NA60+/DiCE: overview and plans

I. Vorobyev for the NA60+/DiCE collaboration

ECT* workshop on penetrating probes of hot high-μ_B matter

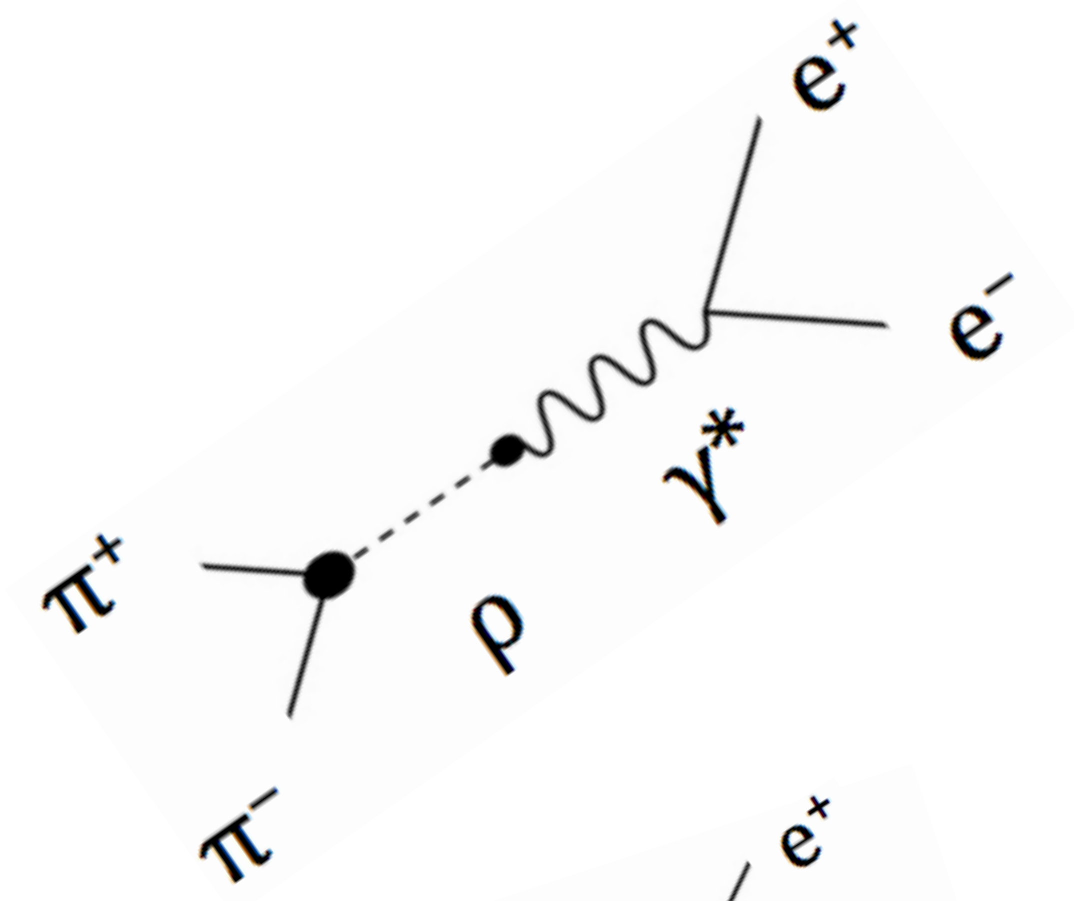
21.07.2025, Trento, Italy

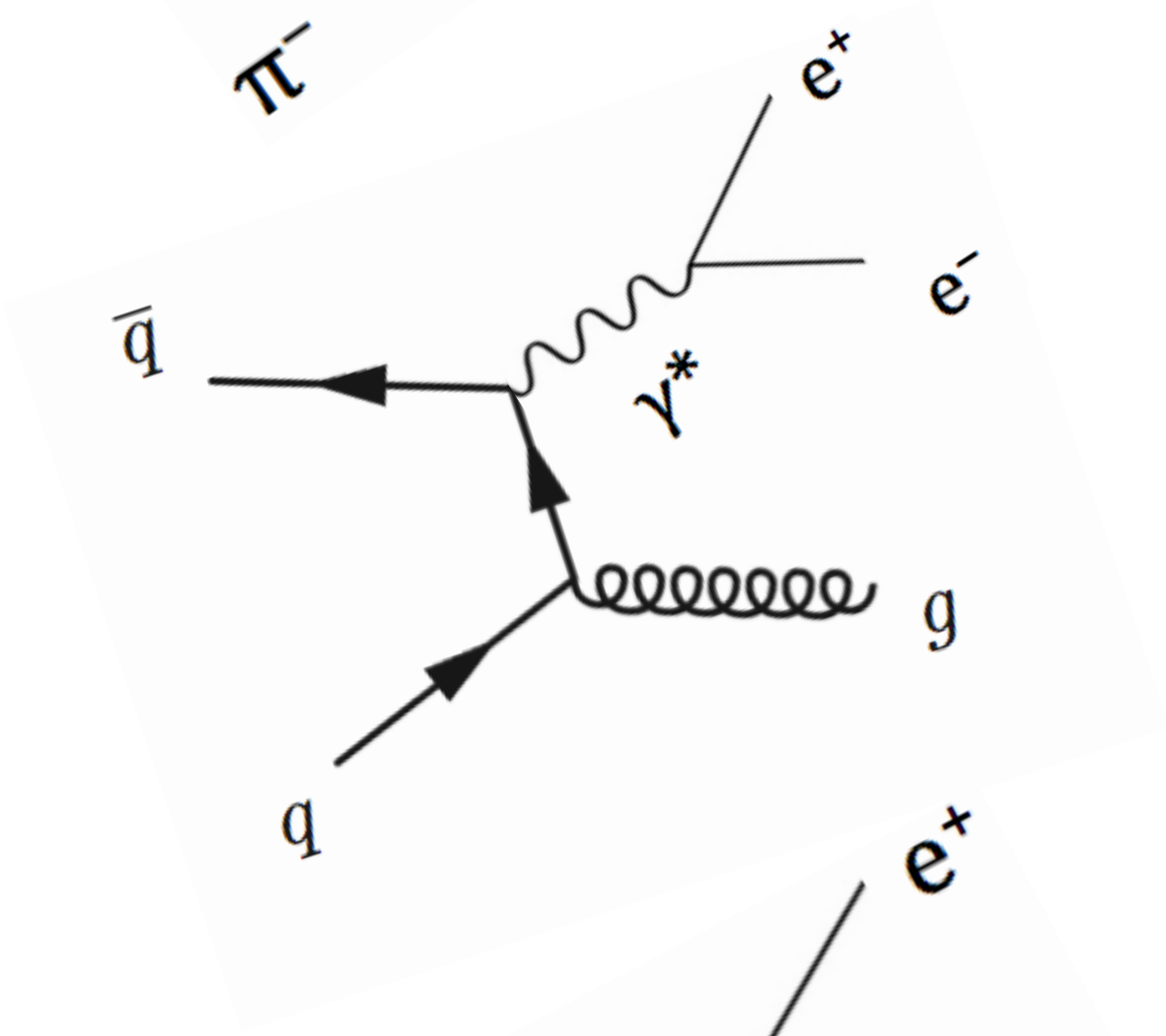
Introduction

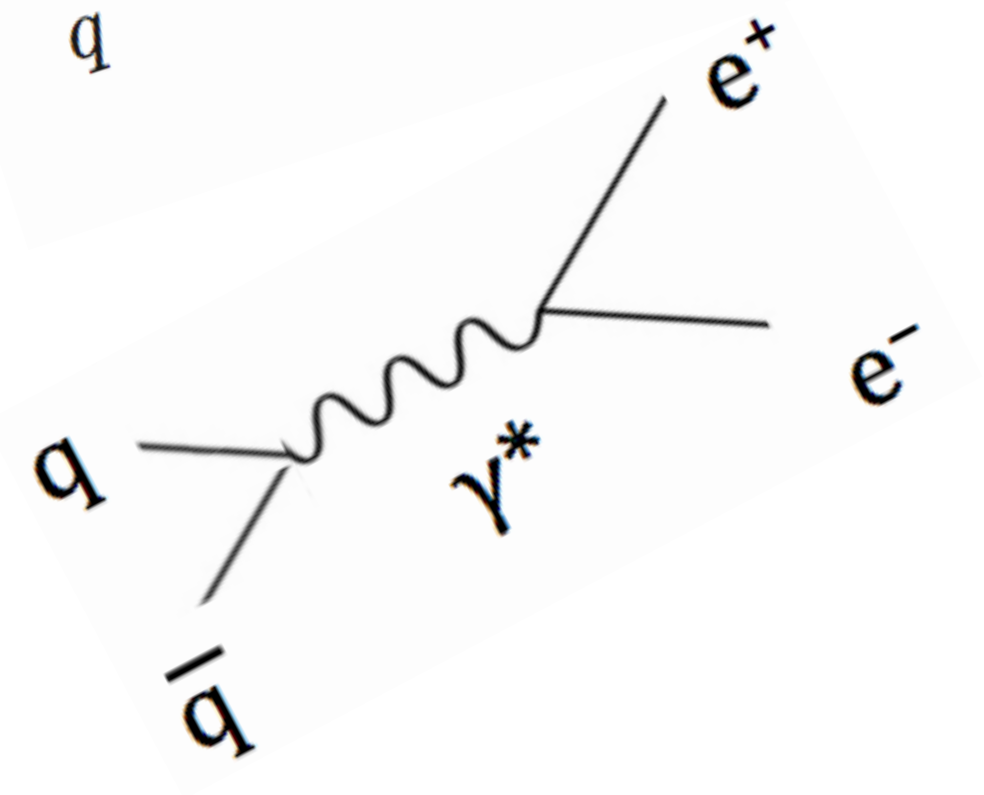
Content of today's talk:
1️⃣ Physics program
2️⃣ Experimental setup
3️⃣ Expected performance and physics results
4️⃣ Status and plans

Particular focus of 1️⃣ and 3️⃣ will be on electromagnetic probes of the QGP
Later at this workshop:
🎤 Overview on open charm, including NA60+/DiCE and CBM prospects (F. Prino, Tue 11:35)
🎤 Hypernuclei production at fixed-target energy (M. Puccio, Tue 16:05)
🎤 Overview on quarkonia, including NA60+ and CBM prospects (E. Scomparin, Wed 11:35)

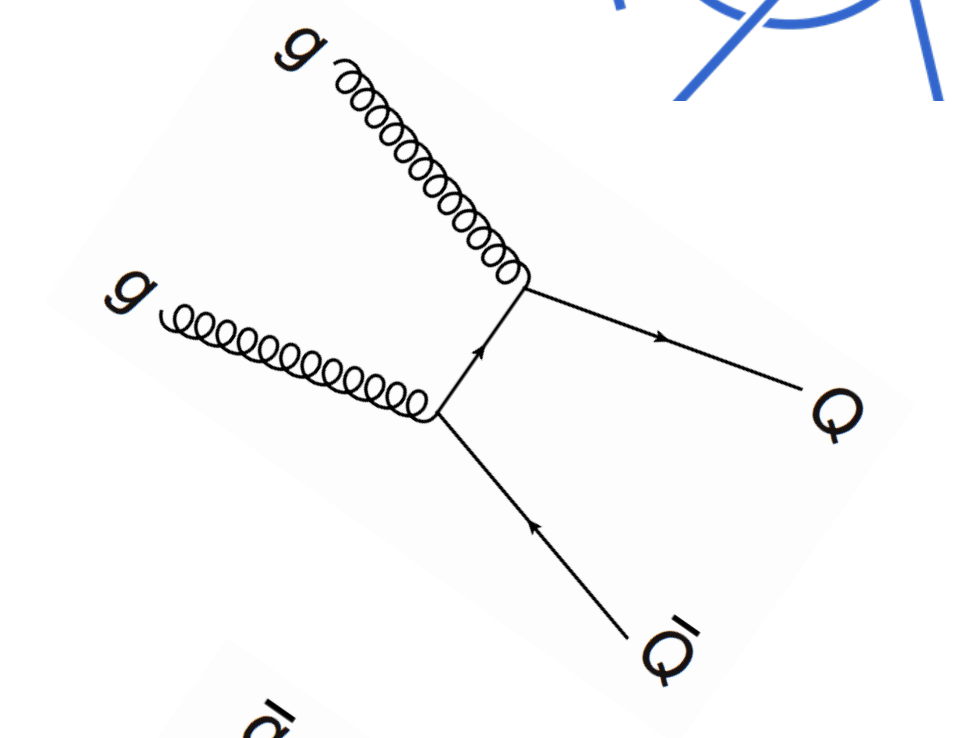
Further reading:
📖 **The NA60+/DiCE experiment proposal, CERN-SPSC-2025-023; SPSC-P-373**
📖 **ESPP 2026: the NA60+/DiCE experiment at the SPS, arXiv:2503.23872**
🛜 **https://na60plus.ca.infn.it/**

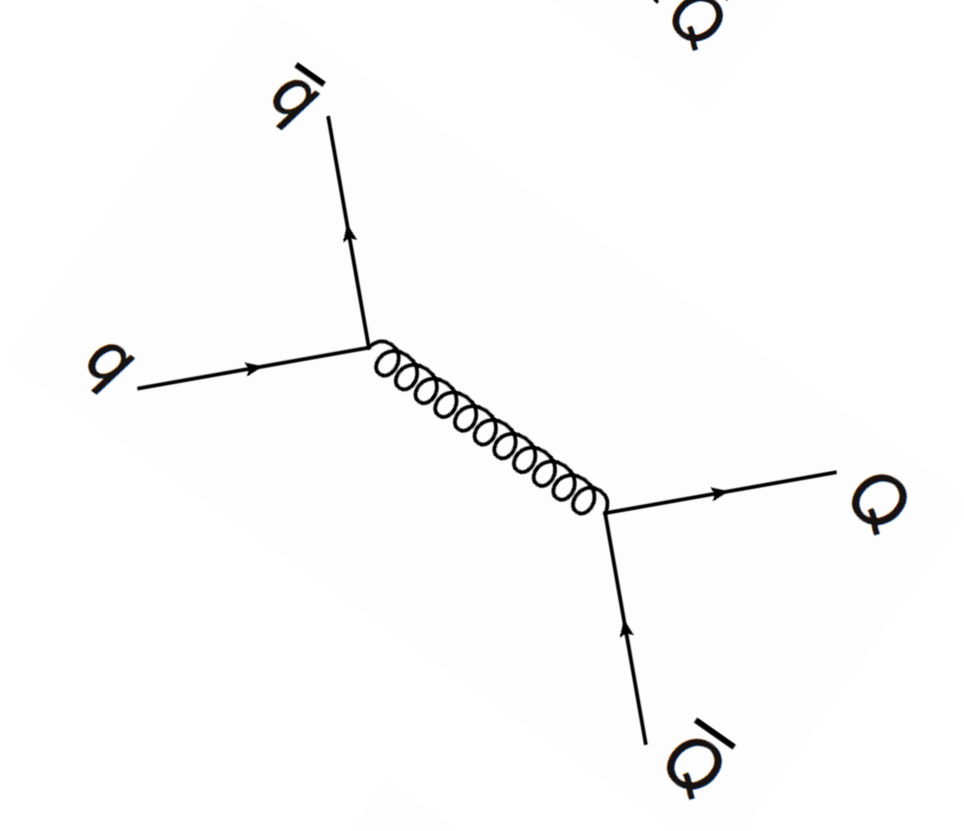


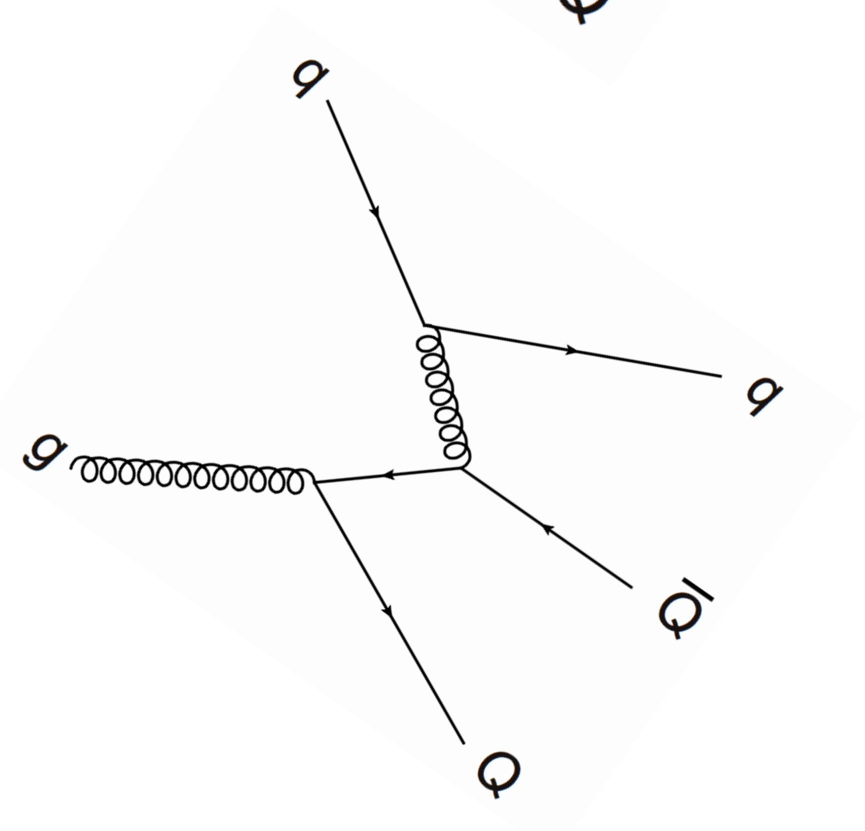




1. Physics program







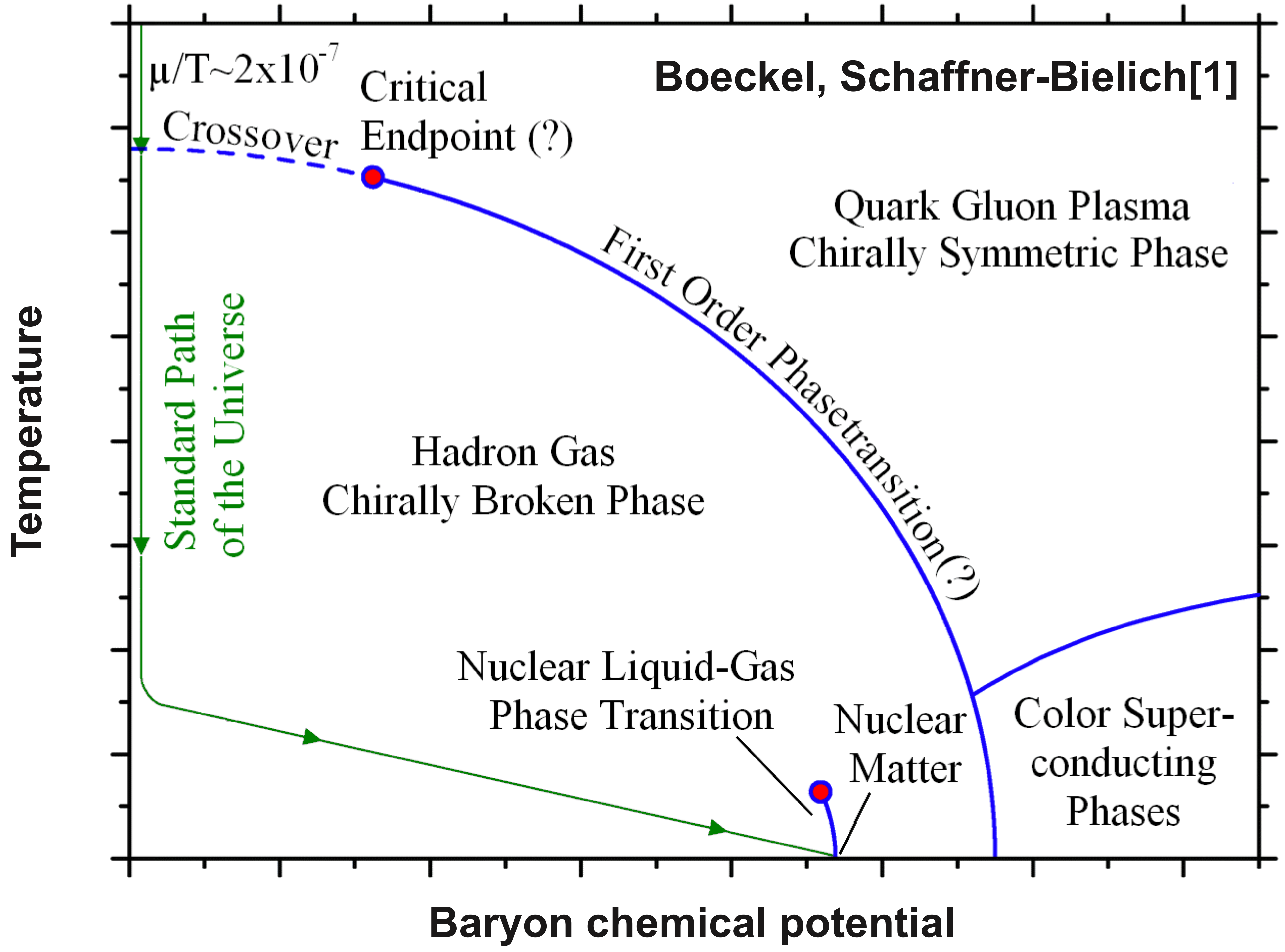
QCD phase diagram

QCD phase diagram at low μ_B:

- Early-Universe like conditions
- Crossover phase transition (from lattice QCD)

QCD phase diagram at high μ_B: ***largely unexplored!***

- Critical endpoint? 1st order phase transition?
- Synergy with astrophysics (neutron star cores)



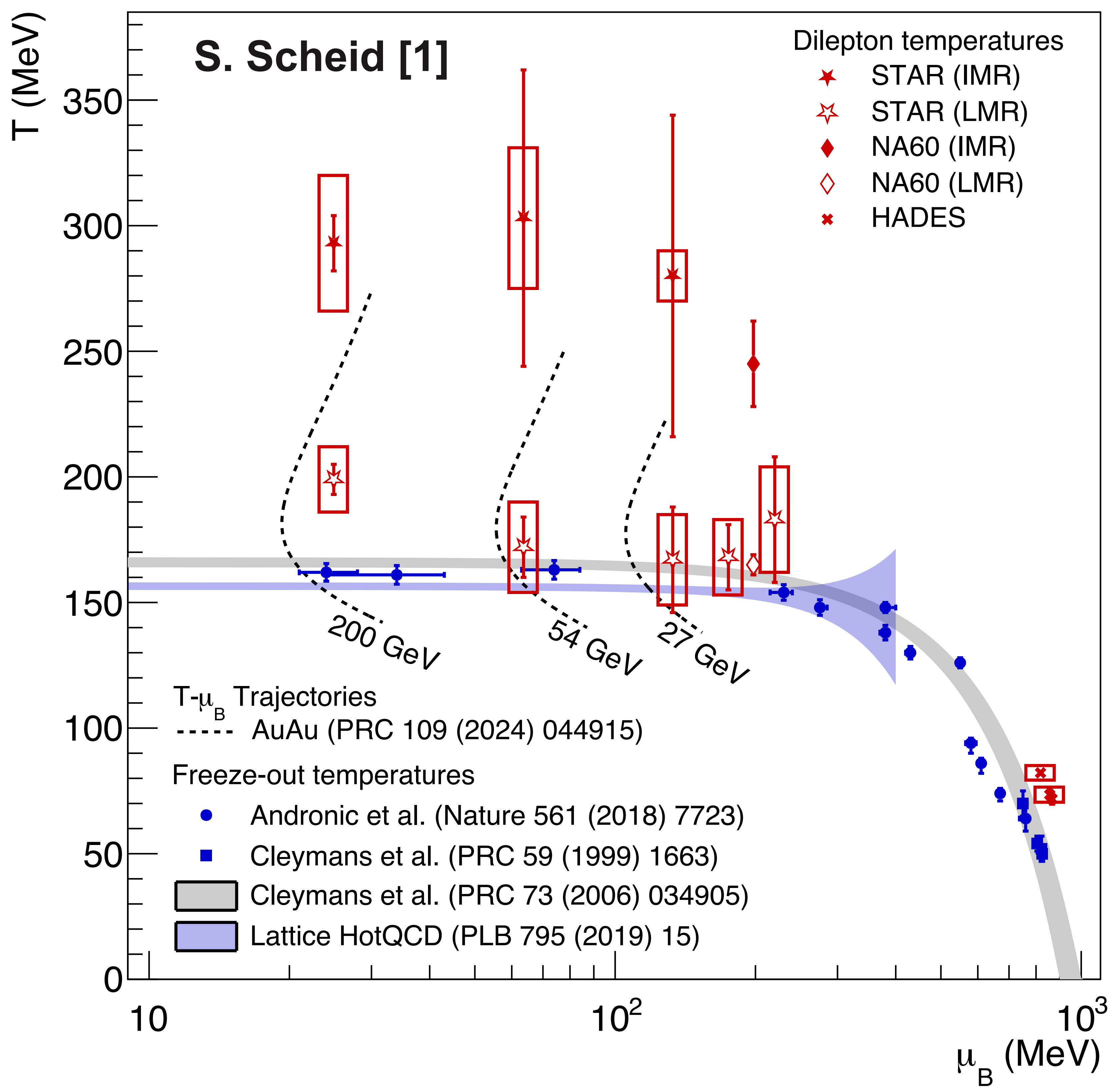
[1] Phys. Rev. D 85, 103506

QCD phase diagram

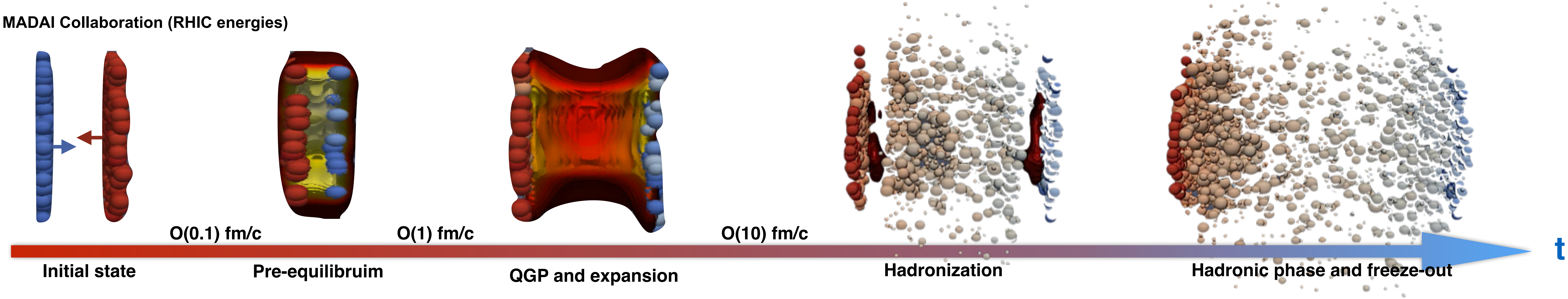
QCD phase diagram at low μ_B:
- Early-Universe like conditions
- Crossover phase transition (from lattice QCD)

QCD phase diagram at high μ_B: ***largely unexplored!***
- Critical endpoint? 1st order phase transition?
- Synergy with astrophysics (neutron star cores)

🛠 Experimental tool to study QCD phase diagram:
heavy-ion collisions *with varied* $\sqrt{s_{NN}}$ → *varied* μ_B



MADAI Collaboration (RHIC energies)

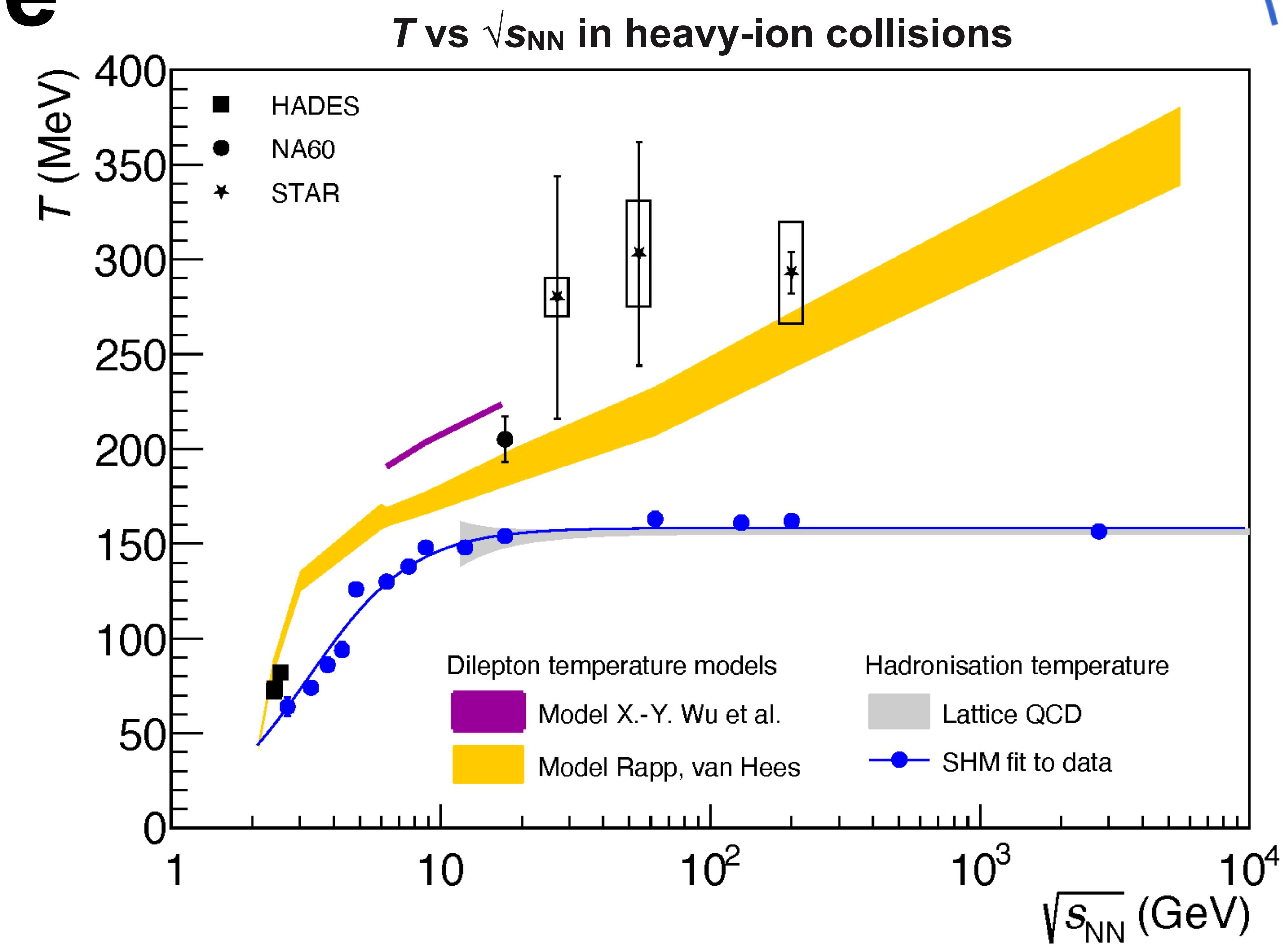


[1] Private communication, to be published in QM2025 proceedings

Establishing QCD caloric curve

Temperature ***T*** is one of the key properties of the medium
- Equation of state
- Order of phase transition

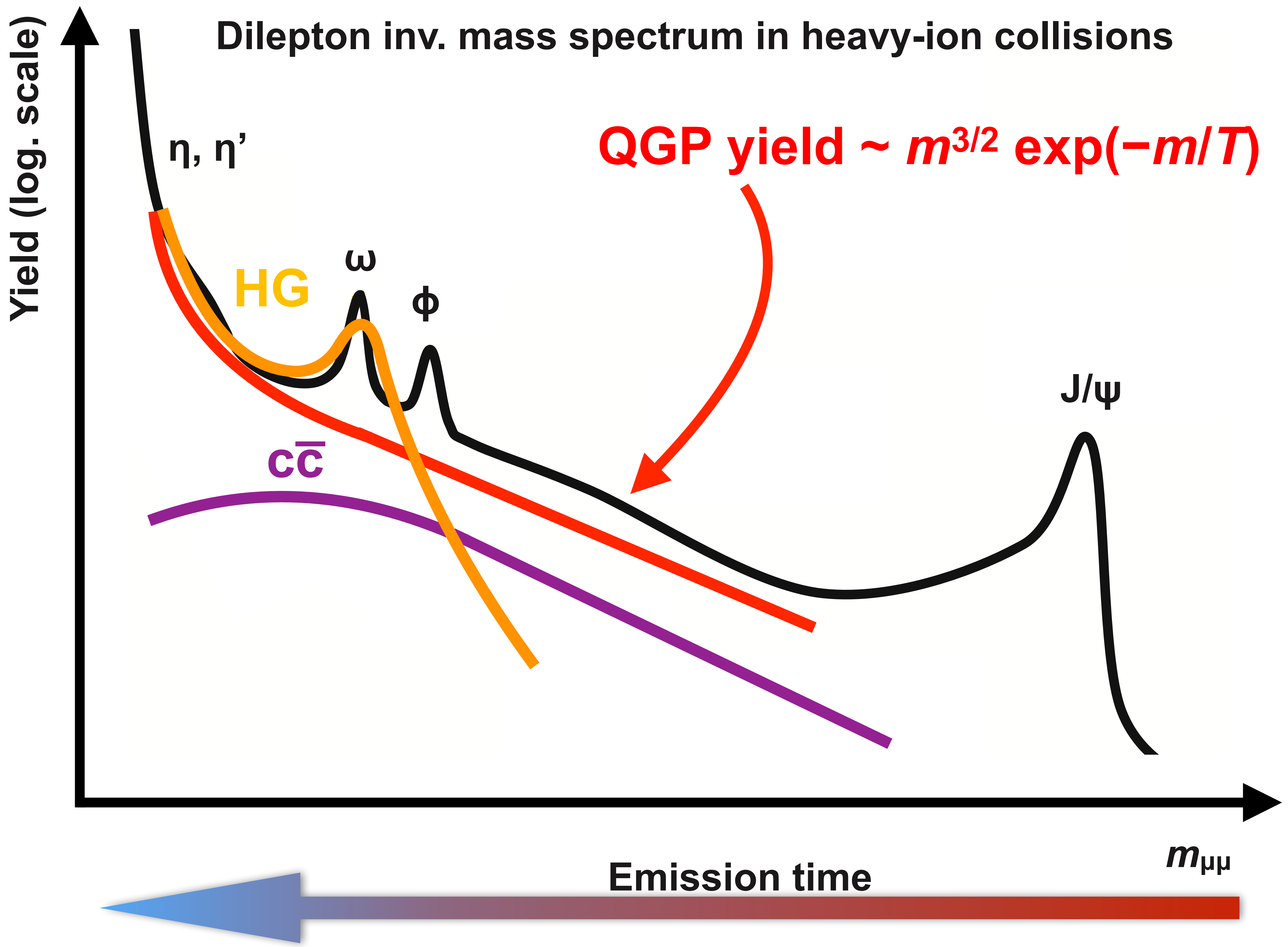
Only a couple of precise measurements so far!

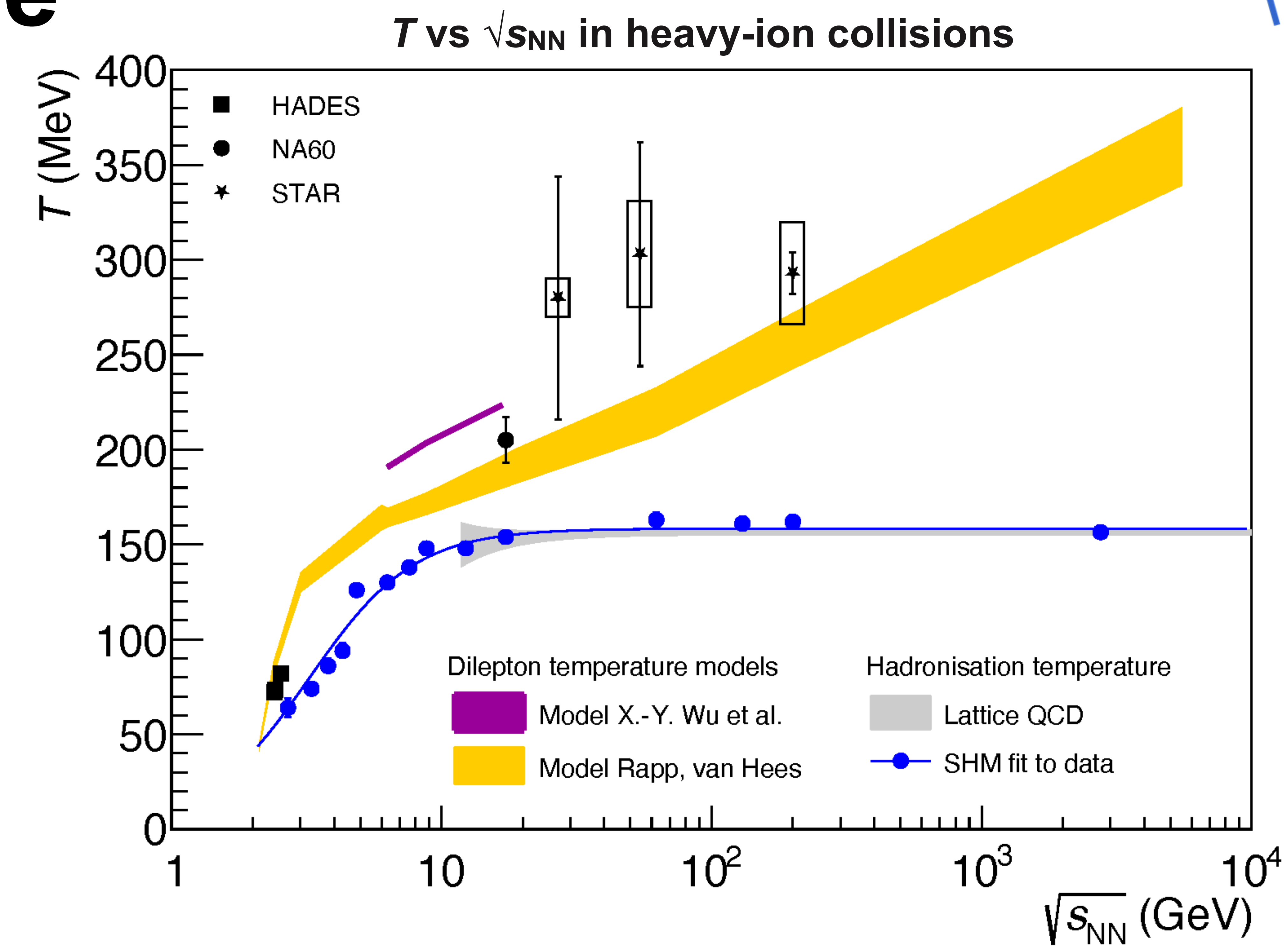


Establishing QCD caloric curve

Temperature ***T*** is one of the key properties of the medium
- Equation of state
- Order of phase transition

Only a couple of precise measurements so far!





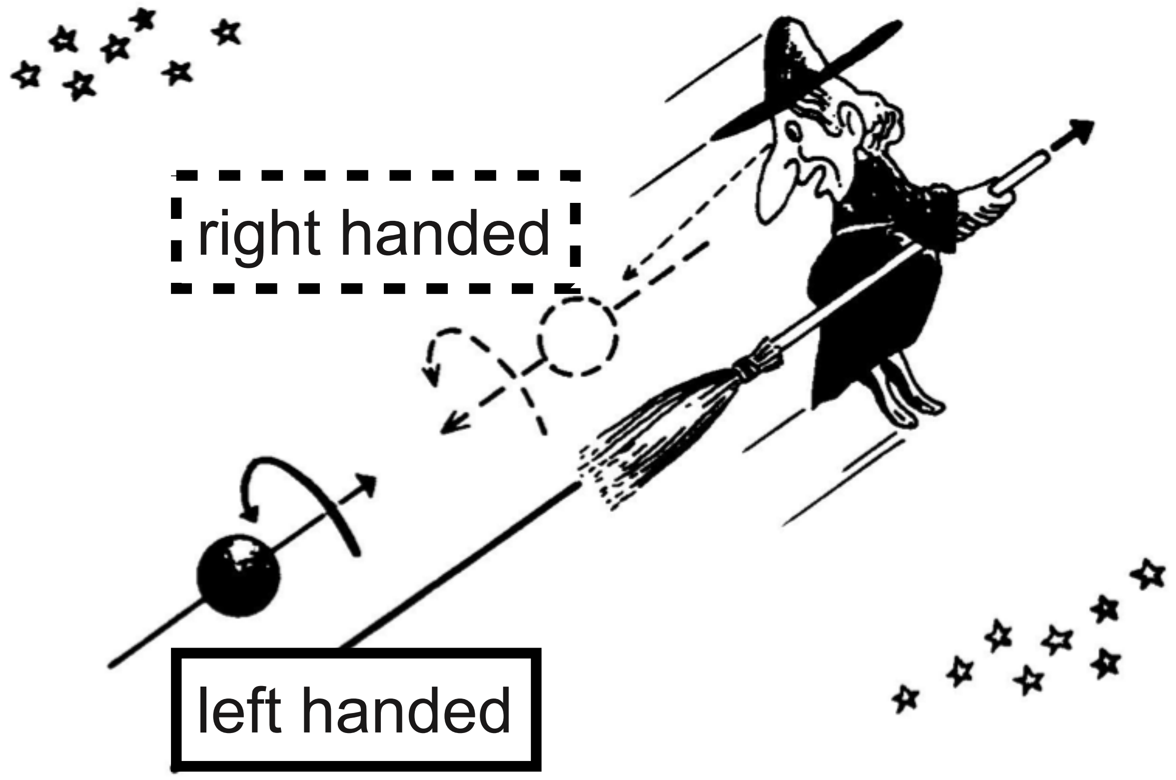
Thermal virtual photons:
🌡️ *Slope of spectrum ↔* ***T*** *of the system*
⏱️ *Not only thermometer, but also a chronometer!*
Yield in low-mass range ↔ fireball lifetime

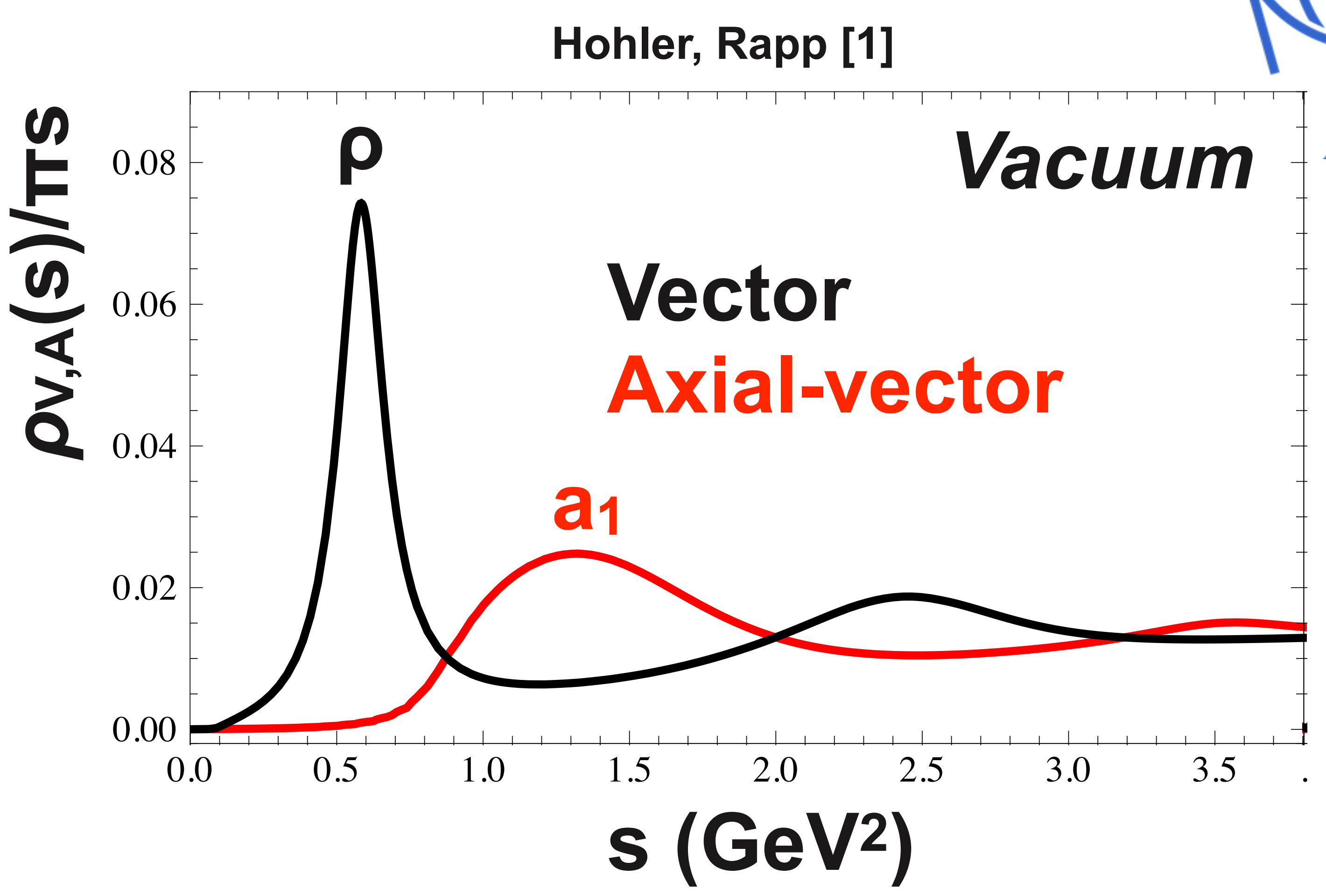
Look for traces of first-order phase transition
- *Flattening of* ***T*** *curve vs energy density?*
- *Variations of lifetime around onset of deconfinement?*

Chiral symmetry

In QCD: *massless* left(right)-handed quarks stay left(right)-handed

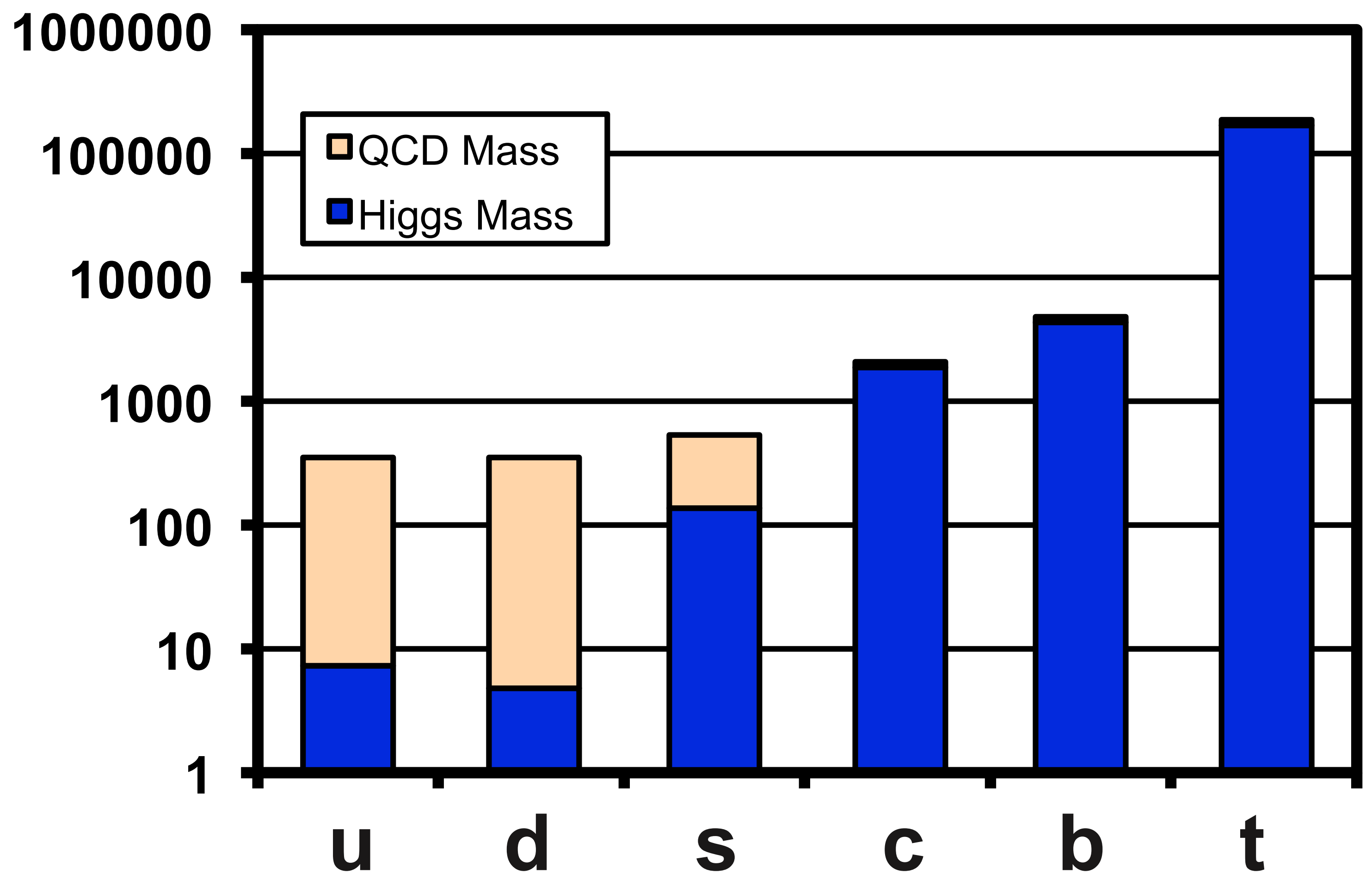
- Chiral partners (with opposite parity) have equal masses





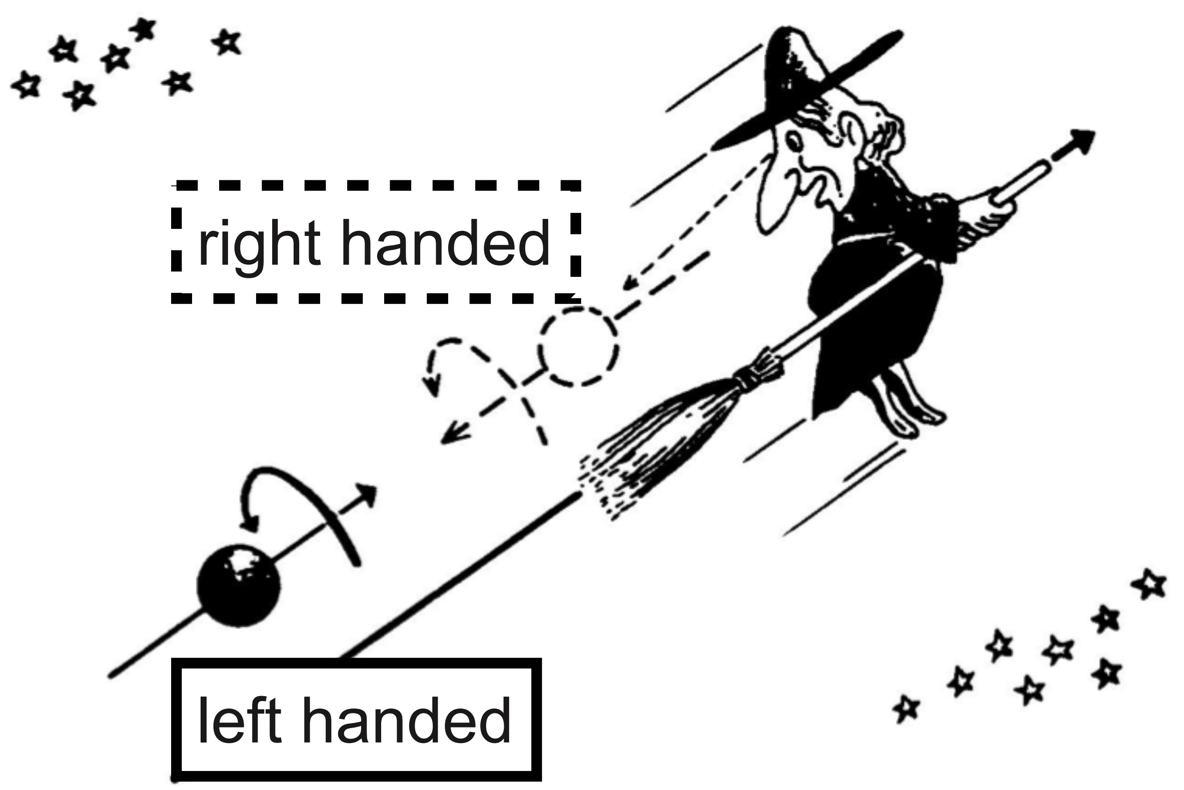
In reality: chiral symmetry is *spontaneously* broken

- Chiral partners ρ and a_1 have **Δm ≈ 500 MeV**
- Generates **~95%** of the visible mass



