BSM phenomenology with FeynRules

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In collaboration with:
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+MC collaborators

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IPMU Focus week

Outline

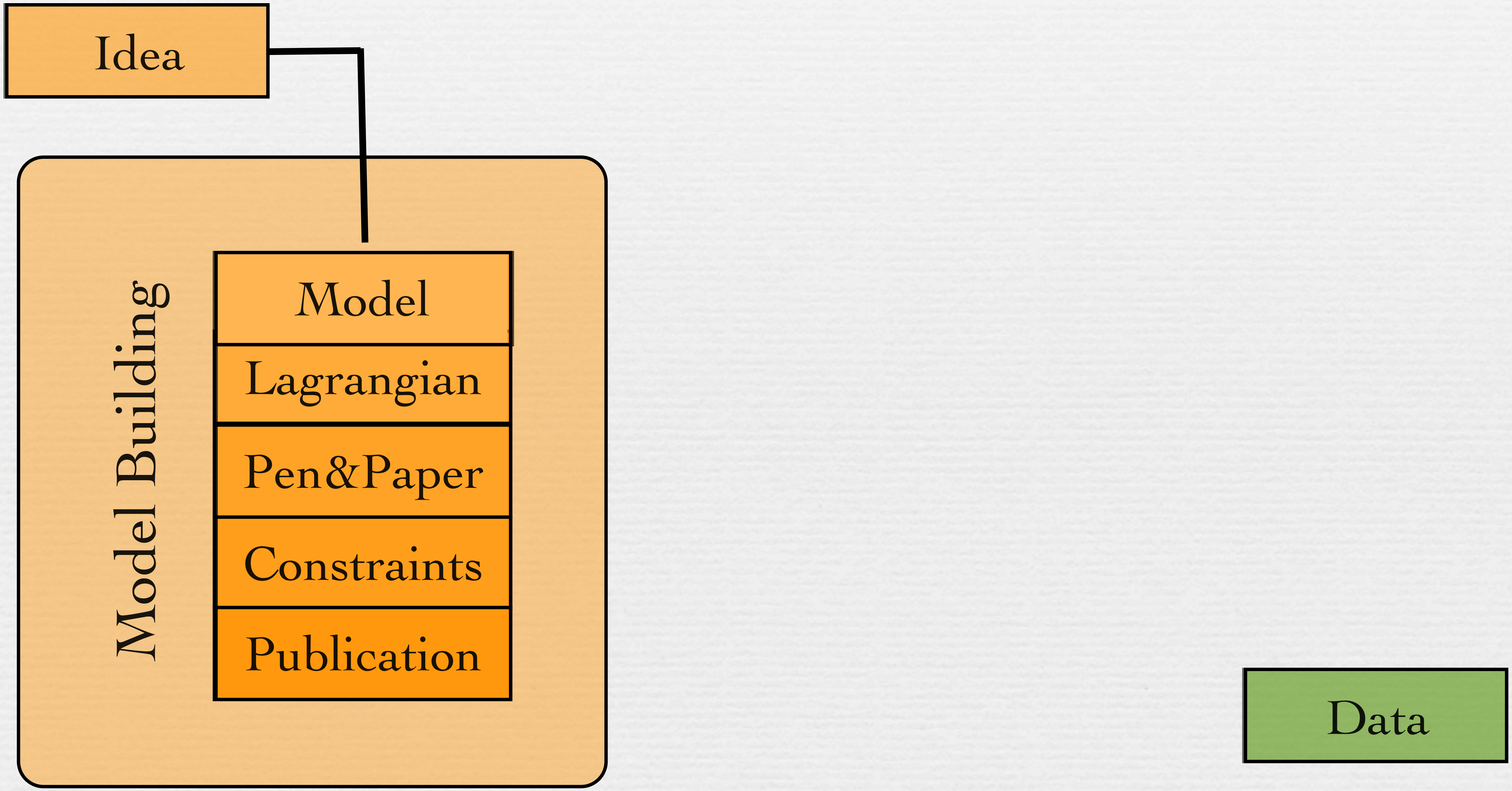
- A RoadMap to BSM @ the LHC
- FeynRules
- A simple example
- Validation of BSM models

