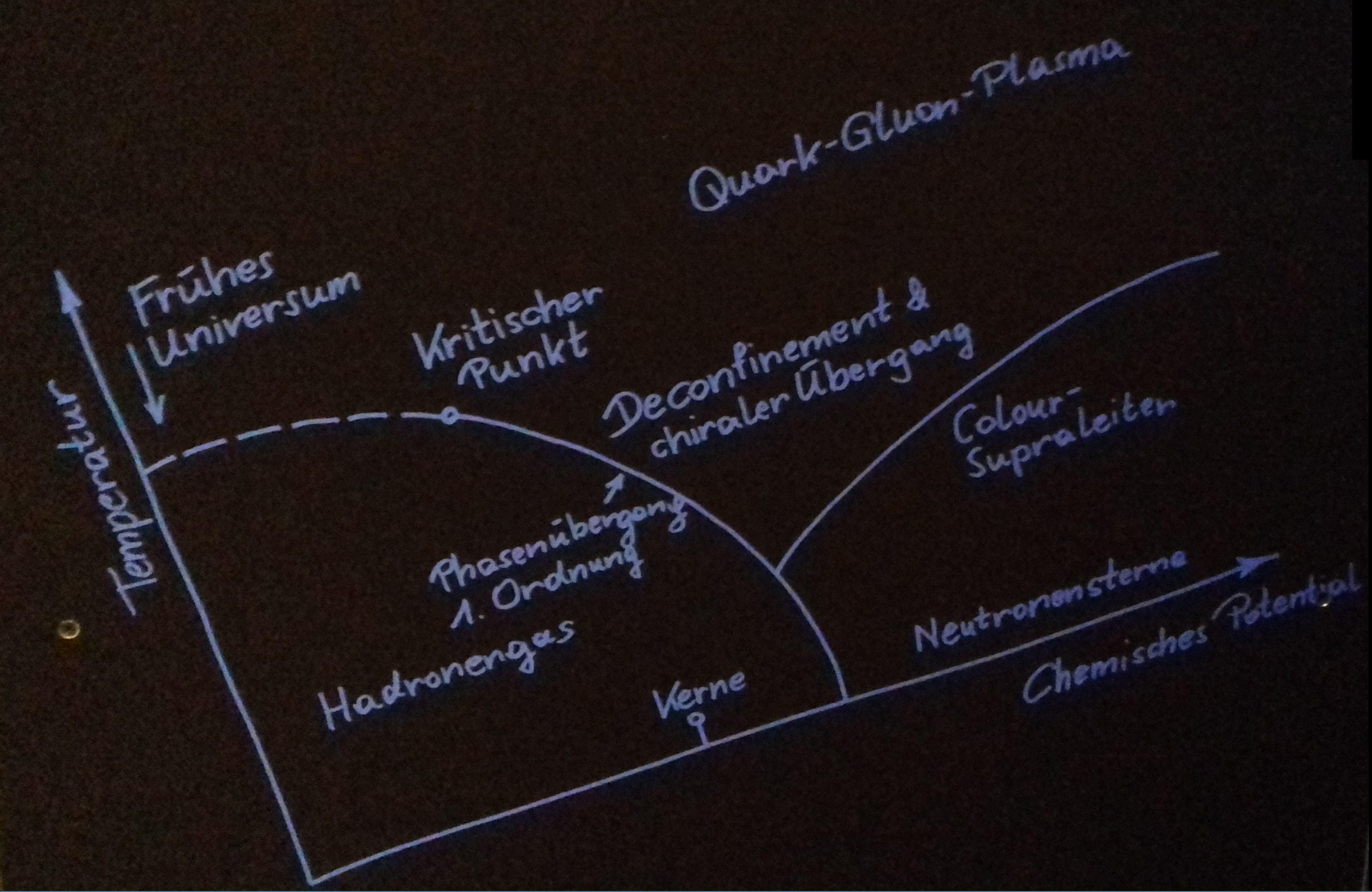
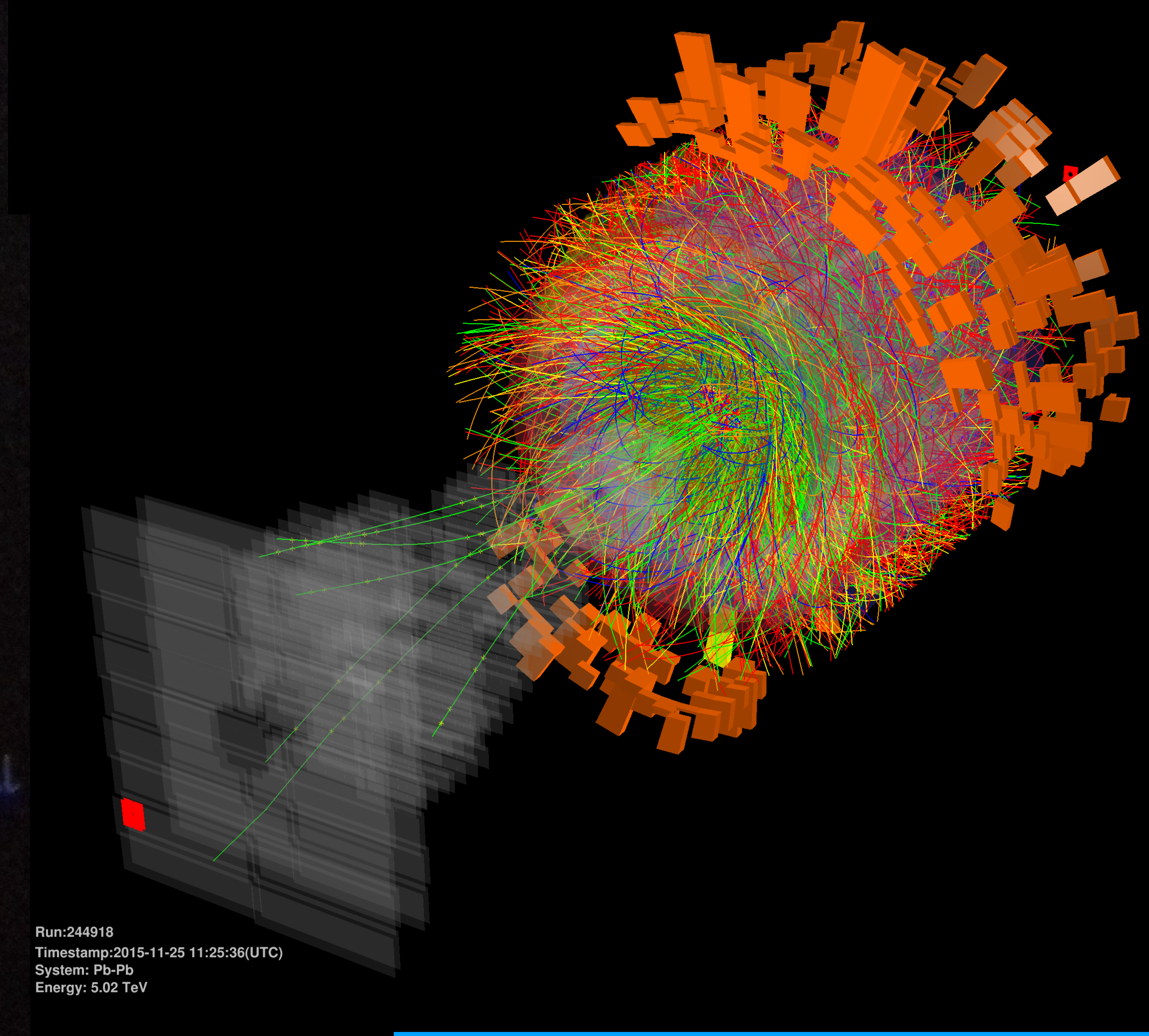
