color meets flavor

Research Area 3: Top & Higgs

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UNIVERSITÄT BONN

technische universität dortmund

Universität Siegen

JÜLICH Forschungszentrum

RA3 in one slide

Top and Higgs as precision laboratories for BSM effects

Precision | Couplings | BSM | Low – High

- Precision measurements and predictions at the highest accessible energies.
- Search for additional CP violation in top-quark and Higgs decays.
- Connect measurements and predictions across energy scales to probe BSM effects.

color meets flavor The scientific program in the proposal

1. Precise Predictions for SM observables
2. Top-quark & Higgs-boson couplings
3. Search for new phenomena at high energies
4. Connecting low & high energy scales

From proposal to active RA3 structure

Timeline

- 07.10.2025 Kick-off meeting in Bonn
  - 16 participants
- 10.06.2026 RA3 plenary meeting in Siegen
  - 38 participants (31 in person), including Malgorzata Worek

Operational structure: RA3 teams

- Simulation (**Andrea Knue**, TUDo)
- Rare processes* (**Tatjana Lenz**, UBo)
- SMEFT (**Christian Grefe**, UBo)
- Tagging (**Diptaparna Biswas**, USi)
- Algebraic Tools* (**Vlad Shtabovenko**, USi)

Funding call outcome

- 20 project applications from 22 PIs
- 13 FTE available funding
- Projects merged where useful, cap of 1.5 FTE per project

Five cross-functional teams and a funded project portfolio

Bell, Shtabovenko	Multiloop FeynCalc
Krieg, Witzel	Grad. flow Λ and α with 4 fermions
Cristinziani	Quark-Gluon tagging using a unified jet flavour tagging algorithm
Diez Pardos	ttbar precision measurements and interpretation
Kilian	Whizard for LHC: $t\bar{t}$ and $t\bar{t}X$
Knue	Pseudo-bound state in ttbar

merged

Duhr, Maltoni	Constraining anomalous Higgs Self-Couplings in gluon-fusion
Grefe, Bechtle, Desch, Hiller,	Higgs potential, high-Scale models & SMEFT for future collider measurements
Schopf	Search for FCNC in top-quark decays to a Higgs boson and a charm or up quark
T. Lenz	Search for new signatures in CP-violating 2HDM

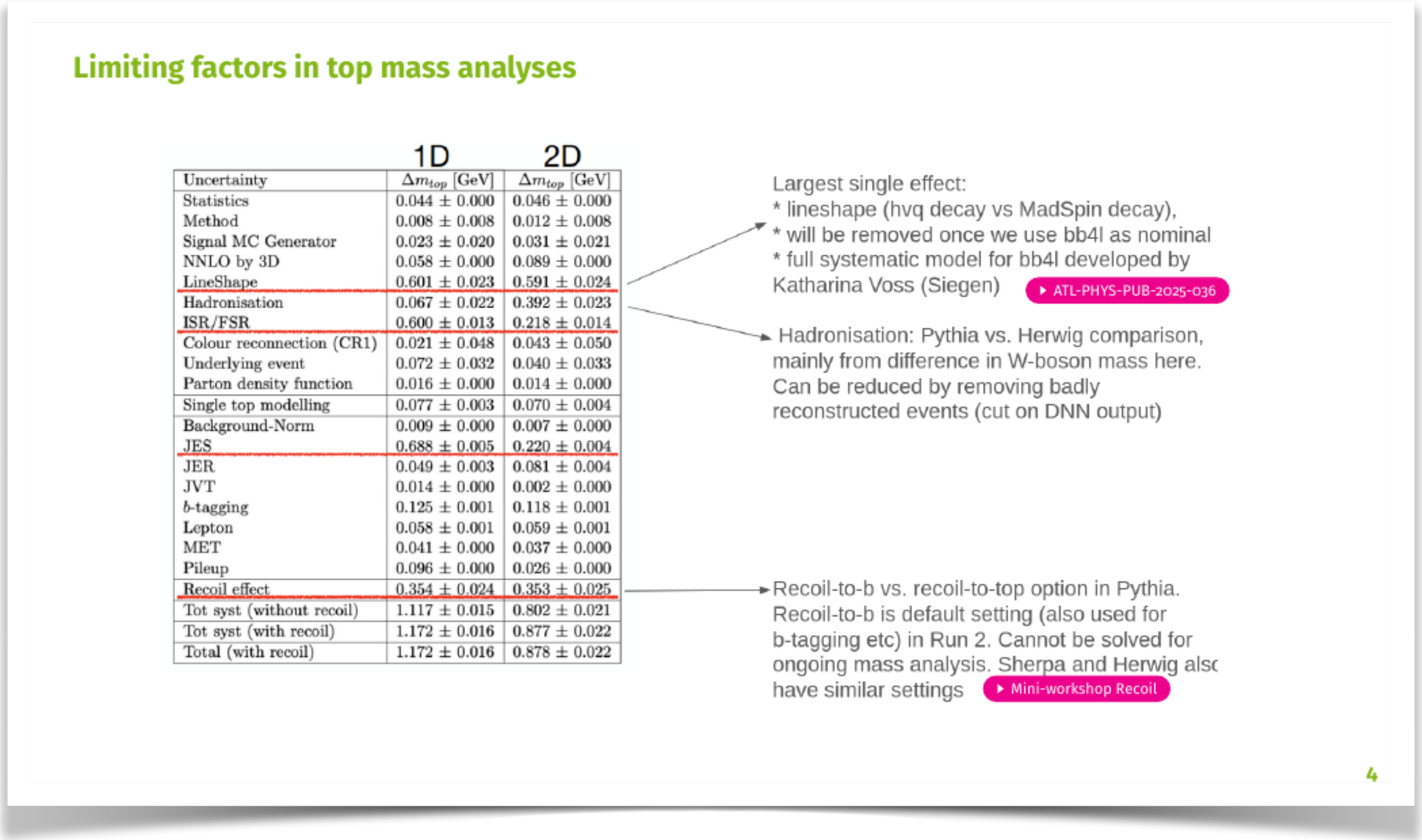
(A) Simulation

Recurring topics across Top, Higgs and BSM:

- Parton shower and hadronisation uncertainties
- Deployment of new matrix-element generators
- Modelling in specific phase-spaces, e.g. $t\bar{t}$ threshold

Examples

- Top mass and differential measurements are already limited by shower, recoil and hadronisation uncertainties.
- The $t\bar{t}$ threshold region requires dedicated modelling beyond standard simulation.
- CmF can connect experimental needs with new WHIZARD, Herwig and MiNNLOPS developments.



