgs tool

[*Hahn, S.H., Hollik, Rzehak, Weiglein '98-'07*]

MSSM w/o complex parameters

2-loop corrections for

correct treatment of on-shell

MSSM Higgs bosons

main problem: conceptual/numerical

`www.feynhiggs.de`

Higgs/theory: two examples

theory

established

partial results

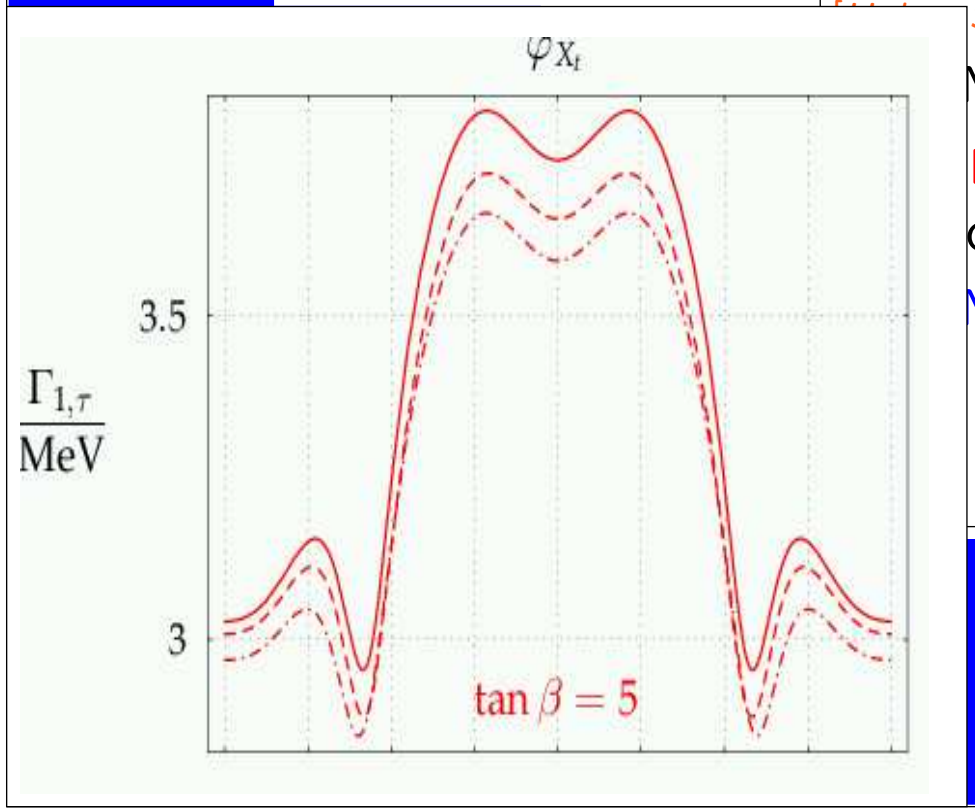
models/observables

⋮

other

MSSM

SM



FeynHiggs: MSSM Higgs tool

[... S.H., Hollik, Rzehak, Weiglein '98-'07]

M w/o complex parameters

p corrections for

ct treatment of on-shell

M Higgs bosons

problem: conceptual/numerical

$\Rightarrow \sim 5\%$ effects possible

LO NLO NNLO N^3LO $\cdots$ precision ("loops")

3. Loops everywhere

Why is it necessary to include all those loop corrections?

3. Loops everywhere

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Experimental situation:

ILC $\rightarrow$ provide high accuracy measurements !

Theory situation:

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

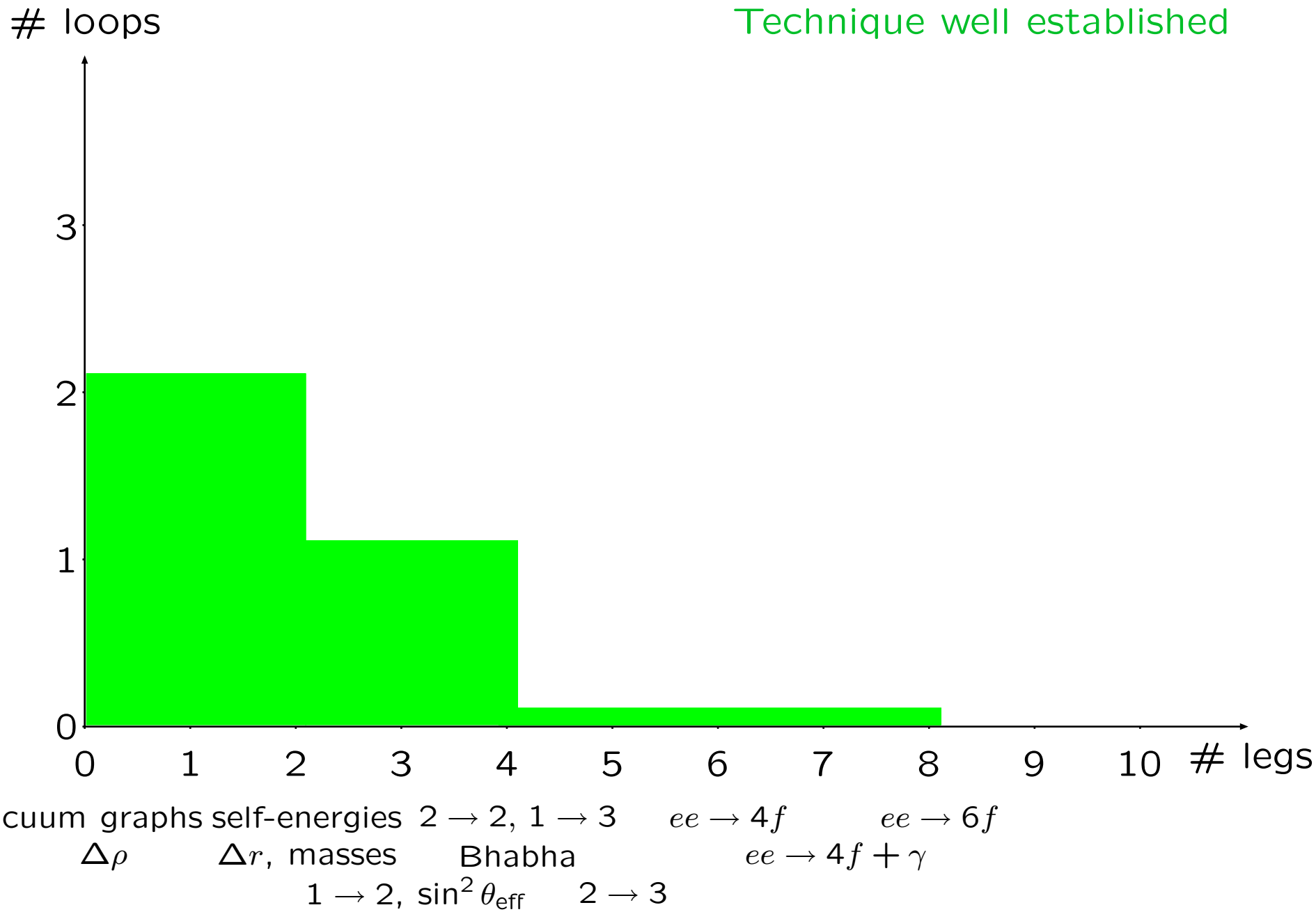
High precision of data can only fully be exploited if it is matched with theoretical calculations at the same level of accuracy