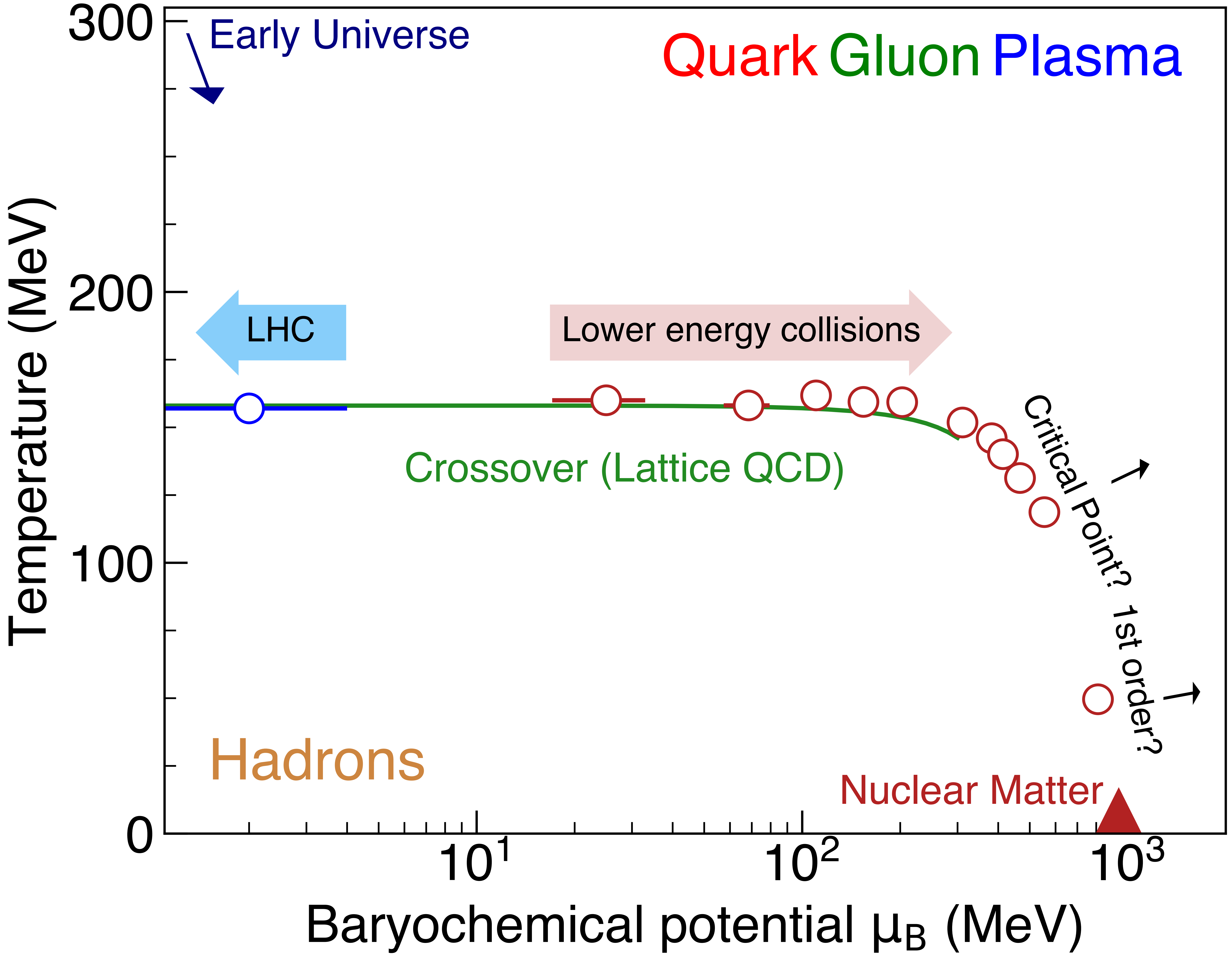




