BSM phenomenology with FeynRules

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In collaboration with:

N.D. Christensen, B. Fuks

+MC collaborators

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IPPP BSM Lunch Club

Three main questions

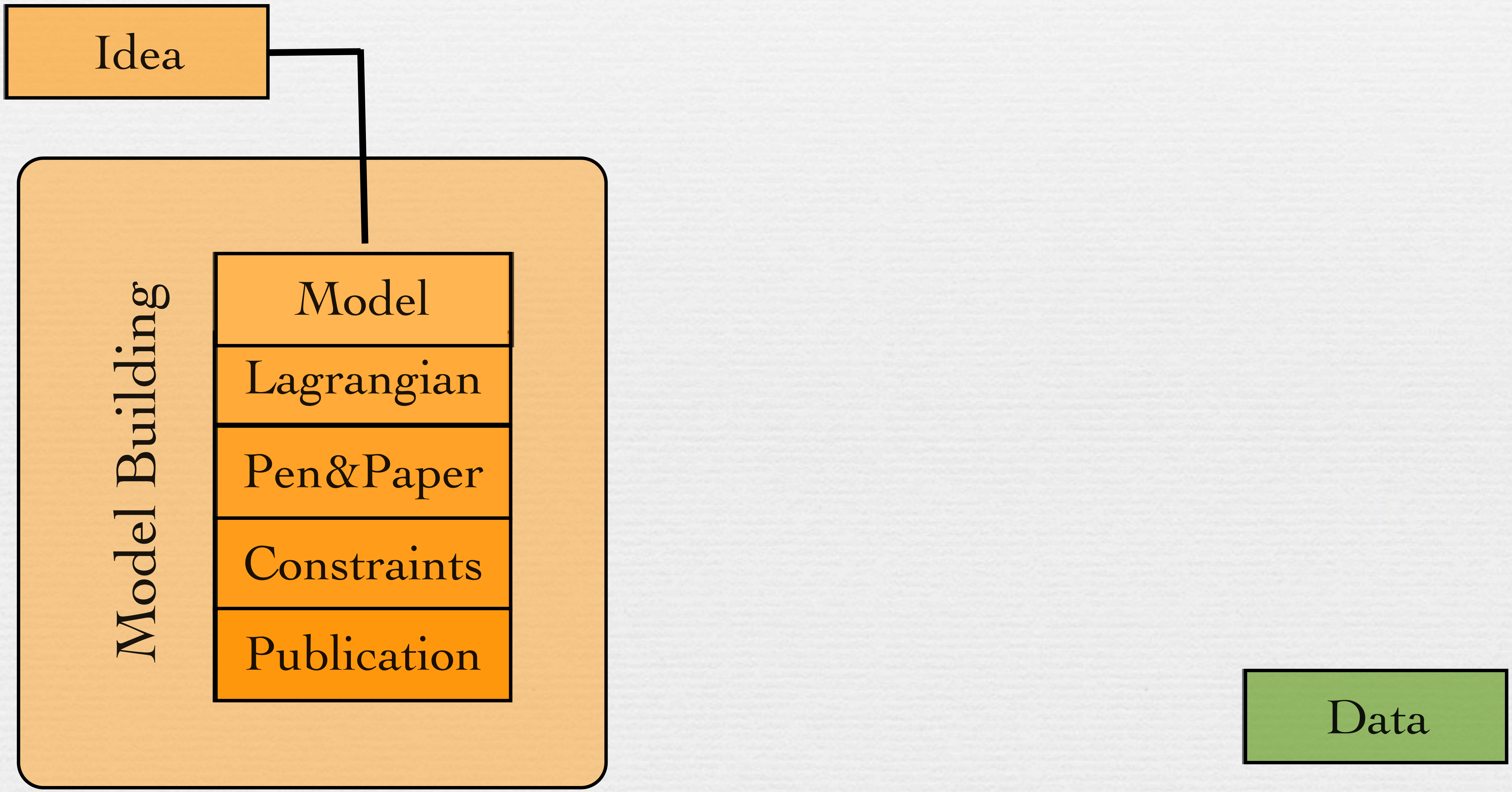
- What is FeynRules?
- What is the philosophy behind it?
- What can you use it for?