Limiting factors in top mass analyses

Uncertainty	1D Δm_{top} [GeV]	2D Δm_{top} [GeV]
Statistics	0.044 ± 0.000	0.046 ± 0.000
Method	0.008 ± 0.008	0.012 ± 0.008
Signal MC Generator	0.023 ± 0.020	0.031 ± 0.021
NNLO by 3D	0.058 ± 0.000	0.089 ± 0.000
LineShape	0.601 ± 0.023	0.591 ± 0.024
Hadronisation	0.067 ± 0.022	0.392 ± 0.023
ISR/FSR	0.600 ± 0.013	0.218 ± 0.014
Colour reconnection (CR1)	0.021 ± 0.048	0.043 ± 0.050
Underlying event	0.072 ± 0.032	0.040 ± 0.033
Parton density function	0.016 ± 0.000	0.014 ± 0.000
Single top modelling	0.077 ± 0.003	0.070 ± 0.004
Background-Norm	0.009 ± 0.000	0.007 ± 0.000
JES	0.688 ± 0.005	0.220 ± 0.004
JER	0.049 ± 0.003	0.081 ± 0.004
JVT	0.014 ± 0.000	0.002 ± 0.000
b-tagging	0.125 ± 0.001	0.118 ± 0.001
Lepton	0.058 ± 0.001	0.059 ± 0.001
MET	0.041 ± 0.000	0.037 ± 0.000
Pileup	0.096 ± 0.000	0.026 ± 0.000
Recoil effect	0.354 ± 0.024	0.353 ± 0.025
Tot syst (without recoil)	1.117 ± 0.015	0.802 ± 0.021
Tot syst (with recoil)	1.172 ± 0.016	0.877 ± 0.022
Total (with recoil)	1.172 ± 0.016	0.878 ± 0.022

Largest single effect:
* lineshape (hvq decay vs MadSpin decay),
* will be removed once we use bb4l as nominal
* full systematic model for bb4l developed by Katharina Voss (Siegen) ATL-PHYS-PUB-2025-036

Hadronisation: Pythia vs. Herwig comparison, mainly from difference in W-boson mass here. Can be reduced by removing badly reconstructed events (cut on DNN output)

Recoil-to-b vs. recoil-to-top option in Pythia. Recoil-to-b is default setting (also used for b-tagging etc) in Run 2. Cannot be solved for ongoing mass analysis. Sherpa and Herwig alsc have similar settings Mini-workshop Recoil