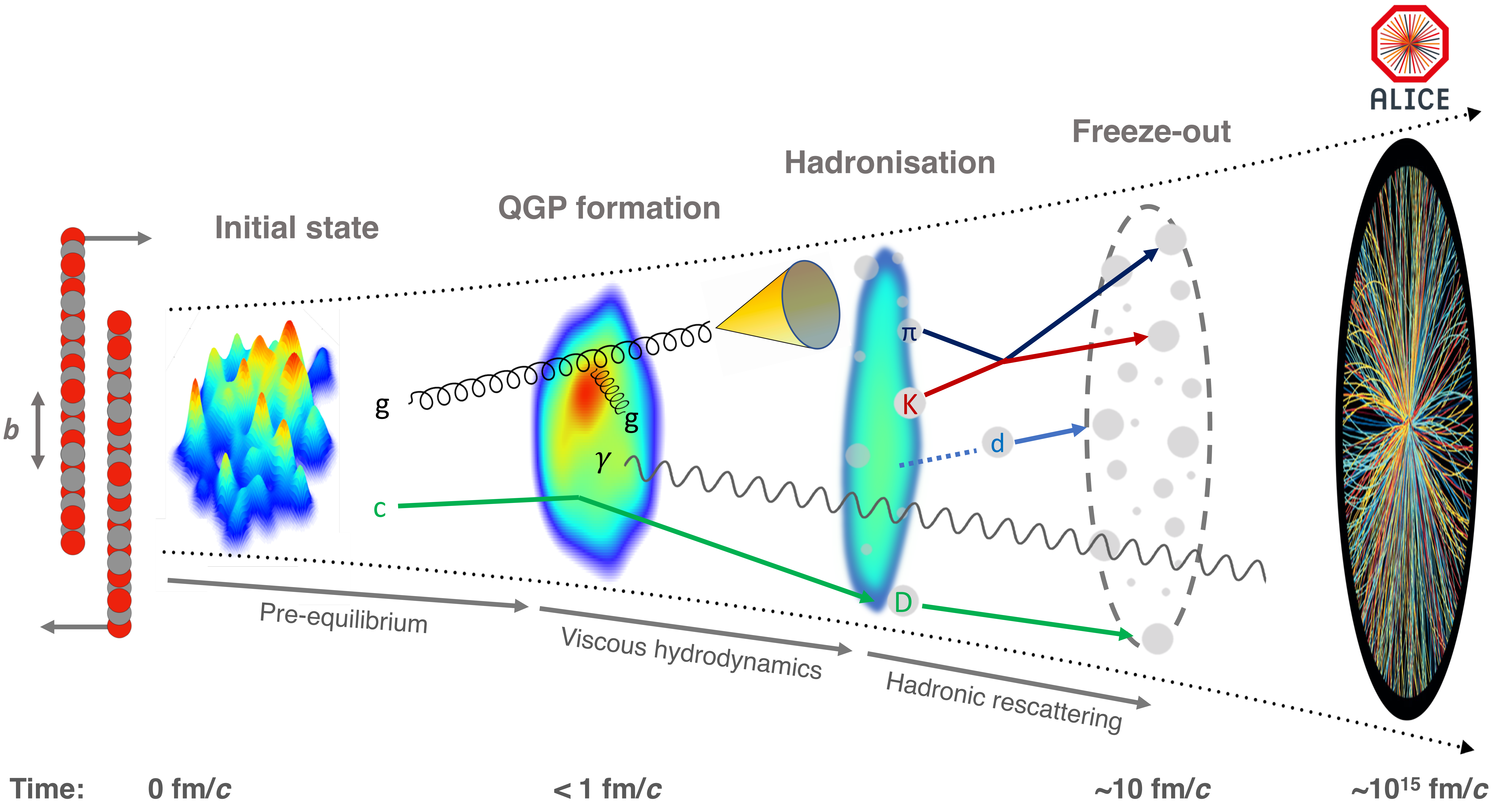
Xiaoming Zhang

Imaging the quark-gluon plasma using heavy quarks

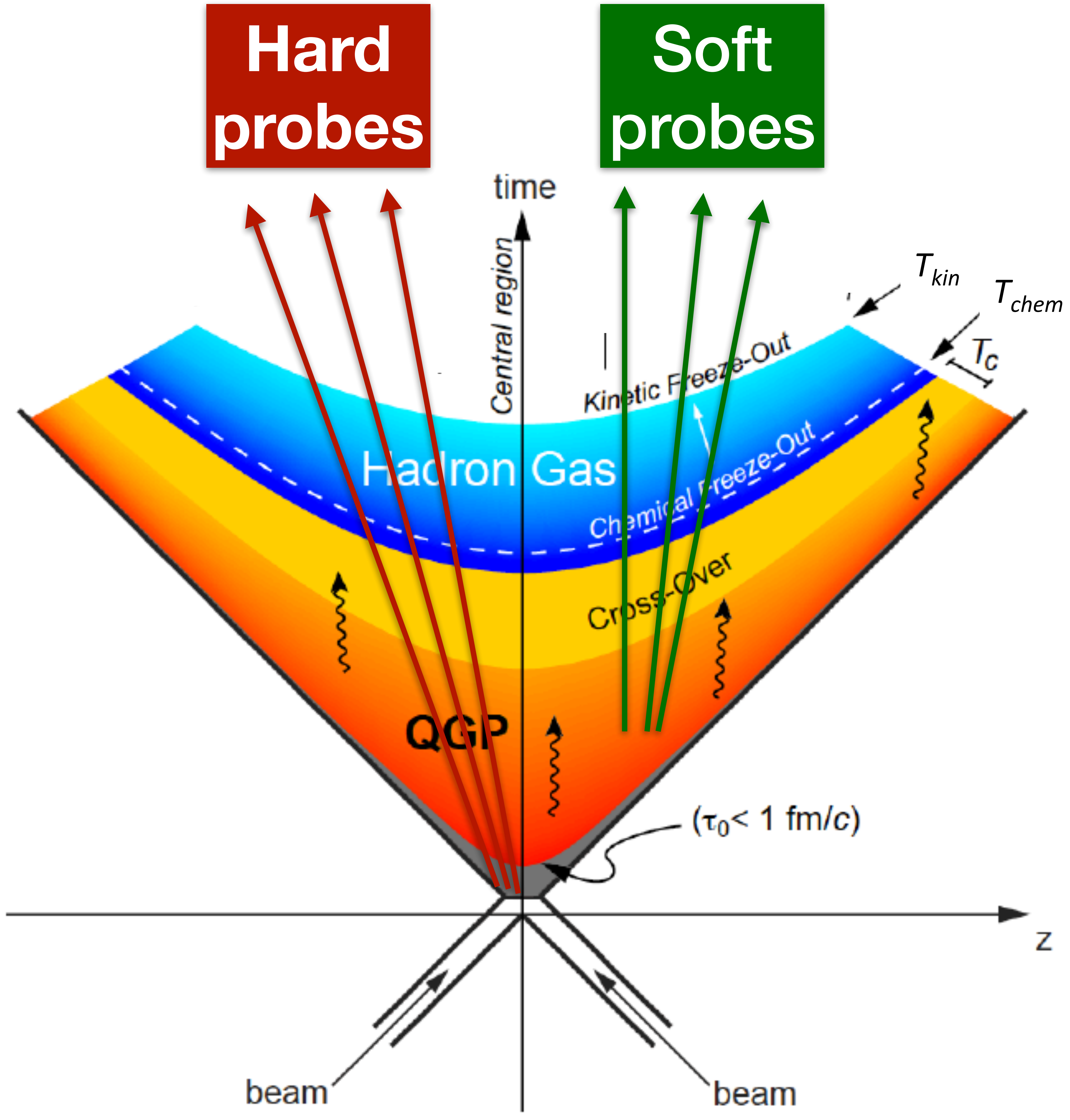
QCD phase diagram



Heavy-ion collisions



Signatures of the QGP



Heavy-ion collisions probe the strongly-interacting matter — the quark-gluon plasma (QGP) under extreme conditions of high temperature and energy density