A Roadmap for BSM @ the LHC

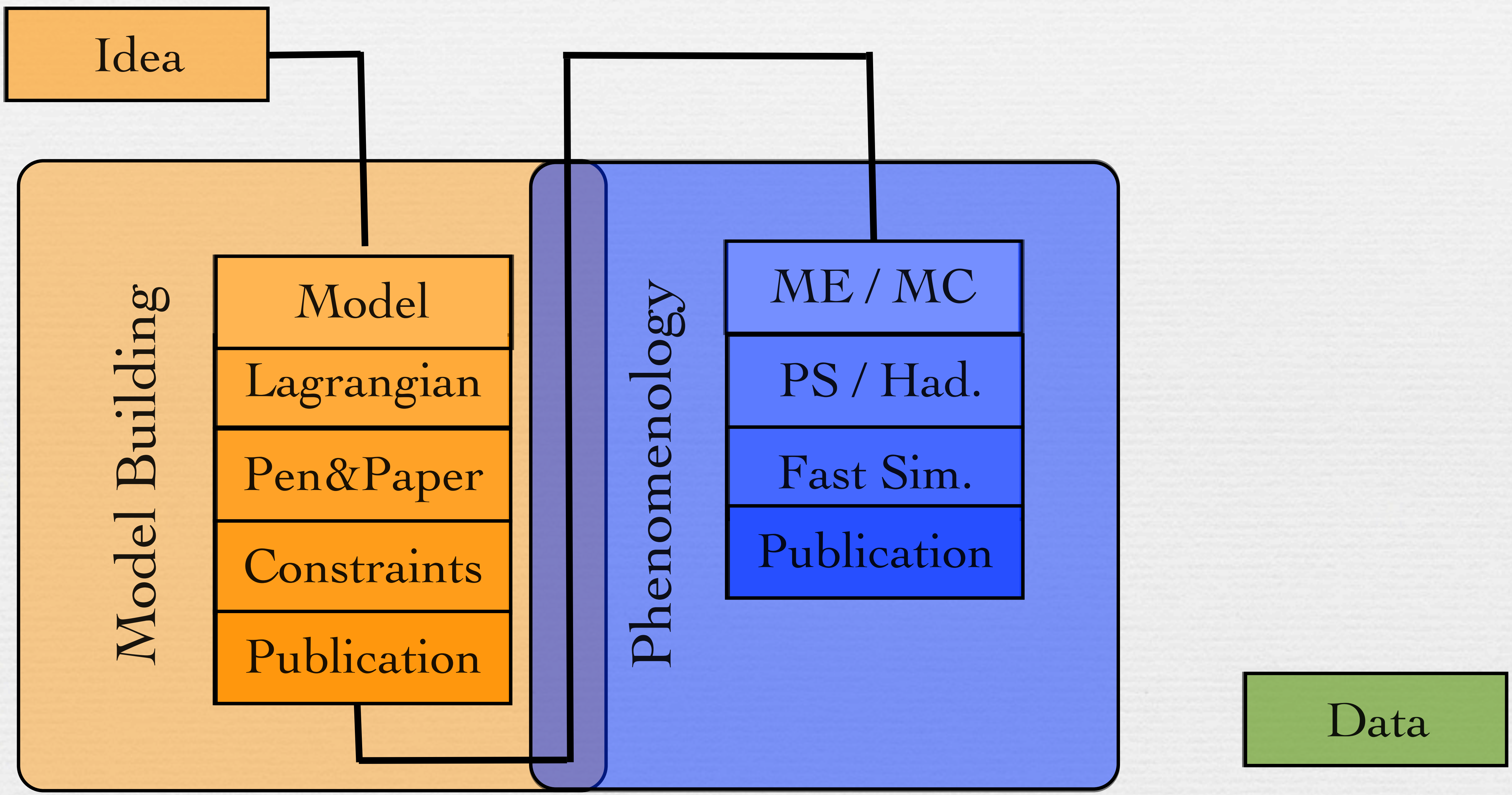
Idea

Data

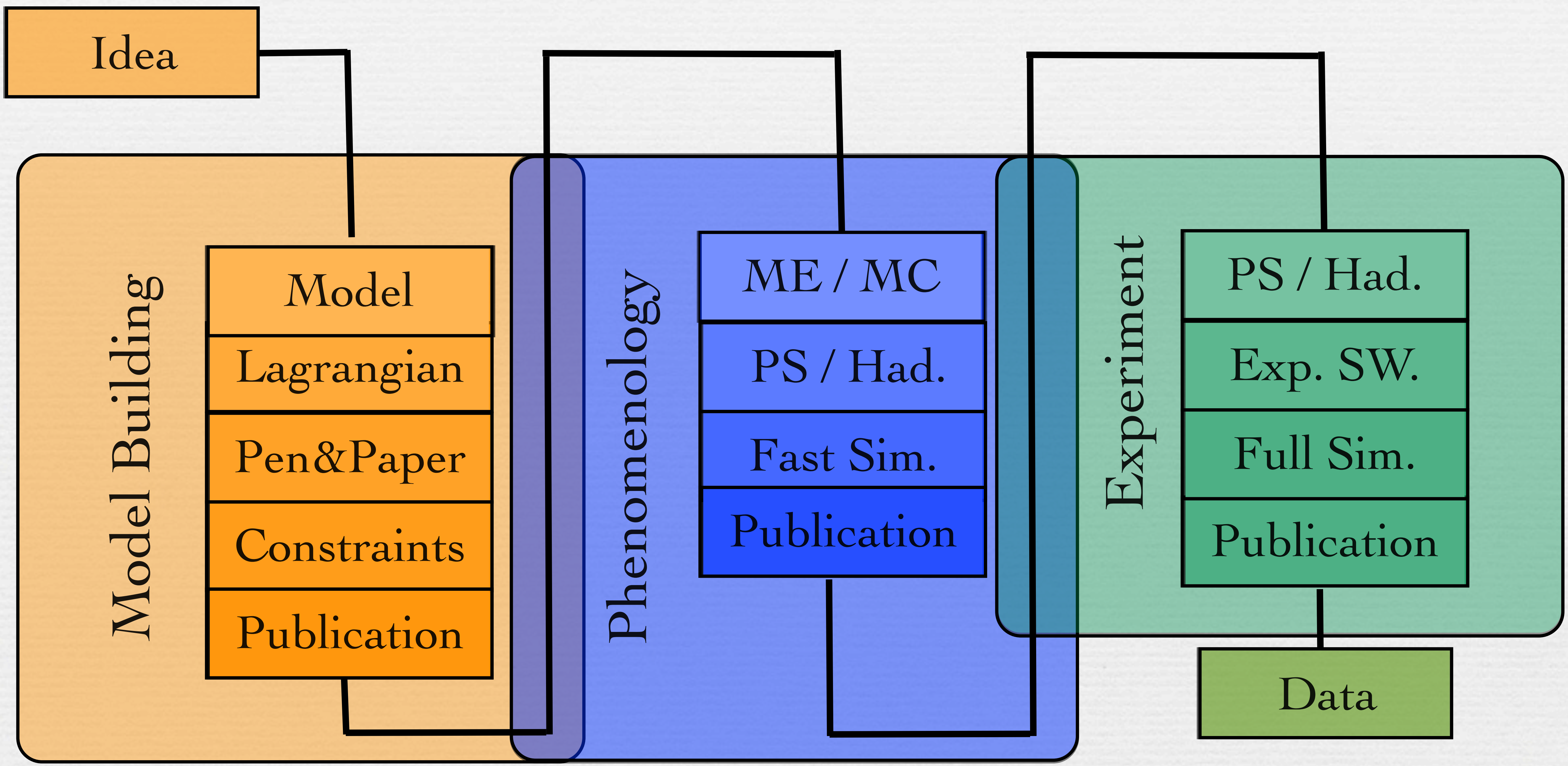