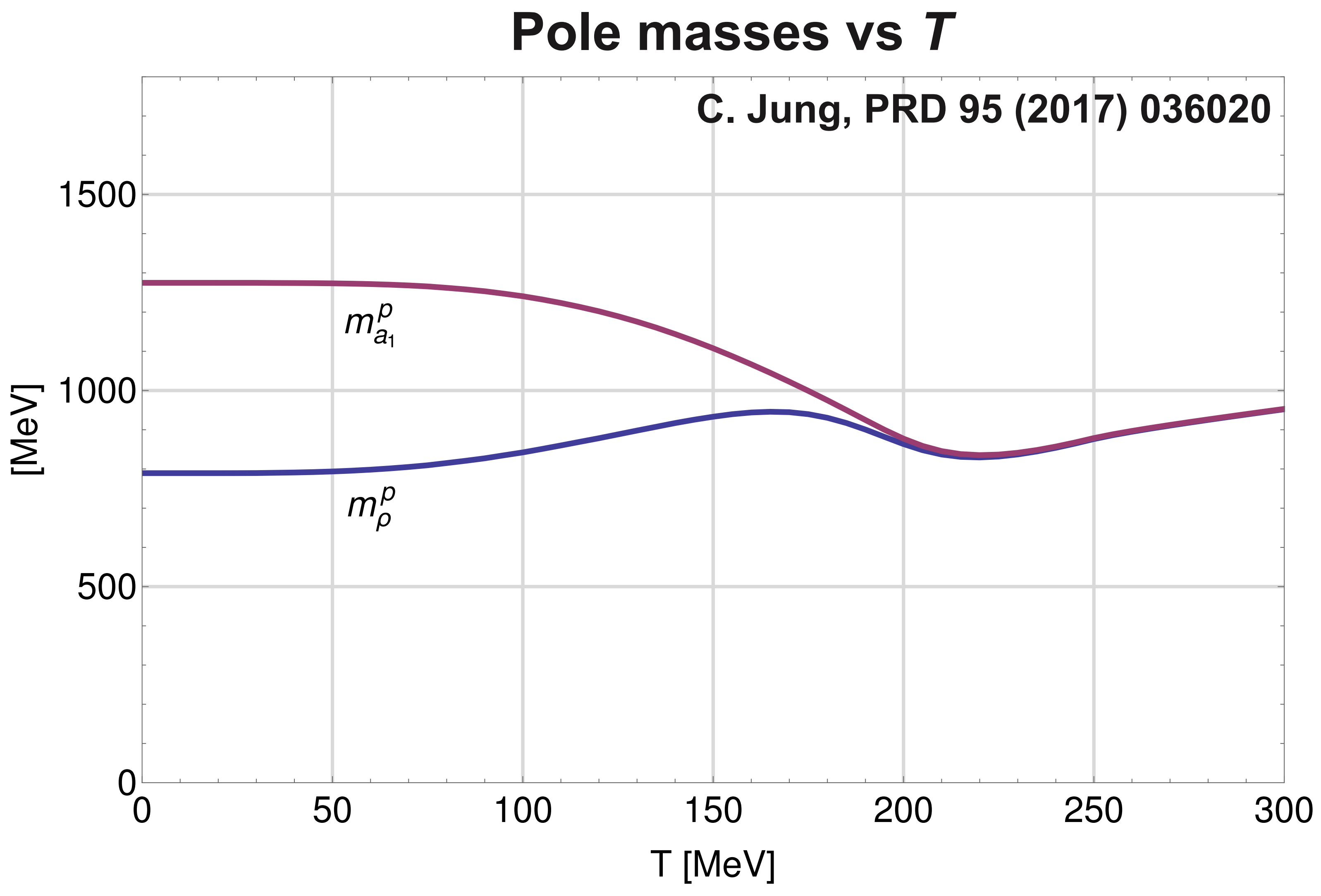
Chiral symmetry

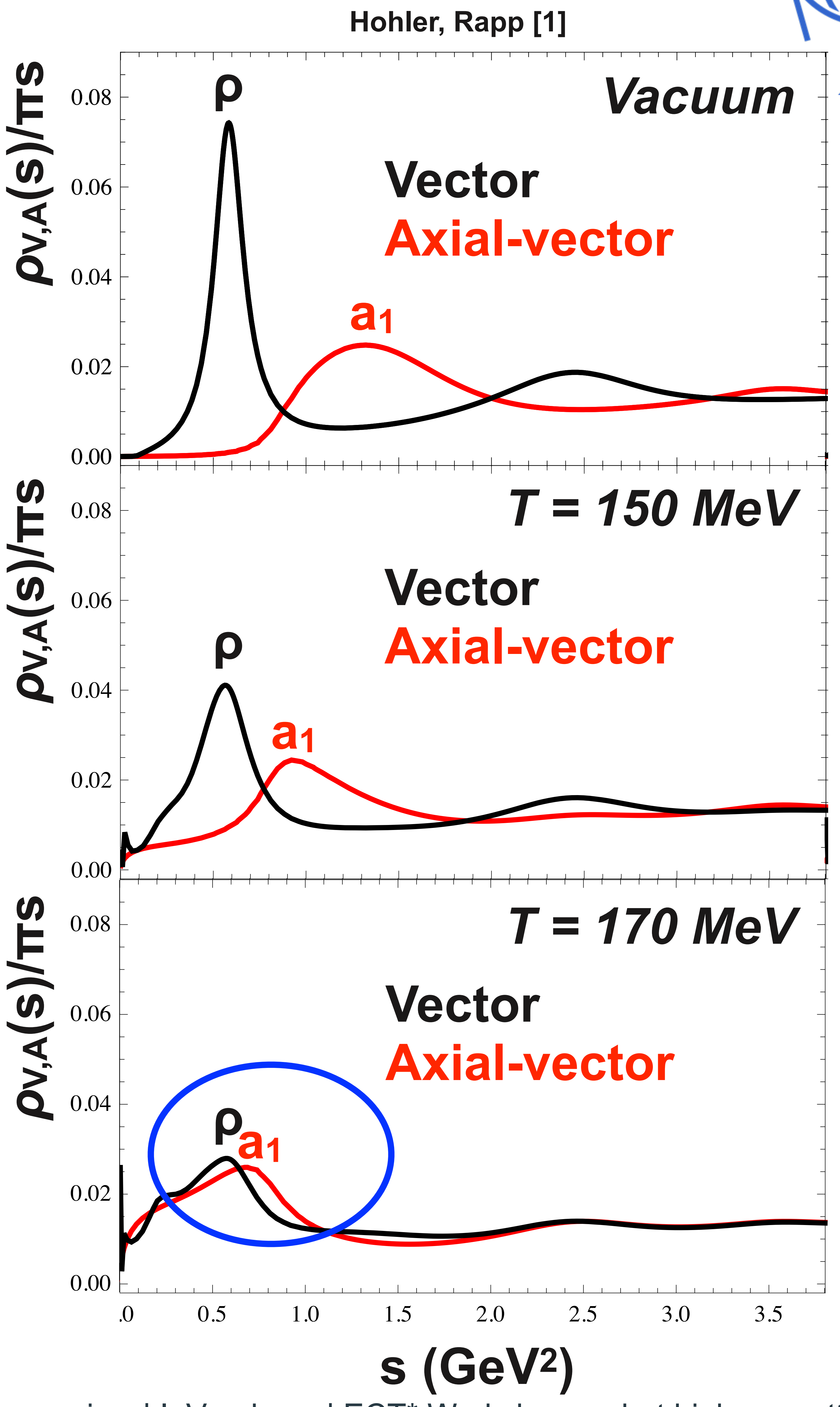
In QCD: *massless* left(right)-handed quarks stay left(right)-handed
- Chiral partners (with opposite parity) have equal masses



In reality: chiral symmetry is *spontaneously* broken
- Chiral partners ρ and a_1 have **Δm ≈ 500 MeV**
- Generates **~95%** of the visible mass

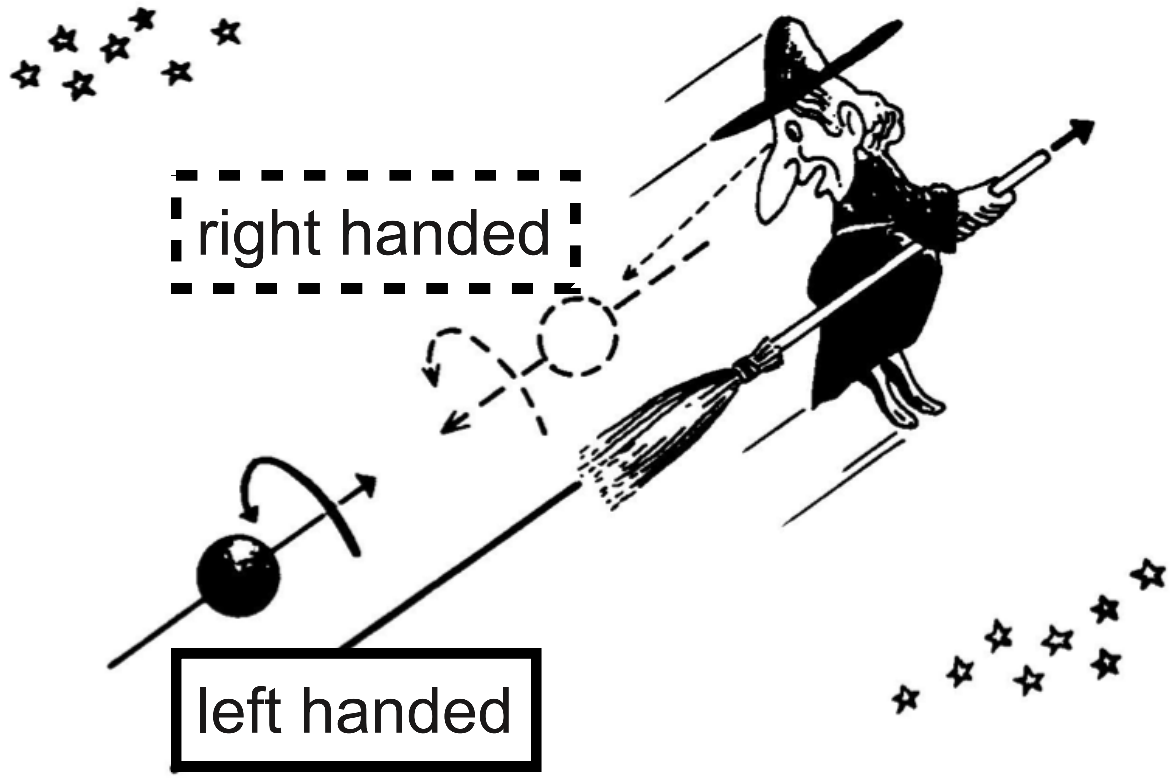
Theoretical predictions:
- (partial) restoration of chiral symmetry at high ***T***
- → *chiral partners get similar masses and mix*





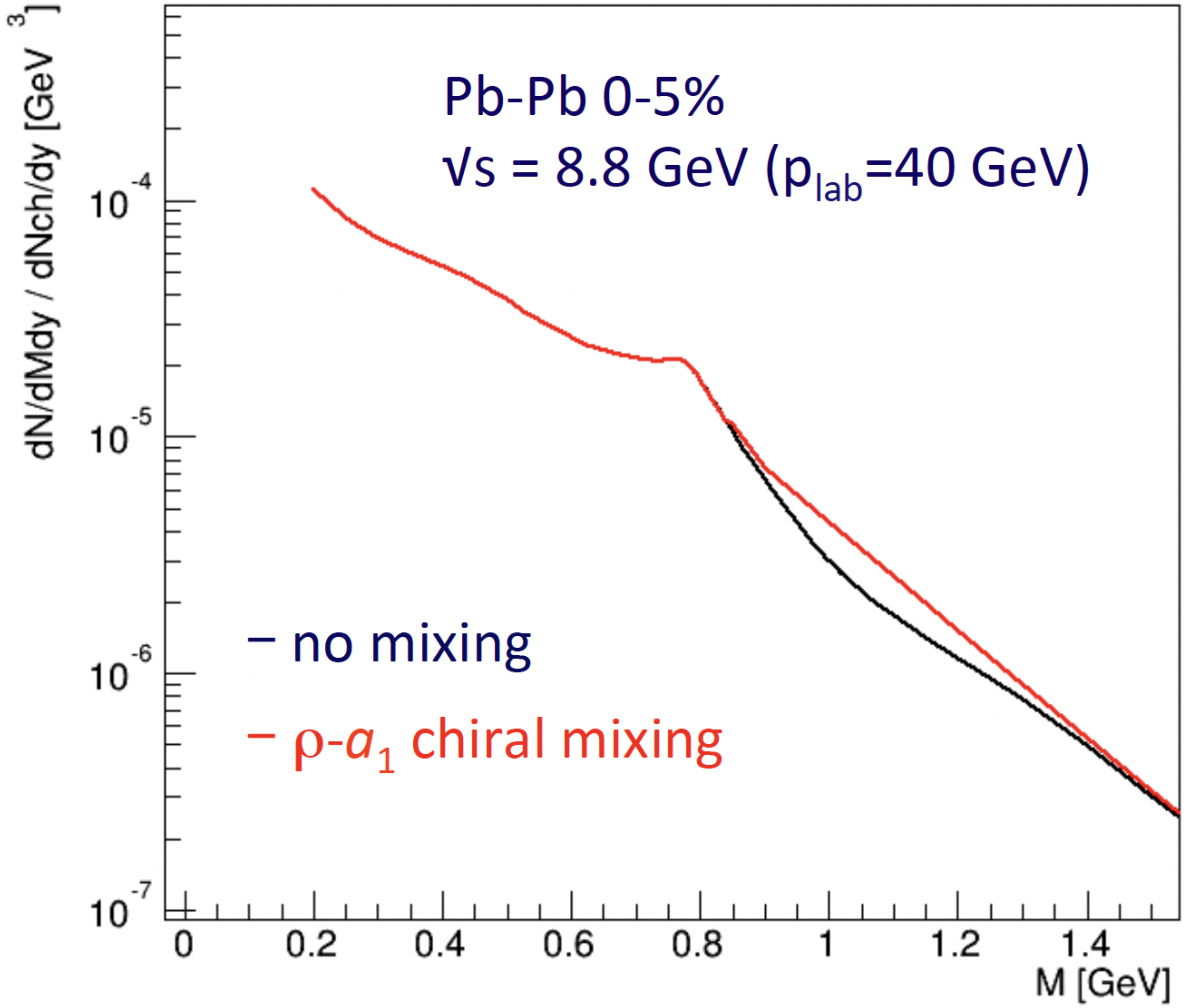
Chiral symmetry

In QCD: *massless* left(right)-handed quarks stay left(right)-handed
- Chiral partners (with opposite parity) have equal masses

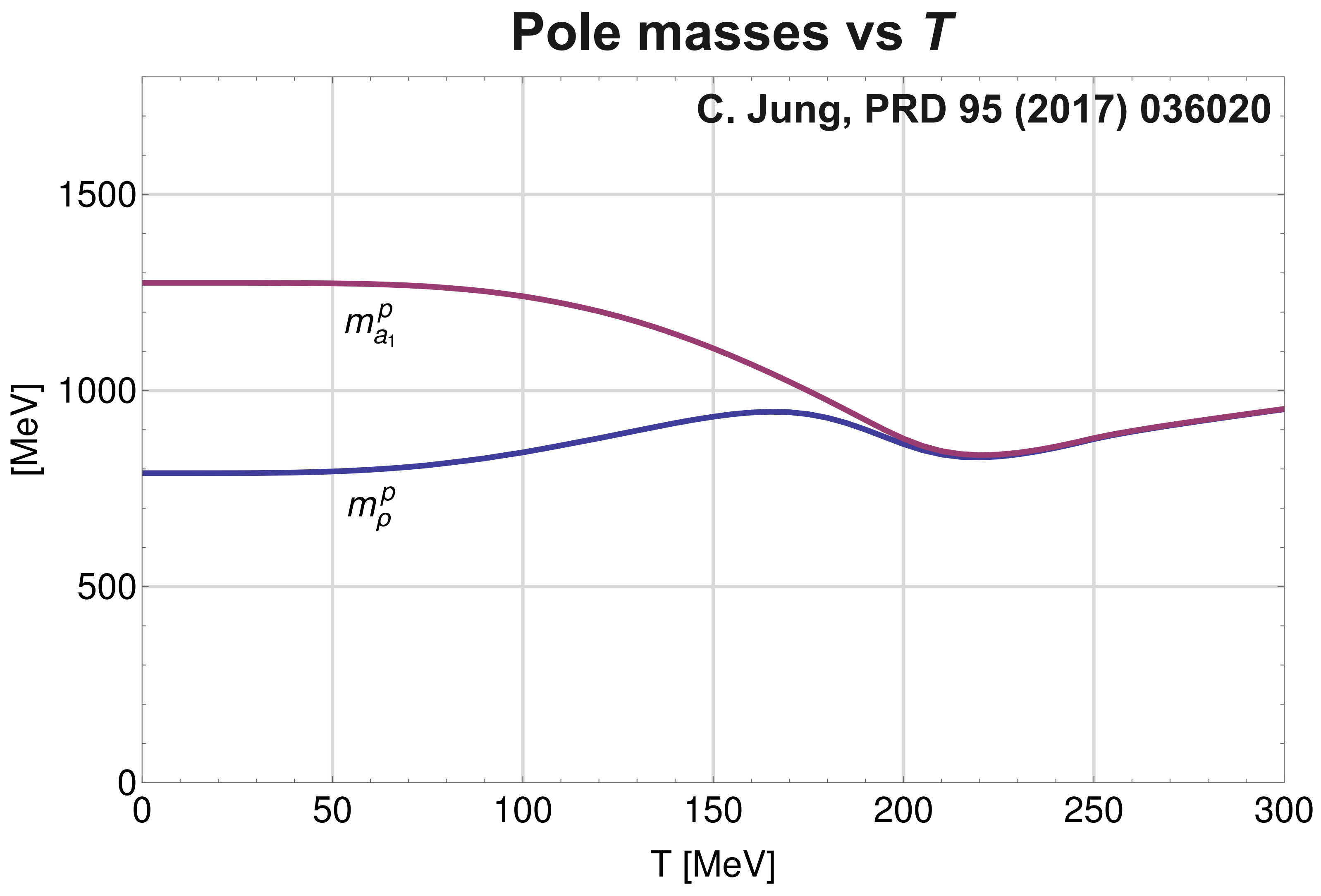


ρ−a1 *chiral mixing*
→ *dilepton enhancement in **0.8 < M < 1.4 GeV/c²***
*(up to **~30%** effect)*

In reality: chiral symmetry is *spontaneously* broken
- Chiral partners ρ and a_1 have **Δm ≈ 500 MeV**
- Generates **~95%** of the visible mass



Theoretical predictions:
- (partial) restoration of chiral symmetry at high ***T***
- → *chiral partners get similar masses and mix*

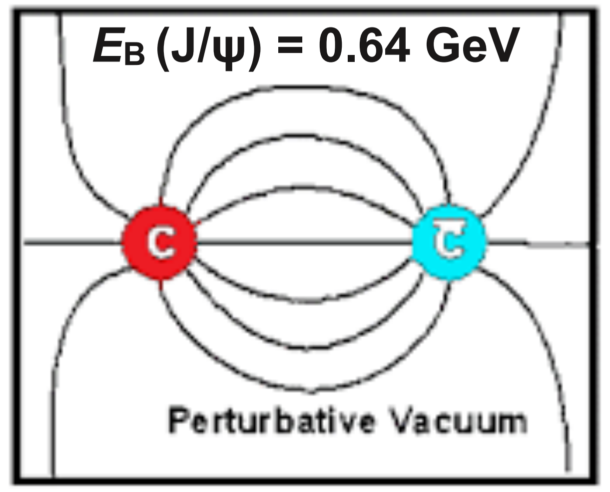


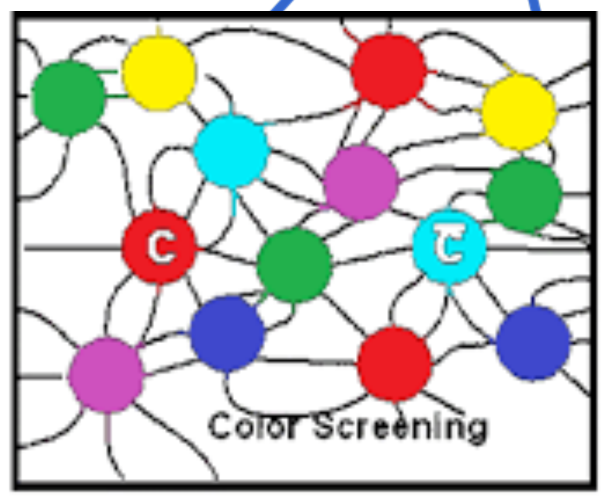
Onset of deconfinement

Dissociation of quarkonia states in the QGP due to screening of QCD binding forces

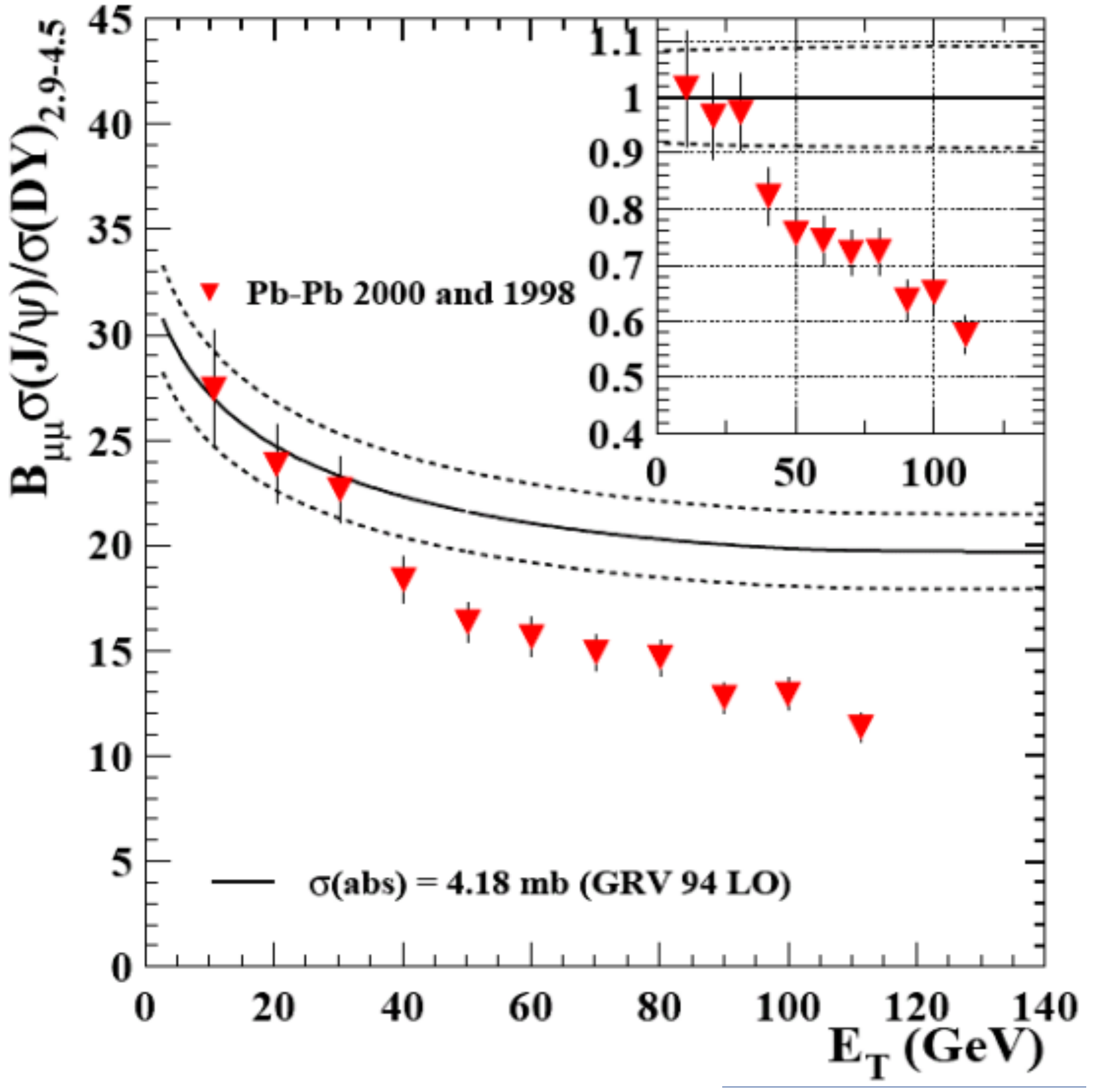
- Studies of quark and gluon deconfinement onset via **J/ψ** suppression

Results from top SPS energy: evidence for suppression beyond **CNM** effects [1, 2]

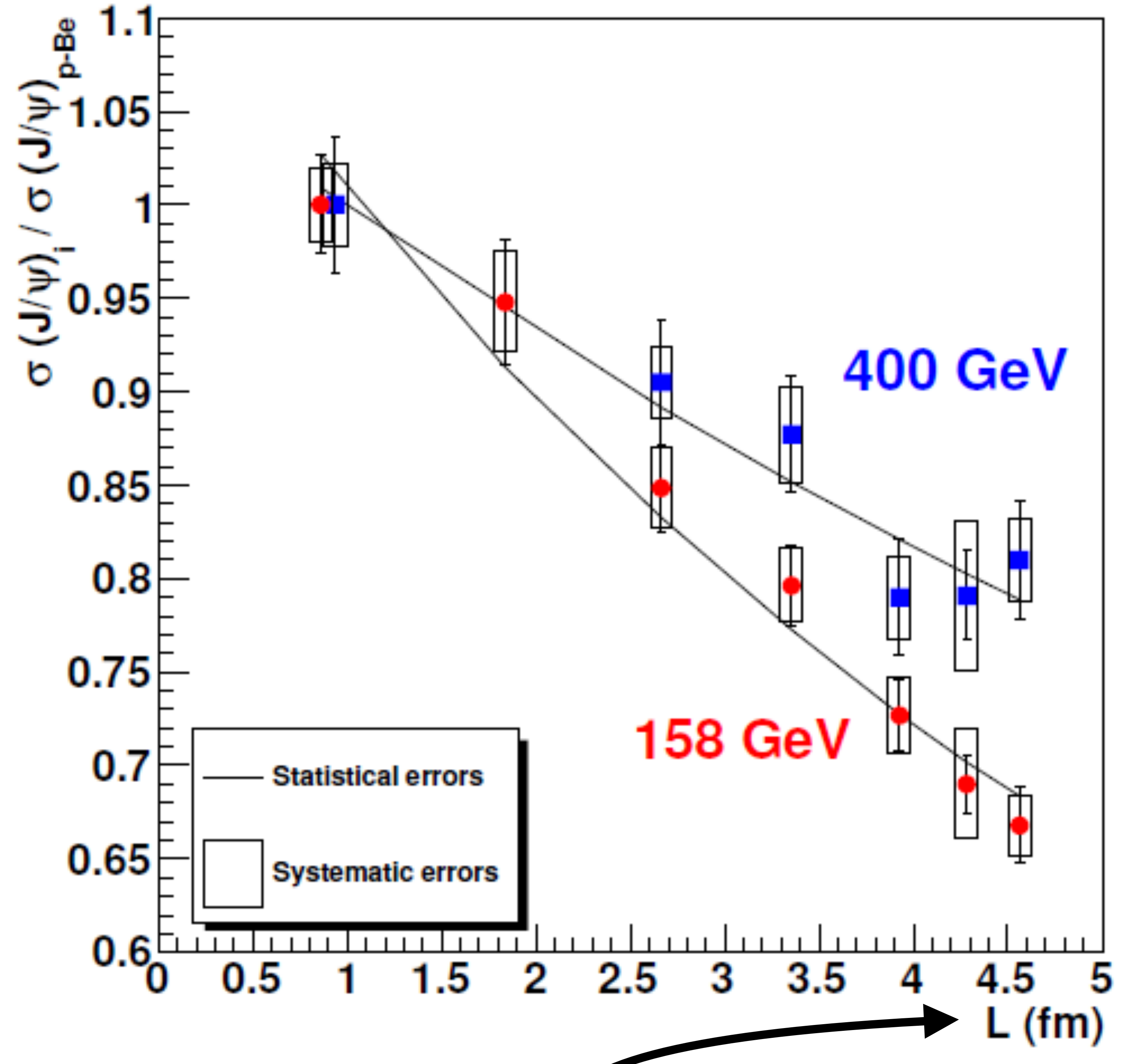




J/ψ / DY cross section vs E_T in NA50 [1]

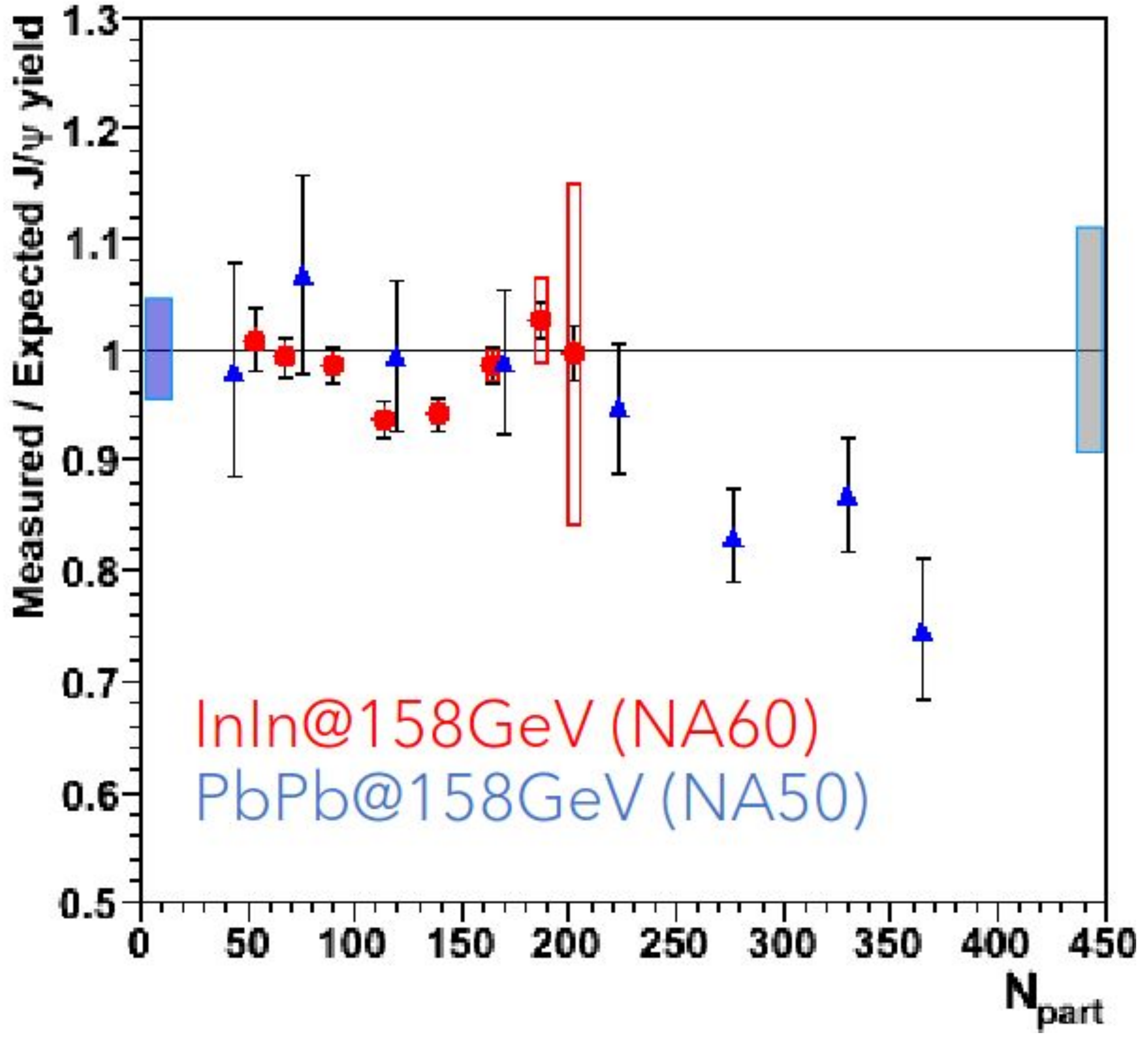


J/ψ cross section normalised to p−Be in NA60 [2]



Mean thickness of nuclear matter crossed by J/ψ

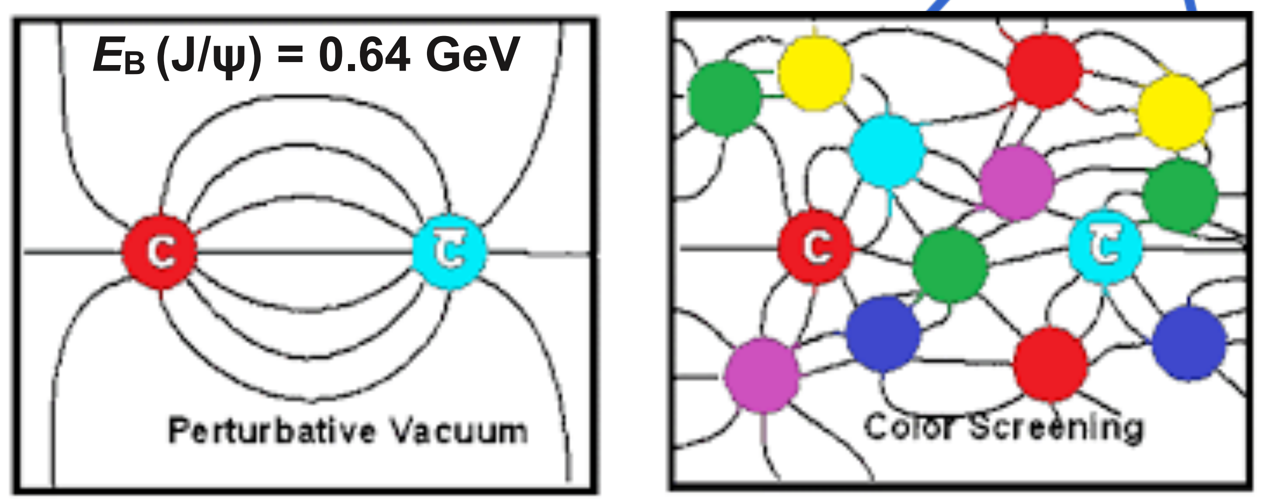
Measured / expected yield of J/ψ



[1] NA50, EPJC 39 (2005) 335
[2] NA60, PLB 706 (2012) 263

Onset of deconfinement

Dissociation of quarkonia states in the QGP due to screening of QCD binding forces
• Studies of quark and gluon deconfinement onset via **J/ψ** suppression



Results from top SPS energy: evidence for suppression beyond **CNM** effects [1, 2]
❗ *No measurements below the top SPS energy!*

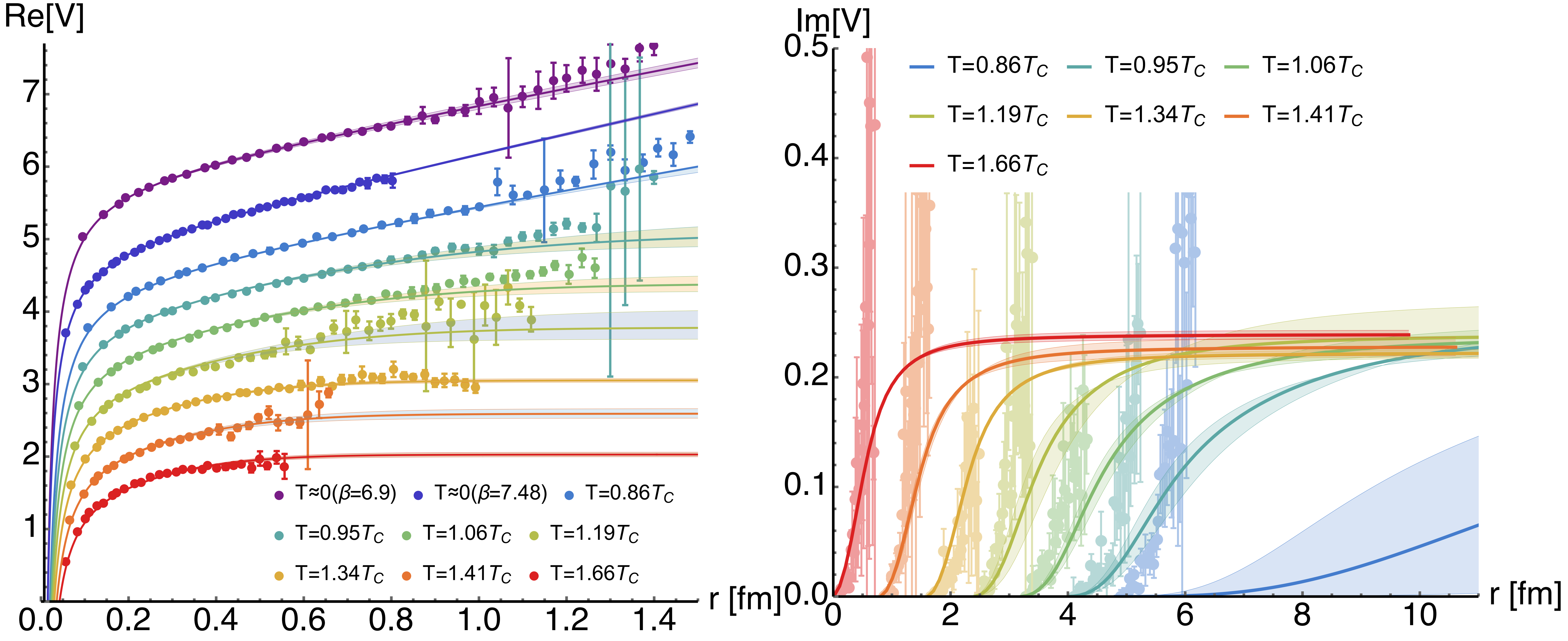
👉 *Explore temperatures closer to* $\boldsymbol{T_c}$

👉 *Investigate the role of feed-down from* ***ψ(2s)*** *and* $\boldsymbol{\chi_c}$

❓ *Correlation of suppression effects with the* ***T*** *of the medium?*

❓ *Increase of* ***CNM*** *effects with lower collision energies?*

In-medium heavy-quark potential from lattice [1]



🎤 *See more in the talk of E. Scomparin (Wed 11:35)*

[1] Burnier et al., JHEP12 (2015) 101

Open charm – open questions

Charm quarks produced in initial *NN* collisions, traverse medium before hadronisation
- Transport properties of the medium, heavy-quark thermalisation
- *Few experimental data, only at the top SPS energy!*

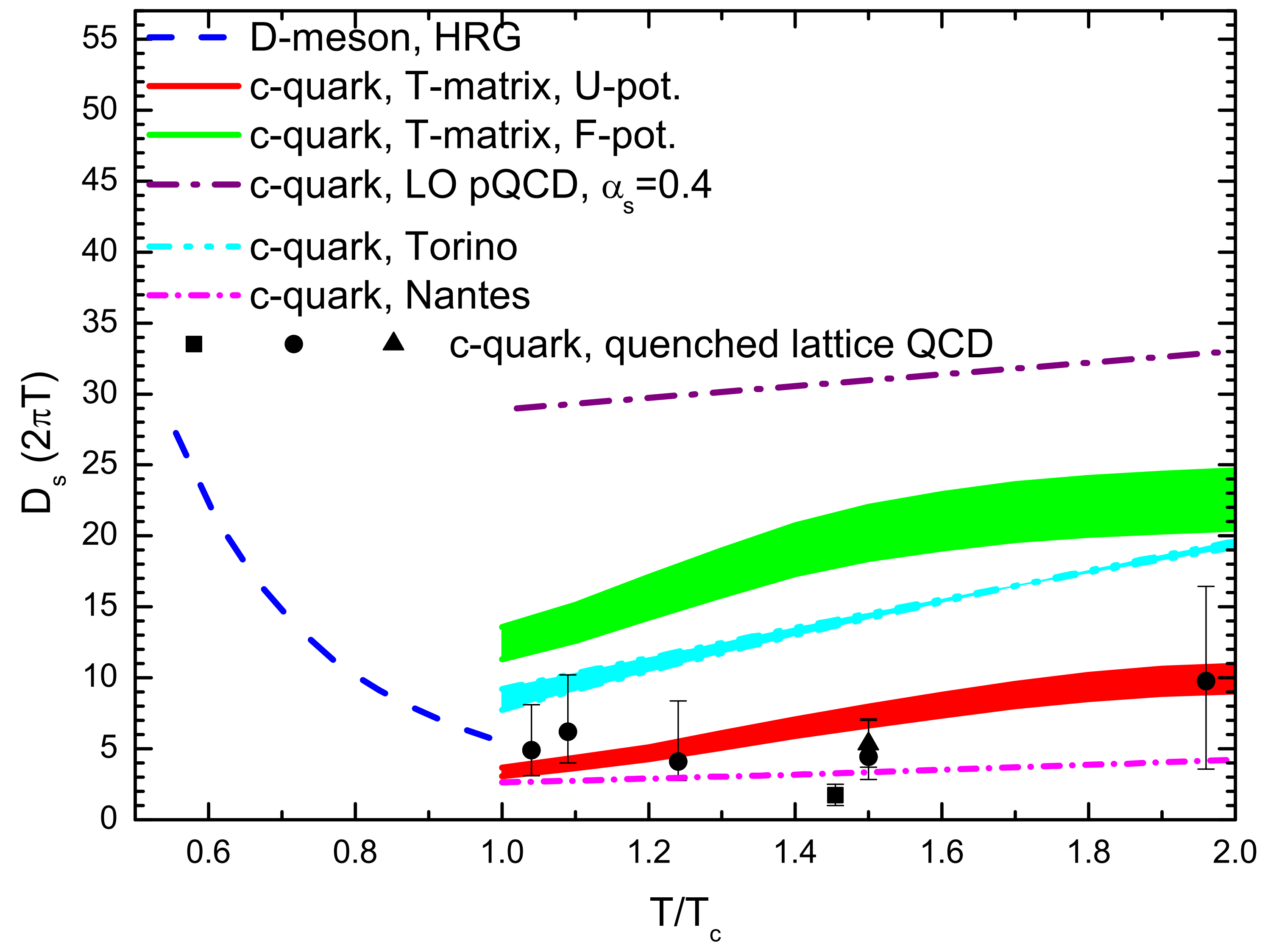
👉 *Expect increase of charm diffusion coefficient for lower collision energies (shorter-lived medium, stronger impact of hadronic phase)*
- Important to constrain models also at higher ***E***

👉 *Impact on charm hadronisation mechanism of a baryon-rich QGP*
- Baryon/meson ratios **(Λ_c/D)**, strangeness **(D_s/D)**

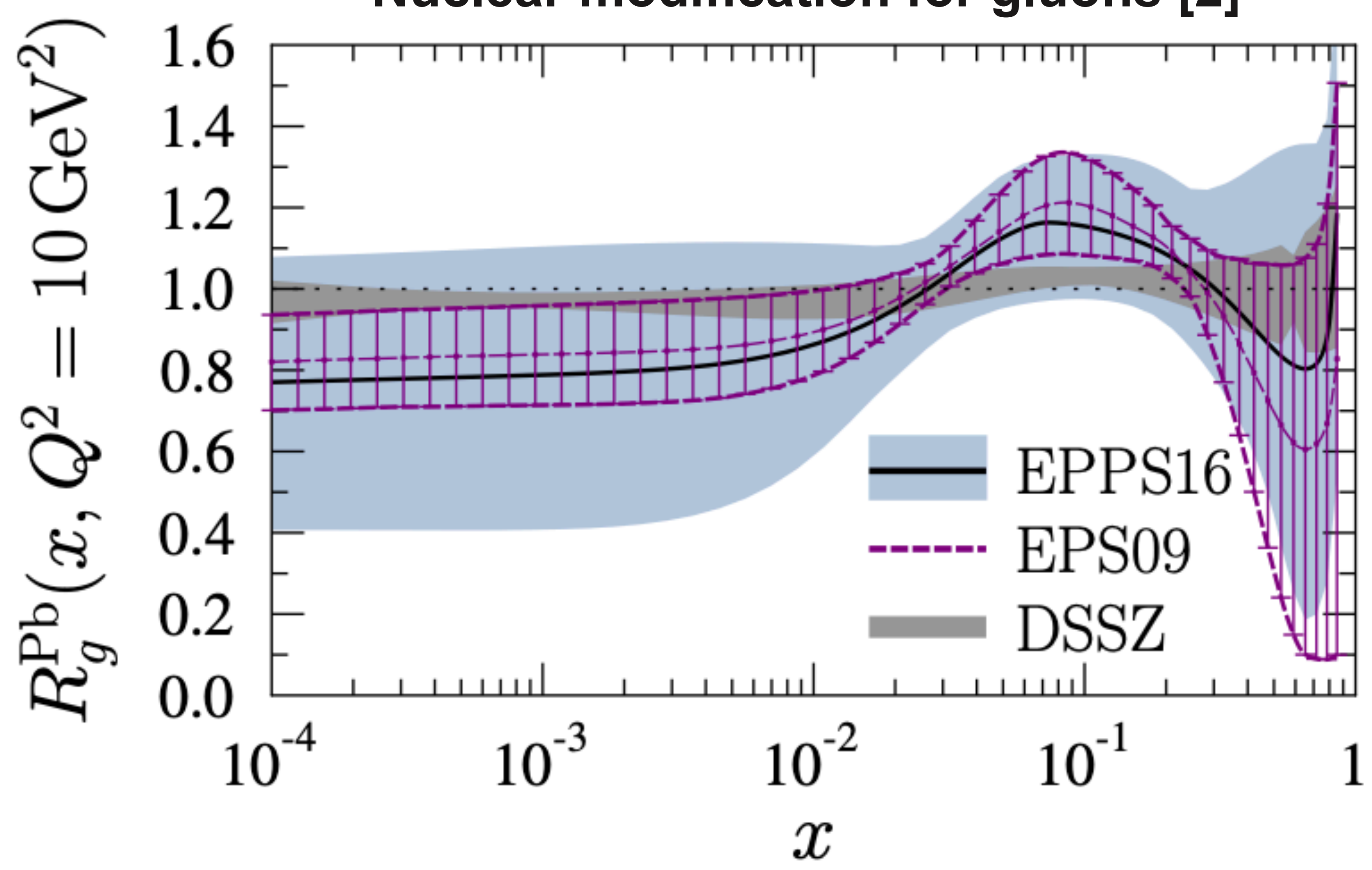
👉 *Open charm cross-section close to threshold*
- nuclear PDF at large Bjorken **x** (anti-shadowing, **EMC** region)
- Reference for charmonium studies

🎤 *See more in the talk of F. Prino (Tue 11:35)*

C quark diffusion coefficient from lQCD and models [1]



Nuclear modification for gluons [2]

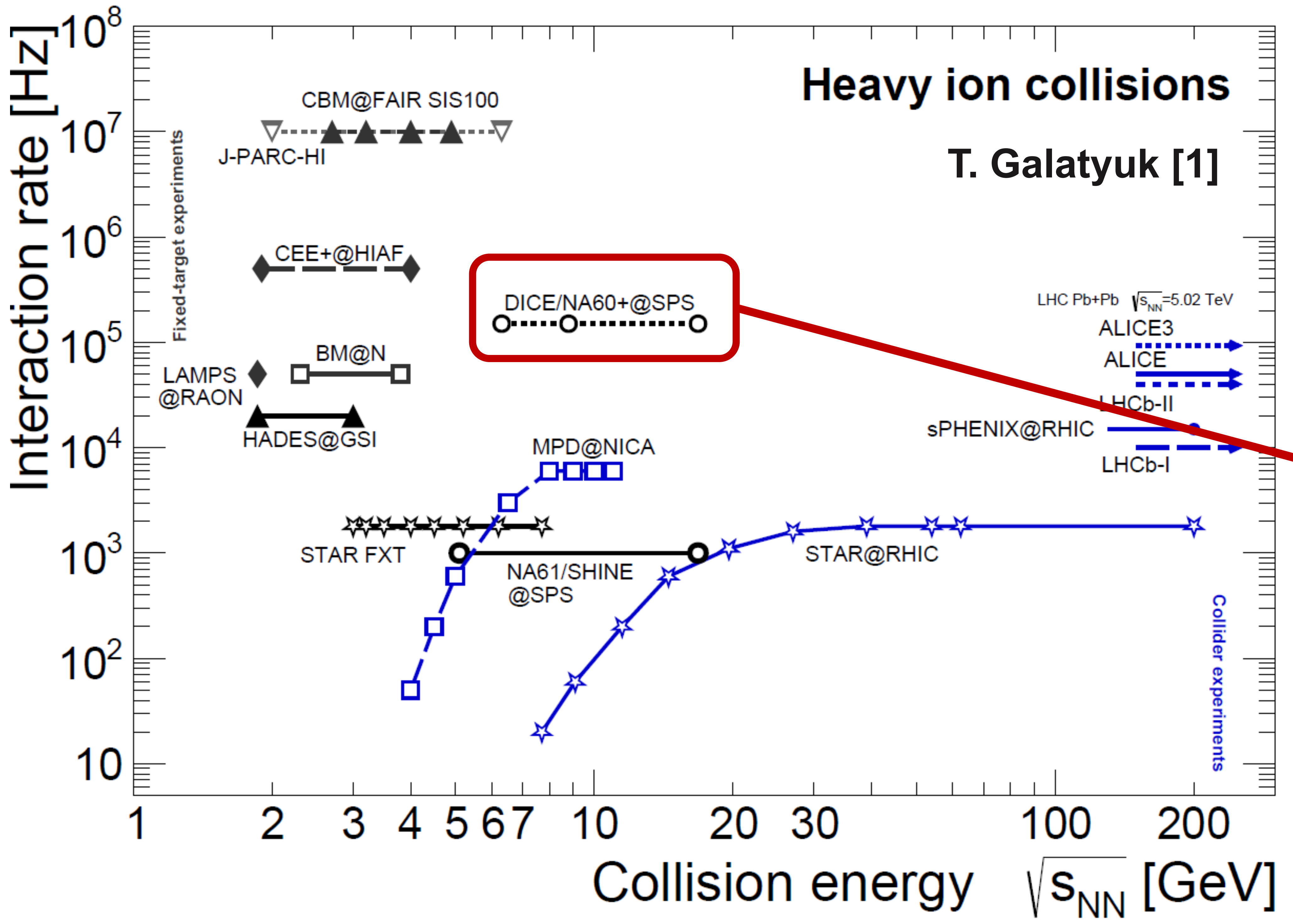


[1] F. Prino, R. Rapp, J.Phys.G 43 (2016) 9, 093002
[2] Eskola et al., Eur.Phys.J.C 77 (2017) 3, 163

Experiment proposal: NA60+/DiCE

***The NA60+ / Dimuon and Charm Experiment** to explore hard and electromagnetic probes of QGP at SPS energies*

- BES: $\sqrt{s_{NN}}$ **= 6.3−16.8 GeV, μ_B ~ 220−480 MeV**
- Muon pair production up to $m_{\mu\mu}$ **~ 4 GeV/c^2** (dimuon continuum, low mass resonances, quarkonia)
- Hadronic decays of strange and charm hadrons and hypernuclei



- *Unique experiment in terms of energy coverage and IR in the HI landscape!*
- *Study of rare probes thanks to large integrated luminosities*
  - **PbPb IR > 10^5 Hz**, reachable with 10^6 Pb/s in a fixed-target environment
- *Complementary w.r.t. other experiments:*
  - **RHIC BES, NA61/SHINE**: hadronic observables in similar energy range (🎤 L. Ruan, Mon 14:40)
  - **CBM@FAIR, MPD@NICA**: similar observables, but in a lower energy range and/or at lower IR (🎤 A. Andronic, Mon 15:20, 🎤 I. Tserruya, Thu 16:35)

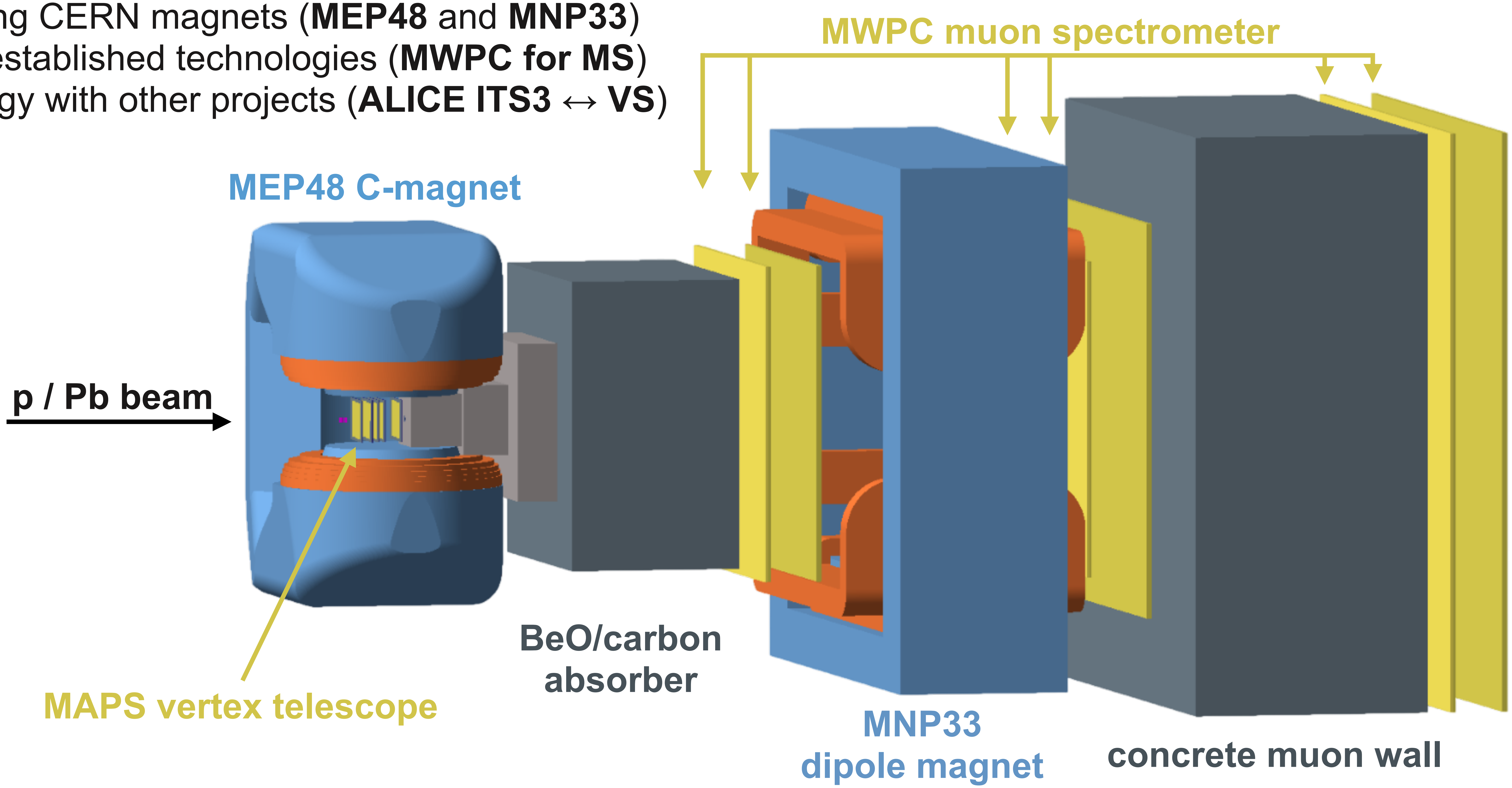
[1] Nucl. Phys. A 982 (2019) 163, QM 2018

2. Experimental setup

Overview of NA60+/DiCE experimental setup

Inspired by the **NA60**, will largely profit from the latest available technologies
Varying z-position of the muon spectrometer stations and hadron absorber thickness
Significant evolution of the detector design since the LoI in 2022 [1], preliminary total cost of ***~10 M CHF***

- Existing CERN magnets (**MEP48** and **MNP33**)
- Well-established technologies (**MWPC for MS**)
- Synergy with other projects (**ALICE ITS3 ↔ VS**)