Hard probes created at initial stage of the collision

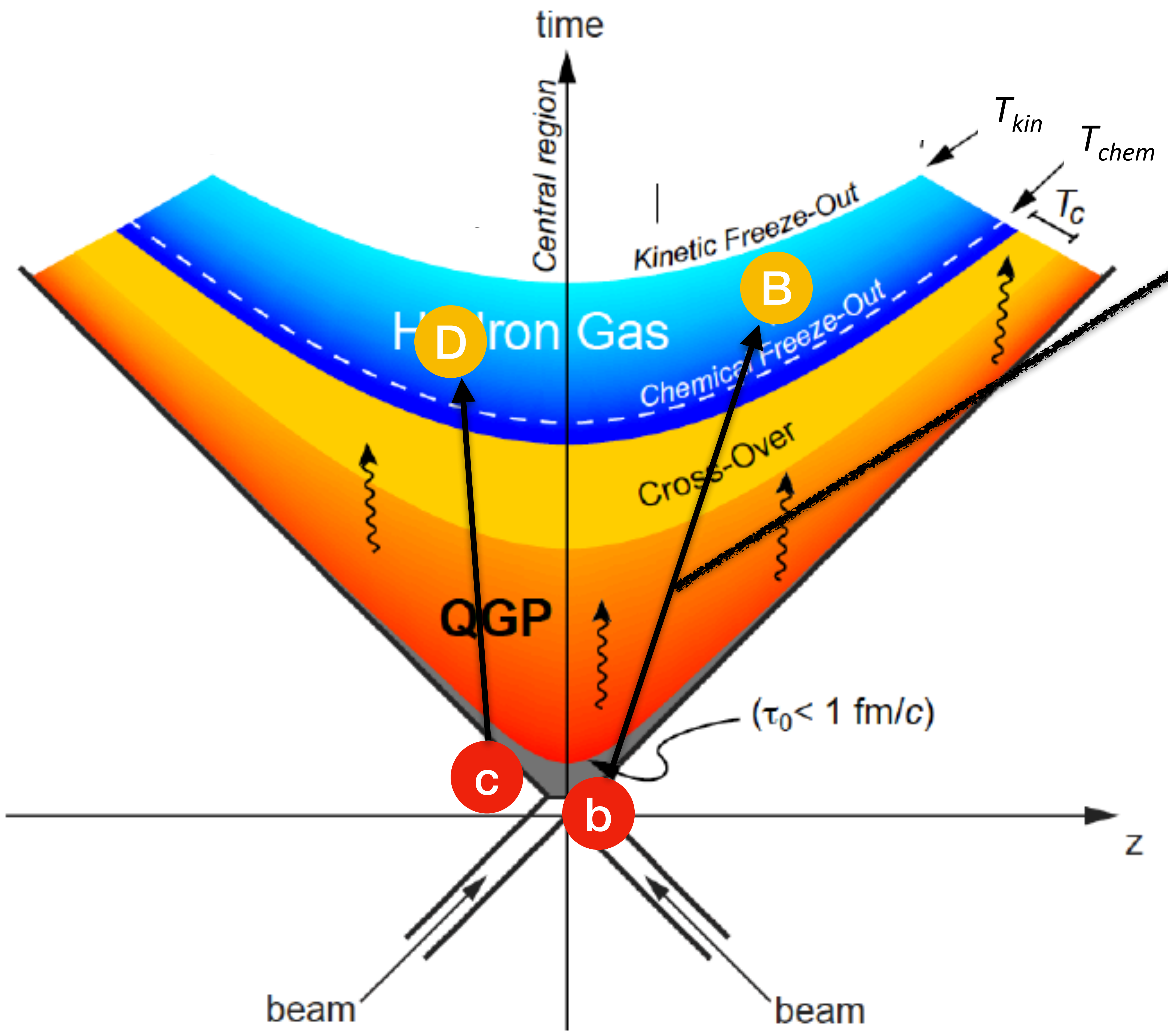
➡ QGP tomography

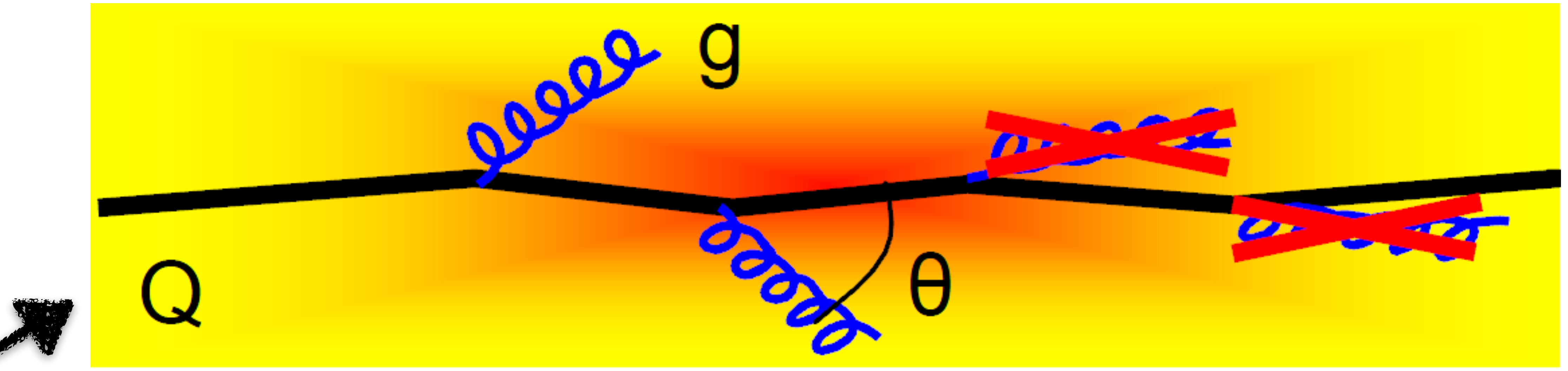
Soft probes created in the "fireball"

➡ Fingerprint of the QGP evolution

Heavy quarks: the QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of the collisions before the QGP creation





