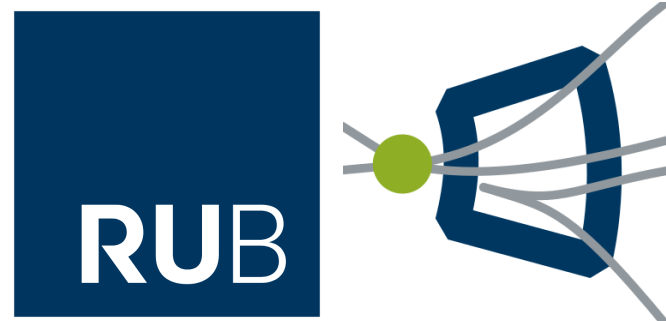




FSP LHCb
Erforschung von
Universum und Materie



Exotic hadrons

and the future of spectroscopy analysis

26/08/2026 GSI Seminar

Mikhail Mikhasenko, 31/07/2026



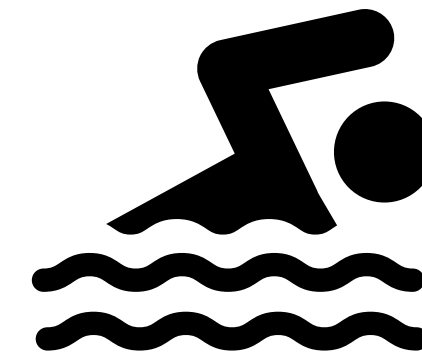
Federal Ministry
of Research, Technology
and Space

Plan for the talk

LHCb
experiment

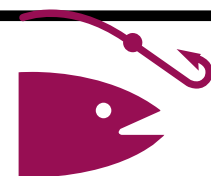


Hadron
Physics



DEMOS
&
AI

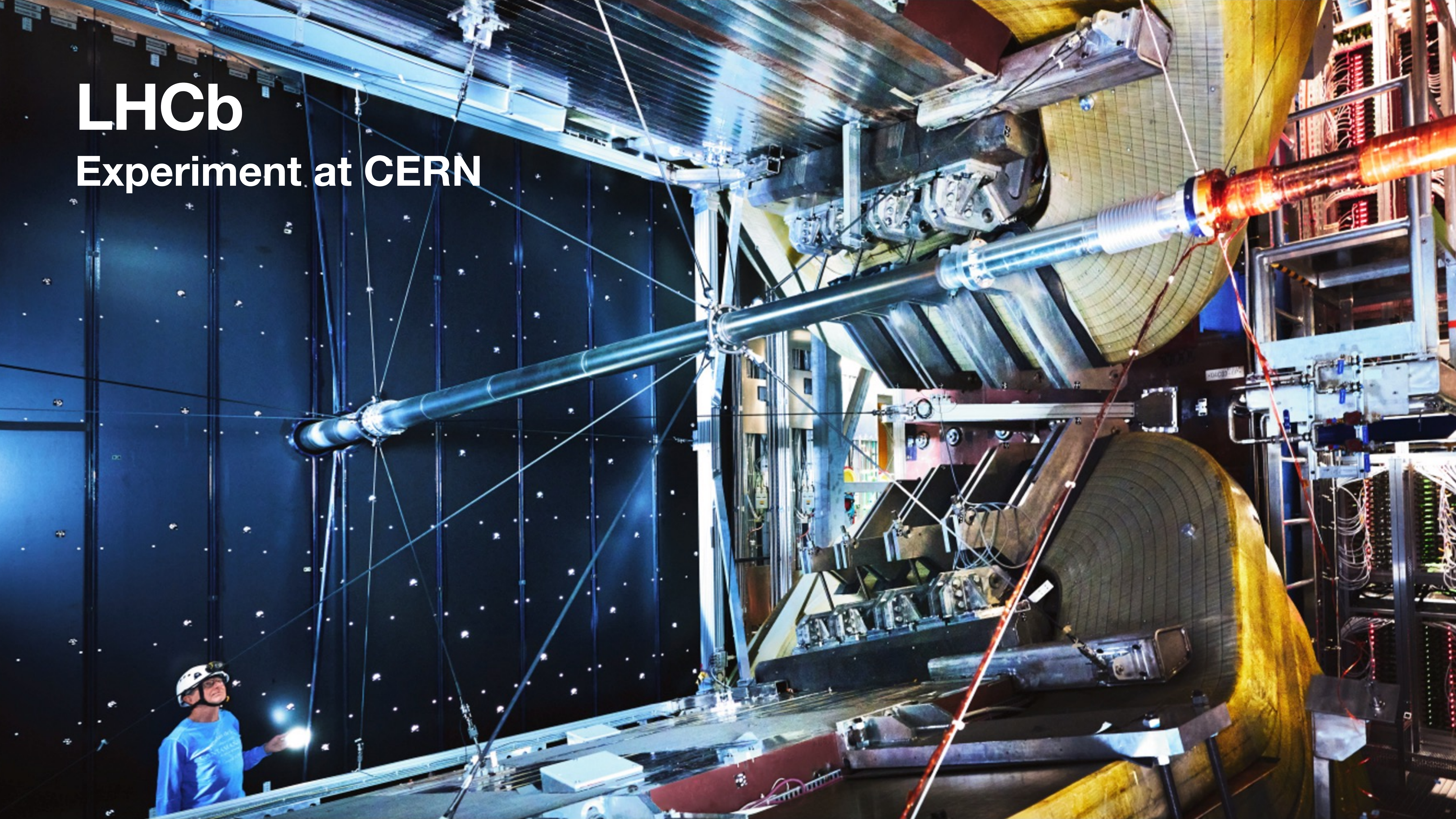
0



50

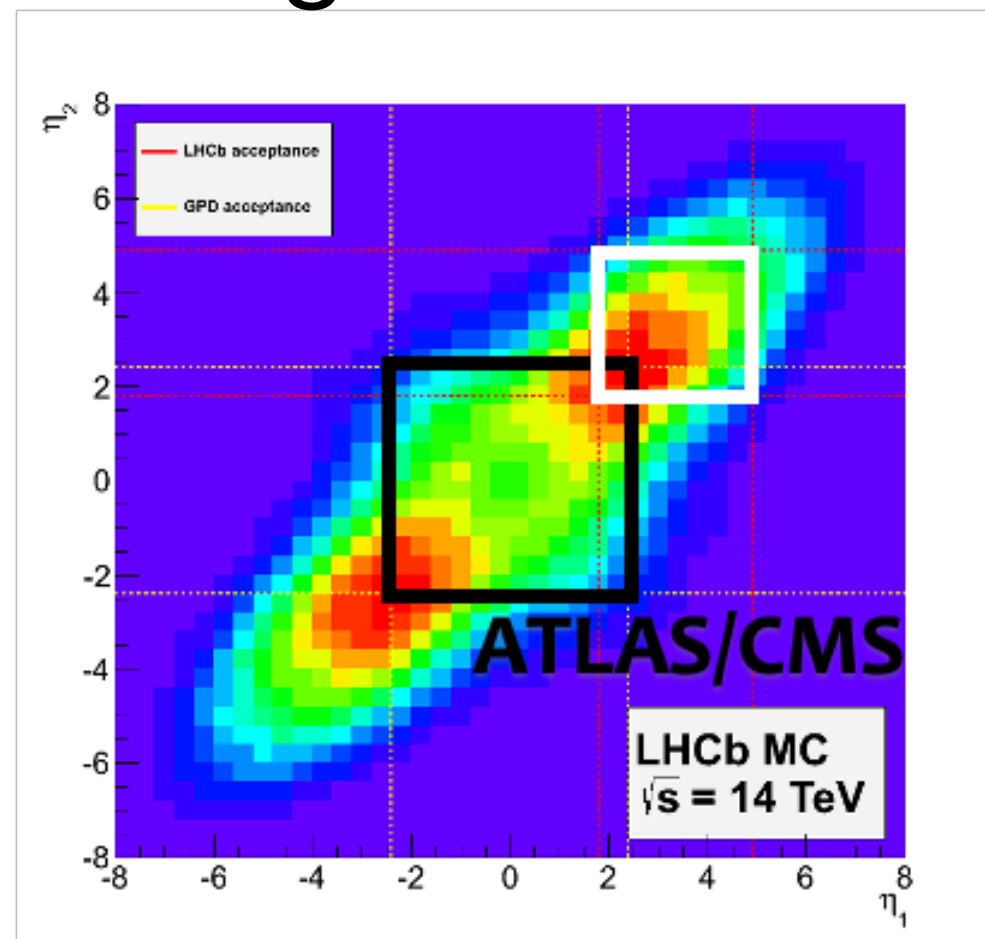
LHCb

Experiment at CERN



LHCb@CERN: heavy flavor quarks factory

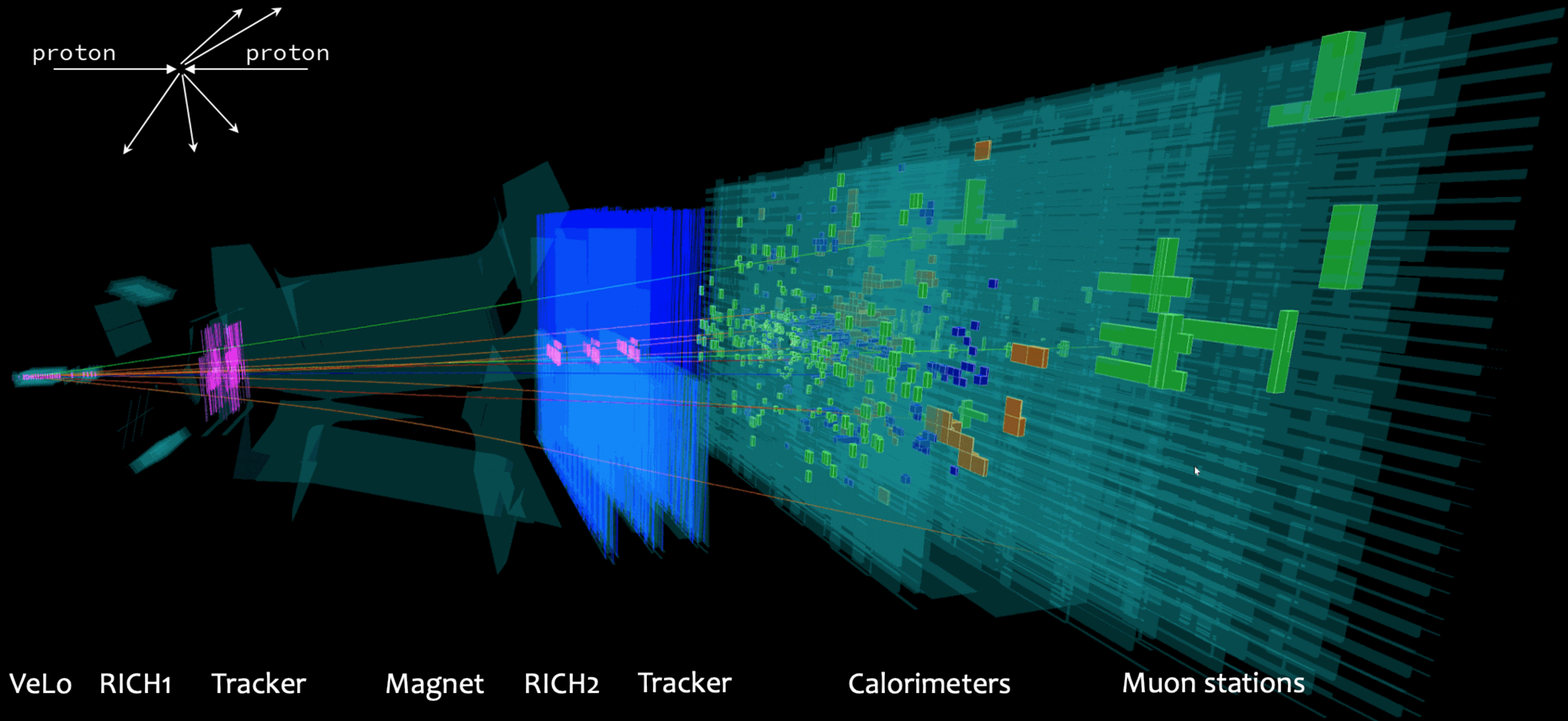
- One of four large experiments at LHC
- LHCb has the largest production cross-sections of b - and c -hadrons ever
- $\sigma(bb) \approx 600\mu\text{b}$ @ 14TeV
 $\sigma(c\bar{c}) \approx 20 \times \sigma(bb)$ in pp collisions
- High track multiplicity



b-quark product
cross-section



LHCb event



Upgraded detector

Software only trigger

New RICH2 optics
new sensors and readout for RiCH

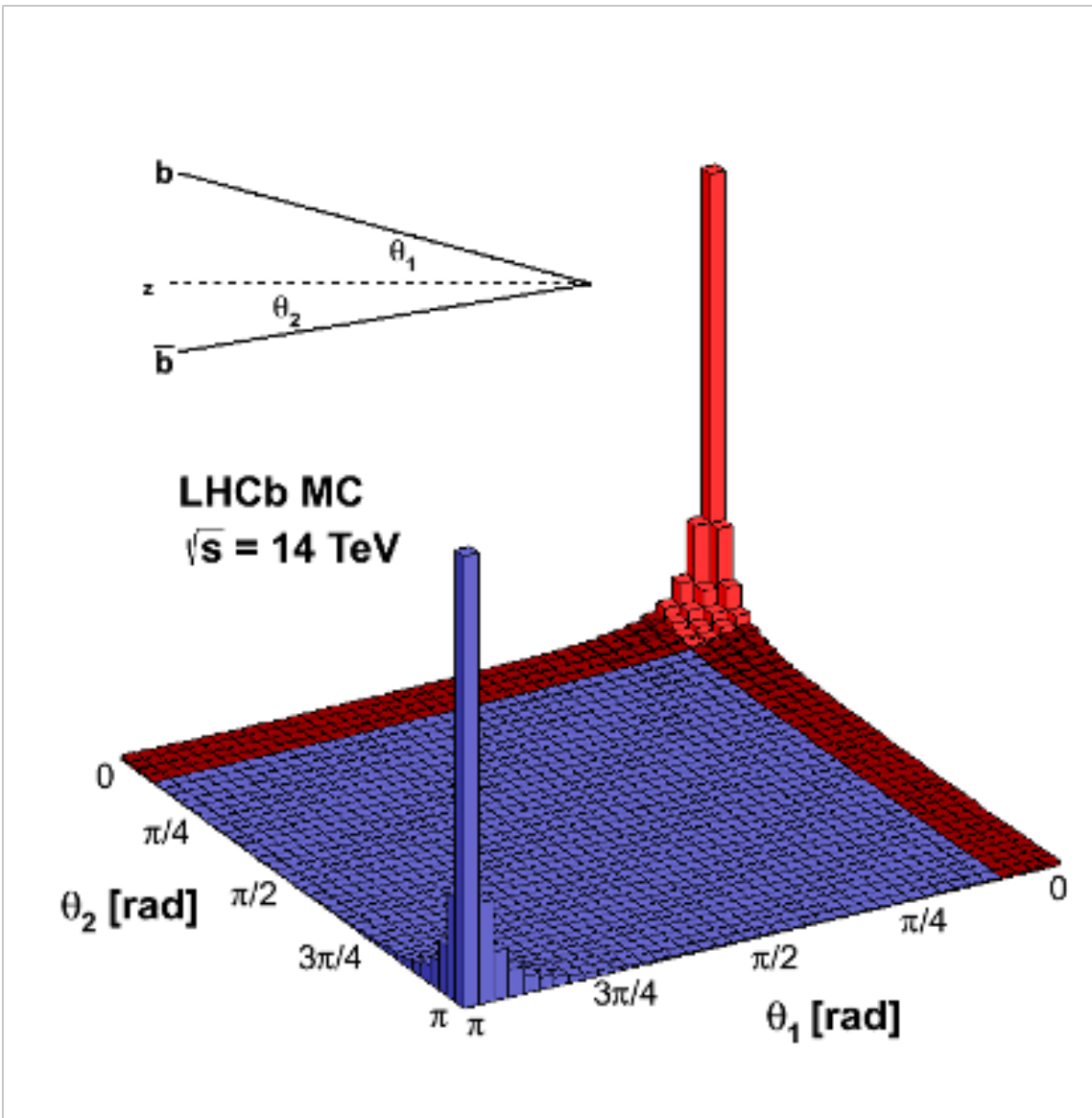
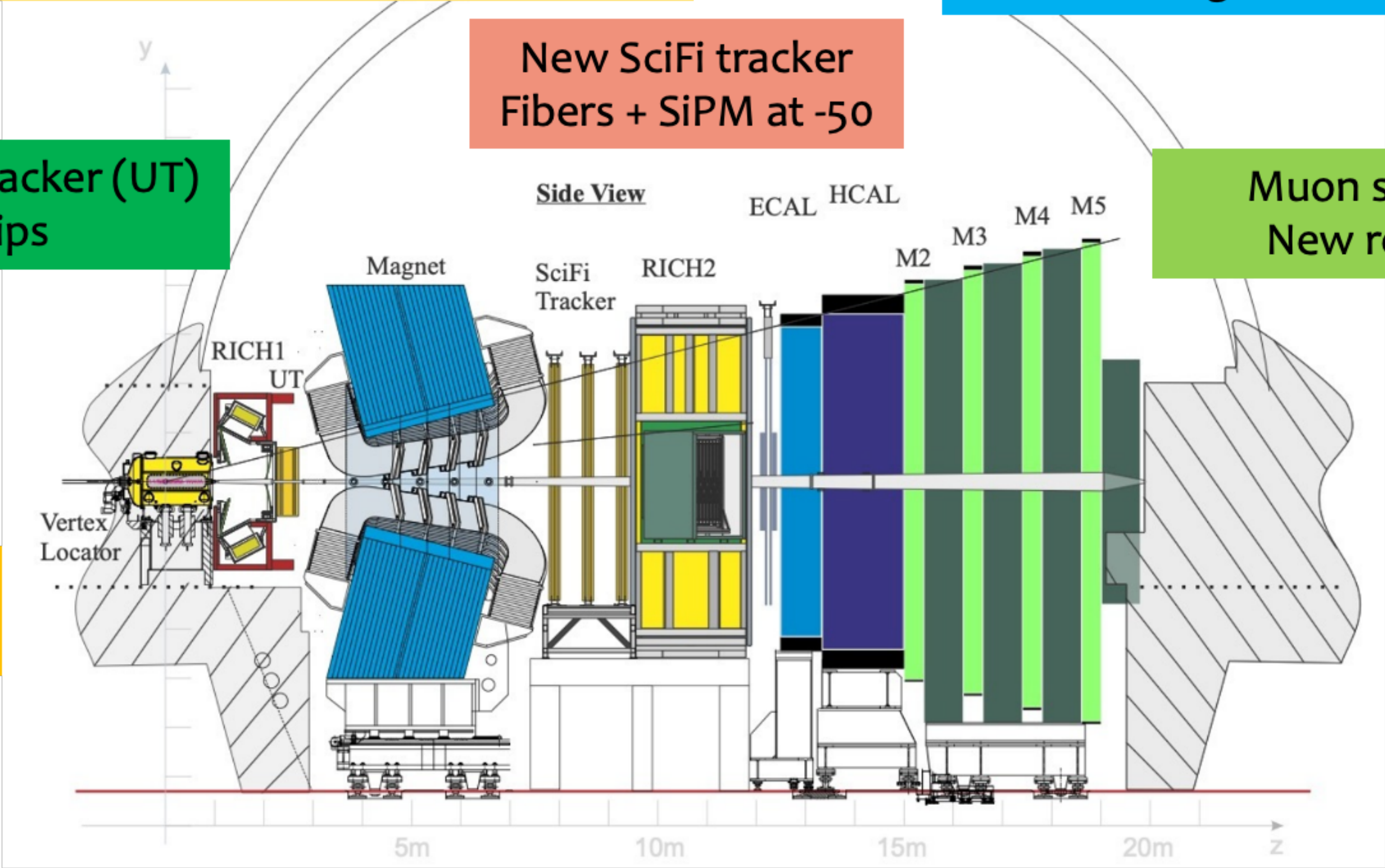
Calo: removed preshower,
Scintillating Pad Detector, new readout