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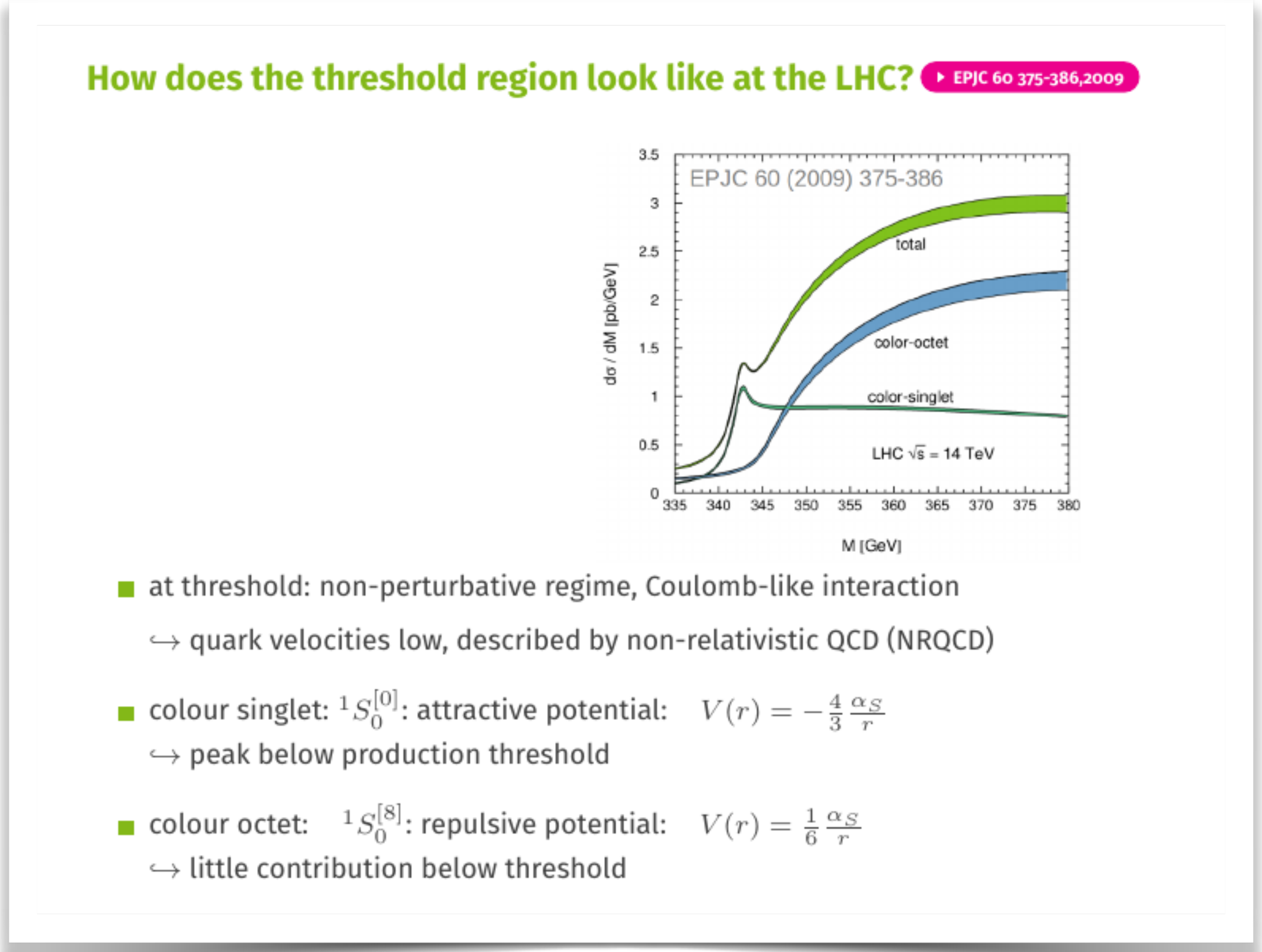
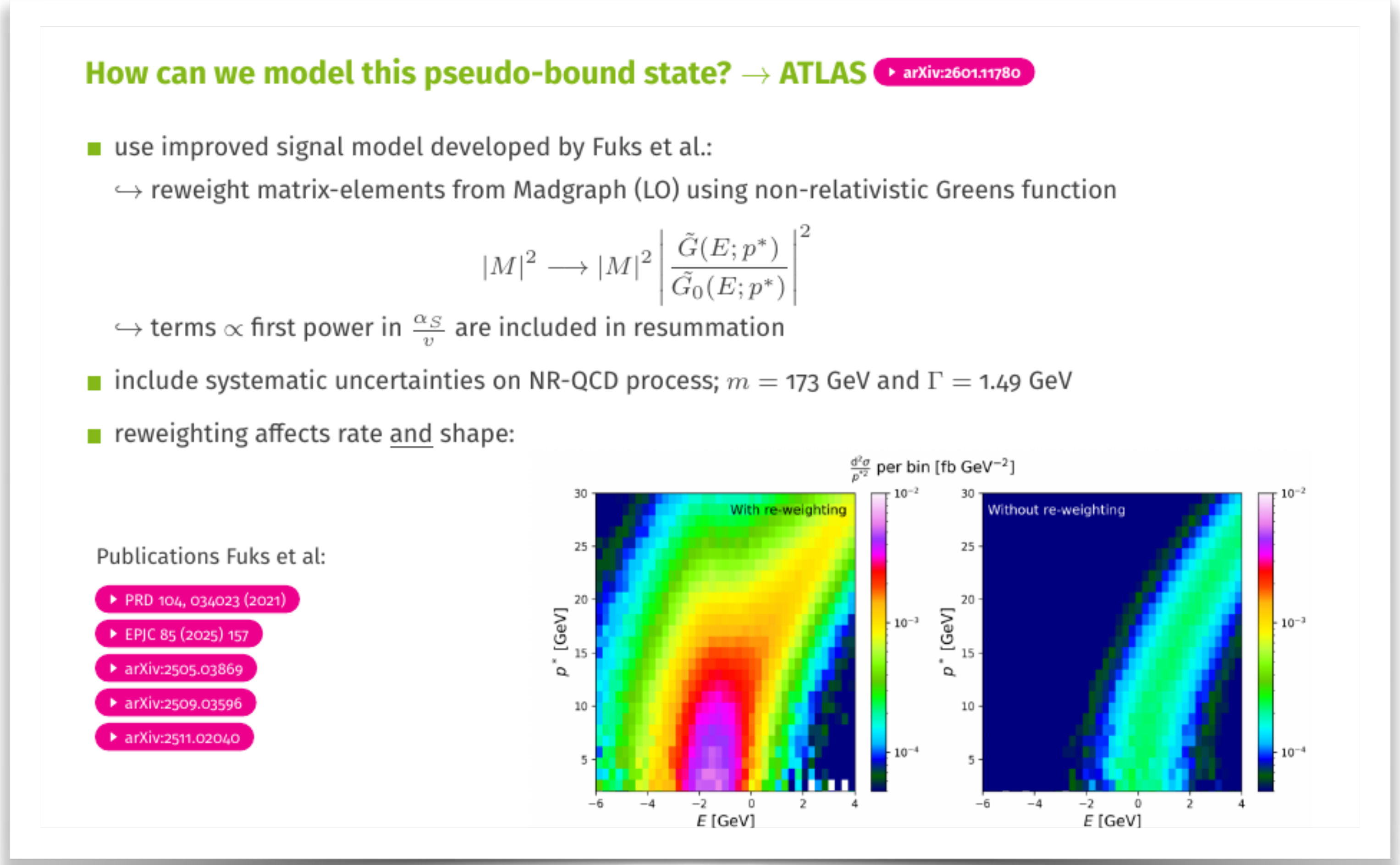
Top threshold / Toponium

A small phase-space region with large consequences

- Non-relativistic Coulomb-like effects are not included in normal $t\bar{t}$ simulation.