Energy loss in QGP medium

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

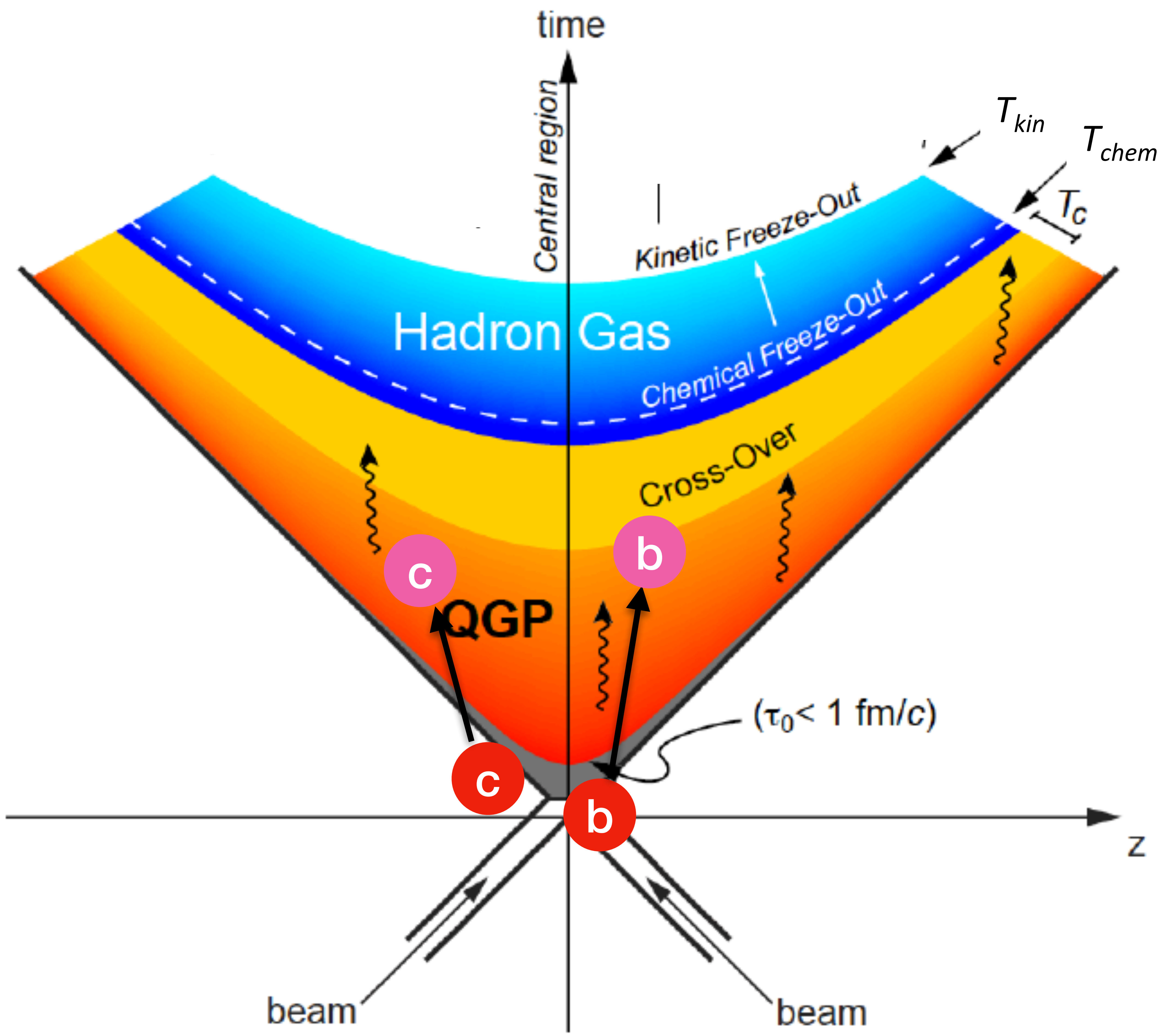
QCD medium

QCD vacuum

- R_{AA} = 1 if no medium effect