New SciFi tracker
Fibers + SiPM at -50

New Upstream Tracker (UT)
Silicon strips

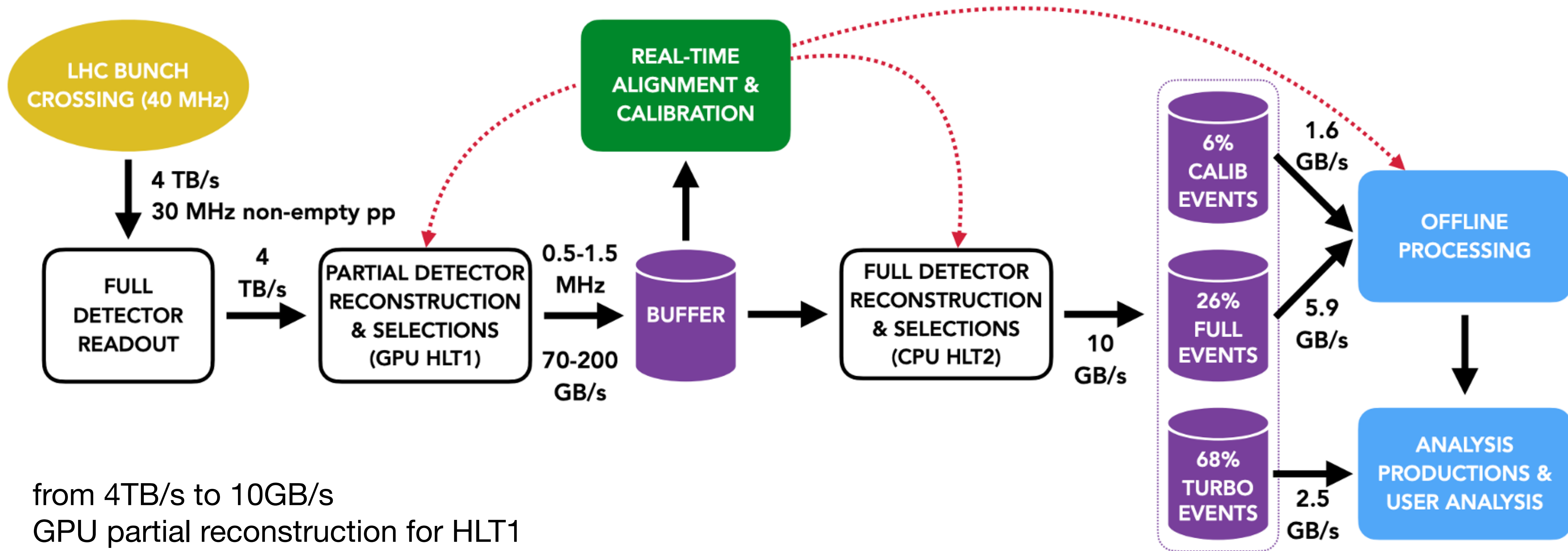
Muon stations:
New readout

New VeLo
Pixel detector



Trigger

from detector signals to four-vectors



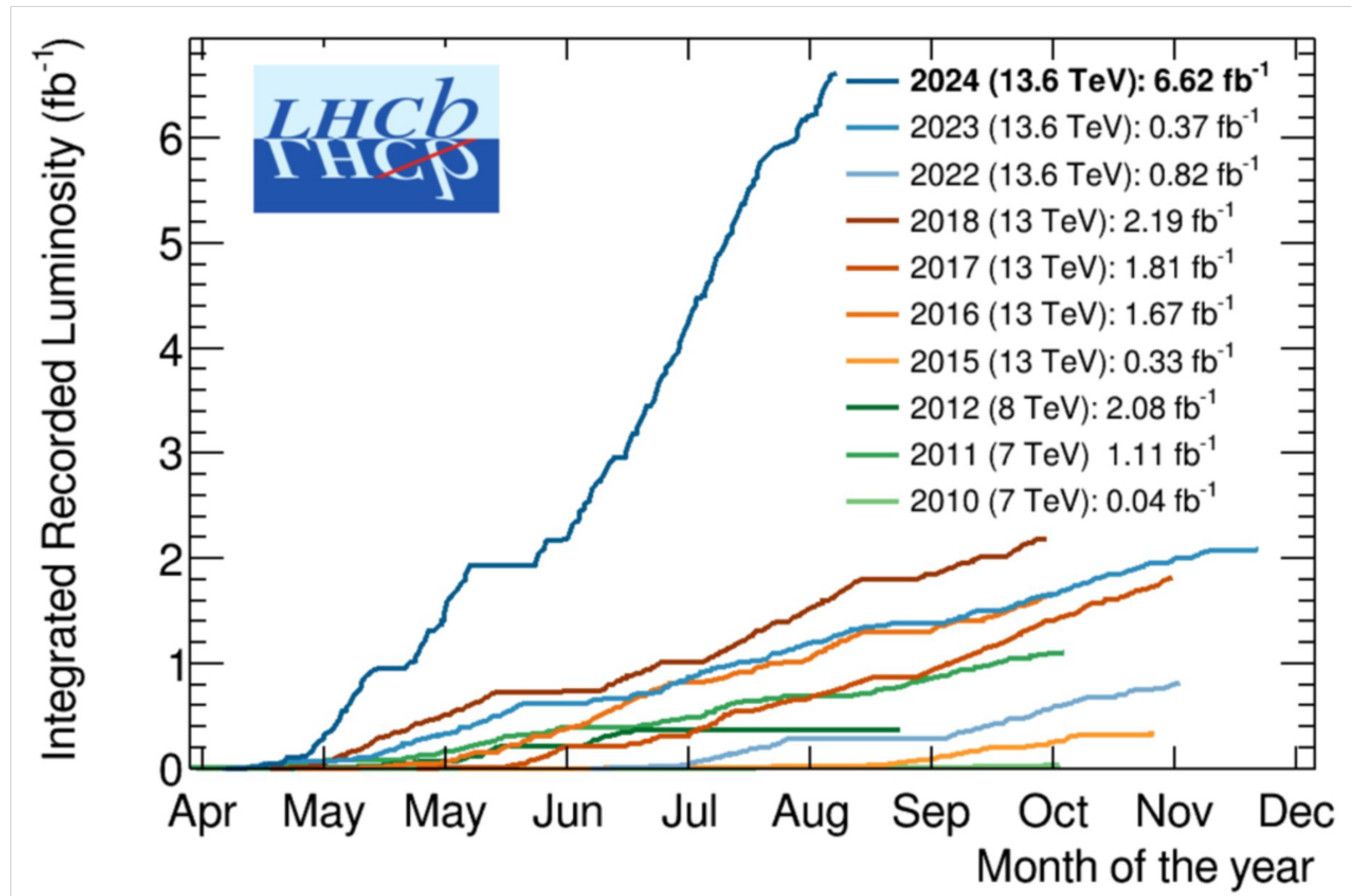
from 4TB/s to 10GB/s

GPU partial reconstruction for HLT1

CPU full reconstruction for HLT2

Data taking campaigns

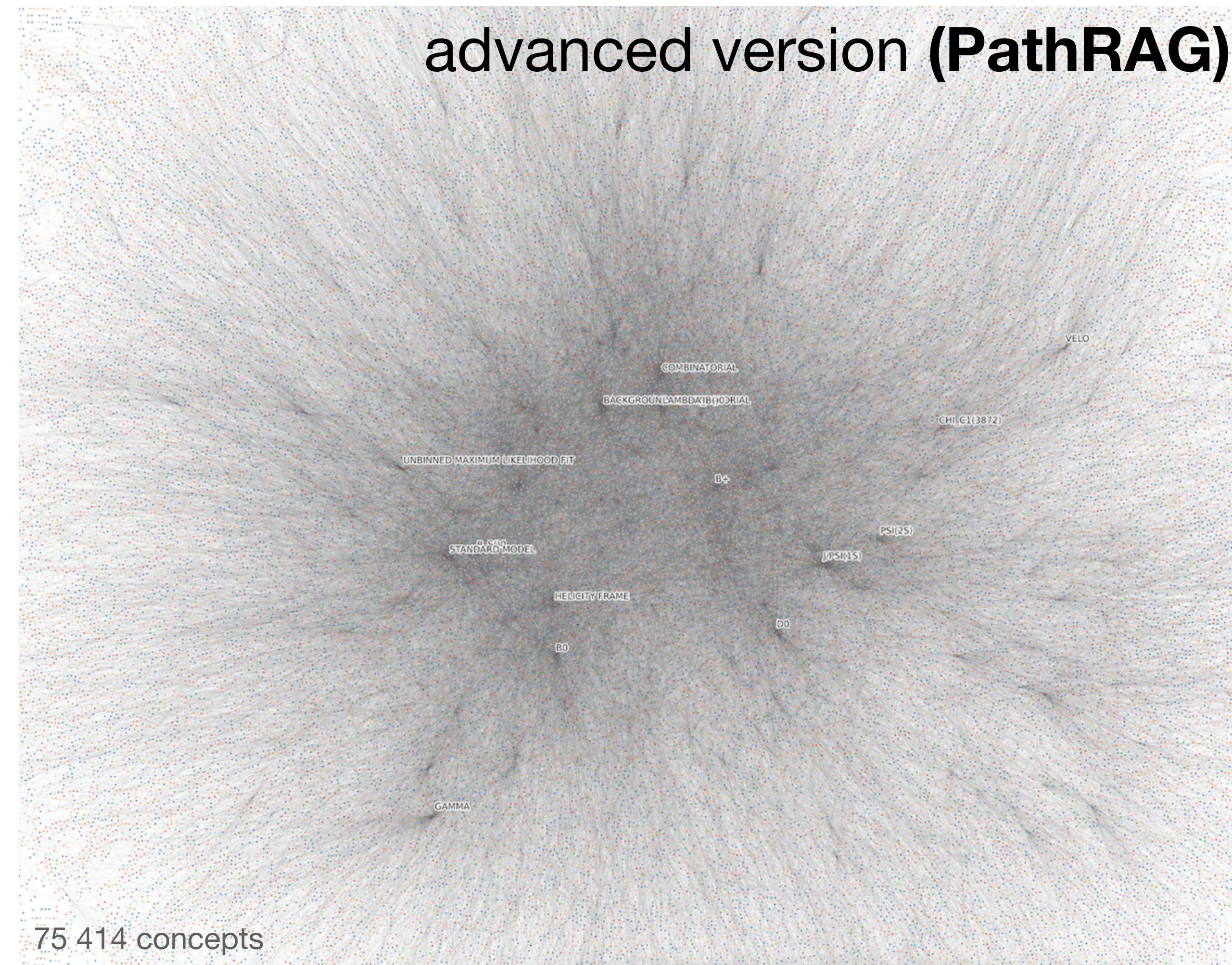
- **Run 1: (2011-2012):**
 $\mathcal{L}_{\text{int}} = 1 \text{ fb}^{-1} @ 7 \text{ TeV}$
 $\mathcal{L}_{\text{int}} = 2 \text{ fb}^{-1} @ 8 \text{ TeV}$
- **Run 2: (2015-2018):**
 $\mathcal{L}_{\text{int}} = 6 \text{ fb}^{-1} @ 13 \text{ TeV}$
- **Run 3: (2022-2026):**
 $\mathcal{L}_{\text{int}} = 20 \text{ fb}^{-1} @ 13.6 \text{ TeV}$
nominal $\mu = 5.5$



LHCb physics

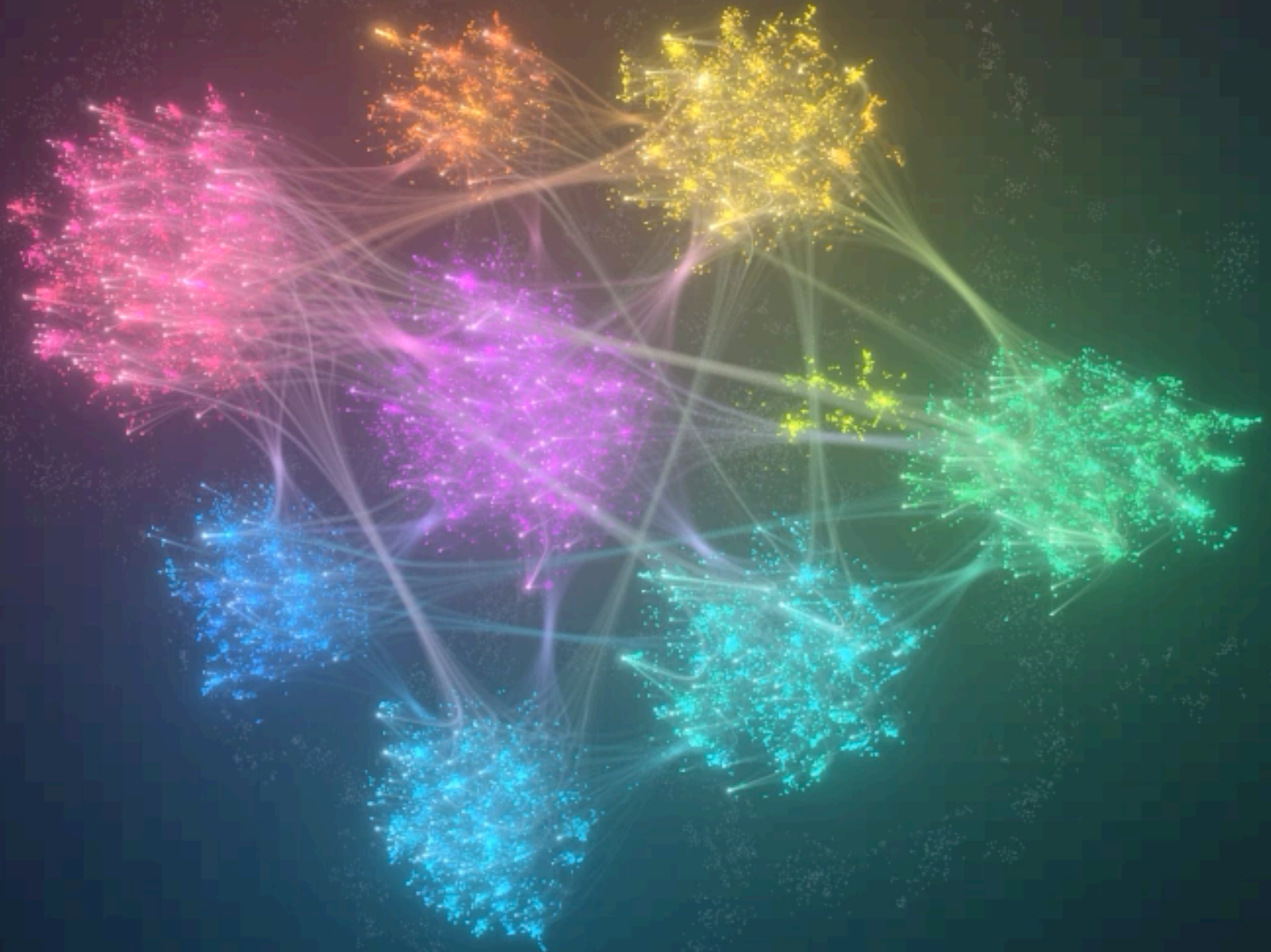
building knowledge retrieval database

- ~800 published papers (~50/year)
- Huge corpus of internal documentation, ~100 pages / analysis
- **Problem:** efficient discoverability
- **RAG:** Retrieval-Augmented Generation
 - Embedding text to vector space
 - Search by cos similarity



LHCb knowledge graph

- Naturally splits in 9 domains of work (Leiden alg.)
- subdomain — node moved closer
- Connection between domains through the “gates”
- z: frequency



PRODUCTION, POLARISATION & NUCLEAR EFFECTS

p_T & rapidity spectra · Y(nS) · R_pPb · forward-backward ratios

CHARMONIUM, B+ DECAYS & EXOTIC STATES

J/ψ · ψ(2S) · χ_c1(3872) · B_c · quarkonium production

RARE DECAYS & CP VIOLATION IN B⁰, B_s⁰

b → sll · φ_s · q² · angular observables · lepton-universality ratios

FITTING, BACKGROUNDS & SYSTEMATICS

maximum-likelihood fits · combinatorial background · sPlot · BDT selection

UPGRADE ELECTRONICS & READOUT

VELOPix · SALT ASIC · GBTx · front-end boards · experiment control

DETECTOR, TRIGGER, SIMULATION & DATASETS

VELO · muon system · Pythia/Geant4/EvtGen · luminosity · Run 1/2 samples

HEAVY BARYONS & DOUBLY-HEAVY STATES

Λ_b · Λ_c · Ξ_b · Ξ_{cc} · T_{cc} · pentaquark channels

CHARM DECAYS & THE CKM ANGLE γ

D⁰ · ΔA_{CP} · r_B · B → DK · RICH particle identification

AMPLITUDE ANALYSES & LIGHT RESONANCES

isobar & K-matrix models · Dalitz plots · Blatt-Weisskopf · fit fractions

colour
size
brightness
fine radial spokes
outer grains
bundled cords
gold rings
gold cords
lit region

one of 9 Leiden domains; hue follows position on the map
degree of the concept
degree x k-core depth
37,485 degree-1 concepts, drawn around their hub
10,059 concepts in isolated fragments, grouped by source paper
inter-domain links, funnelled through domain 'ports'
105 concepts returned by the query, sized by how often the retrieval cites them
163 graph relations between them (91 reported verbatim in the context)
attention veil: the rest of the atlas is dimmed, not removed

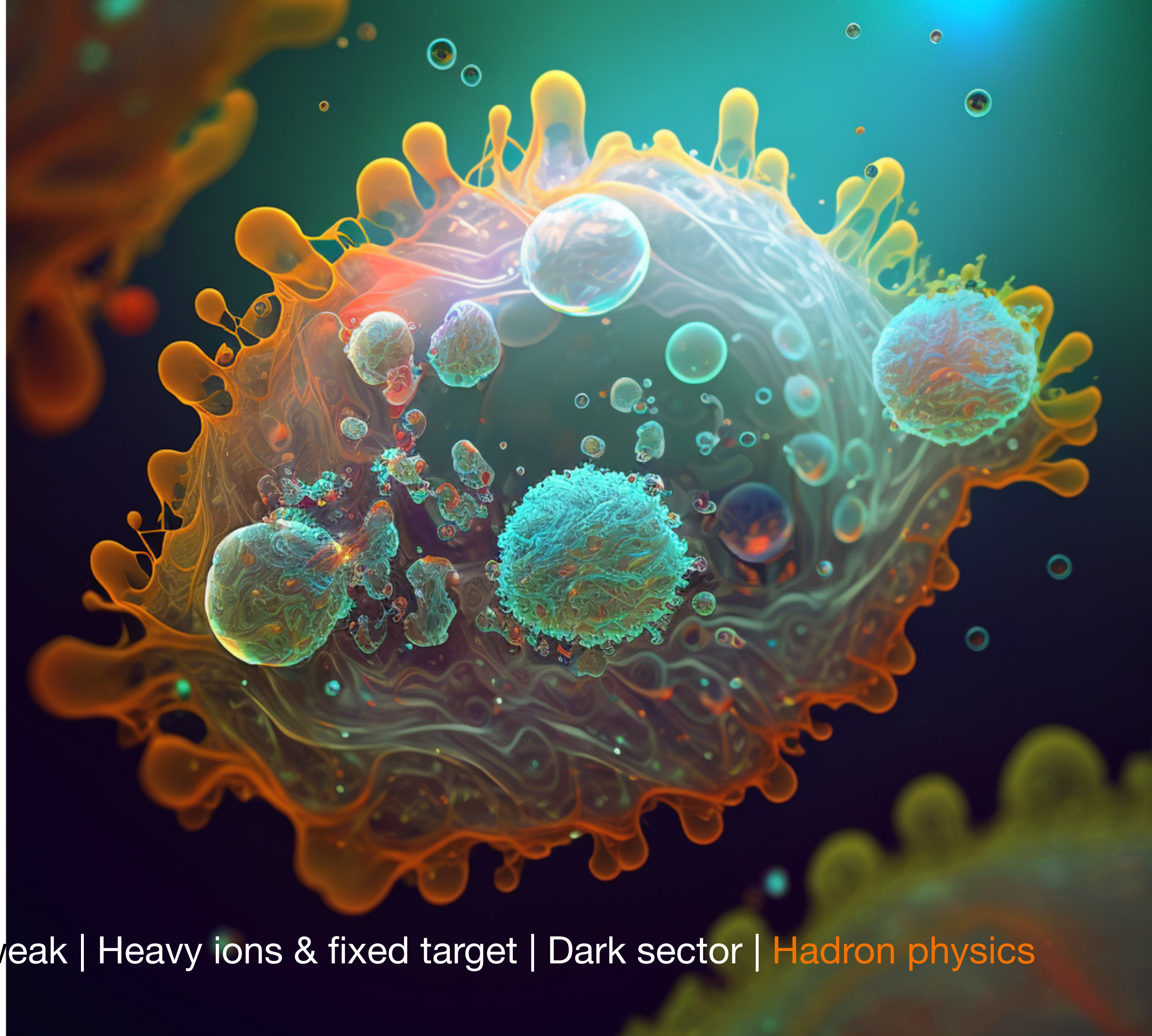
LHCb literature knowledge graph

75,414 concepts · 110,406 relations · 9 domains · 342 sub-communities · modularity Q = 0.70

retrieved sub-graph: 105 concepts from 12 papers

Implications of LHCb measurements and future prospects
Determination of γ and -2β_s from charmless two-body decays of beauty mesons
Measurement of the CKM angle γ from a combination of LHCb results
Measurement of CP observables in B[±] → D[±](*) K[±] and B[±] → D[±](*) π[±] decay...
A model-independent measurement of the CKM angle γ in partially reconstruct...
Measurement of CP observables in the process B⁰ → DK[±] with two- and fou...
A study of CP violation in the decays B[±] → [K[±] K[±] π[±] π[±]] D[±] h[±]...
Angular analysis of the B[±] → K[±]* μ[±] μ[±] decay
Measurement of lepton universality parameters in B[±] → K[±] ℓ[±] ℓ[±]...
A study of CP violation in B[±] → D K[±] and B[±] → D π[±] decays with D → K_S...
Measurement of CP -averaged observables in the B⁰ → K[±] μ[±] μ[±] decay
Measurement of the CKM angle γ using B[±] → D K[±] with D → K[±] S π[±] π...

Hadron Physics



CP violation | Rare decays | Electroweak | Heavy ions & fixed target | Dark sector | **Hadron physics**

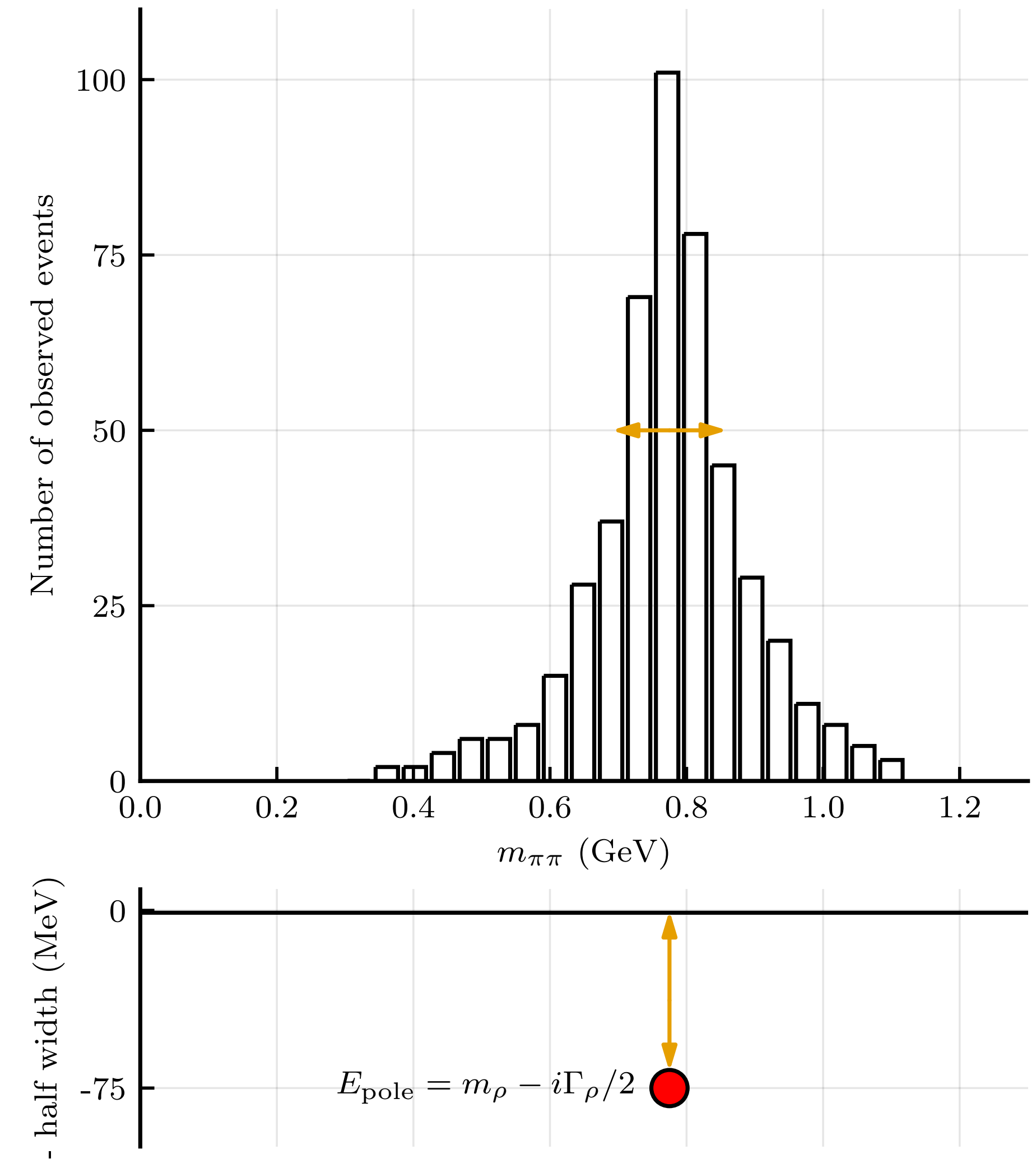
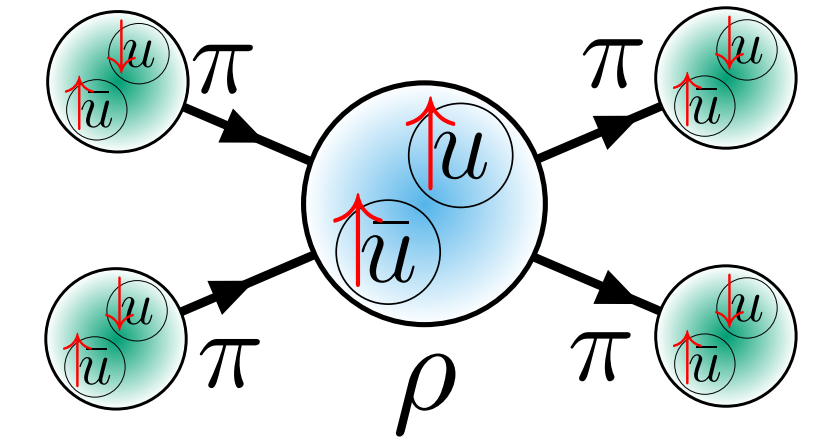
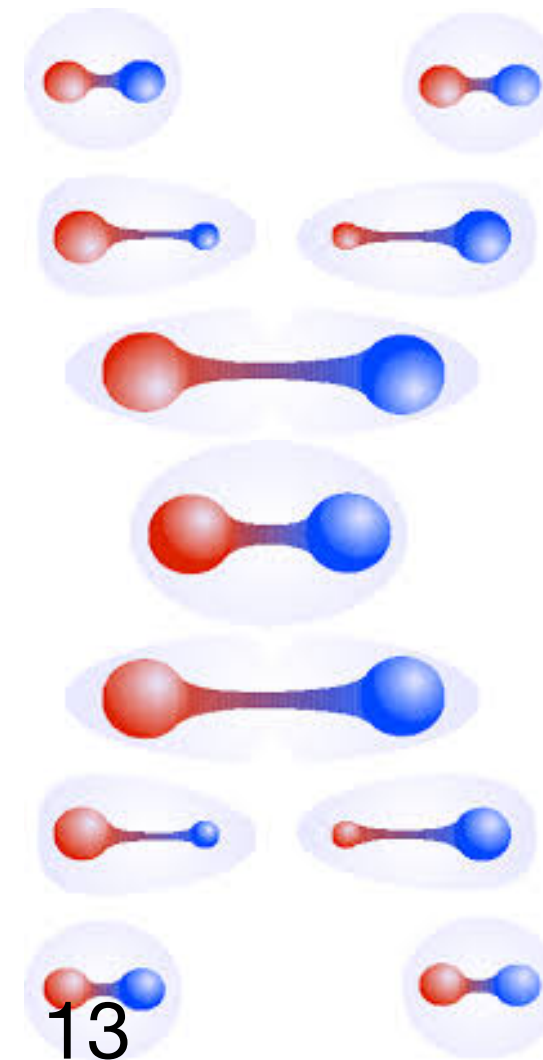
Particles and resonances