A Roadmap for BSM @ the LHC

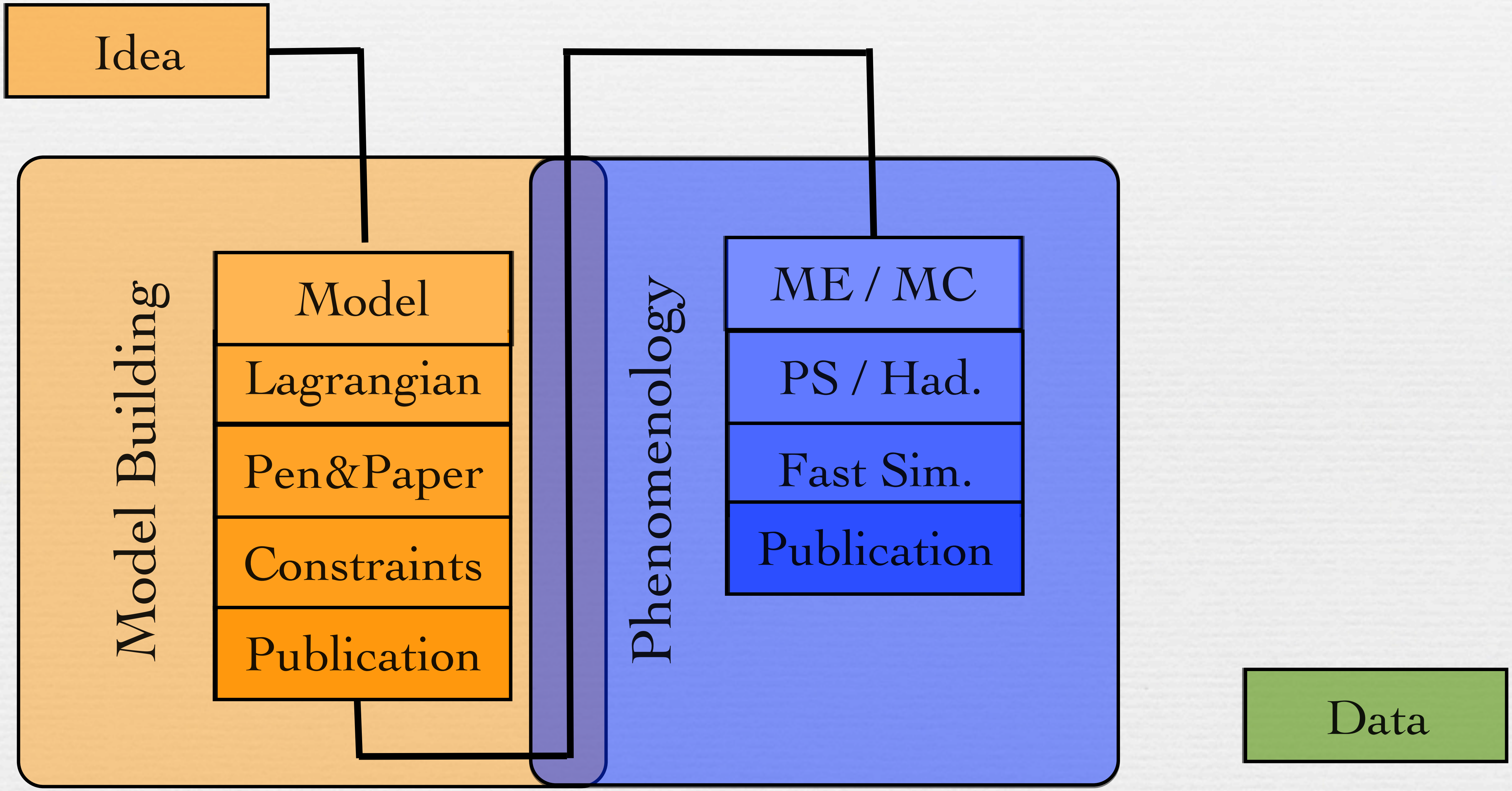
Idea

Data

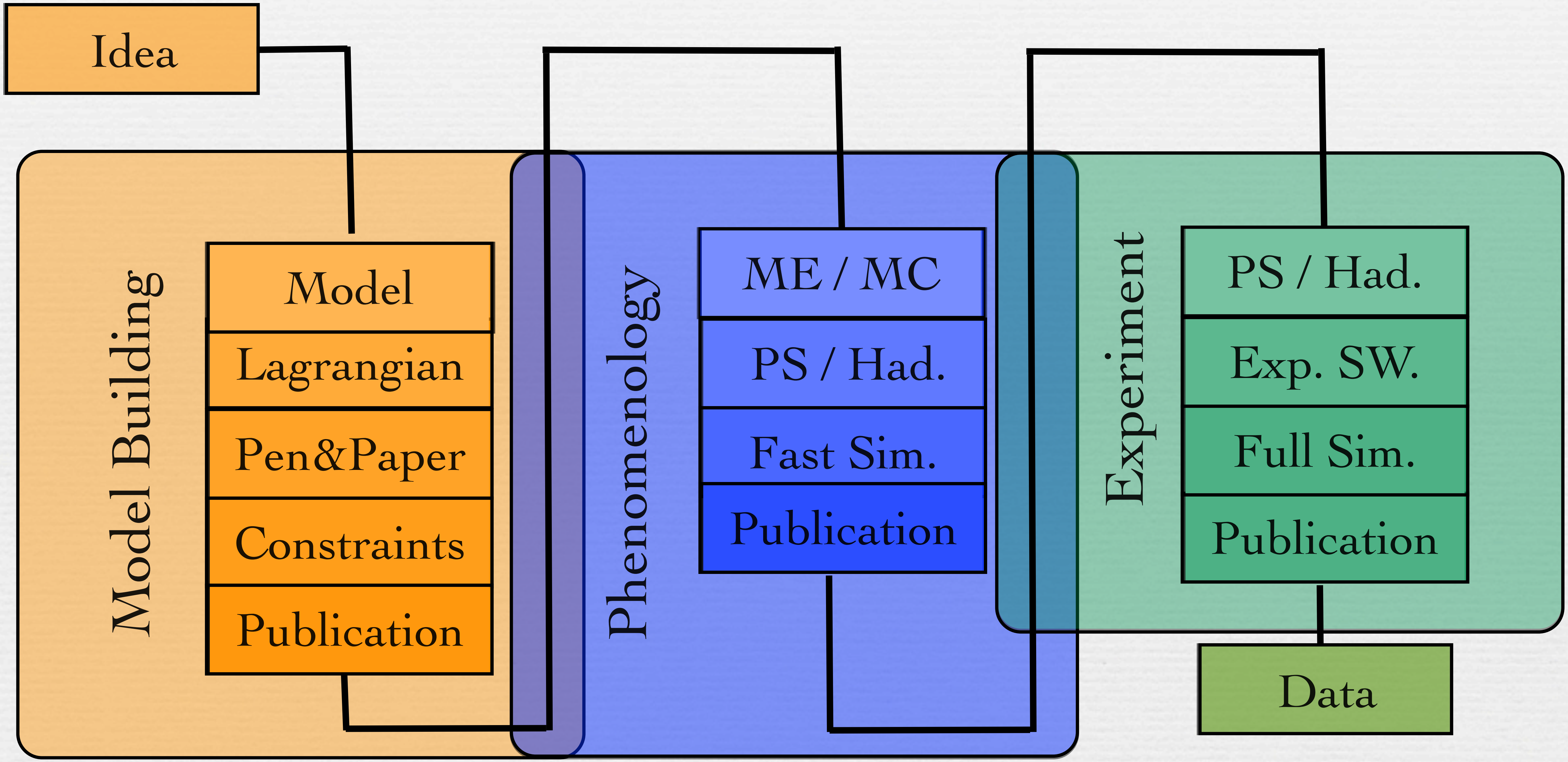
A Roadmap for BSM @ the LHC