A Roadmap for BSM @ the LHC



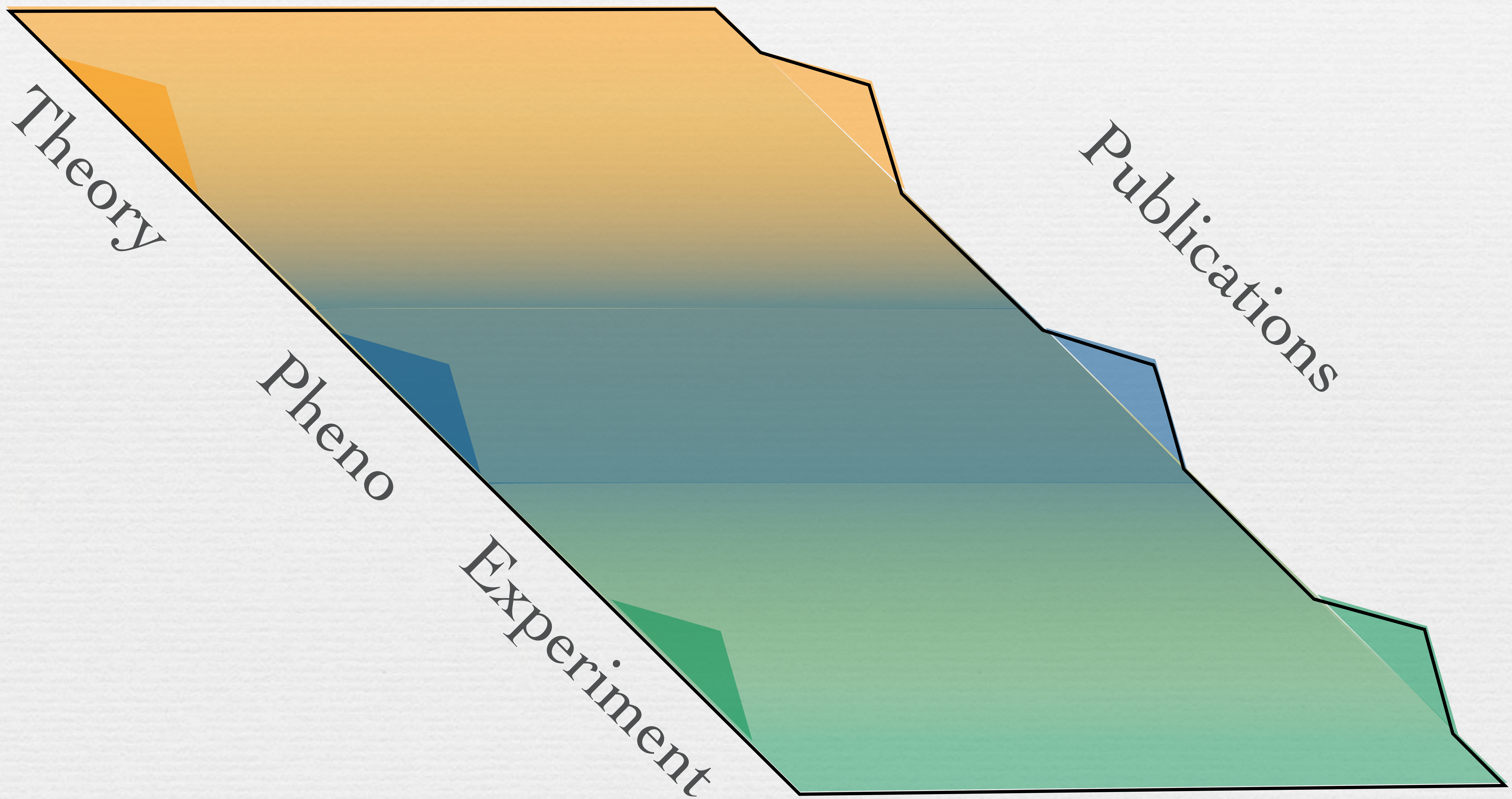
A Roadmap for BSM @ the LHC



A Roadmap for BSM @ the LHC