- Greens-function reweighting changes rate and shape; ATLAS/CMS comparisons expose open questions.
- Incomplete low-$m_{t\bar{t}}$ modelling can mimic BSM peak–dip structures and affect spin-entanglement observables.
- Action item: align phase-space definitions, spin propagation and generator validation.





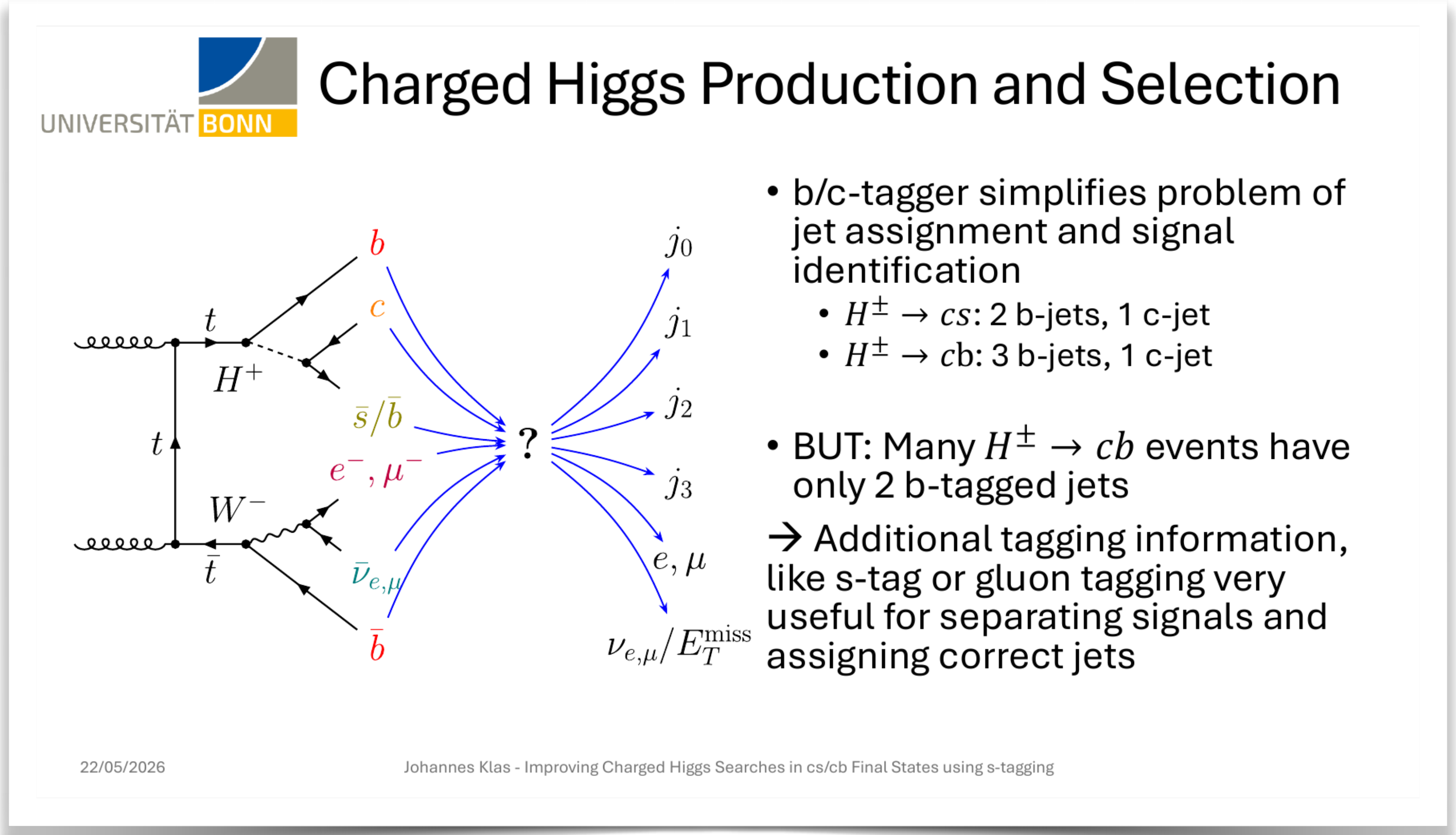
(B) Rare processes: explicit BSM signatures