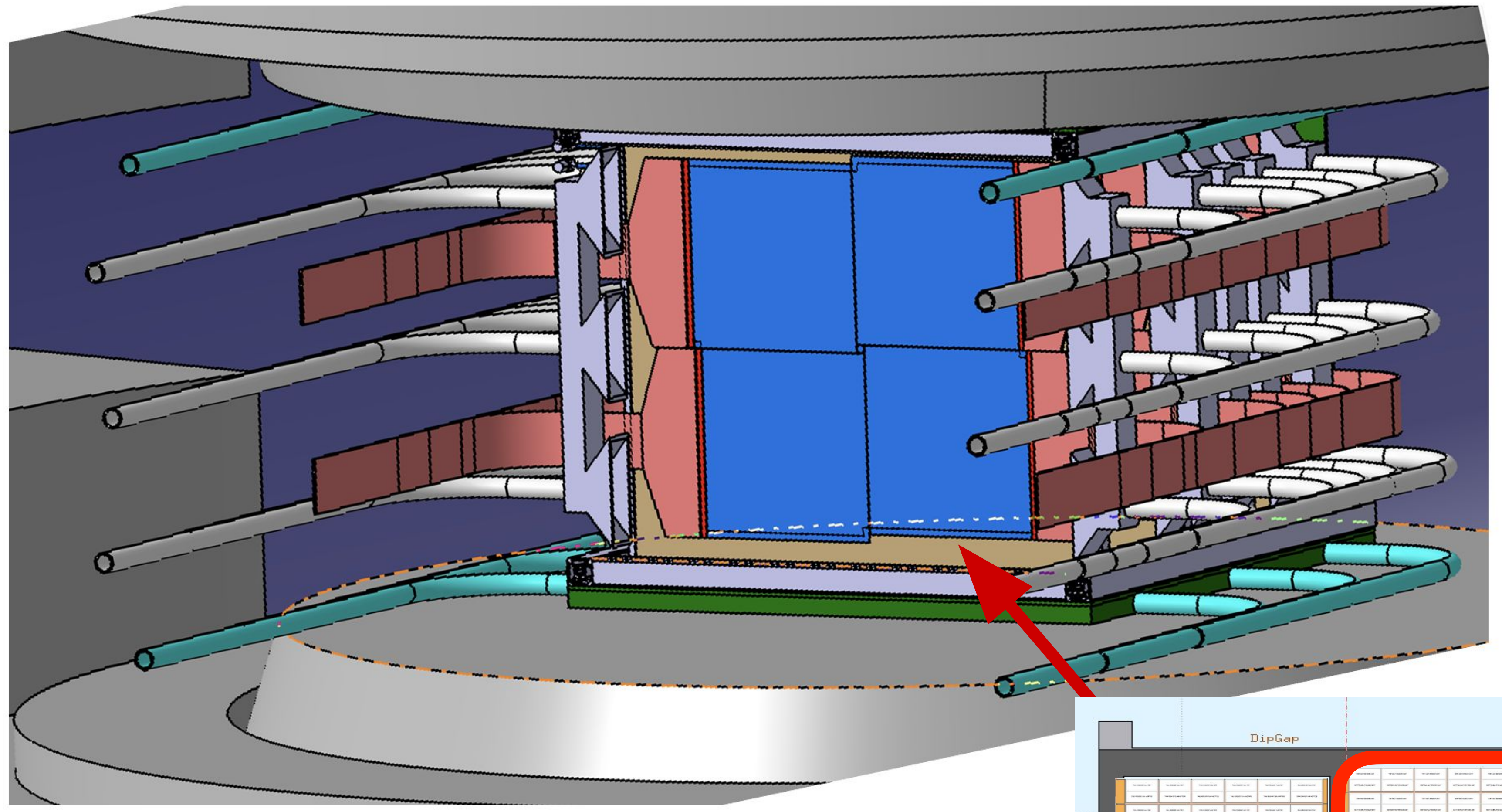


[1] arXiv:2212.14452

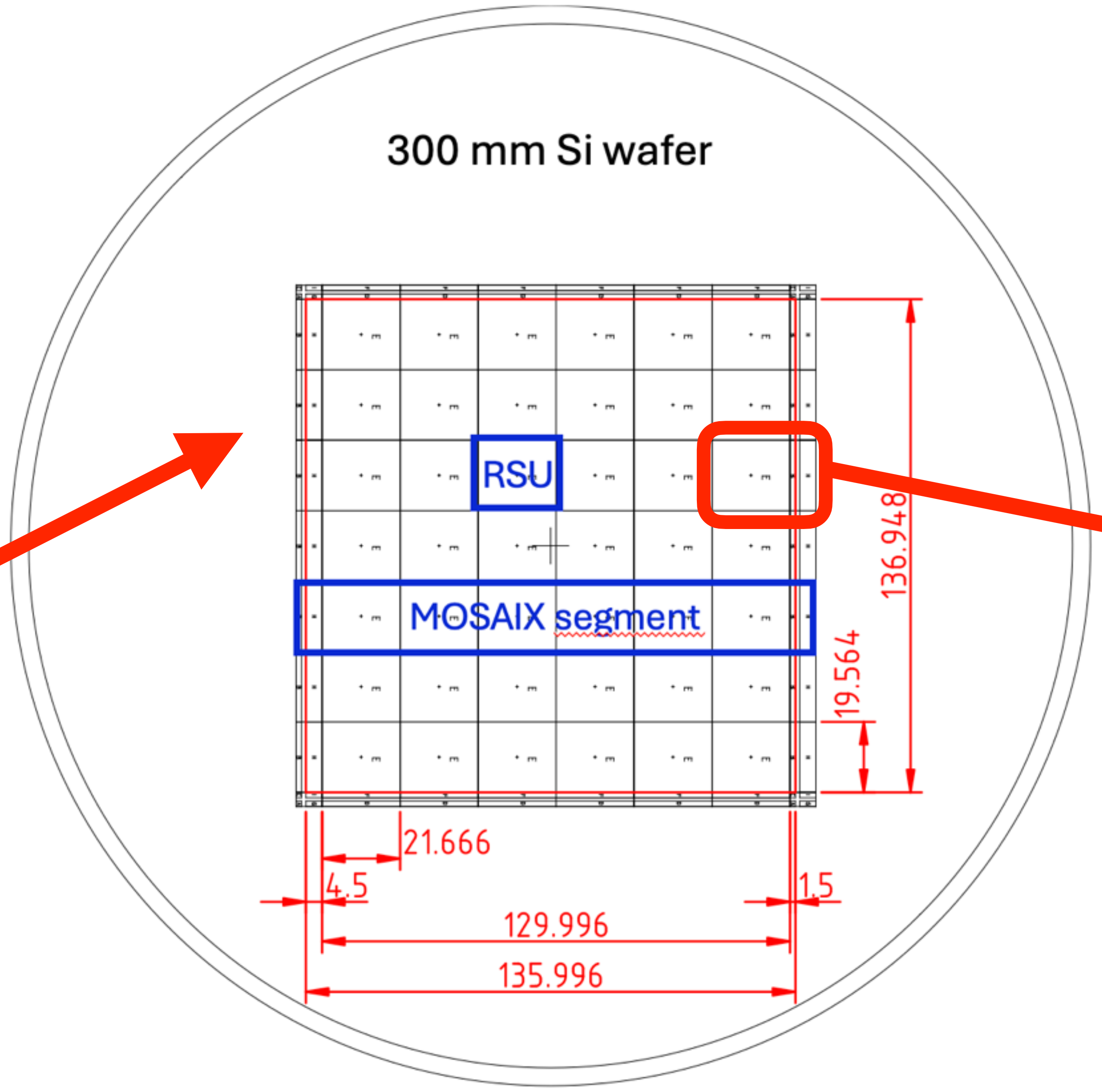
The vertex telescope

Reconstruction of muon tracks before absorber, primary vertex, hadronic tracks (open charm and strangeness)

- **5** layers of MAPS detectors at **7 < z < 38 cm** embedded in **1.5 T** *B* field
- Each layer: four **13.6×13.6 cm²** sensors with a thickness of **0.1% X_0** and **5µm** spacial resolution

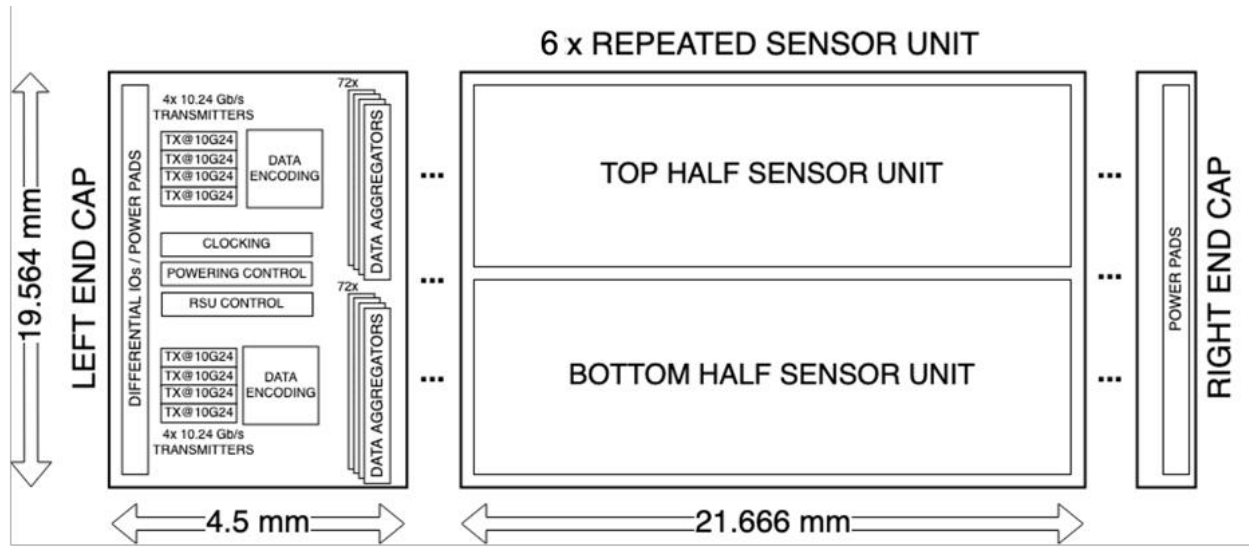


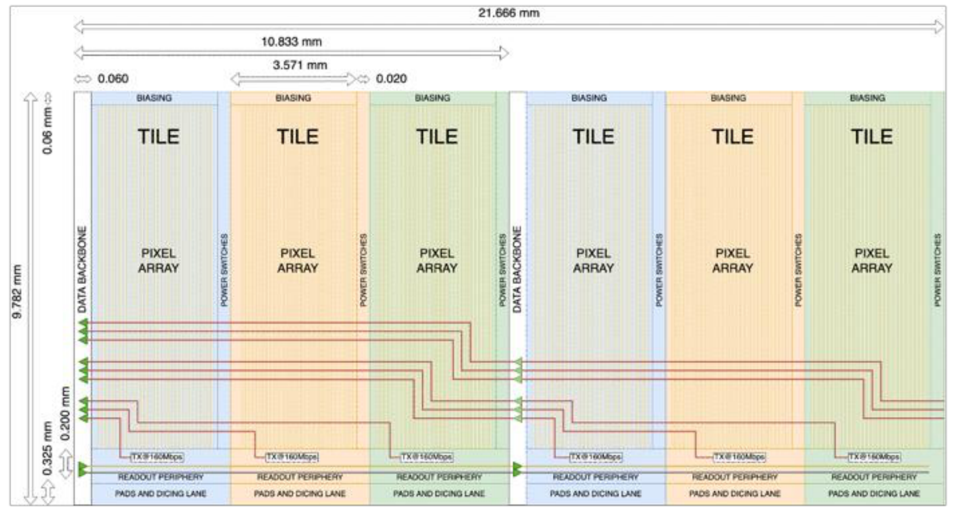
MOSAIX segment with **6** RSU
7 MOSAIX segments replicated vertically



Basic units designed in reticle:

- RSU: **21.67×19.56 mm²** pixel matrix
- Digital periphery with **8×10.24 Gb/s** serialisers





Top half-unit (bottom is mirrored)

First large-area sensor (MOSAIX) is expected in 2025

Absorber

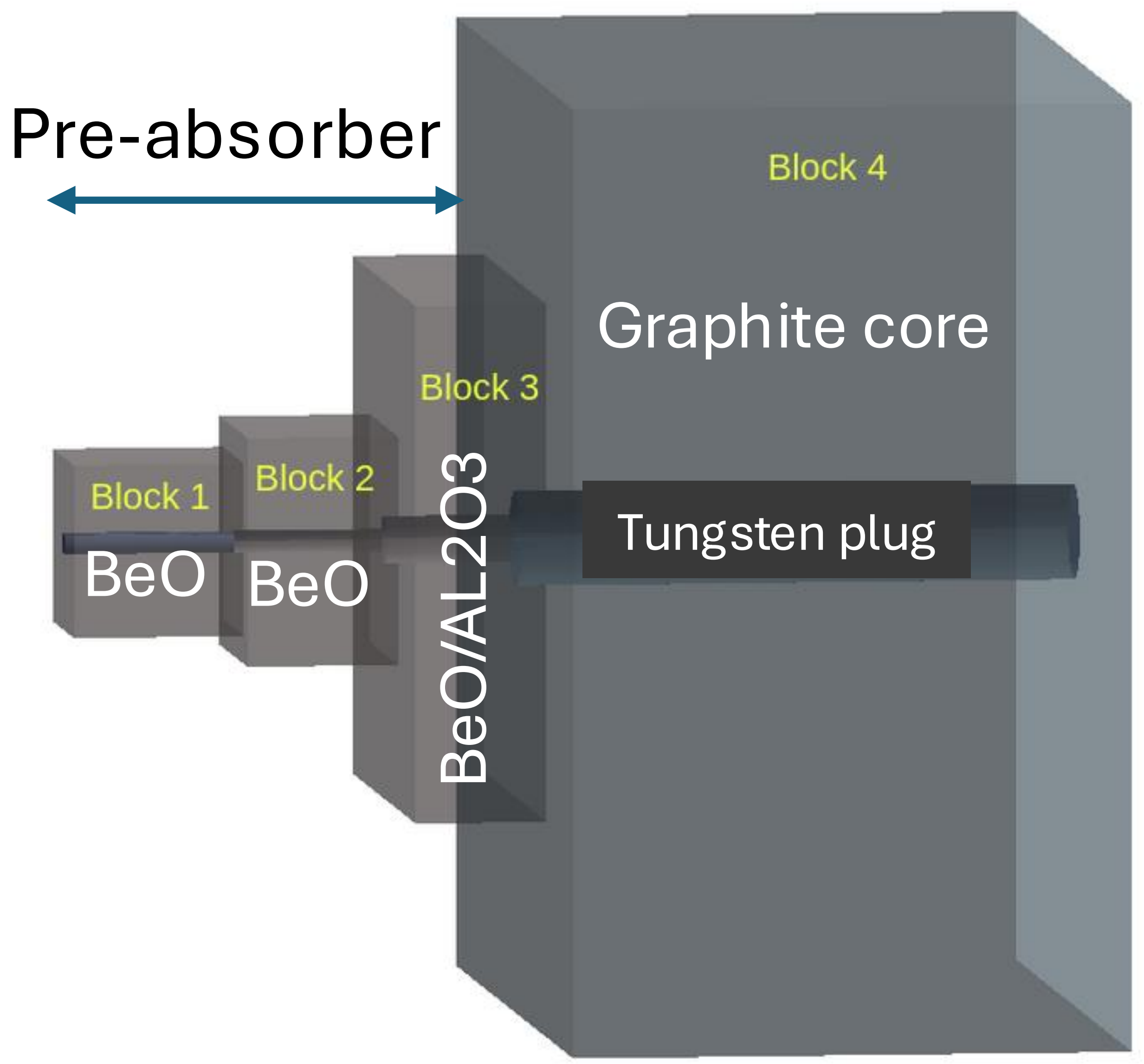
✋ *Stops hadrons, shields the MS from the non-interacting Pb and spectator nucleons*

- Part of the PR shielding of the experiment ☢️
- Thicker absorber for high-energy setup to cope with larger multiplicities at the top SPS energies (**d*N*/d*η* > 400** for central **Pb–Pb**)

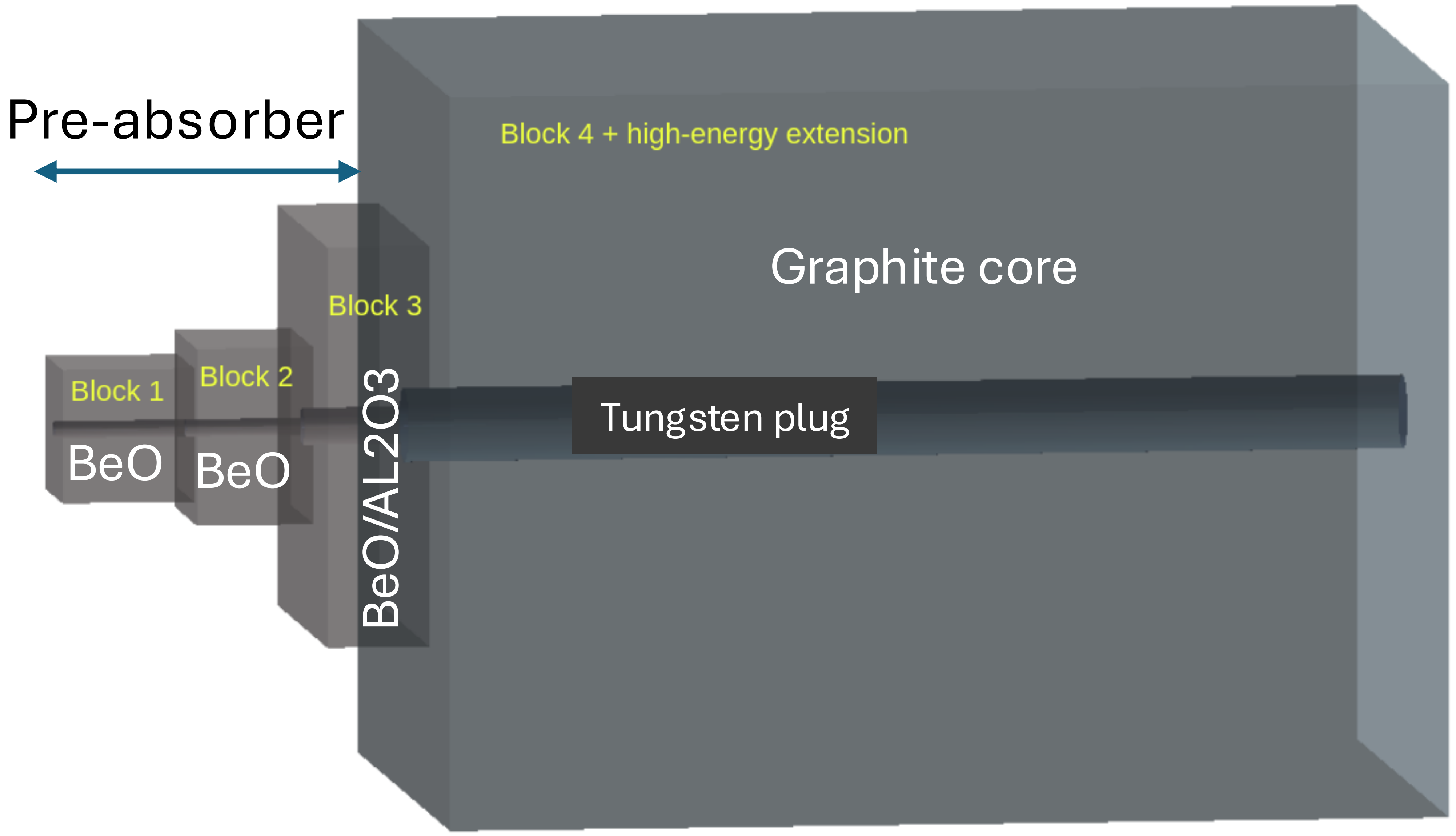
Choice of the materials: trade-off between energy loss and multiple scatterings

Material	ρ [g/cm^3]	λ [cm]	dE/dx [MeV·cm^2/g]	$\frac{\text{Nuclear}}{dE/dx}$ [%]	$\frac{dE/dx}{\lambda}$ [MeV]	X_0 g/cm^2
C	2.0	43	2.1 (2.2)	0.2 (0.6)	160 (170)	42.7
B_4C sintered	2.3	36	1.9 (2.1)	0.2 (0.5)	180 (190)	50.1
Be0	3.0	28	1.9 (2.1)	0.2 (0.6)	170 (180)	41.3
Al_2O_3 sintered	3.7	27	1.8 (2.0)	0.3 (0.9)	190 (210)	27.9
Fe	7.8	17	1.8 (1.9)	0.5 (1.6)	240 (260)	13.8
Shielding concrete	2.3	42	2.1 (2.2)	0.3 (0.9)	200 (215)	26.6
W	19.3	10	1.5 (1.7)	1.1 (3.9)	290 (320)	6.8

Low-energy absorber: **7 λ**



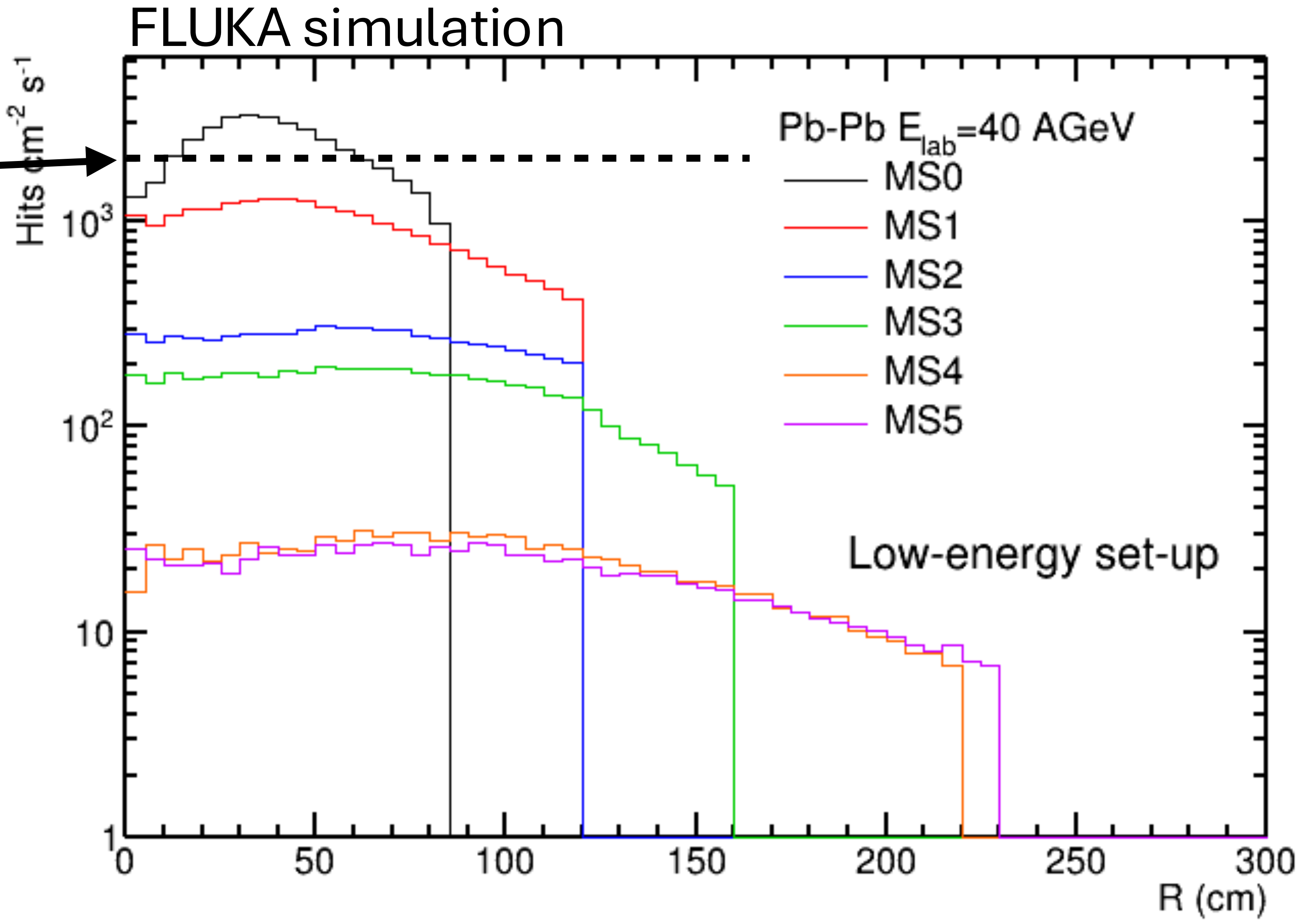
High-energy absorber: **14 λ**

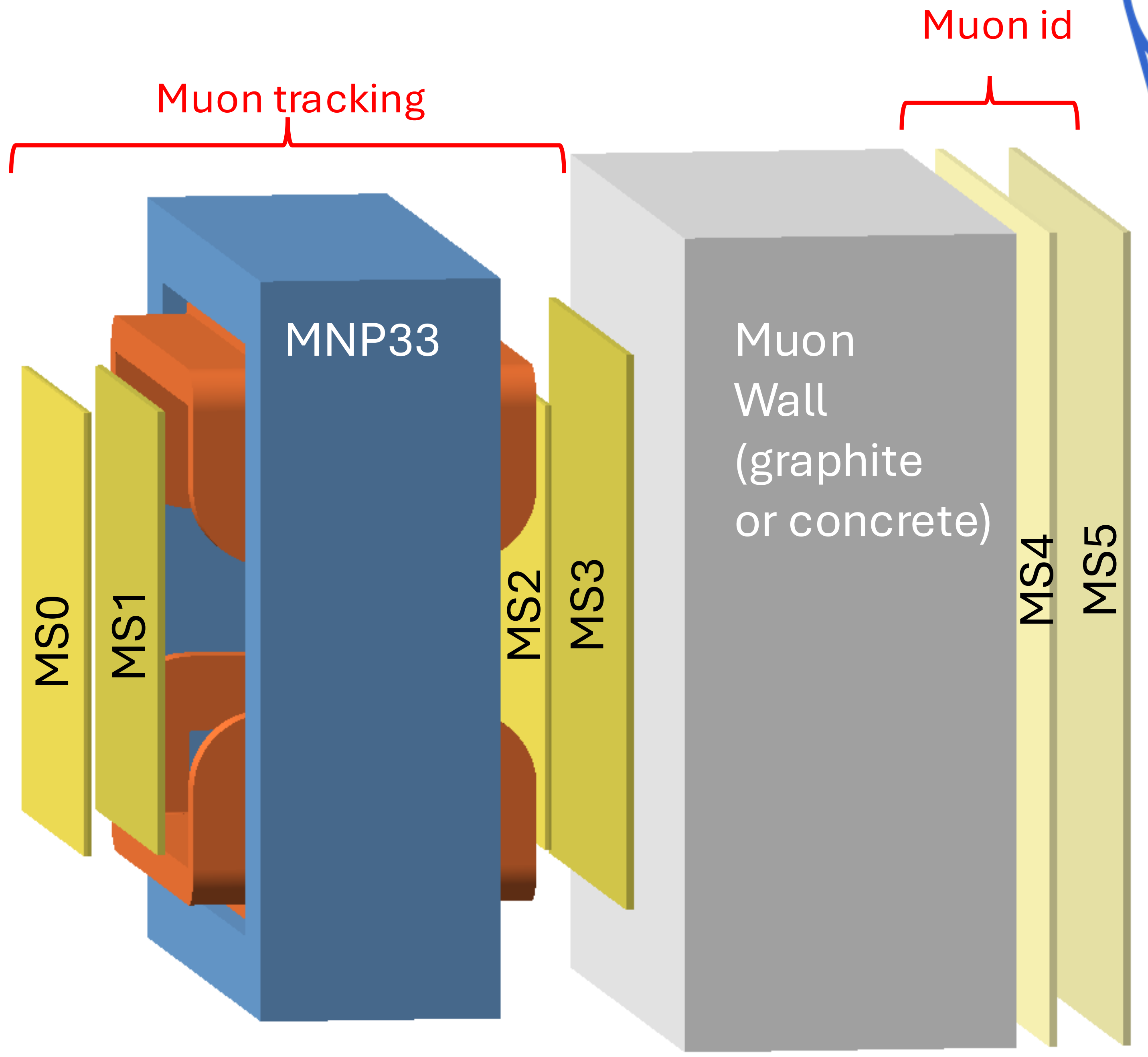


The muon spectrometer

***6** stations to measure kinematic parameters of the muon tracks after absorber and to match muons to vertex spectrometer*

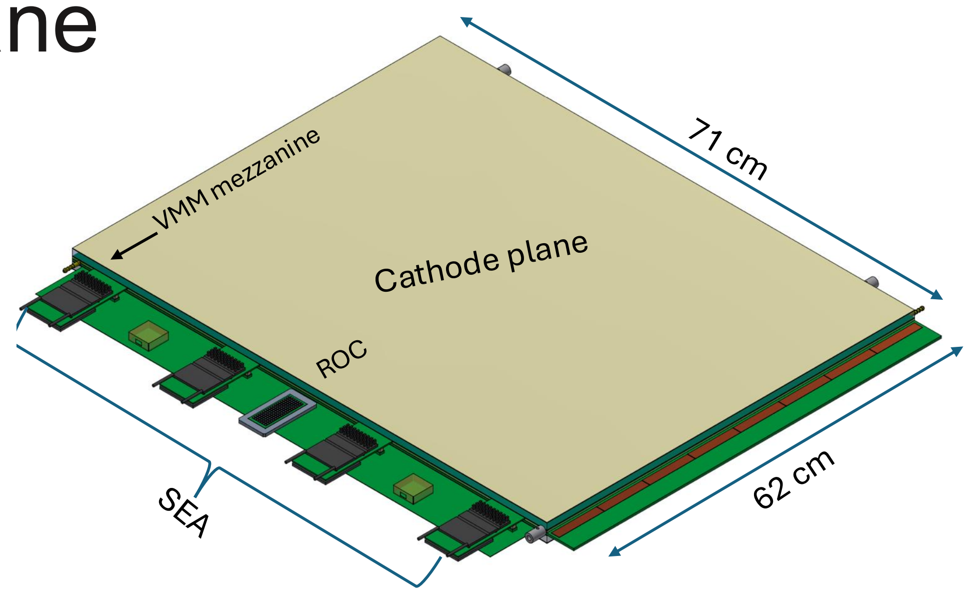
- **MWPC** for stations **MS1−MS5** (max. rate **~2 kHz/cm²**)
- **MS0**: rate at the limit, **GEM-** like option to be considered

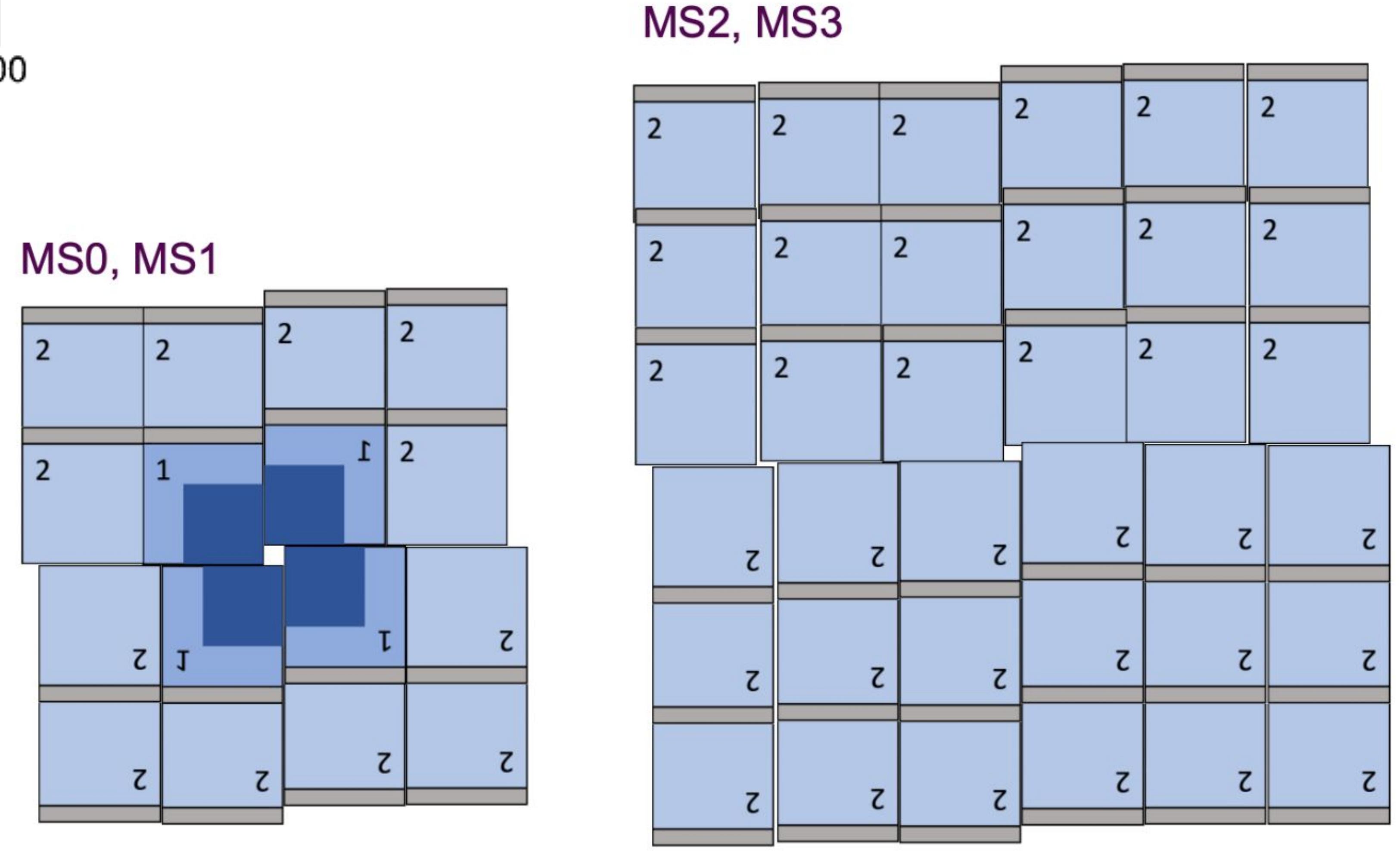




Tracking stations realised with modular structure and varying strip pitch

- **Ar/CO2 (70/30)** gas volume with **6mm** thickness
- **100μm** spatial resolution in bending plane
- **< 3−4% X_0** material budget





The dipole magnet MNP33

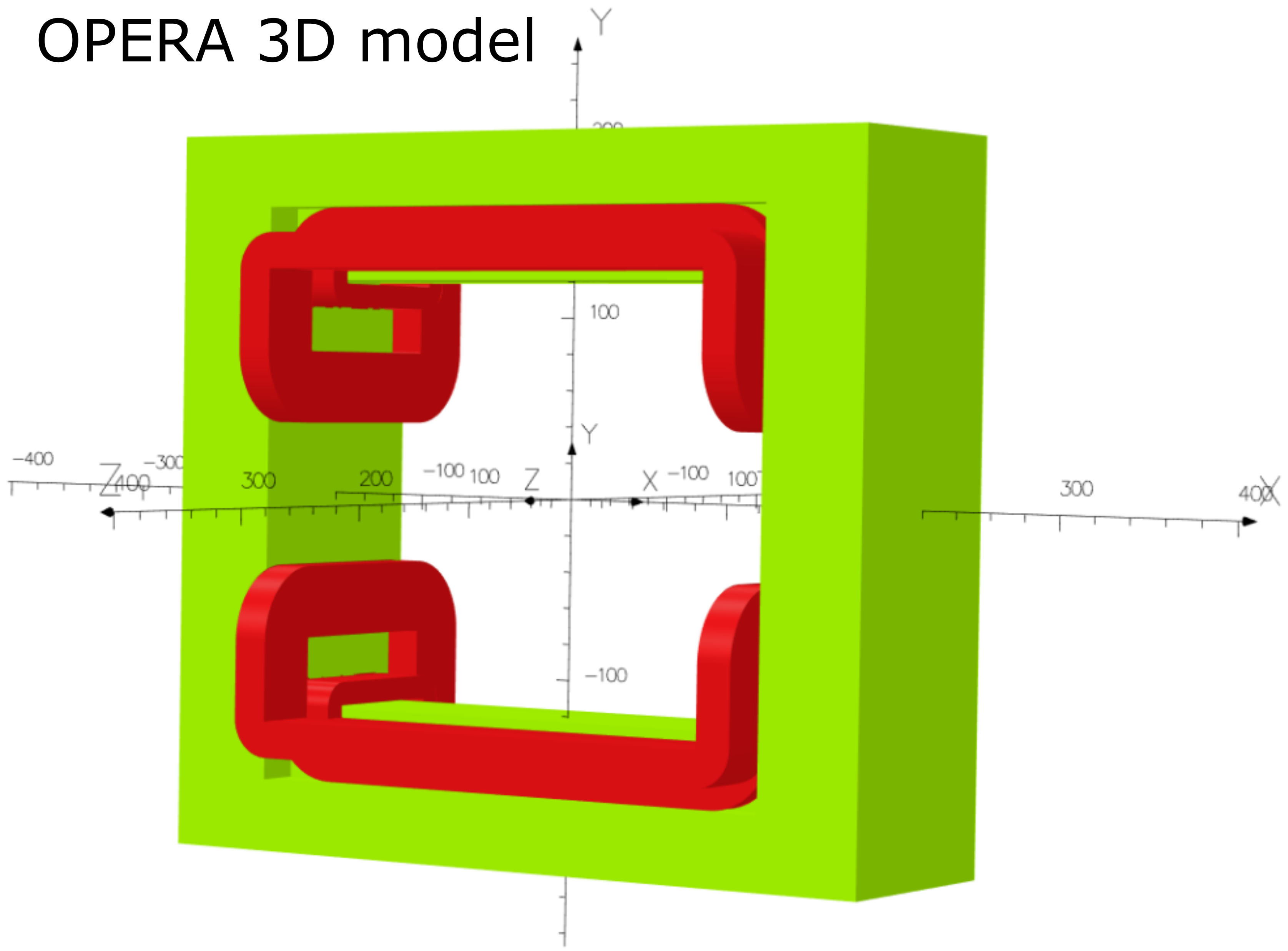
The **NA62** experiment: ultra rare kaon decays $K^+ \to \pi^+ \nu\nu$ [1], completes its program in 2026

🧲 Main dipole magnet **MNP33** will be available after that!

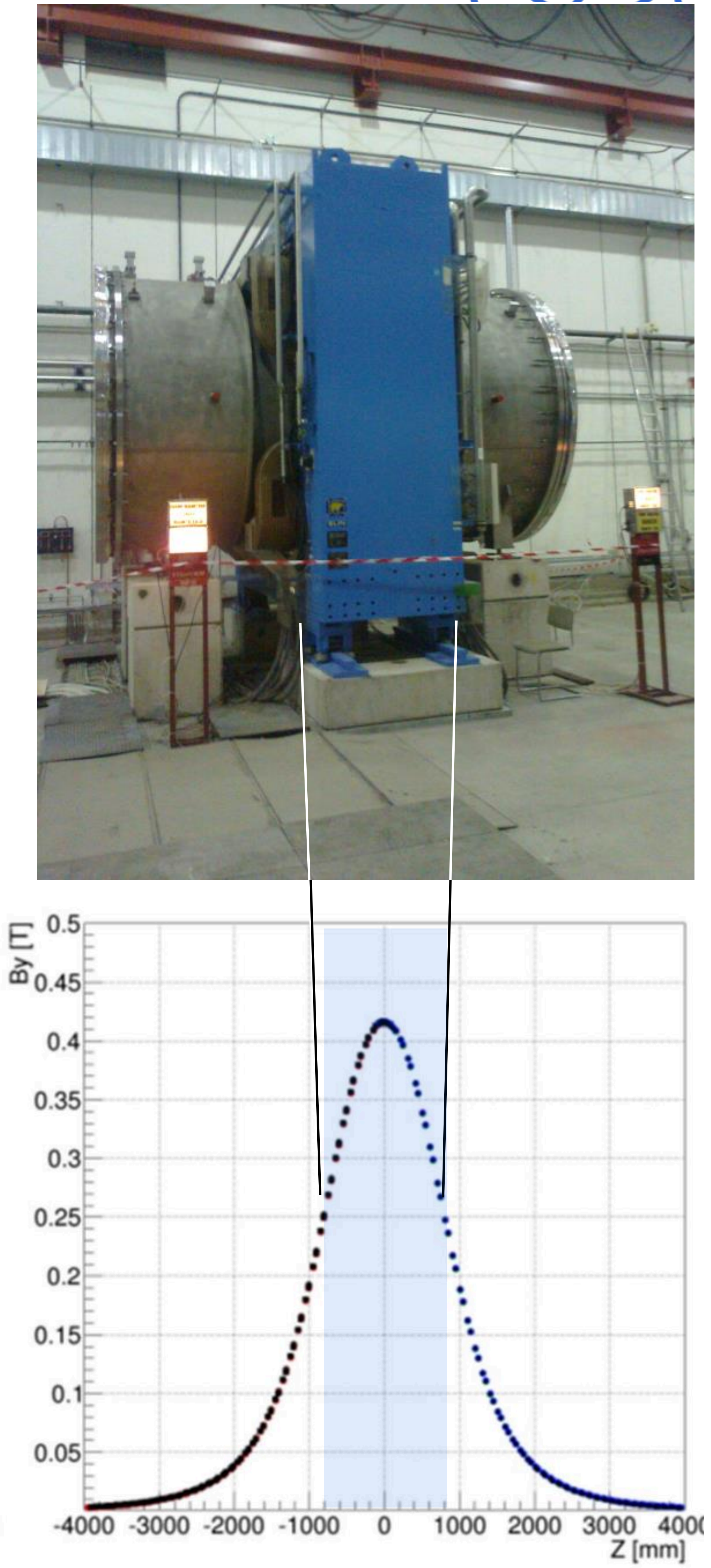
Pros and cons w.r.t. toroidal magnet in the LoI [2]

Pros	Contras
Larger acceptance for soft muons	Need powering two coils
Compactness	Slightly lower ∫Bdl
Essentially no price tag!	

OPERA 3D model



- Gap width: **2.4m × 2.4m**
- **∫Bdl = 0.864 Tm**



💰 *Cost reduction of NA60+/DiCE project by nearly **3M CHF***

[1] NA62, *JHEP* 02 (2025) 191
[2] arXiv:2212.14452

3. Expected performance and physics results

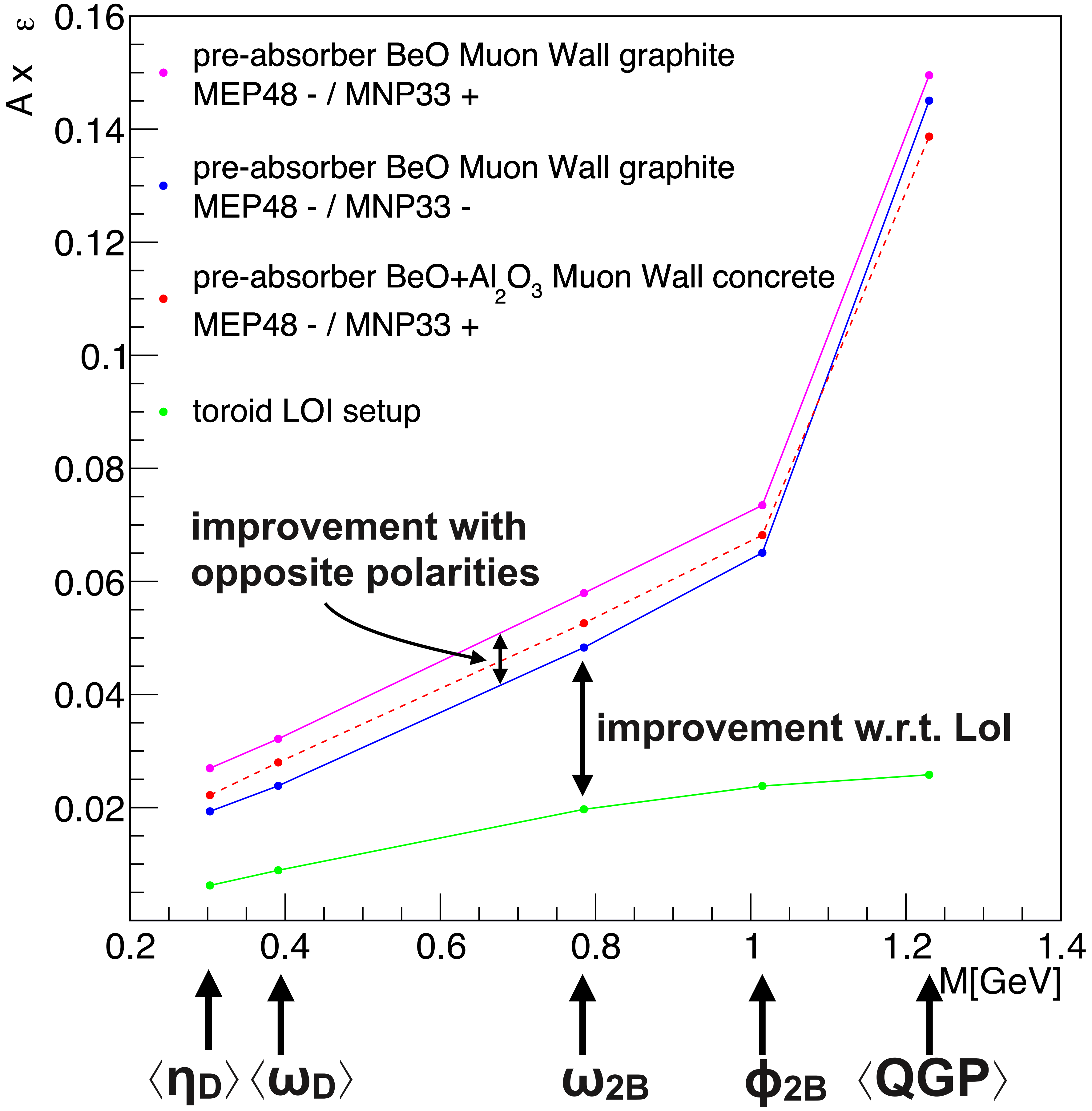
Detector performance: dimuon reconstruction

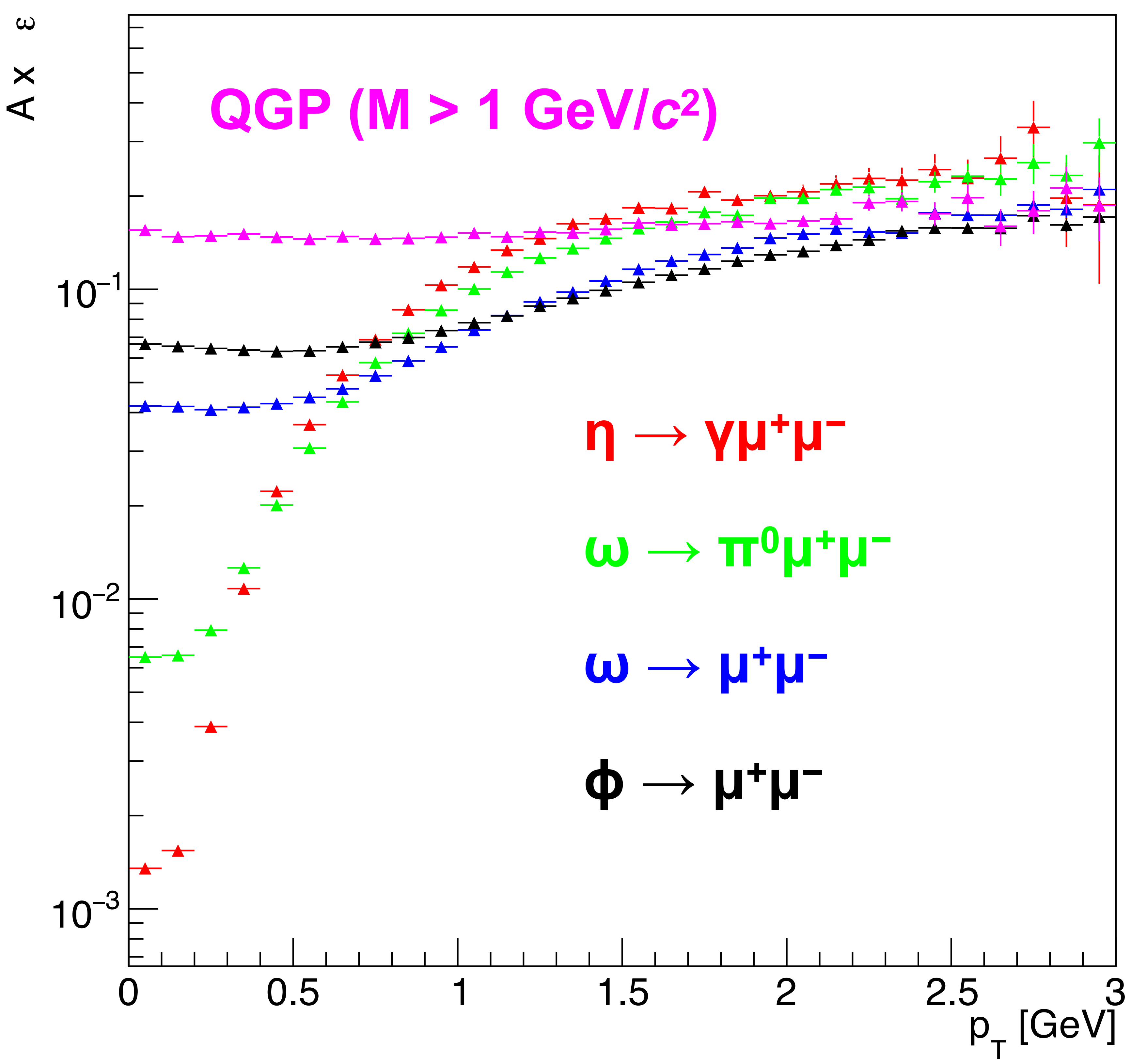
Detector efficiency extends down to low mass and pair p_T

Overall a significant improvement with dipole magnet w.r.t. **toroid from the LoI**

- Better performance with **opposite polarities** for MEP48 / MNP33
- *A factor **~10** better than the **NA60** experiment!*

Acceptance × efficiency vs mass and p_T





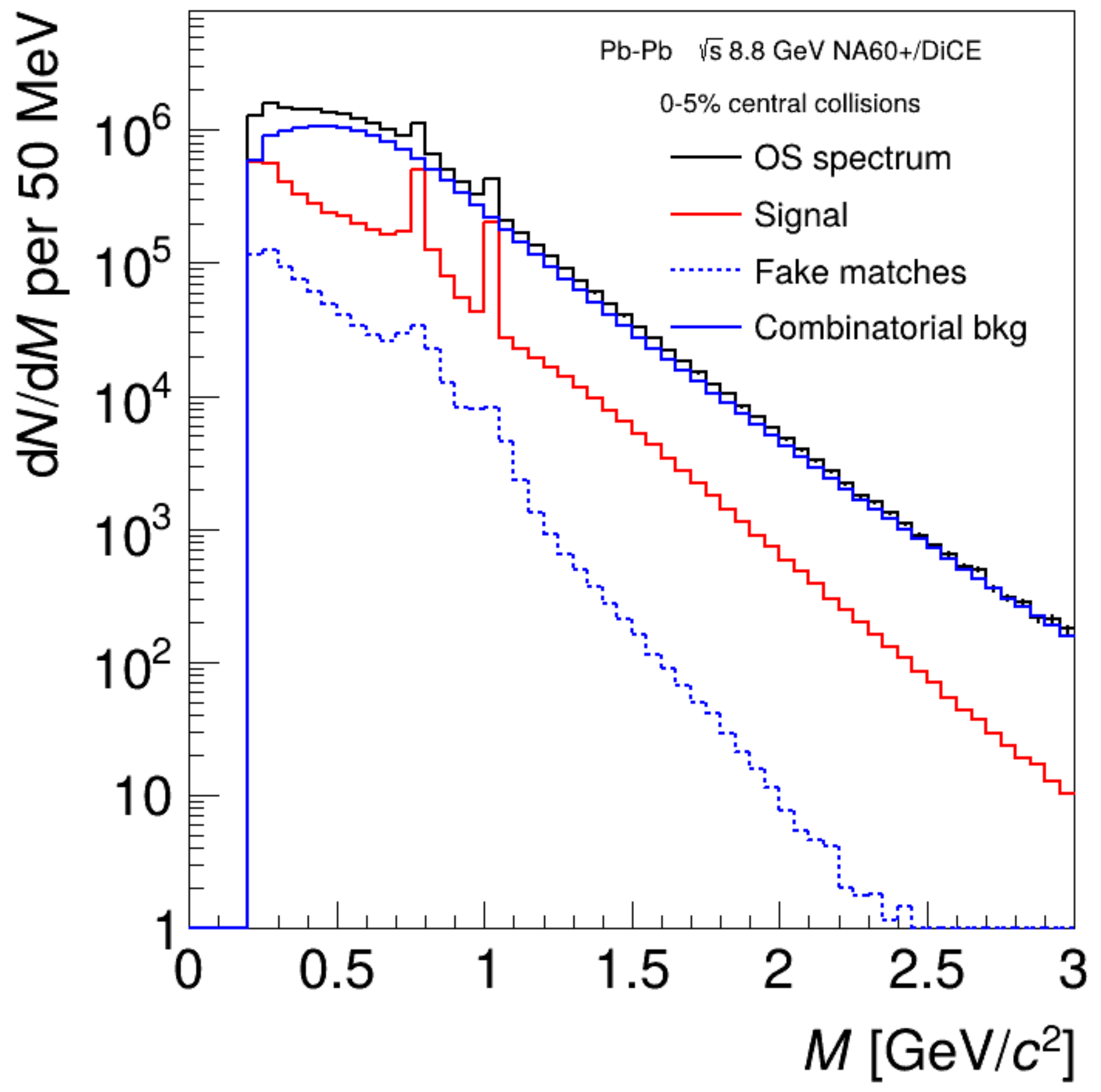
Thermal radiation from QGP

Thermal dimuon yield: **HG** via ρ at low mass, **QGP** radiation up to ***M* = 2.5−3.0 GeV/*c*²**

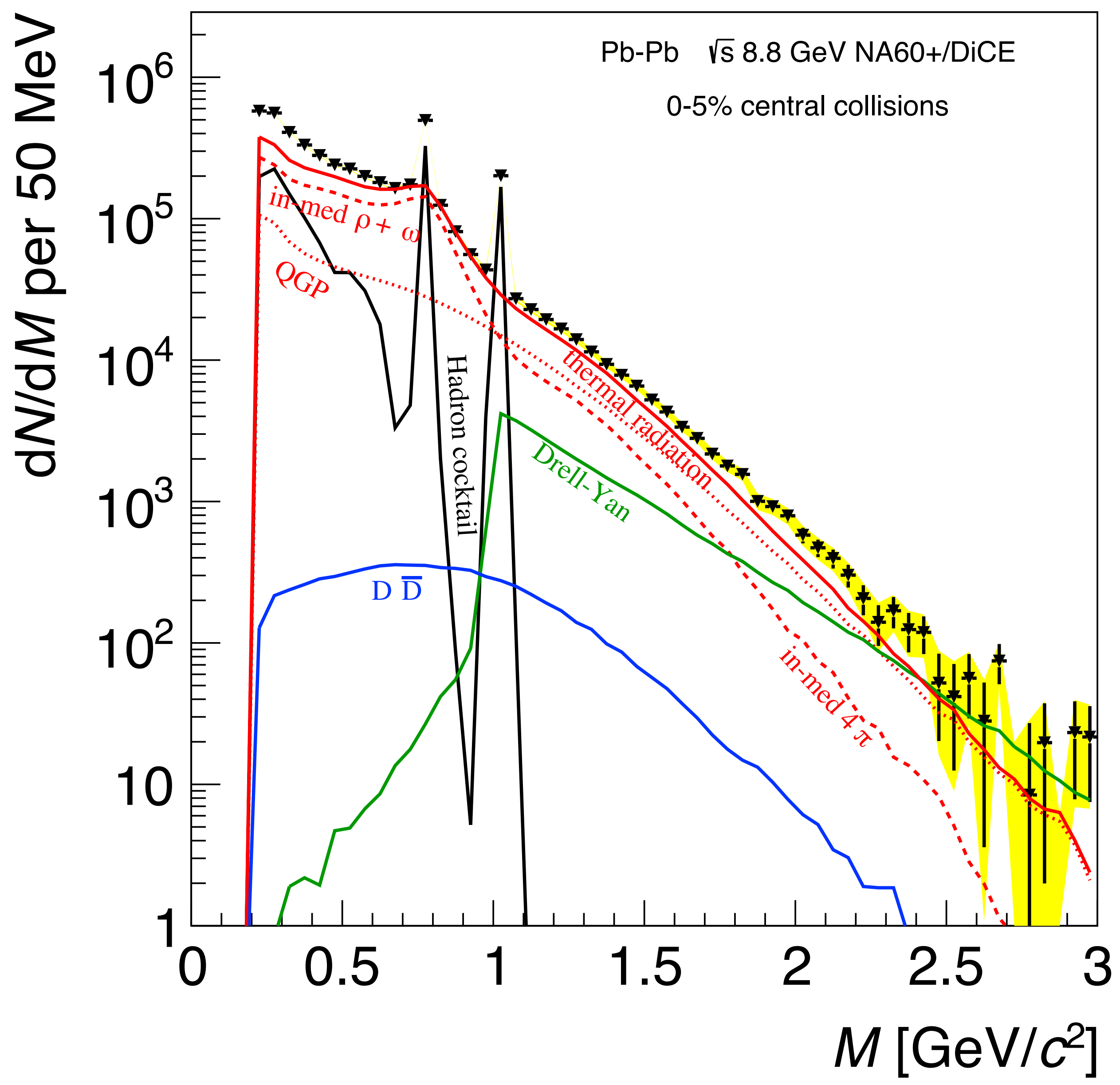
Hadronic cocktail derived from **NA60** Genesis simulations 🍸

- Pythia simulations for **Drell−Yan** (to be measured in pA) and **open charm** (small to negligible)