A Roadmap for BSM @ the LHC

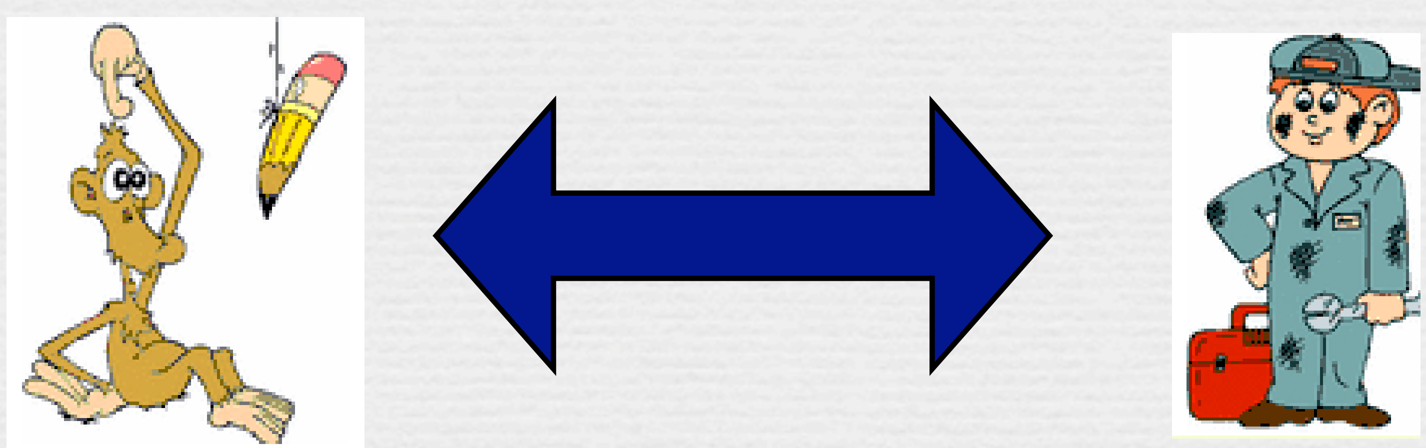


A Roadmap for BSM @ the LHC

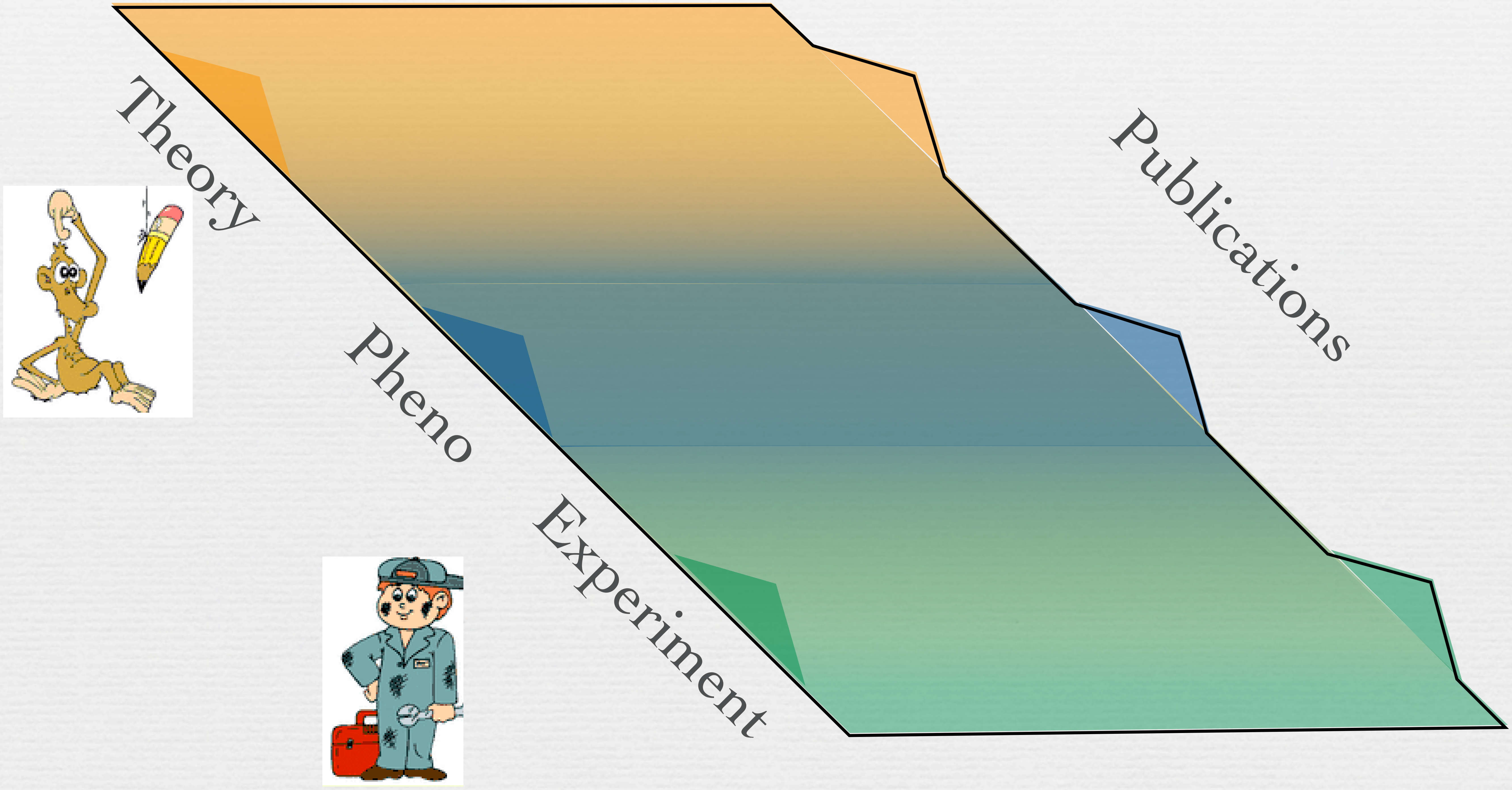


A Roadmap for BSM @ the LHC