Event occurrence as a probe of new matter forms

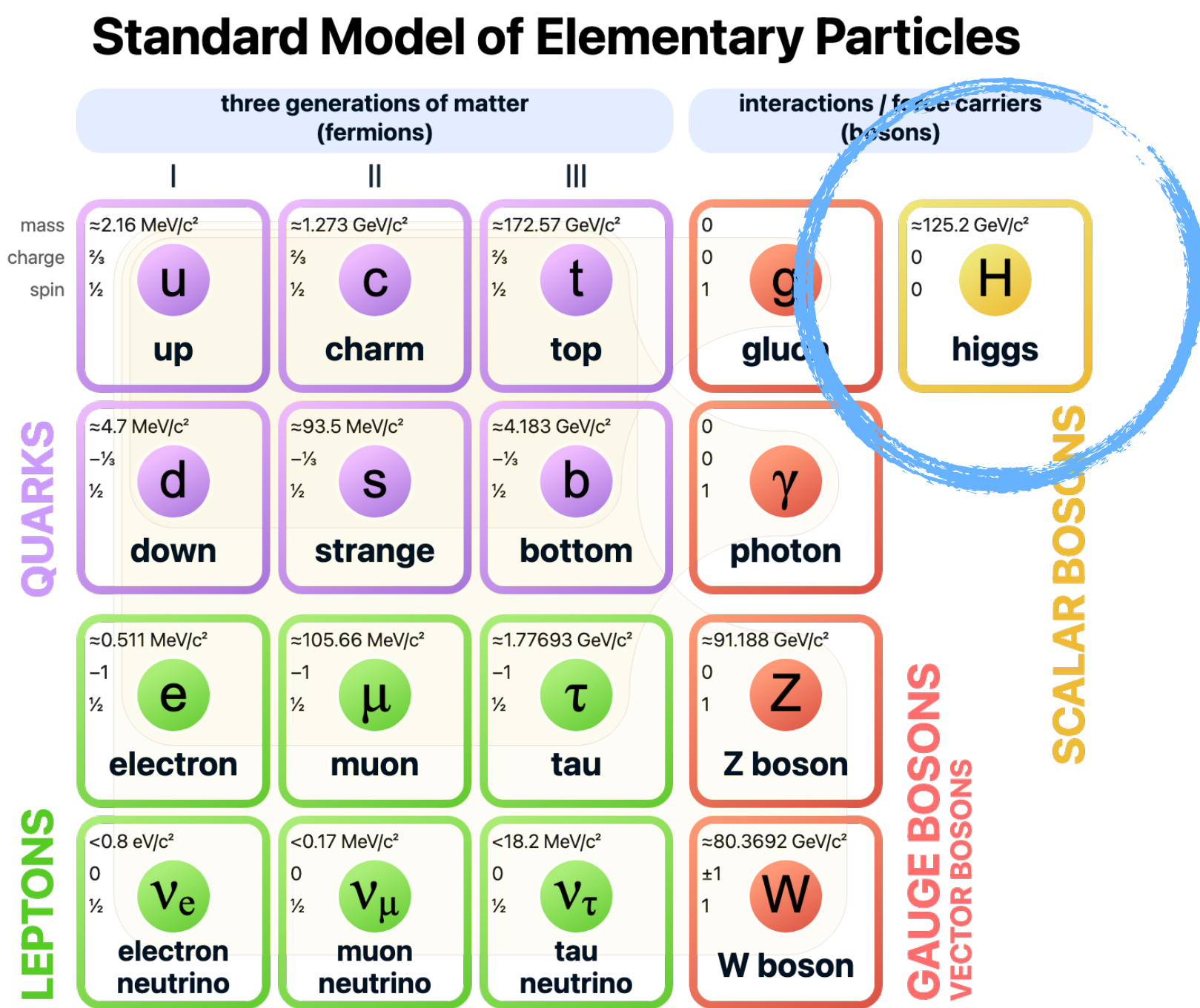
1. - select energy
- smash particles
- check how **likely they are to interact**
(effective cross section)
repeat 1 million times



2. tune system energy,
scan record **probability to interact**
observe resonance phenomenon
3. For a short moment, the colliding
system turns into other form of matter



Higgs particle is a resonance



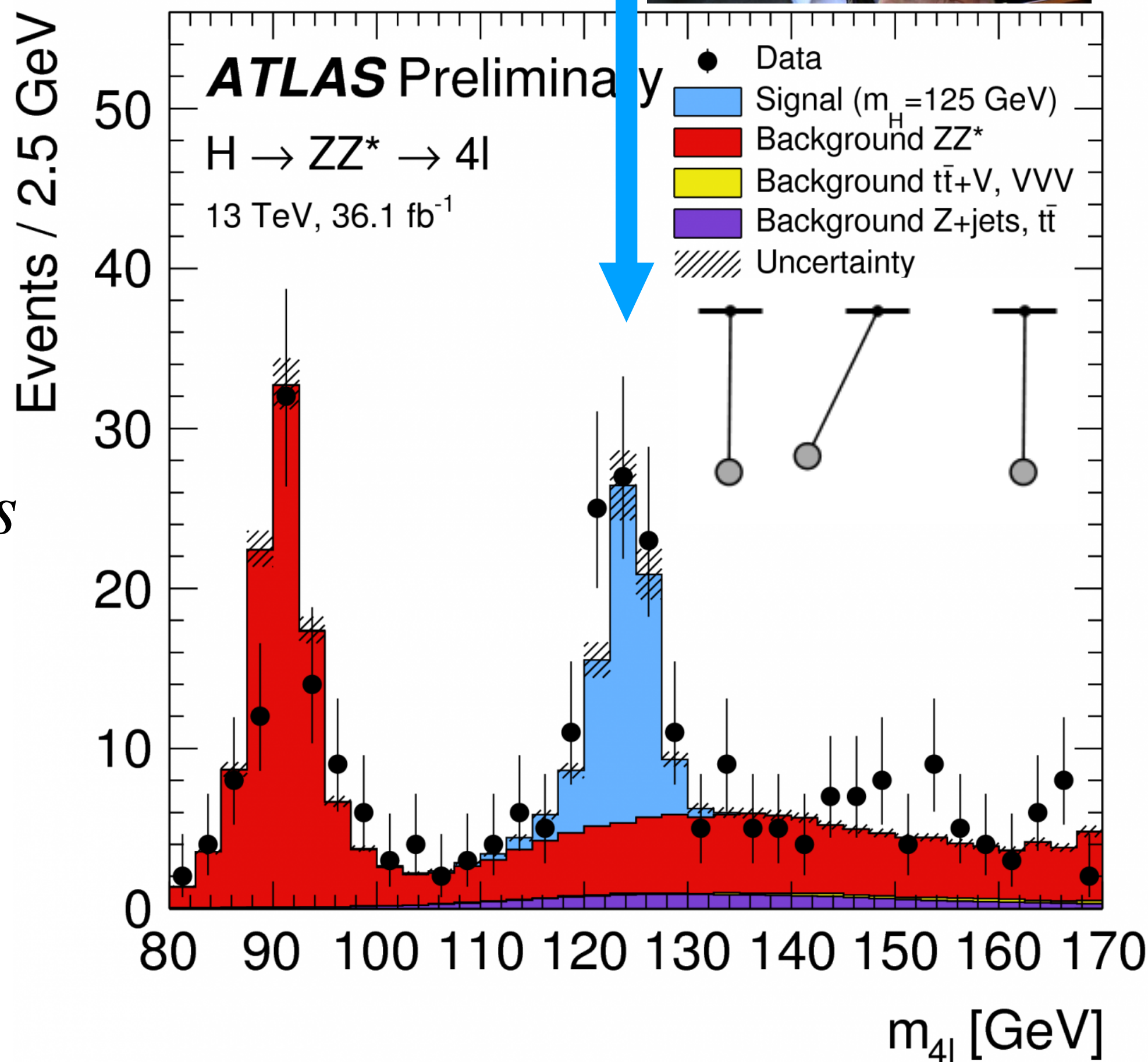
Four muons
resonate at a
frequency
of 125 GeV

$$E = \hbar \nu$$

$$\hbar \approx 6.6 \times 10^{-16} \text{ eV} \cdot \text{s}$$

$$\nu \sim 10^{27} \text{ Hz}$$

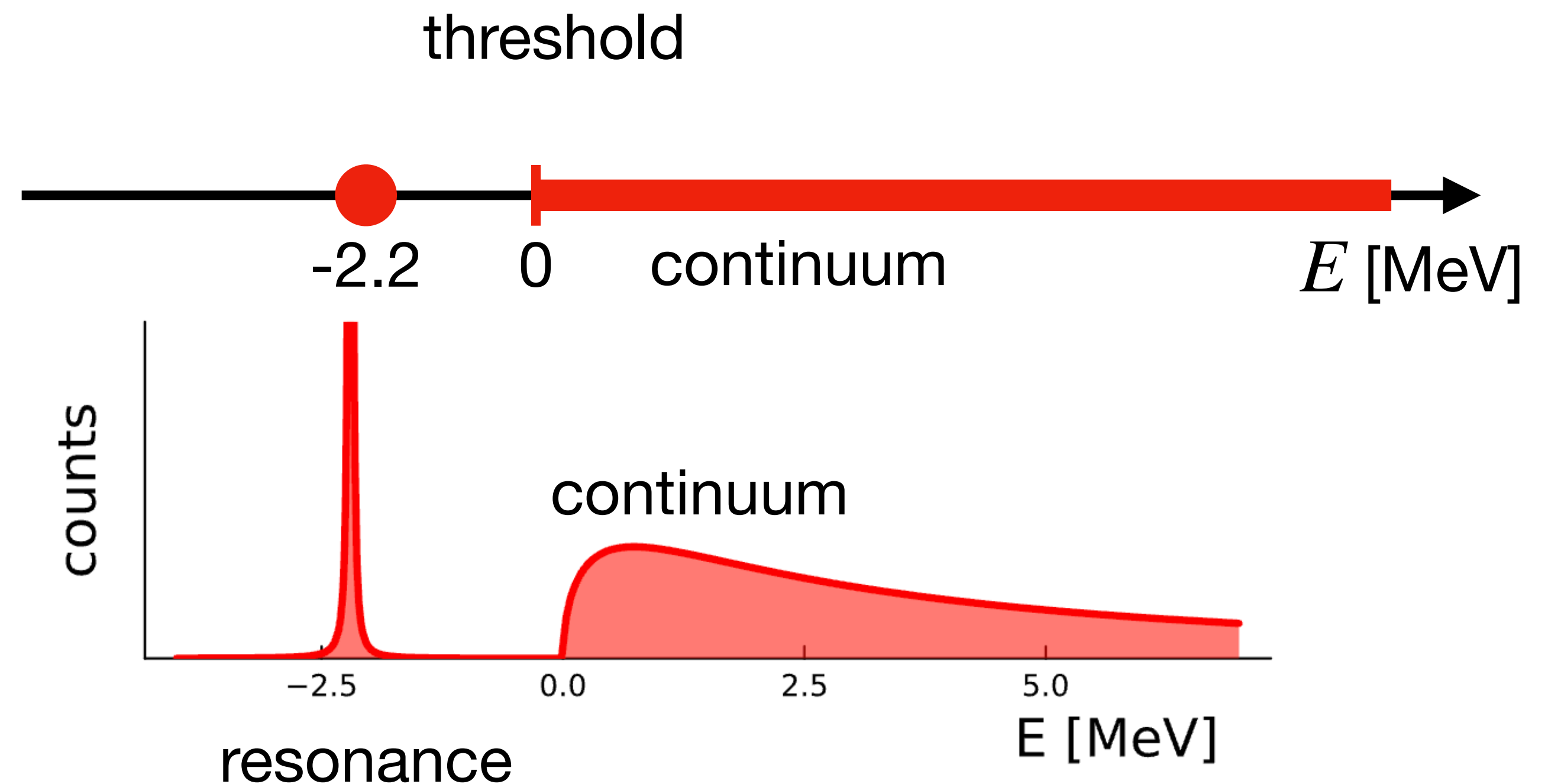
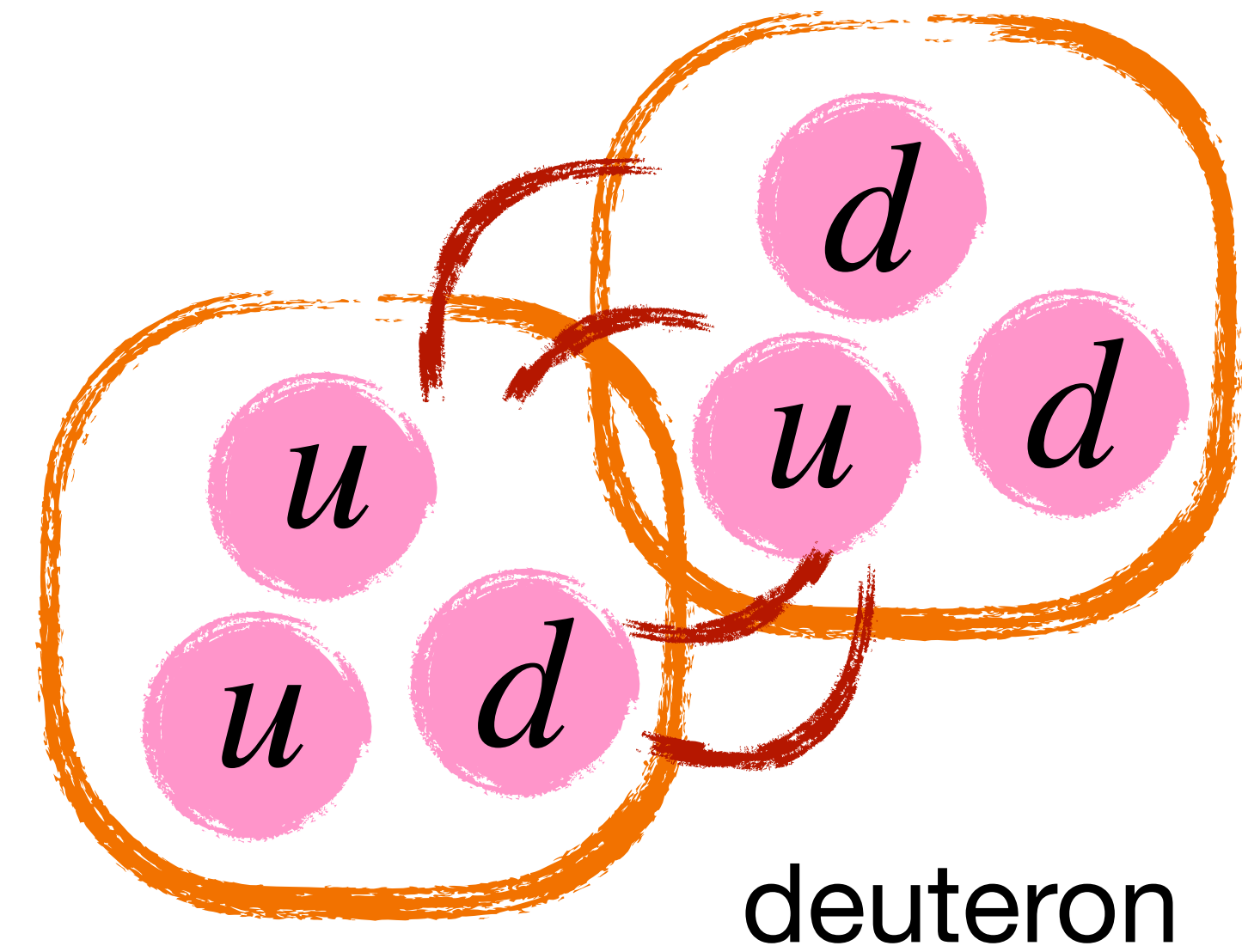
that is the mass
of Higgs boson



Hadronic molecules

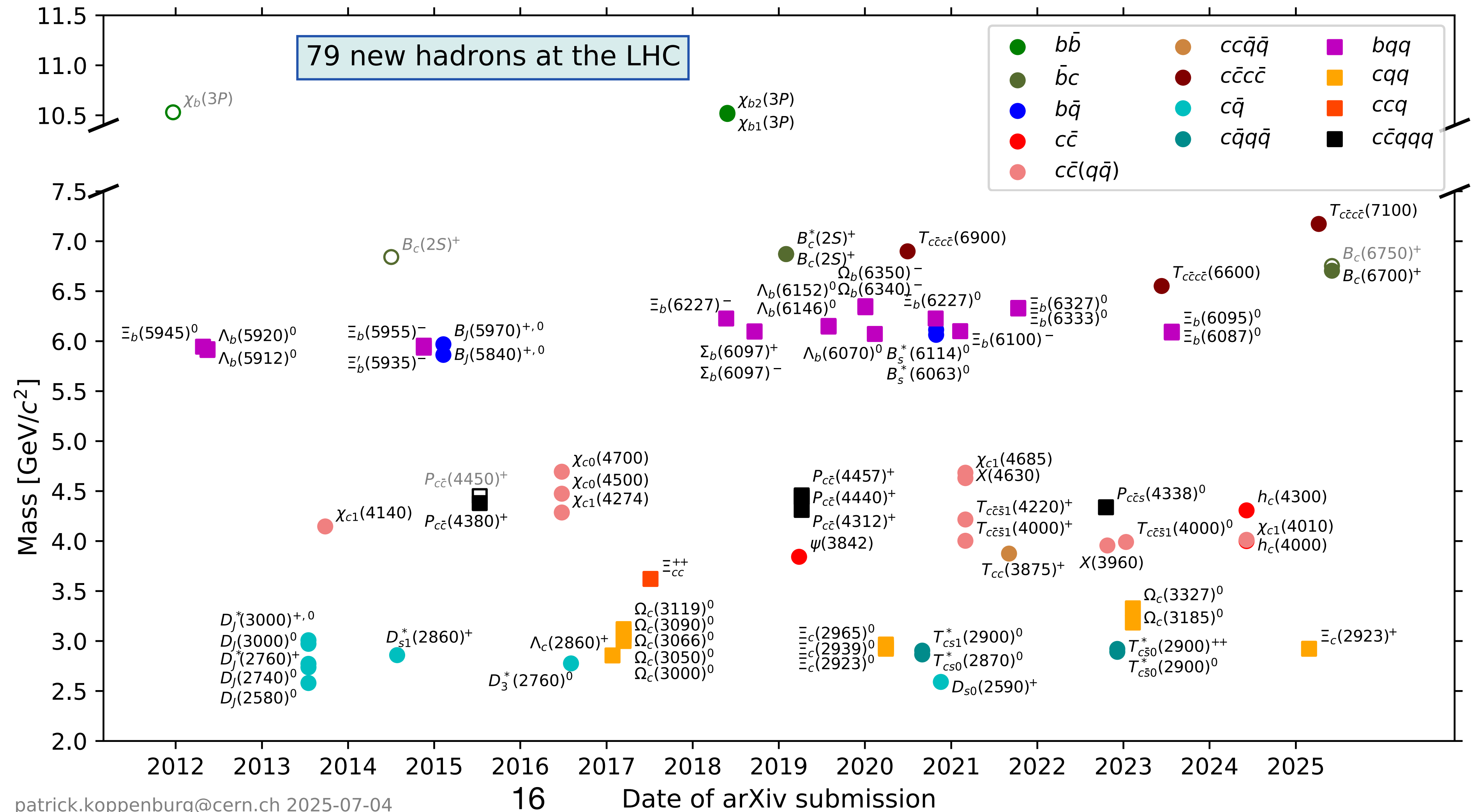
Energy spectrum

- Rest energy of deuteron is smaller than $m_p + m_n$ by the binding energy, about 2.2 MeV
- Had there been a **weakly coupled inelastic channel** for neutron to decay, the spectrum would look like



New hadrons at LHC

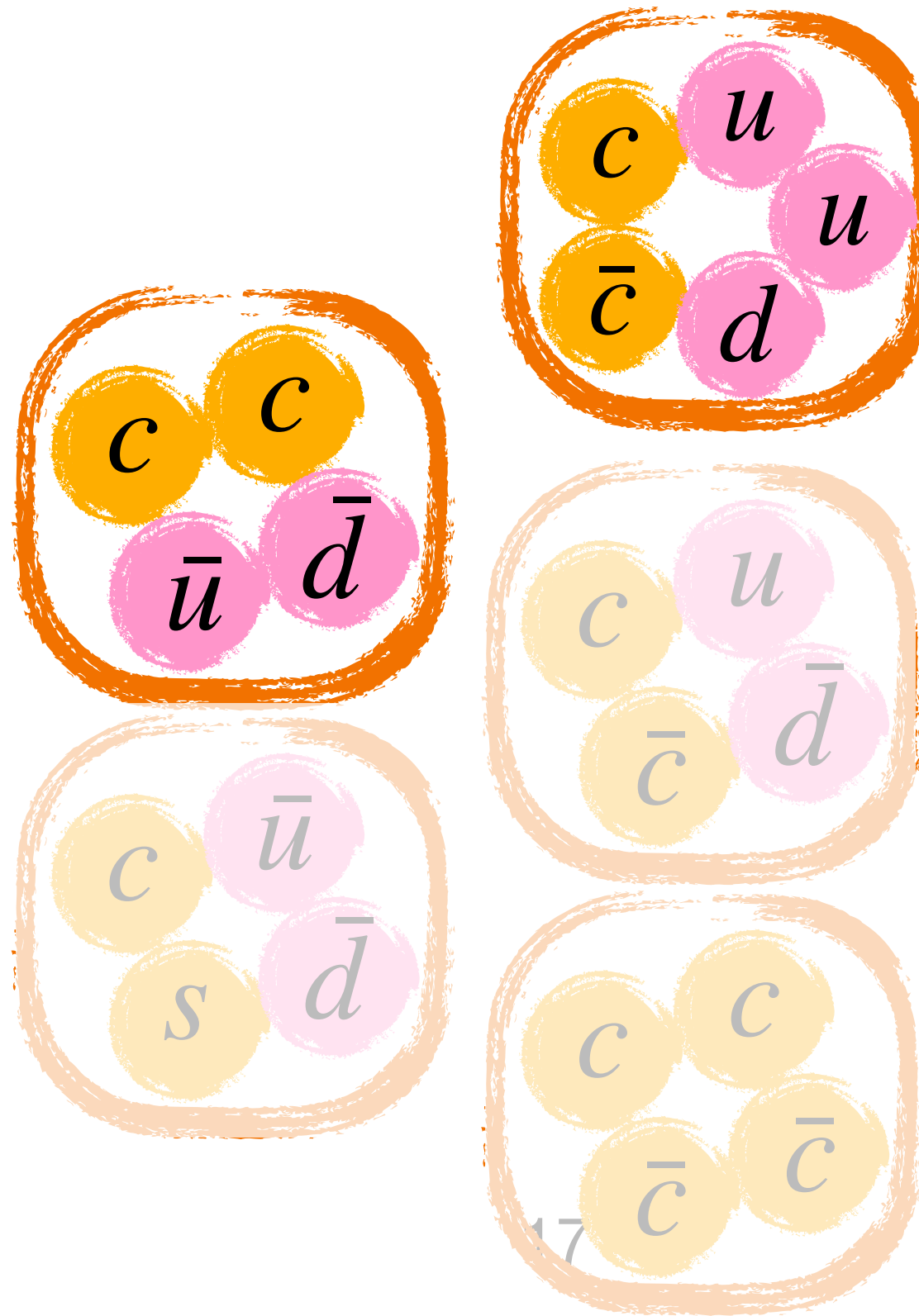
- pp collision data
- new era for heavy flavor sector
- a lot of new particles
- great evidence of exotic phenomena