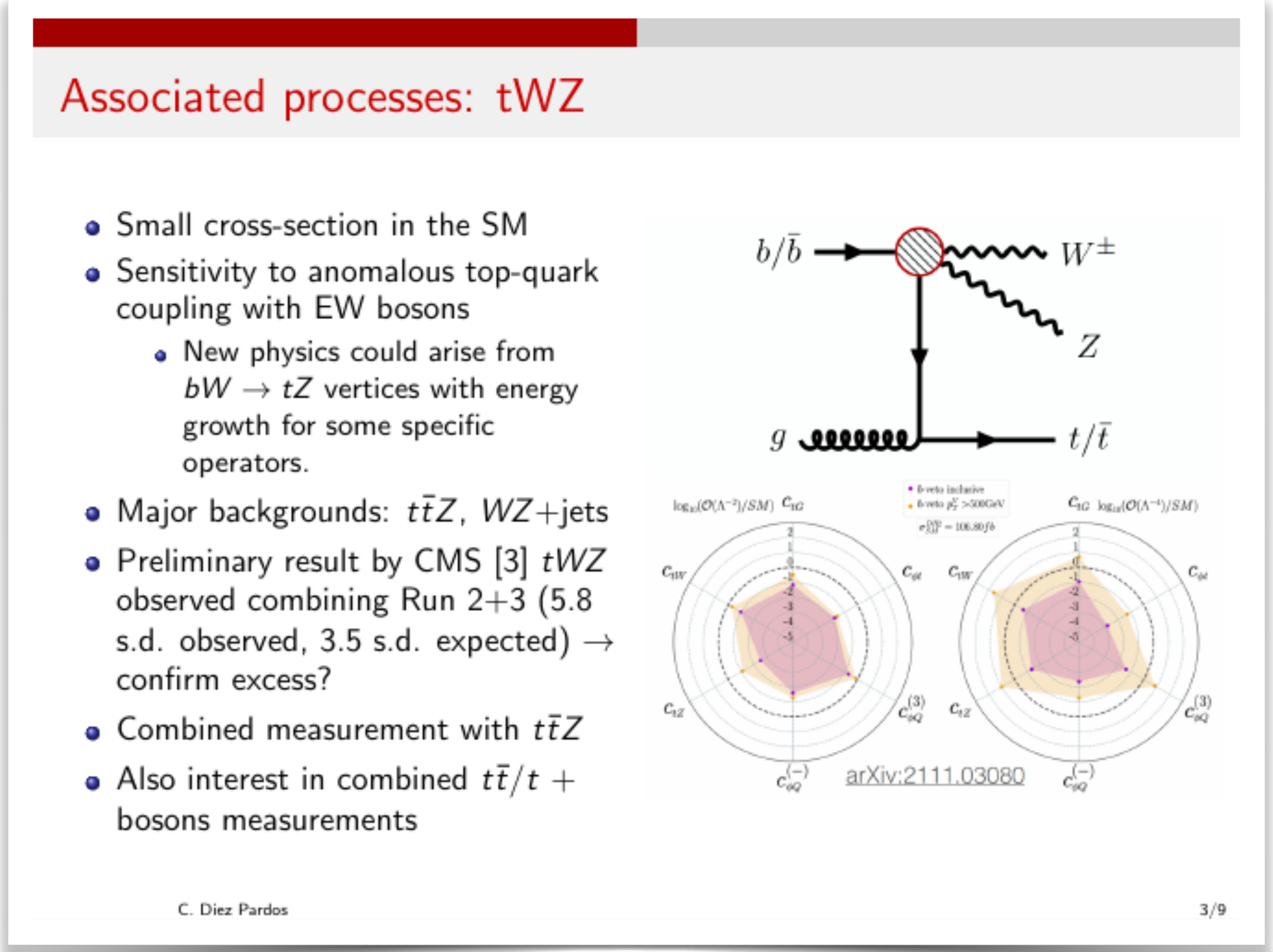
More details on Tuesday [Tatjana Lenz]

First meeting (13.05.) discussed concrete analysis targets and cross-links.

Analysis ideas

- FCNC top decays $t \rightarrow qH(b\bar{b})$ with $q = u,c$
  - exploit full Run-2+3 data and separate Hu/Hc hypotheses.
- CP-violating 2HDM
  - searches for neutral Higgs states with CP-even and CP-odd decay signatures.
- $H \rightarrow \tau\tau$ / $A \rightarrow \tau\tau$
  - reconstruct CP-sensitive observables with ML
  - Run-2 reinterpretation and Run-3 extension.
- Associated charged Higgs $tH^{\pm}$ ($\rightarrow$ cs/cb) search
  - use charm/strange tagging and SPANet-like reconstruction for jet assignment.
- Top precision / $t\bar{t}$+X
  - tWZ, spin correlations, quantum observables and EFT interpretations.