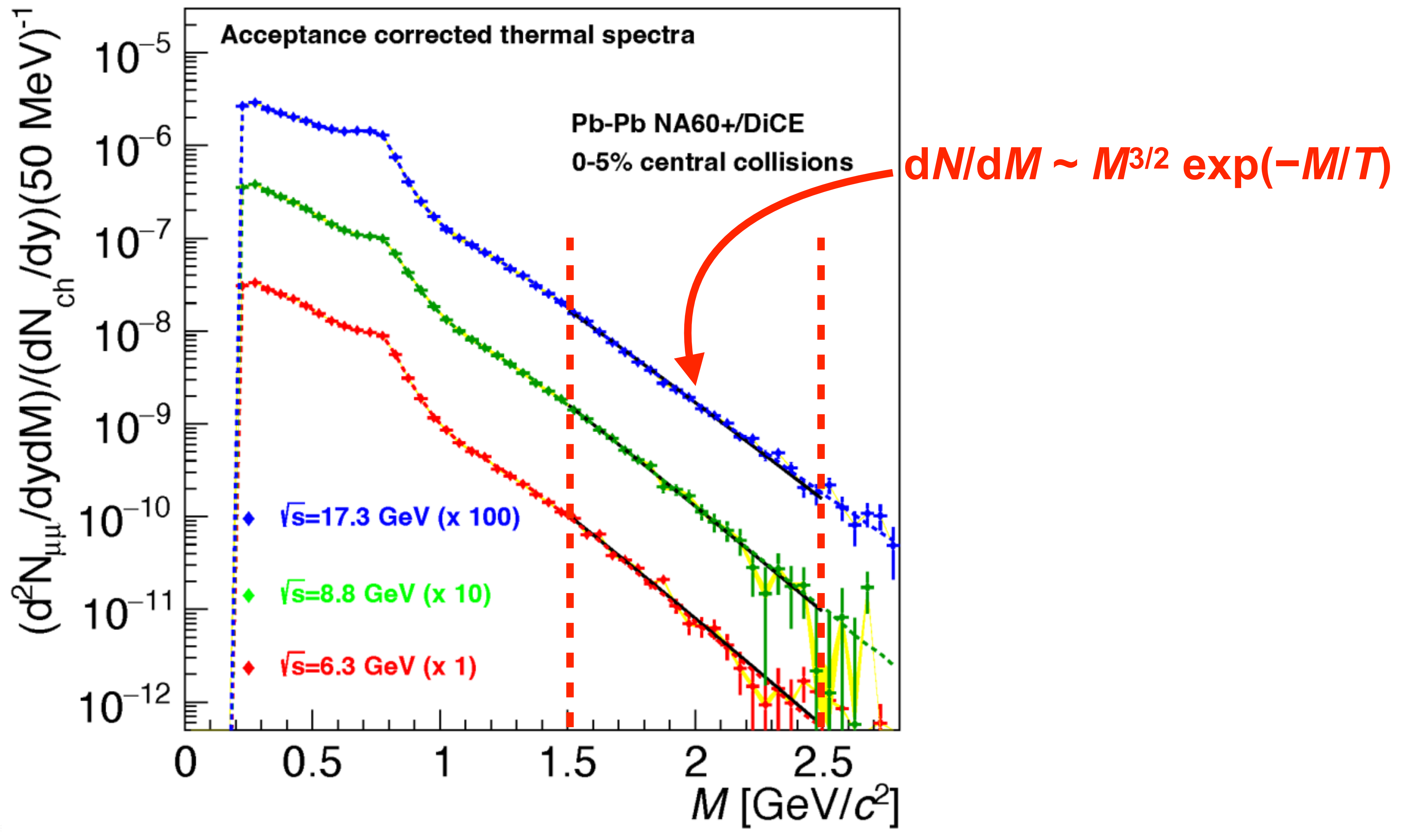
ULS, signal and background



Signal compared to cocktail

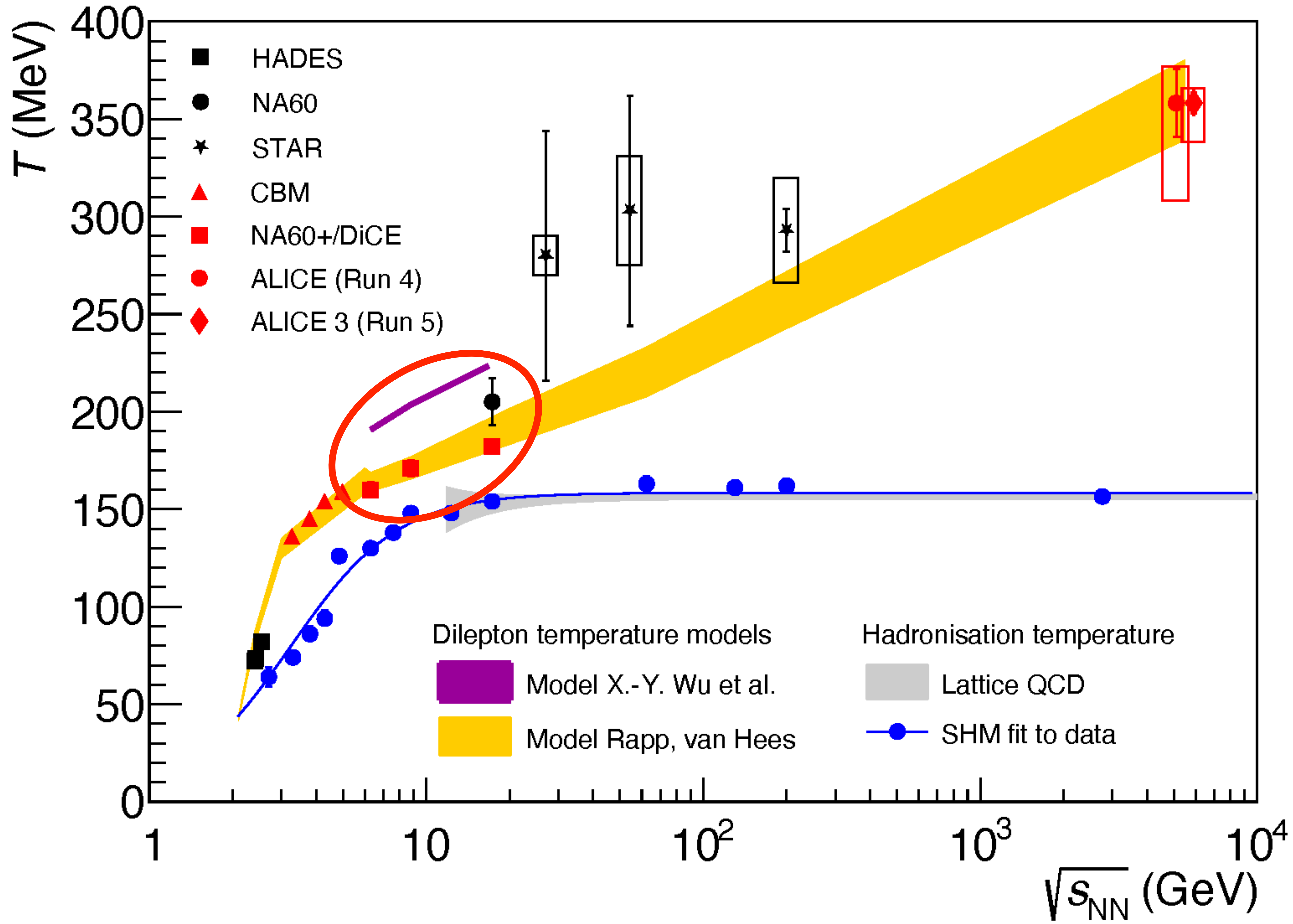


Thermal spectra and fits to 1.5<*M*<2.5 GeV/*c*²



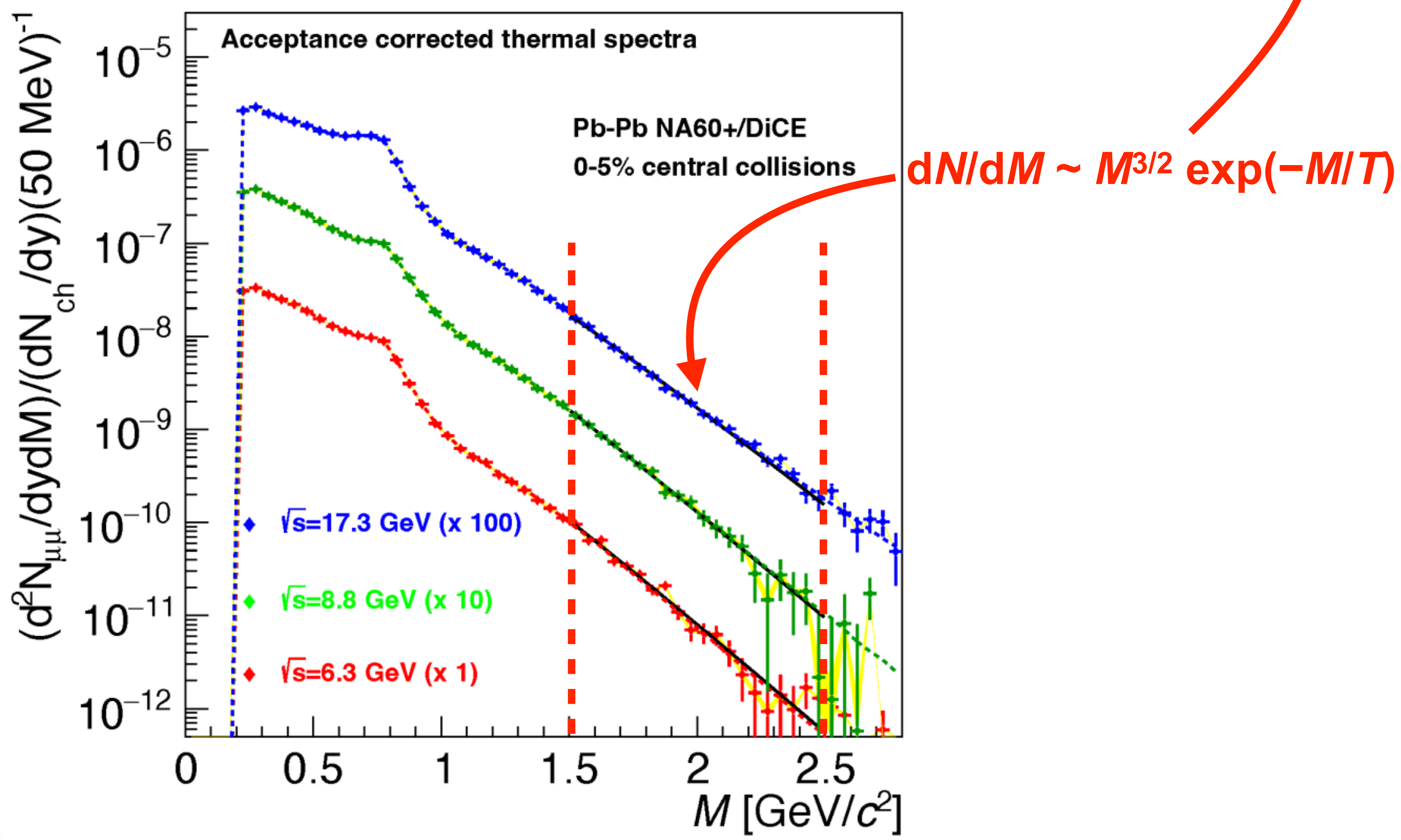
🌡 *Precise measurement of **T** via the fit to thermal radiation continuum in **1.5 < M < 2.5 GeV/c²***

Thermal radiation from QGP: caloric curve



	$\sqrt{s_{NN}}$ (GeV)	Thermal pairs	T_{slope} (MeV)
2 months →	6.3	6.05×10^6	$160 \pm 3 \pm 1$
1 month →	8.8	5.64×10^6	$171 \pm 4 \pm 1$
1 month →	17.3	5.65×10^6	$182 \pm 2 \pm 1$

Thermal spectra and fits to 1.5<*M*<2.5 GeV/*c*²



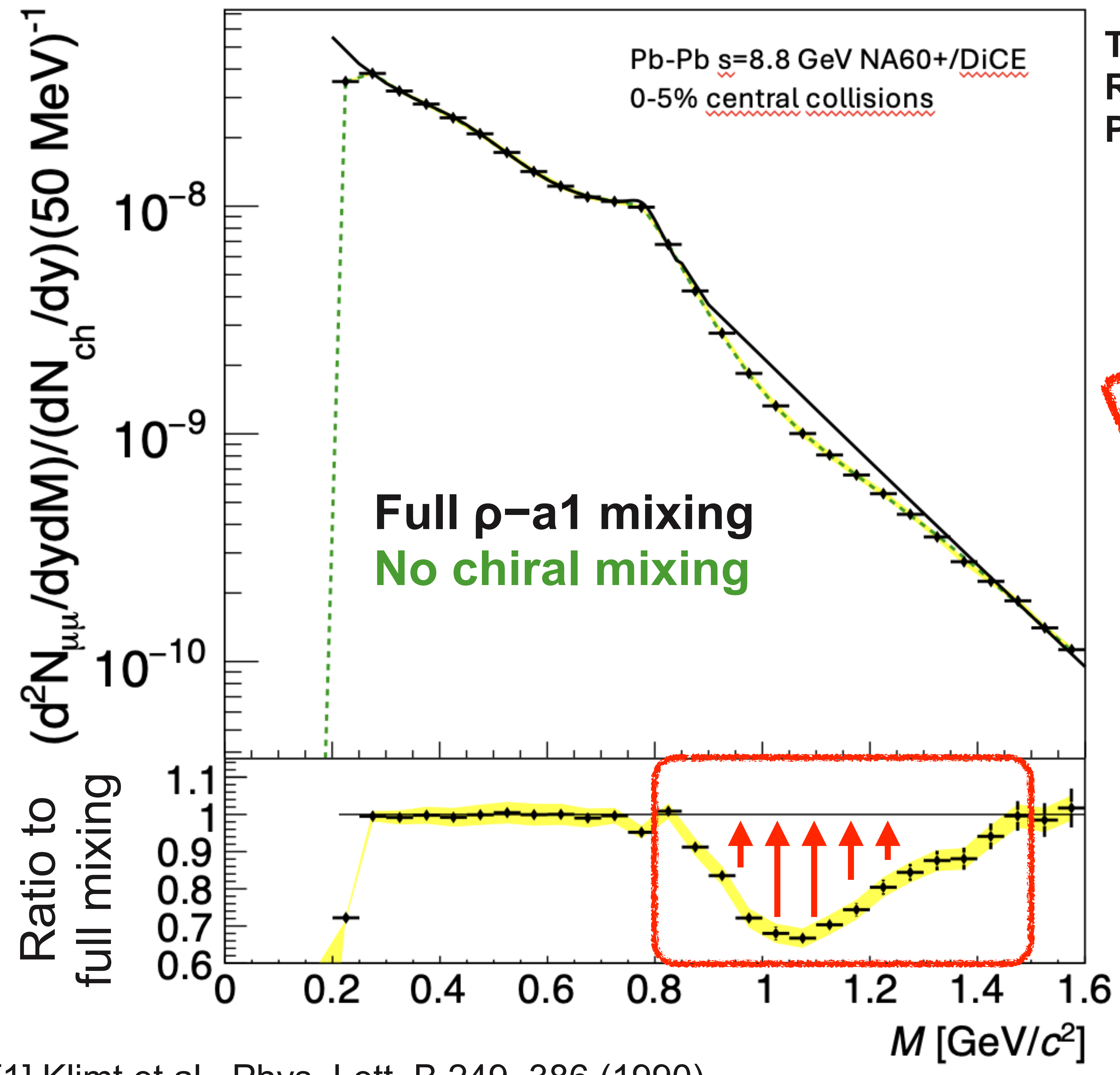
🌡️ *Precise measurement of **T** via the fit to thermal radiation continuum in **1.5 < M < 2.5 GeV/c²***

- **~2% unc.** on the evaluation of ***T*** from **1−2 months** of data taking (**~O(10¹²)** ions on target)
- Accurate mapping of ***T* vs √s_{NN}**, sensitivity to possible flattening of caloric curve (→1st order phase transition)

Chiral symmetry restoration via ρ−a1 mixing

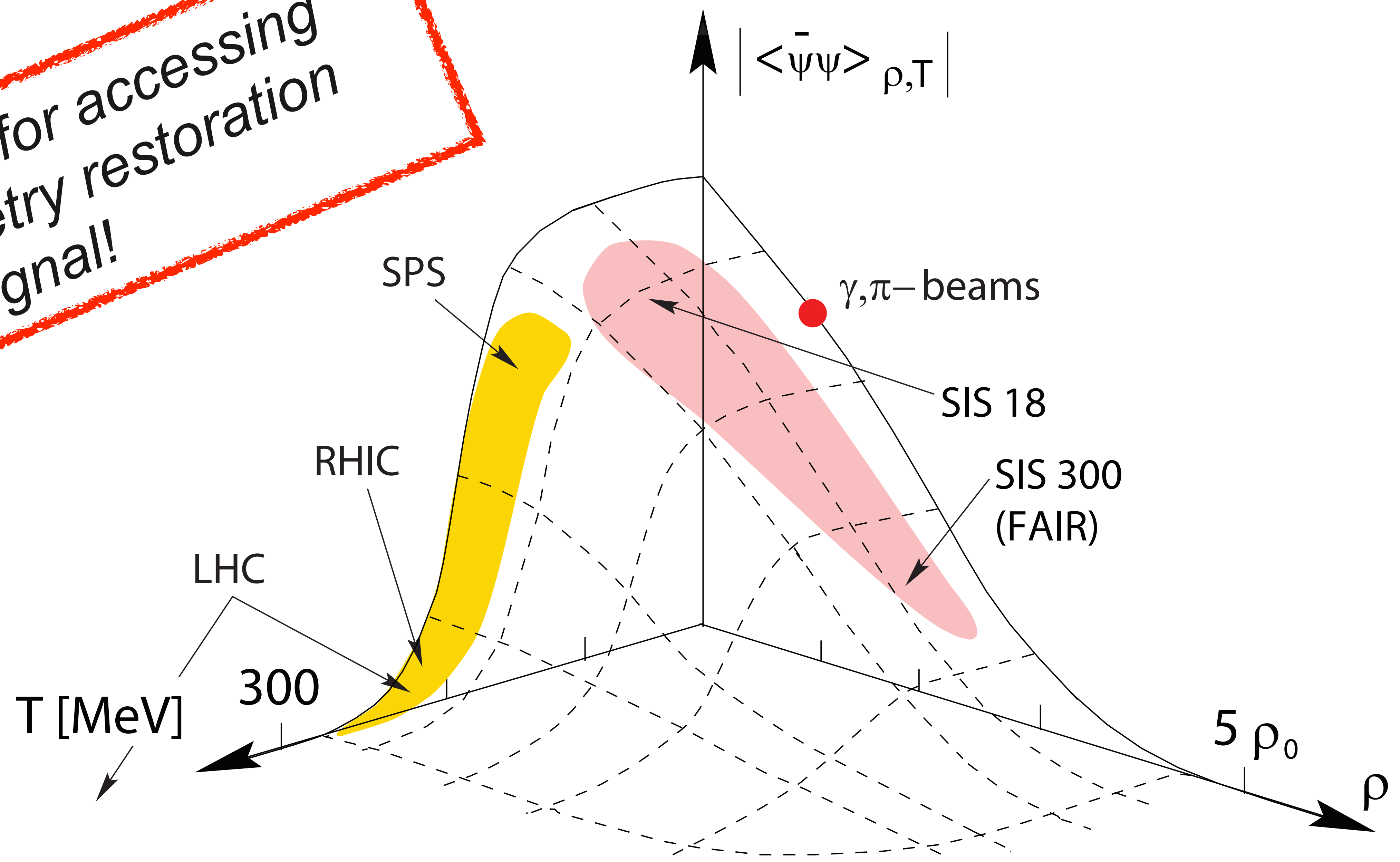
Full **ρ−a1 mixing** → **20−30% enhancement** is expected in the region of **0.8 < *M* < 1.5 GeV/c²**
- *NA60+/DiCE can clearly detect a signal of* ***ρ−a1 mixing****!*

Thermal spectrum with/without chiral mixing



Theoretical predictions:
R. Rapp, H. van Hees,
PLB 753 (2016): 586-590

Breakthrough for accessing chiral symmetry restoration signal!



Chiral condensate vs temperature and density [1]

[1] Klimt et al., Phys. Lett. B 249, 386 (1990)

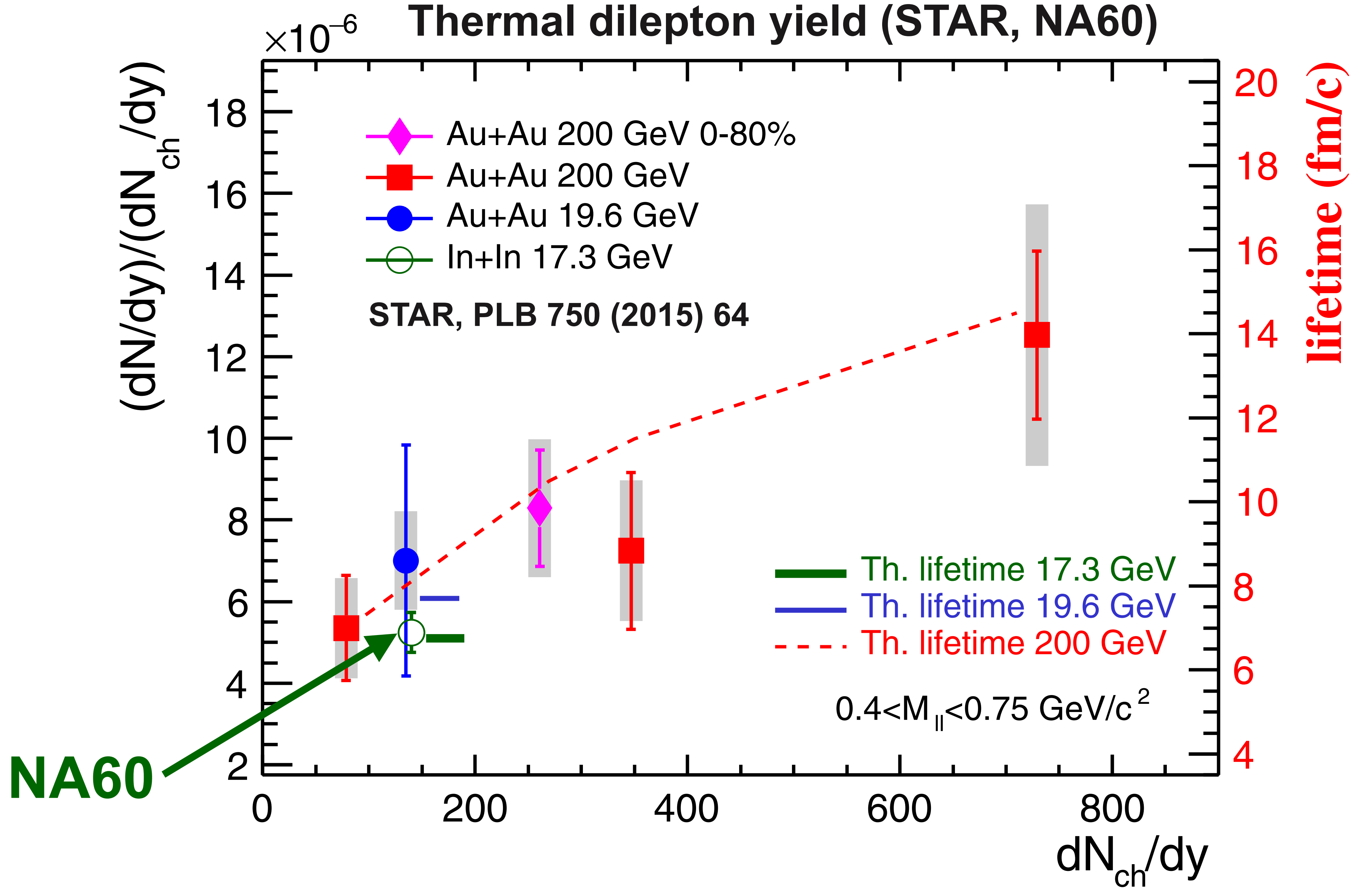
Fireball lifetime

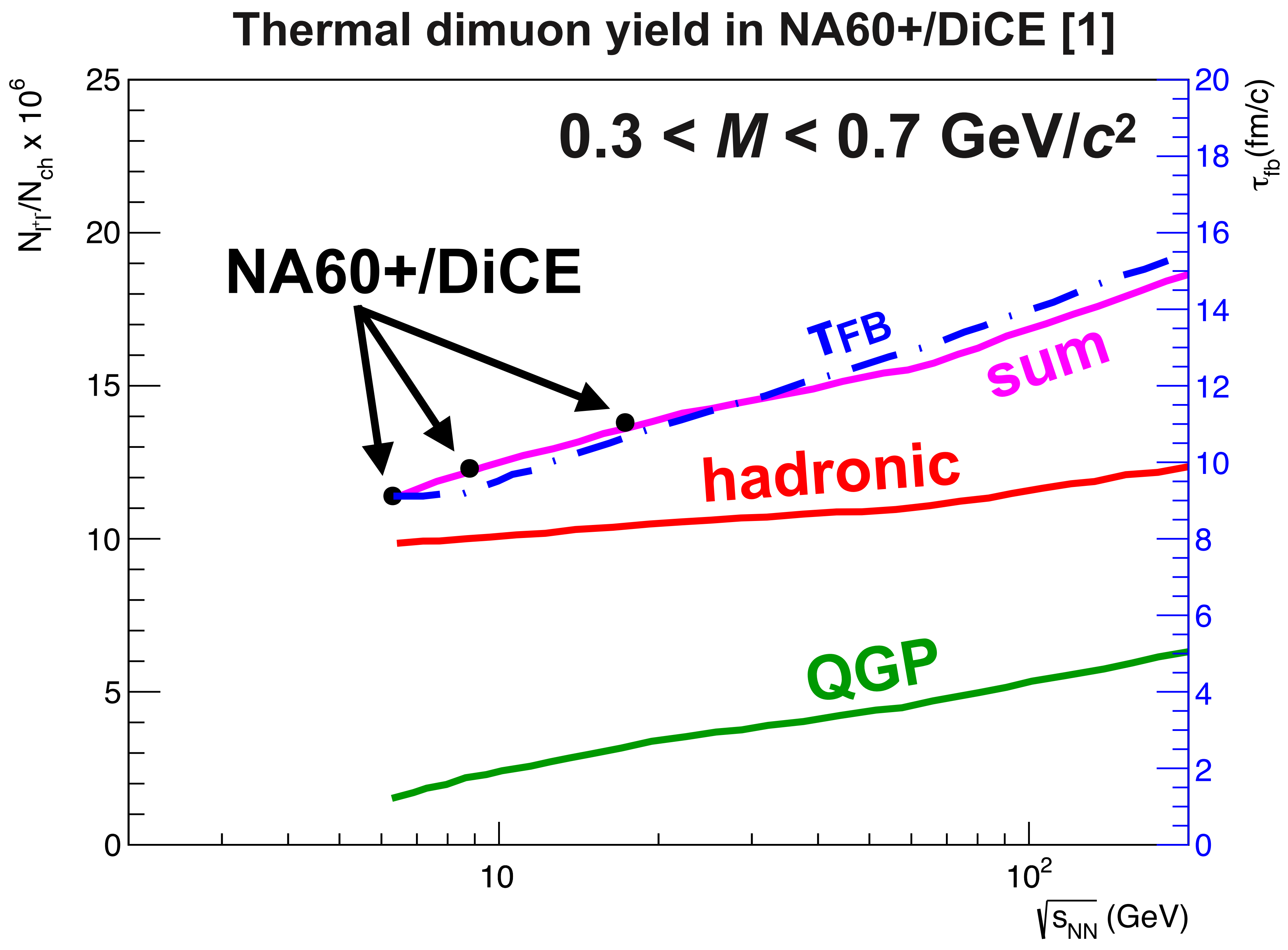
Yield of thermal dileptons in **(0.3, 0.7) GeV**: sensitive to all emission stages

⏱️ Tracking of total fireball lifetime with a **~10% accuracy** or better

NA60 measurement in **In−In at √s_{NN} = 17.3 GeV: τ_{FB} = 8 ± 1 fm/c**

Excellent accuracy is expected for NA60+/DiCE!





[1] R. Rapp et al., PLB753 (2016) 586

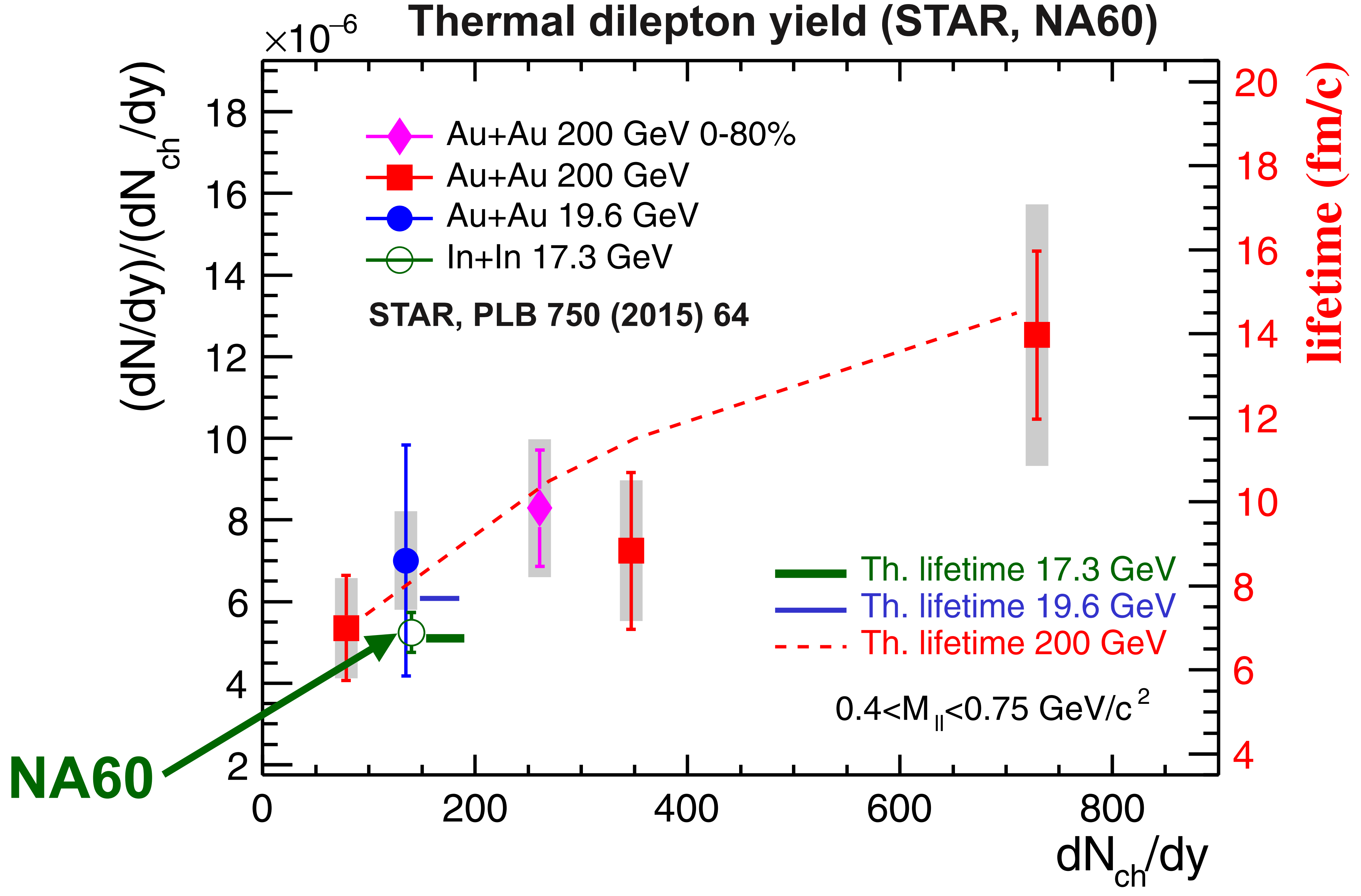
Fireball lifetime

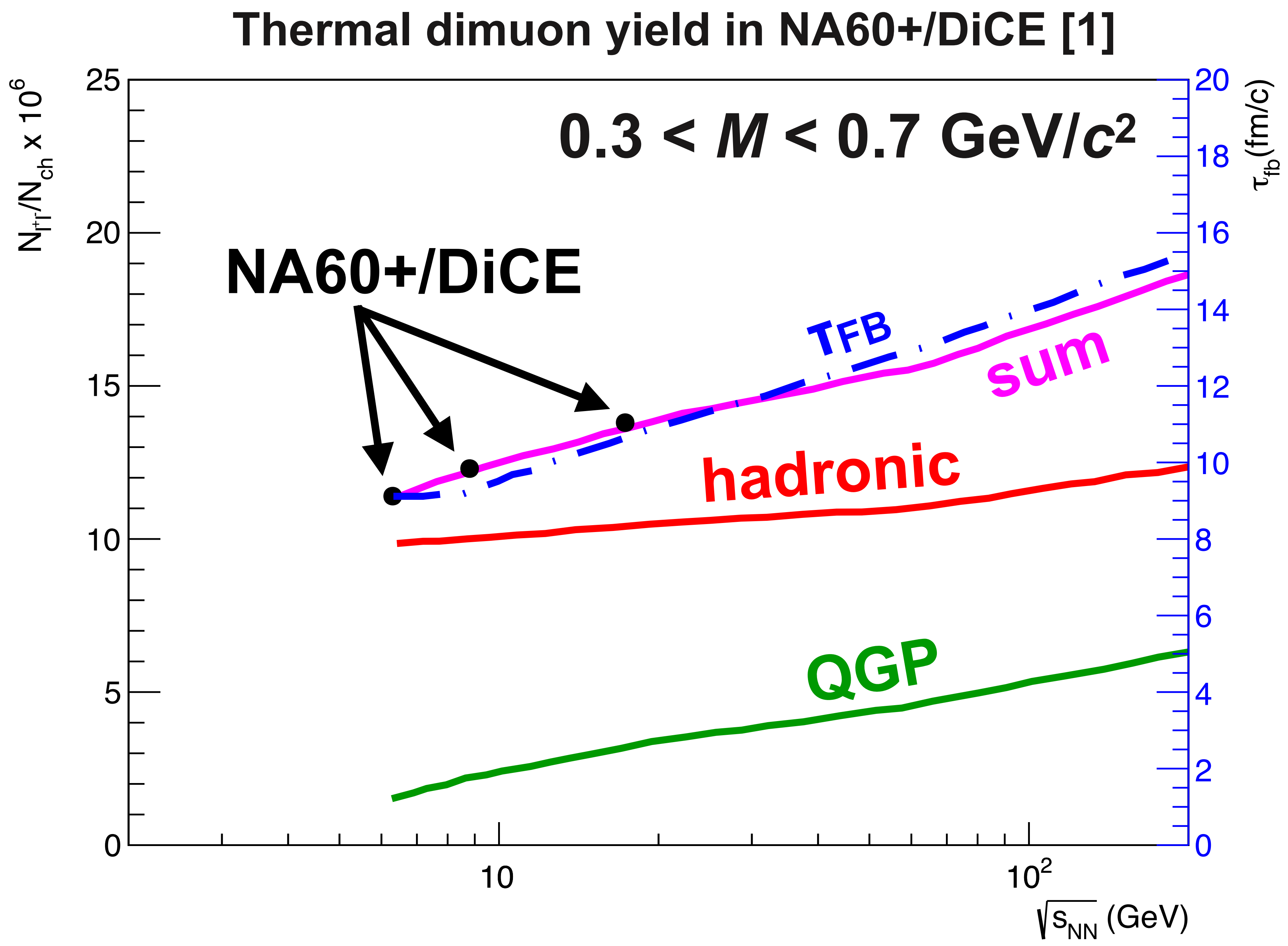
Yield of thermal dileptons in **(0.3, 0.7) GeV**: sensitive to all emission stages

⏱️ Tracking of total fireball lifetime with a **~10% accuracy** or better

NA60 measurement in **In−In at $\sqrt{s_{NN}}$ = 17.3 GeV: τ_{FB} = 8 ± 1 fm/c**

Excellent accuracy is expected for NA60+/DiCE!





🤔 *"Anomalous" variations around onset of deconfinement?*

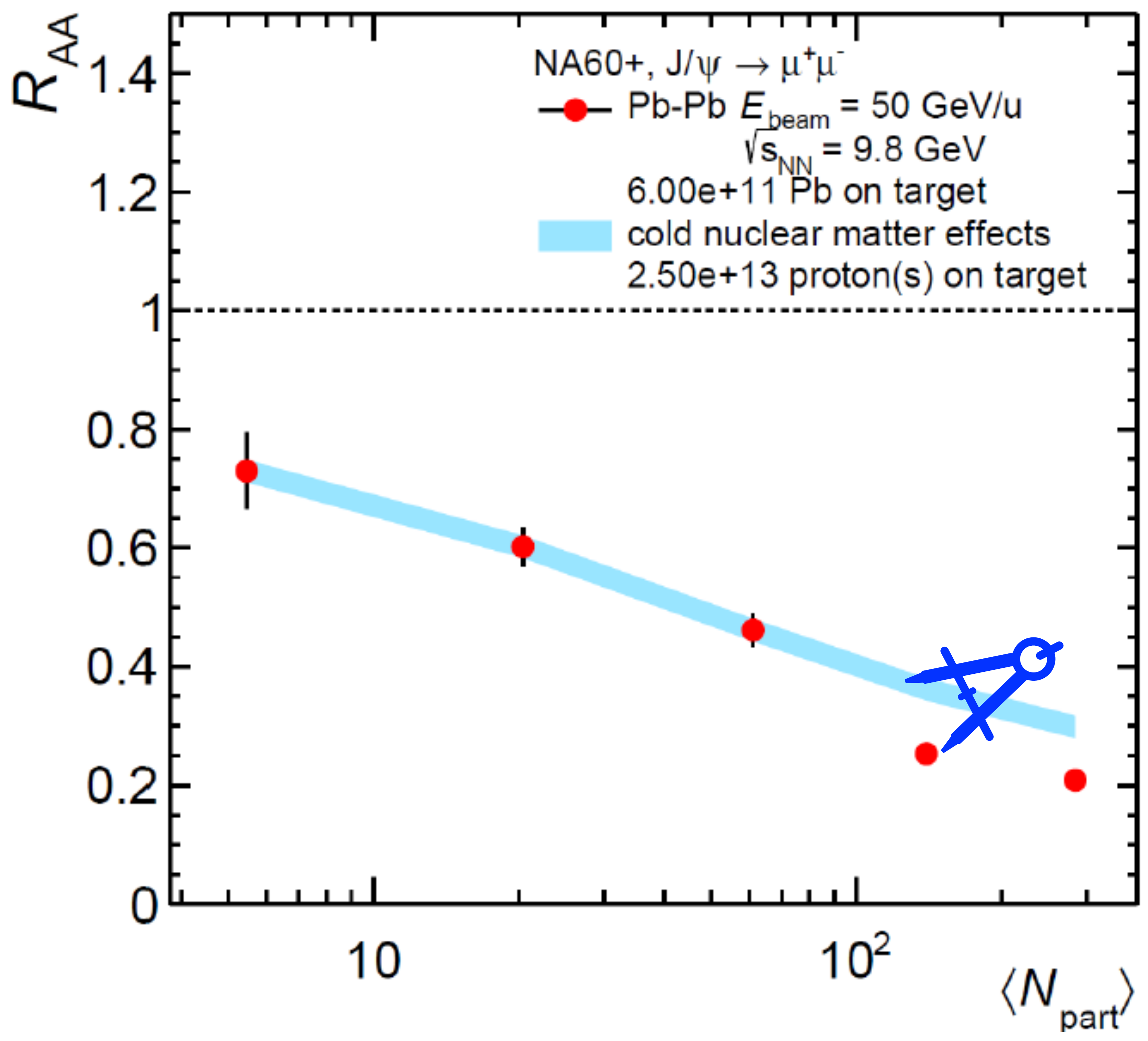
- First order phase transition → small pressure gradients in the system stall the fireball expansion
- Can lead to a longer fireball lifetime due to the burning of latent heat

[1] R. Rapp et al., PLB753 (2016) 586

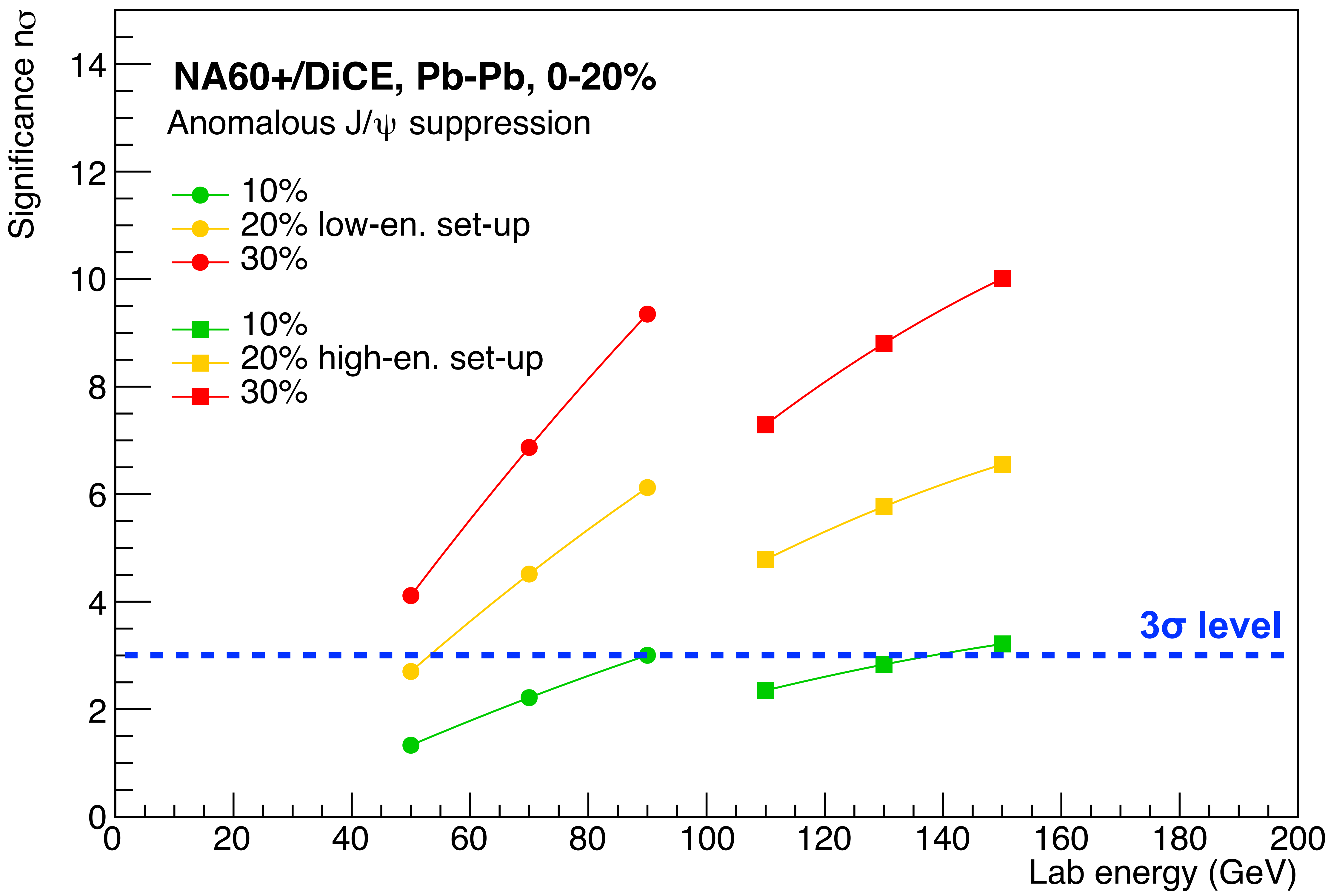
Quarkonium and onset of deconfinement

- Assume **30%** suppression in **0−20%** and **20-40%** centralities, **1 month** of **Pb−Pb** data taking
- **CNM effects:** from **p−Be, p−Cu, p−Pb** data
- **R_{AA}** calculations: extrapolate A-dependence to **pp**

J/ψ R_{AA} vs N_{part} with NA60+/DiCE



Significance of anomalous suppression observation



Suppression beyond CNM effects should be well measurable by NA60+/DiCE!

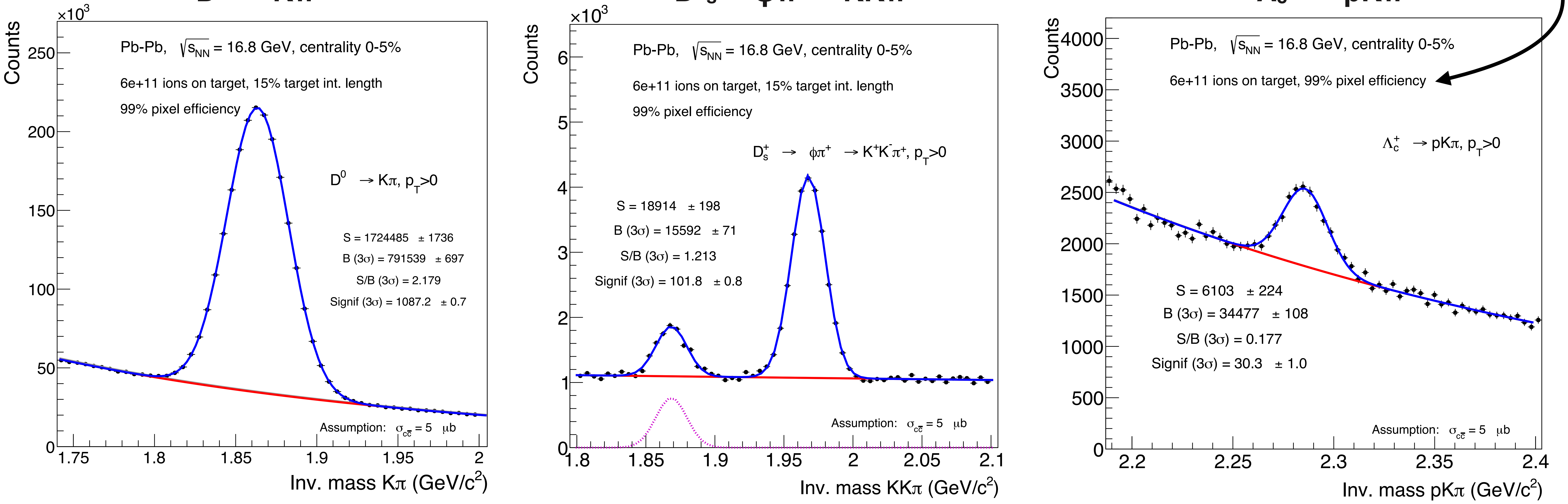
Open charm spectroscopy

Reconstruct decay products in the vertex spectrometer

• Geometrical selections on the displaced decay-vertex topology **(cτ ~ 60−300 μm)** to enhance *S/B*

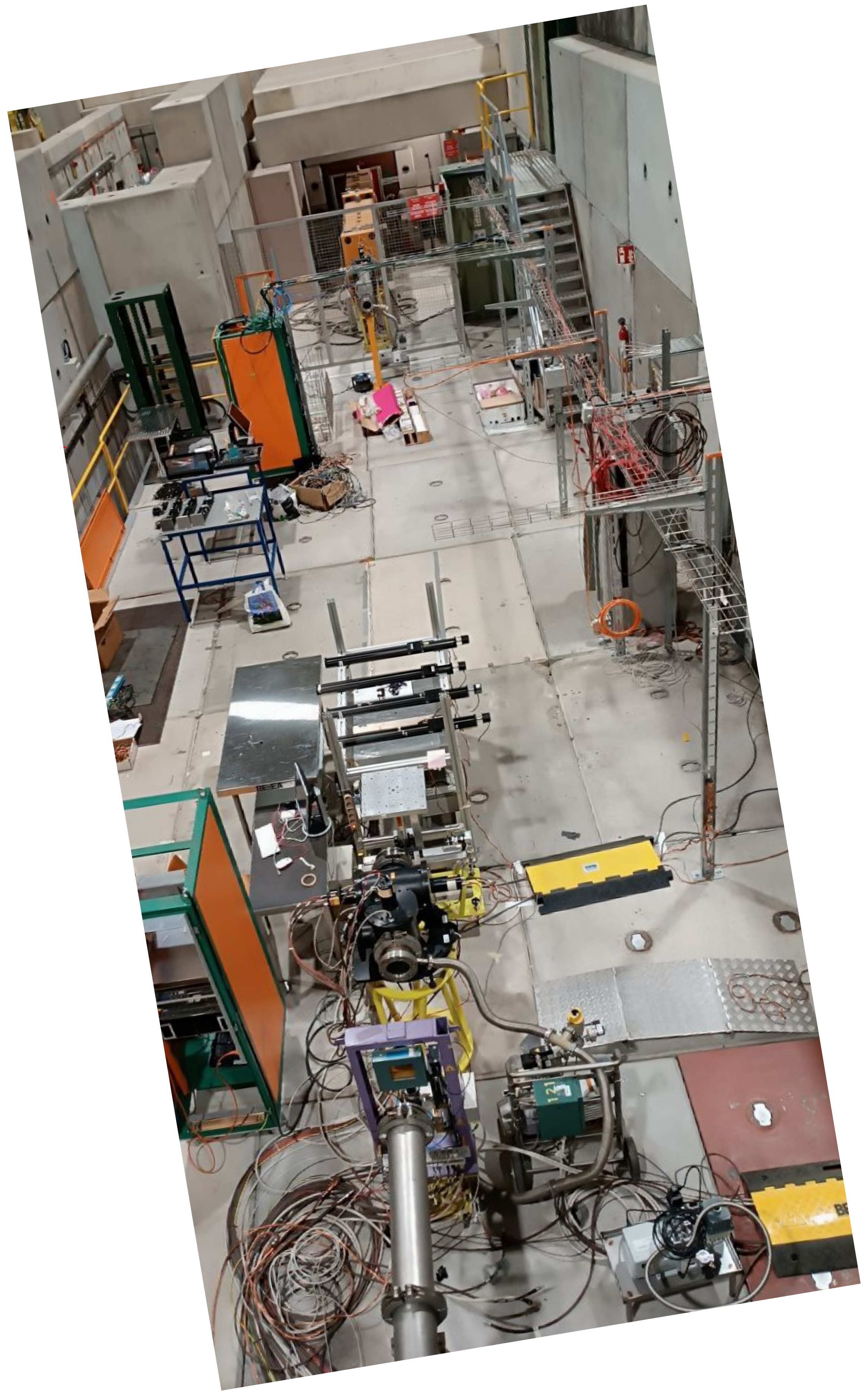
1 month of data taking

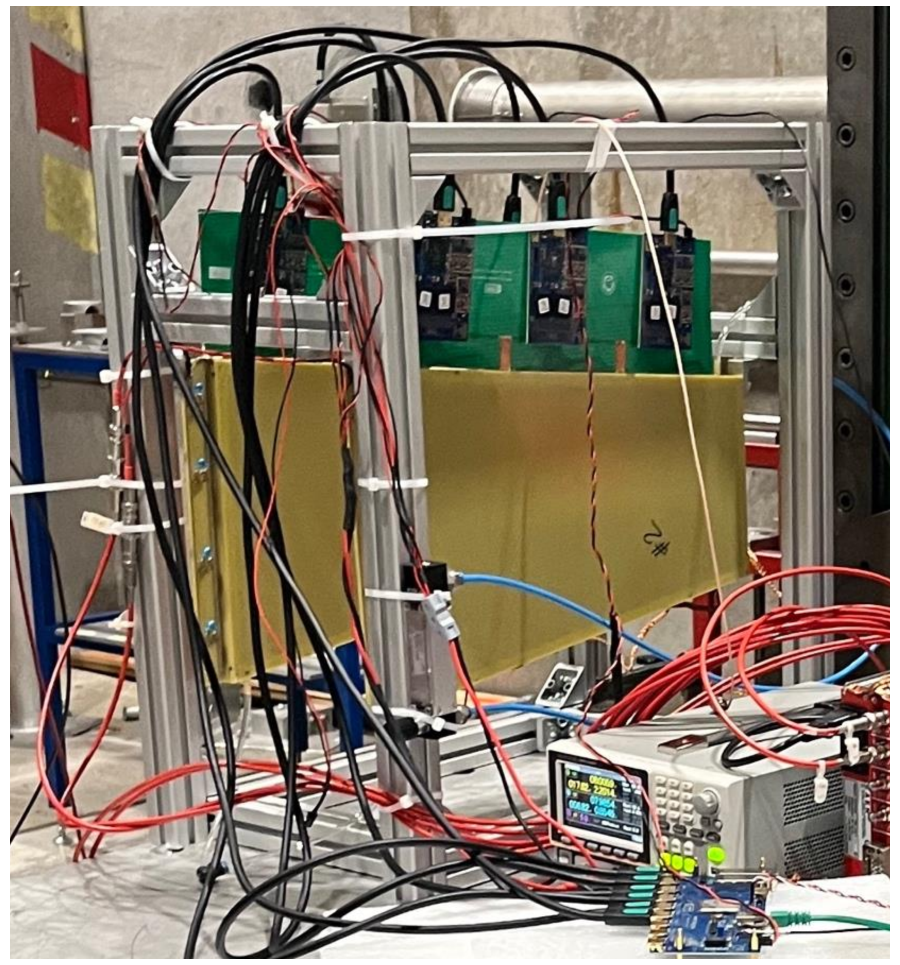
$D^0 \rightarrow K\pi$ **$D^+_s \rightarrow \phi\pi \rightarrow KK\pi$** **$\Lambda_c^+ \rightarrow pK\pi$**



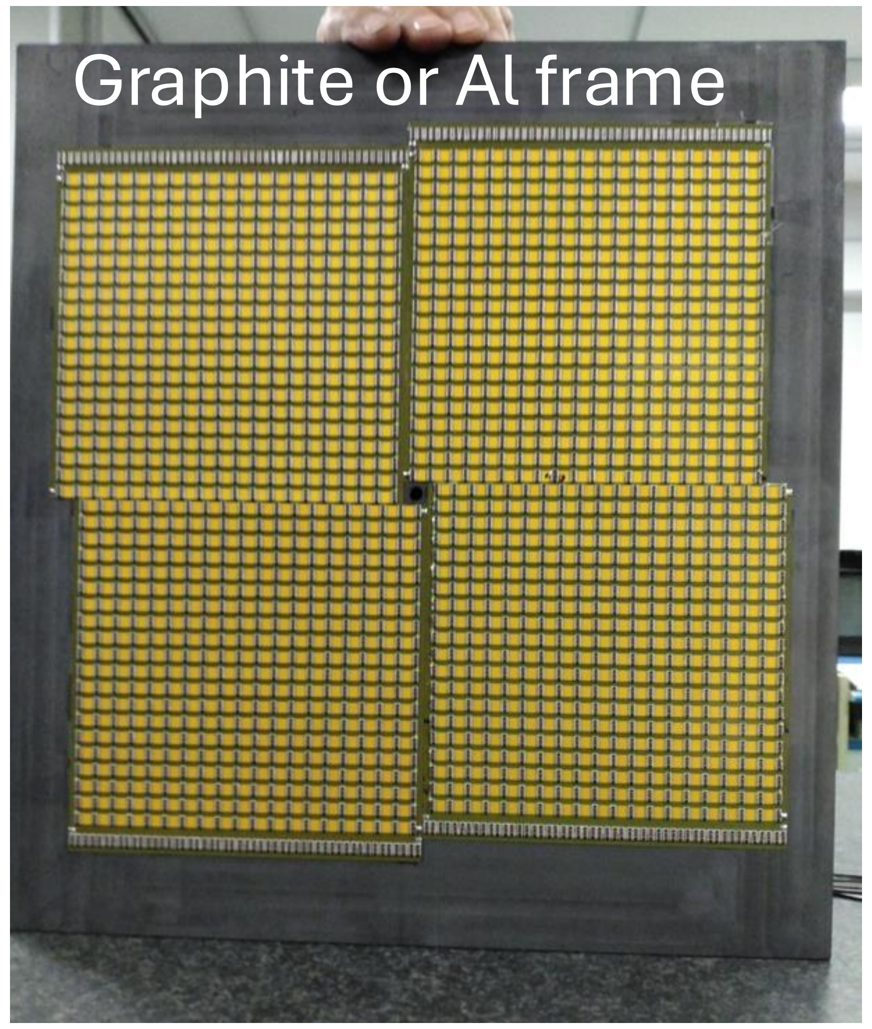
*NA60+/DiCE will allow for multi-differential studies of **HF** hadron **yield** and **v_2** vs **p_T**, **rapidity** and **centrality***