A Roadmap for BSM @ the LHC



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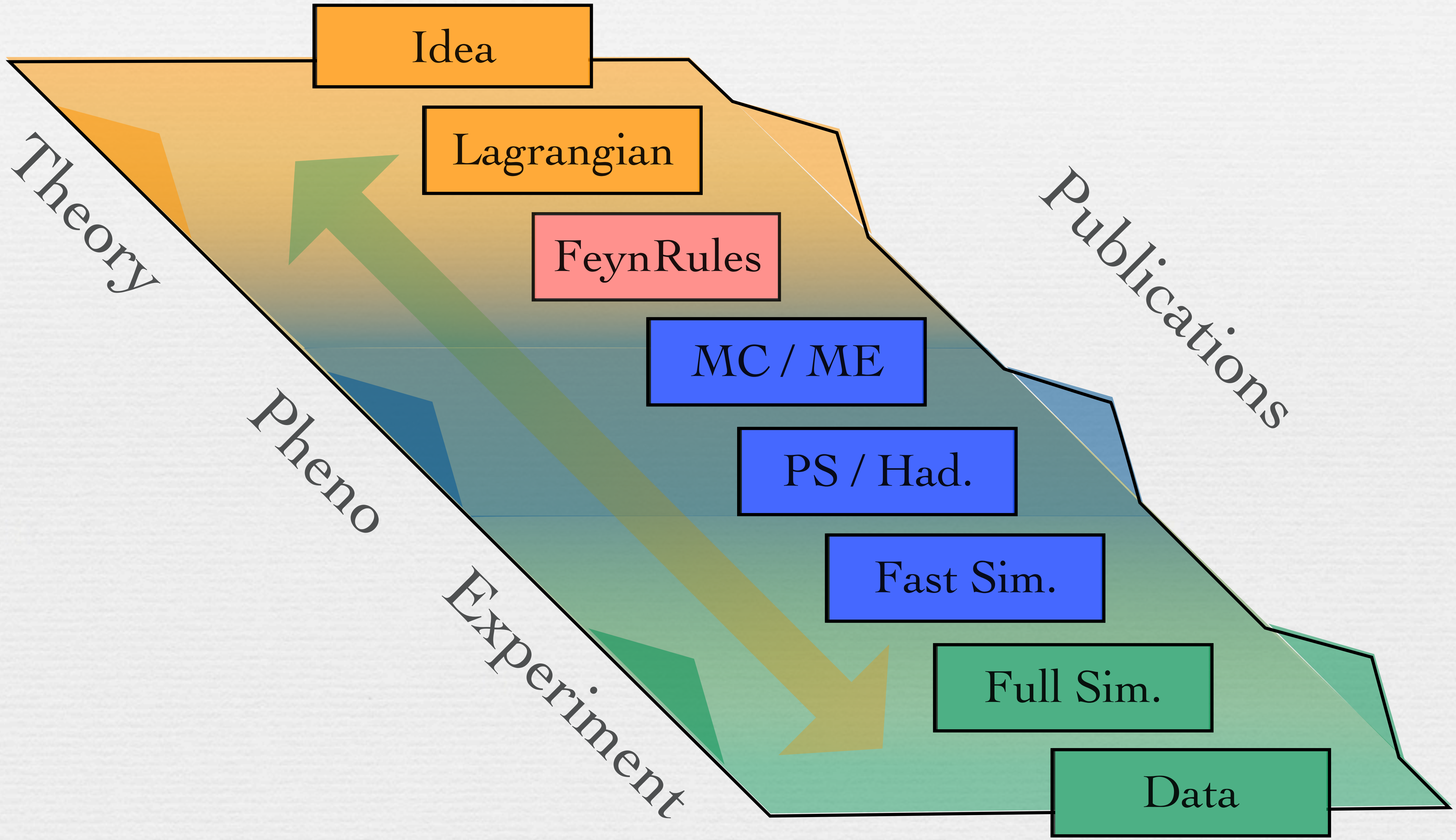