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



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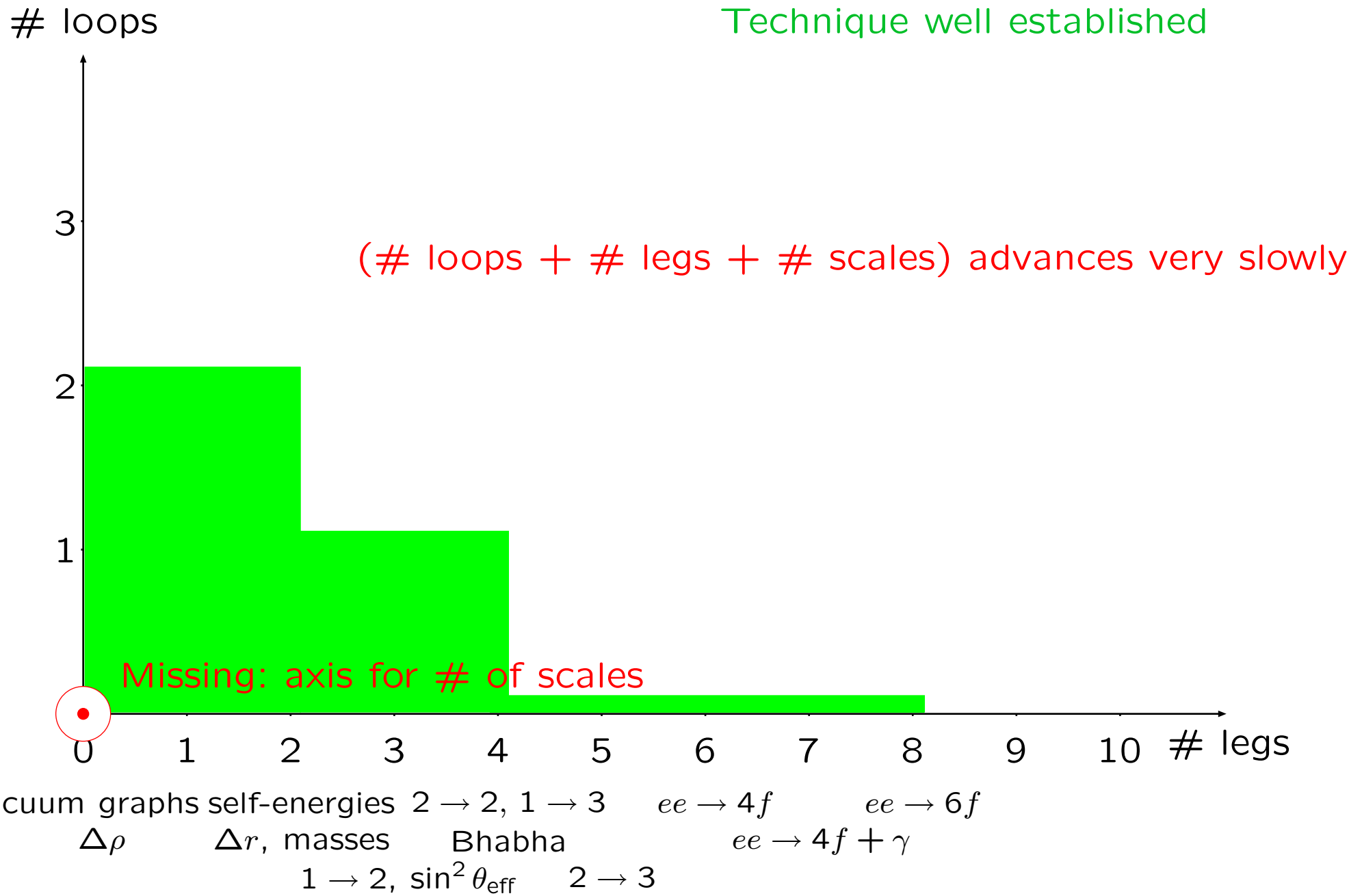

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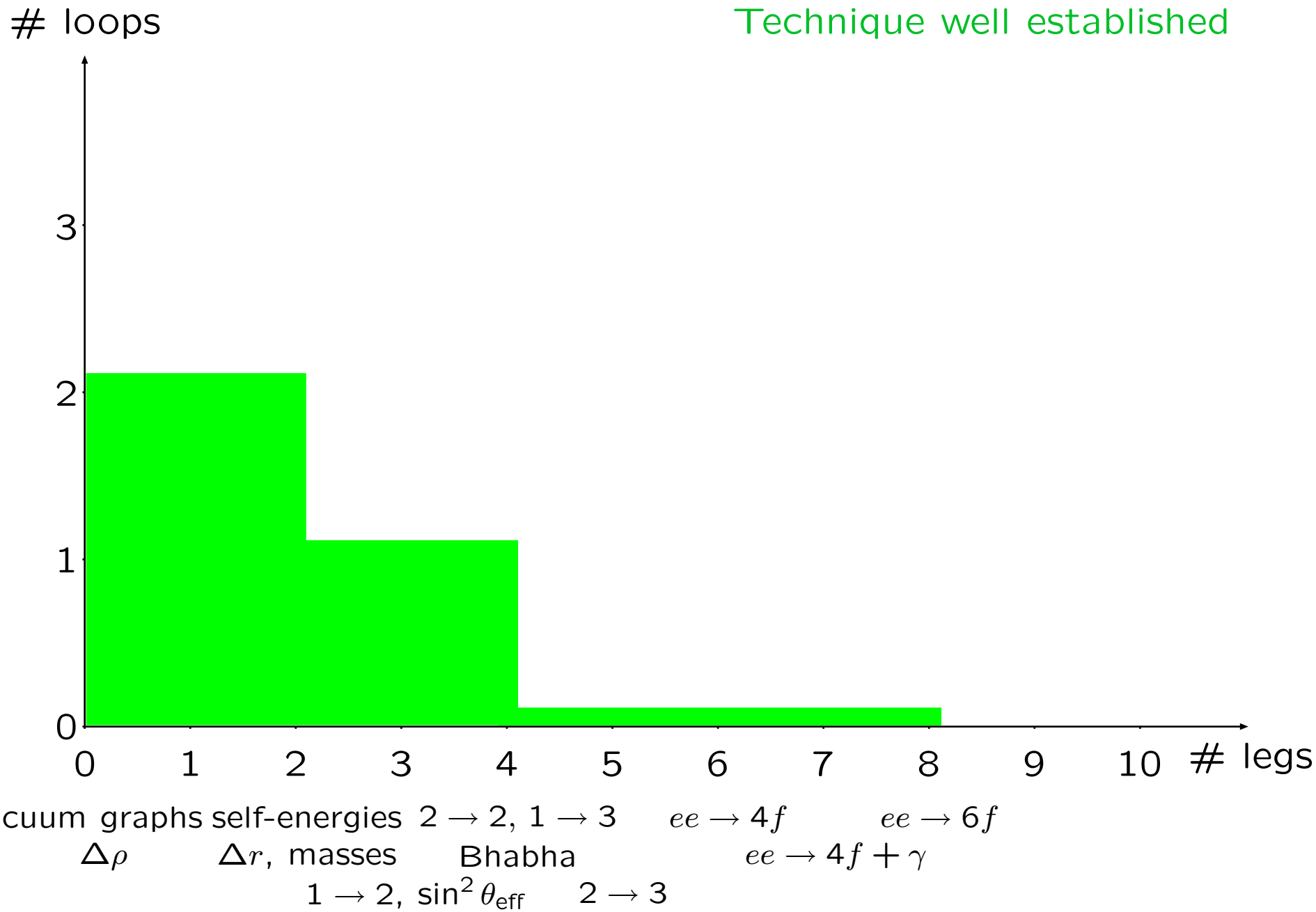