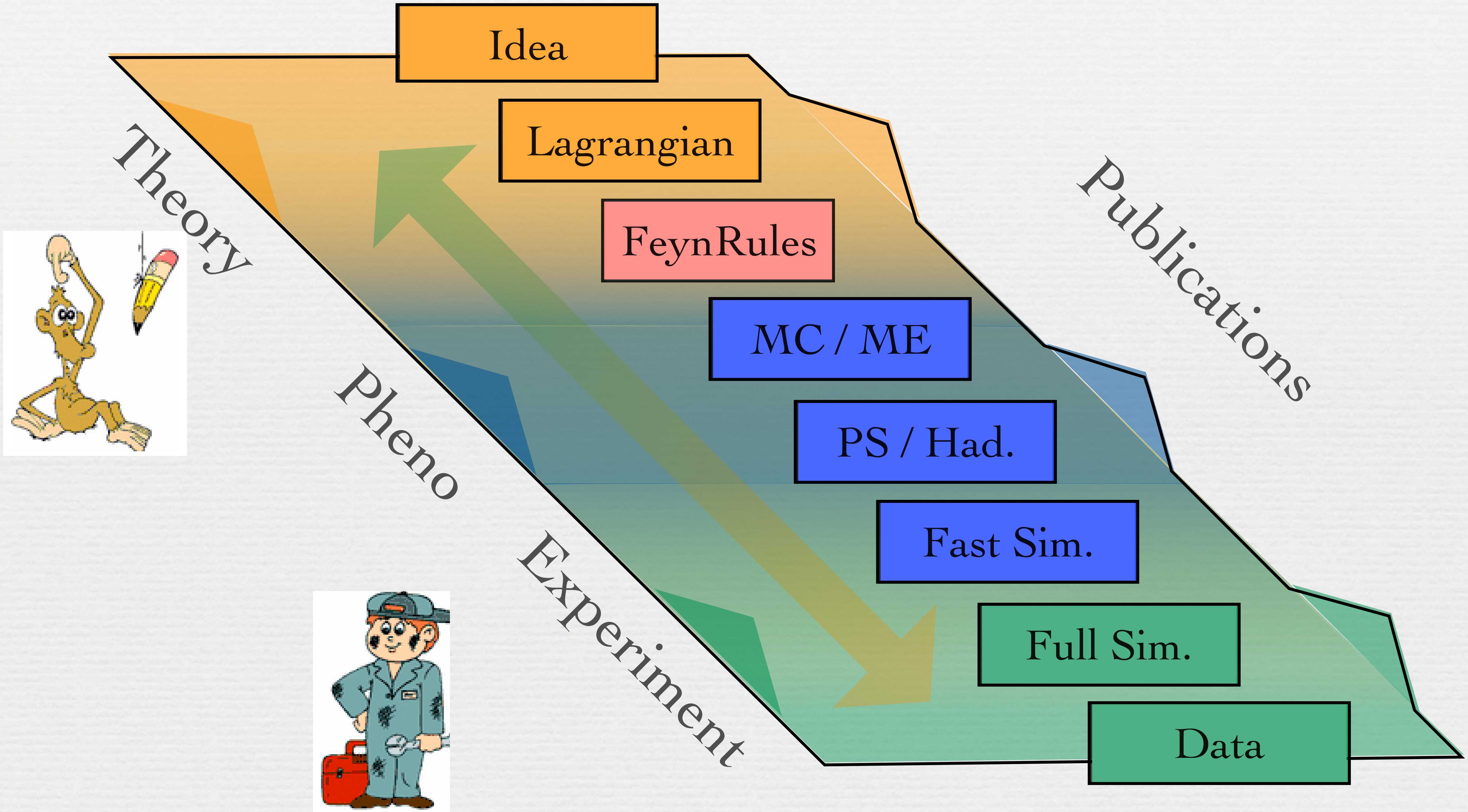
- Workload is tripled, due to disconnected fields of expertise.
- Error-prone, painful validation at each step.
- Proliferation of private MC's/Pythia tunings:
  - ➡ No clear documentation.
  - ➡ Not traceable.
- We need more than just papers to communicate between theorists and experimentalists!