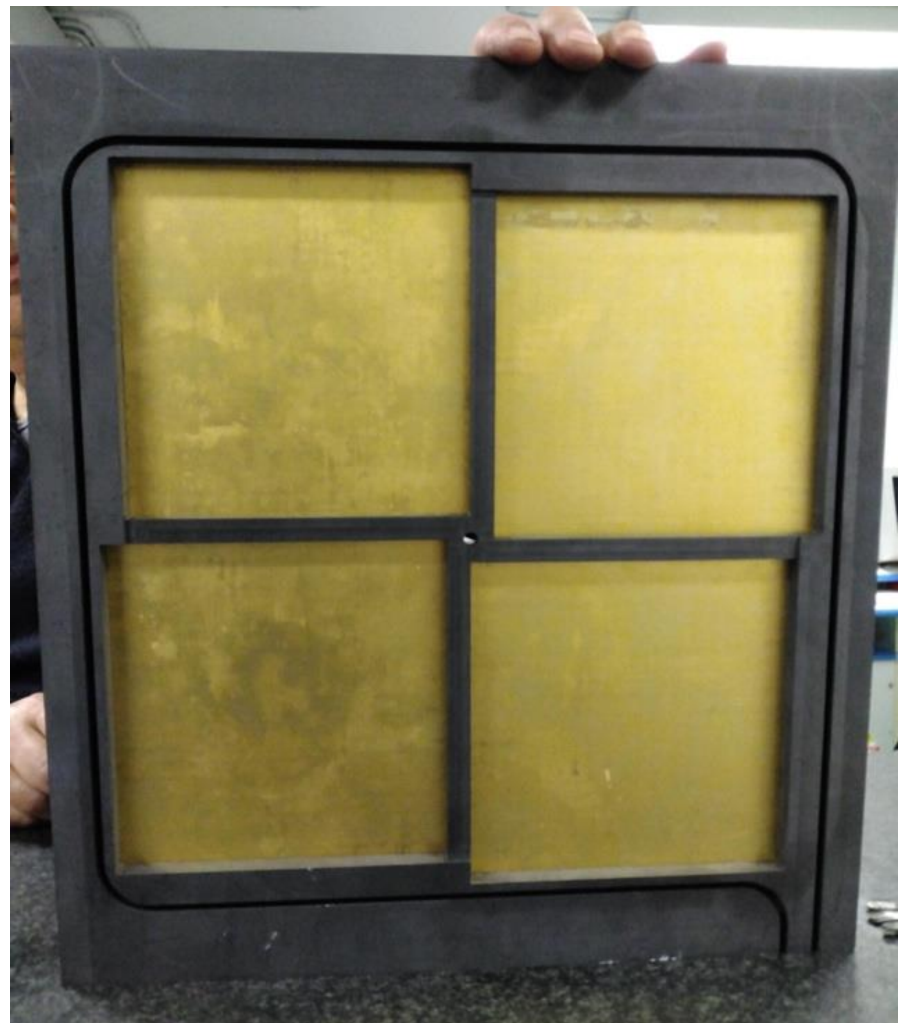
Charm cross section measurements: **D^0, D^+, D^+_s, Λ_c**, *possibly* **$\Xi_c^{0,+}$**

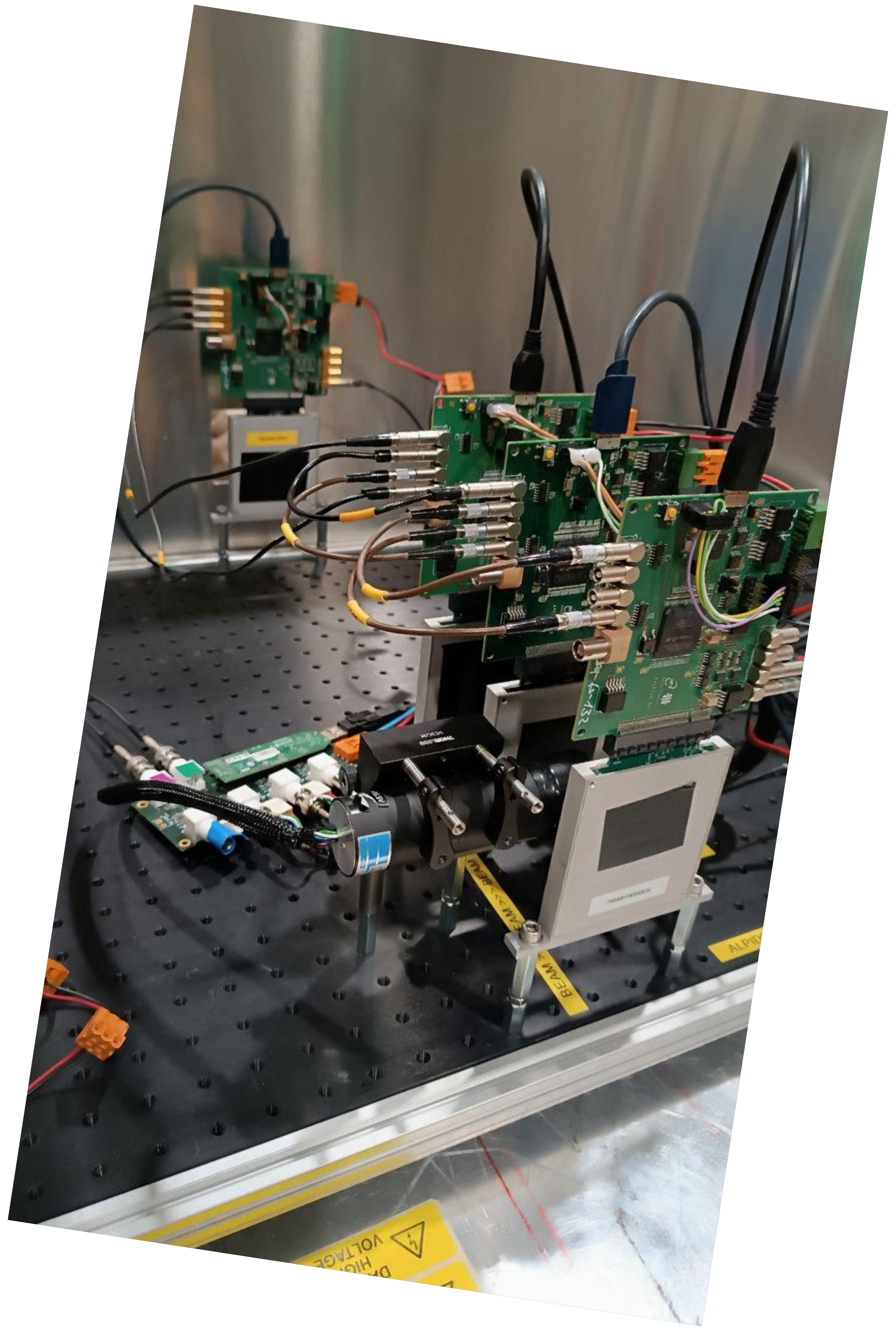




4. Status and further plans





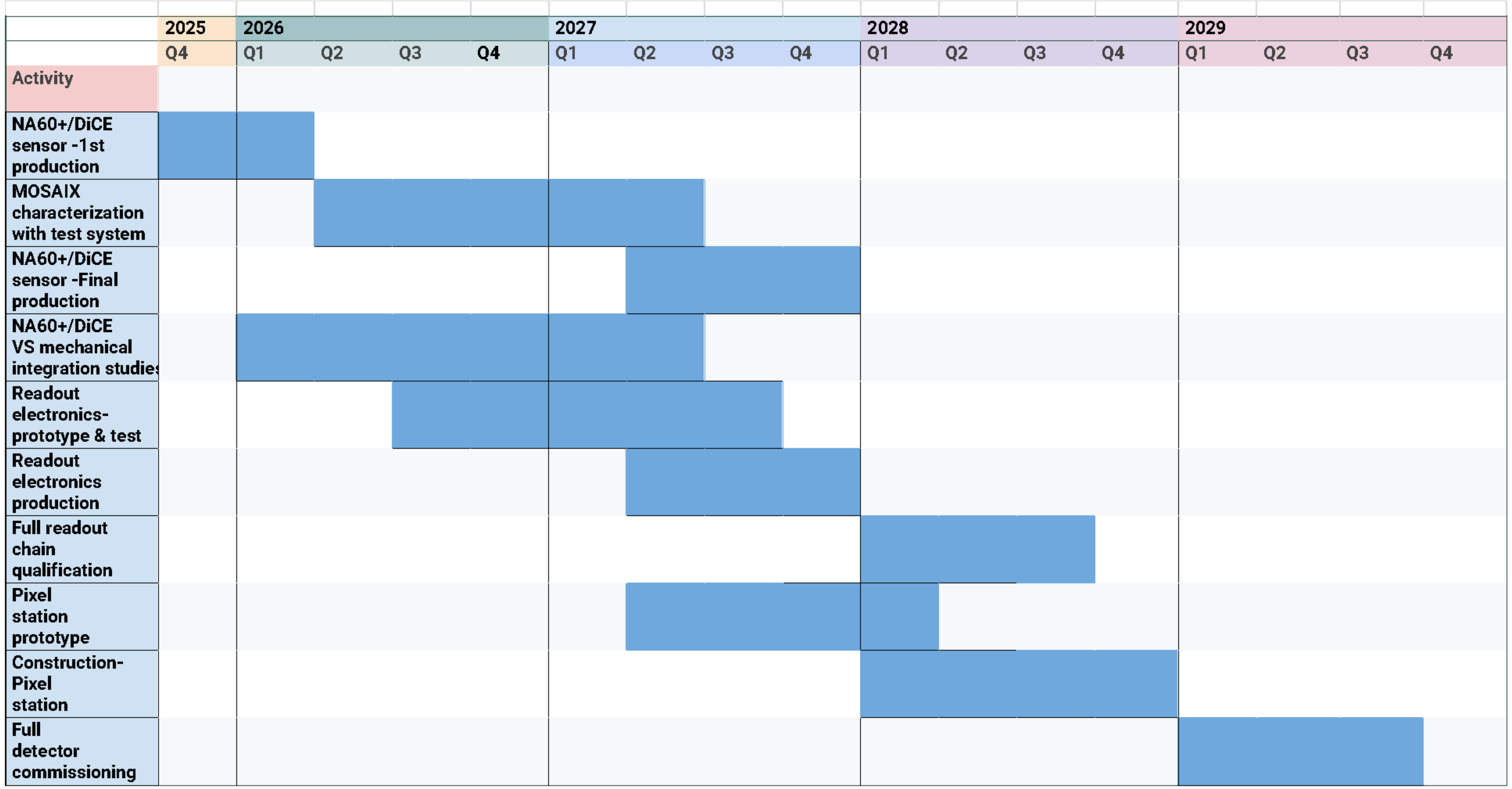


Vertex spectrometer: construction timeline

Pixel stations constructed and tested at Cagliari/Torino INFN labs
☯️ Synergy with **ALICE ITS3** project
🏭 Approximately **50 wafers** to be produced (preliminary)

⏳ Timeline:

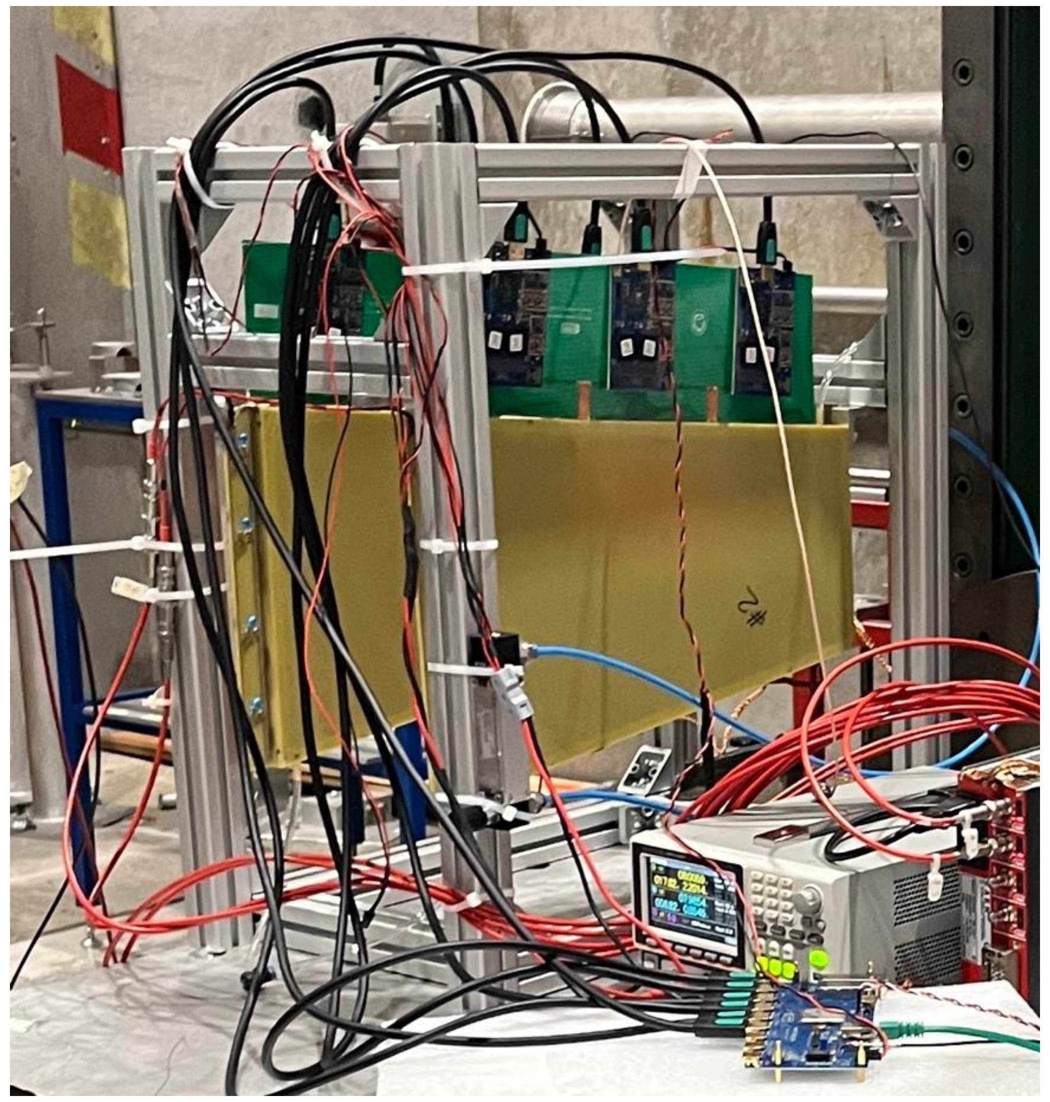
- Prototyping in **2026**
- Production, construction: **2027−2028**
- Commissioning in **2029**



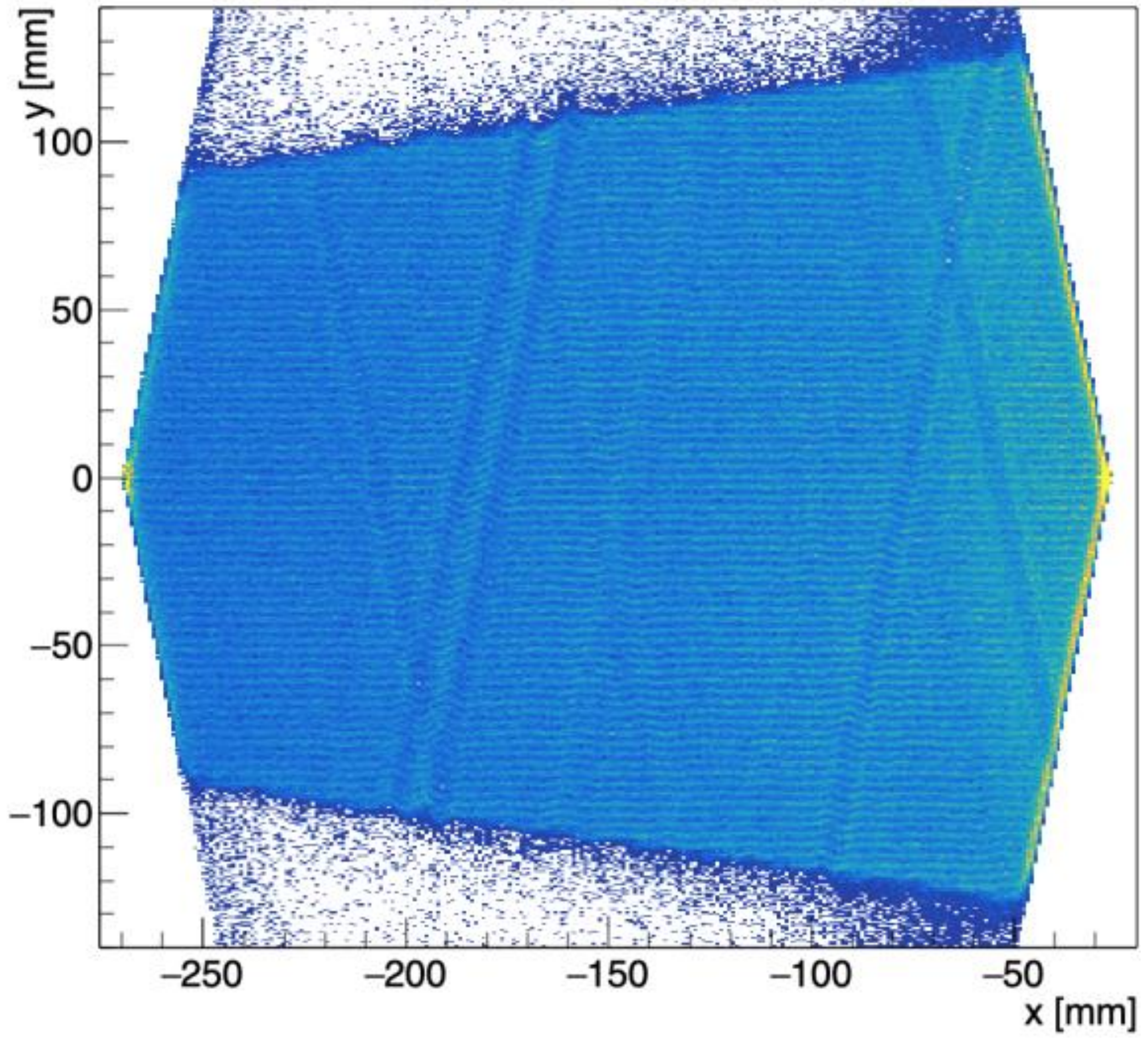
Muon spectrometer: prototype validation & construction

Test beam campaigns in **2023/2024**:

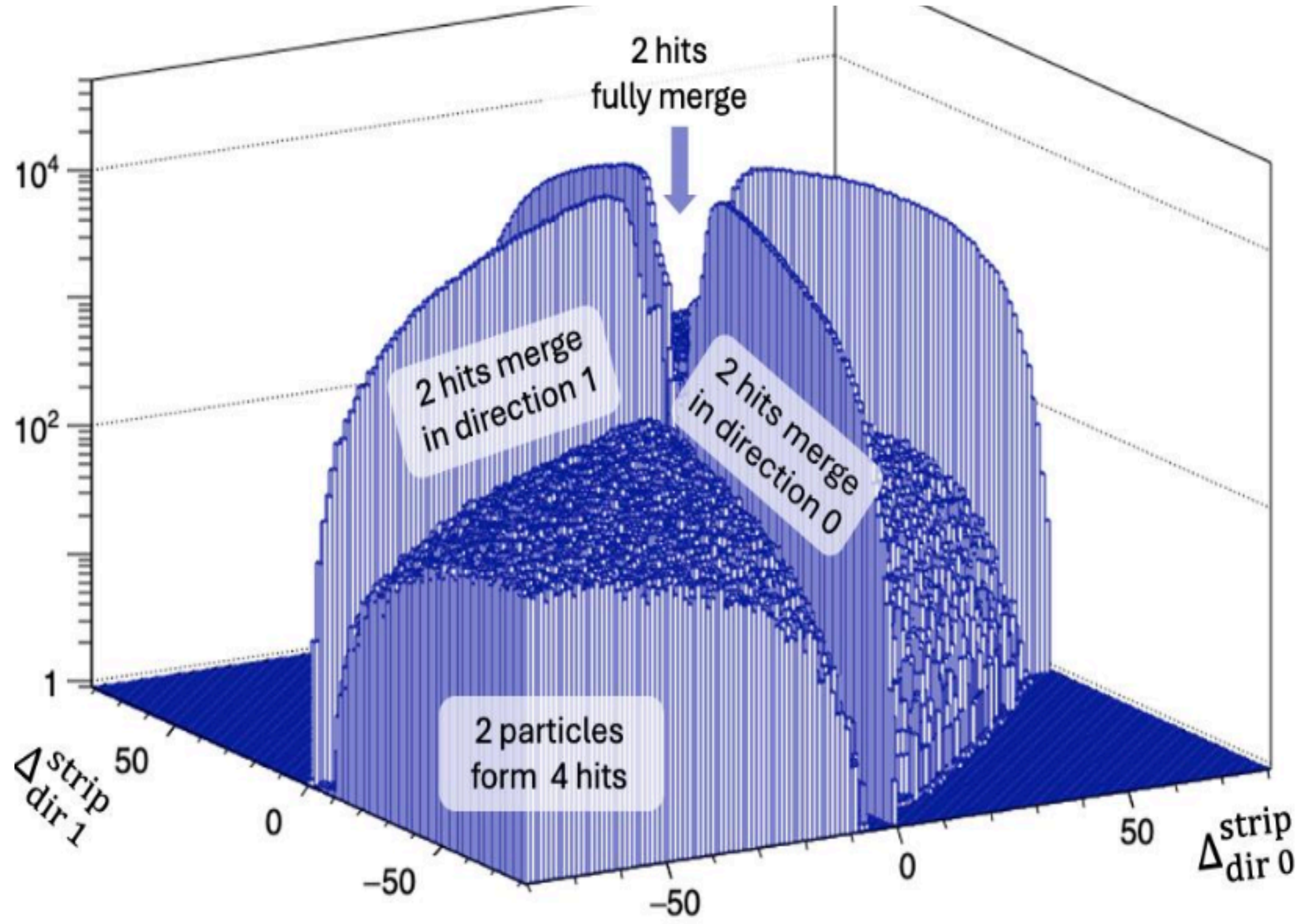
- Strip reconstruction and single hit resolution → **100 μm**
- **Efficiency > 97%** (but difficult to measure due to protons)
- Double-hit resolution



Reconstructed hits in xy



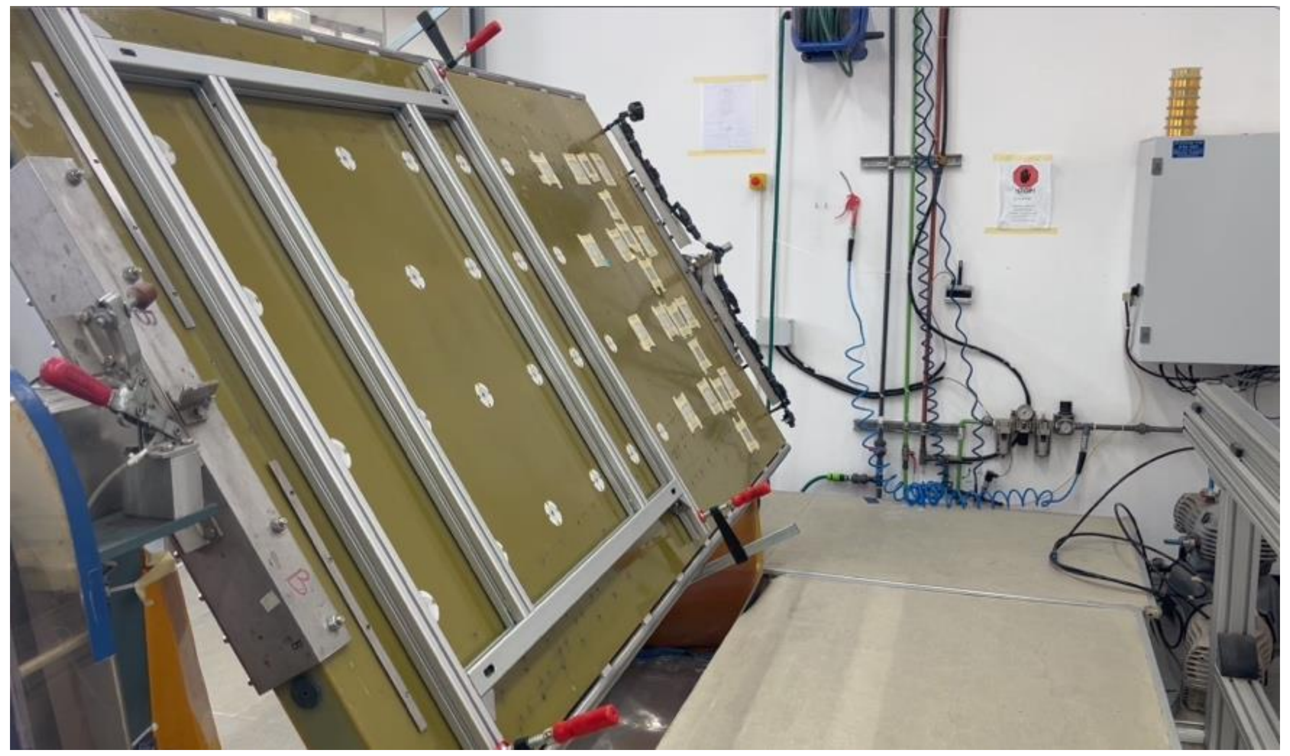
Distances between two rec. hits

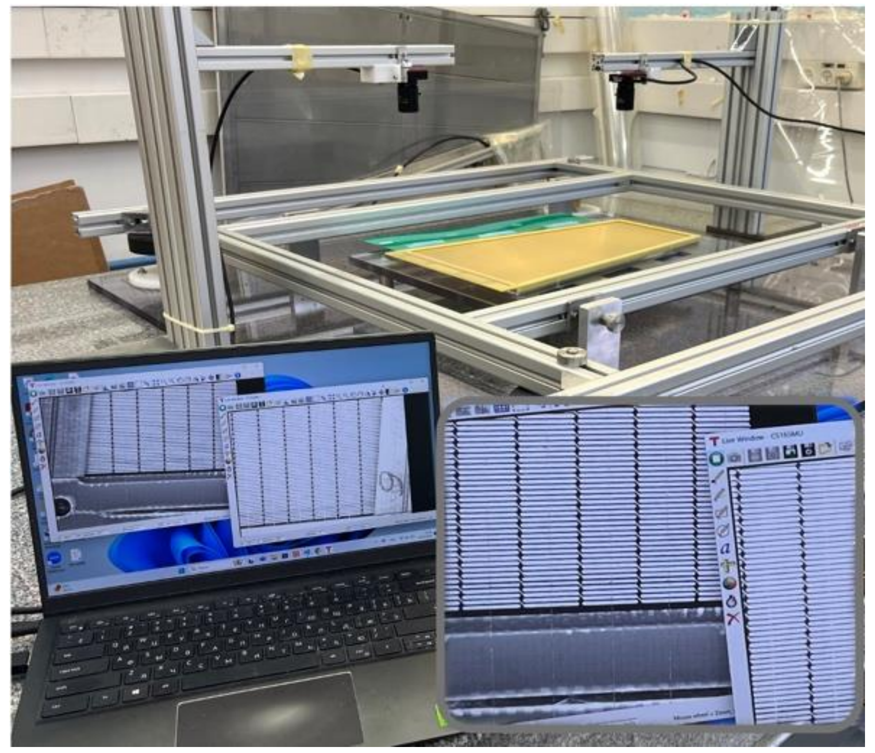


All chambers produced and tested at the Mexico Detector Construction Facility - Weizmann Institute (Israel)

🏭 Approximately **210 modules** to be installed in **6 stations**

⌛ One year estimated time to set up the facility and construction





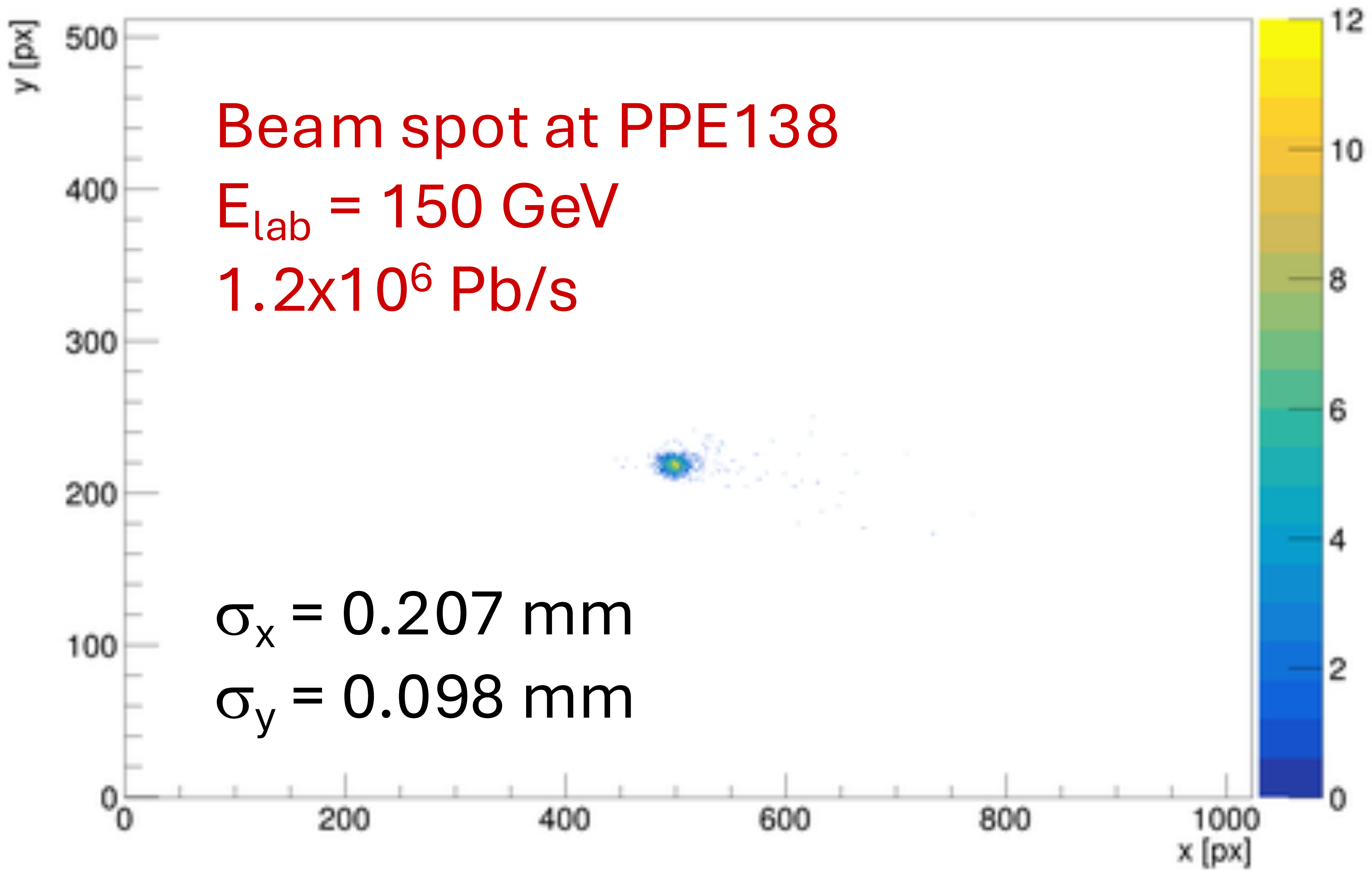
Validating the beam parameters

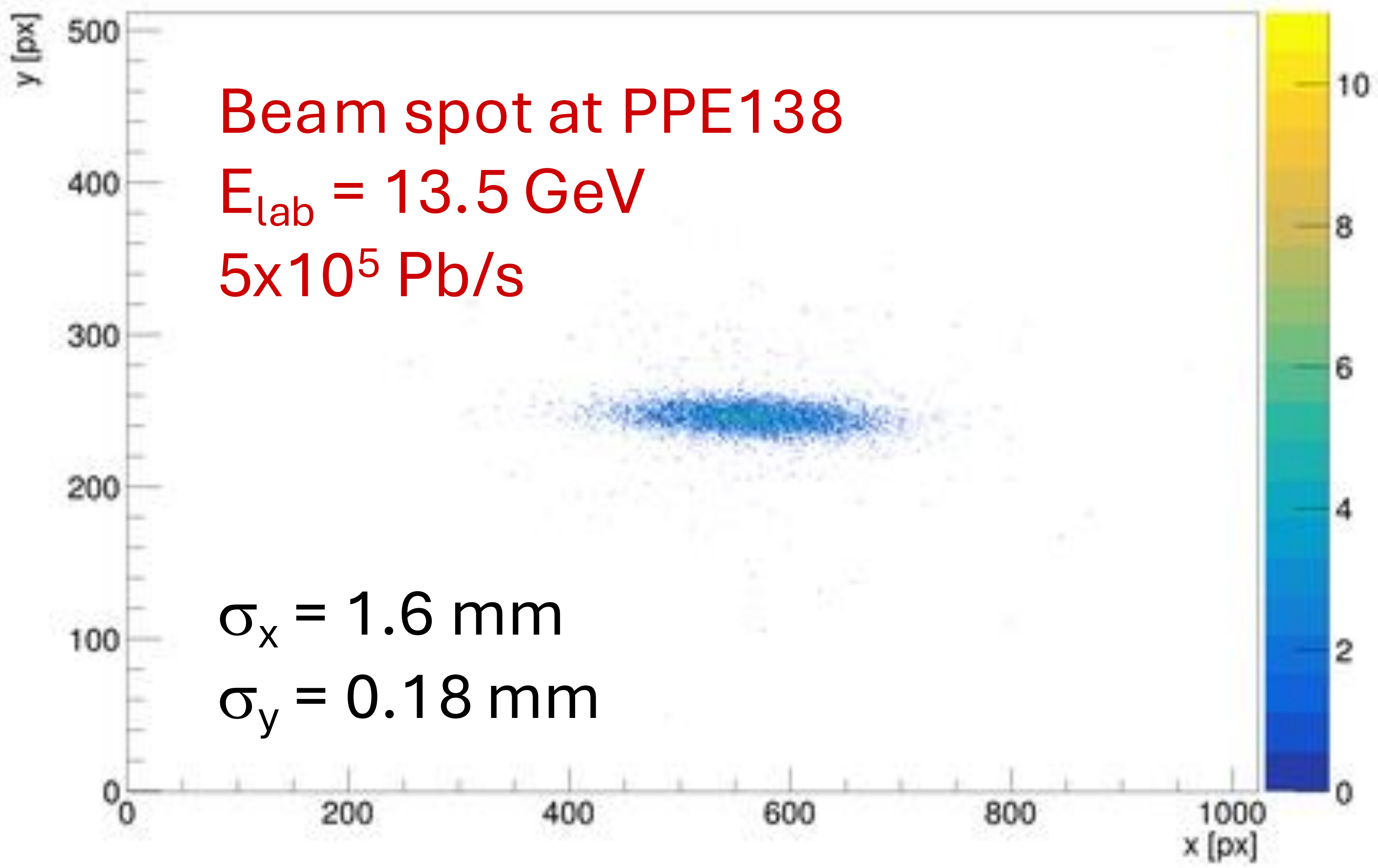
‼️ *Crucial aspect for the feasibility of the experiment: high-intensity Pb and p beams in PPE138 experimental hall*

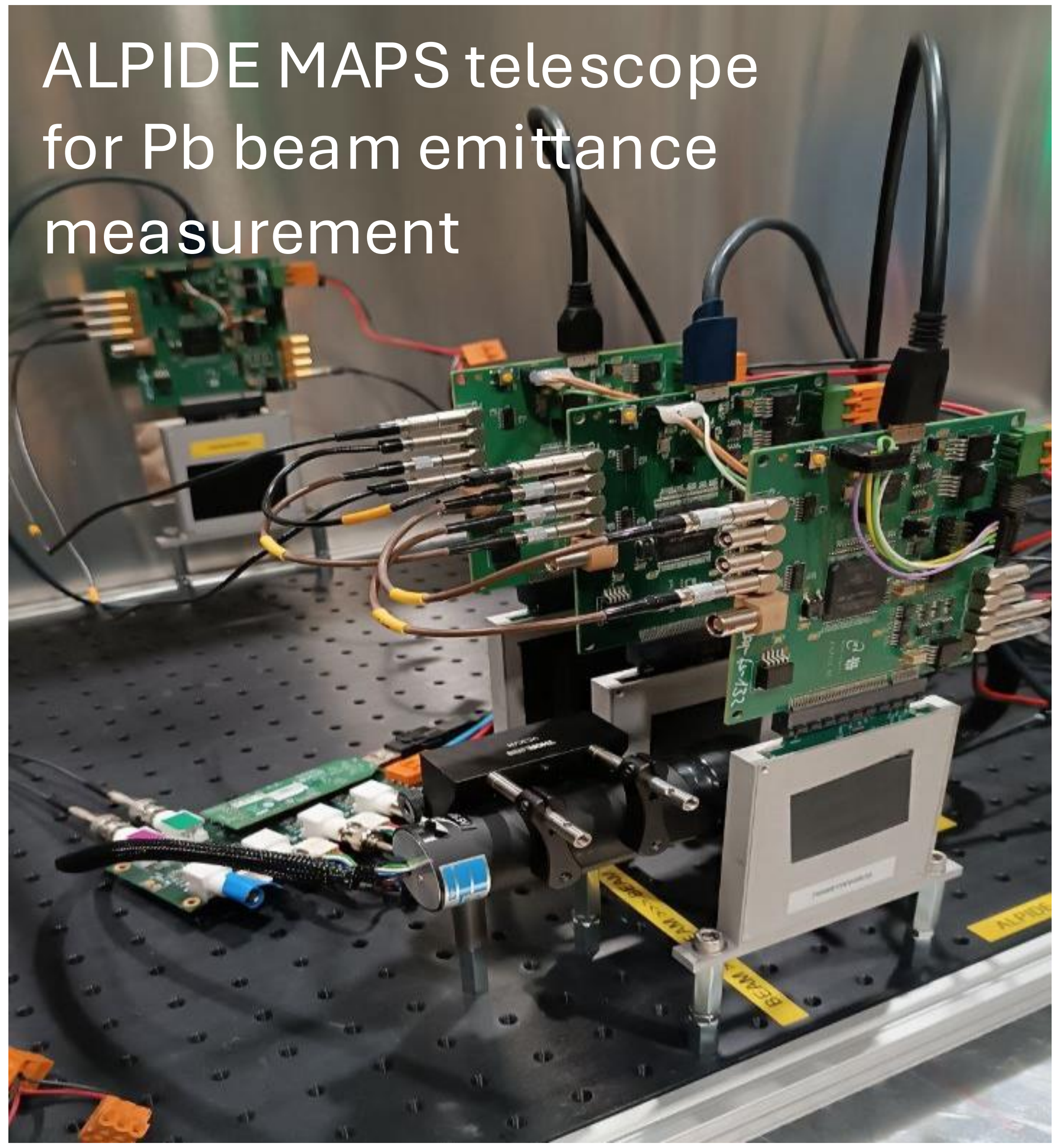
🎯 Should be well focused, as the acceptance hole in VS is only **6×6 mm²!**

Test beam campaigns in **2022/23/24** to study **Pb** beam from **H8** at **13.5** and **150 AGeV/c**

xy position of the test beam at PPE138







✅ Test beam at **150 AGeV/*c***: well focused and intense beam, requirements met

⚠️ Test beam at **13.5 AGeV/*c***:

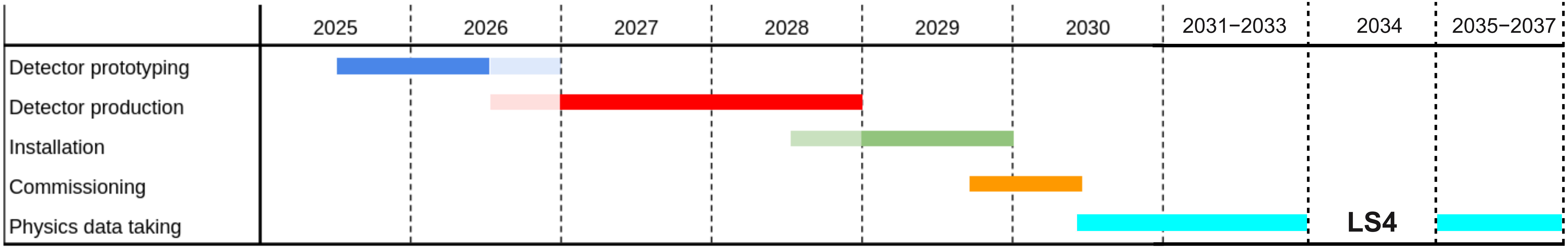
- Spot growth larger than momentum dependence
- Beam losses to be identified: important for optimised collimation
- Adjustment of beam size at T4 and H8 optics to be studied

Timeline and running scheme

✅ *Experiment proposal submitted to SPSC in May 2025*

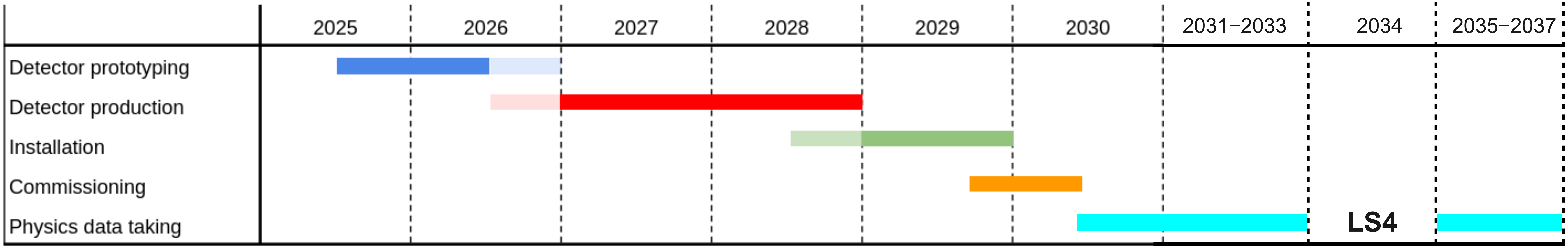
🤞 *"The first impression of the SPSC is very positive"*, detailed questions to be dealt with until SPSC meeting in September

Discussions with funding agencies ongoing, SPSC recommendation is an essential step



Timeline and running scheme

✅ *Experiment proposal submitted to SPSC in May 2025*
🤞 *"The first impression of the SPSC is very positive"*, detailed questions to be dealt with until SPSC meeting in September
Discussions with funding agencies ongoing, SPSC recommendation is an essential step



Pb ions on **Pb** target:
- BES from **E_{lab} = 20 AGeV ($\sqrt{s_{NN}}$ = 6.3 GeV) to E_{lab} = 150 AGeV ($\sqrt{s_{NN}}$ = 16.8 GeV)**
- 1 energy point / year (2 years for lowest $\sqrt{s_{NN}}$)
- **0.4−0.6 × 10^{12} ions on target per month**

Protons on **Be**, **Cu**, **Pb** targets:
- Ideally the same energies as for **Pb** beam
- Low-energy primary protons only during the ion period (extrapolation for other energies)
- **6 × 10^{13} protons on target in 2 weeks**

	Low-energy set-up						High-energy set-up
$^{208}Pb_{82+}$ Momentum [QGeV/c]	50.7 (76.1)	50.7 (76.1)	101	152	216	292	380
$^{208}Pb_{82+}$ Momentum [GeV/c/u]	20 (30)	20 (30)	40	60	85	115	150
$\sqrt{s_{NN}}$	6.3 (7.6)	6.3 (7.6)	8.8	10.7	12.7	14.7	16.8
Pb [10^{12} IoT]	0.6	0.3	0.6	0.45	0.45	0.45	0.45
Number of days	28	14	28	21	21	21	21
Proton momentum [GeV/c]	–	40	–	85	85	150	150
$\sqrt{s}$	–	8.8	–	12.7	12.7	16.8	16.8
Protons on target [10^{13} PoT]	–	6	–	3	3	3	3
Number of days	–	14	–	7	7	7	7

The NA60+/DiCE collaboration (so far) 🌎🌍🌏

Experiment proposal: **74** authors from **18** institutes (Switzerland, Italy, Israel, USA, Japan, China, France)
+ acknowledge to R. Rapp (TAMU)

C. Ahdida[1] , G. Alocco[2,3] , M. Arba[4] , R. Arnaldi[3] , S. Beolè[2,3] , J. Bernhard[1] , L. Bianchi[2,3] , I. Bilinskyi[5] , E. Borisova[5] , S. Bressler[5] , S. Bufalino[6,3] , R. Cerri[2,3] , M. Ciacco[2,3] , C. Cicalò[4] , S. Coli[3] , P. Cortese[7,3] , A. Dainese[8] , H. Danielsson[1] , J. Datta[9] , A. De Falco[10,4] , A. Drees[9] , L. Epshteyn[5] , A. Ferretti[2,3] , F. Fionda[10,4] , M. Gagliardi[2,3] , G.M. Galimberti[4] , S. Girod[1] , T. Gunji[11] , G. Jin[12] , F. Geurts[13] , L. Hu[12] , L. Levinson[5] , F. Li[12] , W. Li[13] , Z. Liu[12] , D. Marras[4] , M. Masera[2,3] , A. Masoni[4] , F. Mazzaschi[1] , P. Mereu[3] , J. Metselaar[1] , L. Micheletti[3] , A. Milov[5] , L. Mirasola[10,4] , A. Mulliri[10,4] , L. Musa[1] , E. Nowak[1] , C. Oppedisano[3] , N. Pacifico[1] , M. Płoskoń[14] , T. Prebibaj[1] , F. Prino[3] , M. Puccio[1] , C. Puggioni[4] , A. Rossi[8] , V. Sarritzu[10,4] , B. Schmidt[1] , E. Scomparin[3] , D. Sekihata[15] , Q. Shou[16] , R. Shahoyan[1] , M. Shoa[5] , S. Siddhanta[4] , X. Su[12] , Z. Tang[12] , S. Trogolo[2,3] , M. Tuveri[4] , A. Uras[17] , G. Usai[10,4] , M. Van Dijk[1] , E. Vercellin[2,3] , I. Vorobyev[1] , B. Yankovsky[5] , D. Zavazieva[5,18]

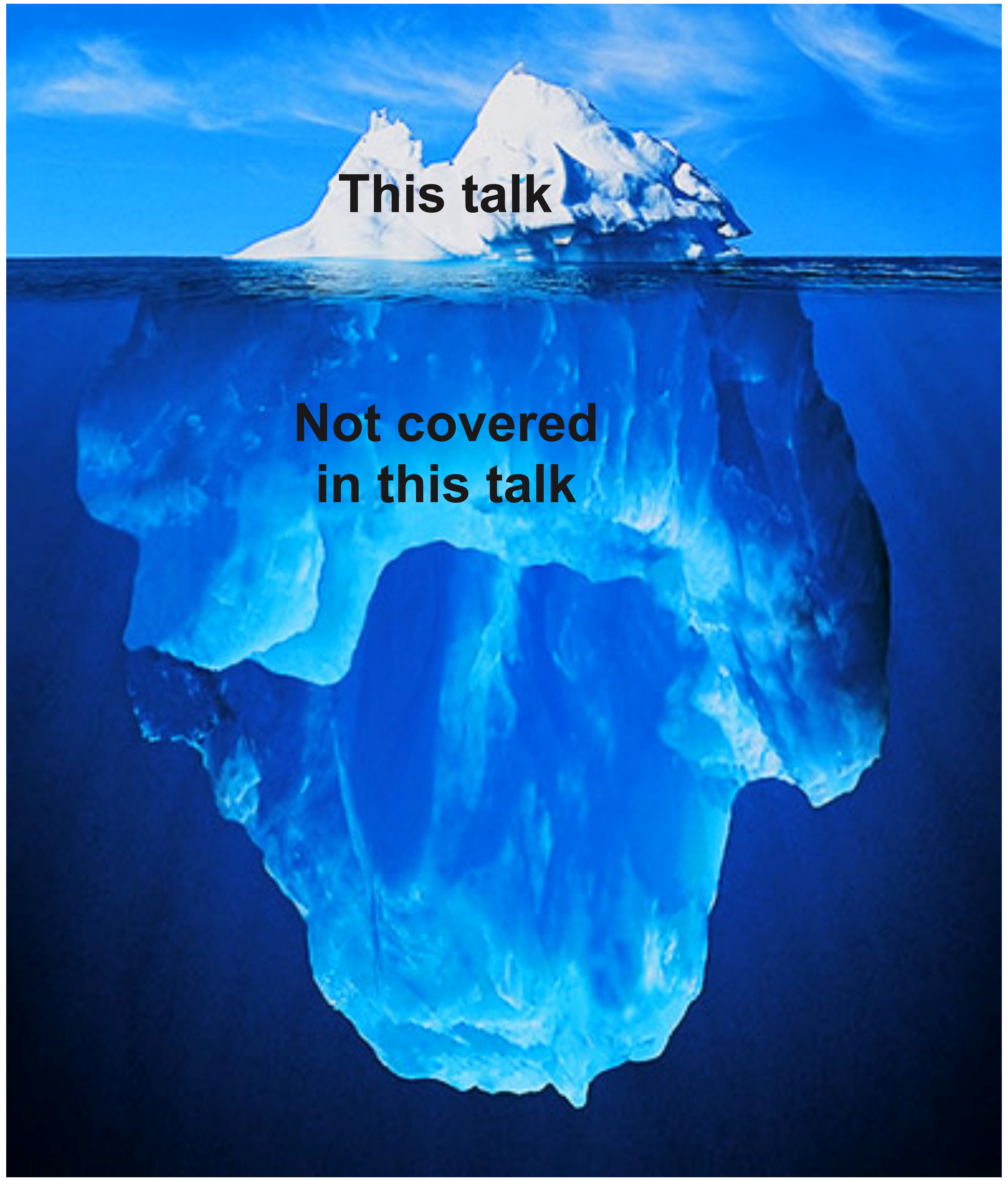
1 .European Organization for Nuclear Research (CERN), Geneva, Switzerland
2 .Dipartimento di Fisica dell Università di Torino, Turin, Italy
3 .INFN, Sezione di Torino, Turin, Italy
4 .INFN, Sezione di Cagliari, Cagliari, Italy
5 .Department of Particle Physics and Astrophysics, Weizmann Insitute of Science, Rehovot, Israel
6 .Dipartimento DISAT del Politecnico di Torino, Turin, Italy
7 .Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale, Alessandria, Italy
8 .INFN, Sezione di Padova, Padova, Italy
9 .Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York, USA
10 .Dipartimento di Fisica dell'Università di Cagliari, Cagliari, Italy
11 .University of Tokyo, Tokyo, Japan
12 .Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui, China
13 .Department of Physics and Astronomy, Rice University, Houston, Texas, USA
14 .Lawrence Berkeley National Laboratory, Berkeley, California, USA
15 .University of Tsukuba, Ibaraki, Japan
16 .Institute of Modern Physics, Fudan University, Shanghai, China
17 .Institut de Physique des 2 Infinis de Lyon, Université de Lyon, CNRS/IN2P3, Lyon, France
18 .Faculty of Engineering Sciences, Ben Gurion University of the Negev, Beer Sheva, Israel

Summary and conclusions

Precision studies of electromagnetic and hard probes in the region of **6 < $\sqrt{s_{NN}}$ < 17 GeV** are currently lacking

Newly proposed NA60+/DiCE experiment will allow for accurate studies of several extremely relevant physics topics at finite μ_B!

- *Caloric curve measurement*
- *Chiral symmetry restoration via ρ−a1 mixing*
- *Charm thermalisation and hadronisation*
- *Onset of charmonium anomalous suppression*
- *QGP transport properties*
- *Strangeness, hypernuclei production*
- *…*

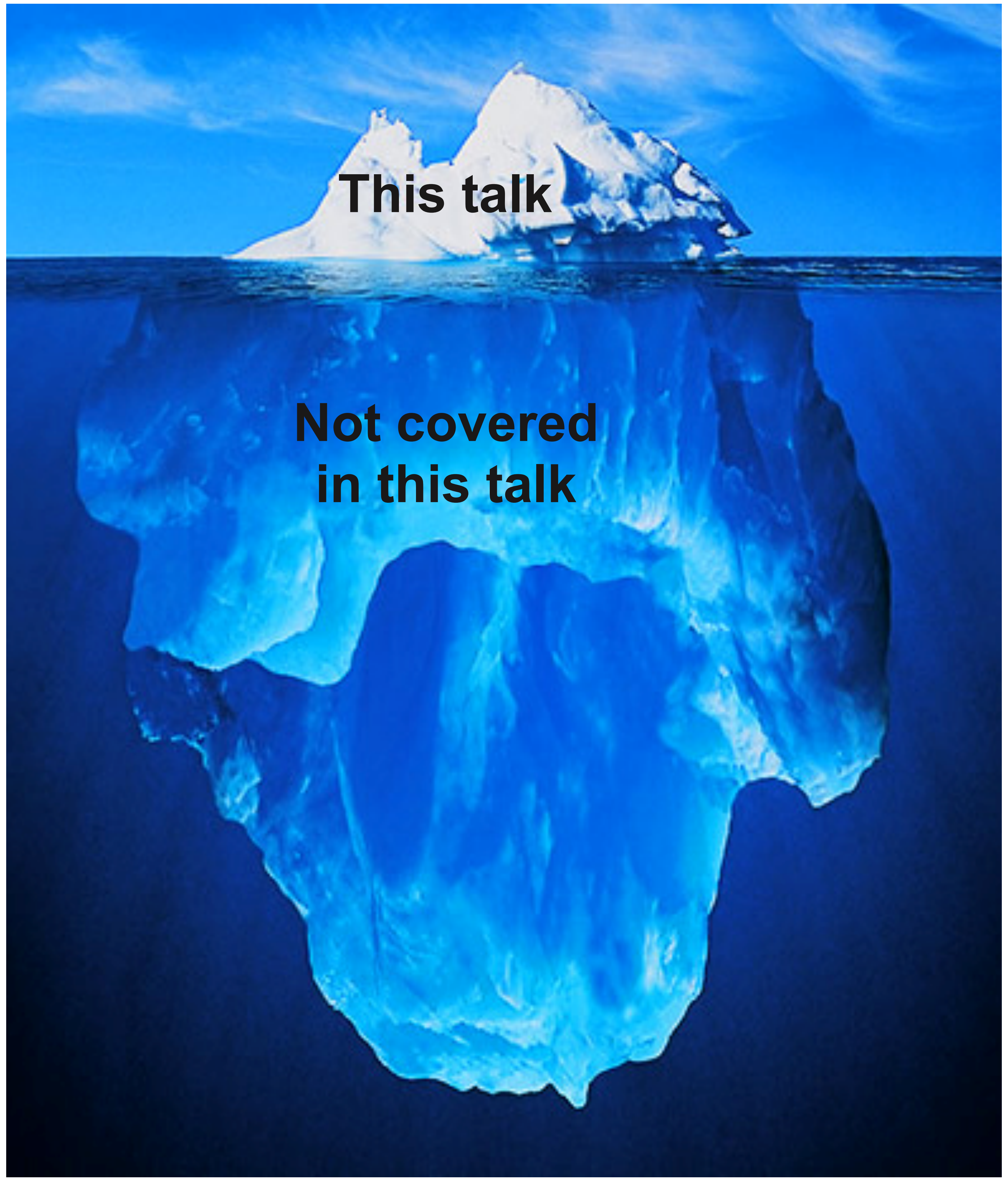


Summary and conclusions

Precision studies of electromagnetic and hard probes in the region of **$6 < \sqrt{s_{NN}} < 17$ GeV** are currently lacking

Newly proposed NA60+/DiCE experiment will allow for accurate studies of several extremely relevant physics topics at finite μ_B!

- *Caloric curve measurement*
- *Chiral symmetry restoration via ρ−a1 mixing*
- *Charm thermalisation and hadronisation*
- *Onset of charmonium anomalous suppression*
- *QGP transport properties*
- *Strangeness, hypernuclei production*
- *…*



Thank you for your attention!