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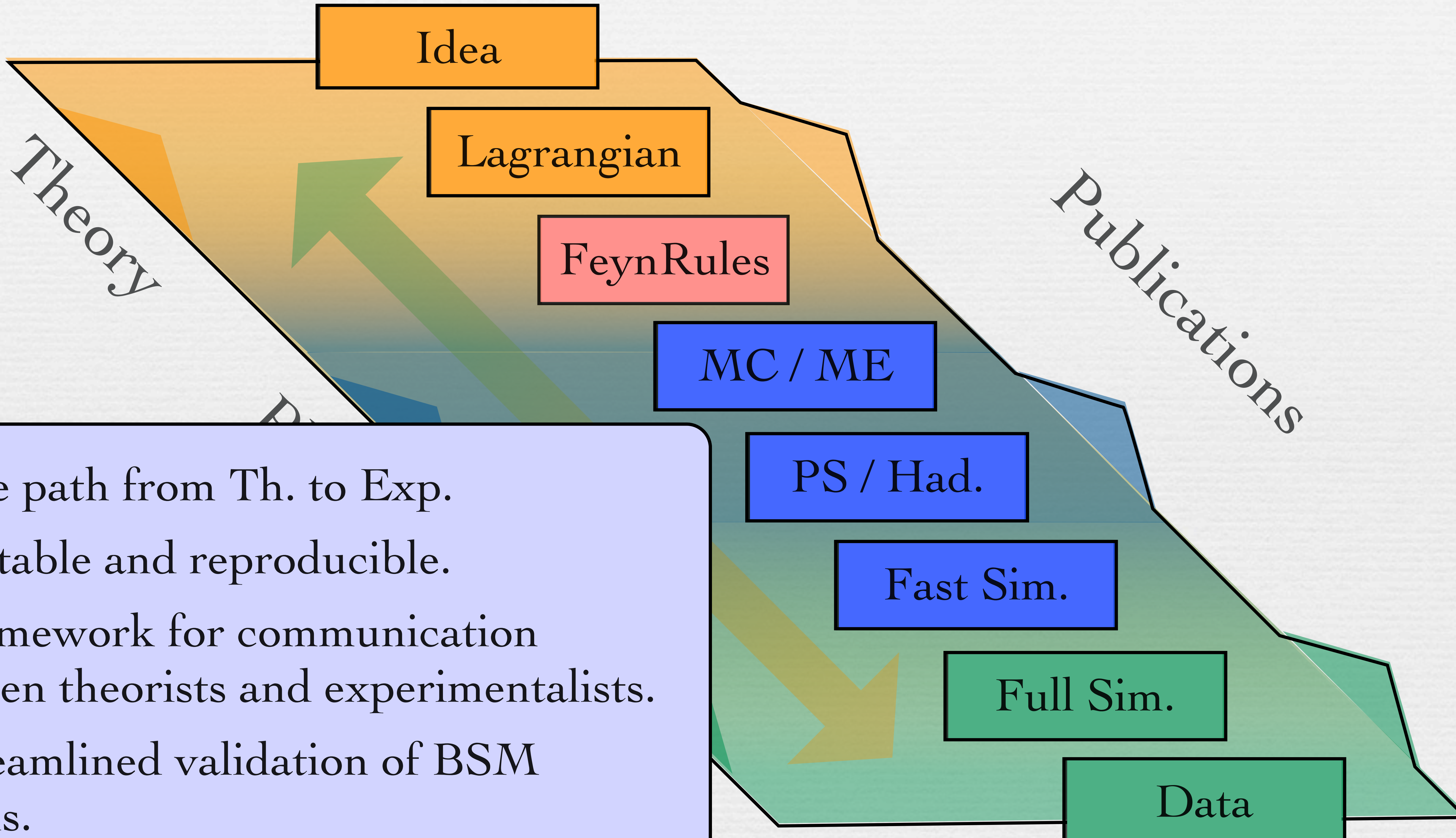

- One path from Th. to Exp.
- Portable and reproducible.
- Framework for communication between theorists and experimentalists.
- Streamlined validation of BSM models.

FeynRules

- Mathematica package that allows to derive Feynman rules directly form a Lagrangian.

  - ➡ Scalars
  - ➡ Fermions (Dirac & Majorana)
  - ➡ Vectors
  - ➡ Spin 2
  - ➡ Ghosts