- Radiative vs. collisional energy loss

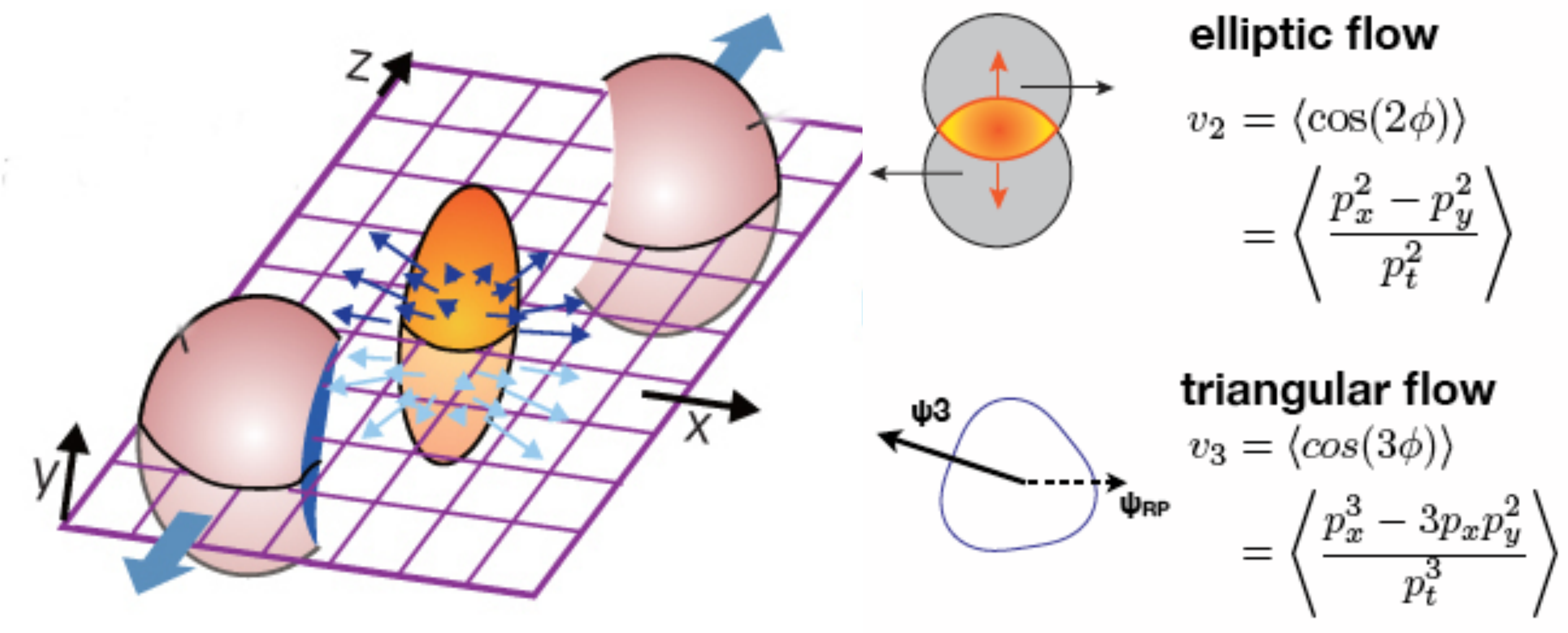
Heavy quarks: the QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of the collisions before the QGP creation