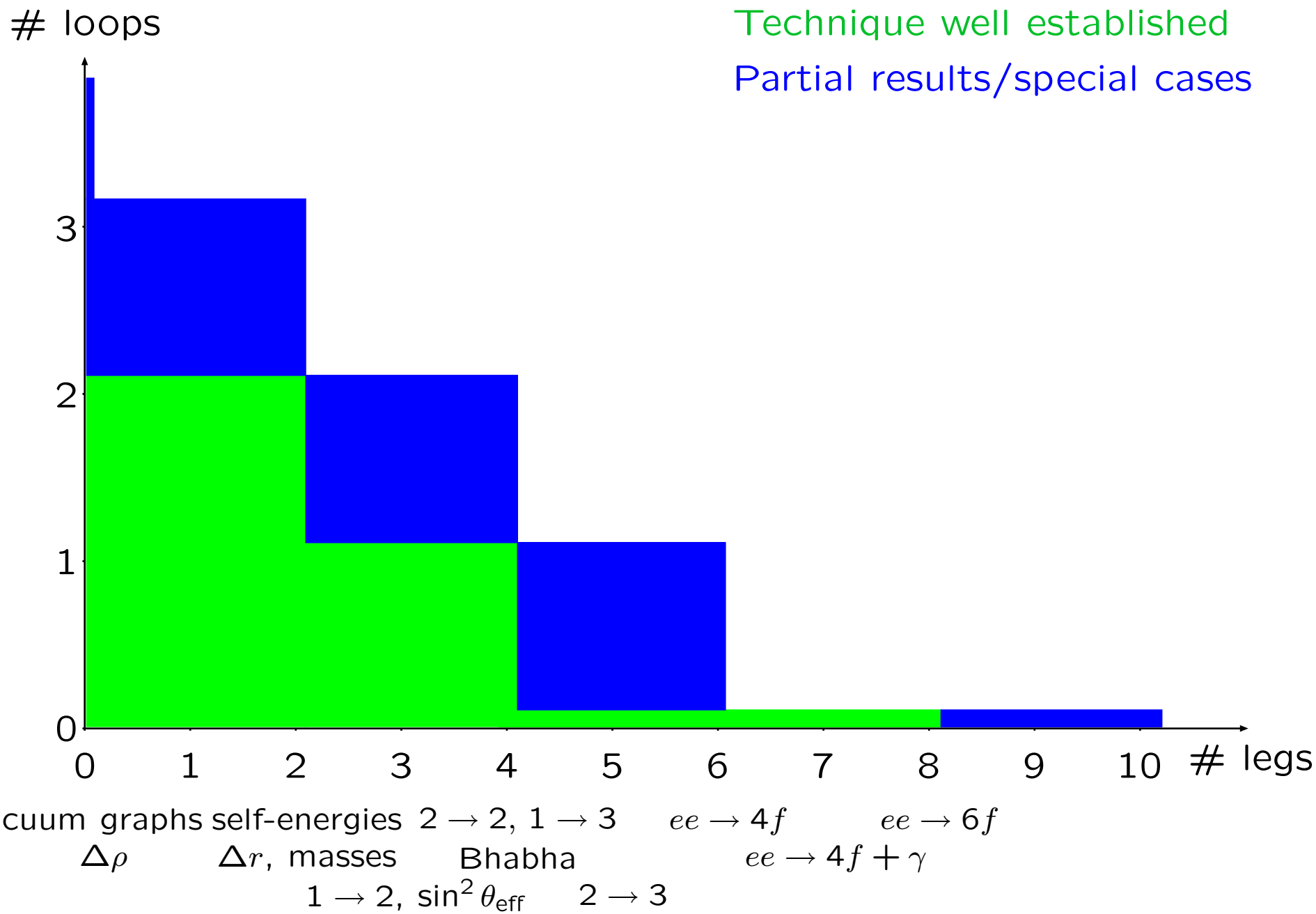
Technique well established
Partial results/special cases
loops
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legs
vacuum graphs
self-energies
$2 \to 2$, $1 \to 3$
$ee \to 4f$
$ee \to 6f$
$\Delta\rho$
Δr, masses
Bhabha
$ee \to 4f + \gamma$
$1 \to 2$, $\sin^2\theta_{\text{eff}}$
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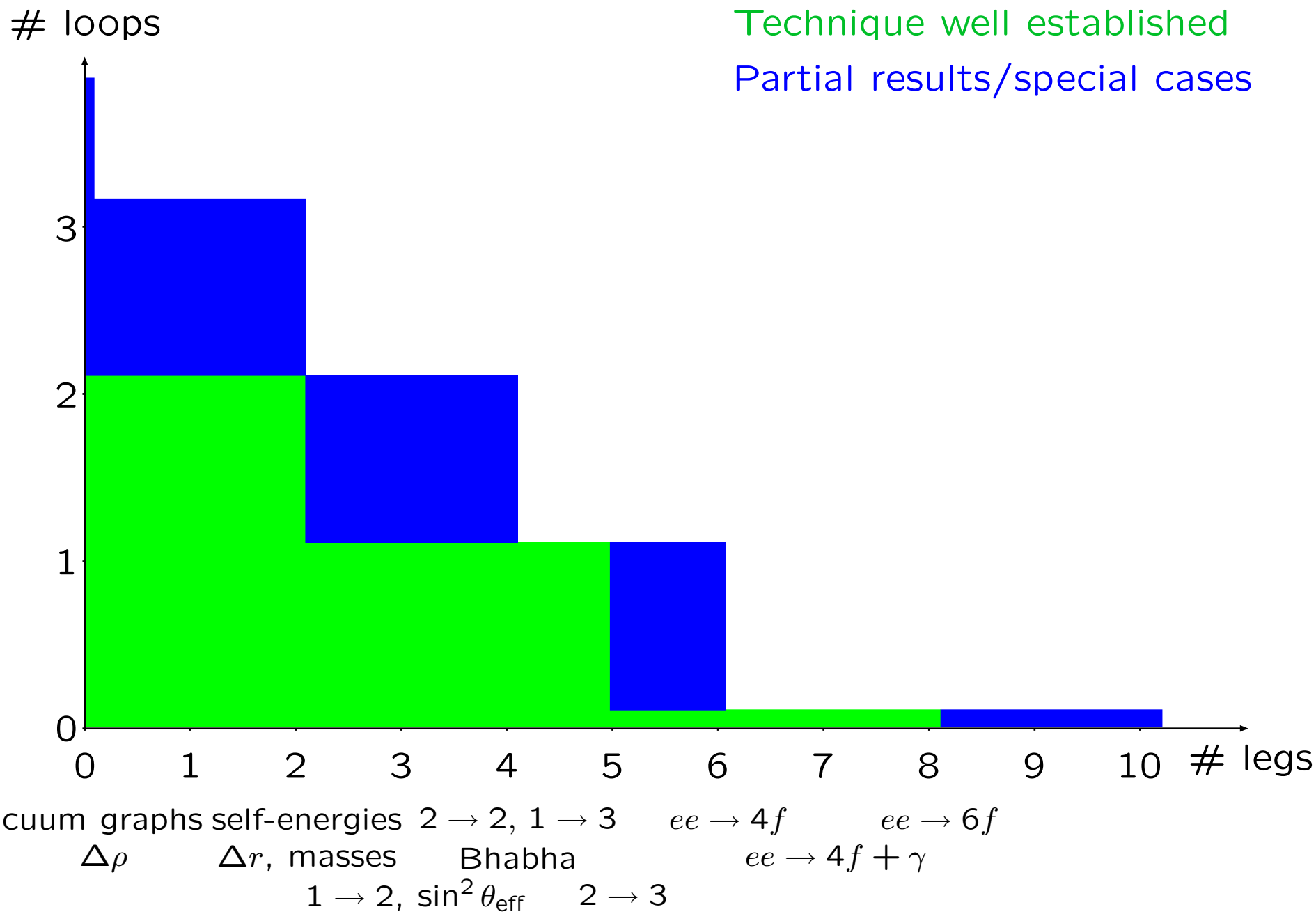
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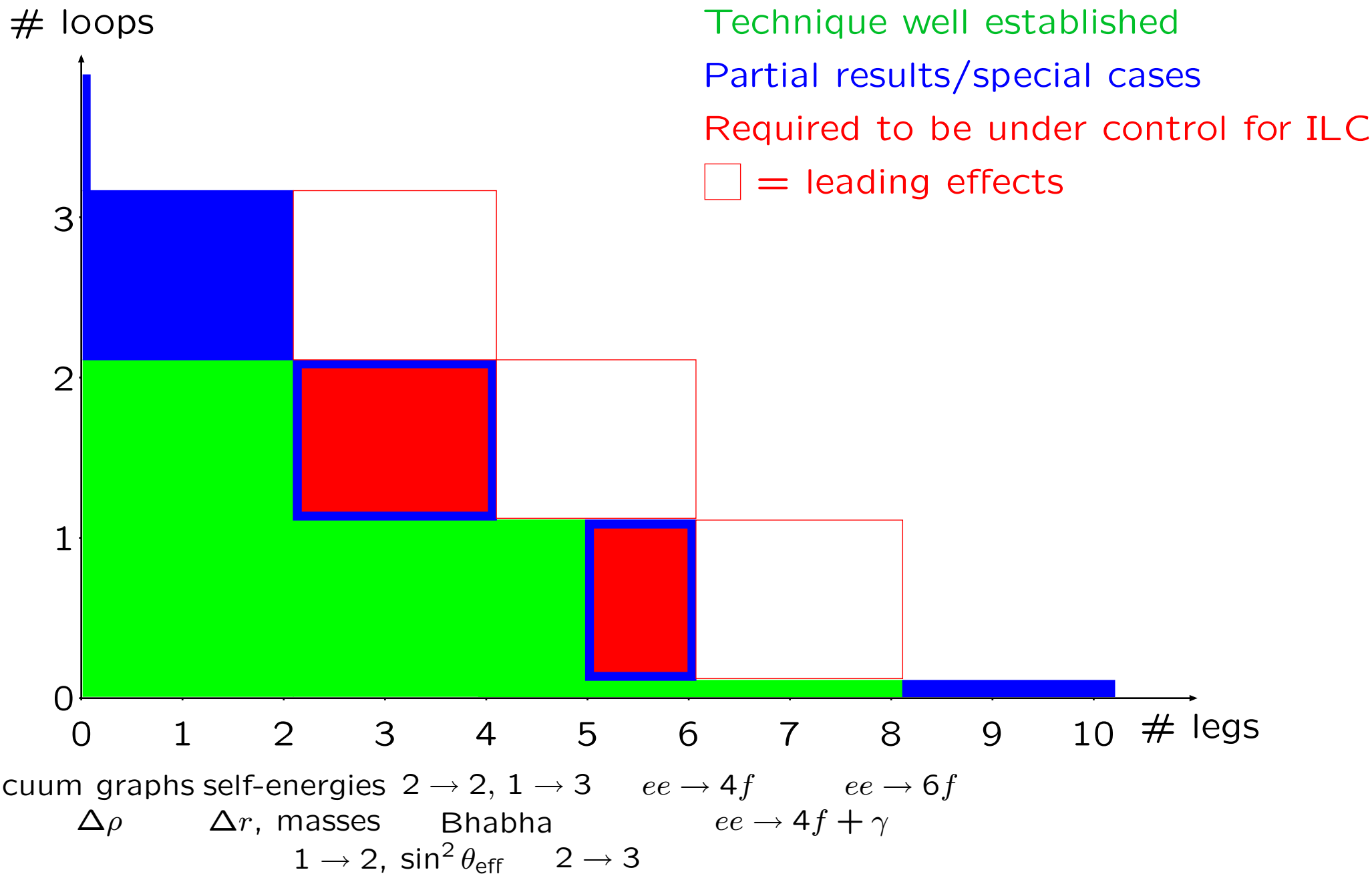