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FeynRules

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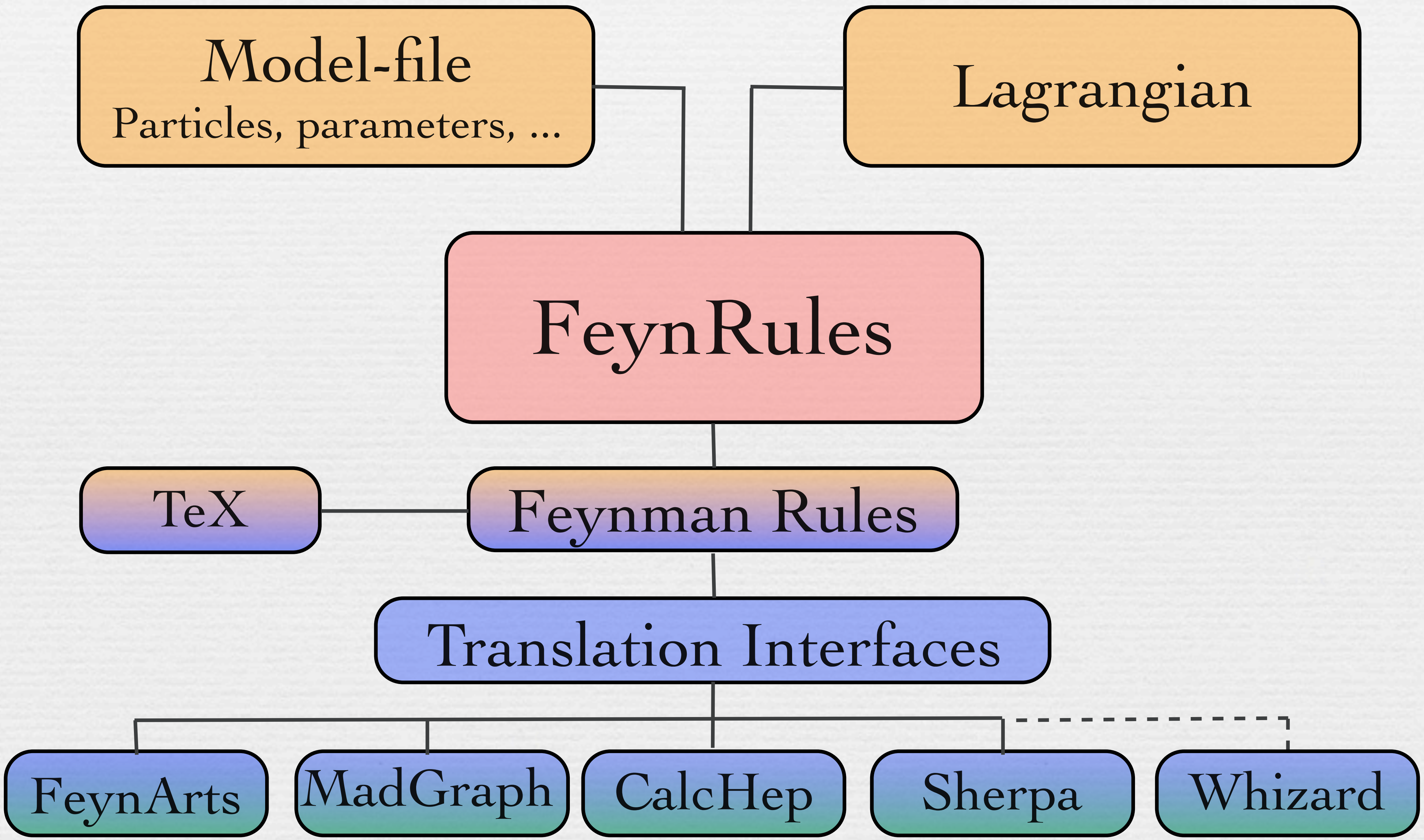
- No special requirements on the form of the Lagrangian (apart from Lorentz and gauge invariance).
- Supported field types:
  - ➡ Scalars
  - ➡ Fermions (Dirac & Majorana)
  - ➡ Vectors
  - ➡ Spin 2
  - ➡ Ghosts

FeynRules



Model-file
Particles, parameters, ...
Lagrangian
FeynRules
TeX
Feynman Rules
Translation Interfaces
FeynArts
MadGraph
CalcHep
Sherpa
Whizard

A simple example

How to Find a Hidden World at the Large Hadron Collider

James D. Wells

MCTP, University of Michigan, Ann Arbor, MI 48109
CERN, Theory Division, CH-1211 Geneva 23, Switzerland

- Simple extension of the SM with a new broken U(1) gauge group.

The Lagrangian

$$\mathcal{L}_X^{KE} = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\chi}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$$

$$\begin{aligned}\mathcal{L}_\Phi &= |D_\mu \Phi_{SM}|^2 + |D_\mu \Phi_H|^2 + m^2_{\Phi_H}|\Phi_H|^2 + m^2_{\Phi_{SM}}|\Phi_{SM}|^2 \\ &\quad -\lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \kappa|\Phi_{SM}|^2|\Phi_H|^2,\end{aligned}$$

- The new sector couples to the SM only through the gauge kinetic mixing and the quartic term in the potential.
- The model is simple, so making predictions for the LHC using a Monte Carlo should be simple, but...

The Lagrangian

- The kinetic term induces a mixing between the U(1)Y and U(1)X fields.

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- The photon and the Z mix with the new gauge boson.
- All their gauge couplings get modified.
- After EWSB, the scalars mix.
- As a consequence, all the SM vertices get modified...