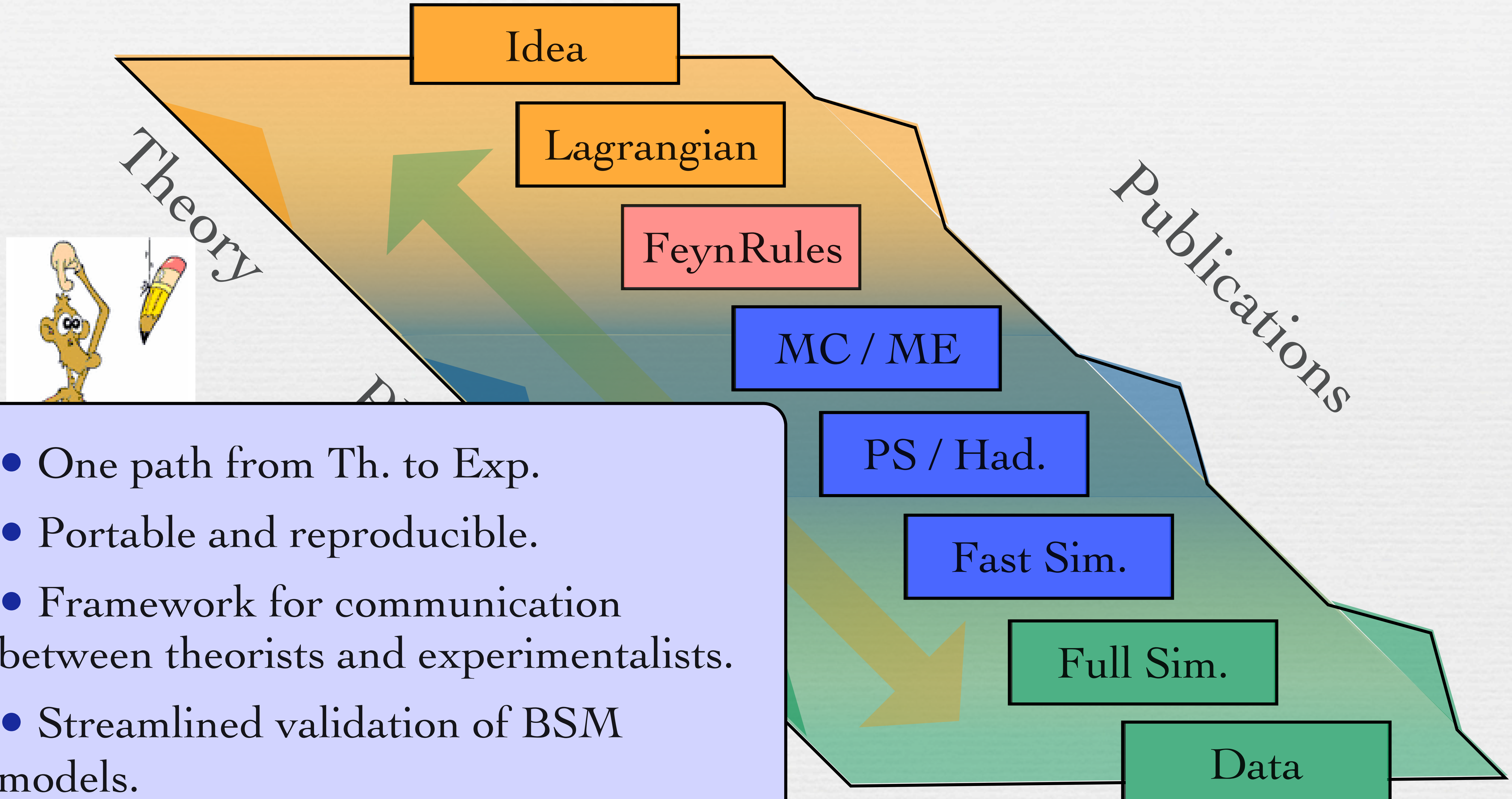
A Roadmap for BSM @ the LHC



A Roadmap for BSM @ the LHC

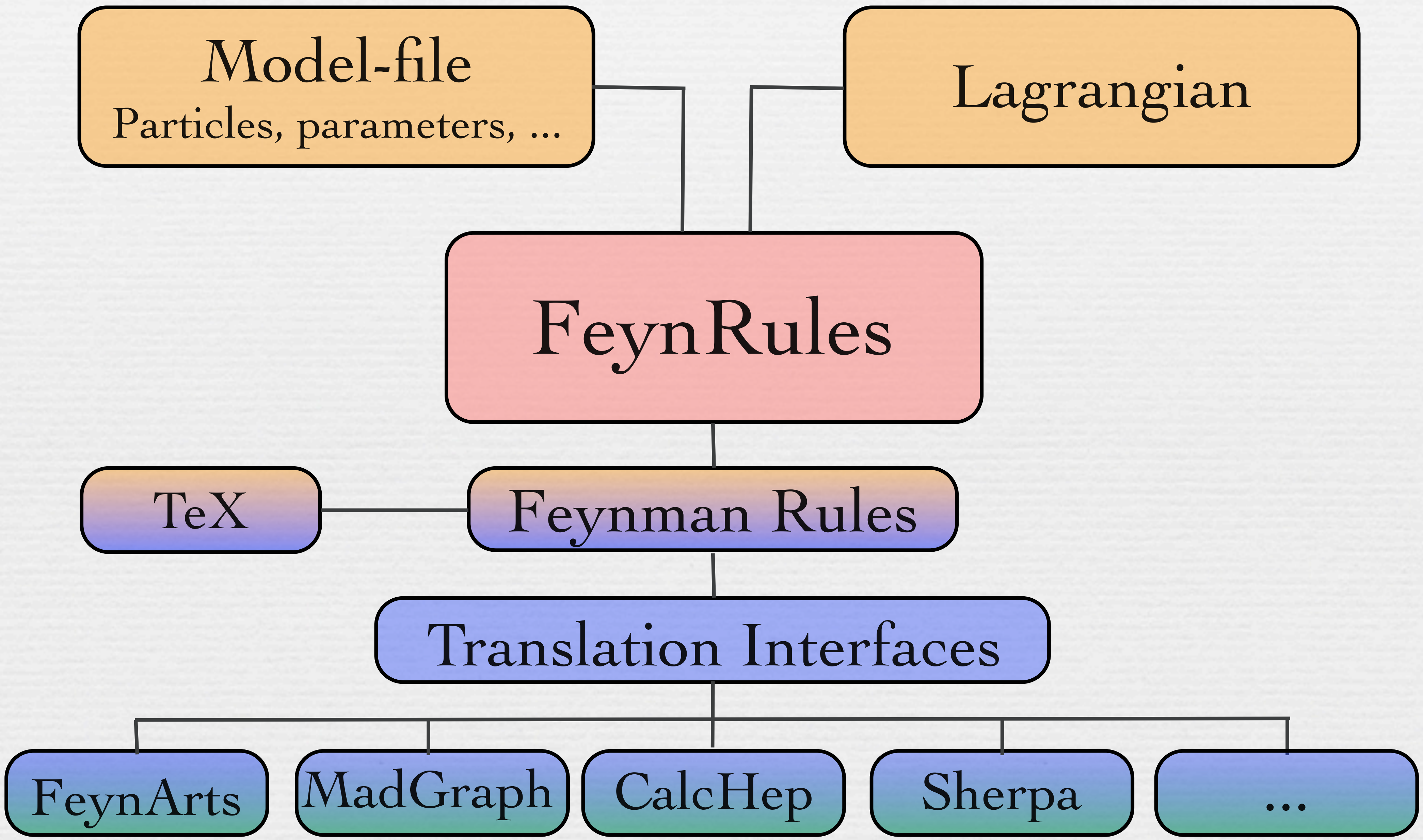


A Roadmap for BSM @ the LHC



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

FeynRules


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

A simple example

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_X$$

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

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

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 simple example

- **Step II:** Write your Lagrangian:

```
LX = 1/2 del[X, mu] del[X, mu]

  + 1/2 MX^2 X^2

  + lX X^2 HC[Phi].Phi;
```