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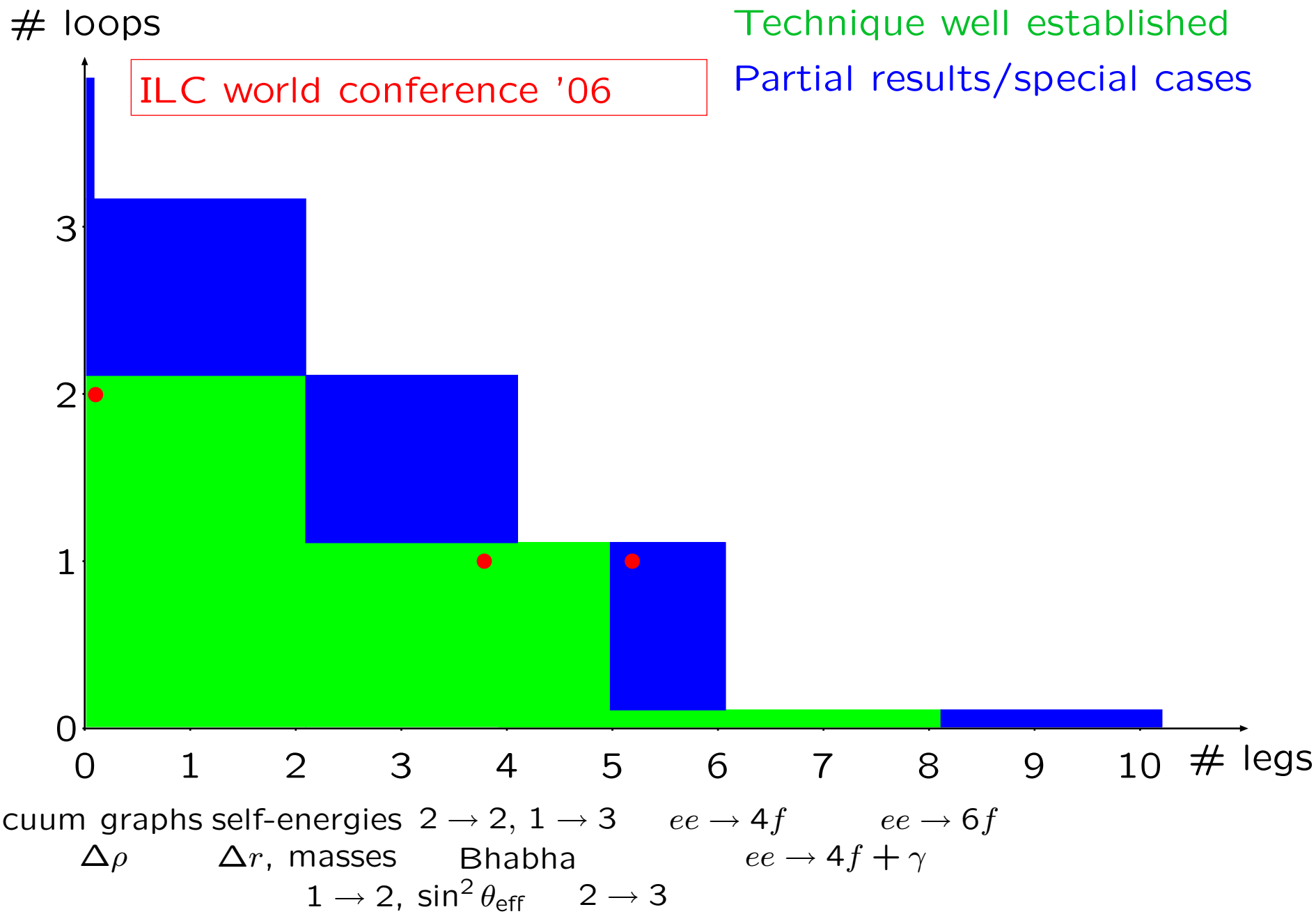
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ILC world conference '06
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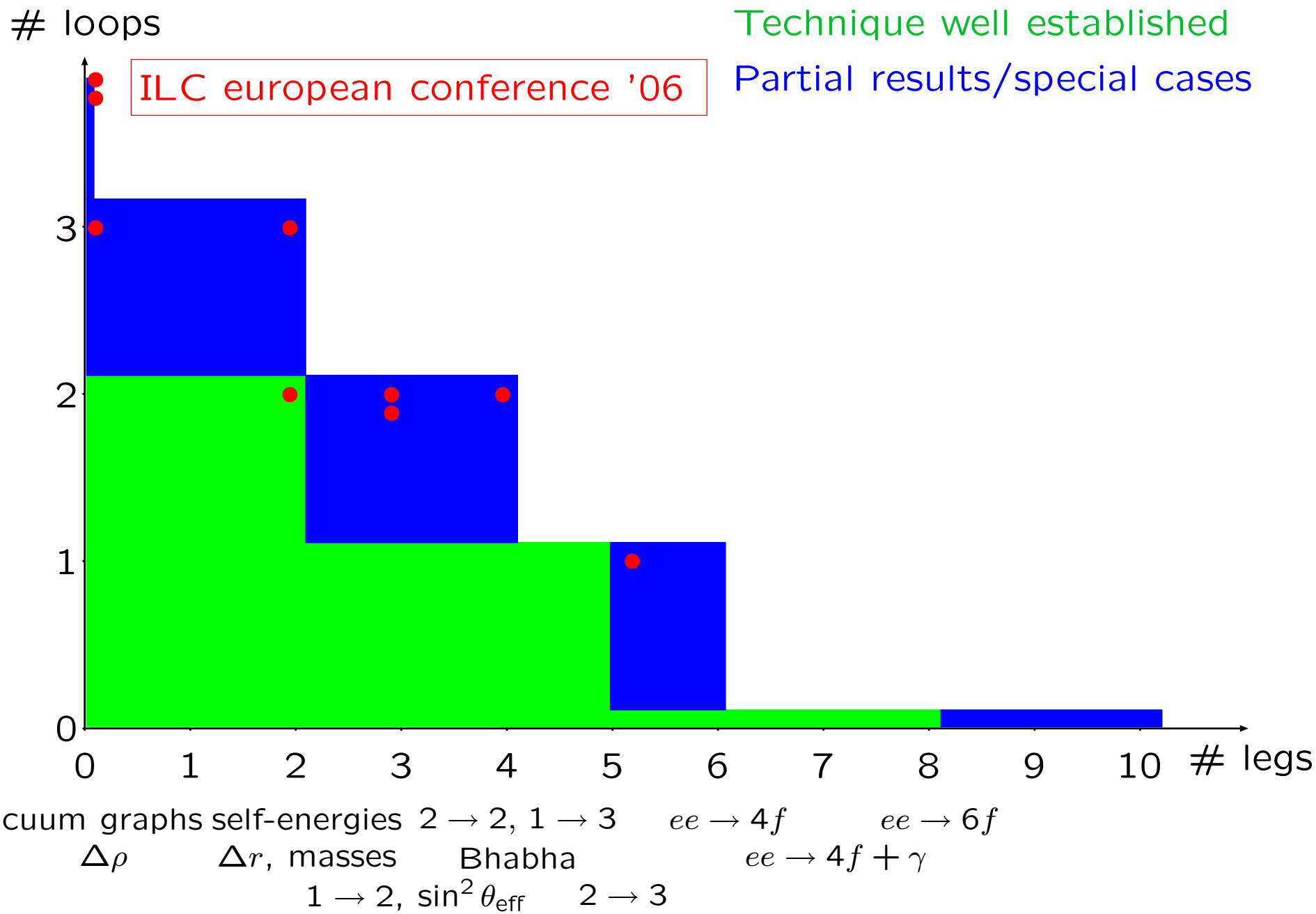
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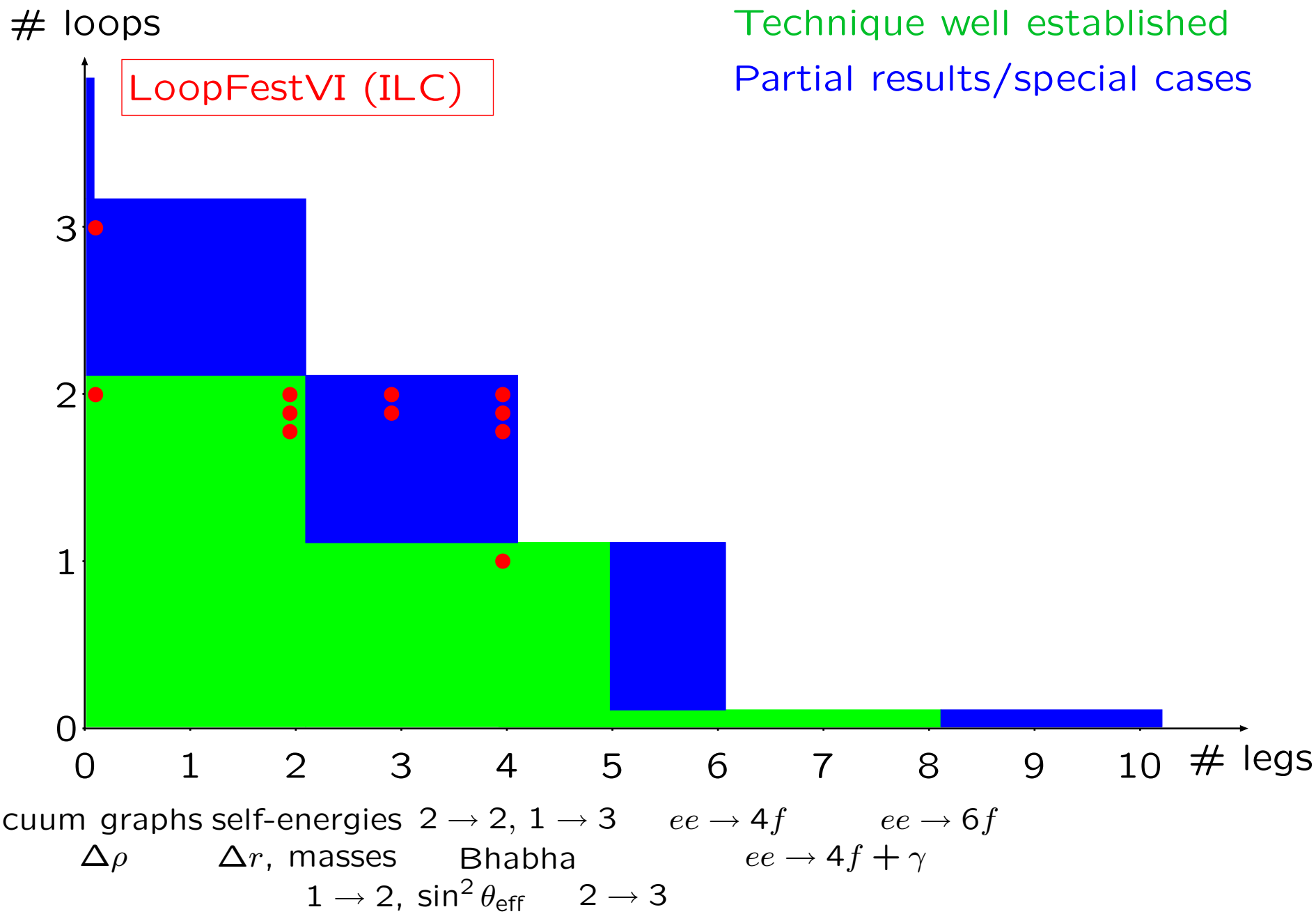
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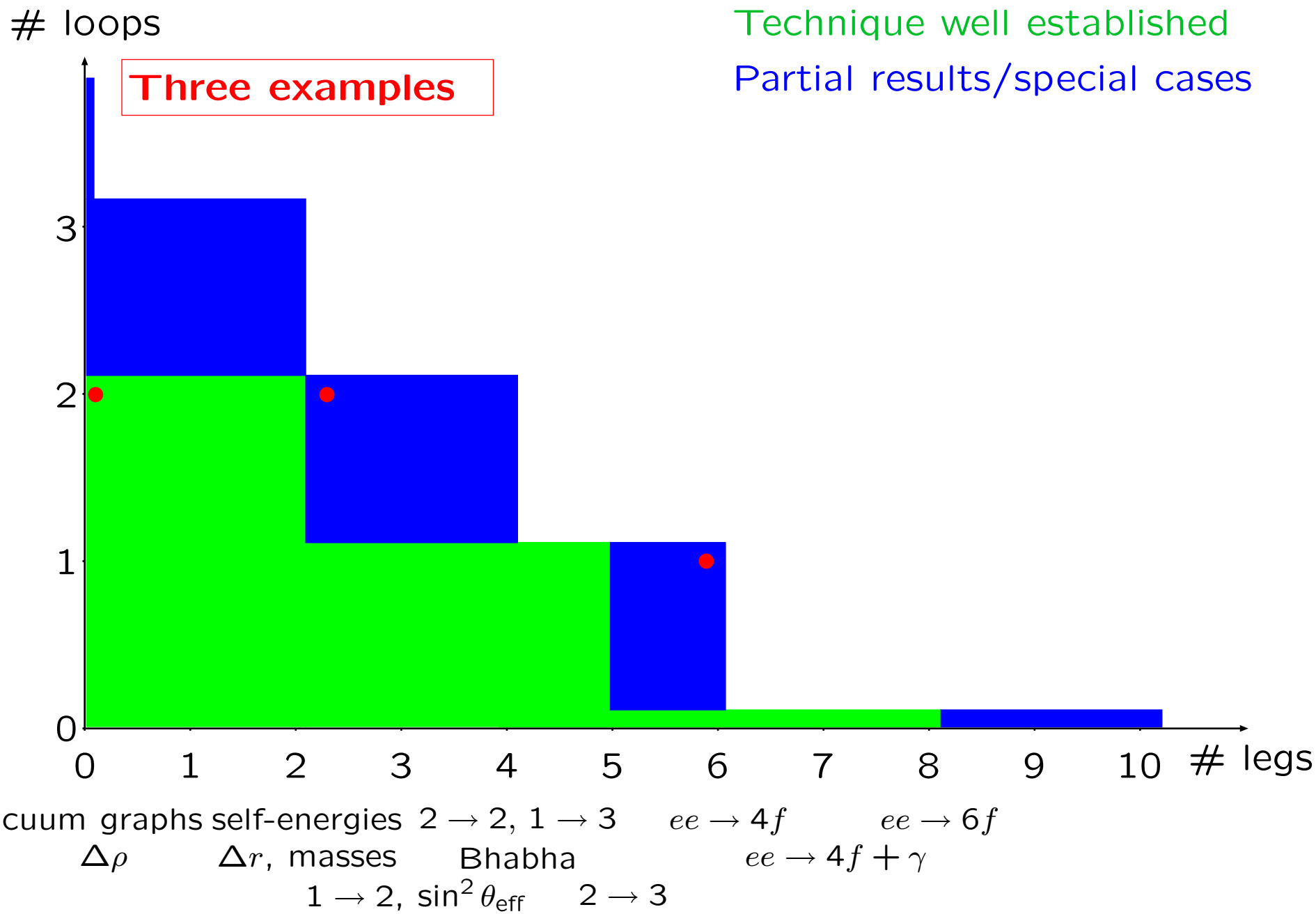