Zoo trip

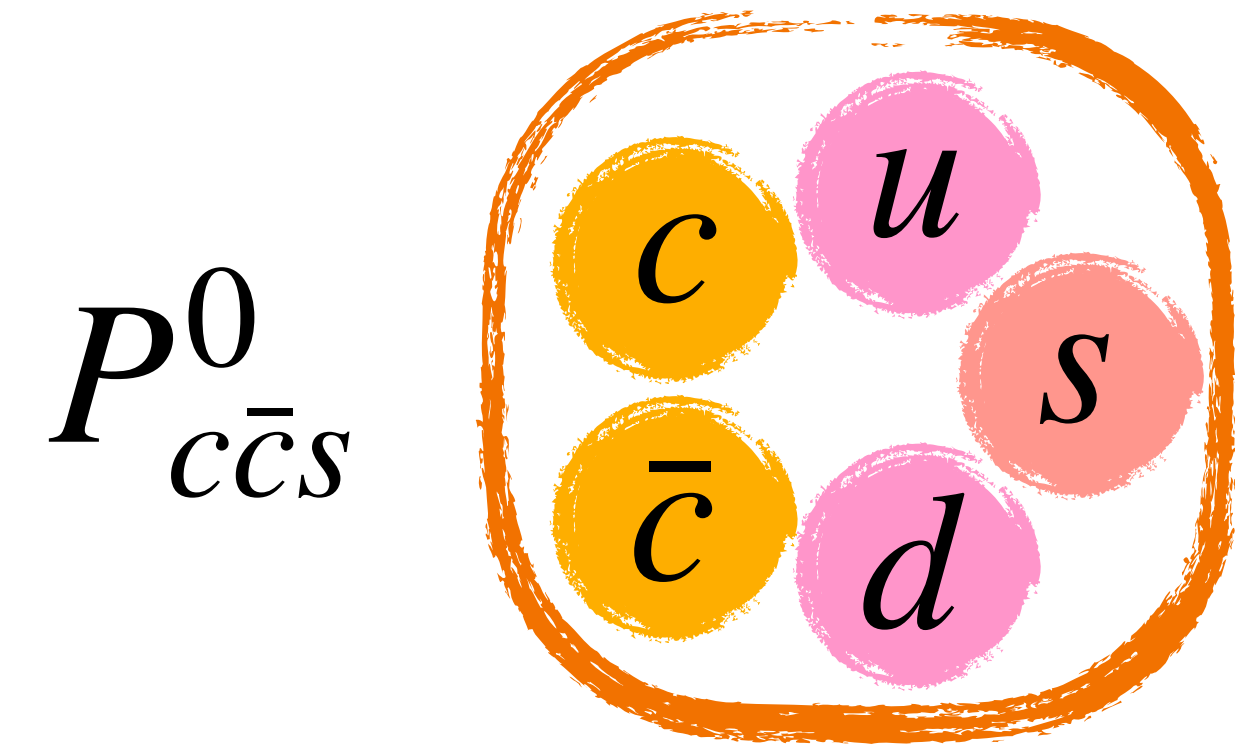
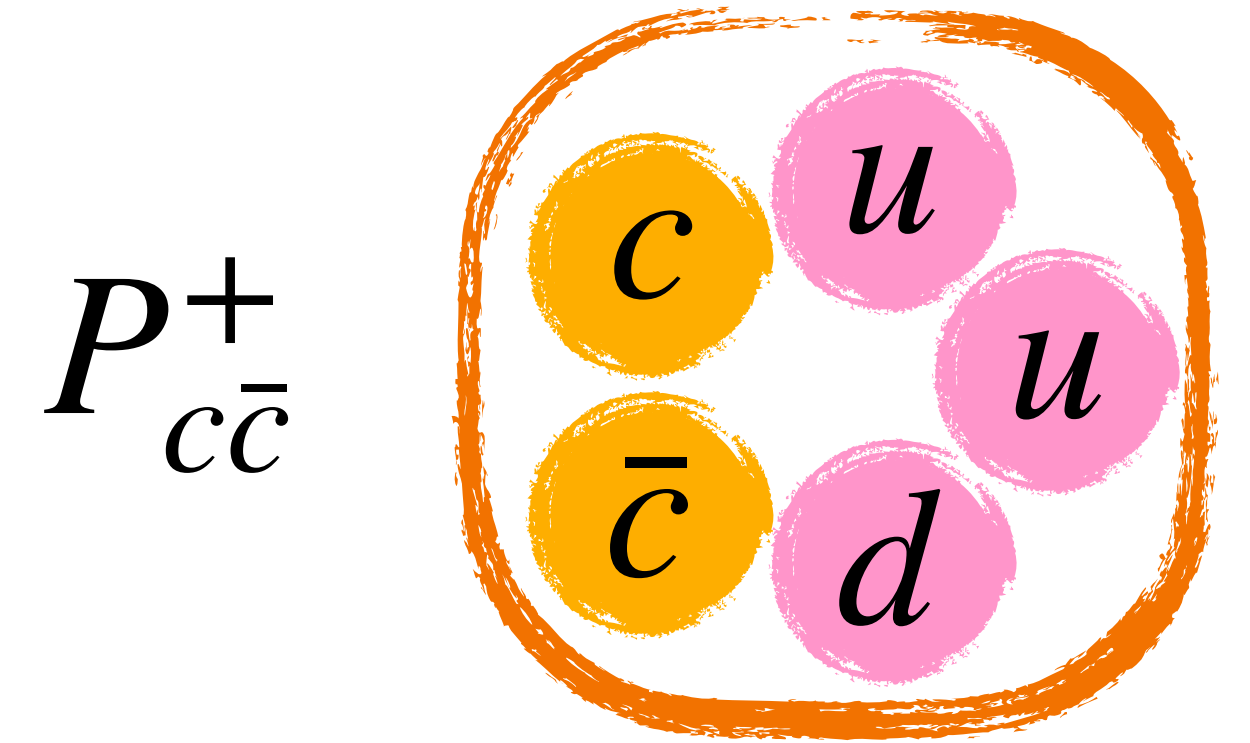
Over the last year, vast variety of new color-neutral forms (hadrons) is discovered

- **Pentaquarks**
- **Doubly heavy tetraquarks**
- Charge charmonium-like
- Open-flavor tetraquarks
- Fully heavy tetraquarks



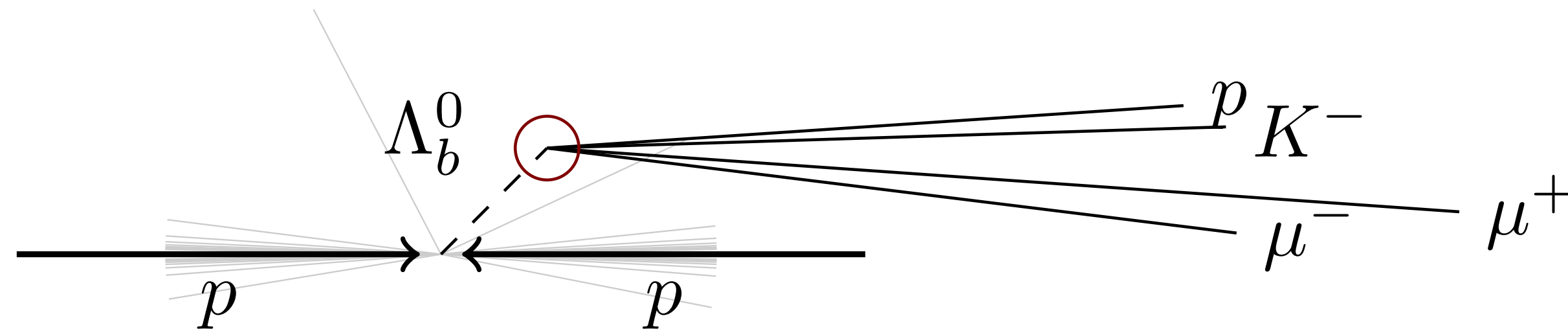
Pentaquarks

- $J/\psi p, \Lambda_c^+ \bar{D}, \Sigma_c^+ \bar{D}$
- $J/\psi \Lambda, \Xi_c \bar{D}$
- $J/\psi \Xi, \Omega_c \bar{D}, \Xi_c \bar{D}_s$

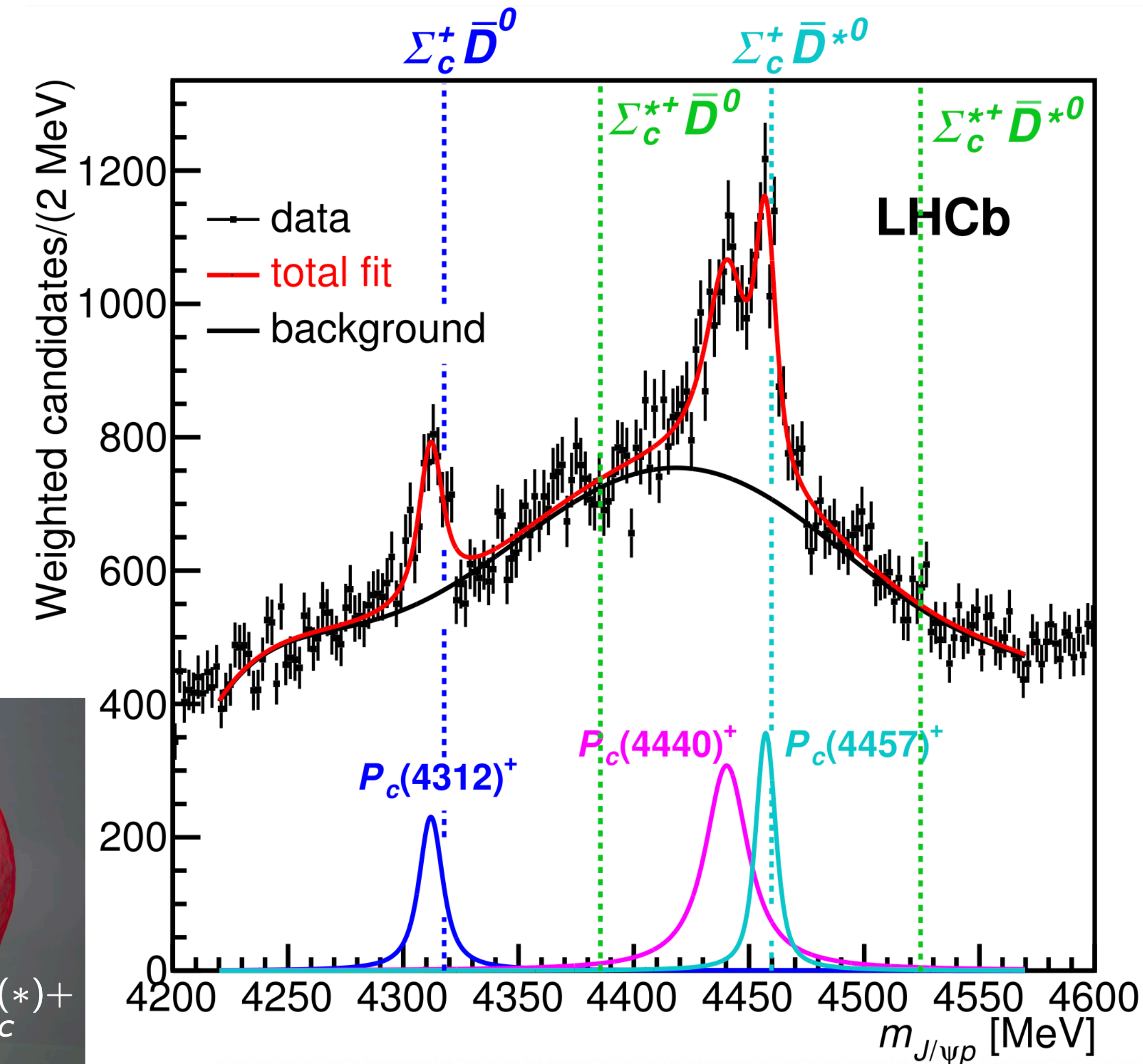
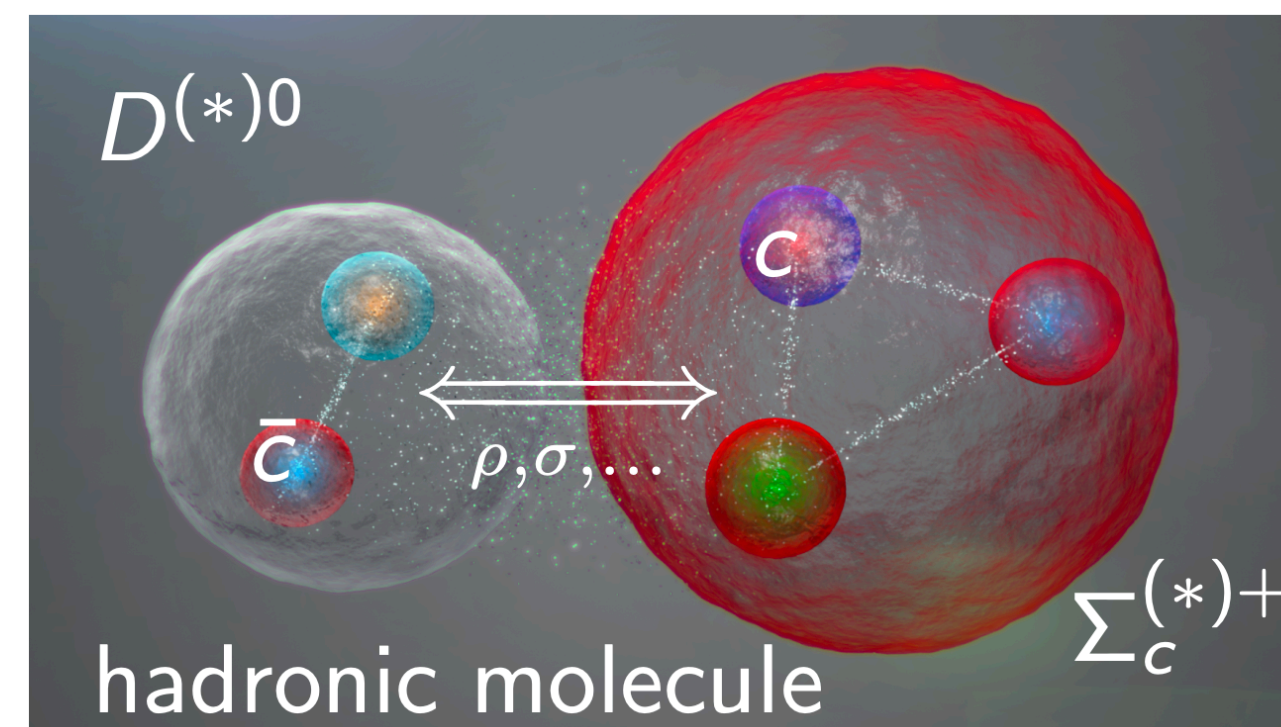


Pentaquarks

Hidden-charm



- Rare events: 200k events with the data collected over 10 years (2008-2018), 9 fb^{-1}
- clear resonances in spectrum of $J/\psi[c\bar{c}]p[uud]$
- About the rest mass of $\Sigma_c^{(*)+}[cud] \bar{D}^{(*)0}[\bar{c}u]$



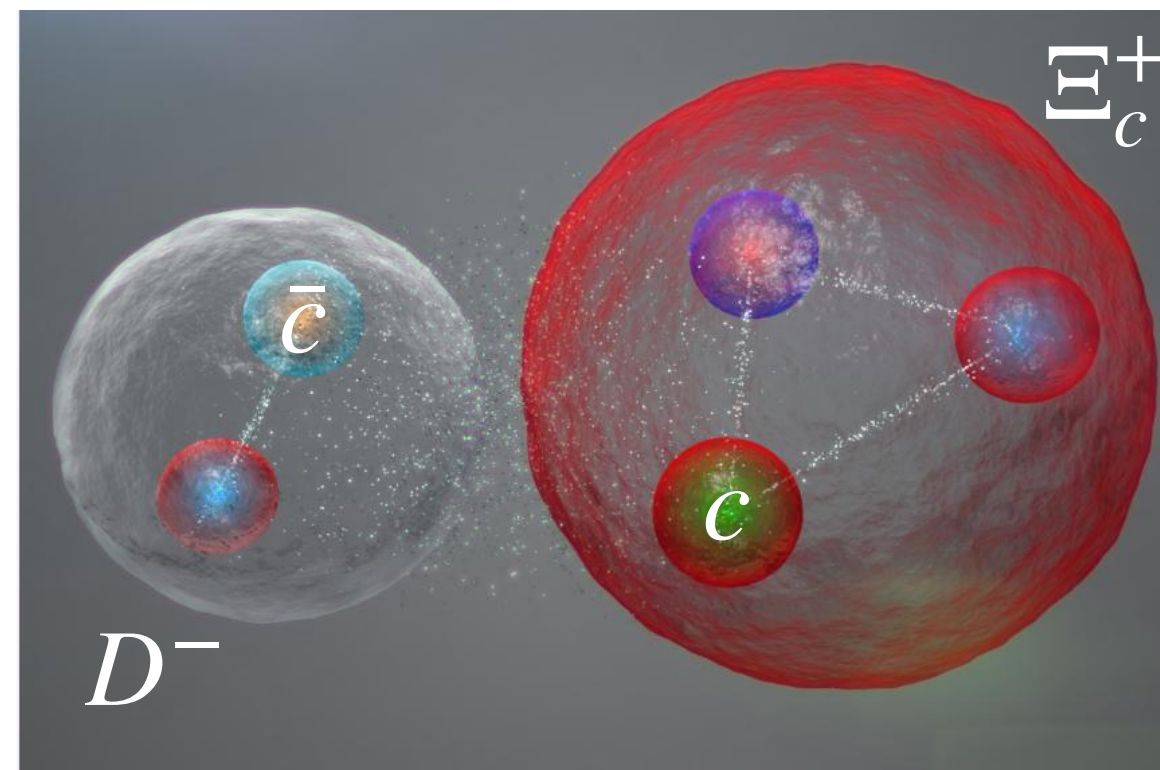
Strange pentaquarks

$$B^- \rightarrow J/\psi \Lambda \bar{p}$$

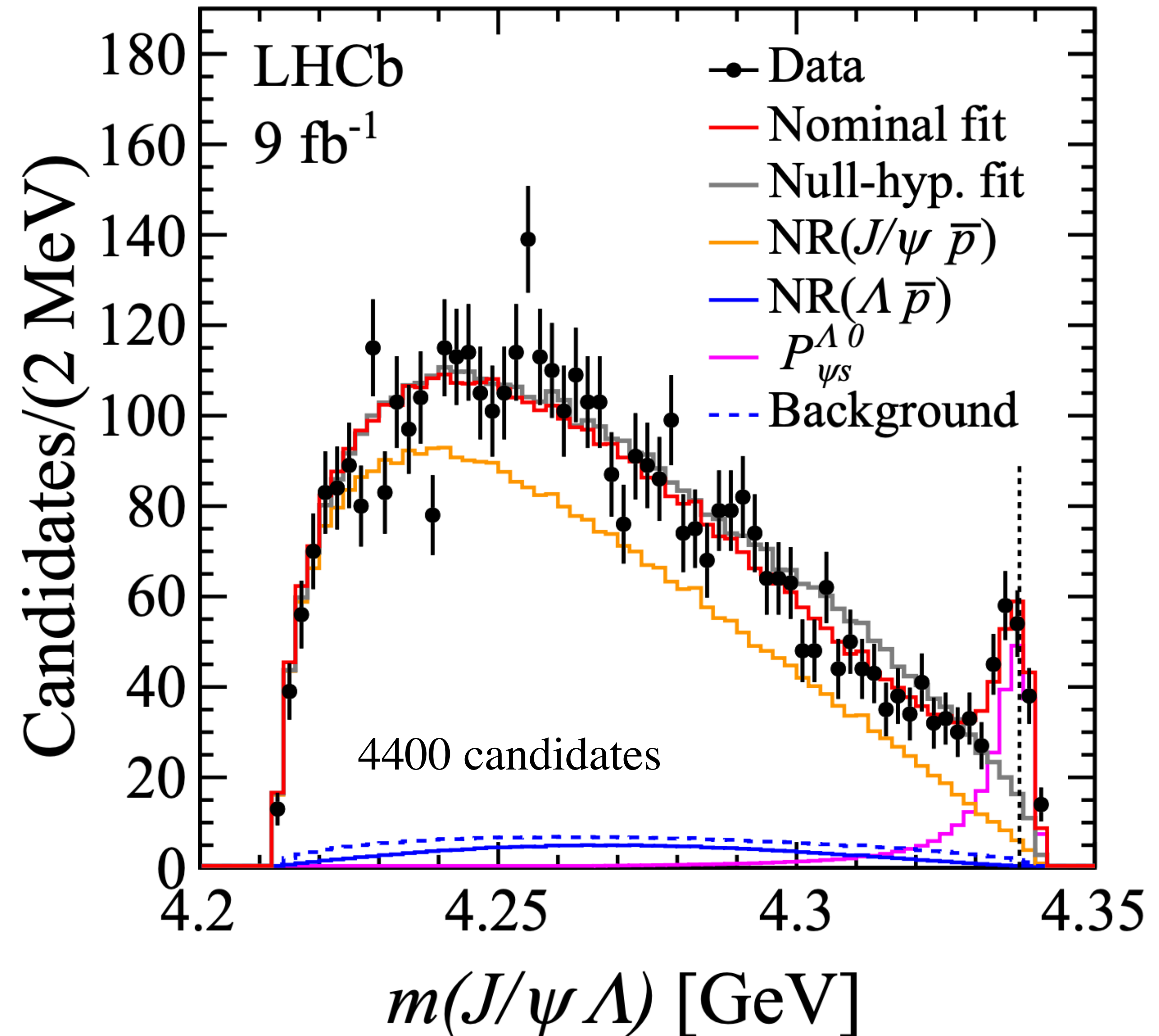
- The decay rate is dominated by structureless background
- Pentaquark signal** is a narrow peak of about 7 MeV width

BW mass is

- 0.8 MeV above $\Xi_c^+ D^-$
- 2.2 MeV above $\Xi_c^0 \bar{D}^0$



[LHCb, PRL 131 (2023) 3, 031901]



Doubly-heavy tetraquarks

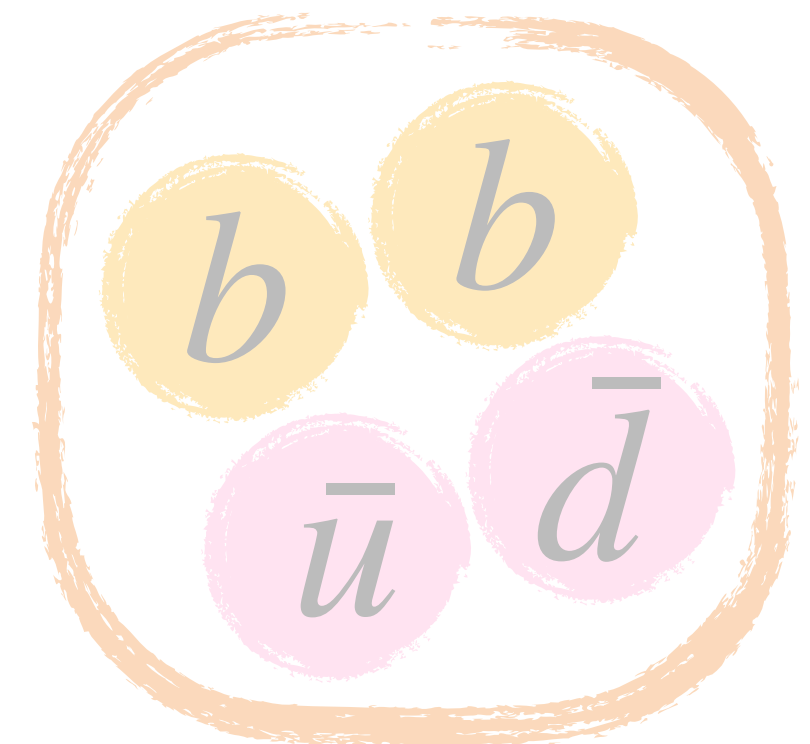
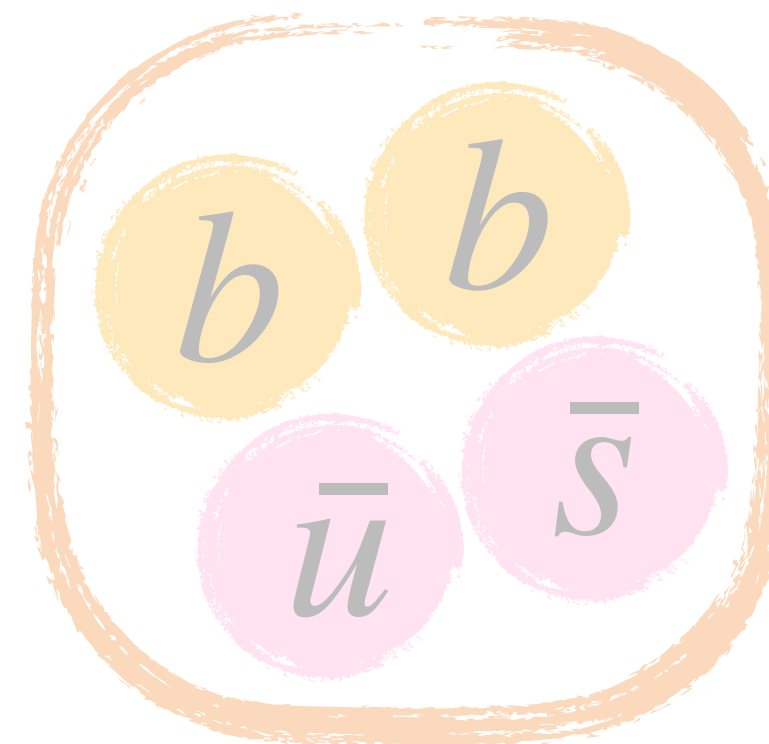
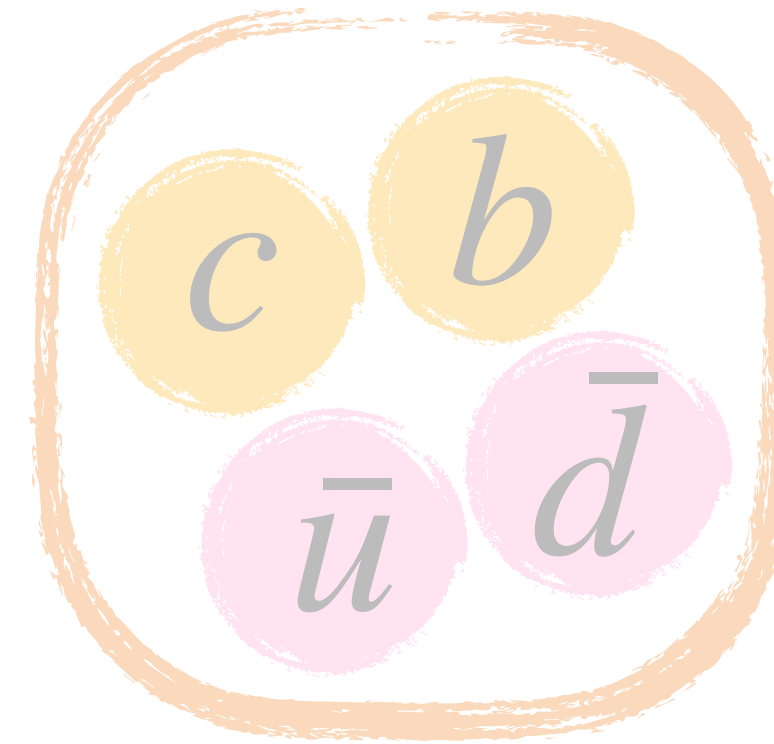
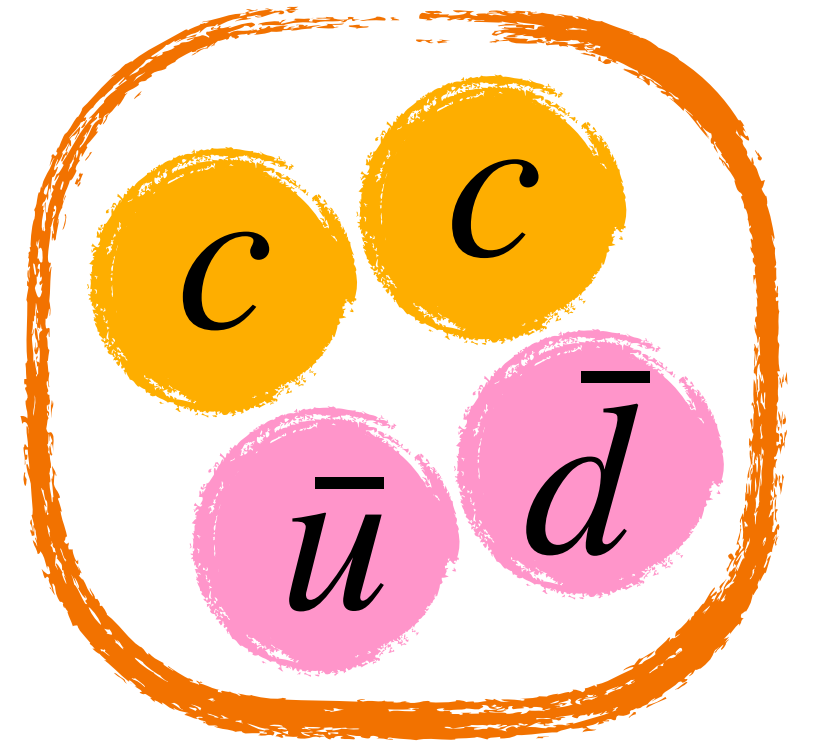
- $D^0 D^{*+}: D^0 D^0 \pi^+, D^0 D^0 \gamma$