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

A simple example

- Step III: Feynman Rules

```
FeynmanRules[ LX]
```

Vertex 1

Particle 1 : Scalar , H

Particle 2 : Scalar , H

Particle 3 : Scalar , X

Particle 4 : Scalar , X

Vertex:

$-2\, i\, \mathrm{lX}$

Vertex 2

Particle 1 : Scalar , H

Particle 2 : Scalar , X

Particle 3 : Scalar , X

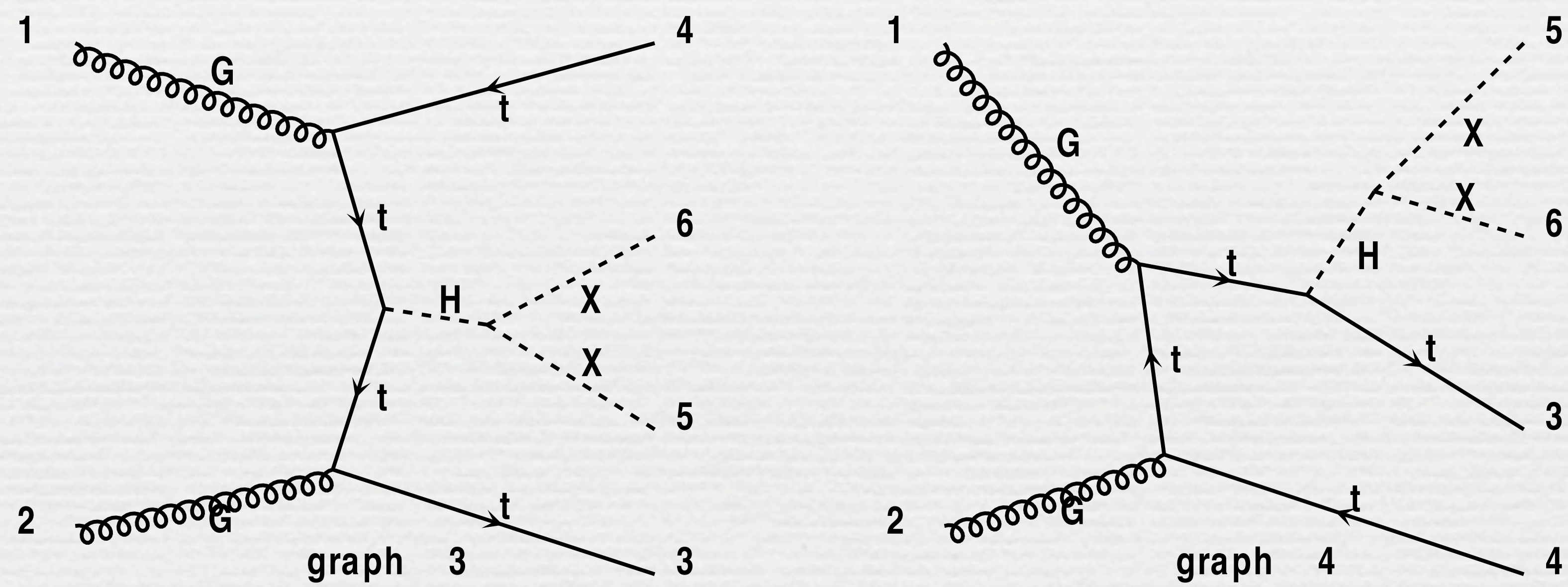
Vertex:

$-2\, i\, \mathrm{lX}\, v$

A simple example

- Step IV: Do Phenomenology!

```
WriteMGOutput[LSM, LX]
```



- This model can now be used just as any other MadGraph model, both at the theory and the experimental side.
  ➡ No private MC needed!

A simple example

- In this approach, we 'standardize' the validation of the model:
  - ➡ Use Feynman rules to cross-check some simple hand-made calculations.
  - ➡ This step can even be automatized by using FeynArts/FormCalc.
  - ➡ Use different Monte Carlo's with different conventions to validate the model (Different gauges, unitarity...).

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
$gg \to gg$	116 490.	116 490.	116 490.	116 490.	116 520.	116 460.
$u\bar{u} \to gg$	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:
      320 1-to-2 decays.
      456 2-to-2 processes.
      2700 2-to-3 processes.
    - ✓ CalcHep validation on-going.

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%
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n11,n11~>W+,W-	5.9018×10^{-1}	5.9009×10^{-1}	5.901×10^{-1}	OK: 0.0152507%

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).