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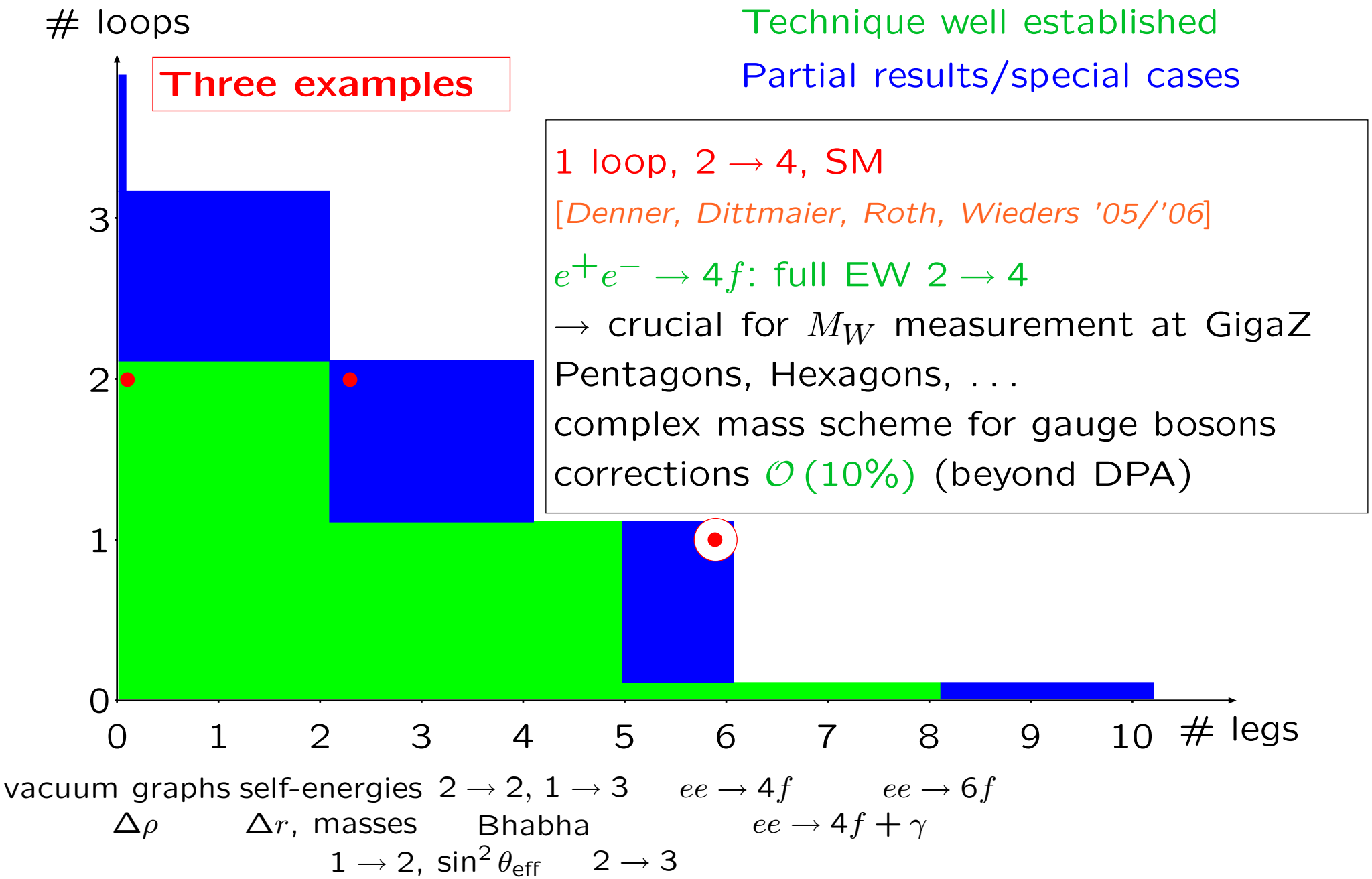
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Three examples
1 loop, 2 → 4, SM
[Denner, Dittmaier, Roth, Wieders '05/'06]
$e^+e^- \to 4f$: full EW 2 → 4
→ crucial for M_W measurement at GigaZ
Pentagons, Hexagons, . . .
complex mass scheme for gauge bosons
corrections $\mathcal{O}(10\%)$ (beyond DPA)
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loops