- $D^0 B^+$

[\[LHCb, I.Polykov et al.\]](#)

- $B_c^+ X$ inclusive

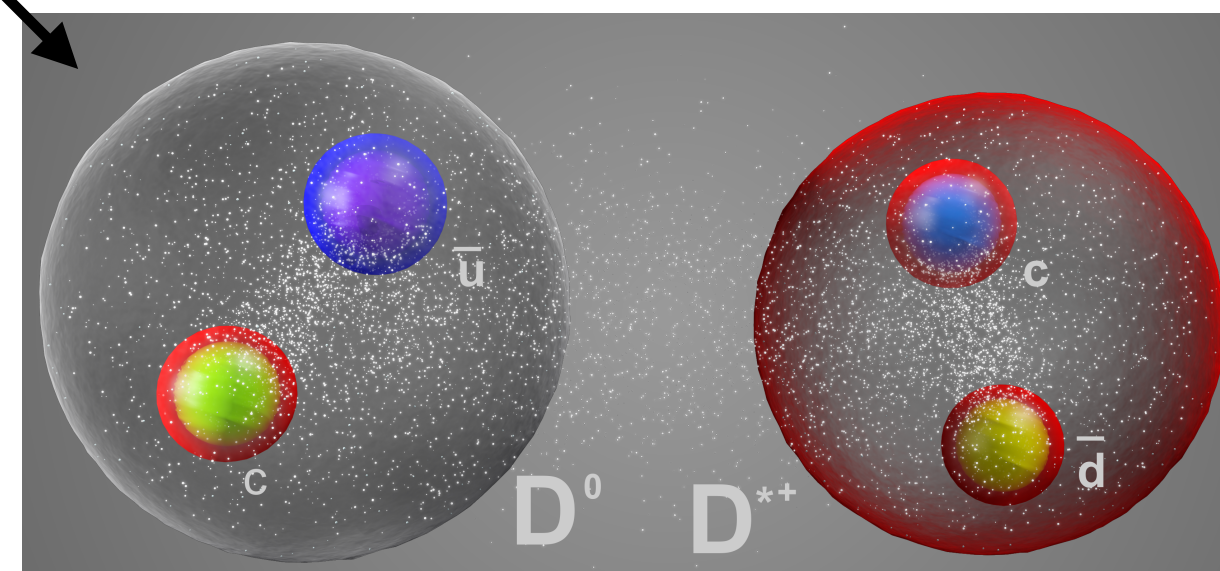
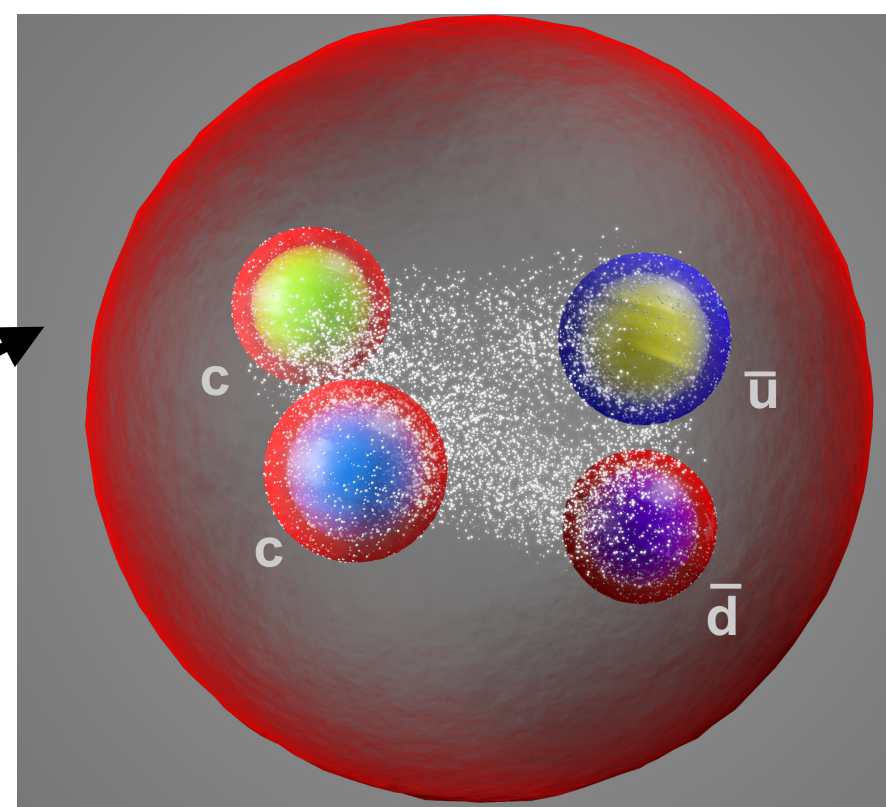
[\[T.Gershon, A.Poluektov, JHEP 01 \(2019\) 019\]](#)



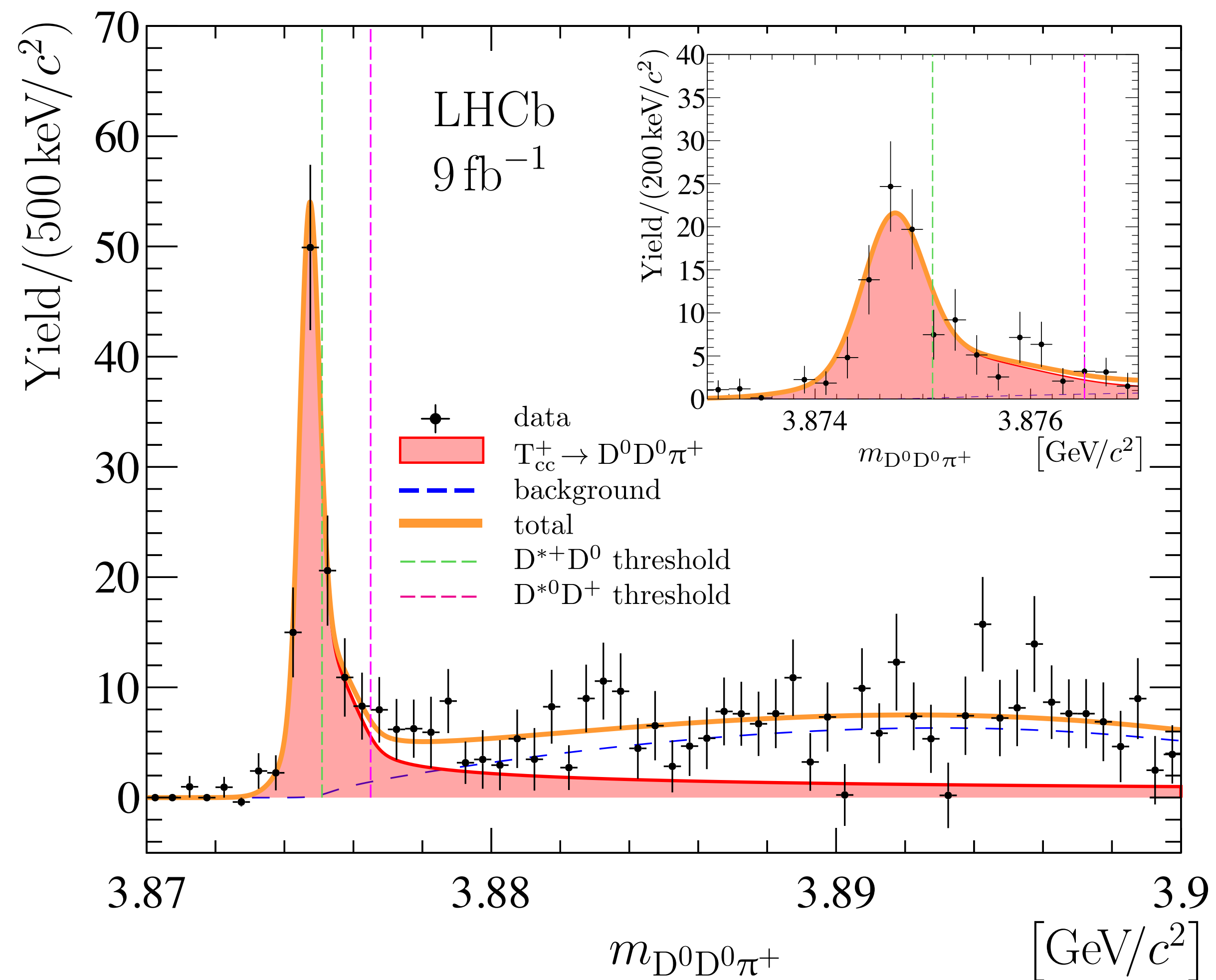
Doubly charm tetraquark discovery

- Resonance in $D^0[c\bar{u}] D^0[c\bar{u}] \pi^+[u\bar{d}]$

- Prove existence of $T_{cc}^+[cc\bar{u}\bar{d}]$
 - tetraquark state
 - falls apart as



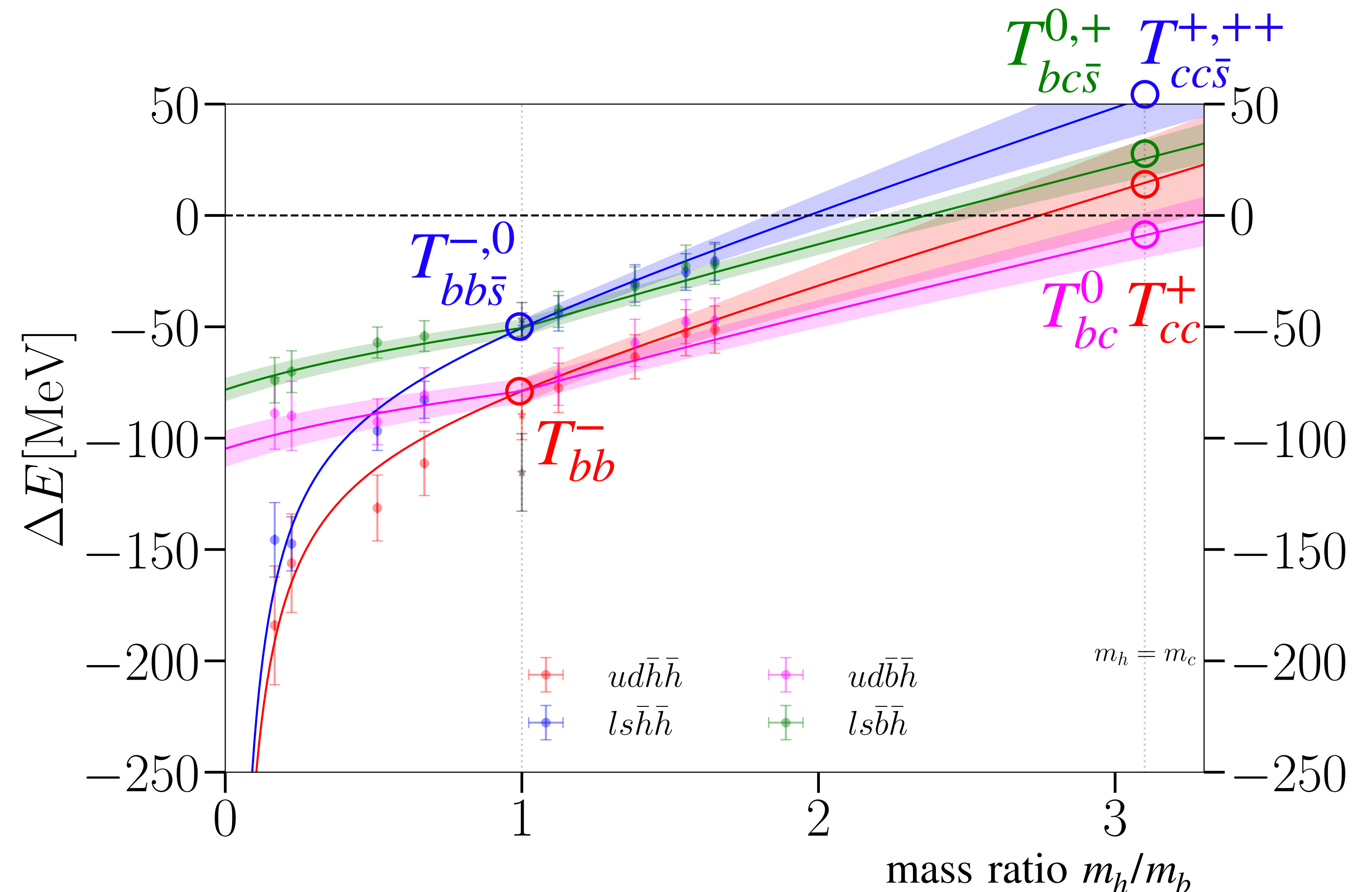
- Nearly stable



Binding energy of T_{bb}^-

Tuning the quark masses with lattice QCD

- Generally agreed that $T_{bb}^-[bb\bar{u}\bar{d}]$ is **deeply bound**
- Stable with respect to the strong interaction (flies cm at LHC)
- Lattice QCD computations show consistent picture



Challenges of the field

- No fundamental way to get theoretical input on amplitude description
(lattice QCD is getting there, but not yet)
- Knowledge build across model in many analysis
(spectrum and lineshapes of K^* states needed for tetraquark background, Λ for pentaquarks)
- Large data sets — low iteration speed
(fits take hours to days)
- Models are complex, no benchmarks

SHARING MODELS

Project problematics and core goals



- **Problem statement:** Lack of accessible, reproducible model across disciplines, slowing scientific progress
- **Core goal:** Establish an accessible platform/interface for researchers to share, integrate, and build upon models across ErUM (high-energy physics, **hadron physics**, QED/laser physics, astro particles, neutrino experiments, dark matter searches), foster a new habit of publishing models (likelihood)



Benefits of accessible research models

- Reproducibility and Open Science

“We have tried implementing past amplitude analysis from papers many times, and have never succeeded.
It’s impossible, do not even try”



- **Correctness/Validity** check for new Frameworks

Many domain-specific frameworks: just for PWA (hadron physics), 4 in COMPASS, ~10 in LHCb
Every PWA research implements its own framework, it's ok. We need to have a way to validate it

- Inference from model results — likelihood, reinterpretation

Get something not computed in original paper (parity violation / pole positions, couplings)



- Integration with Monte Carlo generators



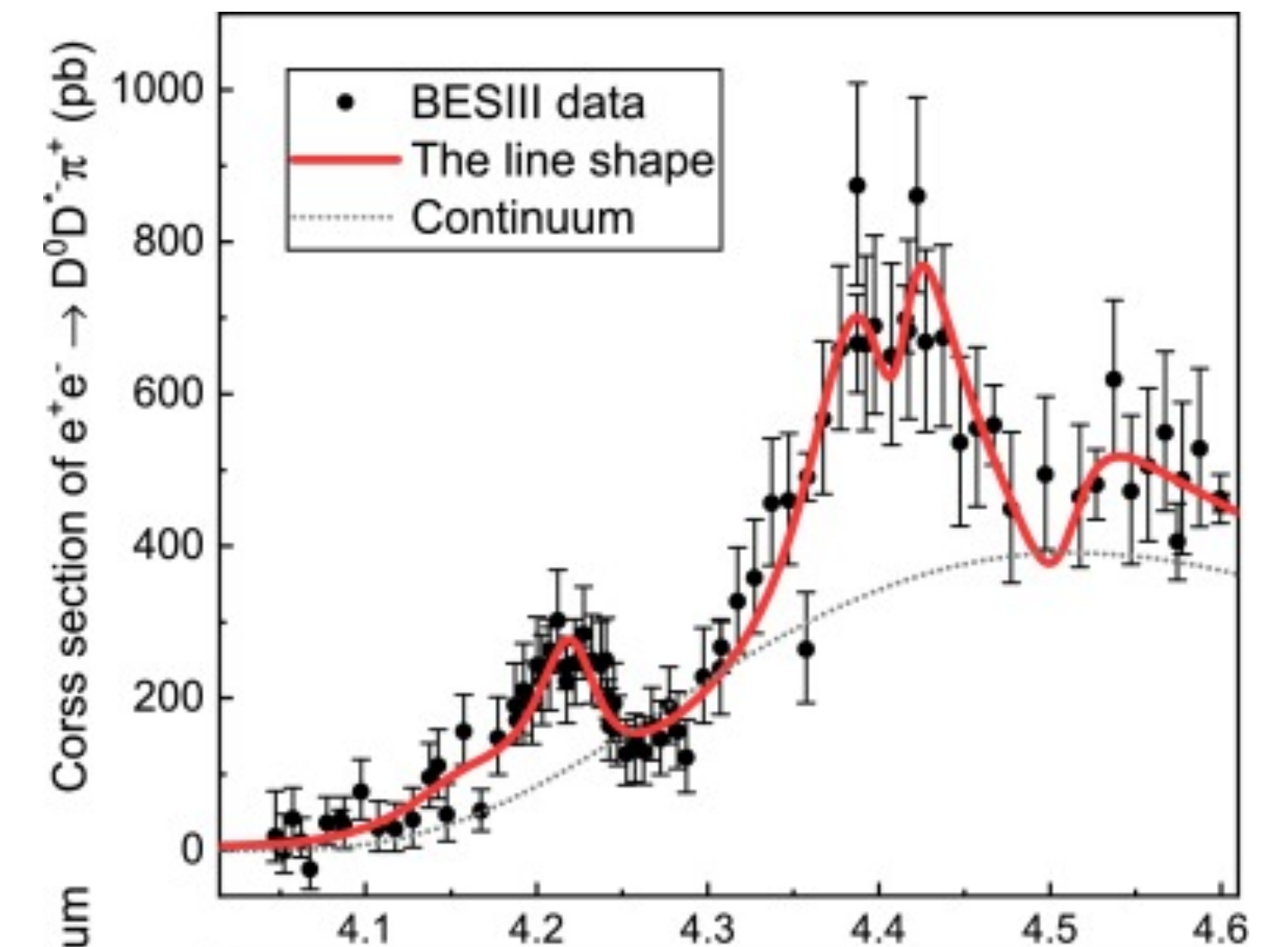
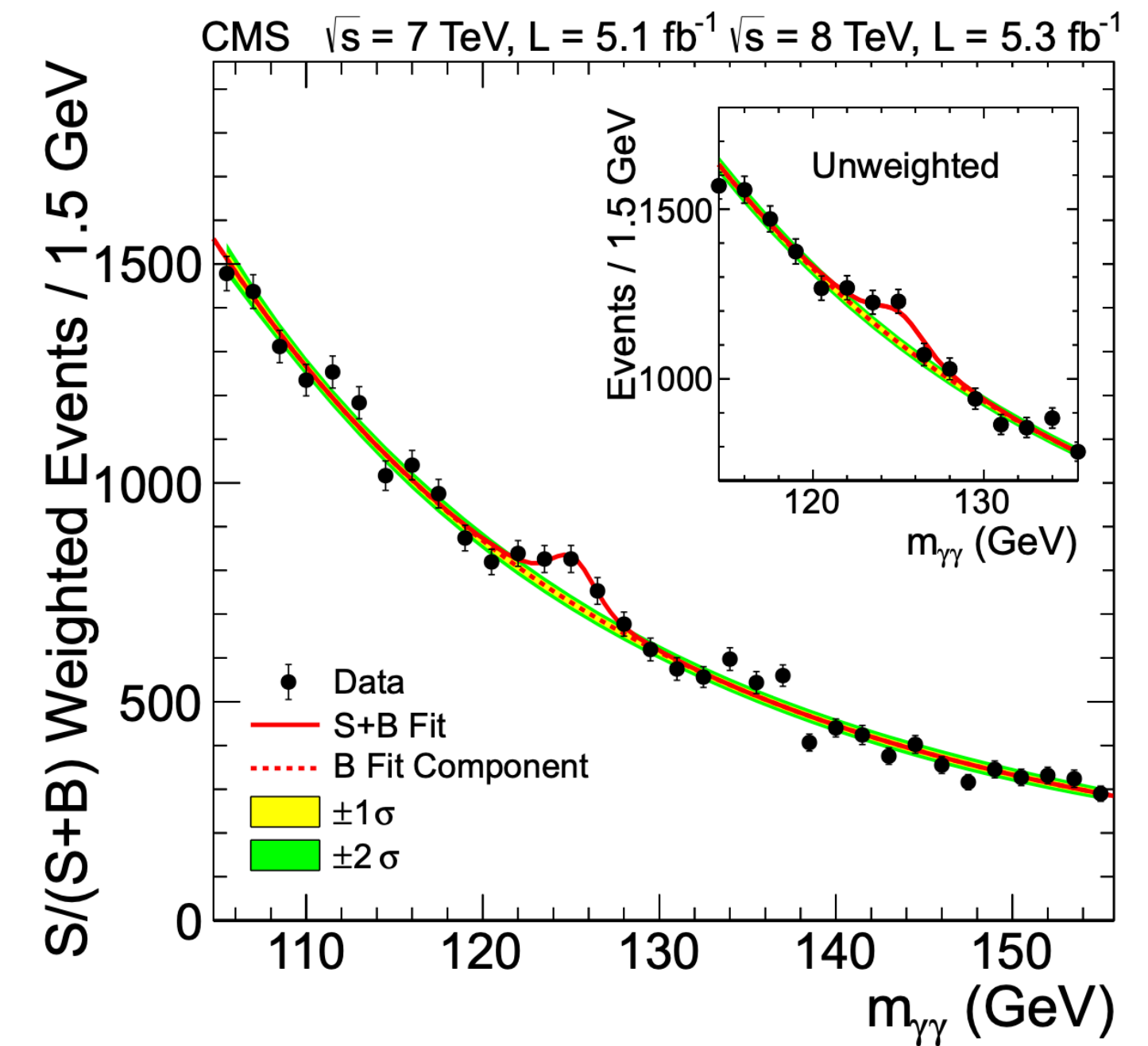
- Benchmark of frameworks and new computational devices

GPU/TPU speed up? jax is fast or not? does one need autodiff?

Curves and crosses

How the research results is presented digitally?