Back-up slides

QCD and chiral symmetry

The QCD Lagrangian:

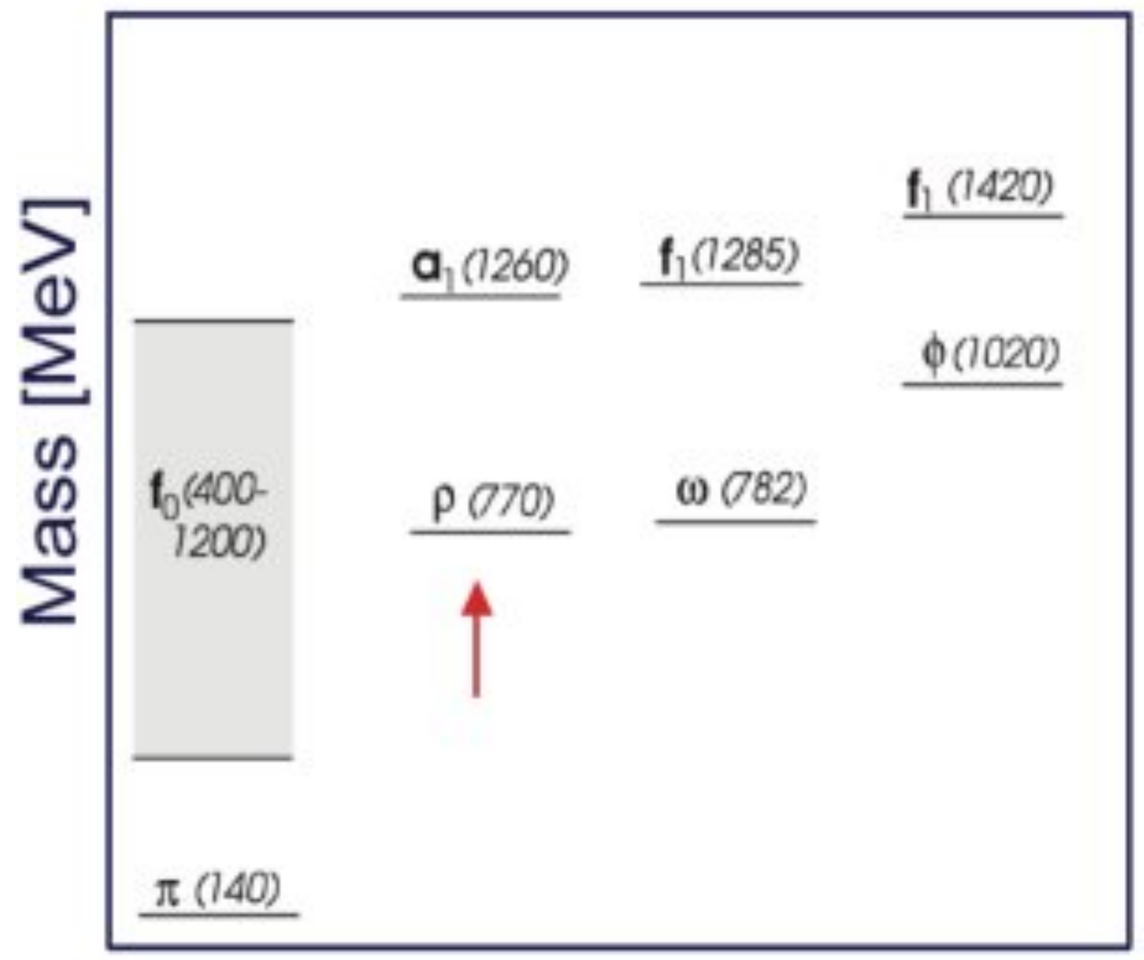
$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - \mathcal{M}_q)q - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a \quad , \qquad D_\mu = \partial_\mu + ig_s\frac{\lambda_a}{2}A^a_\mu$$

Explicit chiral symmetry breaking due to $\bar{q}M_q q$ term

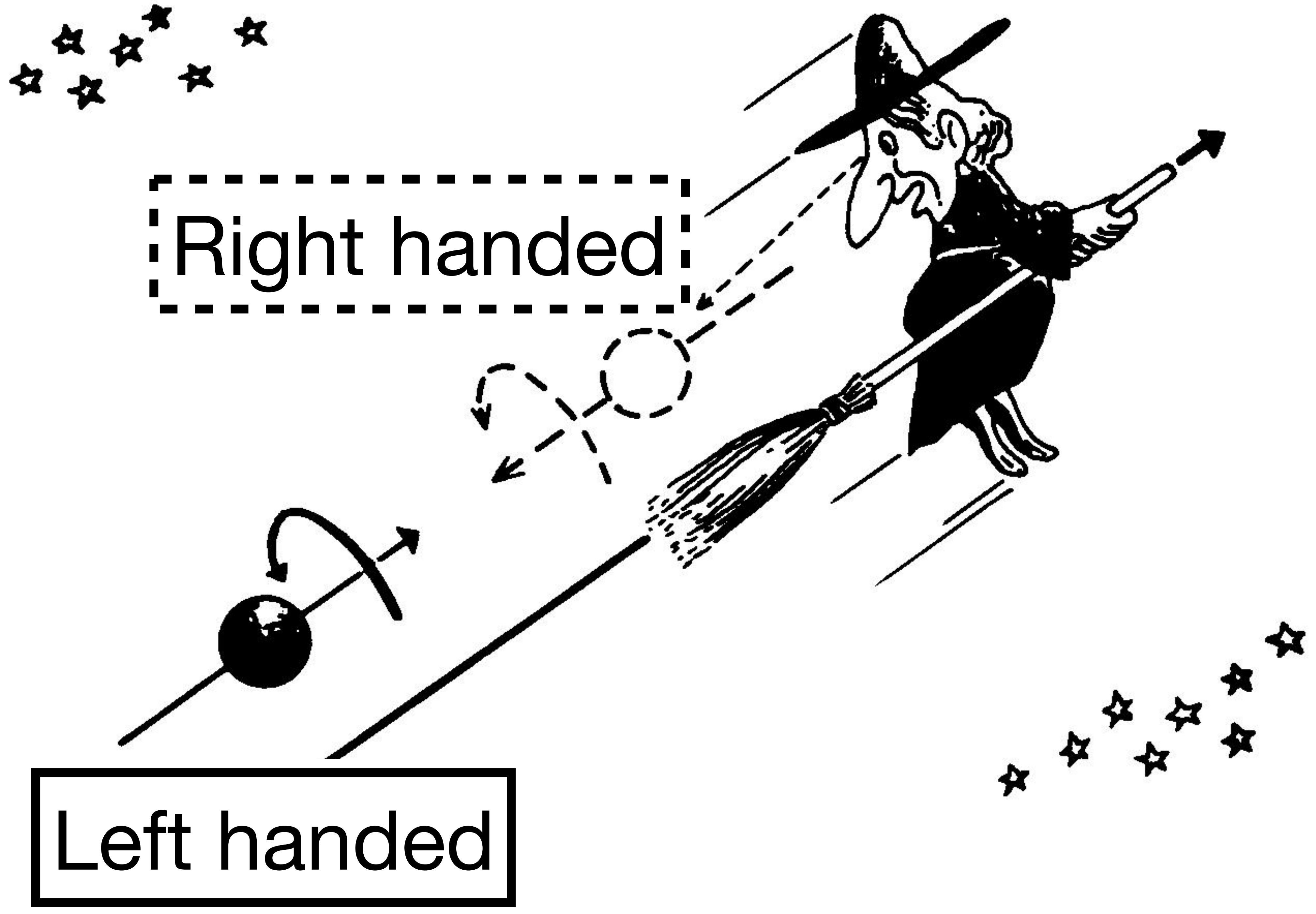
- In the limit of $m_u = m_d = m_s = 0$ chirality would be conserved
- All states have a chiral partner with opposite parity and equal mass

Real life:

- a_1 ($J^p = 1^+$) and ρ ($J^p = 1^-$) have $\Delta m \approx 500$ MeV
- Small current quark masses do not explain this!
- *Chiral symmetry is also spontaneously broken*



Dainese et al, Frascati Phys.Ser. 62 (2016)

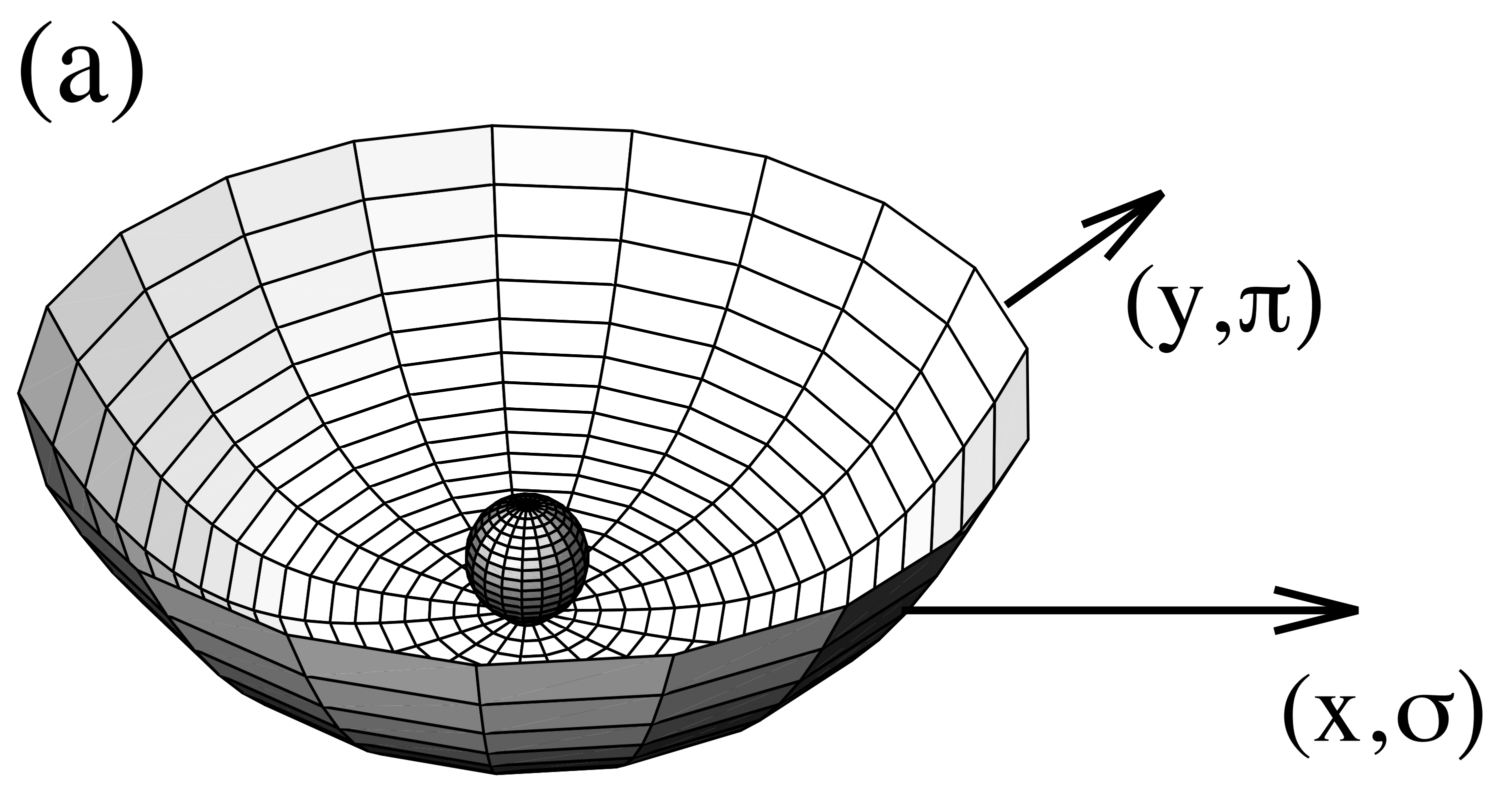


Spontaneous breaking of chiral symmetry

a) (unbroken) symmetric potential with symmetric ground state: small deviations in any direction do not cost energy

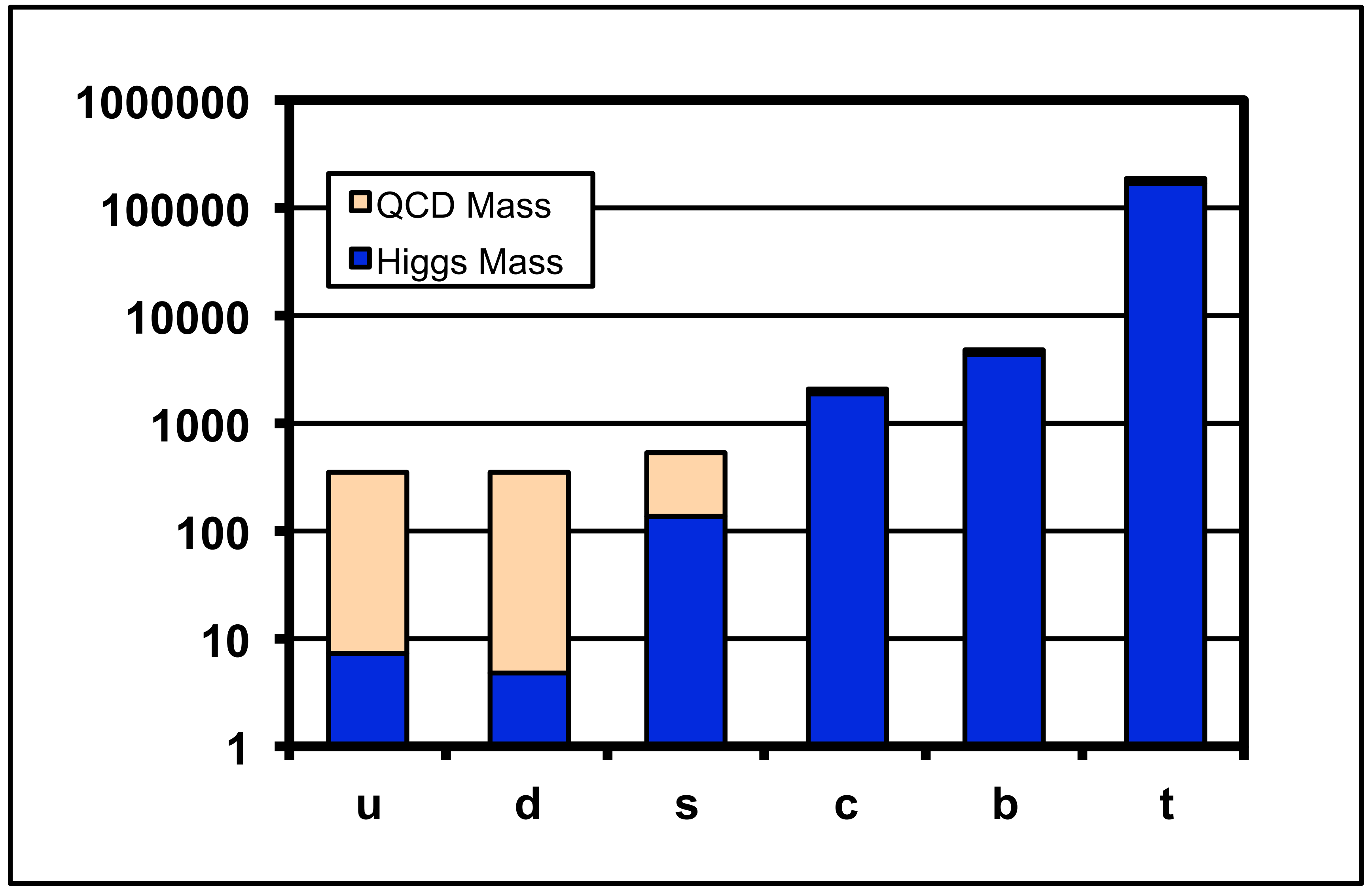
b) symmetric potential, infinite number of degenerate ground states:

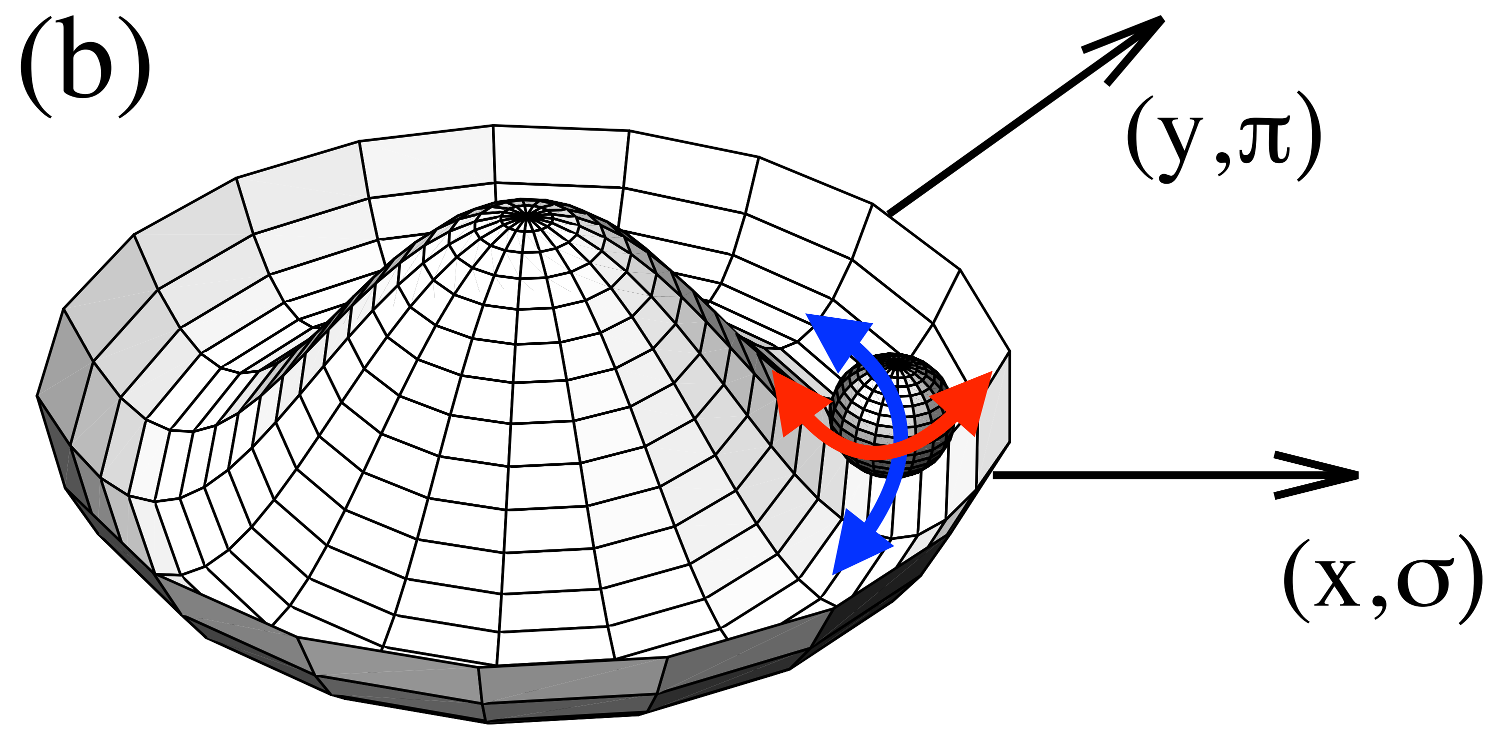
- choosing one randomly spontaneously breaks symmetry
- deviations along the valley cost no energy: massless Golddstone bosons (π, K, η)
- deviations perpendicular cost energy: massive mesons (e.g. σ)



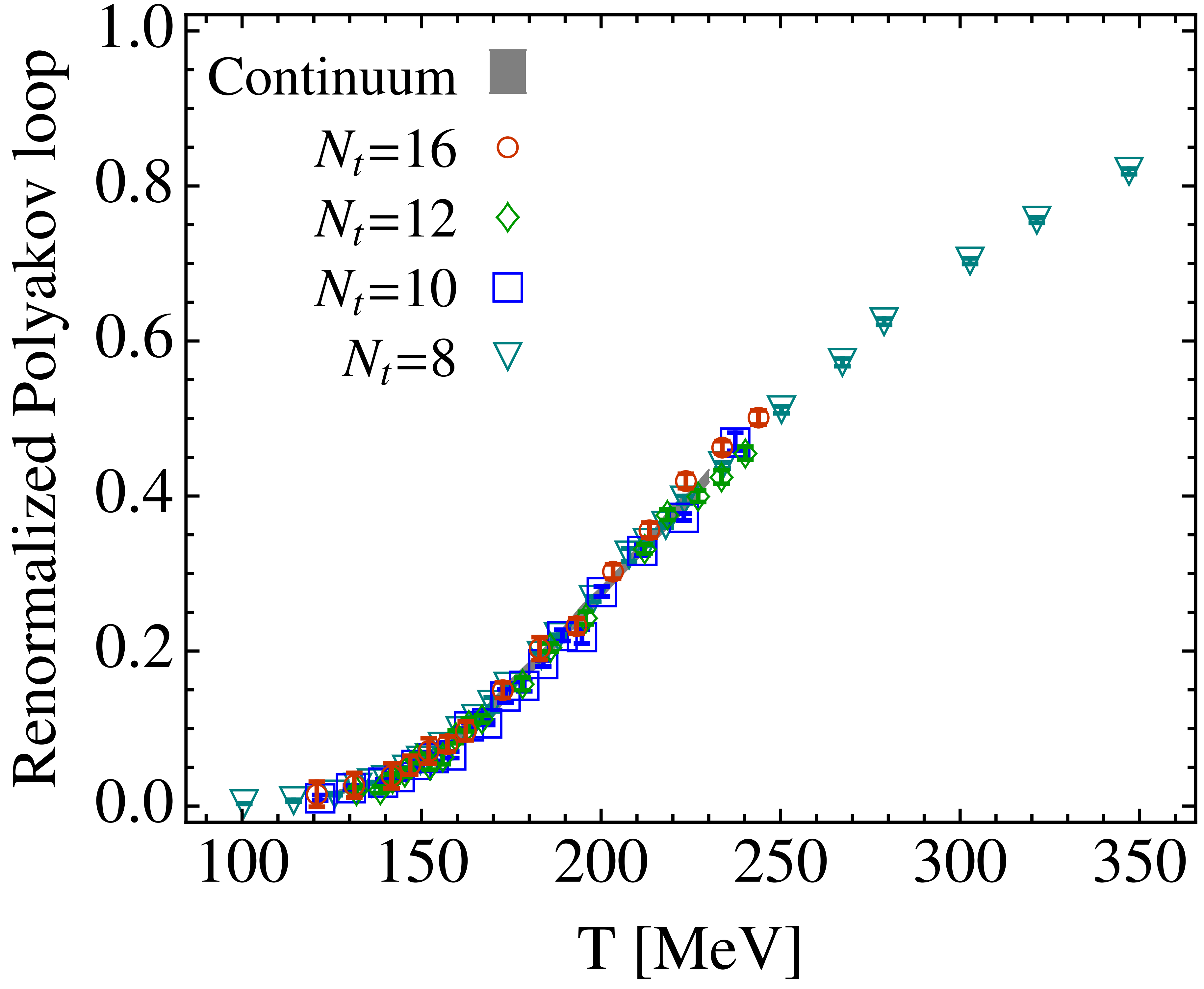
Consequences for the constituent quark masses:

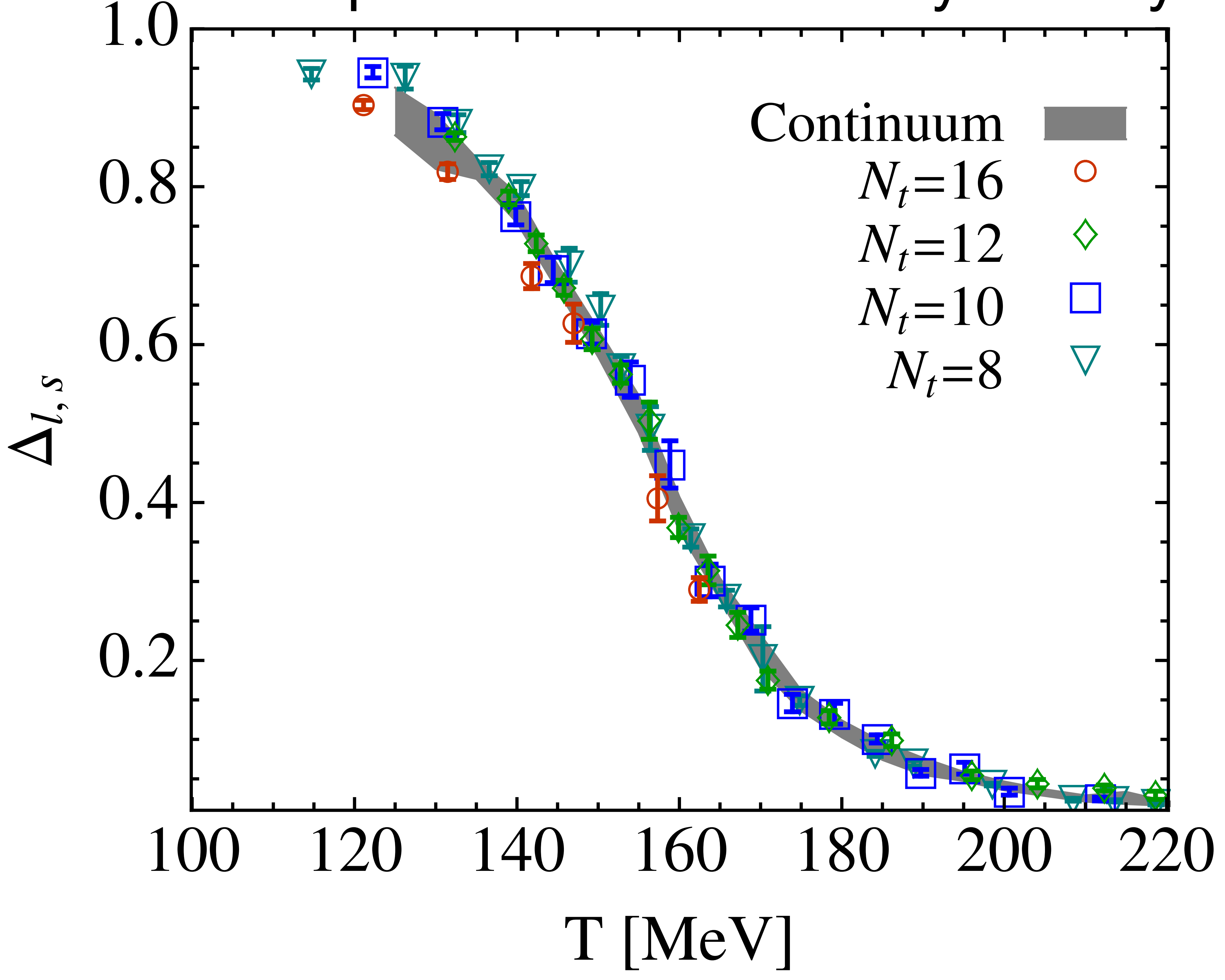
- 95% generated by spontaneous chiral symmetry breaking (QCD mass)!





Chiral phase transition





Wuppertal-Budapest Collaboration,
JHEP 09 (2010) 073

- Lattice QCD calculation
  - Predict chiral symmetry restoration already a T lower than deconfinement phase transitions

Caloric curve: theoretical predictions

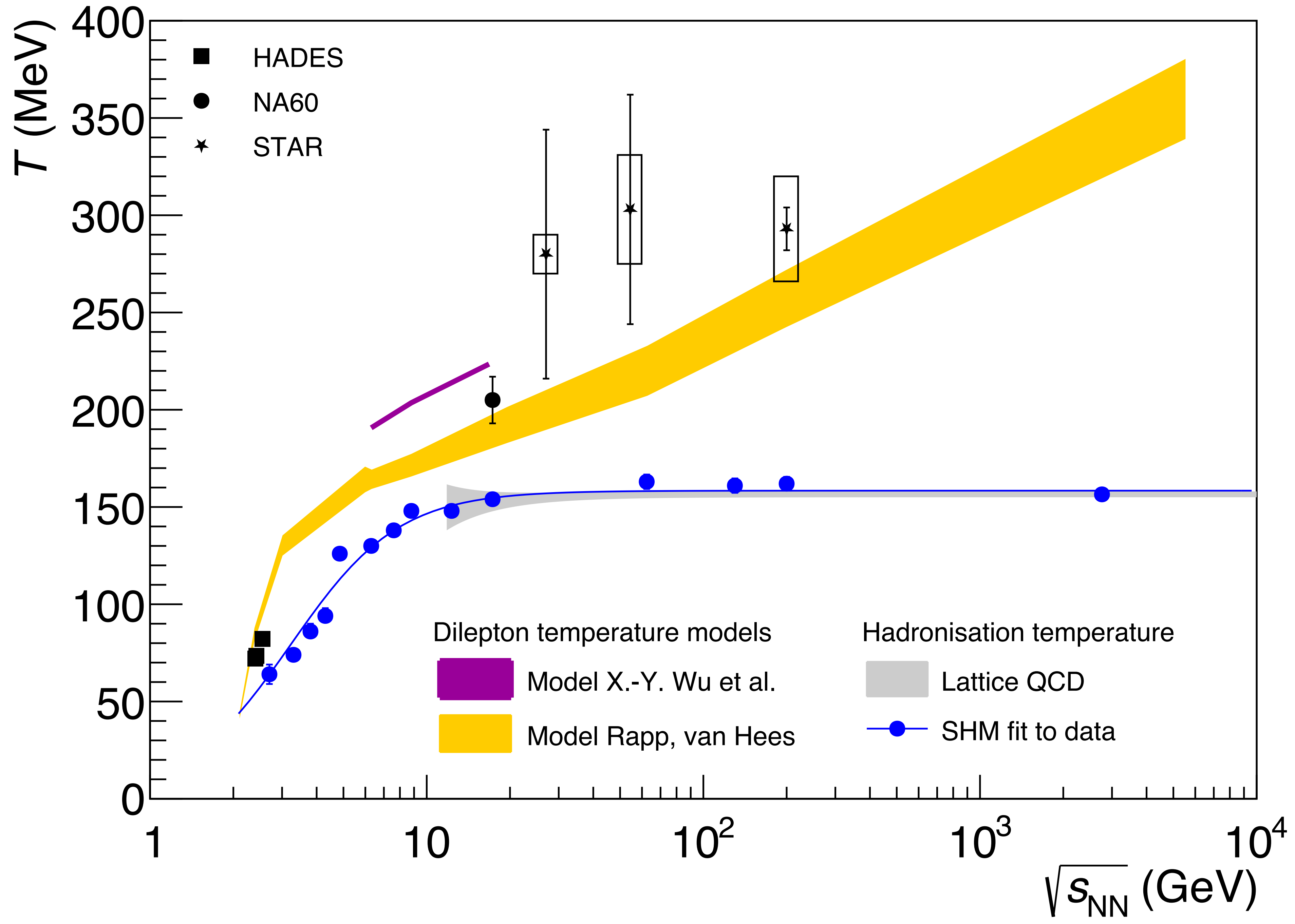
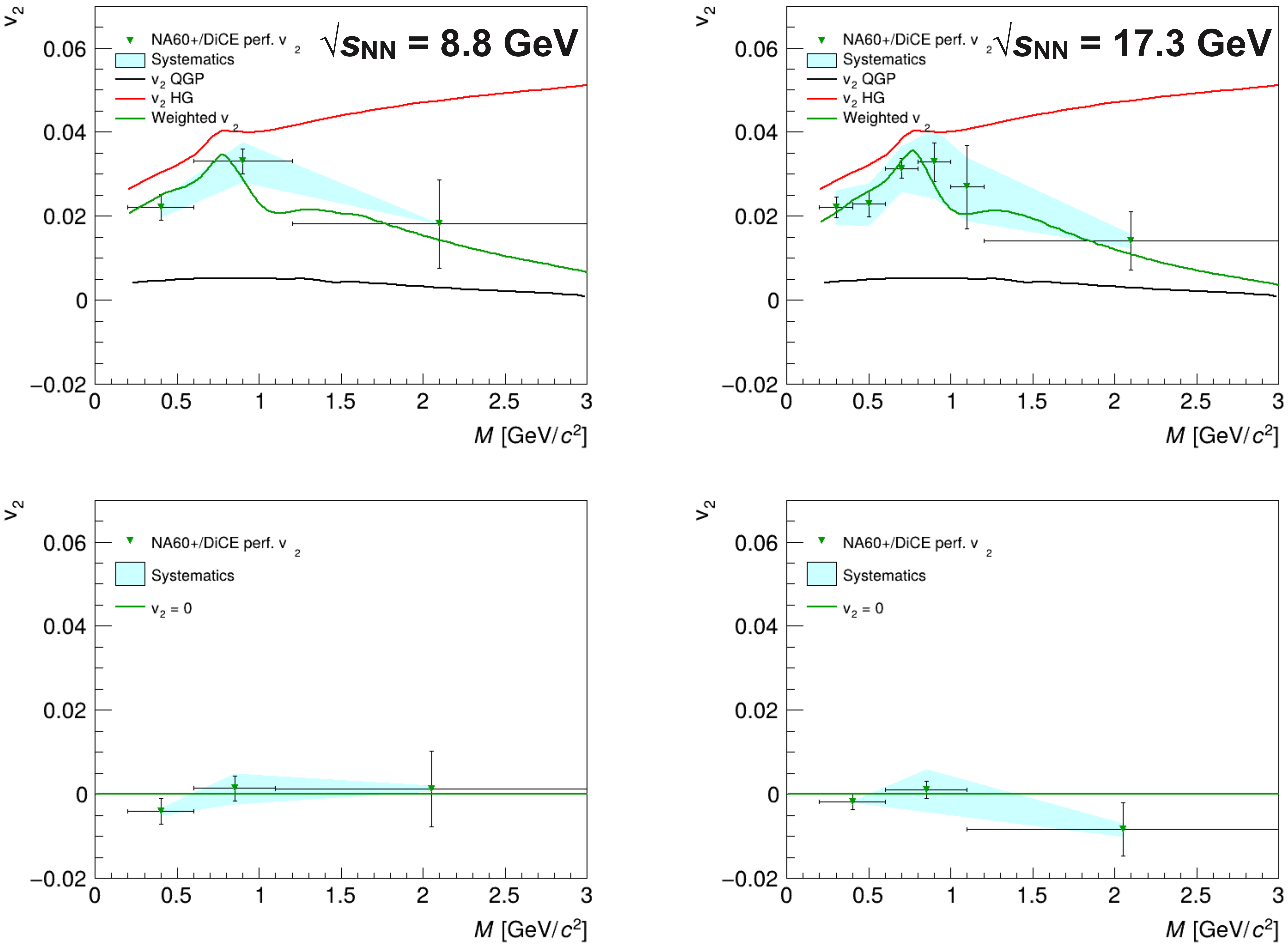


Fig. 3: Temperature measurements from fits to dilepton mass spectra as a function of $\sqrt{s_{NN}}$ [4–9]. The calculations by Rapp and van Hees are an expanding fireball model with lattice QCD-based EoS shown as yellow band, with the width of the band representing the uncertainty from variations of the fireball size by $\pm 30\%$ [10]. The predictions by X.-Y. Wu et al. (purple line) employ 3D dynamical MC Glauber model for initial stages, MUSIC framework for hydrodynamical evolution and URQMD for hadronic cascade [11–14]; only statistical uncertainties are shown. The hadronization temperature from lattice QCD predictions [1] and from statistical hadronization model fit to experimental data [15] is shown as well.