Three examples

Technique well established

Partial results/special cases

1 loop, $2 \to 4$, SM

[*Denner, Dittmaier, Roth, Wieders '05/'06*]

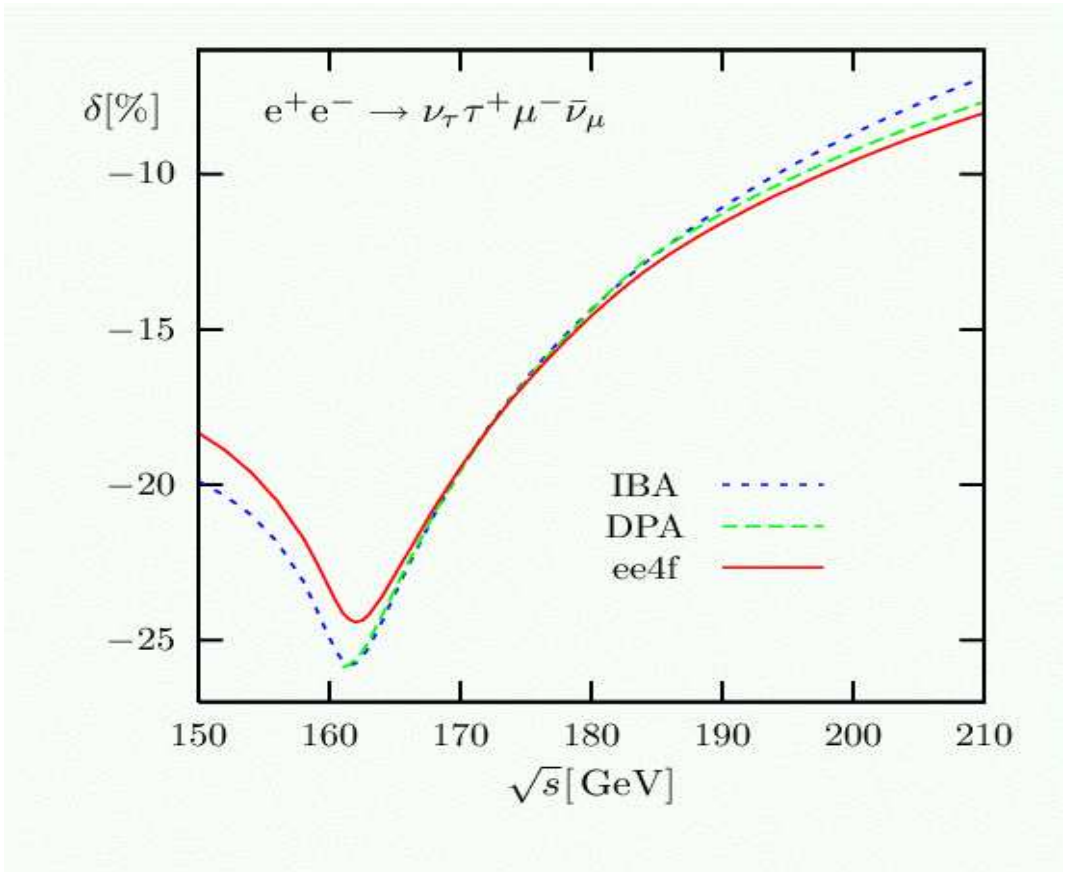
full EW $2 \to 4$

or M_W measurement at GigaZ

Hexagons, . . .