- Data points “+” (**crosses**) — several services (e.g. HEPData)
- Models (**curves**) — nowhere, models are barred in the paper text in vague formulations



Broader Impact

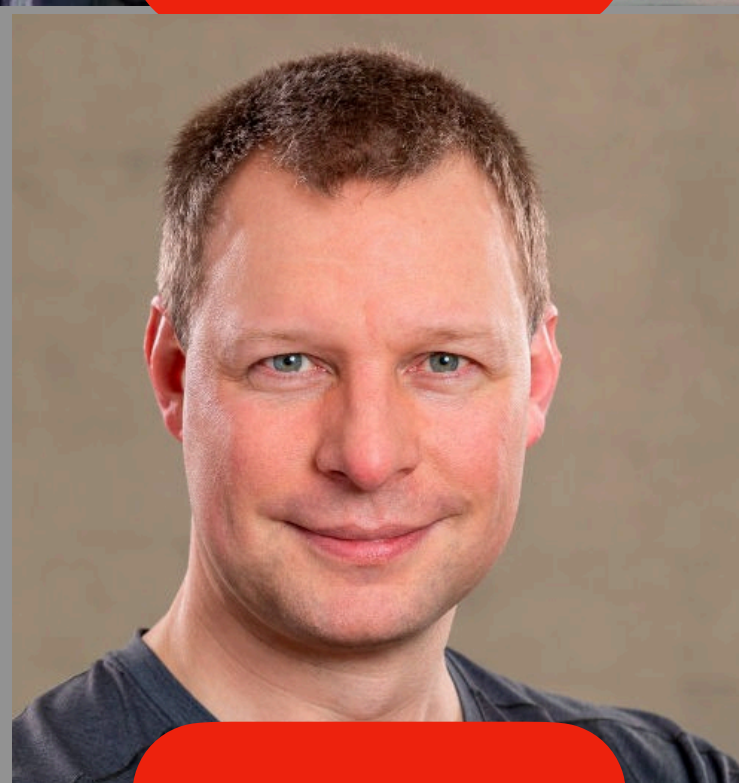
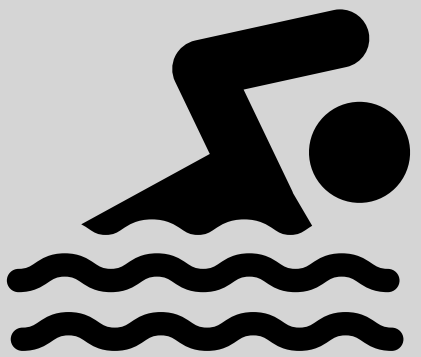
AI for science:

- Facilitate ability of AI agents build, use complex models
- Part of the world knowledge to learn — *AI gets better in complex science*

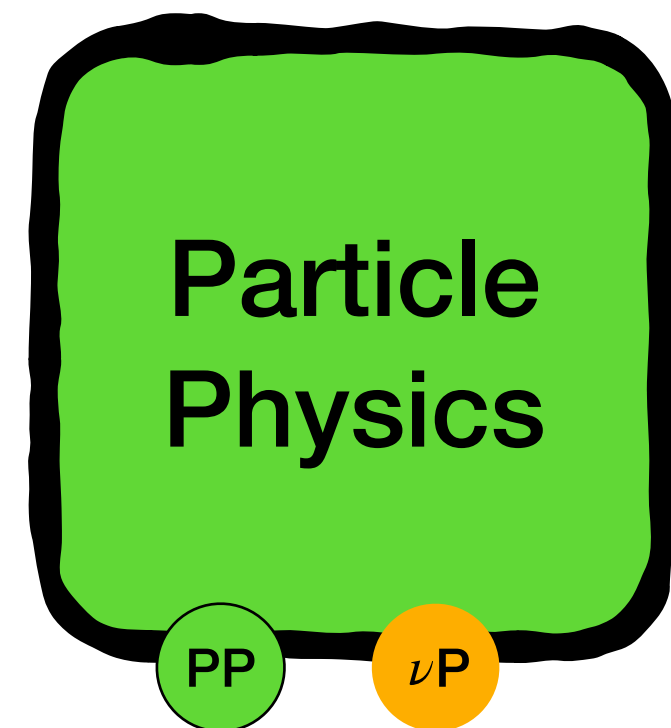
Democratization aspect:

- Link between domains (e.g. *me* running a model from Astro in one click)
- Possibility of advanced outreach events, *citizen scientist*



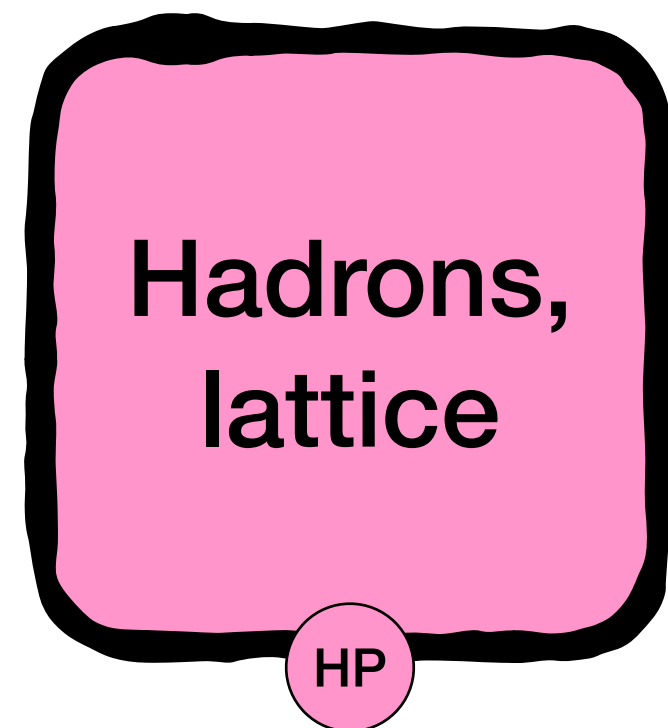


Domains



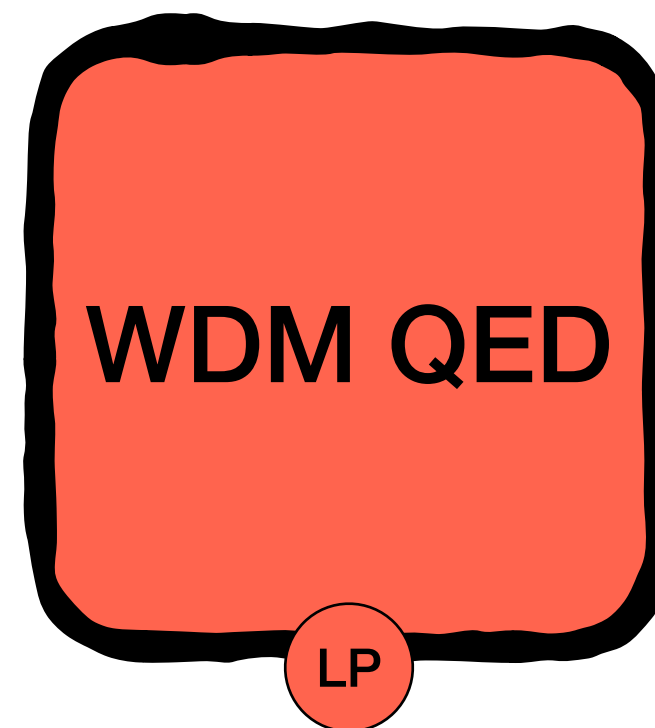
Native

*Output: **stat. models,***
combination of
pdfs, likelihood
meta: framework



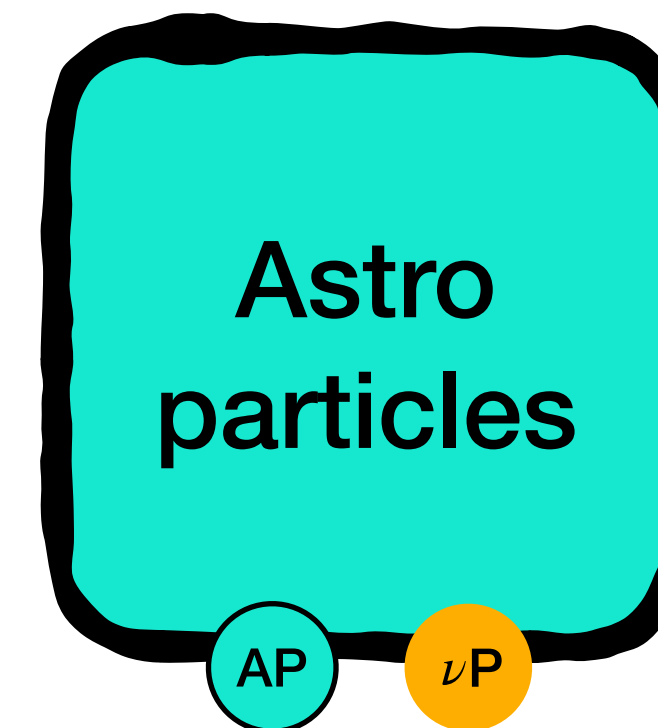
Native

*Output: **amplitude models**²,*
combination of
amplitudes



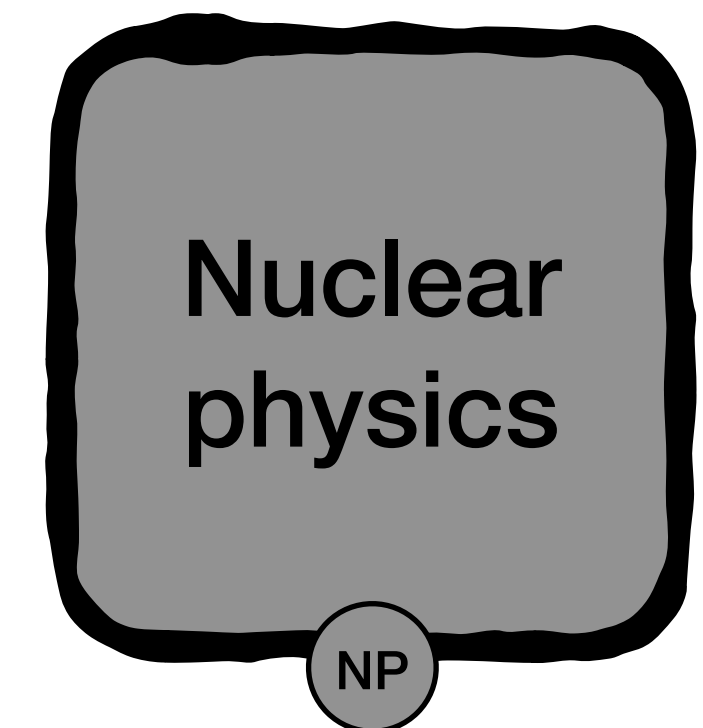
Containerized

Input: distributions
meta: config
output: functional,
histograms



Native/Containerized

Input: pdf
meta: config
output: posteriors
as histogram



Containerized

output: Lagrangian
terms

WIP: Format and Engines

And their capabilities

Native support of nested statistical models, with limited numbers of primitives.

- PDF builder
- Amplitude builder

$$d(x) = fd_1(x) + (1 - f)d_2(x)$$

$$d(x) = N \left| A_1(x) + cA_2(x) \right|^2$$

PYTHON

scikit hep
pyhf
pyhs3
Fit

JULIA

Distributions.jl
HEPDistributions.jl
HadronicLineshapes.jl
NumericalDistributions.jl
InstructionalDecayTrees.jl

C++

ROOT
EvtGen

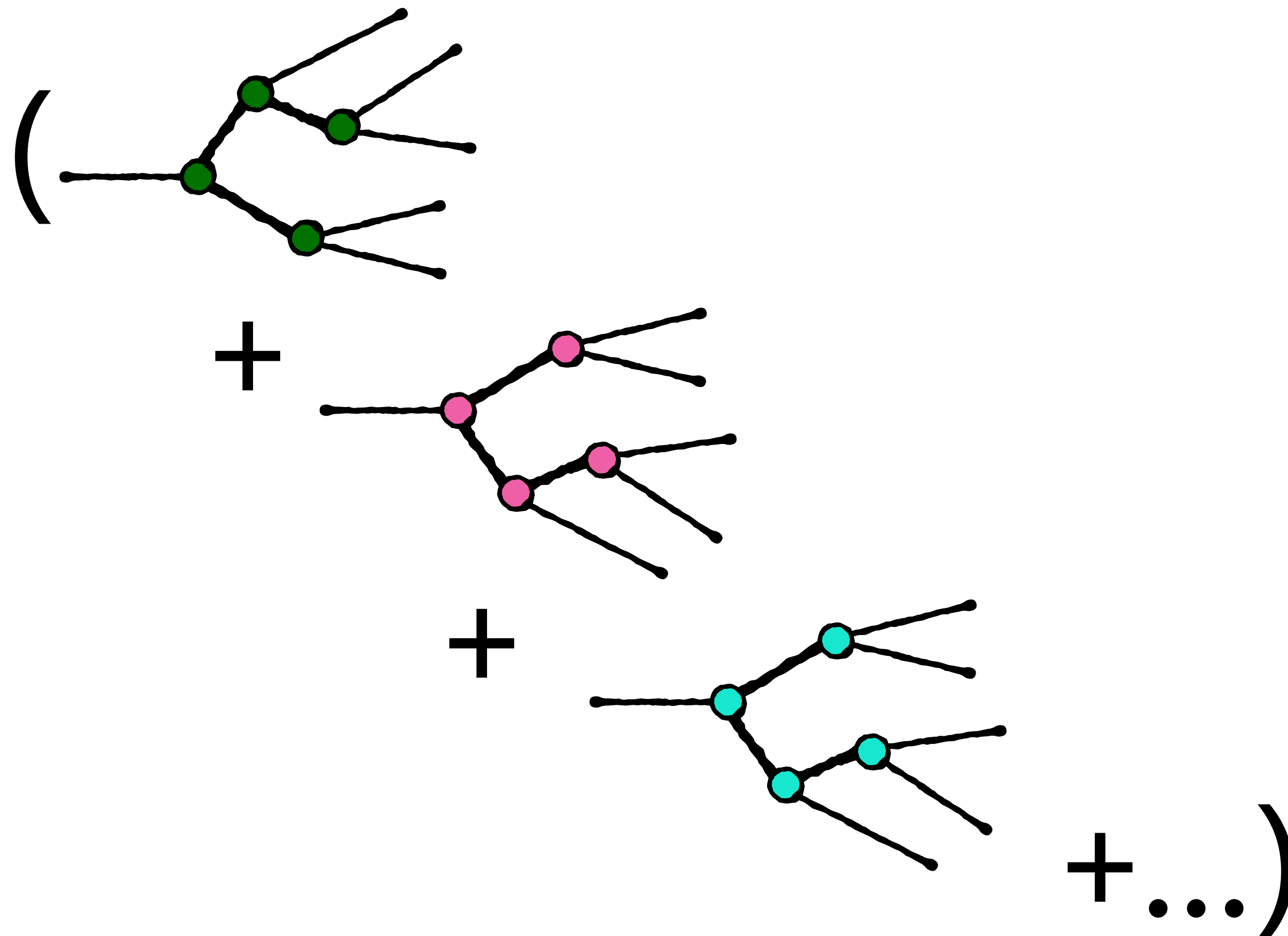
Rust

JS

DECAY DESCRIPTION

Decay model standard — helicity basis

isobar “model”, spin quantization



- **distribution** (pdf):

- unpolarized

$$I(\tau) = \sum_{\{\lambda\}} |A_{\{\lambda\}}(\tau)|^2$$

- polarized

$$I(\tau | P) = \sum_{\lambda_0, \lambda'_0} \rho_{\lambda_0, \lambda'_0}(P) \sum_{\{\lambda_i\}}^{i!=0} A_{\lambda'_0; \{\lambda\}}^* A_{\lambda_0; \{\lambda\}}$$

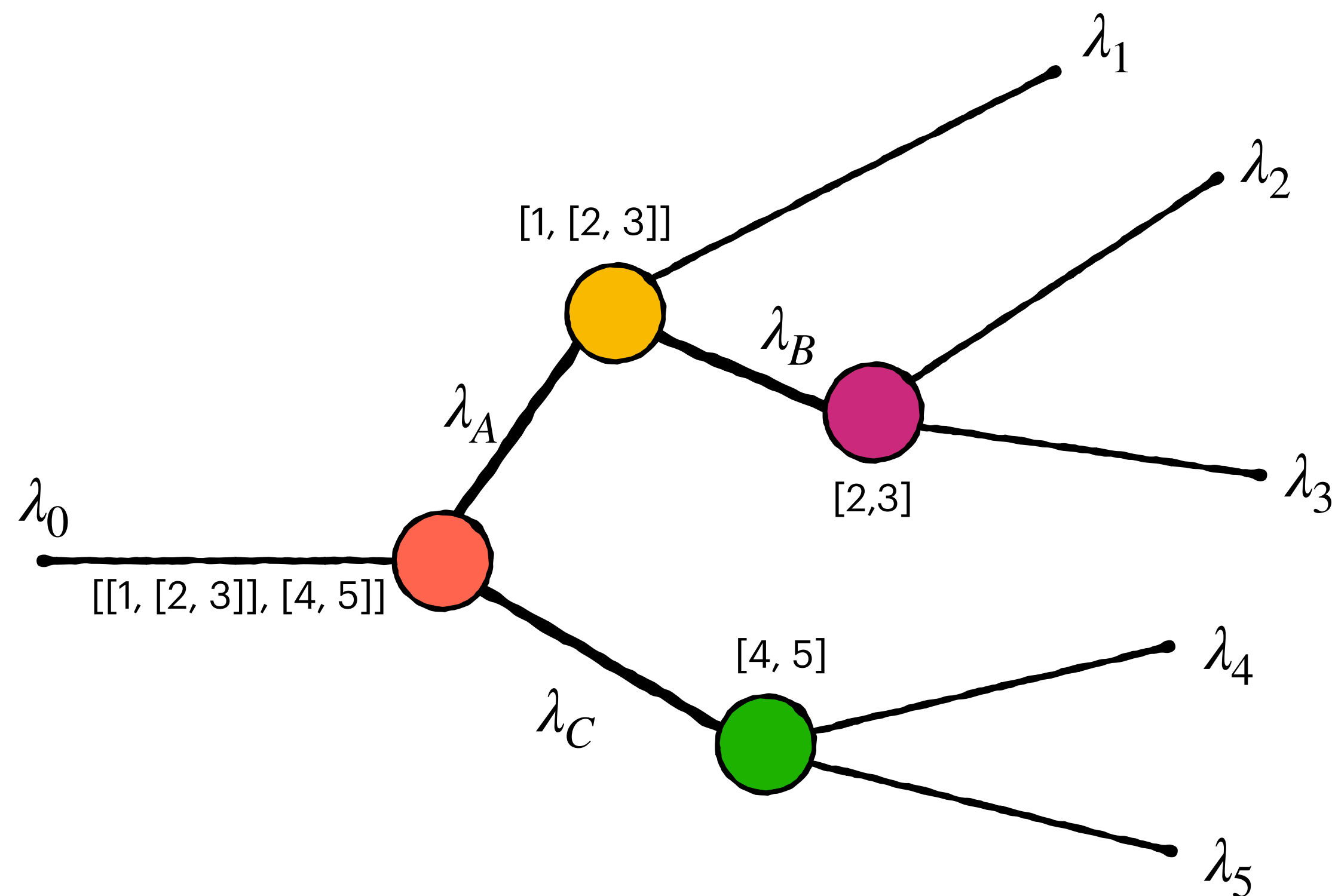
- **model_description:**

array of chains

$$A_{\{\lambda\}}(\tau) = \sum_i A_{\{\lambda\}}^i(\tau)$$

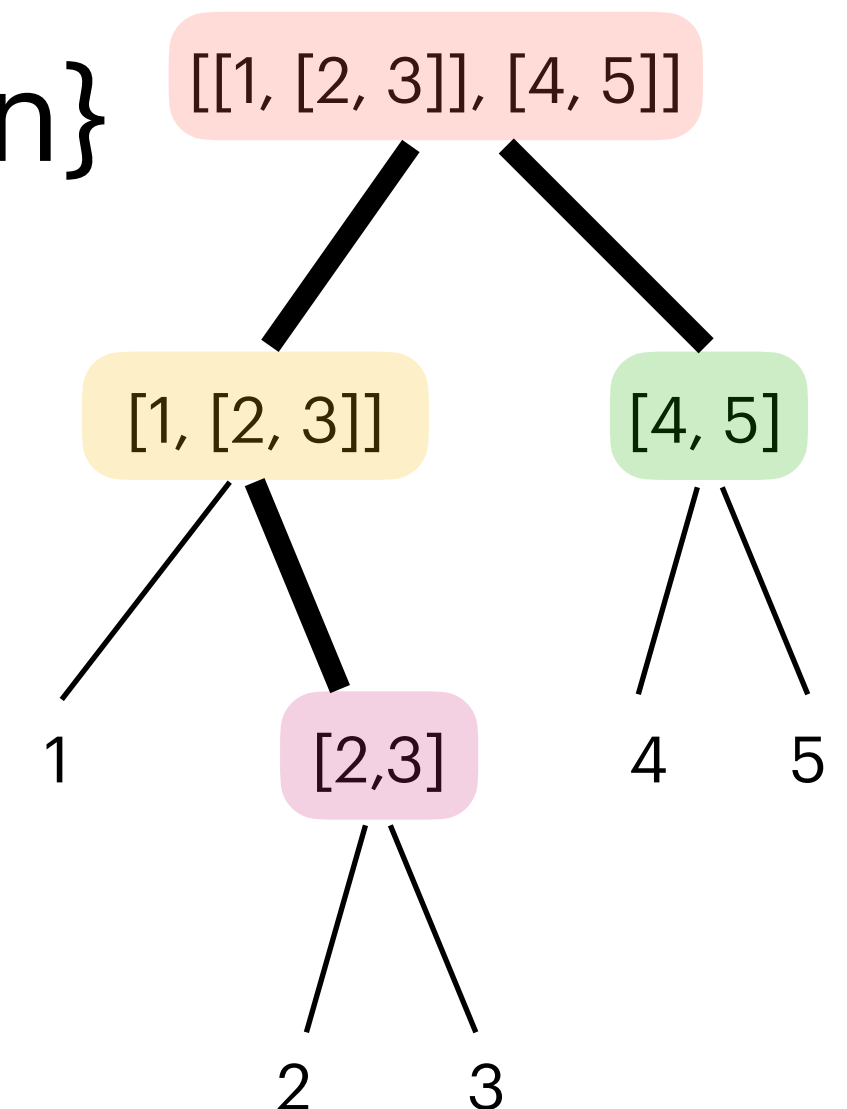
Decay chain

Topology and Nodes



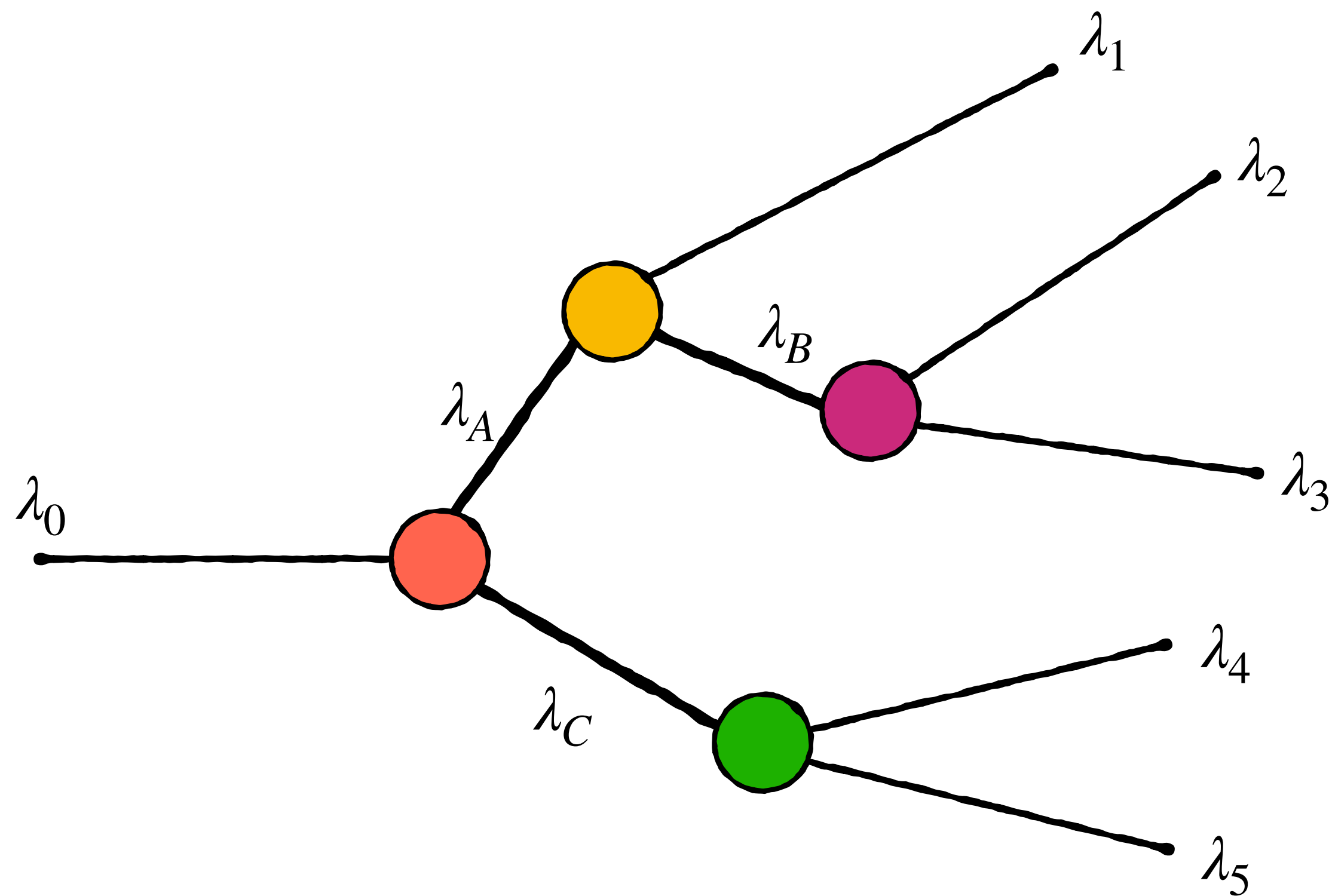
The chain gives prescription to every

- **vertices:**
{node, recoupling, form-factor}
- **propagators:**
{spin, parametrization}
- **topology**