The Lagrangian

- Source of the complications:
  - ➡ The Lagrangian is simple when written in terms of gauge eigenstates.
  - ➡ The MC's require mass eigenstates.

- Since FeynRules works at the level of the Lagrangian, it avoids this problem in a natural.

  - Step 1: Define your new particles and parameters.
  - Step II: Write your lagrangian.

A simple example

- Define your particles and parameters:

```
V[22] ==
    ClassName -> Zp,
    SelfConjugate -> True,
    Mass ->  MZp, 500 ,
    Width ->  WZp, 0.0008252 ,
    PDG -> 1023
```

A simple example

- Write down your Lagrangian

  - FeynRules:

```
LU1 = -1/4 FS[X,mu,nu] FS[X,mu,nu] +chi/2
          FS[B,mu,nu] FS[X,mu,nu]
```

  - Textbook:

$$\mathcal{L}_X^{KE} = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\chi}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$$

A simple example

- As soon as a FeynRules model exists, we are ready to play!
- E.g., deriving the Feynman rules
- We can directly use the Feynman rules inside Mathematica to compute some simple cross section, decay rates, etc.
- We would also like to check all direct and indirect constraints.

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A simple example

- Example 1: the ρ parameter

$$\Delta\rho = \frac{\Pi_{WW}(0)}{m_W^2} \qquad \frac{\Pi_{ZZ}(0)}{m_Z^2}.$$

- We can now directly use FeynArts/FormCalc to do the computation:

```
WriteFeynArtsOutput[ L ]
```

- This output can now be read directly into FeynArts...

A simple example

- Example 1: the ρ parameter

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```
WriteFeynArtsOutput[ L ]
```

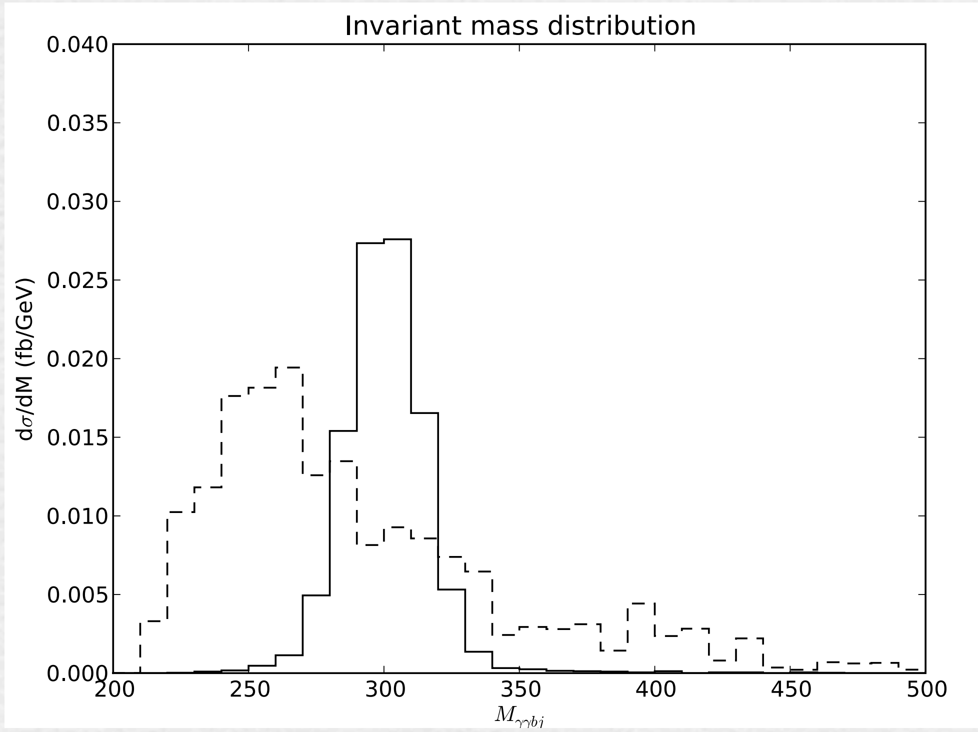
- Example 2: DM relic density
- We can use Micr'Omegas just by implementing the model into CalcHep:

```
WriteCHOutput[ L ]
```

A simple example

- If a model implementation in FeynRules exist, we can directly implement the model into various MC's

WriteMGOutput[L]	creates a MadGraph input file
WriteSHOutput[L]	creates a Sherpa input file



Validation

- SM (N.D. Christensen, CD)
  - ✓ FeynArts
  - ✓ CalcHep/CompHep (31 2-to-2 processes)
  - ✓ MadGraph/MadEvent (31 2-to-2 processes)

Process	CalcHEP Stock	CalcHEP Feynman	CalcHEP Unitary	CompHEP Feynman	MadGraph Stock	MadGraph
$gg \to gg$	116490.	116490.	116490.	116490.	116520.	116460.
$u\bar{u} \to gg$	199.95	199.95	199.95	199.94	200.24	200.07
$t\bar{t} \to gg$	64.595	64.595	64.595	64.592	64.619	64.577
$e^+e^- \to \mu^+\mu^-$	0.37195	0.37195	0.37195	0.37194	0.372	0.37142
$e^+e^- \to e^+e^-$	734.15	734.15	734.15	734.16	733.65	735.09
$e^+e^- \to \nu_e\bar{\nu}_e$	49.145	49.145	49.145	49.145	49.135	49.086
$t\bar{t} \to u\bar{u}$	16.018	16.018	16.018	16.018	16.002	16.016
$u\bar{u} \to s\bar{s}$	9.6103	9.6102	9.6103	9.6097	9.6257	9.6205
$u\bar{d} \to c\bar{s}$	0.23864	0.23864	0.23864	0.23864	0.23867	0.23859
$u\bar{s} \to c\bar{d}$	0.018947	0.018947	0.018947	0.018947	0.018954	0.018916
$t\bar{t} \to W^+W^-$	17.265	17.265	17.265	17.265	17.256	17.272
$t\bar{t} \to ZZ$	1.2686	1.2686	1.2686	1.2686	1.2679	1.2705

Validation

- 3-Site Model (N.D. Christensen)
  - ✓ 222 2-to-2 processes in CalcHep and MadGraph/MadEvent.
- Triangle Moose Model (N.D. Christensen)
  - ✓ 222 2-to-2 processes in CalcHep (MadGraph on-going).
- Universal extra dimensions (P. de Aquino)
  - ✓ 118 2-to-2 processes in CalcHep and MadGraph/MadEvent.

e1R-,m1R->e-,m-	6.5807×10^{-1}	6.5818×10^{-1}	6.5818×10^{-1}	OK: 0.0167142%
e1R-,m1R+>e-,m+	4.7857×10^{-1}	4.7682×10^{-1}	4.7682×10^{-1}	OK: 0.366343%
e1R-,e1R+>A,A	2.0803×10^{-1}	2.0788×10^{-1}	2.0788×10^{-1}	OK: 0.072131%
n11,n11~>u,u~	1.6364×10^{-1}	1.6354×10^{-1}	1.6354×10^{-1}	OK: 0.0611284%
n11,n11~>Z,Z	4.1402×10^{-1}	4.1349×10^{-1}	4.1349×10^{-1}	OK: 0.128095%
n11,n11~>W+,W-	5.9018×10^{-1}	5.9009×10^{-1}	5.901×10^{-1}	OK: 0.0152507%

Validation

- Generic MSSM (120 free parameters, B. Fuks)
  - We checked the SPS1a cMSSM limit.
    - ✓ FeynArts (2-to-2 hadroproduction cross-sections).
    - ✓ MadGraph/MadEvent & CalcHep:
      320 1-to-2 decays.
      456 2-to-2 processes.
      2700 2-to-3 processes.
    - ✓ Sherpa and Omega/Whizard validation on-going.

e1R-,m1R->e-,m-	6.5807×10^{-1}	6.5818×10^{-1}	6.5818×10^{-1}	OK: 0.0167142%
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Perspectives

- Weyl fermion (in debugging phase right now).
- Superfield formalism.
- Automatic diagonalisation of mass matrices.
- One-loop evolution equations.

Conclusion

- FeynRules derives Feynman rules from a Lagrangian.
- Automatic implementation of BSM models into various Feynman diagram generators:
  - CalcHep/CompHep
  - FeynArts/FormCalc
  - MadGraph/MadEvent
  - Sherpa
  - ...
- This approach could provide a new way to implement, validate and test BSM models implementation for the LHC.
- The package can be downloaded from:

  http://feynrules.phys.ucl.ac.be

Higher-Dim. Operators

- FeynRules can derive Feynman rules for higher dimensional operators.
- Some ME generators have restrictions on the Lorentz structures available (e.g. the HELAS routines for MadGraph).
- In the FeynRules approach these routines could be generated by FR itself (all the information needed is in the Feynman rules).
- On-going projects to write Lorentz structures in an automated way directly from the Feynman rules for MadGraph and FeynArts.

Eta-Eta' mixing

- The default version of FeynArts does not support non-linear sigma model interactions.
- Solution:

FR → Feynman rules → Lorentz structure → FeynArts

- This approach was applied in [arXiv:0901.2860] to compute the eta-eta' mixing in FeynArts (with the use of FR).

A simple example

- **Step I:** Define your particles and parameters:

```
lX == {
     Value -> 0.5,
     InteractionOrder -> {QED, 2}}
```

```
S[4] == {
     ClassName -> X,
     SelfConjugate -> True,
     Mass -> {MX, 40},
     Width -> {WX, 0}}
```

$$\mathcal{L}_X = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2} m_X^2 X^2 + \lambda_X X^2 \Phi^\dagger \Phi$$

A Roadmap for BSM @ the LHC

- Workload is tripled, due to disconnected fields of expertise.
- Error-prone, painful validation at each step.
- Proliferation of private MC's/Pythia tunings:
  - ➡ No clear documentation.
  - ➡ Not traceable.
- We need more than just papers to communicate between theorists and experimentalists!