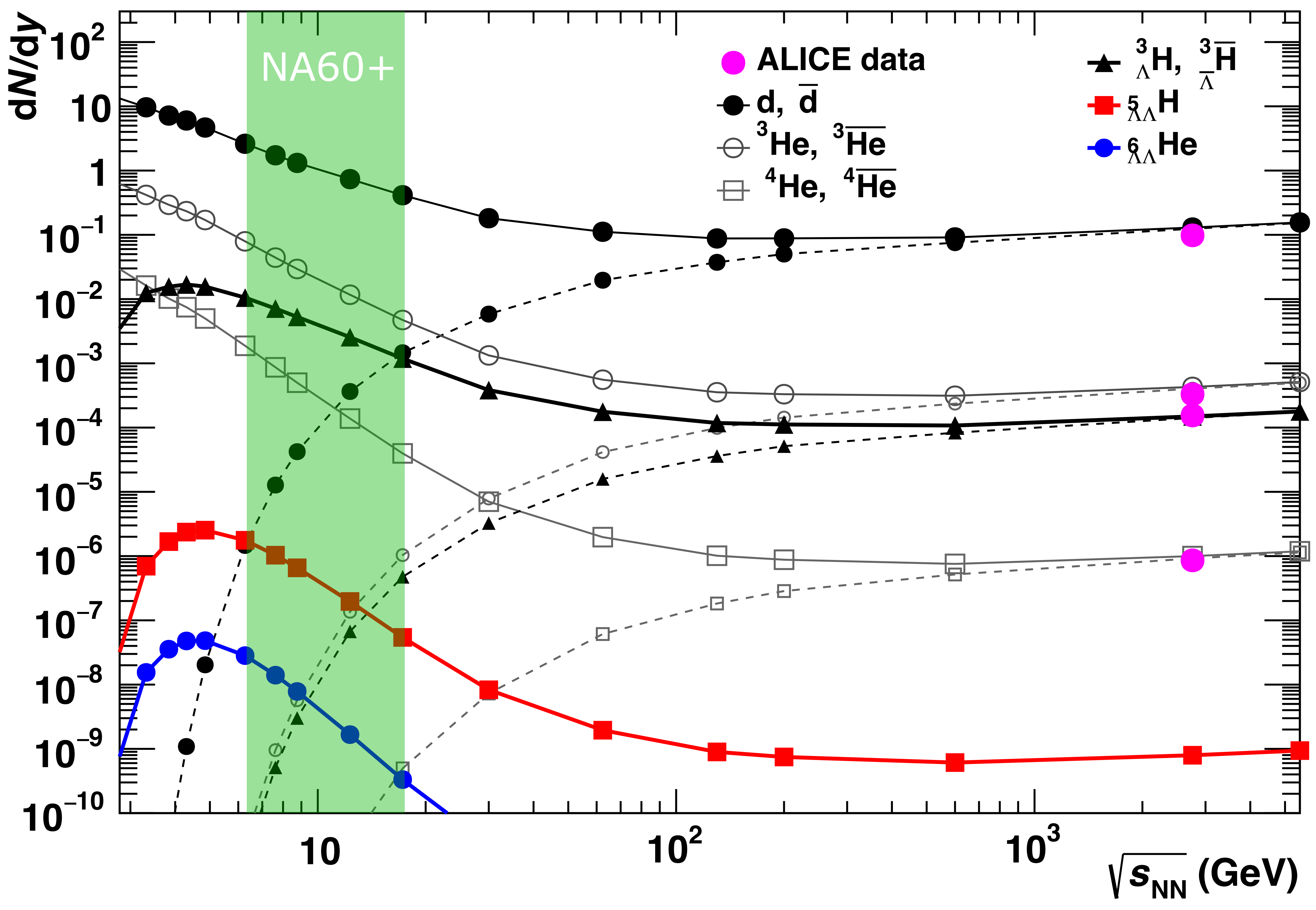
Elliptic flow of thermal dileptons

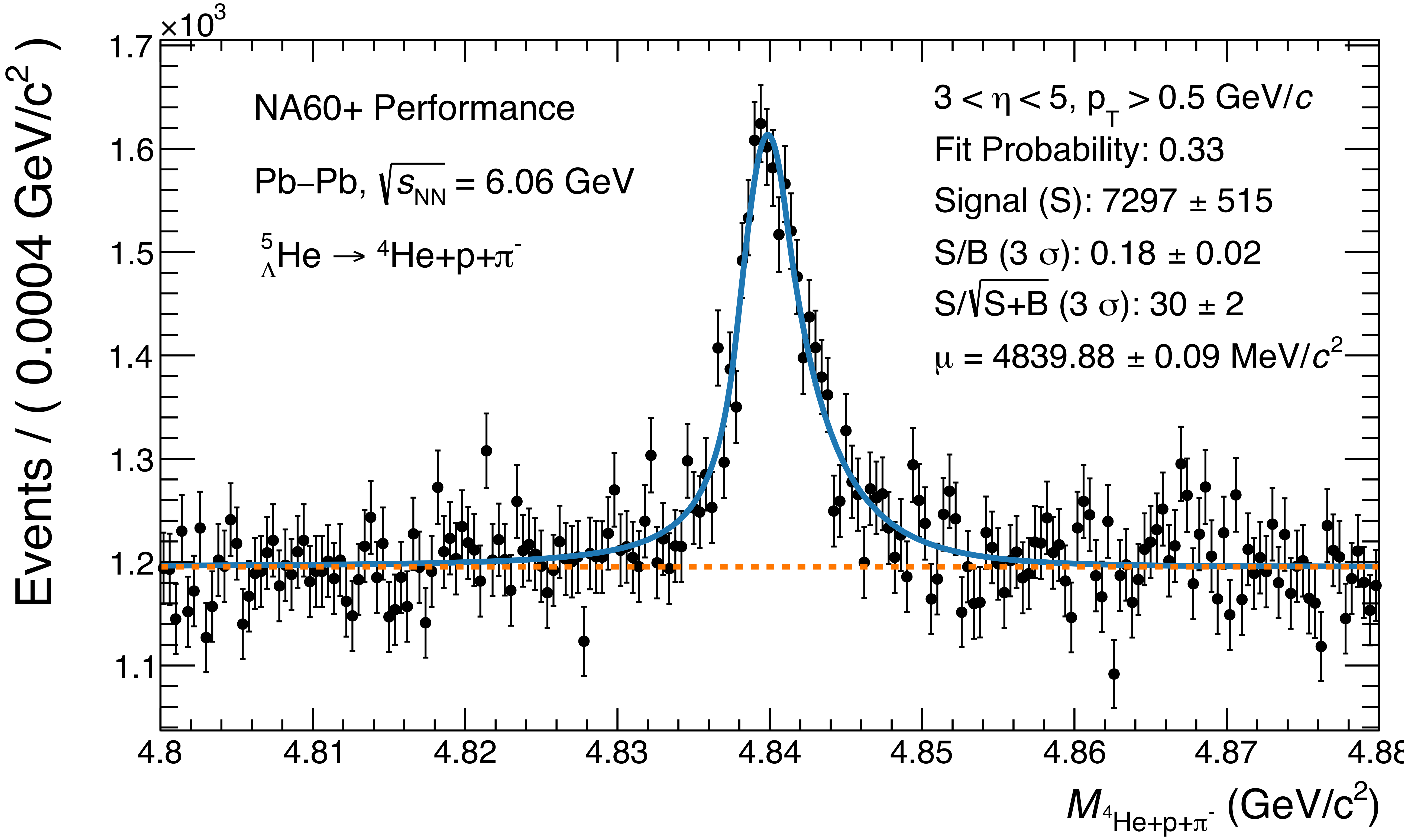


v_2 as expected at RHIC

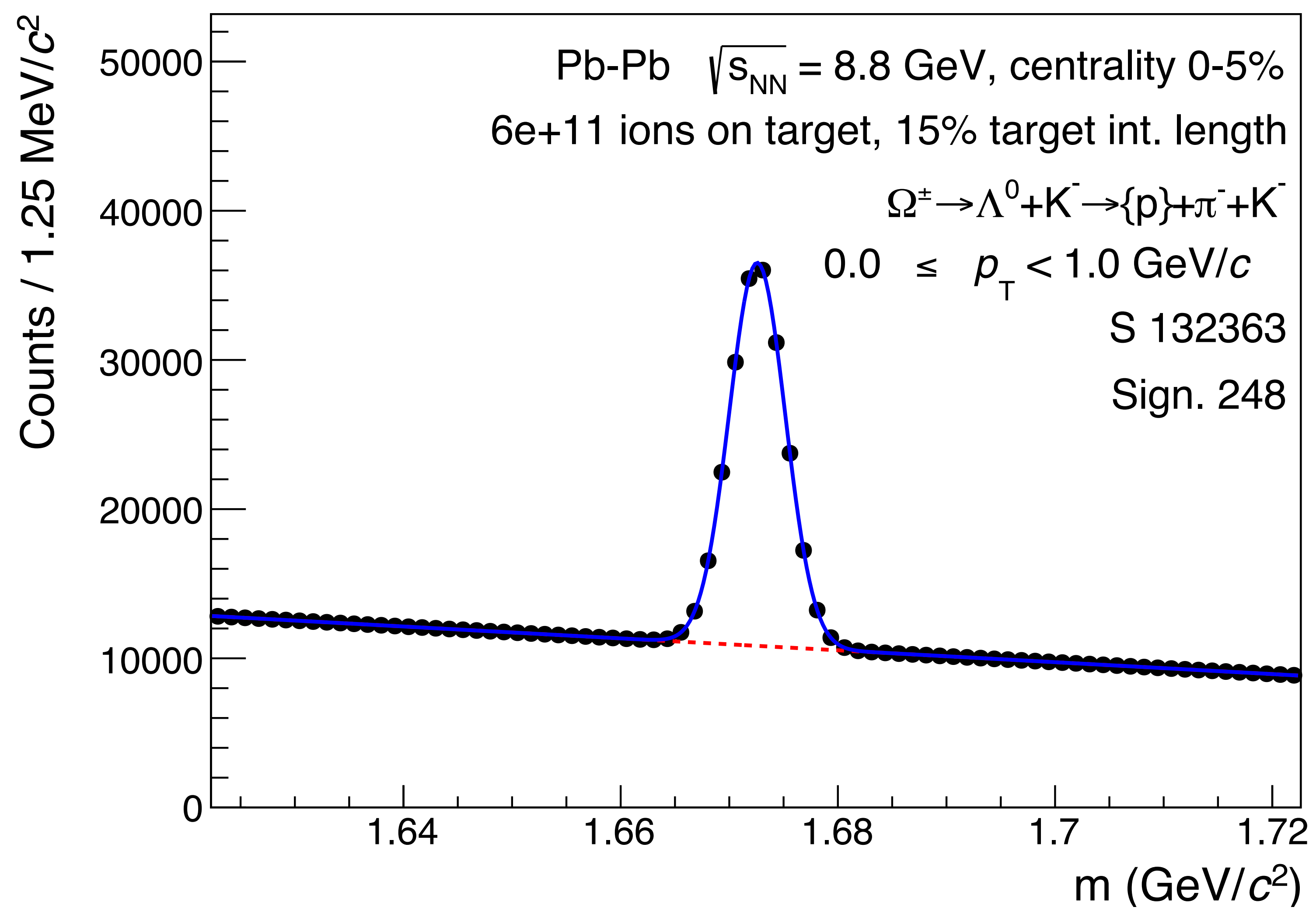
$v_2 = 0$

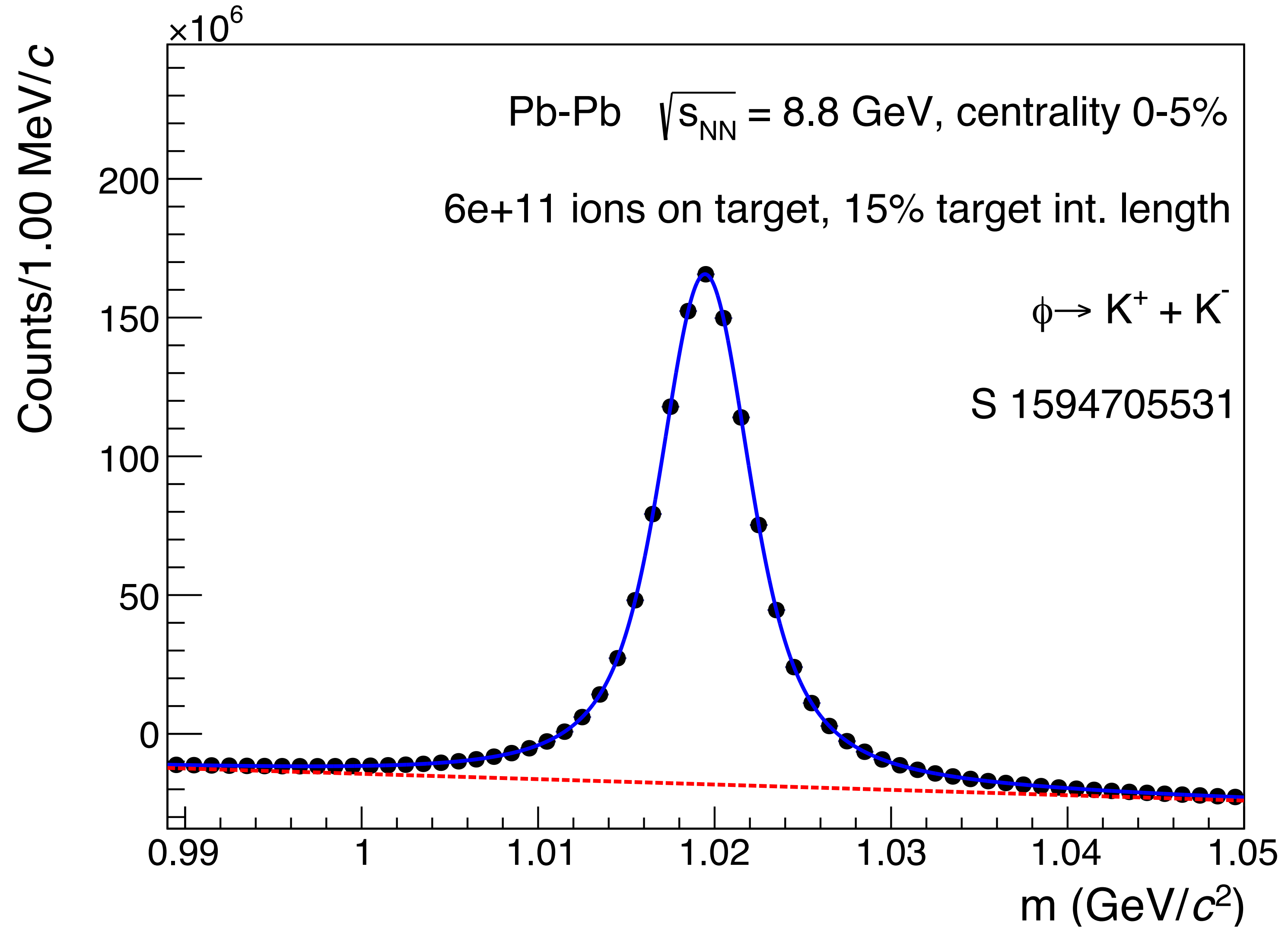
(Anti)(hyper)nuclei with NA60+

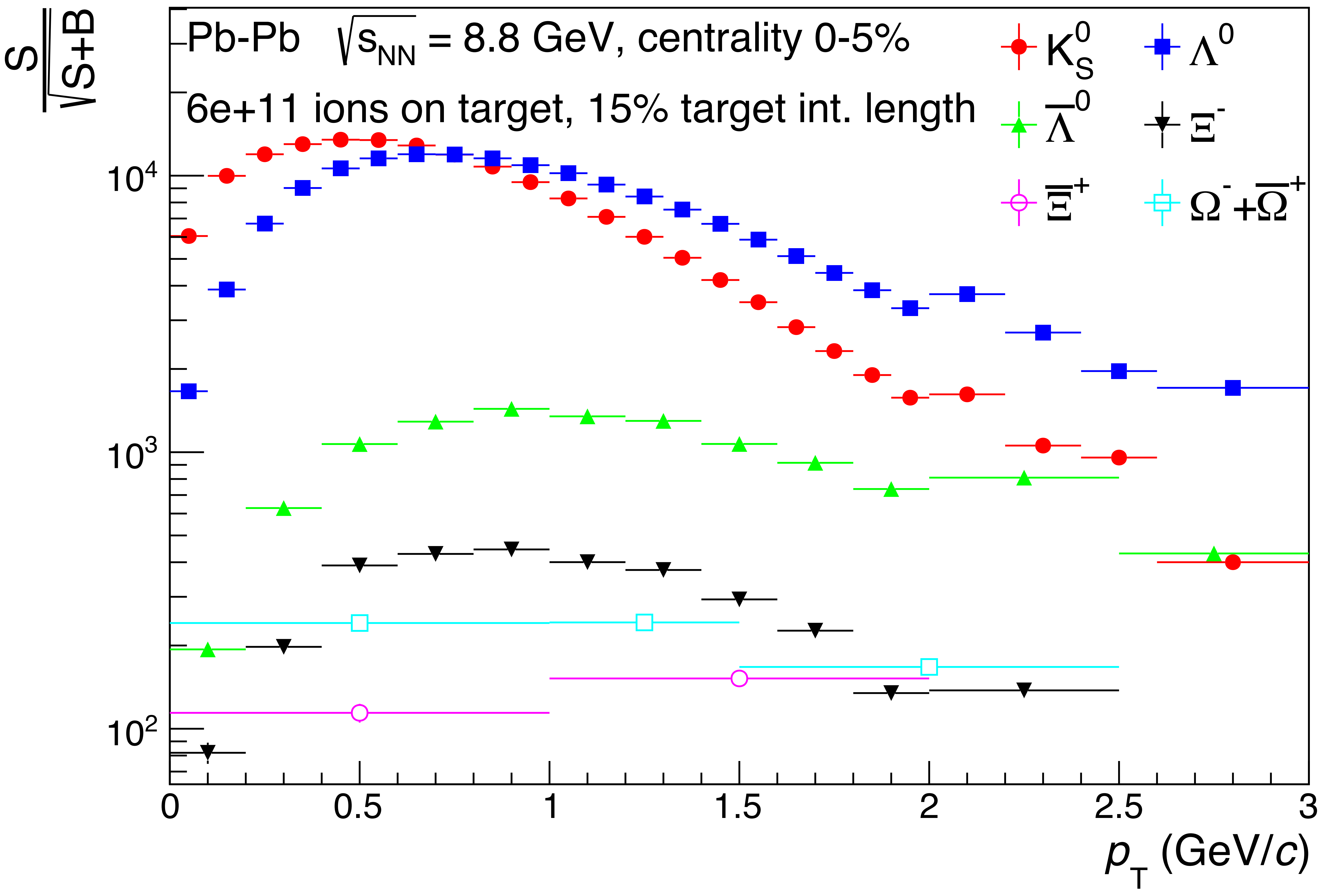




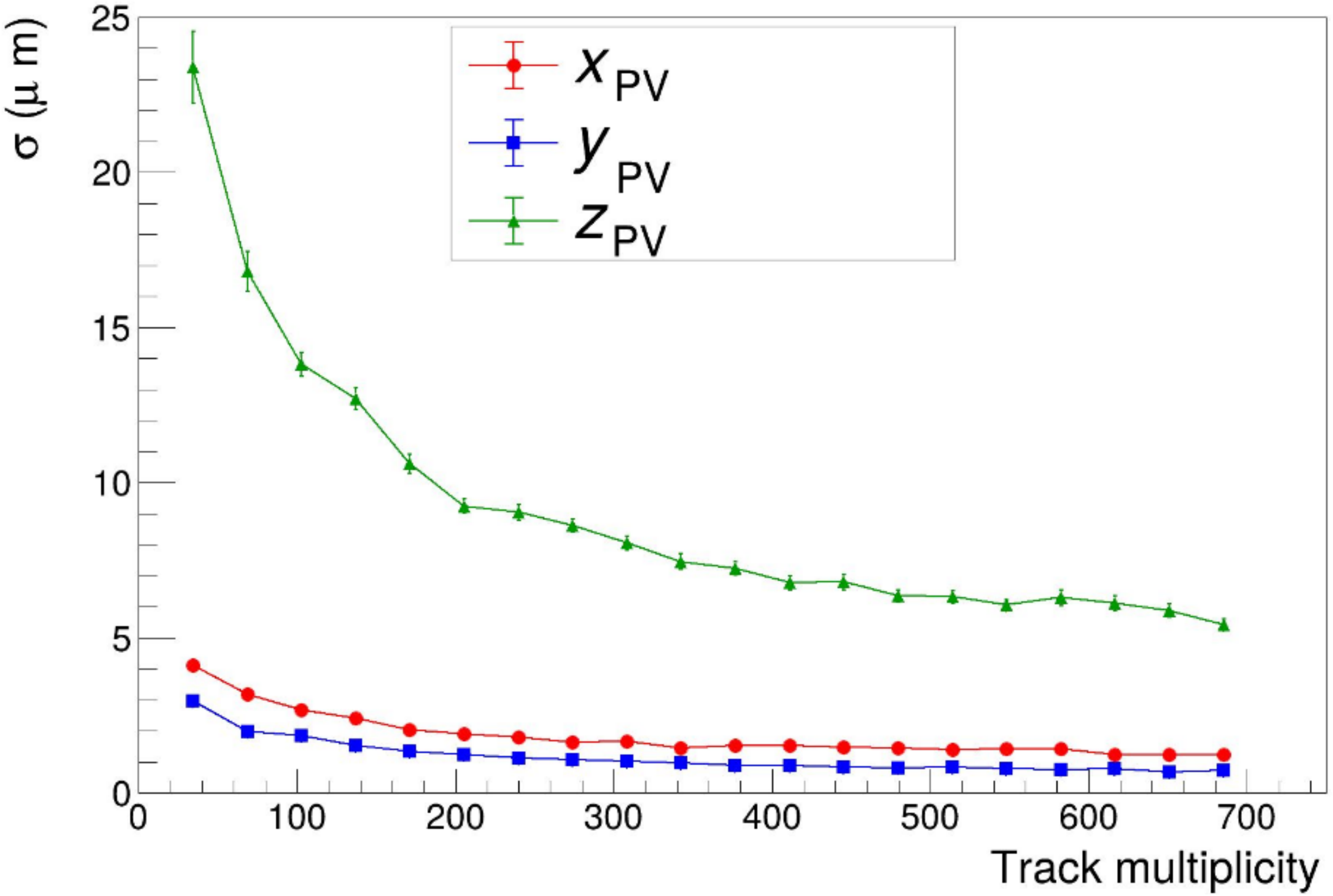
Strangeness production



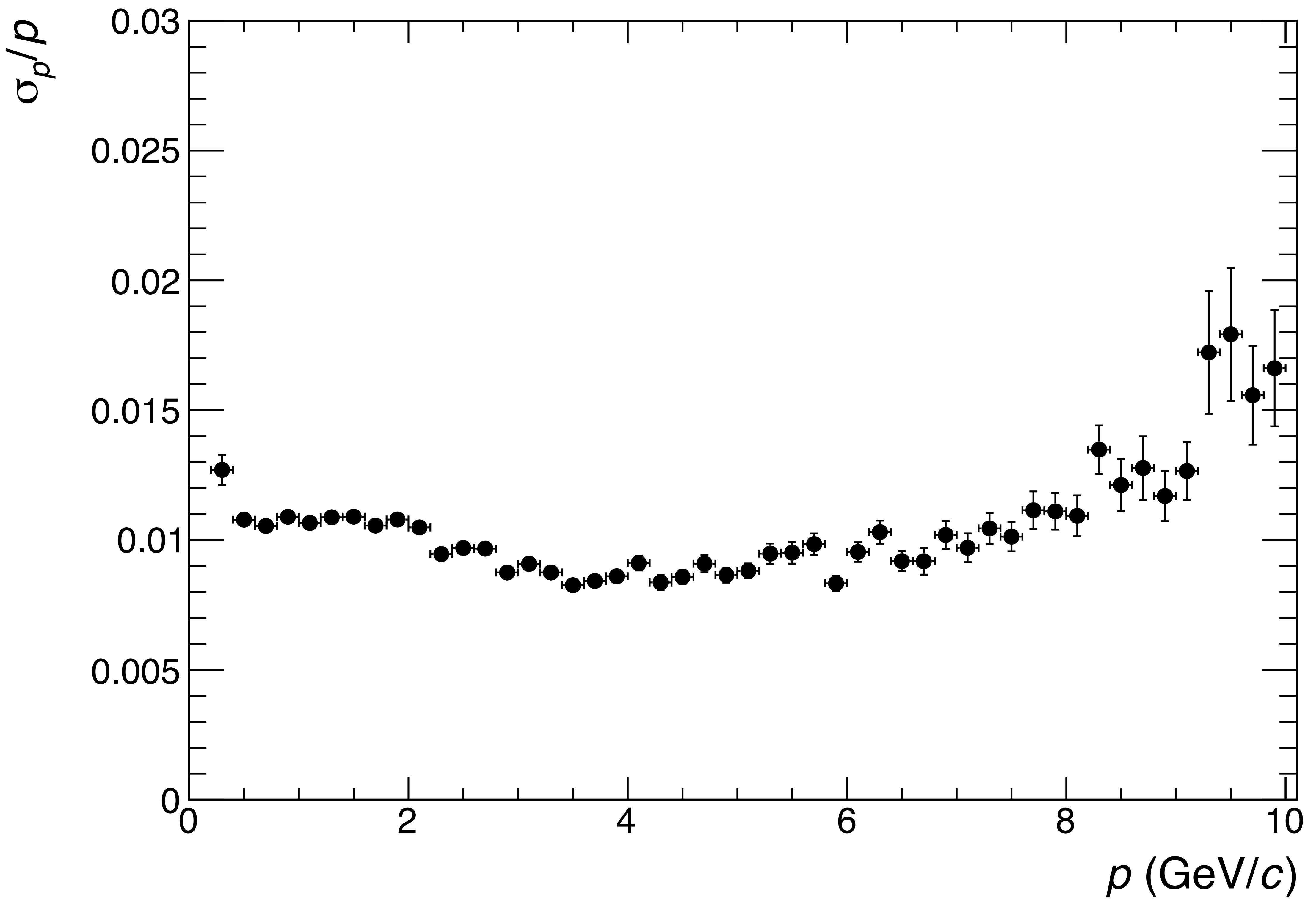


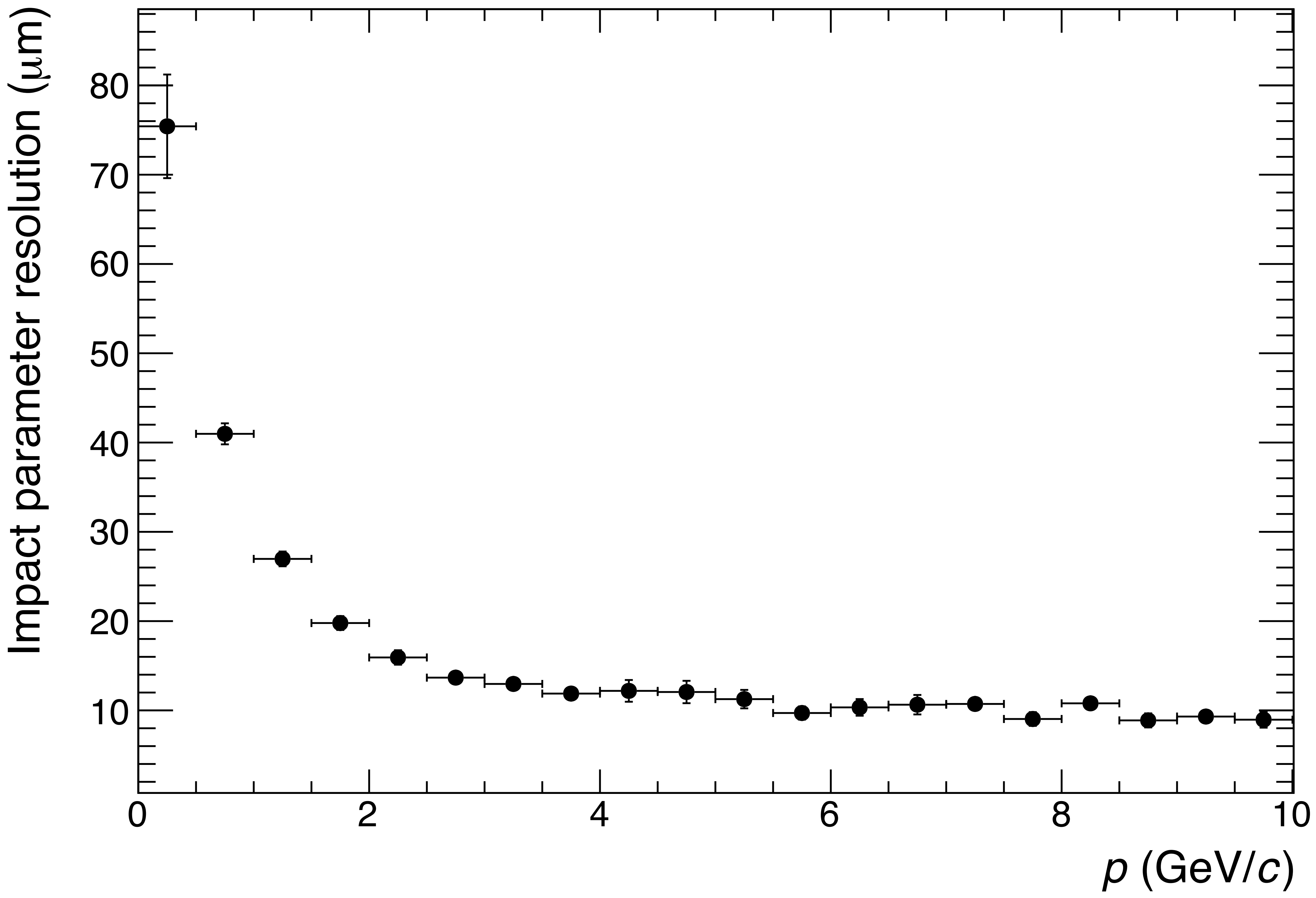


Primary vertex resolution in the vertex spectrometer



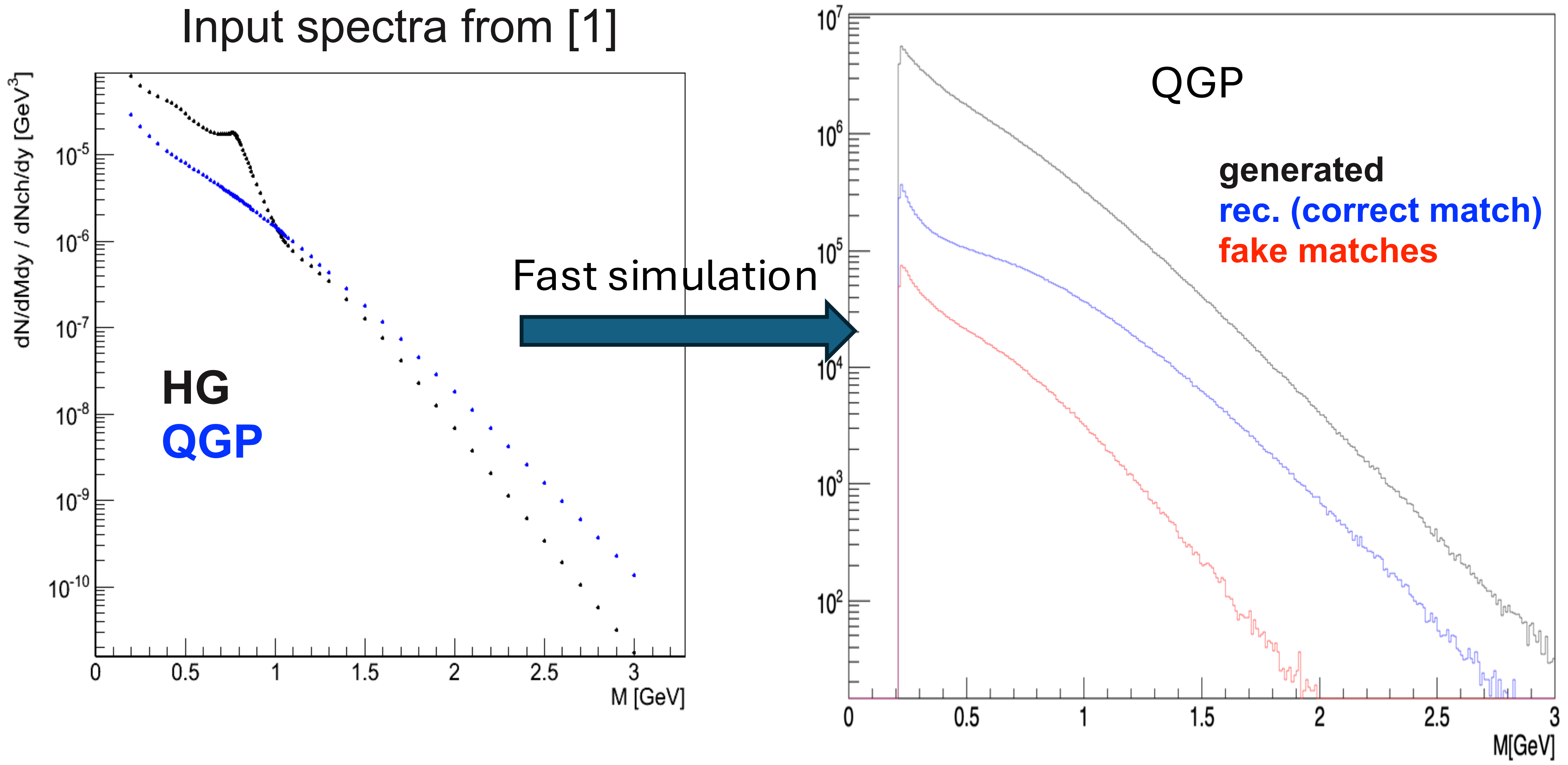
Momentum and impact parameter resolution



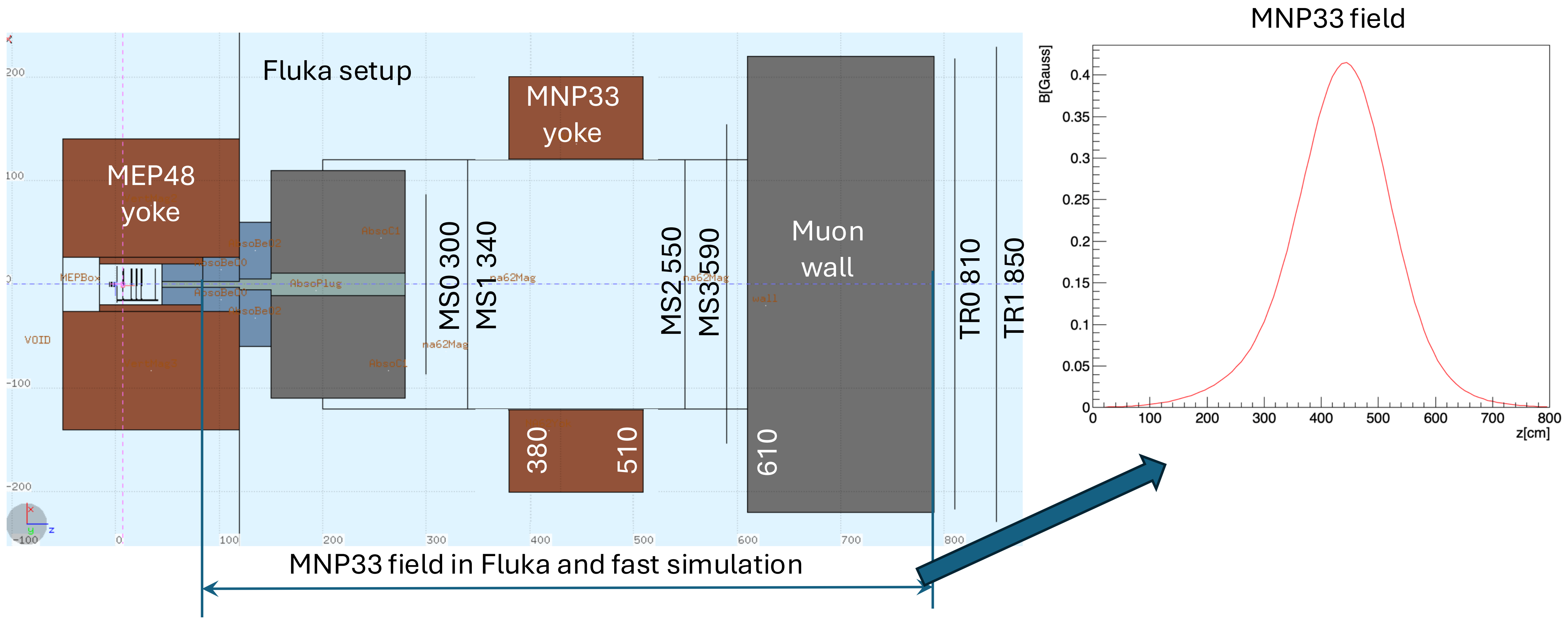


Simulations for thermal radiation

- Thermal radiation: calculations by Rapp and van Hees [1]
  - HG radiation based on in-medium ρ and ω spectral functions
  - QGP radiation based on lattice-QCD constrained rate
- Propagation of tracks to vertex with Kalman filter
  - Vertex telescope is populated with hits from hadrons using SPS measurements [2]

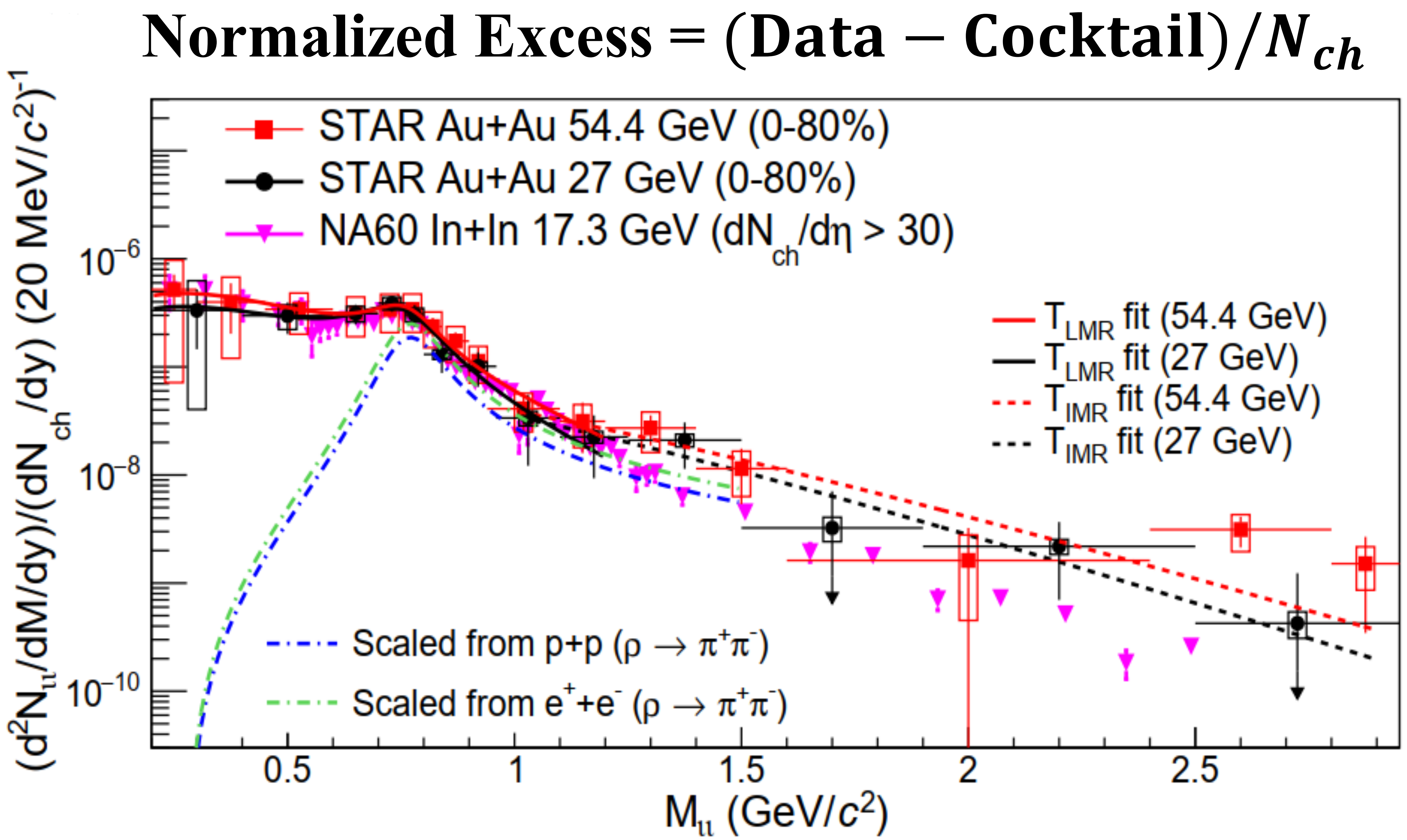


Background estimations with FLUKA
- Primary π±, K±, p generated in 1.5 < y < 4.5 following measurements at SPS [2]
- Di-track background shape is estimated by sampling momentum distributions of charged tracks and by convoluting it with single-track rec. efficiencies



[1] Phys. Lett. B 753 (2016) 586
[2] Phys. Lett. B 530 (2002) 33, Phys. Lett. B 530 (2002) 43

STAR results at 27 and 54.4 GeV



Collisions System	T at LMR (MeV)	T at IMR (MeV)
54.4 GeV Au+Au	172 ± 12 (stat.) ± 18 (sys.)	303 ± 59 (stat.) ± 28 (sys.)
27 GeV Au+Au	167 ± 21 (stat.) ± 18 (sys.)	280 ± 64 (stat.) ± 10 (sys.)
17.3 GeV In+In	165 ± 4	245 ± 17

Low Mass Region

$$(a * BW + b * M^{3/2}) \times e^{-M/T}$$

- Similar T_{LMR} for STAR and NA60 measurements
- T_{LMR} ~ pseudo critical temperature T_{pc} (156 MeV)

Intermediate Mass Region

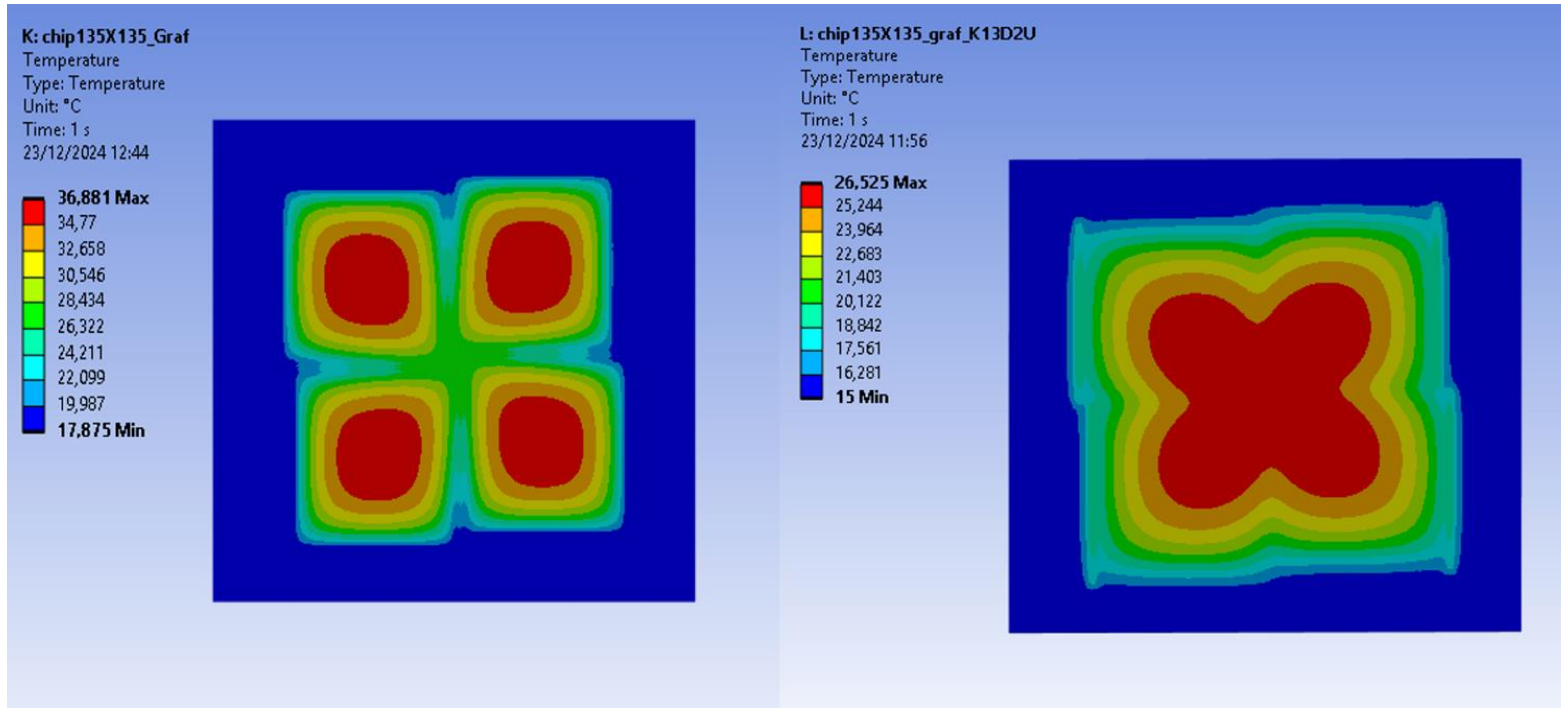
$$M^{3/2} \times e^{-M/T}$$

- QGP thermal radiation is predicted to be the dominant source
- T_{IMR} is **higher** than T_{pc}

STAR, arXiv: 2402.01998
NA60: EPJC 59, 607–623 (2009)
T_{pc}: HotQCD, Phys. Lett. B 795, 15-21 (2019)

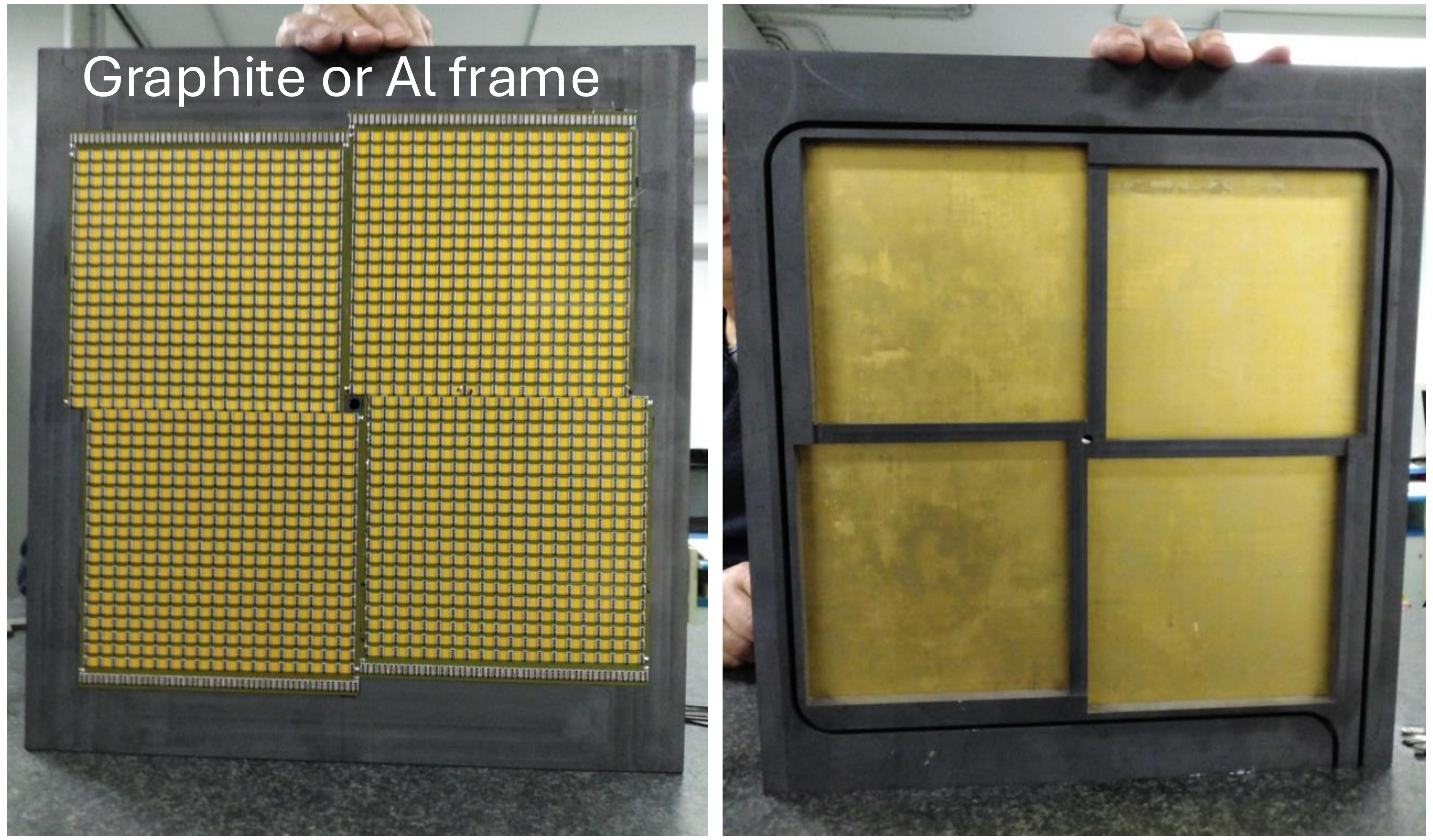
Cooling & mechanics of vertex telescope

- Cooling imposes constraints to the mechanical system:
  - 40 mW/cm^2 power dissipation in pixel matrix (+ 790 mW/cm^2 in periphery)
  - Goal 25 °C over sensor surface



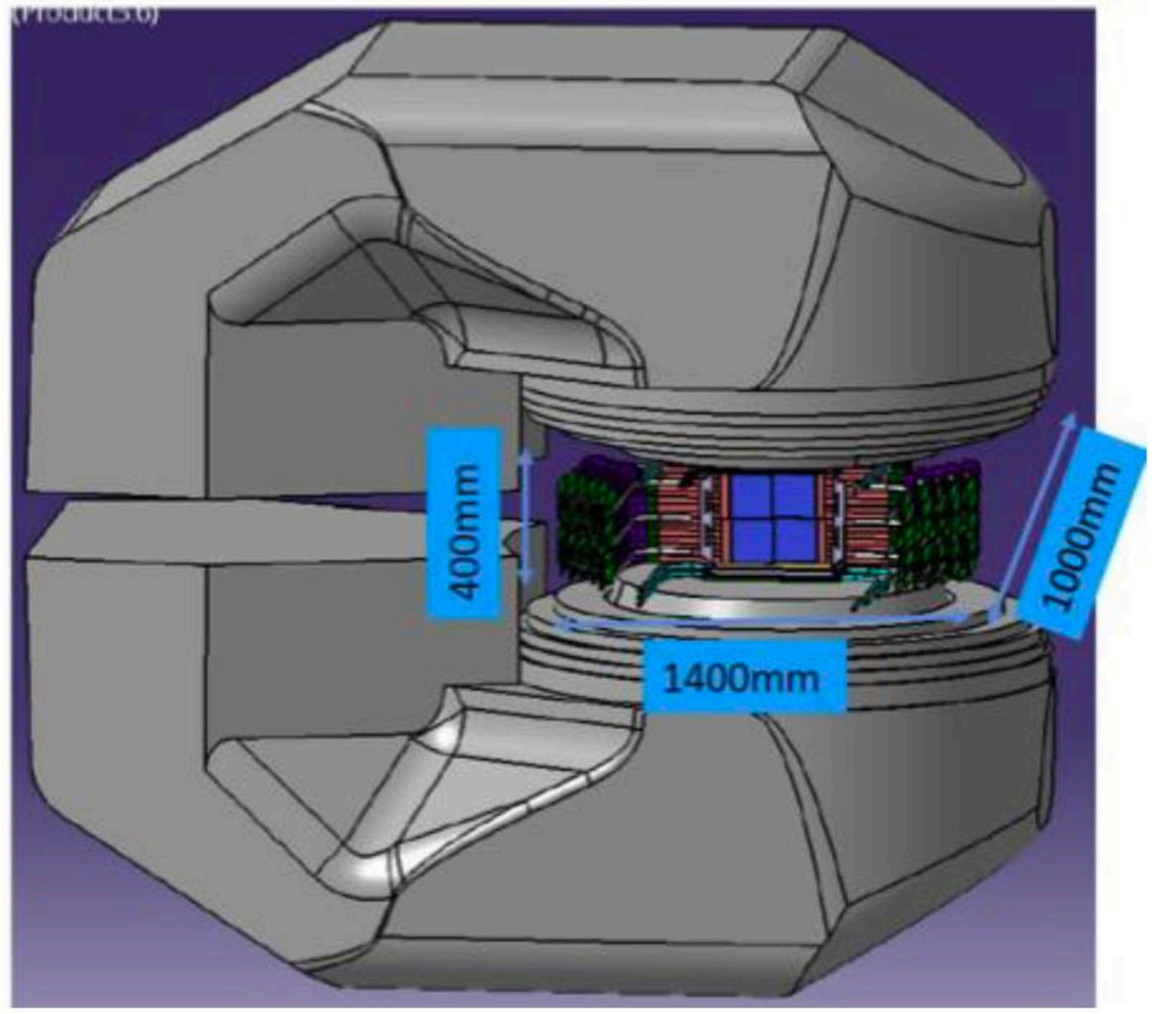
- COMSOL/ANSYS simulations:
  - Mixed water (18-20 °C)+ air cooling (1-2 m/s)
  - 0.4 mm carbon fiber substrate to improve heat dissipation in larger planes

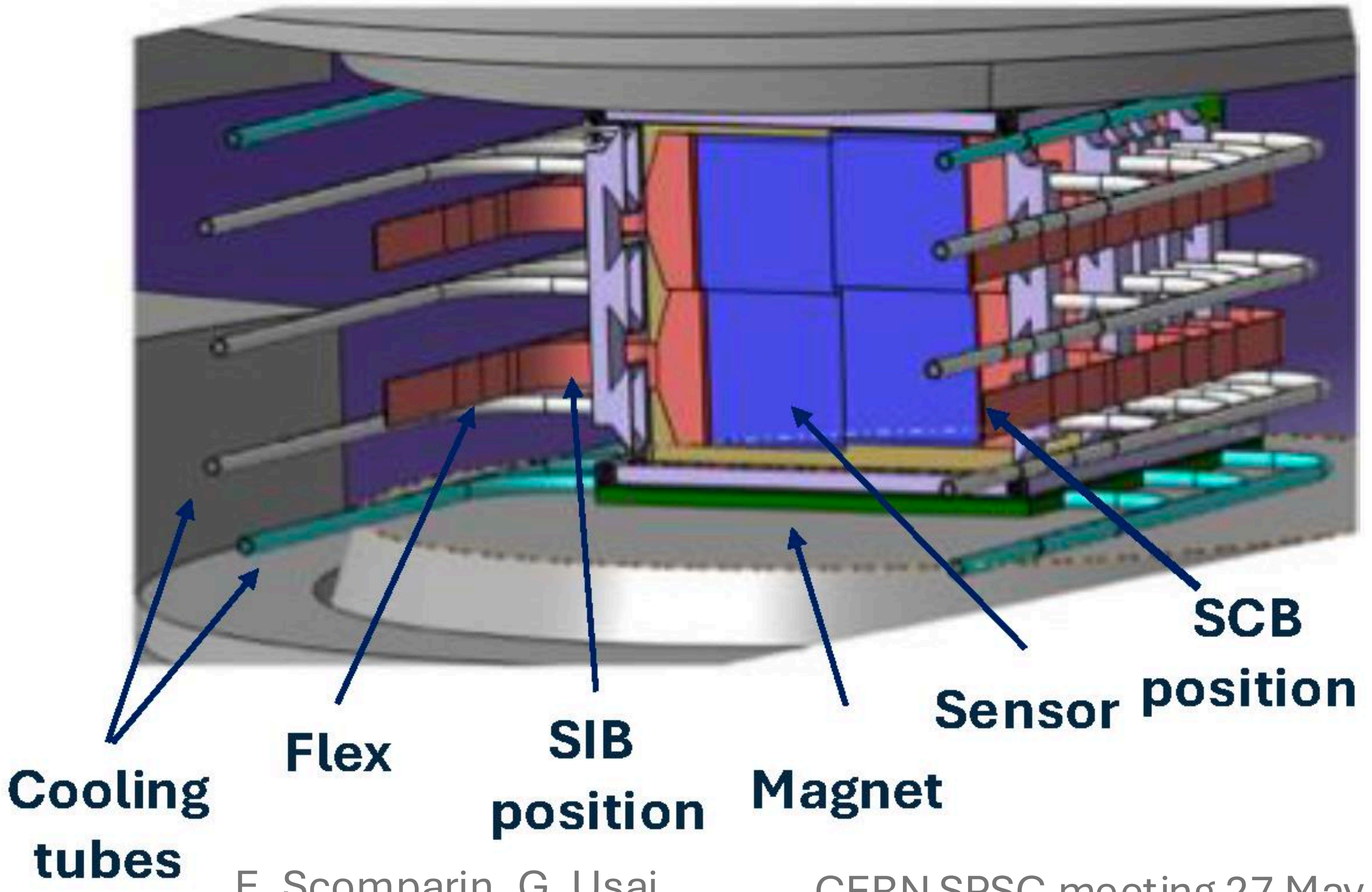
- Carbon fiber substrate glued on periphery frame (graphite or aluminum):
  - Machined groove to accommodate a stainless steel pipe for water cooling



- Simulations calibrated on a test set-up:
  - PCBs with resistor arrays mounted on graphite frame to mimic power dissipation

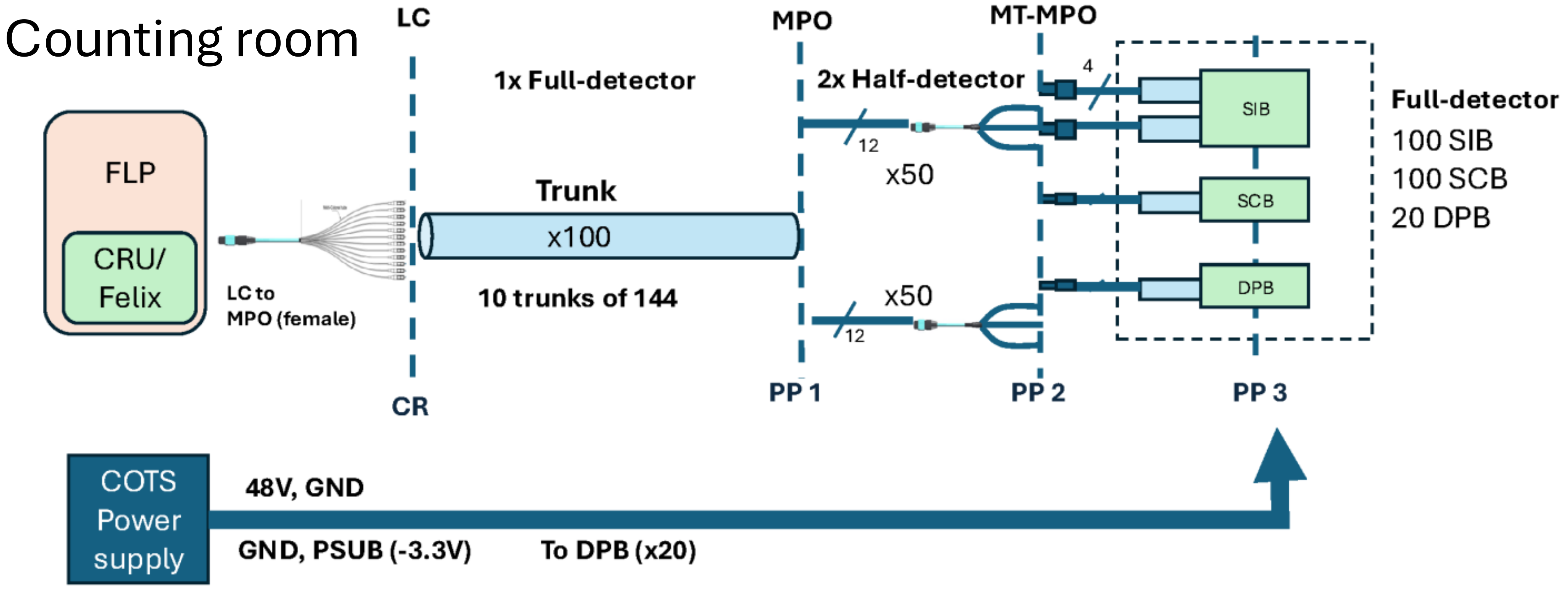
Vertex spectrometer: compact integration





E. Scomparin, G. Usai

CERN SPSC meeting 27 May 2025

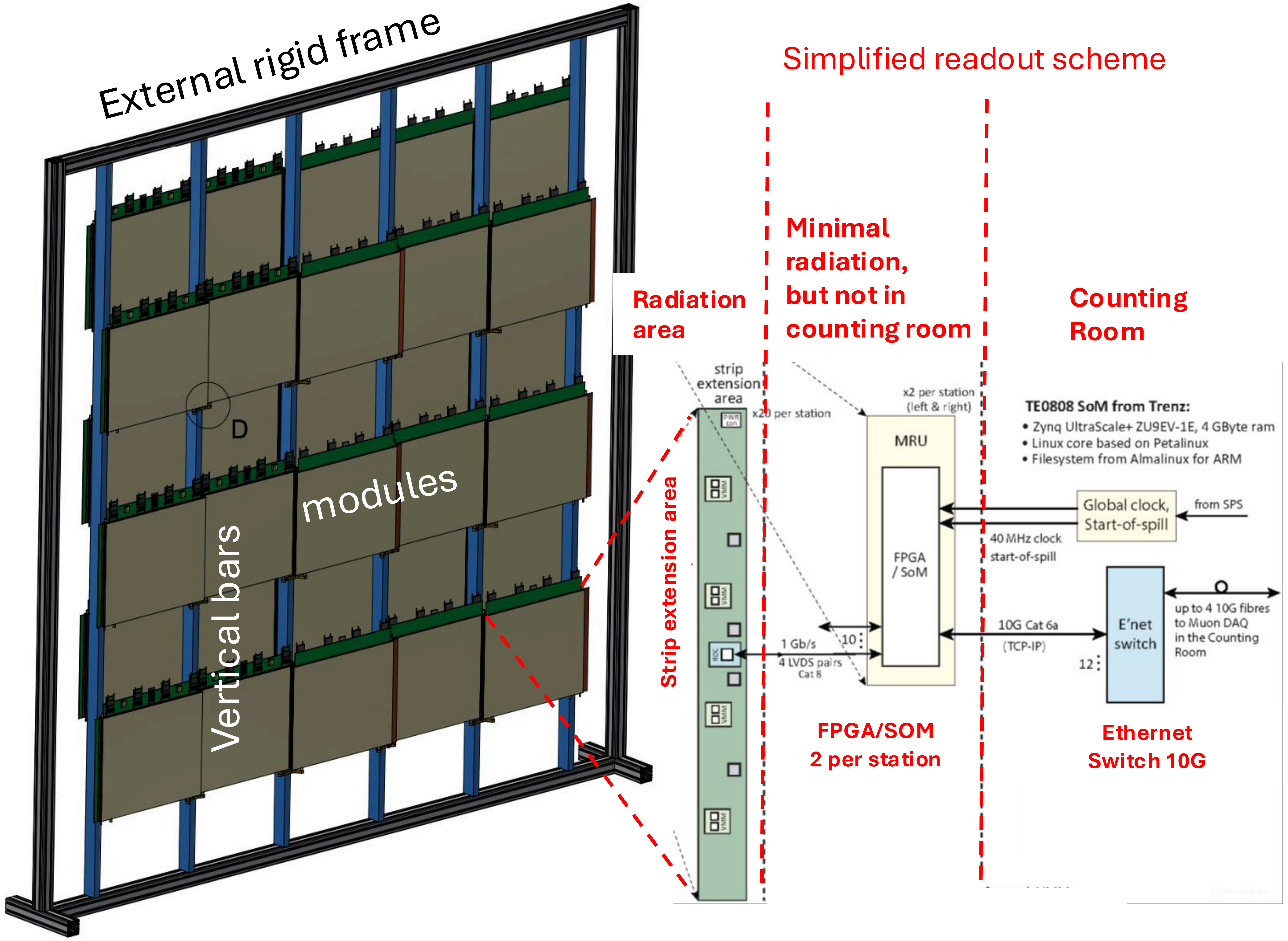


- Versatile Link+ system for readout and DCS:
  - Bidirectional high-speed 10 Gb/s optical communication system
  - minimal on-detector footprint (only Electric to Optical conversion and low-voltage power boards)
  - Optical fibers connect directly to counting room
- Counting room:
  - 35 CRU/FELIX hosted in First Level Processors (FLPs)
  - Powering with CAEN mainframe SY4527 with OPC server and gigabit Ethernet hosting
- System of pipes for air and water cooling:
  - Air compressed and chillers included in integration study

12

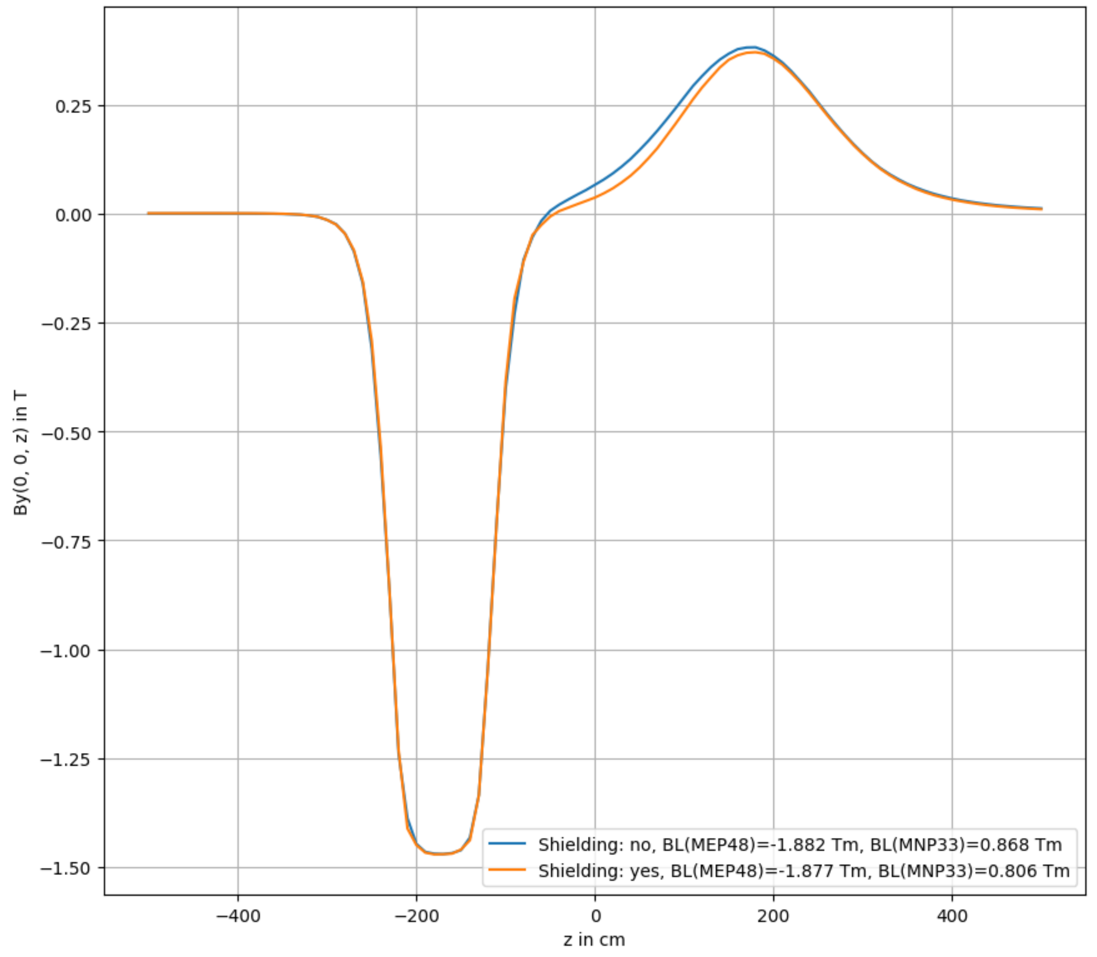
Muon station assembly and integration

- ❑ Preliminary layout of the MS station:
  - Rigid frame outside acceptance
  - Chambers aligned on rows mounted on vertical bars
- ❑ Gas distribution and HV:
  - 100 l/h all stations (standard bottle/2 days)
  - Standard HV multichannel CAEN housed in mainframe
- ❑ Readout:
  - SOM FPGA with Linux system
    - Transfer data to/from CR via 10G Ethernet optical link
  - Single Ethernet switch in counting room with 24 10 Gbit/s optical fibre ports



The magnets system

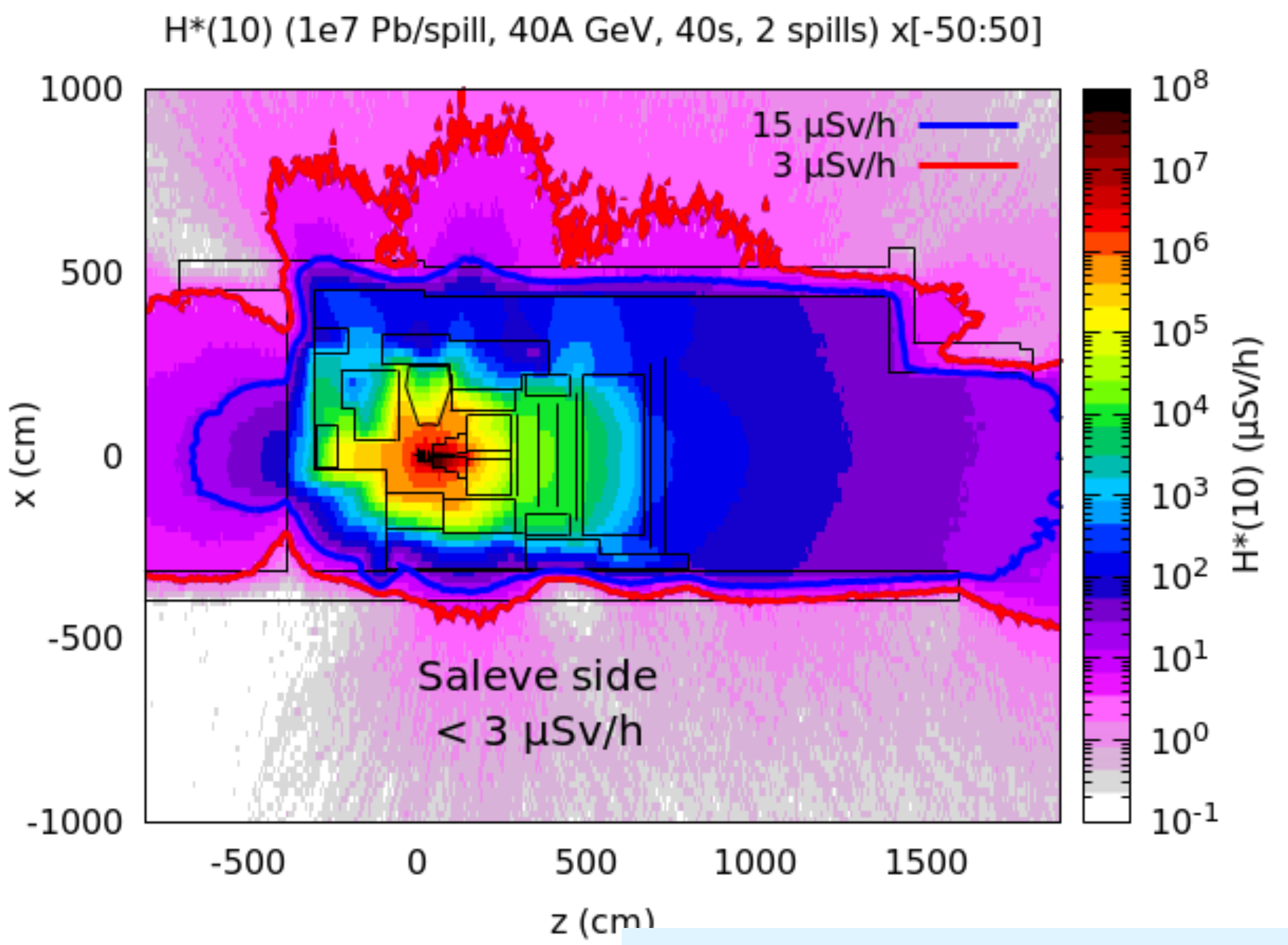
- ❑ MEP48 dipole is proposed for the vertex spectrometer:
  - 40 cm gap, round pole tips 1 m diameter
  - 1.47 T@2000 max current
  - Power 400 kW
- ❑ MNP33 dipole is proposed for the muon spectrometer:
  - 2400 mm gap, 2450 mm aperture width
  - 2 coils: 0.9 Tm @1250+2500A max current
  - Power 2.3 MW
  - Already mounted on rails
- ❑ Powering :
  - Run4: existing power converters in BA81
  - Run5: 3 new BOREAL to be installed in BA81 (LS4)
- ❑ Cooling:
  - 2 m^3/h water (MEP48) - 56 m3/h (MNP33) water - feasible
- ❑ MEP48 refurbishment (tbd in LS3):
  - Short in lower coil. Tooling prepared to replace both coils
- ❑ Missing parts (tbd in LS3):
  - Transport attachments from ECN3 to EHN1-H8
  - 400 V / 2000 A feeder in BA81 (used for both)