Decay chain — amplitudes in helicity basis

Vertices and propagators

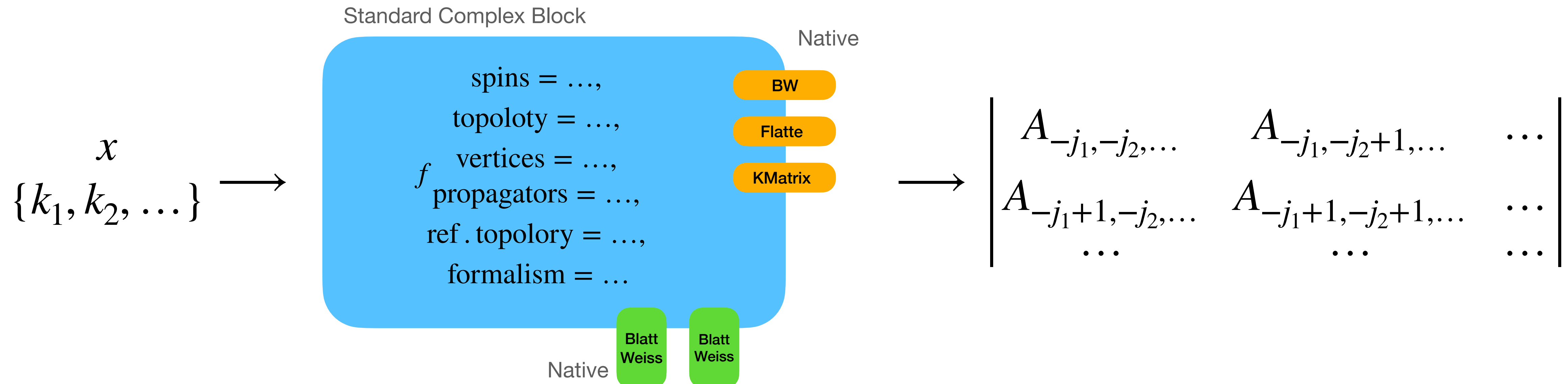


- **vertex**: node, recoupling, form-factor
- **propagator**: spin, parametrization

$$\begin{aligned}
 A_{\lambda_0; \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5}^i = & \\
 & D_{\lambda_0, \lambda_A - \lambda_C}^{j_0*} H_{\lambda_A, \lambda_C} D_{\lambda_A, \lambda_1 - \lambda_B}^{j_A*} H_{\lambda_1, \lambda_B} D_{\lambda_B, \lambda_2 - \lambda_3}^{j_B*} H_{\lambda_2, \lambda_3} D_{\lambda_C, \lambda_4 - \lambda_5}^{j_C*} H_{\lambda_4, \lambda_5} \\
 & \times P_A(s_A) P_B(s_B) P_C(s_C) \\
 & \times D_{\lambda'_1, \lambda_1}^{j_1}(R_1^w) D_{\lambda'_2, \lambda_2}^{j_2}(R_2^w) D_{\lambda'_3, \lambda_3}^{j_3}(R_3^w) D_{\lambda'_4, \lambda_4}^{j_4}(R_4^w) D_{\lambda'_5, \lambda_5}^{j_5}(R_5^w)
 \end{aligned}$$

Cascade amplitude DSL (option 1)

The complex **standard** block that will connect people



- Define complex but standard function on four-vectors
- Small building block for $n \times 100$ models

Native (option 2) ➡

How the format might look like

Prototype with cool web assembly integration

Let **a** and **b** denote two dimensionless kinematic observables, and let **c** be a model parameter. We define a simple response function as

$$D(a,b;c) = \sin(b + a^b + c a).$$

For the physical measurement, however, the response must be symmetrized under interchange of the two kinematic variables, **a** and **b**. For given values **a1**, **b1**, and **c1** in the **interval [-1, 1]**, the symmetrized response is

$$X(a1,b1;c1) = D(a1,b1;c1) + D(b1,a1;c1).$$

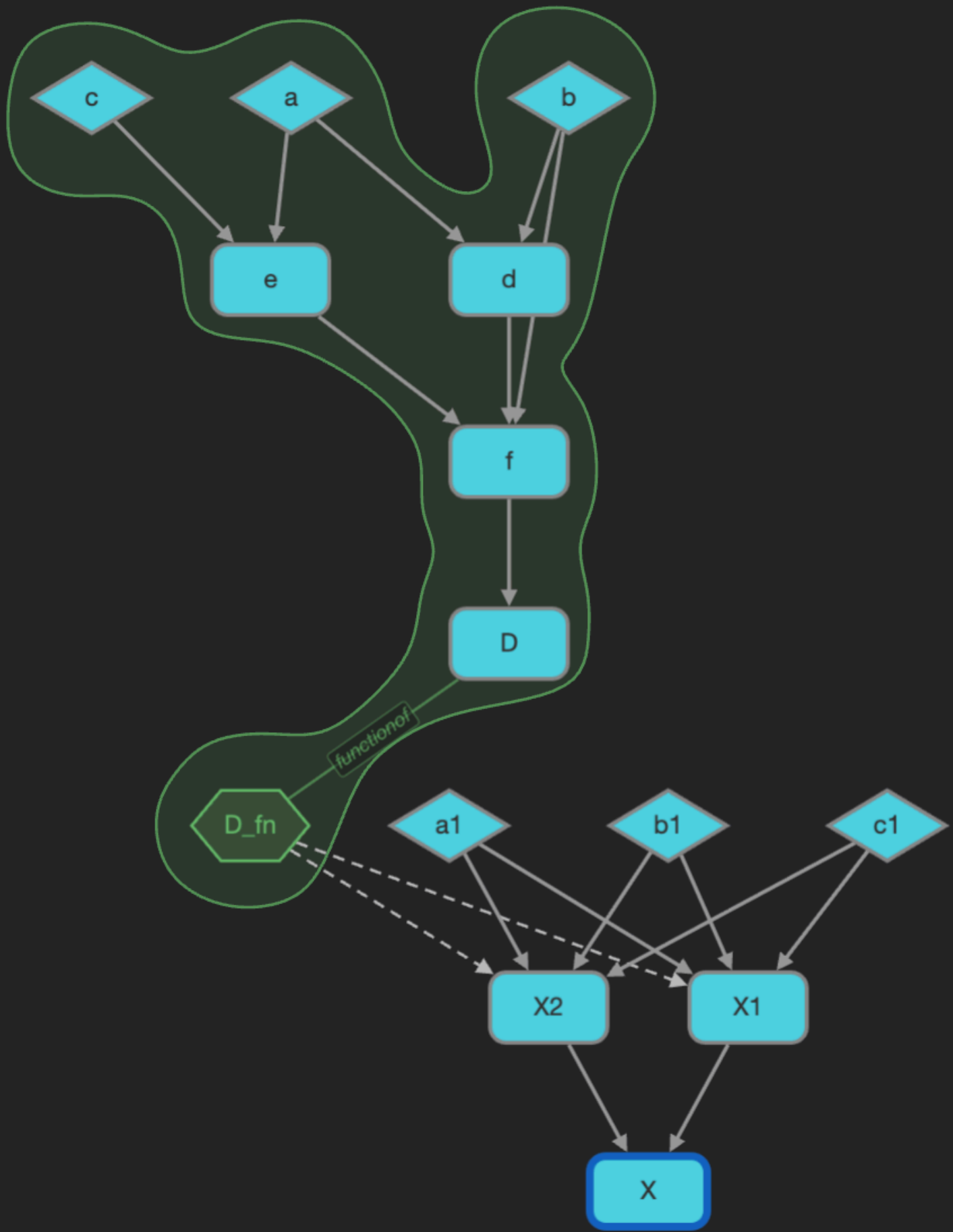
```
# this is a part of a function
# =====
a = elementof(reals)
b = elementof(reals)
c = elementof(reals)
d = a^b
e = c*a
f = b + d + e
D = sin(f)
D_fn = functionof(D, a=a, b=b, c=c)
# =====

a1 = elementof(interval(-1.0, 1.0))
b1 = elementof(interval(-1.0, 1.0))
c1 = elementof(interval(-1.0, 1.0))

X1 = D_fn(a1, b1, c1)
X2 = D_fn(b1, a1, c1)
X = X1 + X2

plot_point = record(
  a1 = 1.0,
  b1 = 1.0,
  c1 = 1.0
)

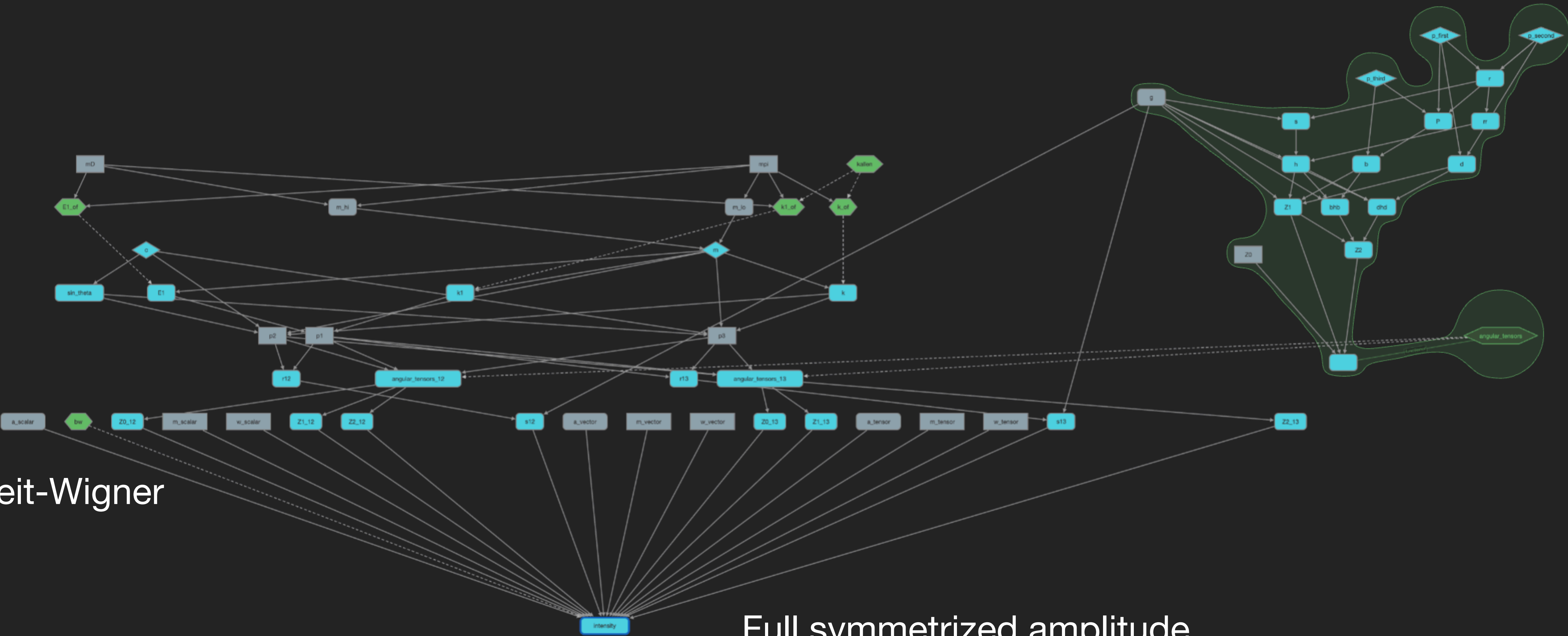
ddd(a,b,c) = sin(a^b + c*a + b)
```



Example: $D^+ \rightarrow \pi^+ \pi^+ \pi^-$

Using tensor contraction

Angular tensors



Breit-Wigner

Full symmetrized amplitude

Models and frameworks

Frameworks

and analysis specific code

- Working with dynamic languages is simpler (**TBDs.jl**, **ComPWA**, **TFPWA**, ...),
- but also possible with static (**EvtGen**, Laura++, AmpTool, PAWIAN, RootPWA)

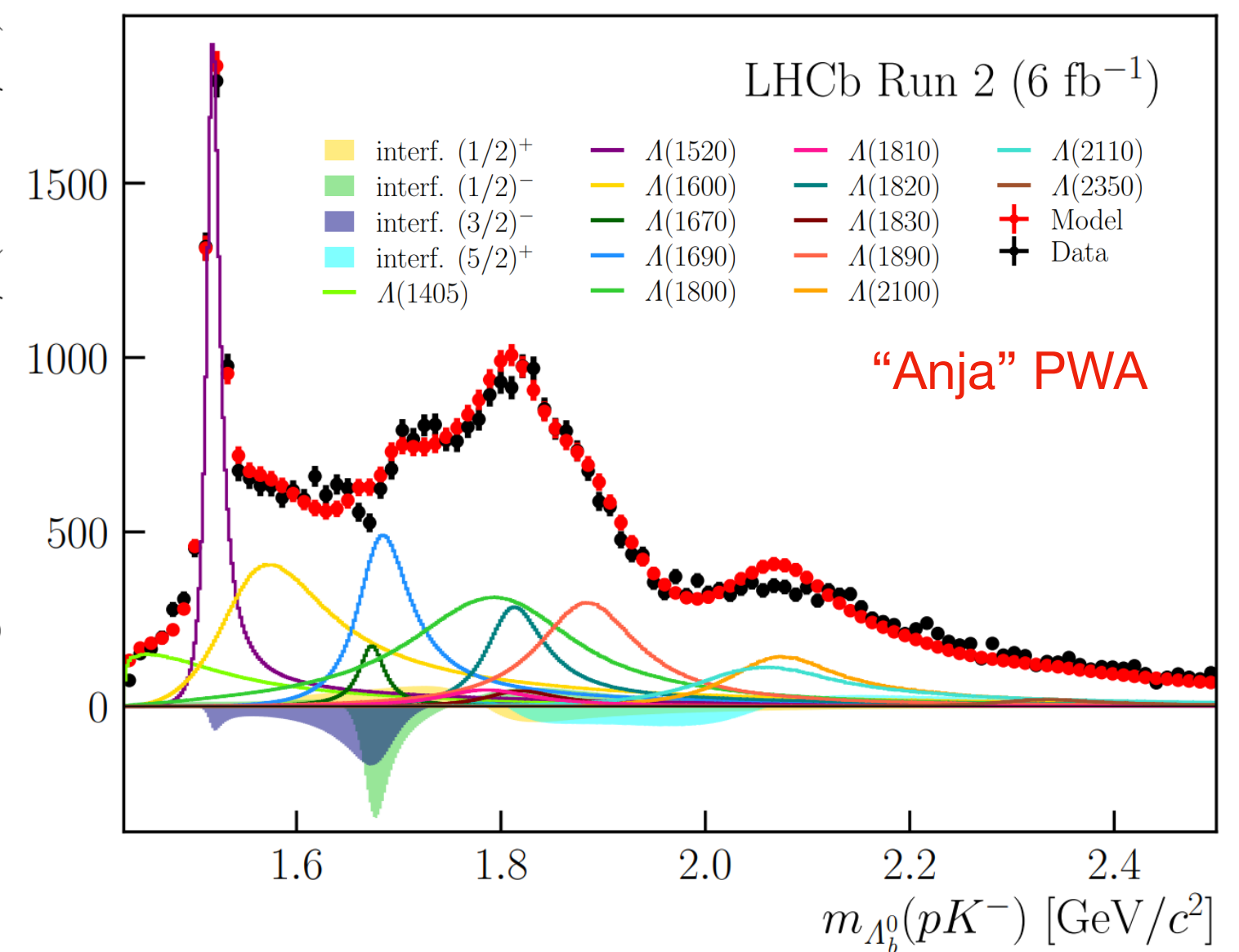
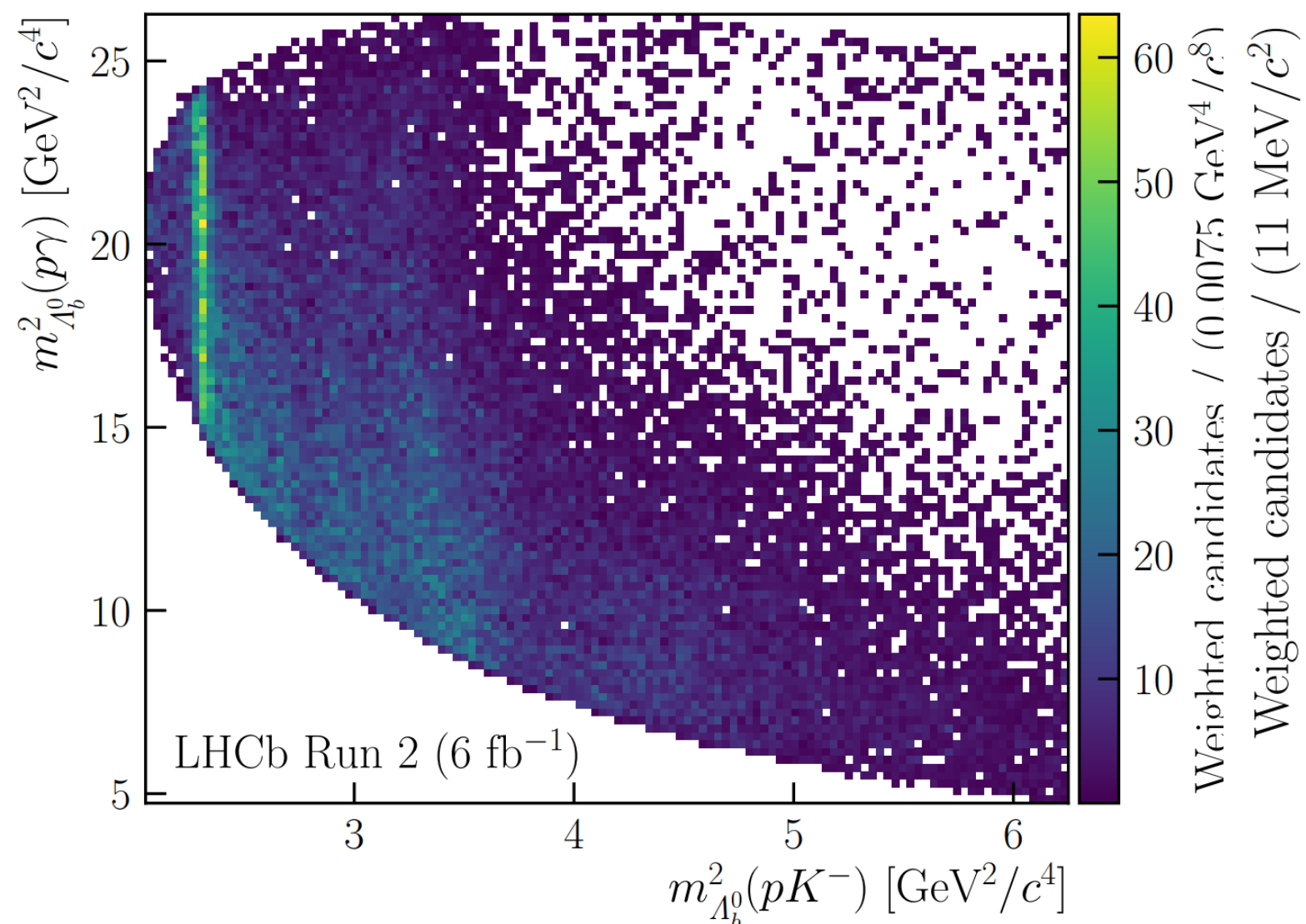
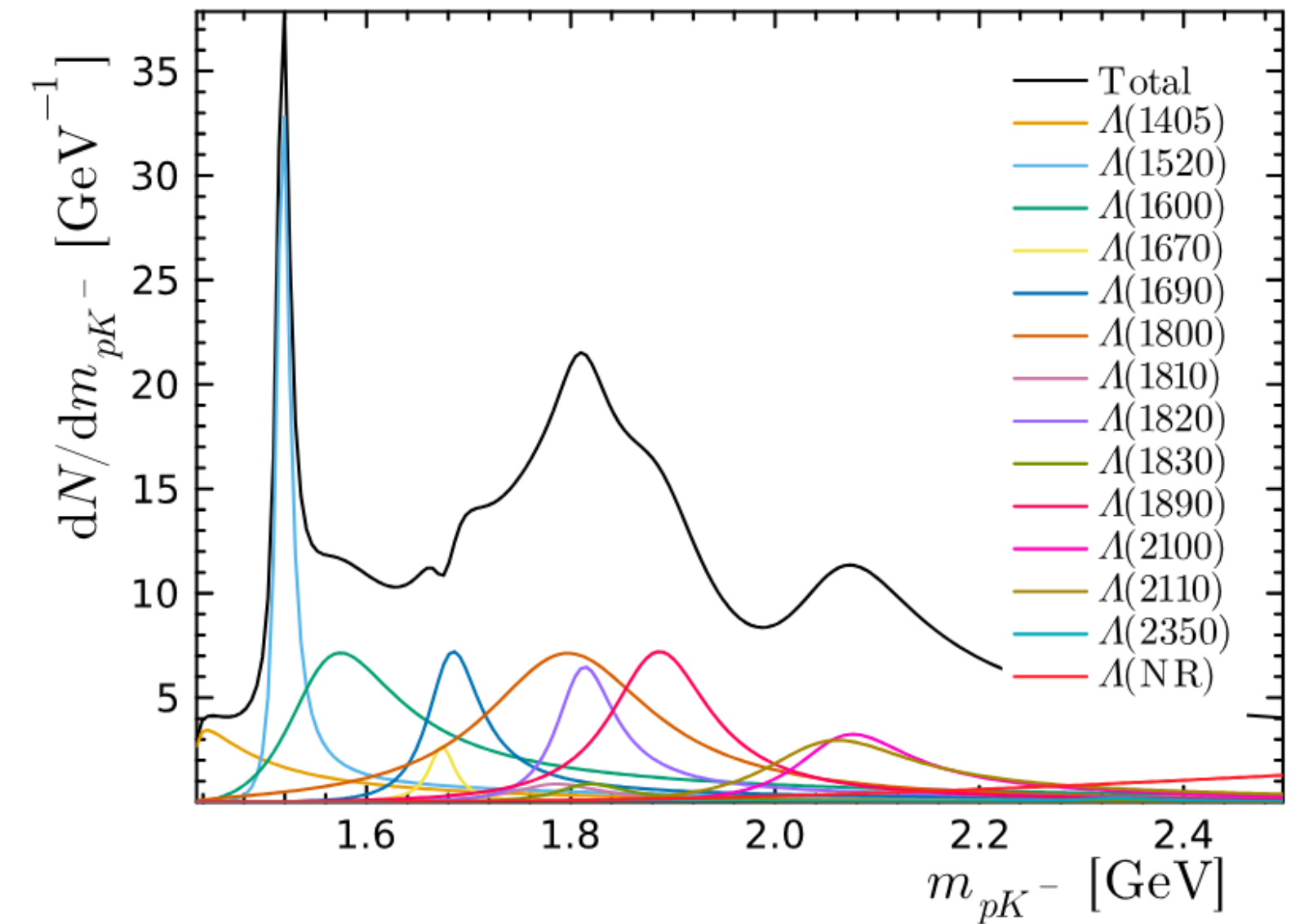
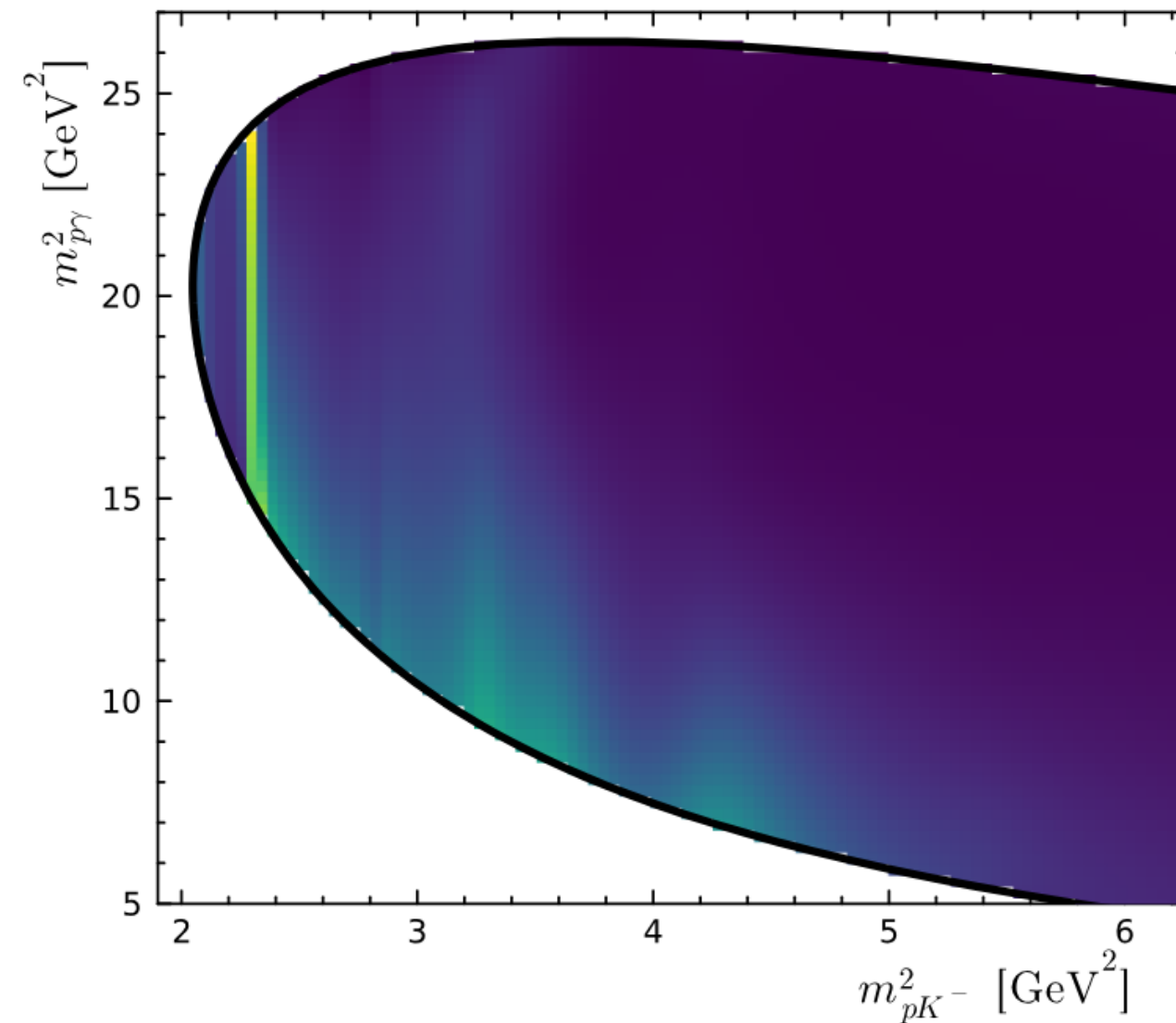
Project		Collaboration	Since	Latest commit	C++
AmpGen		CLEO / LHCb	2018	02/2025	✓
AmpTools		BESIII / GlueX	2011	07/2026	✓
BruFit		CLAS12	2020	06/2026	✓
ComPWA (C++)			2012	01/2024	✓
ComPWA project			2020	07/2026	
cFit			2012	05/2018	✓
FDC-PWA		BESIII	2000		✓
GPUPWA		BESIII	2011		✓
HAMMER			2016	06/2026	✓
Ipanema			2017	03/2019	✓
Laura++		LHCb	2013		✓
laddu		GlueX	2024	05/2026	
Mint2			2016	01/2020	✓
Pawian		BESIII / PANDA	2010	06/2026	✓
PyPWA		JLab	2014	05/2023	
Rio++		LHCb	2016		✓
ROOTPWA		COMPASS	2009	06/2020	✓
TARA		Crystal Barrel	1999		✓
TensorFlowAnalysis		LHCb	2016	12/2025	
TF-PWA		BESIII / LHCb	2019	05/2026	
ThreeBodyDecays.jl		LHCb	2019	07/2026	