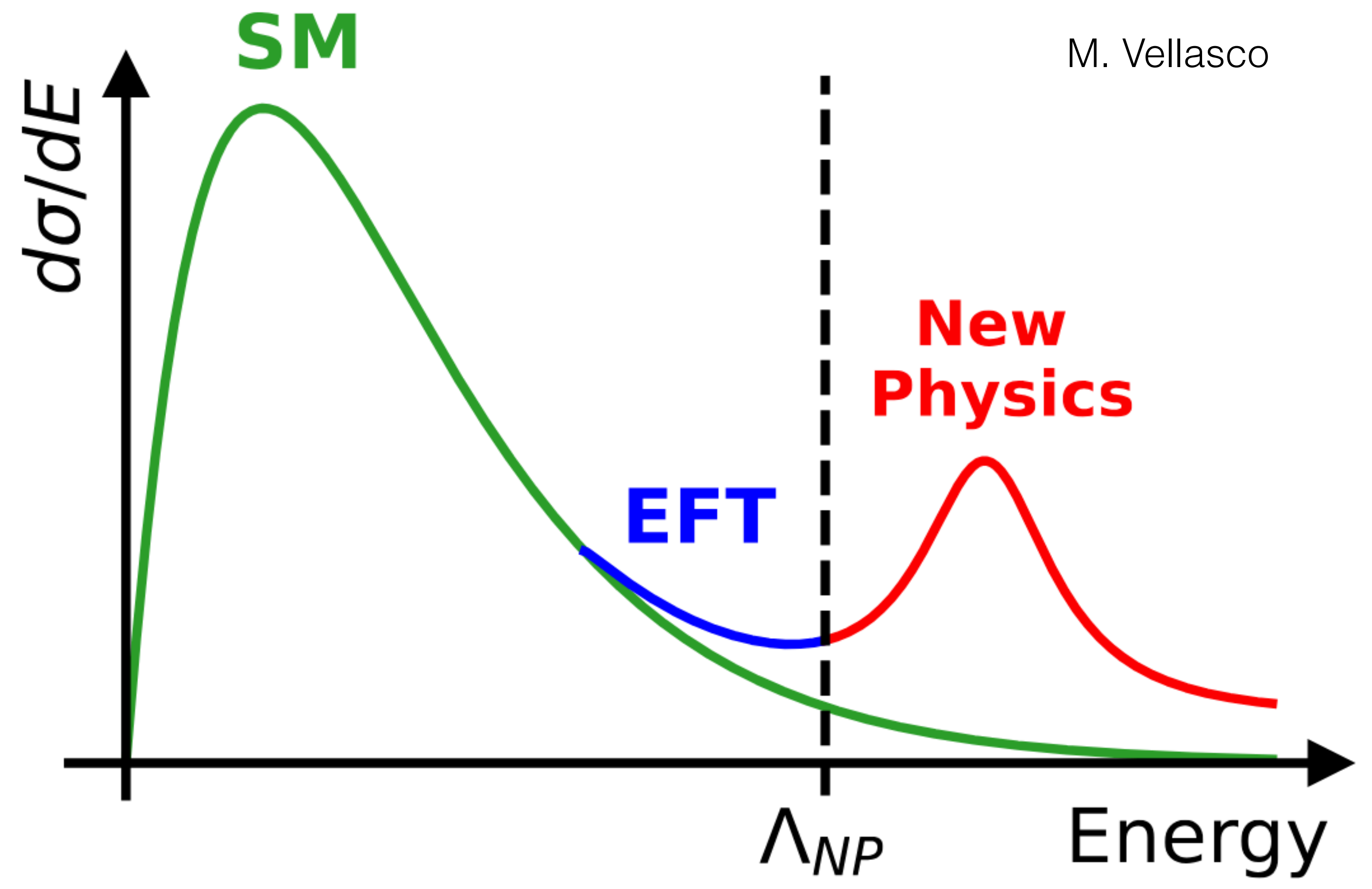




Effective Field Theories

Assume that new physics is directly observable only at a much higher energy scale (Λ_{NP})

- New physics will modify observable couplings through loop contributions.
- Parametrise modifications to the SM as an effective model valid at $E \ll \Lambda_{\mathrm{NP}}$
- SMEFT introduces ~2.5k additional operators at $\mathcal{O}^{(6)}$
- Allows to combine information from different measurements that are sensitive to similar couplings in a consistent way
- There can be cancellations so all operators should be considered
- Cut-off at $\mathcal{O}^{(6)}$ is driven by practical considerations, $\mathcal{O}^{(8)}$ can be relevant depending on the size of the WC



Wilson coefficients

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda_{\mathrm{NP}}} \sum_k C_k^{(5)} \boxed{O_k^{(5)}} + \frac{1}{\Lambda_{\mathrm{NP}}^2} \sum_k C_k^{(6)} \boxed{O_k^{(6)}} + \mathcal{O}\left(\frac{1}{\Lambda_{\mathrm{NP}}^3}\right)$$

Operators

(C) SMEFT: the common interpretation layer

Subgroup to converge on shared tools and fit conventions.

- Goal: connect SMEFT interpretations and global fits across CmF groups, experiments and energy scales.
- Bonn: $H \to \tau\tau$ STXS / CP information and future e^+e^- single-Higgs constraints; planned global-fit implementation.
- Dortmund: sustainable framework for Wilson coefficients, observables, derivatives and statistical evaluation.
- Siegen: spin correlations in $t\bar{t}$ and EFT interpretations of top+X measurements.
- Common tool direction: HEPfit / EFTfitter experience, plus smelli / jelli for global likelihoods and RGE-connected fits.