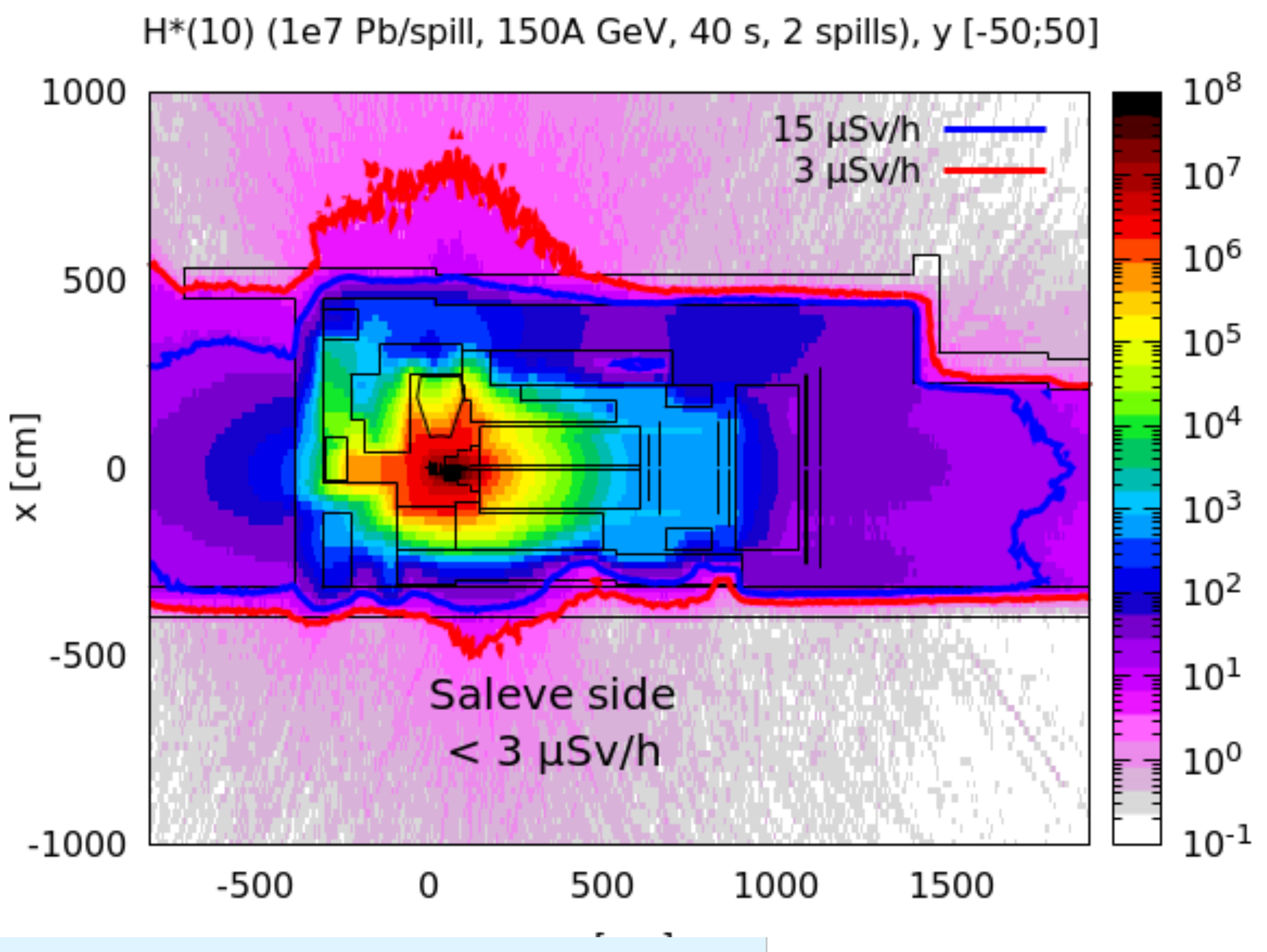


- ❑ MEP48+MNP33 field map:
  - Simulation including also iron shielding

Shielding for radiation protection

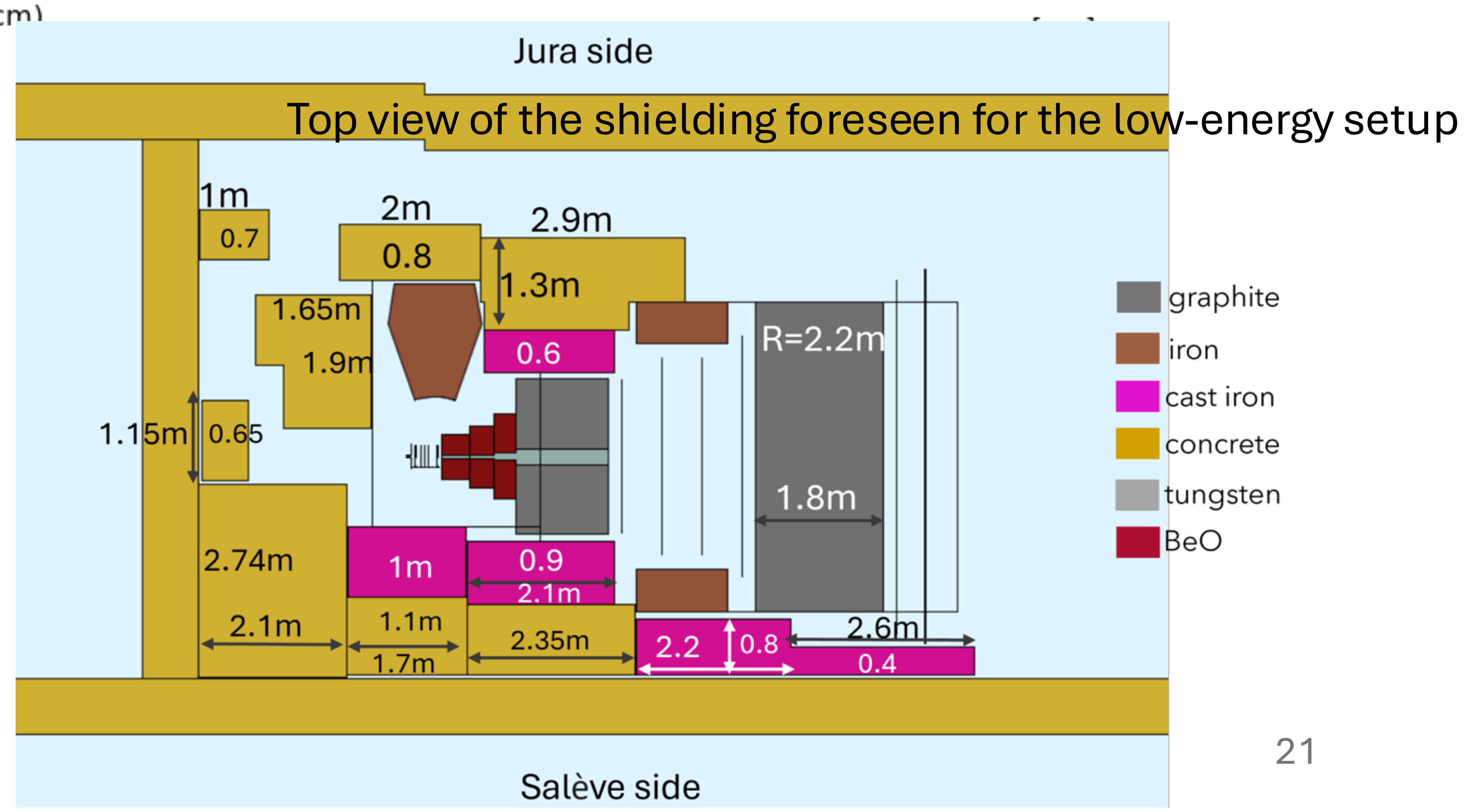
- Operation with 40 GeV/c and 150 GeV/c high intensity p and Pb beams :
  - average beam intensity of 5×10^5 Pb ions/s and 10^8 p/s over full SPS cycle → RP studied with FLUKA





- Goal:
  - 3 µSv/h on Saleve side (CRs)
  - 15 µSv/h on Jura side (classified as a Supervised Area)

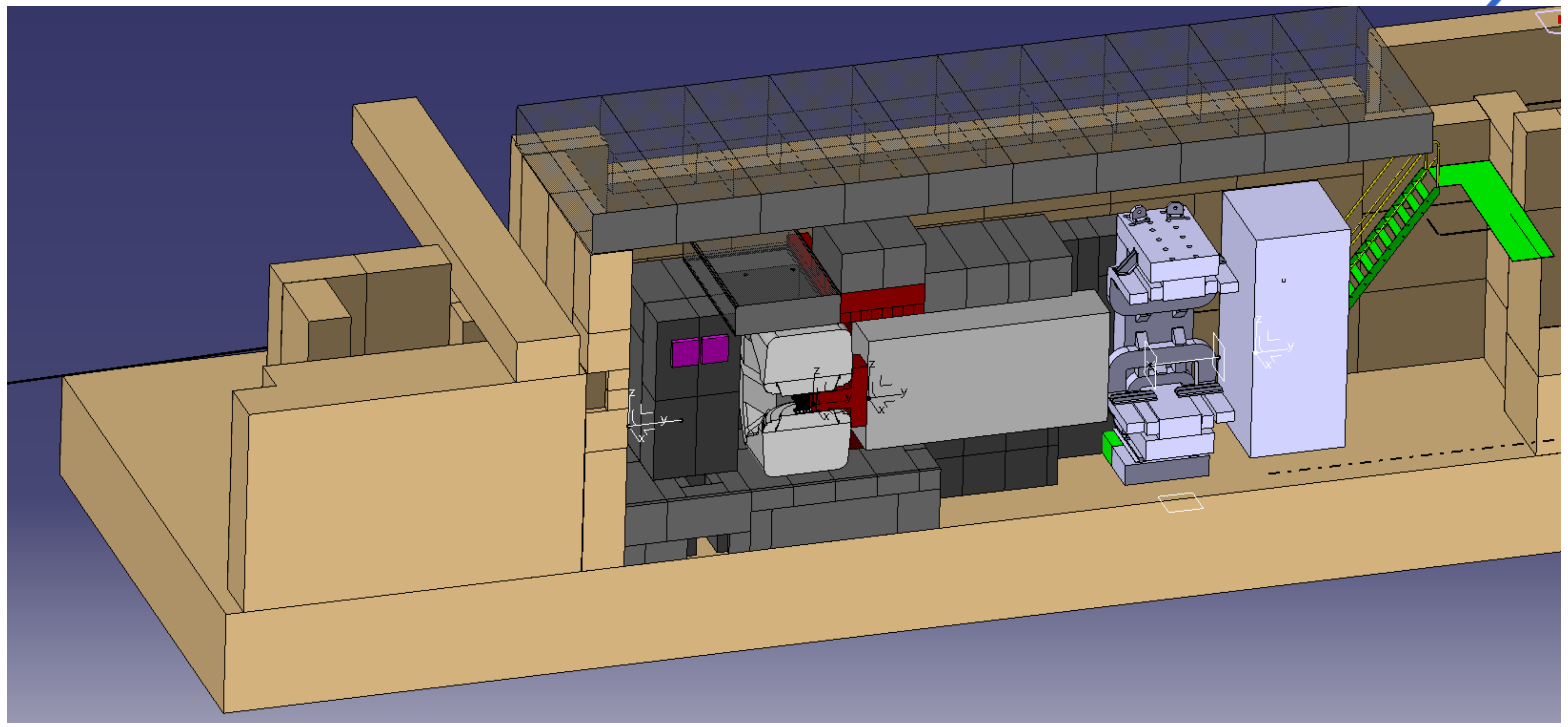
- Shielding around the target and behind the Muon Wall:
  - Iron in critical region around the target and absorber
  - Additional concrete shielding
  - Chicane upstream of the target will be added to allow access to the target region
  - Concrete roof spanning the whole experiment setup to reduce sky-shine radiation

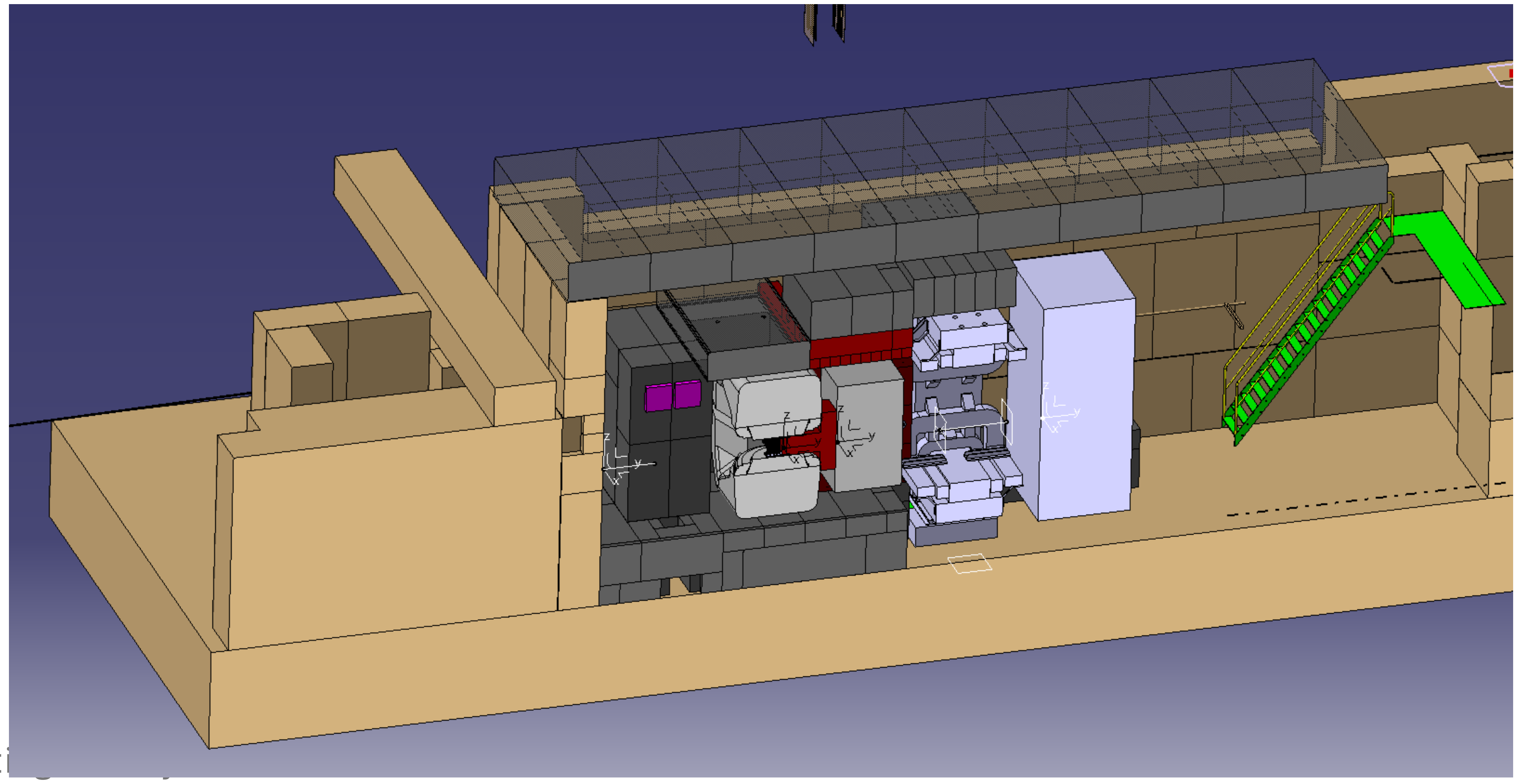


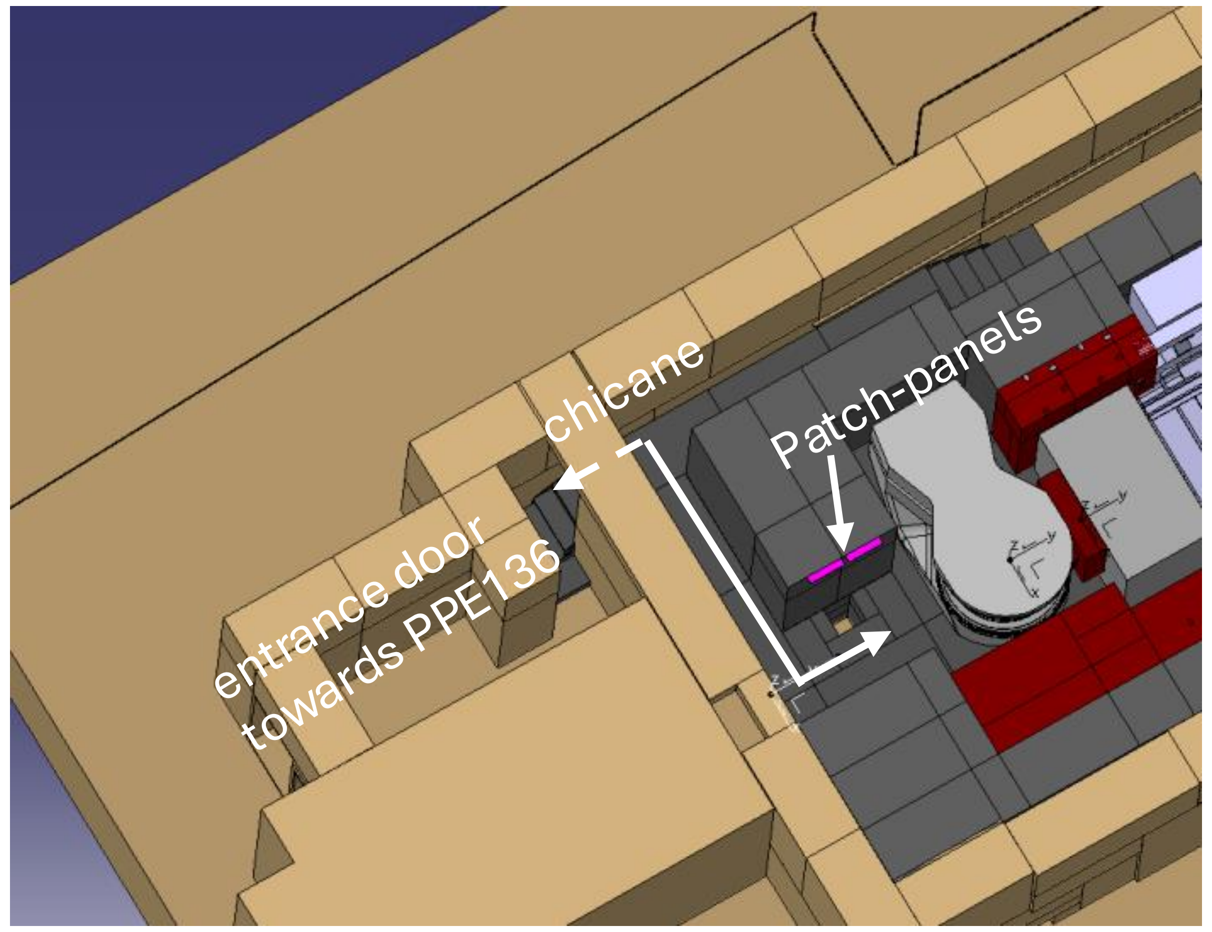
→ Defined shielding meets the requirements

PPE138: integration layout

- ❑ Full experiment and shielding expected to fit mostly within the current footprint of PPE138
- ❑ Integration under detailed study:
  - o Changes in area:
    - ▪ Racks, cable trays, access doors, stairs, ecc.
  - o Magnet powering and cooling
  - o Detector services: power, gas, water, data cables
  - o Alignment supports
  - o New RP monitors





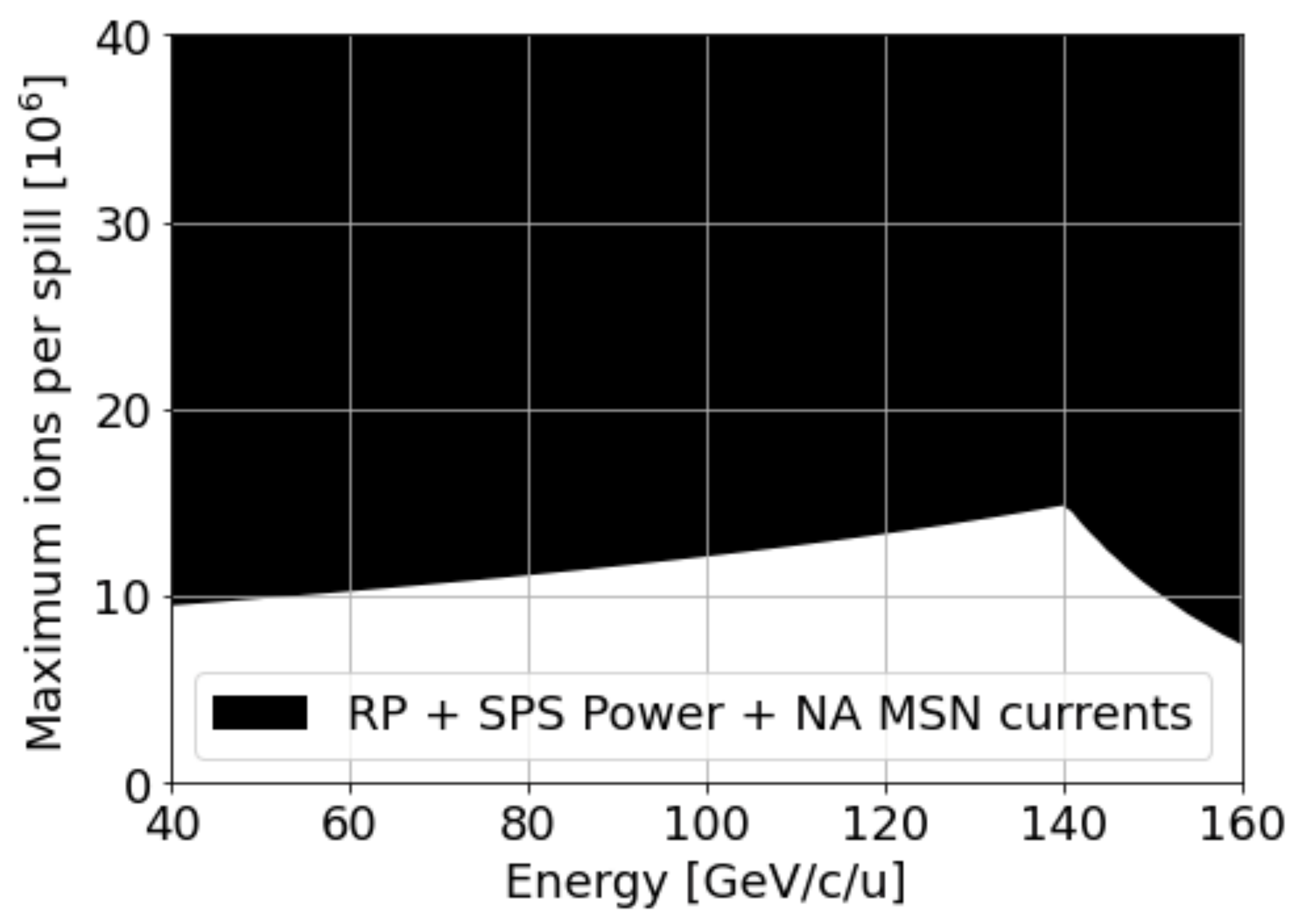


E. Scomparin, G. Usai

CERN SPSC meeti

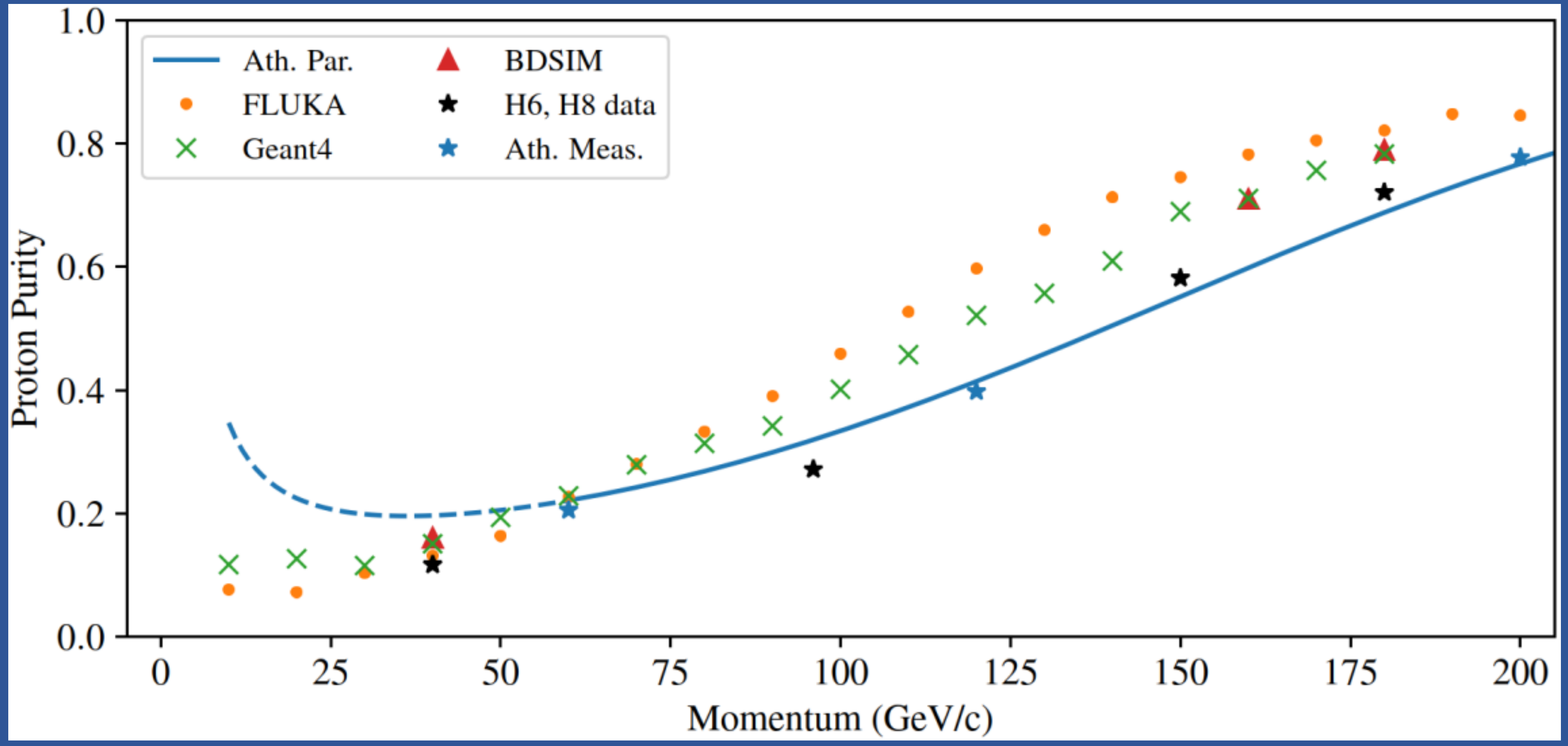
High-intensity Pb and proton beams

Pb



- ❑ Maximum possible **Pb ions/spill ~ 10^7**
- ❑ Estimate of **0.6×10^{12} Pb on target** assuming ~4 weeks running time and realistic machine efficiency (dominated by RP considerations)
- ❑ Interaction probability is 15%, leading to 150 kHz interaction rate → L_{int} ~ 14.7 nb^{-1}

p

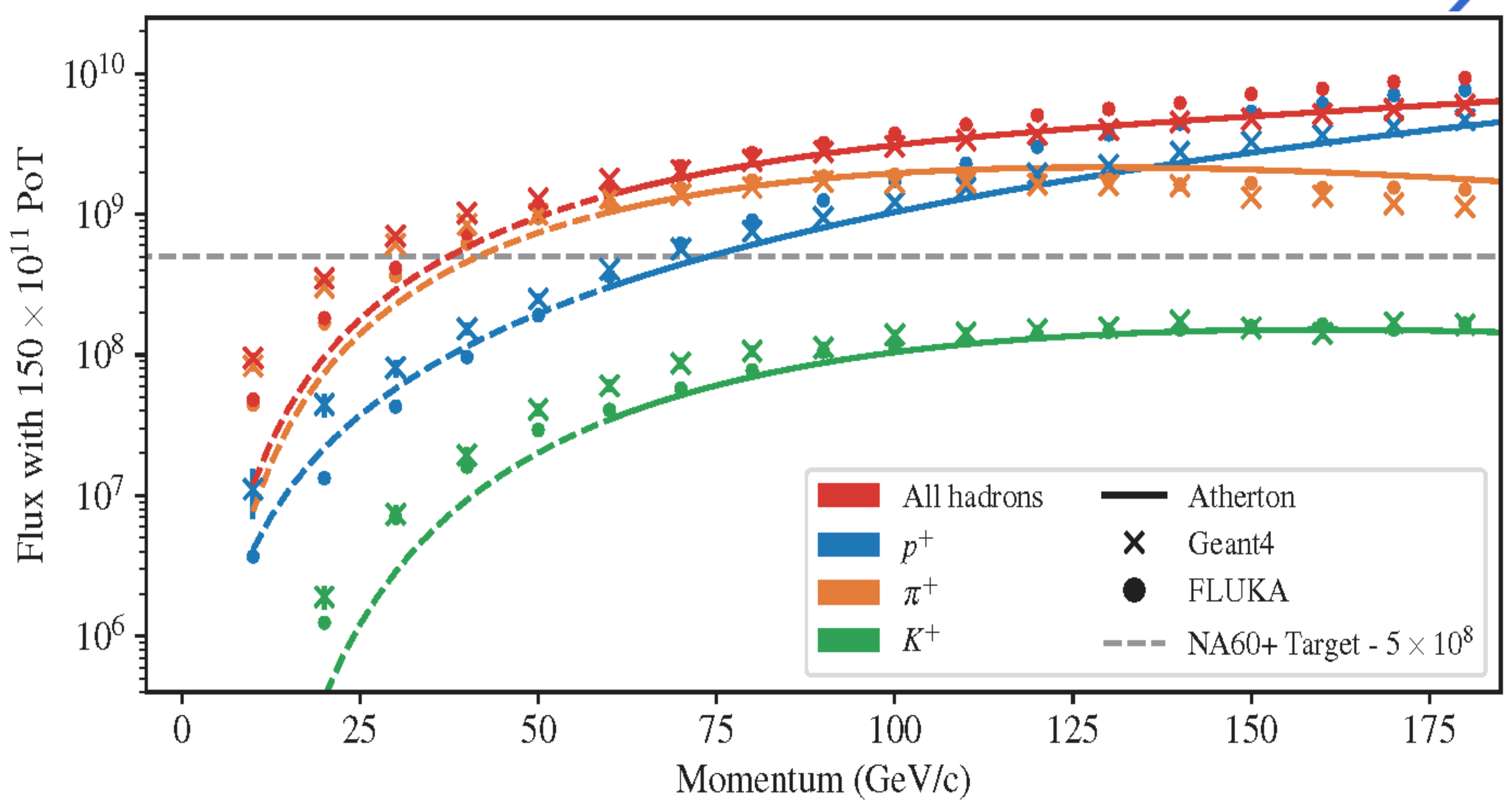


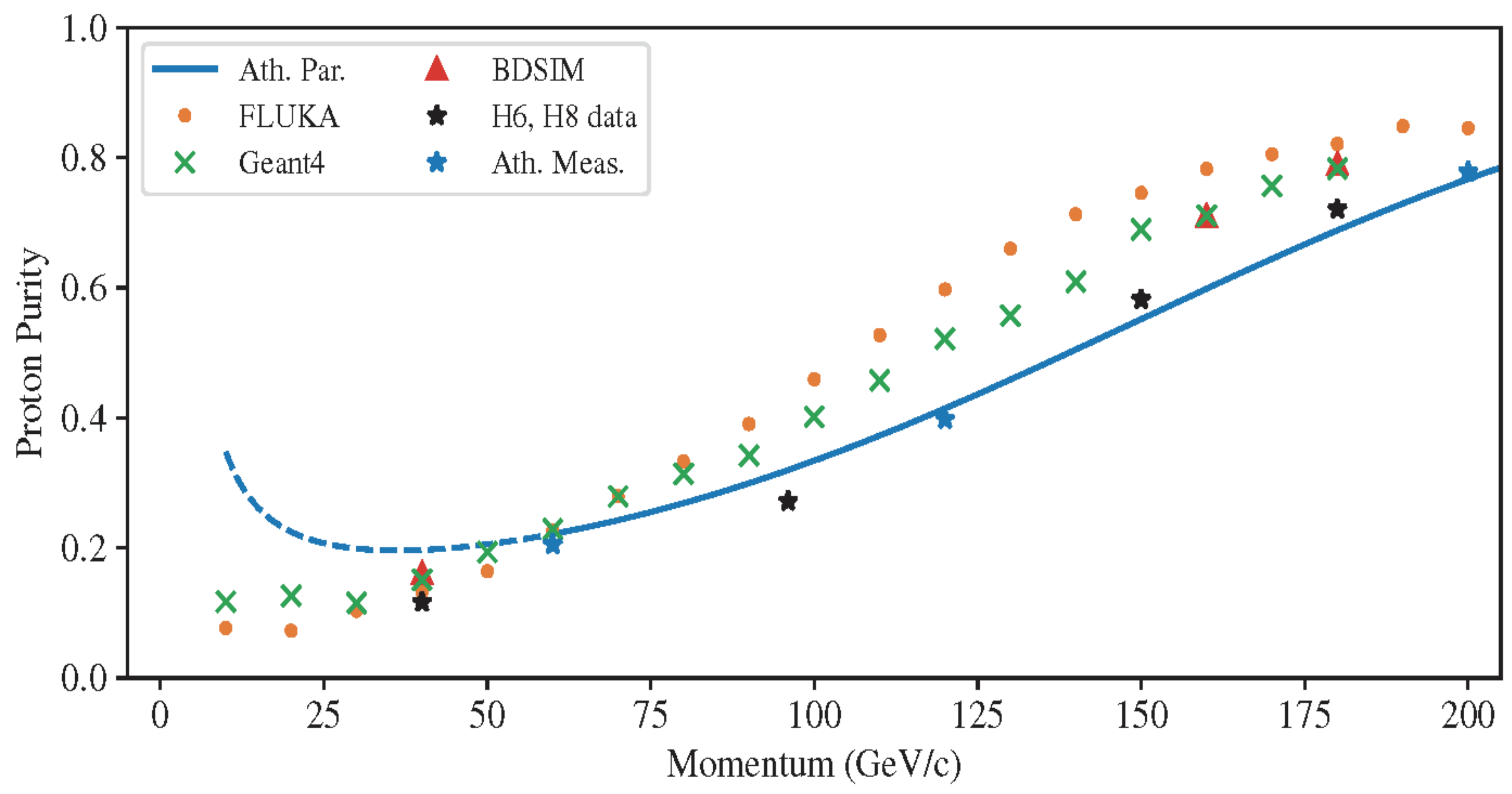
- ❑ Need a similar number of nucleons on targets(s)
- ❑ **Secondary beams** from fragmentation of 400 GeV primary proton beam → insufficient purity and luminosity
- ❑ Use **primary proton beam** from SPS (technical issues under investigation)

Proton beams

- ❑ Protons with energy 20-150 GeV needed for reference:
  - ○ Drell-Yan, J/ψ in pA
  - ○ 5×10^8 p/spill (9 s spill)
- ❑ Possible use of secondary p beams investigated (FLUKA, data):
  - ○ Significant proton intensity drop below 60 GeV/c
  - ○ Very large π, K contamination at all energies
    - ▪ 60%(150 GeV) to 90%(20GeV)

→Complex PID detector with rate performance 3 times better than NA62 KTAG: unrealistic within NA60+/DiCE timeline





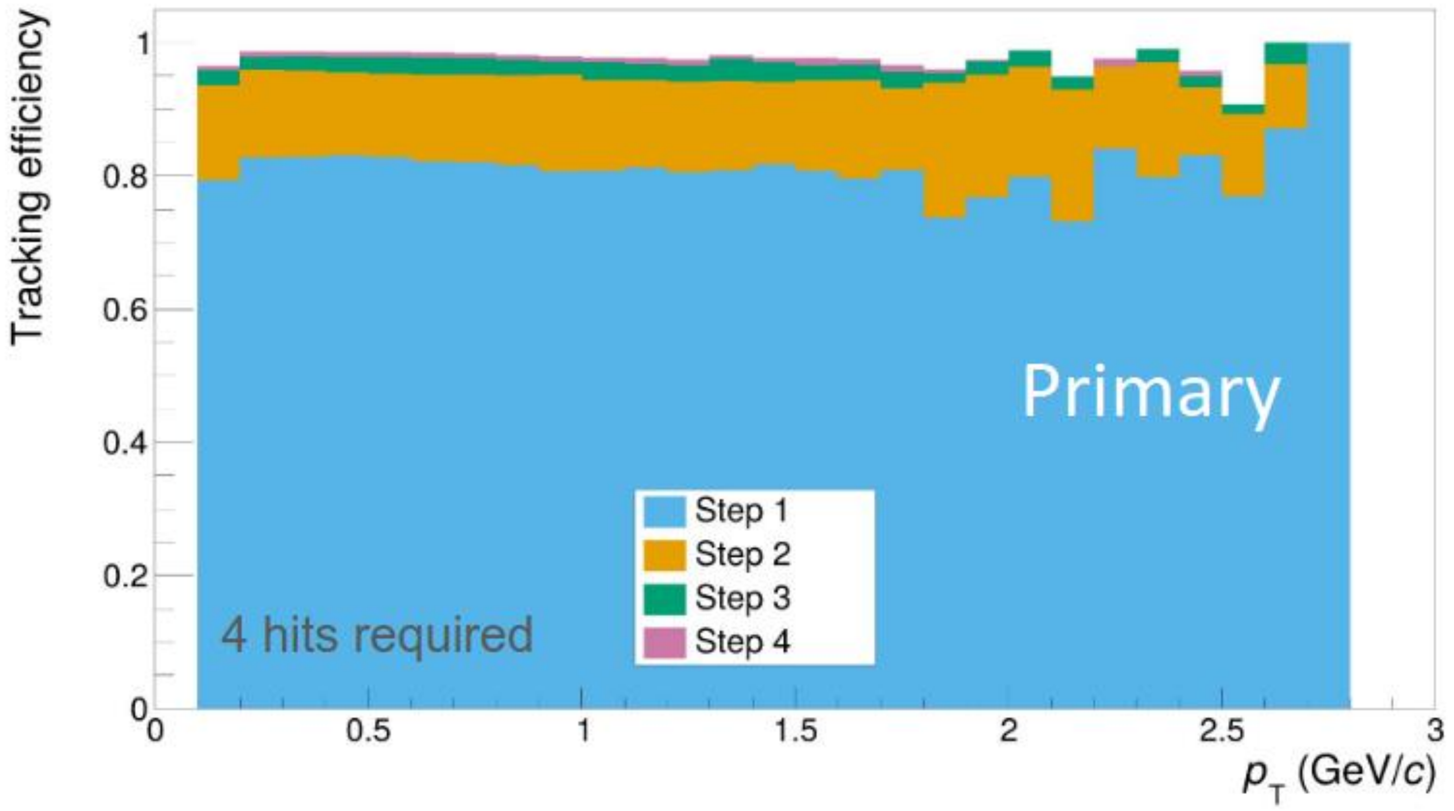
- ❑ Primary protons from the SPS:
- ○ Extraction of low energy protons only feasible under the ion interlock:
  - ▪ Total charge in the ring limited to the equivalent of 2×10^{11} protons
  - ▪ No limitation on the energy
  - ▪ Requires adjustment of a number of imposed software limitations
    →Technical implementation to be investigated

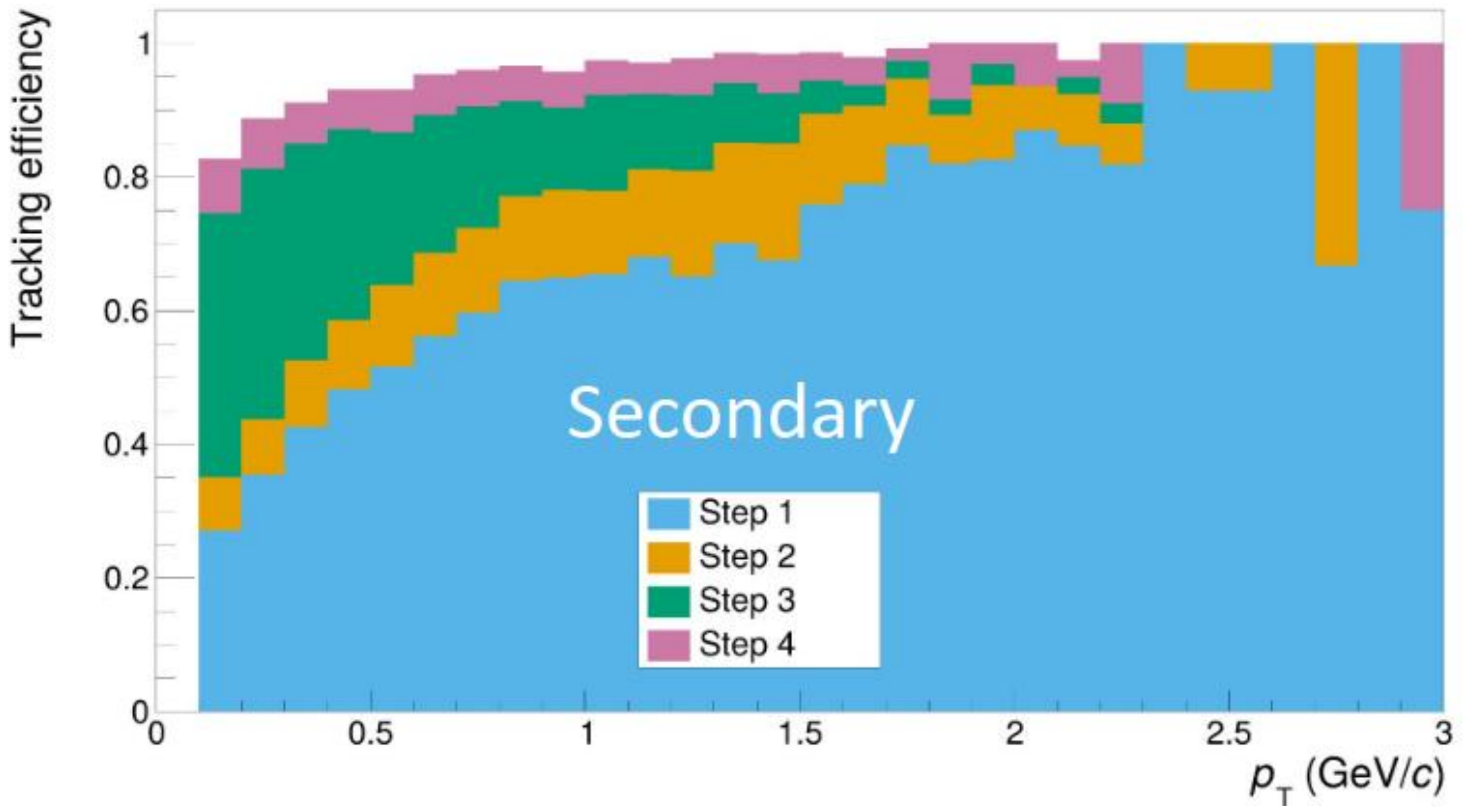
This is presently the baseline option for proton runs proposed by NA60+/DiCE

24

MC, reconstruction and analysis framework

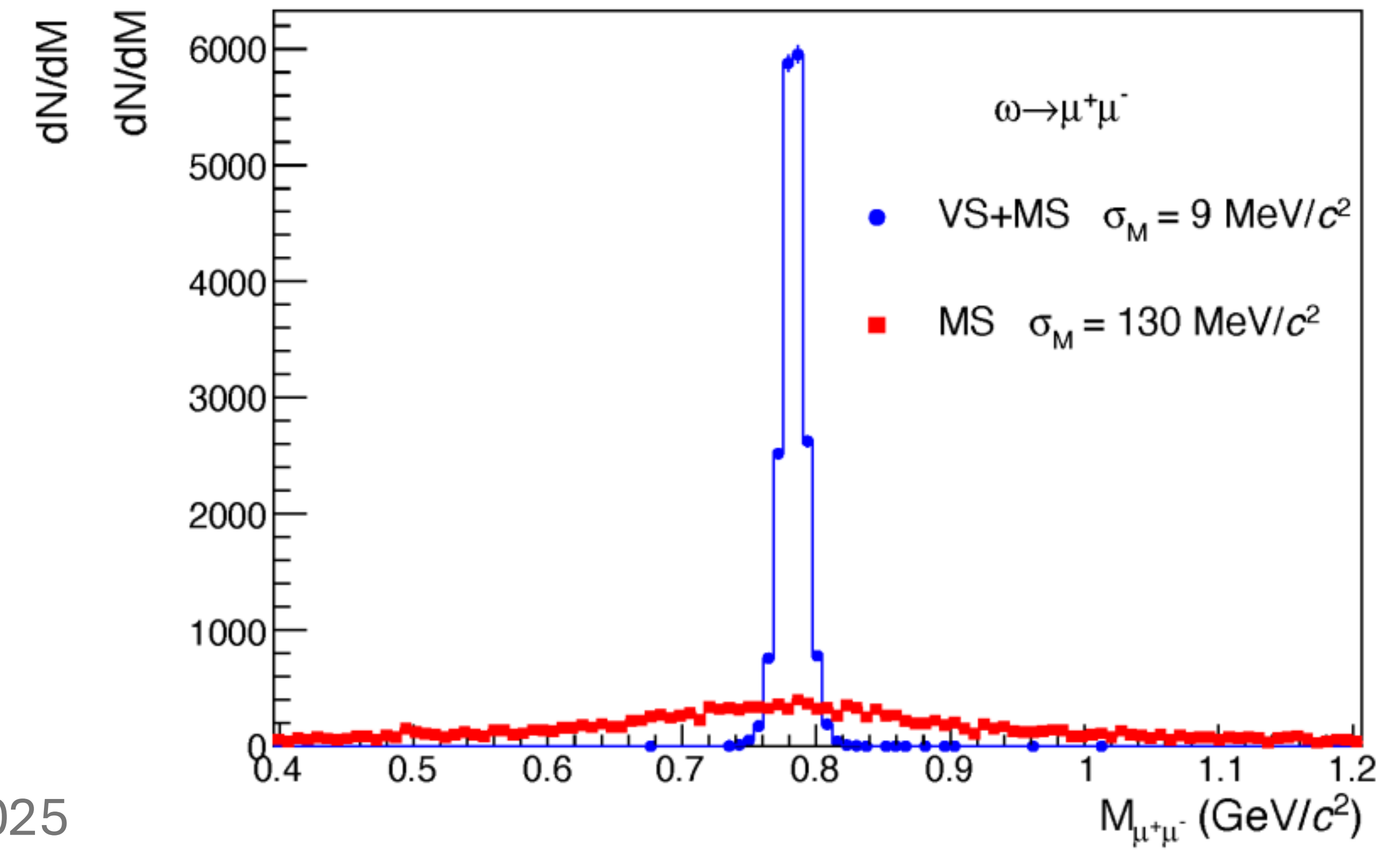
- MC tools:
  - FLUKA and GEANT4 complete frameworks
  - Fast-simulation: semi-analytic particle transport and reconstruction with Kalman filter
- ACTS (A Common Tracking Software):
  - Full track reconstruction

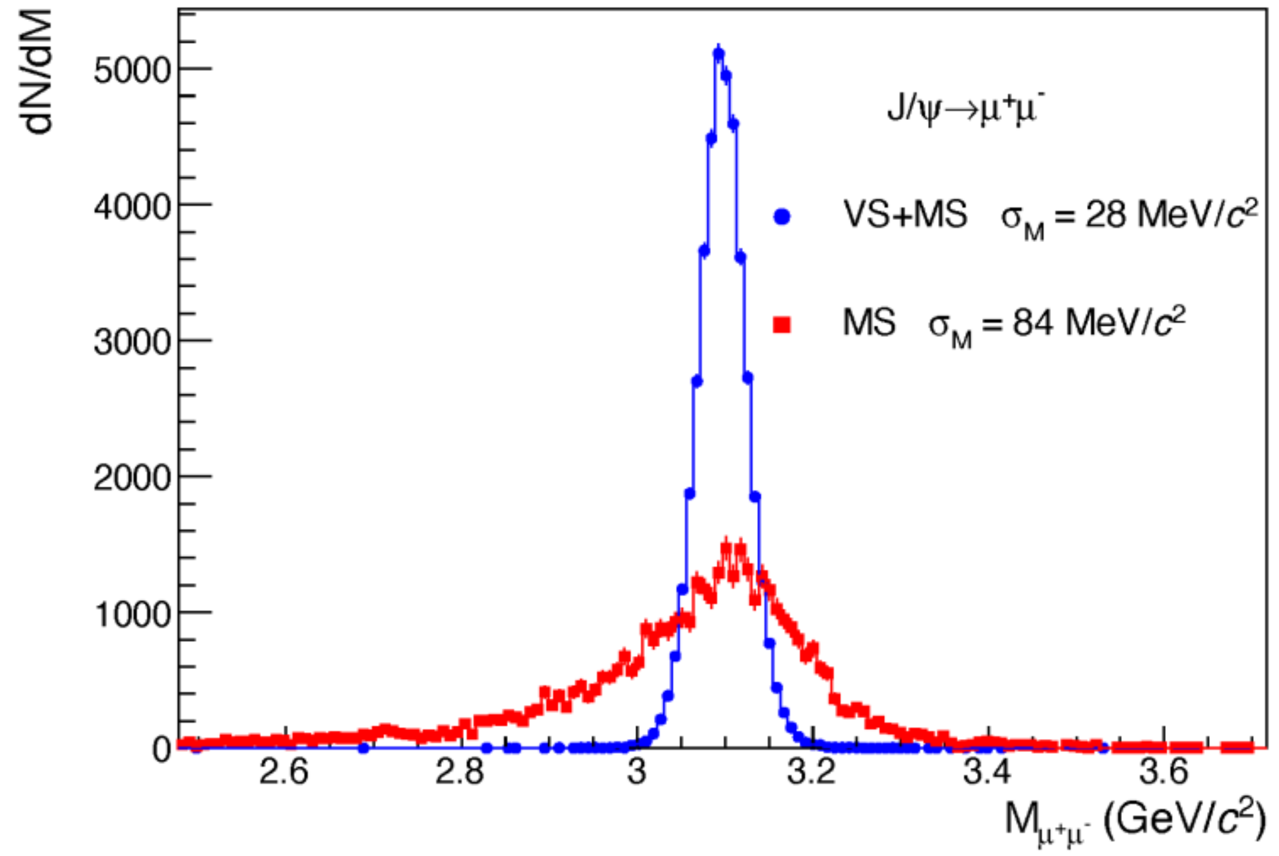




- ACTS: very good track reconstruction efficiency in vertex spectrometer (high multiplicity environment)

- ACTS: MS and VS track matching in momentum and coordinate space:
  - Drastic improvement in muon kinematics
    - $\sigma(\omega)$=9 MeV
    - $\sigma(J/\psi)$=30 MeV





E. Scomparin, G. Usai CERN SPSC meeting 27 May 2025 26

Collaboration: responsibilities and cost sharing

- ❑ Areas of contribution of institutes belonging to the NA60+/DiCE Collaboration

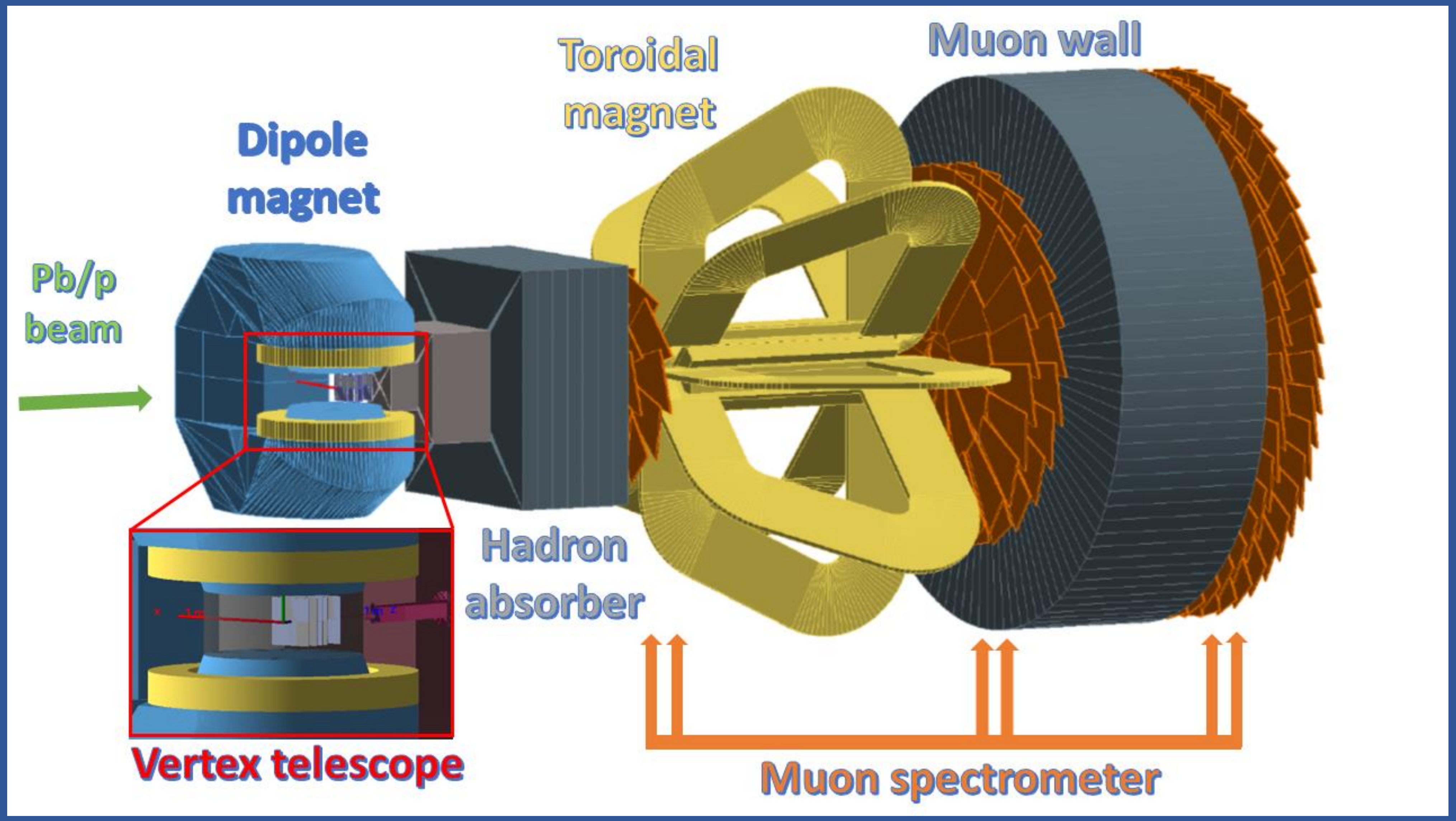
Institute	Sub-detector
Istituto Nazionale di Fisica Nucleare, (INFN), Cagliari, Padova, Torino (Italy)	Vertex spectrometer (MAPS detector & read-out)
Weizmann Institute of Science, Rehovot (Israel)	Muon spectrometer (MWPC detectors)
Stony Brook University, NY (USA)	Muon spectrometer (MPGD detectors)
University of Science and Technology of China, Hefei (China)	Muon spectrometer (read-out electronics)
Institut de Physique des 2 Infinis de Lyon, CNRS/IN2P3 (France)	Trigger detector (scintillator system)
CERN	Infrastructure, beam and magnet refurbishment

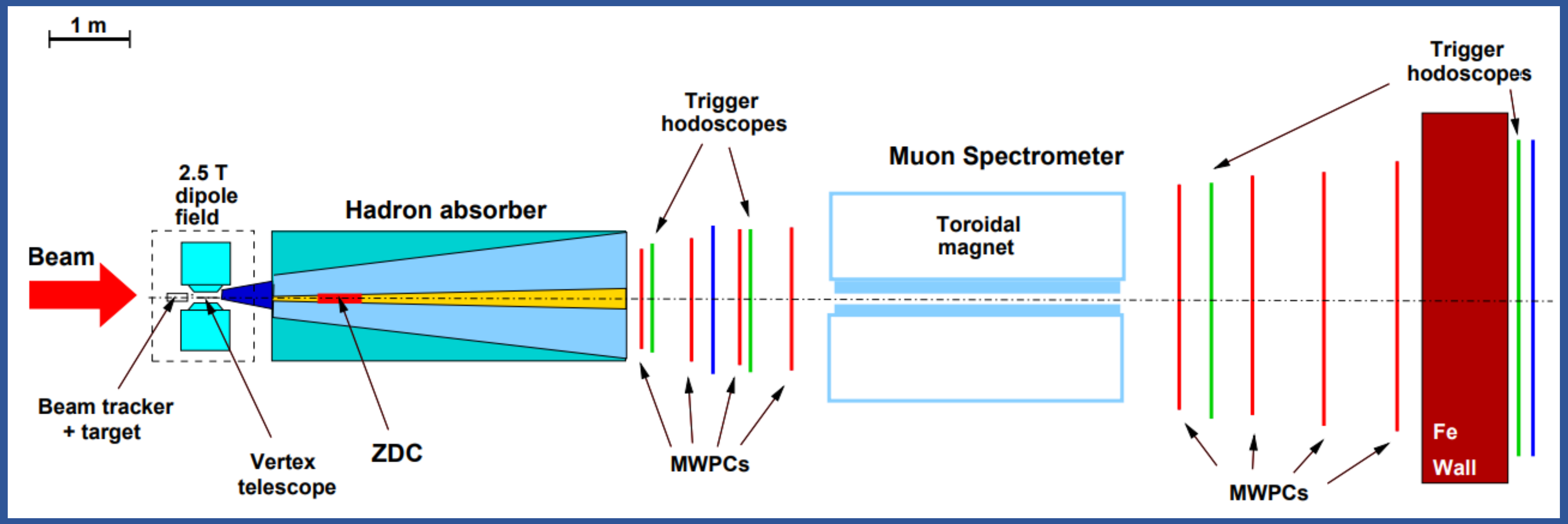
- ❑ Infrastructure, beam, magnets:
  - If the experiment is approved, essential that CERN could be able to cover the corresponding costs

- ❑ Institutes in the process of joining the NA60+/DiCE Collaboration

Institute	Area of interest
Rice University, Houston, TX, USA	DAQ
University of Tokyo, Tokyo, Japan	DAQ
Fudan University, Shanghai, China	Simulation and data analysis
University of Tsukuba, Ibaraki, Japan	Simulation and data analysis
Lawrence Berkeley National Laboratory, Berkeley, CA, USA	Vertex spectrometer / DAQ

NA60+ vs NA60





Some important improvements:

Physics program extended to lower energy
→ Fundamental to explore rare probes in the high-μ_B region

Larger angular acceptance
→ cope with lab rapidity shift when varying energy down to low SPS energy

Access new observables (open charm etc.)
NA60: (di)muon trigger ~ 5 kHz
NA60+: MB trigger (>100 kHz)

State-of-the art detectors
Pixel size: from 50x425 μm^2 (NA60) to 30x30 μm^2 (NA60+), thinner sensors (from 2% to 0.1% X_0)
→ Improved resolution and signal over background
from 21 to 8 MeV at the ω mass
from 70 to 30 MeV at the J/ψ mass

Total cost estimate

Table 14: (Preliminary) estimated costs of the various NA60+/DiCE subsystems.

Sub-system	Estimated cost (MCHF)	Section
Vertex spectrometer	1.95	2.3.5
Muon spectrometer	2.66 [7]	2.4.8
Hadron absorber and beam plug	0.55	2.4.2
Interaction detector	0.05	2.5
Computing	0.19	2.7.2
Magnet refurbishment, installation, powering	1.62	2.6.3
Infrastructure, shielding	2.60	2.8.4
Total	9.62	