ass scheme for gauge bosons

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



7 8 9 10 # legs

va

$4f$ $ee \to 6f$

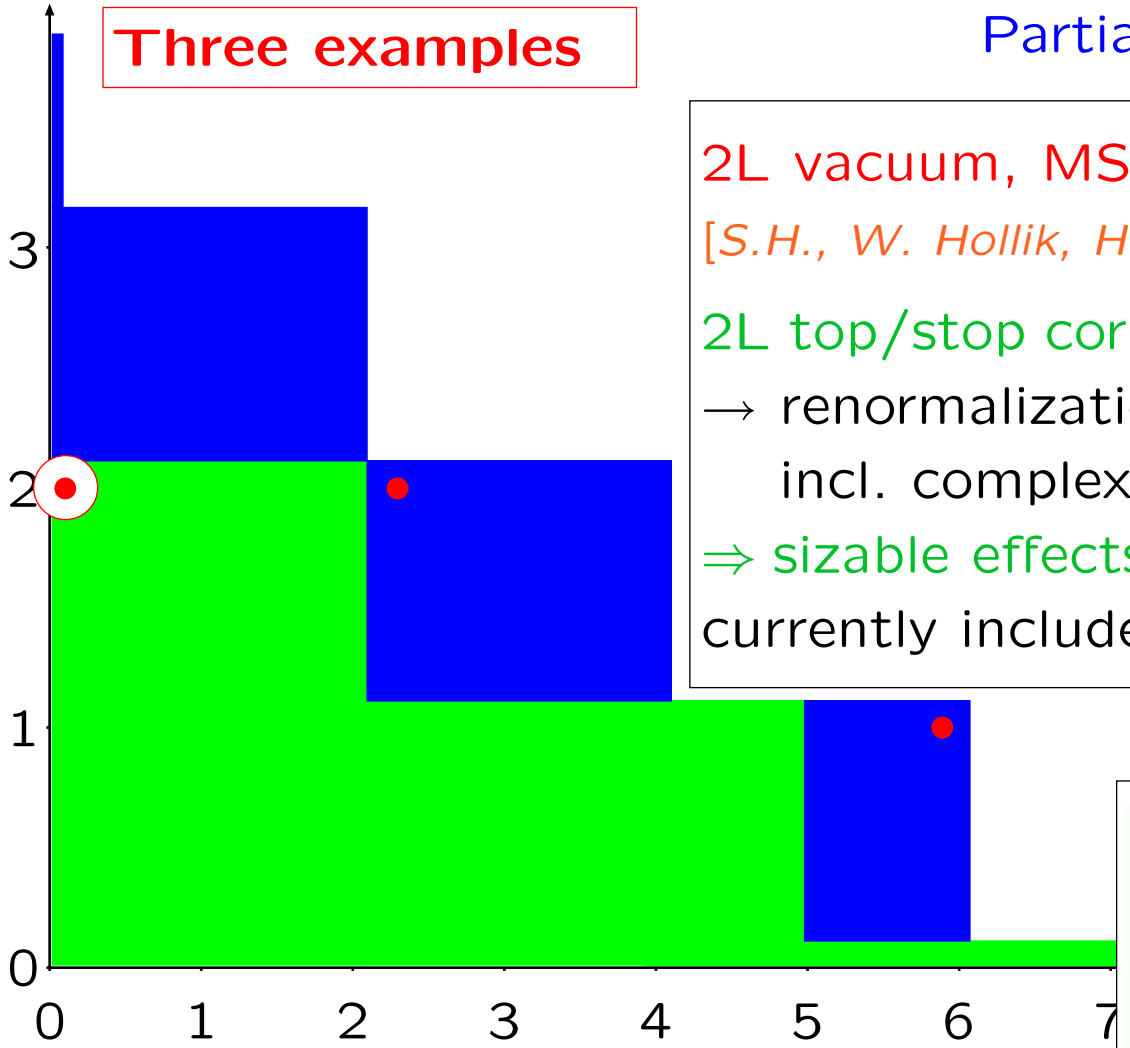
$ee \to 4f + \gamma$

loops

Technique well established

Partial results/special cases

Three examples



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

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

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

2L vacuum, MSSM + renormalization

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

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

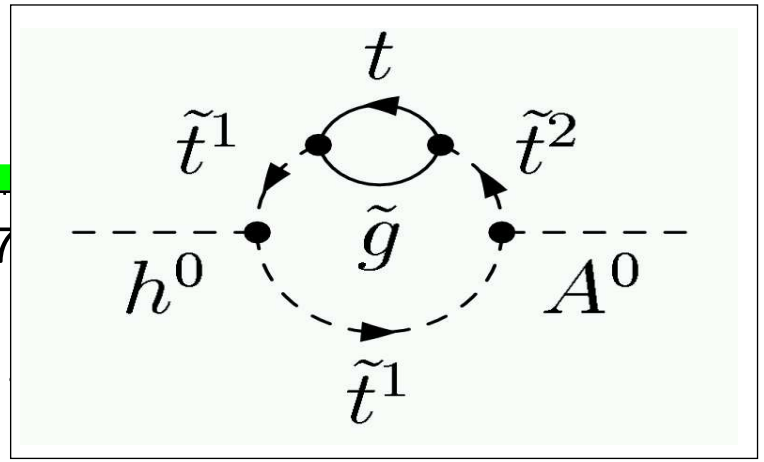
$\to$ renormalization at 2L/1L level

incl. complex phases

$\Rightarrow$ sizable effects for M_h

currently included in `FeynHiggs`

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



loops

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Technique well established

Partial results/special cases

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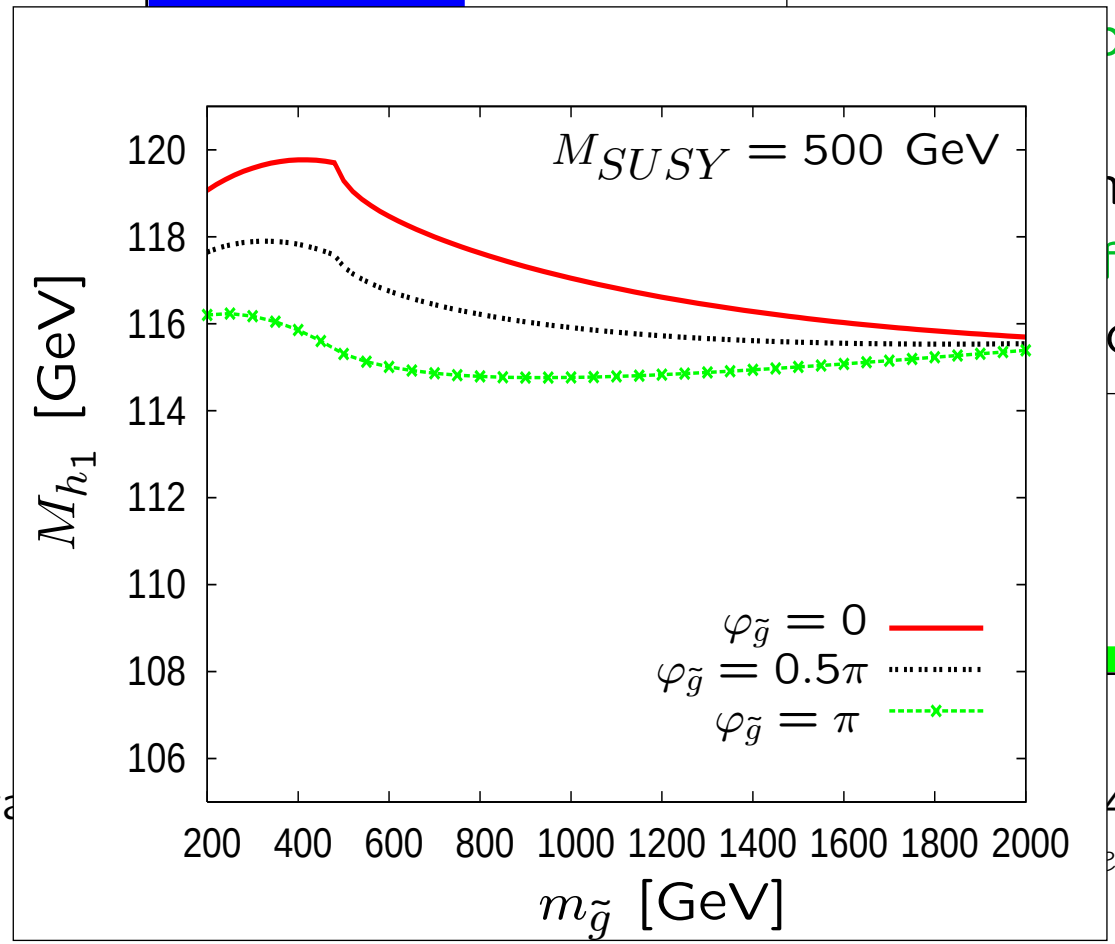