Activities in Dortmund (Kröninger)

- Plan to develop a framework to investigate the sensitivity of observables on Wilson coefficients in global fits (1 PhD position funded by CmF)
  - Develop tool to store and manage EFT models, their free parameters, and the relevant observables and measurements.
  - Provide observable parametrisation and calculate their derivatives, as well as statistical tools and goodness of fit evaluation
- Experience with EFTfitter

ATLAS EXPERIMENT 4

Towards truly global fits

- **smelli** (SMEFT Likelihood): calculates a **global likelihood** given values for SMEFT Wilson Coefs. Builds upon:
- **flavio**: a general observable calculator, contains a large database of measurements
- **wilson**: uses the renormalization group equations to connect Wilson Coefs. between the WET and the SMEFT

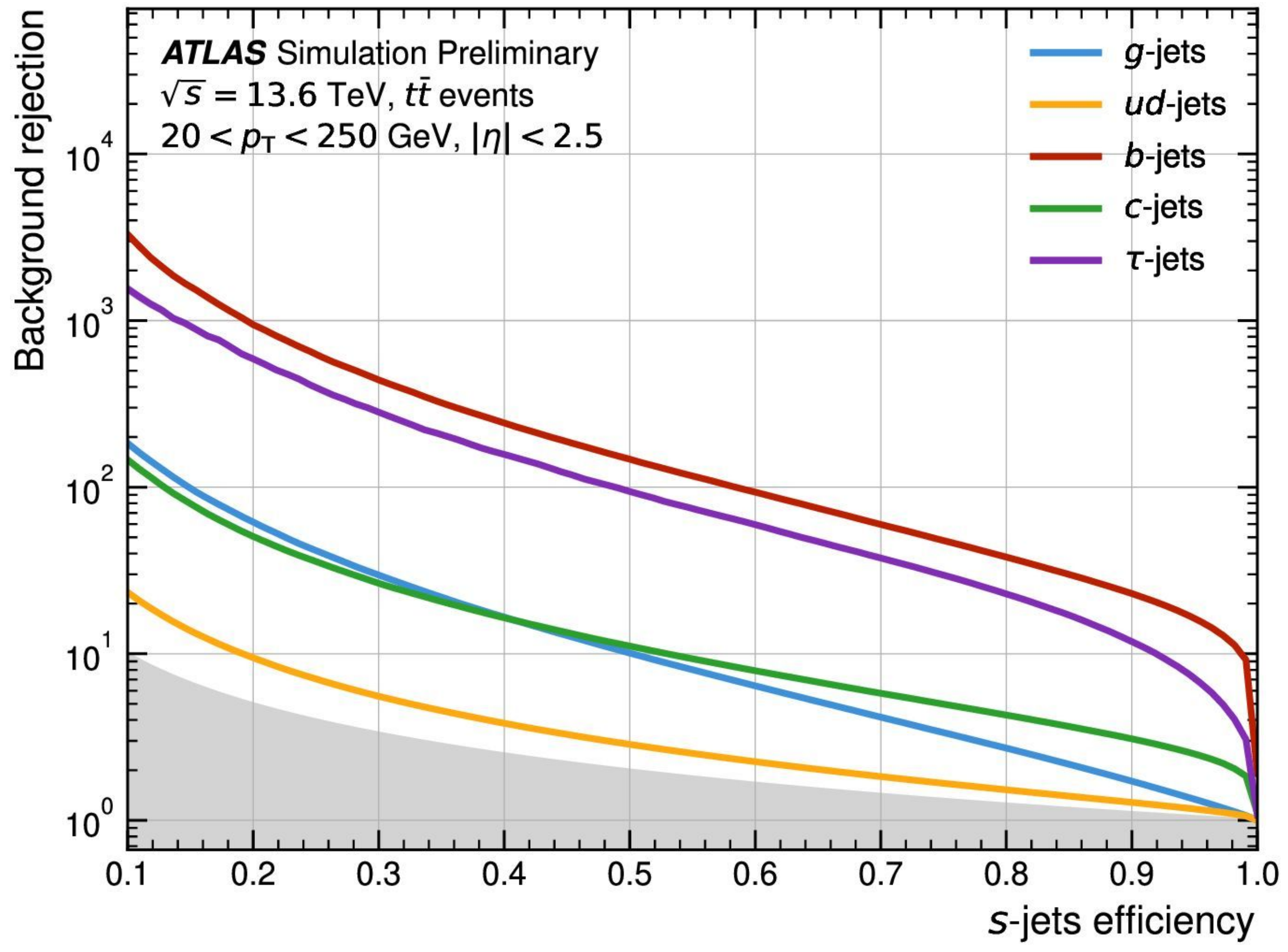
- Current version: "jelli" (JAX-based EFT Likelihoods) https://jelli-pheno.github.io/
- Based on JAX: Just-In-Time (JIT) compilation, automatic differentiation
  - Fast, efficient and flexible

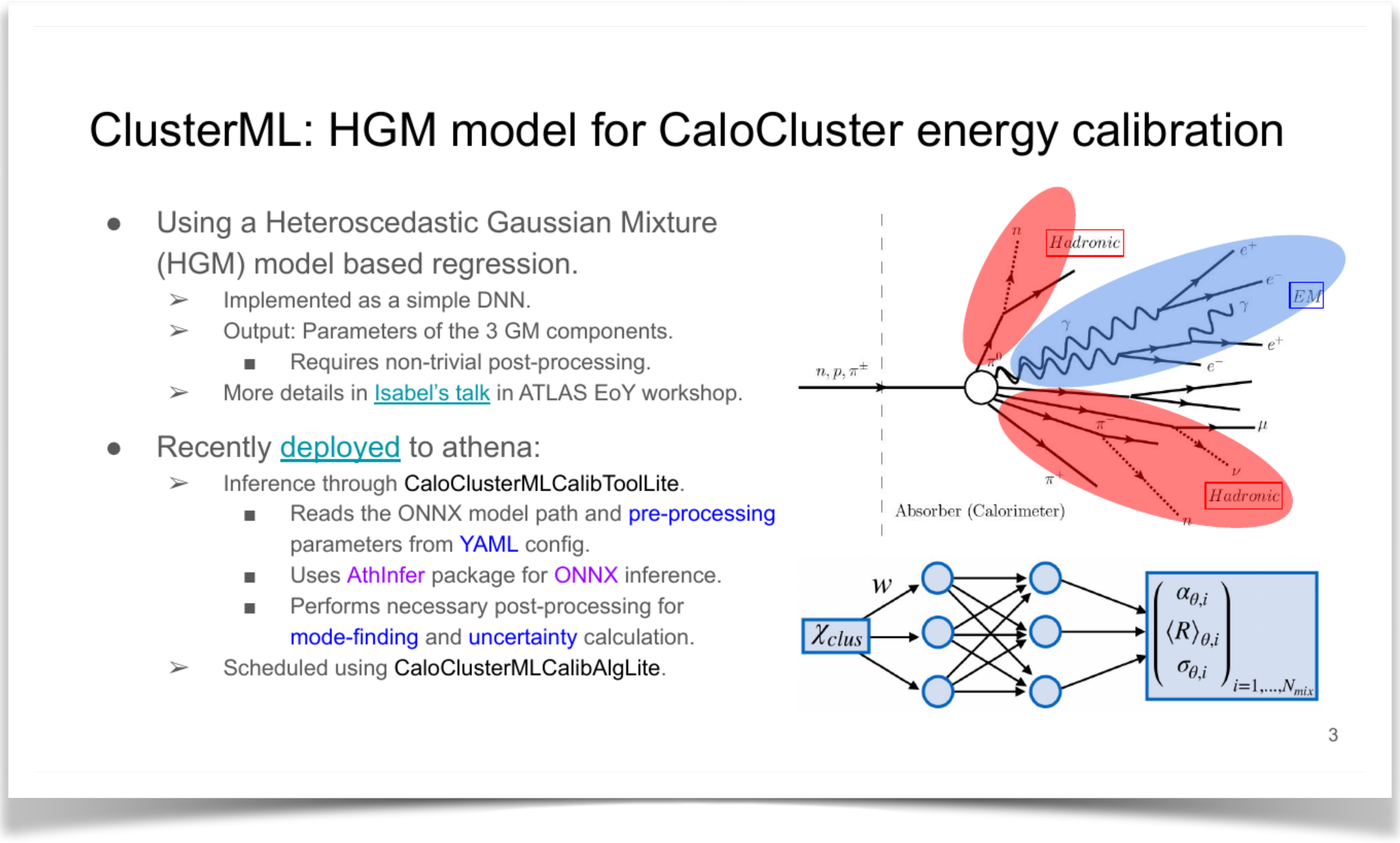
02/06/2026 RA3 SMEFT Activities Meeting - Murillo Vellasco 7