Examples-I

lb2pkg-lhcb-2765817

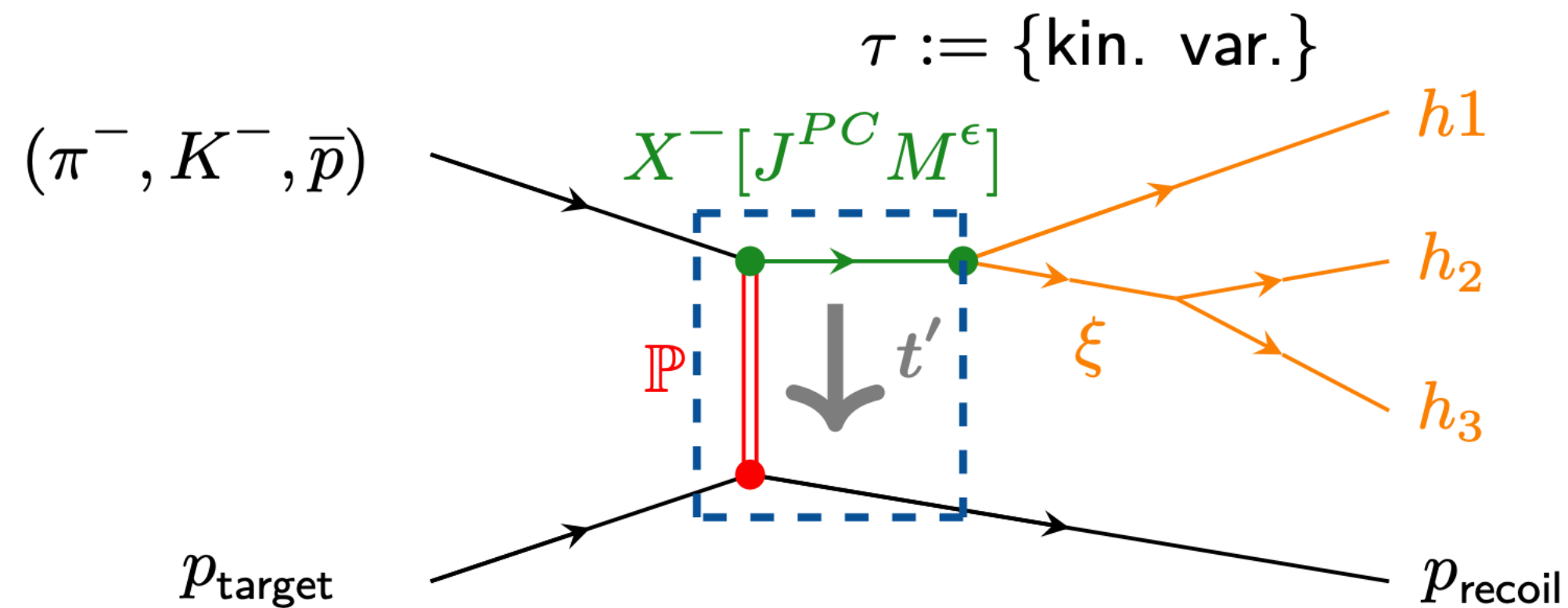
- Analysis of Λ baryons in $\Lambda_b^0 \rightarrow pK^-\gamma$
- Search for pentaquarks
- 74 decay chains
- orbital momentum ≤ 6

[LHCb-PAPER-2023-036]



PWA in COMPASS

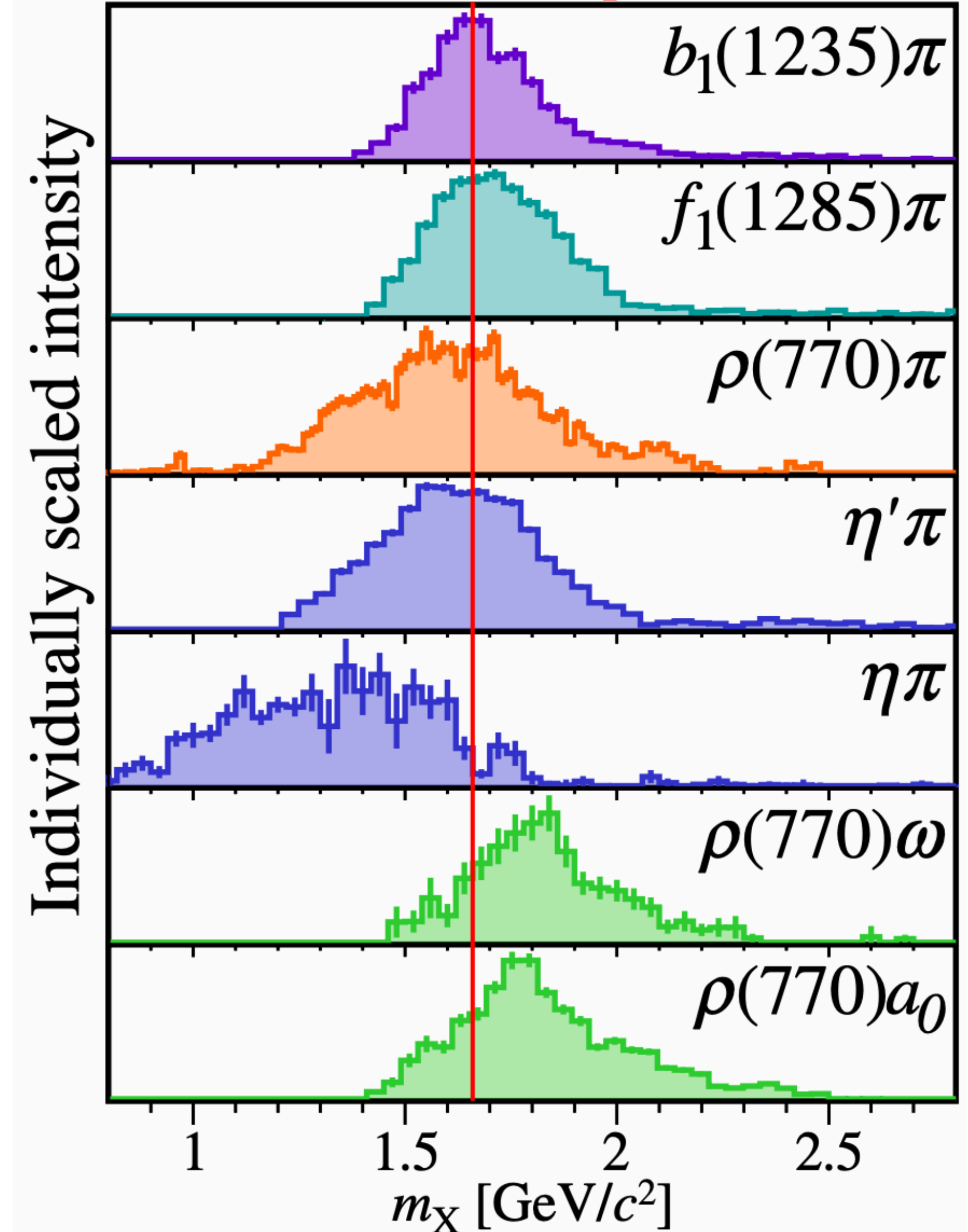
Studies of hybrid candidate $\pi_1(1600)$



- ^{ROOTPWA} 3π : 1100 bins (independent models) $\rightarrow$ DPD
- ^{Bonn PWA} $\eta 3\pi$: ~1000 bins (models) $\rightarrow$ DPD
- ^{"Tobias" PWA} $\eta^{(\prime)}\pi$: ~40 bins (models) $\rightarrow$ Julia
- ^{ROOTPWA} $\omega 2\pi$: ~1000 bins (model) $\rightarrow$ DPD

Spin-exotic $J^{PC}=1^{-+}$ waves at COMPASS
preliminary

Nominal $\pi_1(1600)$ position



Example-III

x2pipipi-compass-1391643

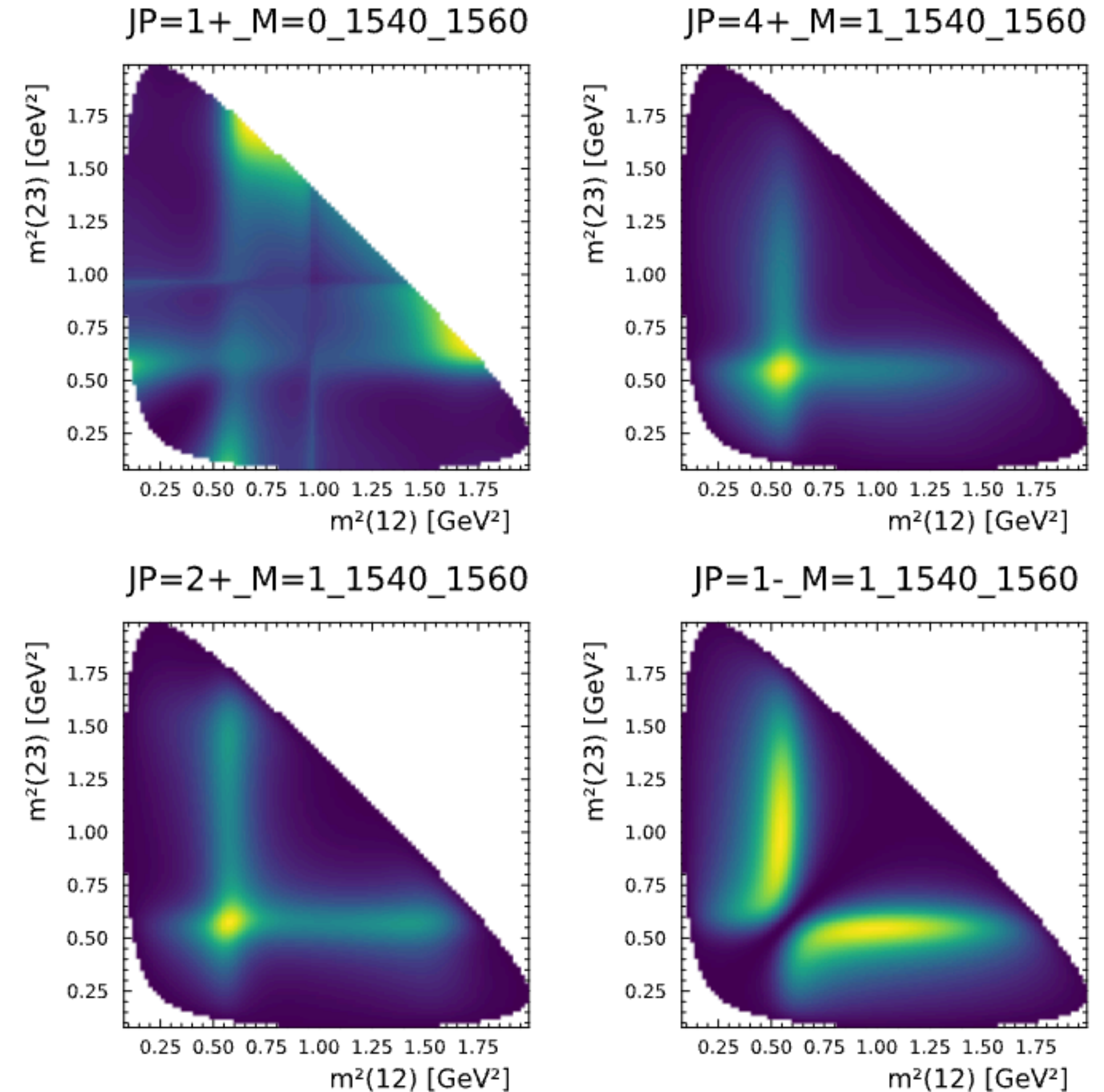
- Partial-wave analysis is performed of bins of $m_{3\pi} \times t'$ (100 * 10 bins)
- Every analysis contains ~170 chains with JP in $[0^+, 1^-, 1^+, \dots]$

Dalitz plot

The Dalitz plot shows the probability distribution across two dimensional phase space of the decay. Below the distribution is shown for all models in the file

[CERN-PH-EP-2015-233]

► Dalitz plot plotting



Magic prompt



What should we build in MyFavoritePWAFramework?

MyFavoritePWAFramework Local main

Here is a the general framework that can do any topologies, any particles, spins,
<https://github.com/RUB-EP1/CascadeDecays.jl>

clone it and find all the matching factors to align <function to compute the amplitude> to CascadeDecays.jl
construction up a numerical precision,

Hints on pitfalls:

<https://rub-ep1.github.io/CascadeDecays.jl/dev/convention-matching/>

+ ⌚ Approve for me

5.6 Sol High ▾



Codex ▾



📝 New chat

🔗 Pull requests

📁 Sites

🕒 Scheduled

🔌 Plugins

Projects

📁 MyFavoritePWAFramework

No chats

📁 BESIII-meeting

Compile Alex talk PDF

Create acrylic zoo guide comic

Edit Keynote slides

📁 InstractionalDecayTrees.jl

Write release short message

📁 Polarization Vortices

Analyze Lb2Lc3pi phase vortices ⚙️

📁 B2DxpD0K.jl

Extract PDF comments to Markdown

MM Mikhail Mikhasenko

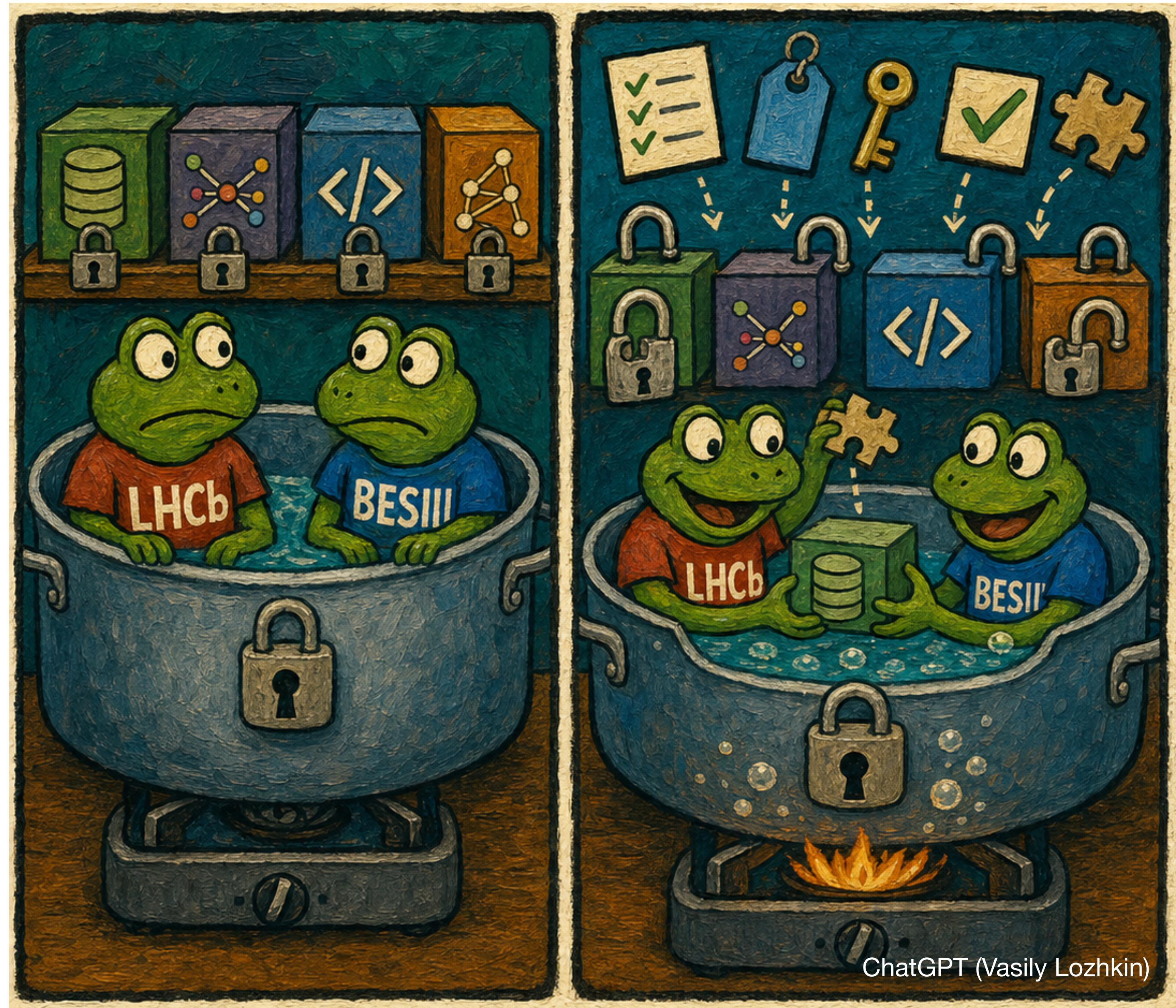


Action plan for hadron physics

- Establish standard
- Map existing frameworks
- Push through collaboration practices and policies on publishing models

Cook slow

1. Shared analysis frameworks
2. Open code
3. Research model
4. Likelihood:
 - Data
 - MC



Outlook

AI speeding up research

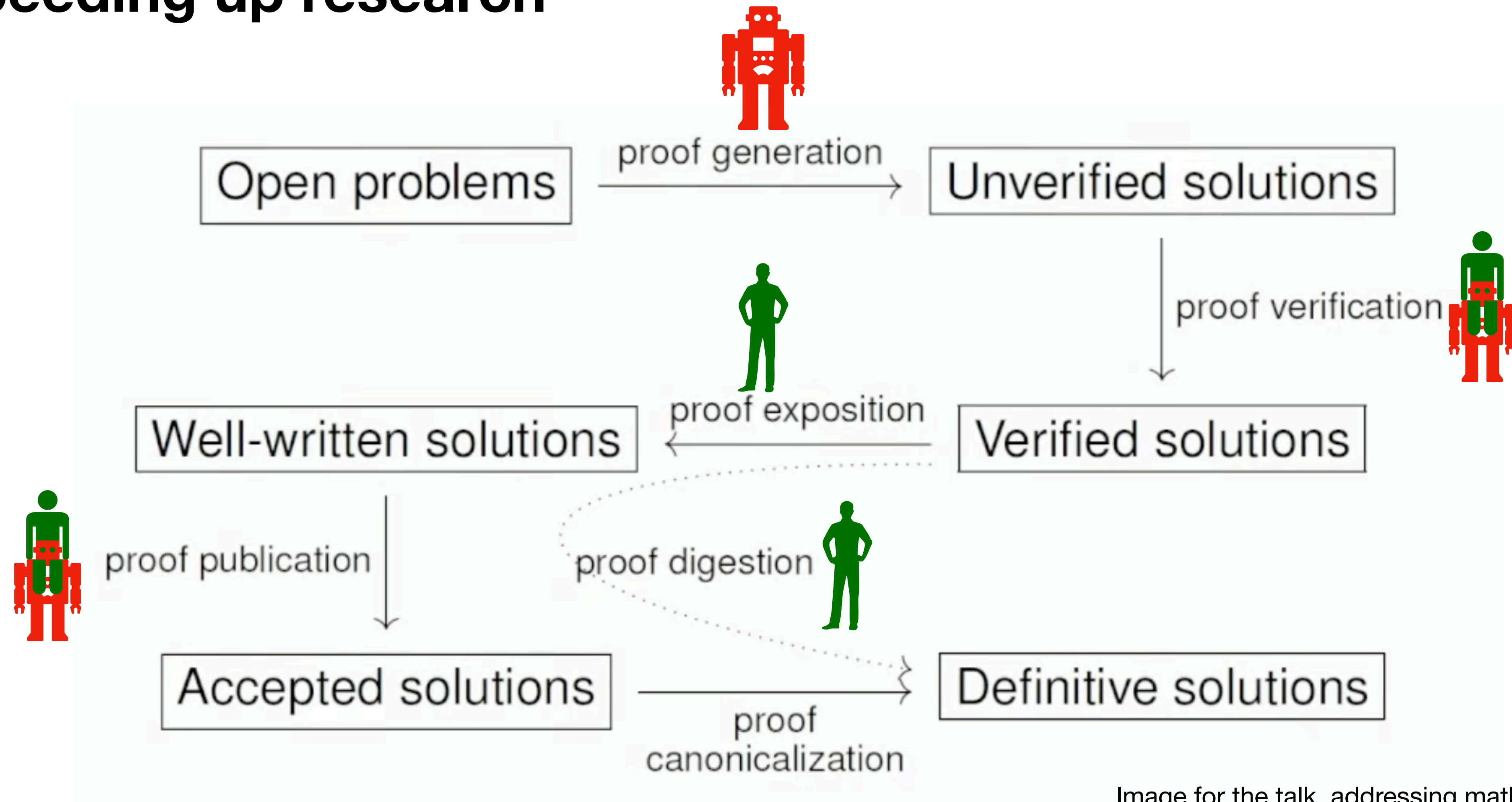


Image for the talk, addressing mathematics

BACKUP