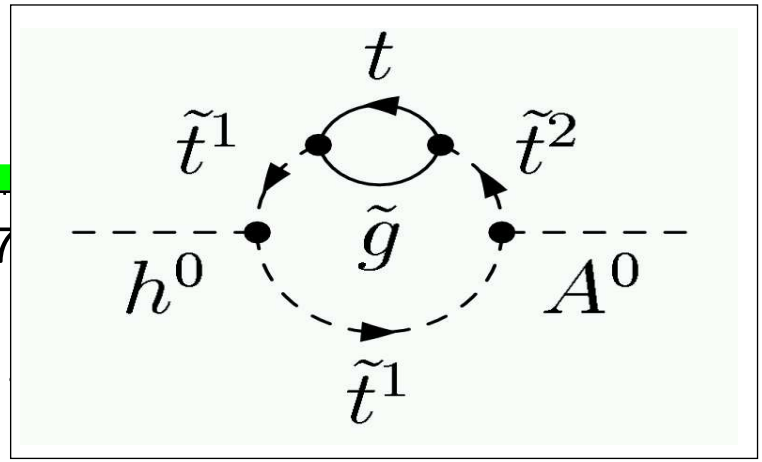

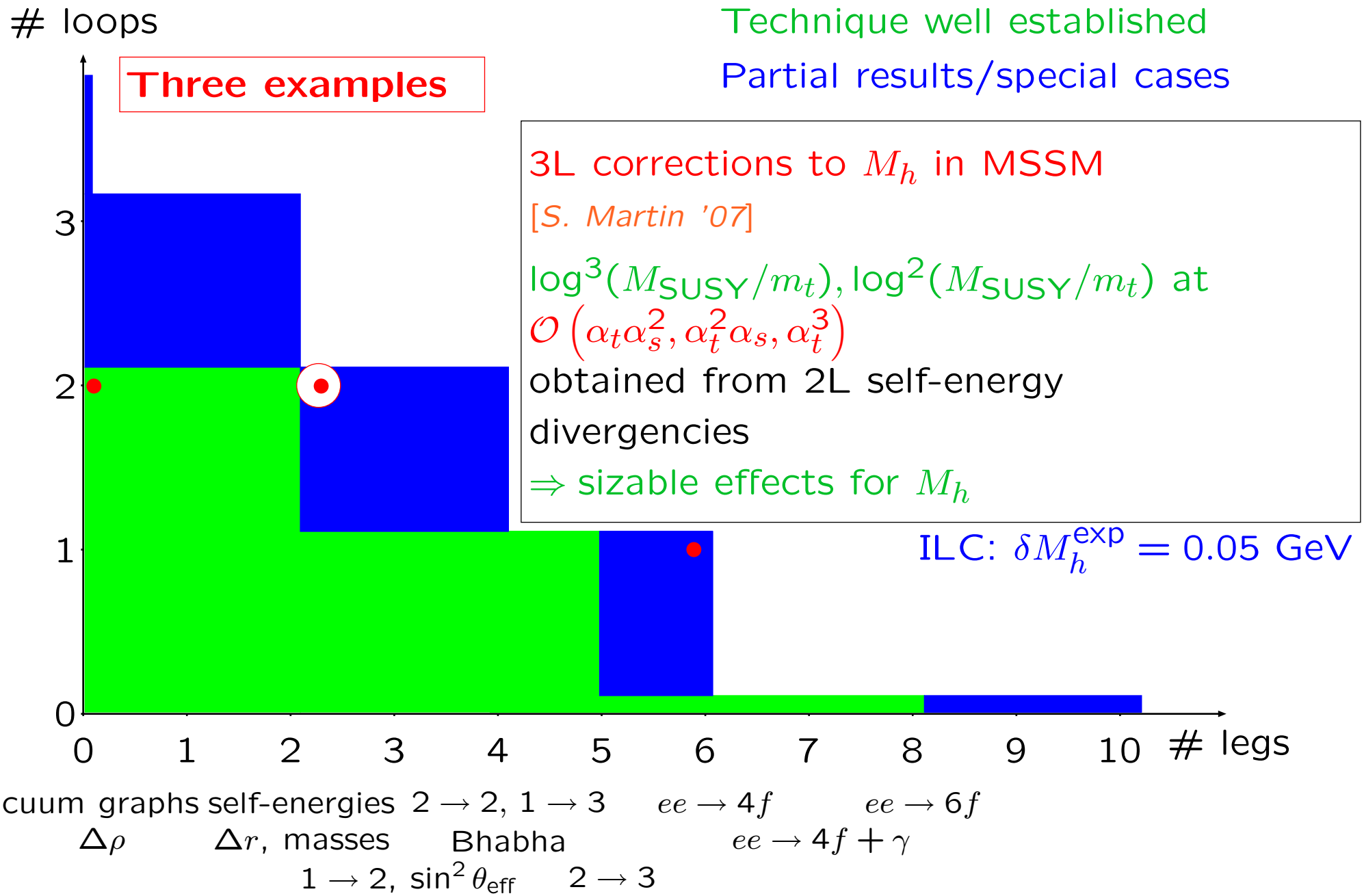
Technique well established
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3L corrections to M_h in MSSM
[S. Martin '07]
$\log^3(M_{\rm SUSY}/m_t), \log^2(M_{\rm SUSY}/m_t)$ at
$\mathcal{O}\left(\alpha_t\alpha_s^2, \alpha_t^2\alpha_s, \alpha_t^3\right)$
obtained from 2L self-energy divergencies
$\Rightarrow$ sizable effects for M_h
ILC: $\delta M_h^{\rm exp} = 0.05$ GeV
0
1
2
3
0 1 2 3 4 5 6 7 8 9 10
legs
vacuum graphs
$\Delta\rho$
self-energies
Δr, masses
$1 \to 2$, $\sin^2\theta_{\rm eff}$
$2 \to 2$, $1 \to 3$
Bhabha
$2 \to 3$
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loops

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3L corrections to M_h in MSSM

[*S. Martin '07*]

$/m_t), \log^2(M_{\rm SUSY}/m_t)$ at

$\alpha_s, \alpha_t^3)$

om 2L self-energy

s

ffects for M_h

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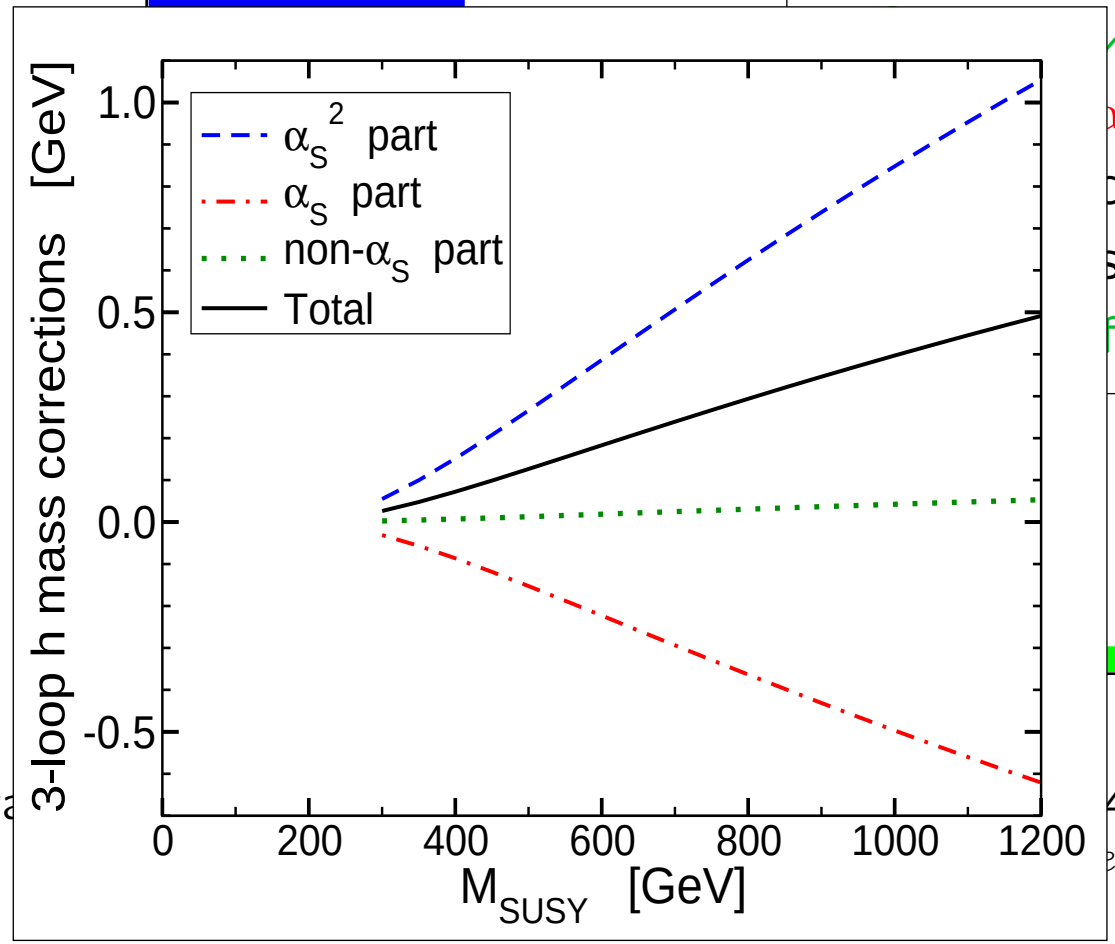

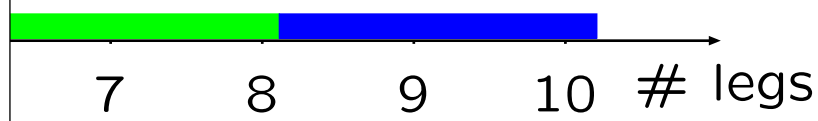

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$/m_t), \log^2(M_{\text{SUSY}}/m_t)$ at

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om 2L self-energy

s

ffects for M_h

next step:

$\log^1(M_{\text{SUSY}}/m_t), \log^0(M_{\text{SUSY}}/m_t)$ at

$\mathcal{O}\left(\alpha_t\alpha_s^2, \alpha_t^2\alpha_s, \alpha_t^3\right)$

at two-loop they are sizable

$\Rightarrow$ real three-loop vacuum diagrams with many scales

+ SUSY 2L renormalization

(what about SUSY restoring CTs?)

needed even for LHC: $\delta M_h \approx 0.20$ GeV

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

7 8 9 10 # legs

va

$4f$ $ee \to 6f$

$ee \to 4f + \gamma$

4. Outlook

There is progress in the right direction,
at least for Higgs, 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

4. Outlook

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⇒ 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