(D) Tagging and reconstruction

Discussions broadened “tagging” into reconstruction and global performance.

- ATLAS flavour tagging already uses transformer architectures with low-level tracks and calorimeter clusters.
- Beyond heavy flavour: q/g-tagging and s-tagging are central for FCNC, charged-Higgs and precision analyses.
- FastSim validation/training is needed because many BSM and systematically varied samples are FastSim.
- ClusterML: HGM CaloCluster energy calibration deployed in Athena; next step is calibration + pile-up suppression.
- Transformer b-jet calibration and end-to-end event transformers create shared building blocks for multiple analyses.
- Multi-jet tagging for multi-Higgs final states





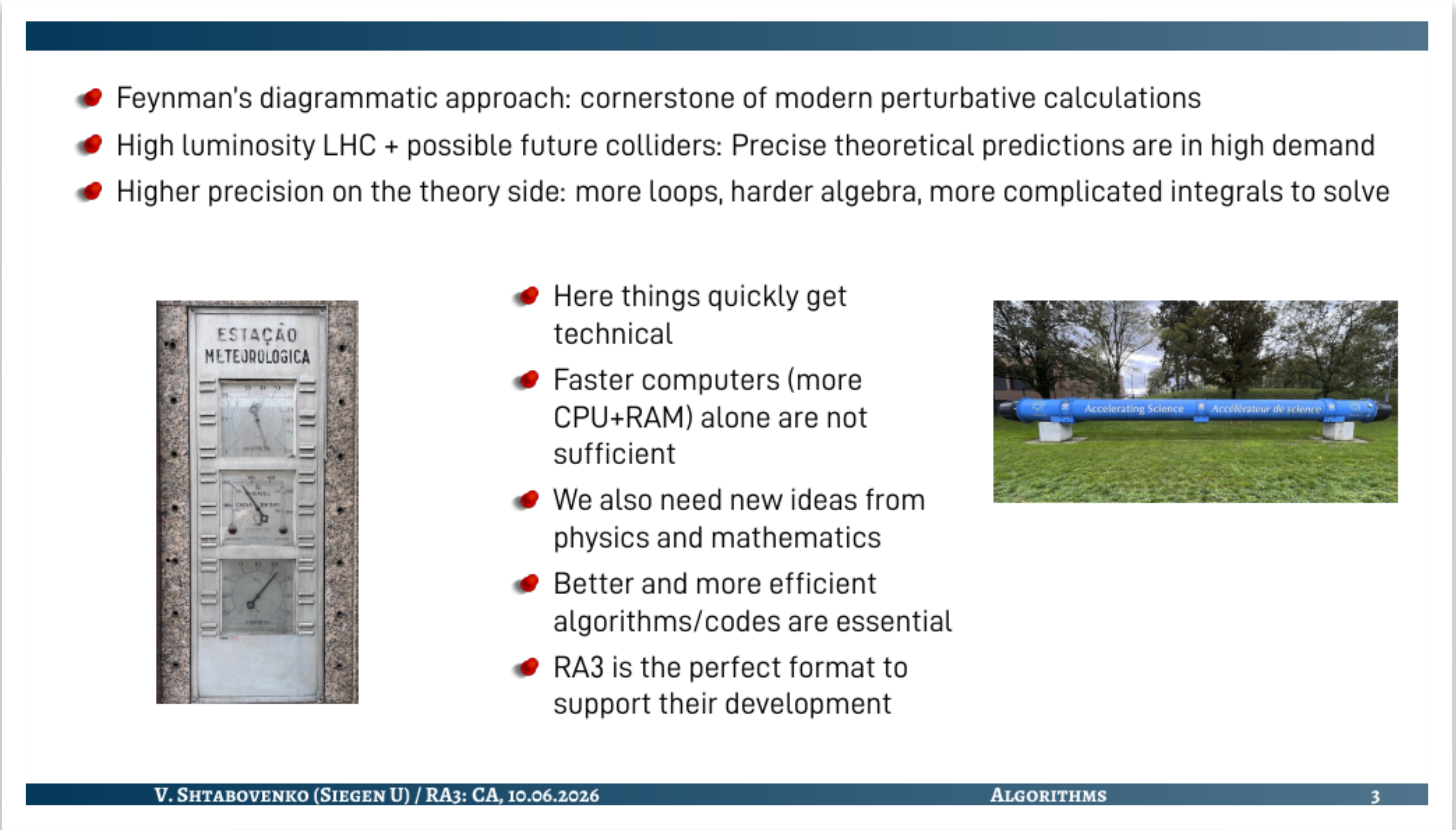
(E) Computer algebra

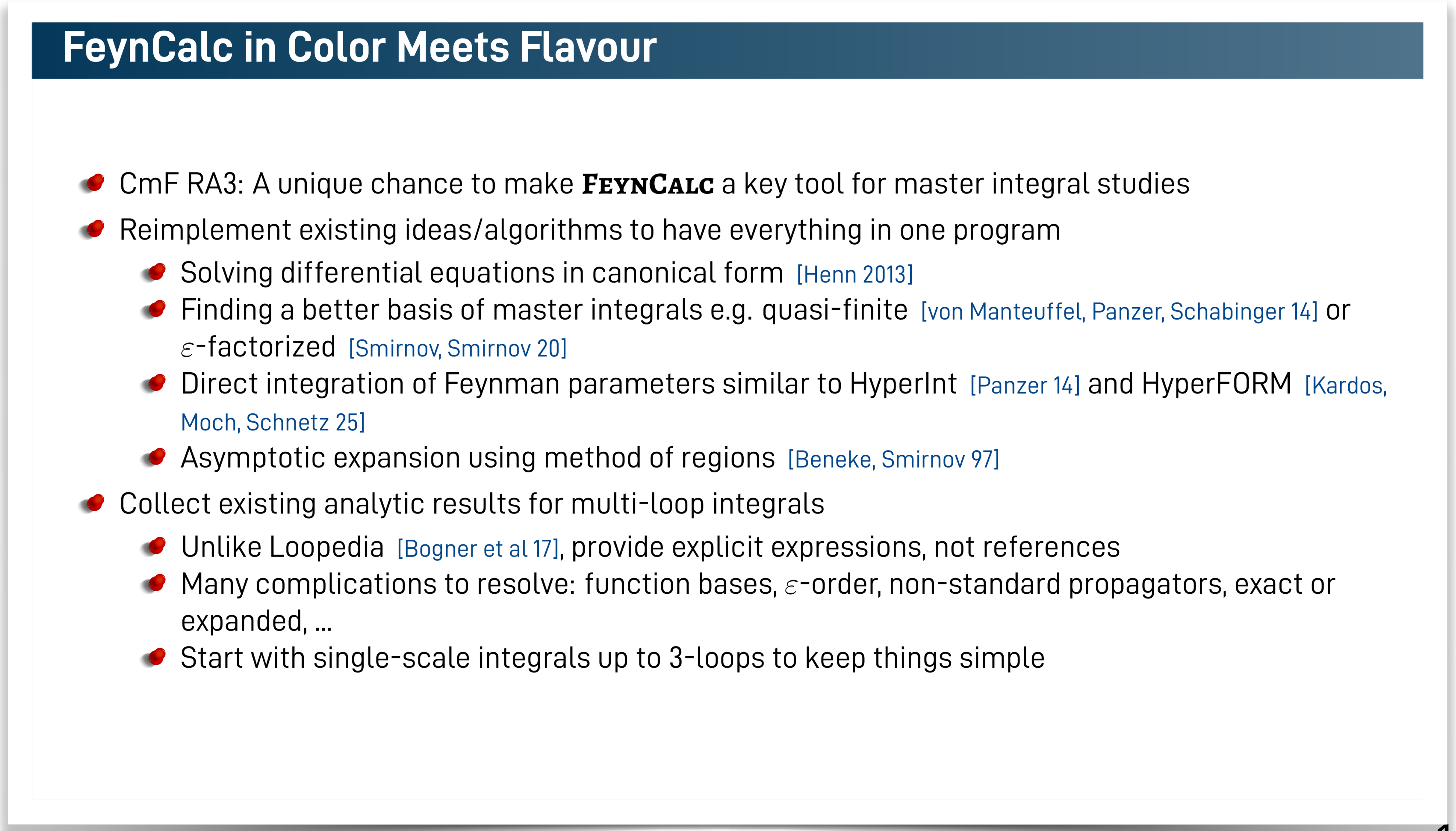
More details on Tuesday [Vlad Shtabovenko]

New algorithms and software for high-precision predictions

- Higher precision means more loops, harder algebra and more complicated integrals.
- Bonn: new methods for Feynman integrals, canonical forms and iterated integrals.
- Siegen: automation of large-scale multiloop calculations, IBP reduction, FeynCalc and SoftSERVE.
- Goal: better theory predictions, uncertainty control and reusable public tools.

Precision theory is not only "support": it shapes what can be measured and interpreted.





RA3: one feedback loop

Measurements, modelling, reconstruction and interpretation must be developed together.

Feedback: deviations, tensions and dominant uncertainties define the next benchmark calculations and analyses.

Examples of cross-links

- $t\bar{t}$ threshold: modelling ↔ entanglement ↔ heavy Higgs searches.
- FCNC / charged Higgs: rare processes ↔ q/g/s/c tagging ↔ SMEFT.
- $H \to \tau\tau$: CP observables ↔ differential measurements ↔ EFT fits.
- $t\bar{t}$+X: generator uncertainties ↔ top precision ↔ global interpretation.

Near-term priorities

RA3 is now operational, let's make the teams a success!

- Subscribe to cmf-ra3@listen.uni-bonn.de, if not done already.

Next steps include

- Define common benchmarks
  - Top threshold, $tWZ/t\bar{t}+X$, $H\to\tau\tau/A\to\tau\tau$, FCNC, charged Higgs and multi-Higgs scalar resonances.
- Align generators and phase spaces
  - Agree samples, truth definitions, tunes, threshold modelling and uncertainty prescriptions.
- Package reusable ML tools
  - Tagging, calibration, jet-parton matching and event-level transformers should be analysis-ready → connect to IAL
- Start interpretation early
  - Keep SMEFT/global-fit conventions and observable parameterisations with the measurements → connect with RA2
- Establish regular forum for discussion
  - Plenary meetings ~twice per year; team meetings more often

Summary

RA3 is operational

- teams, conveners and a first round of funded projects are in place

The science is connected

- Top/Higgs precision, rare signatures, tagging, modelling and EFT interpretation are mutually dependent.

Timely opportunities

- New generator and algebraic tools meet Run-3 measurements and future-collider interpretation needs.

Backup

Challenges in modelling pp→tt̄X @NLO

Work by Malgorzata Worek

Fixed-order predictions:

- Full off-shell NLO QCD predictions
  - Need also EW corrections
- Complete NLO predictions

Parton-shower based predictions:

- NLO + PS predictions

tt̄→bb4ℓ available

- need also ℓ+jets and fully hadronic predictions