Collective expansion

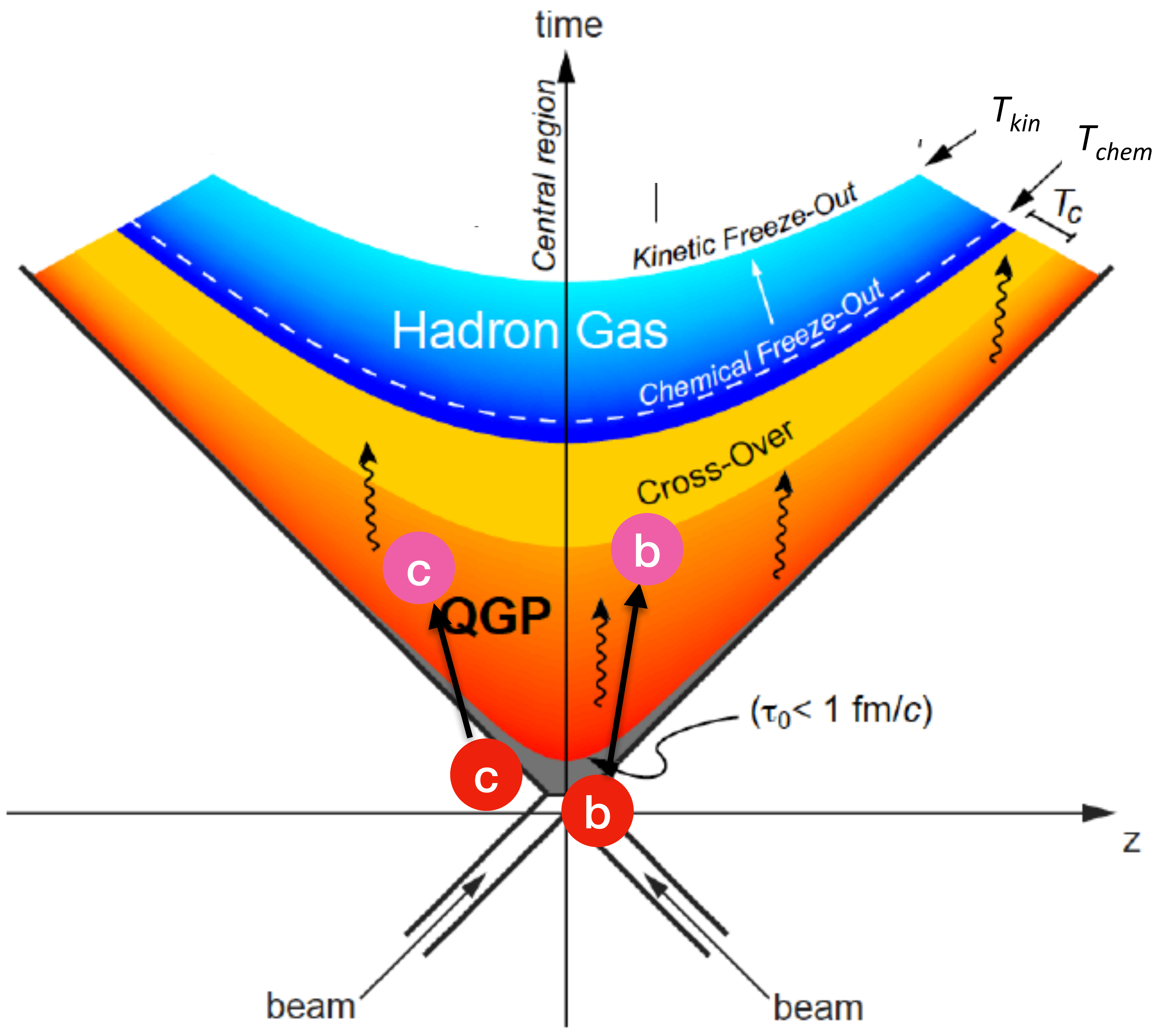
➡ Anisotropic flow



➡ Results in complex azimuthal structure of final state particles

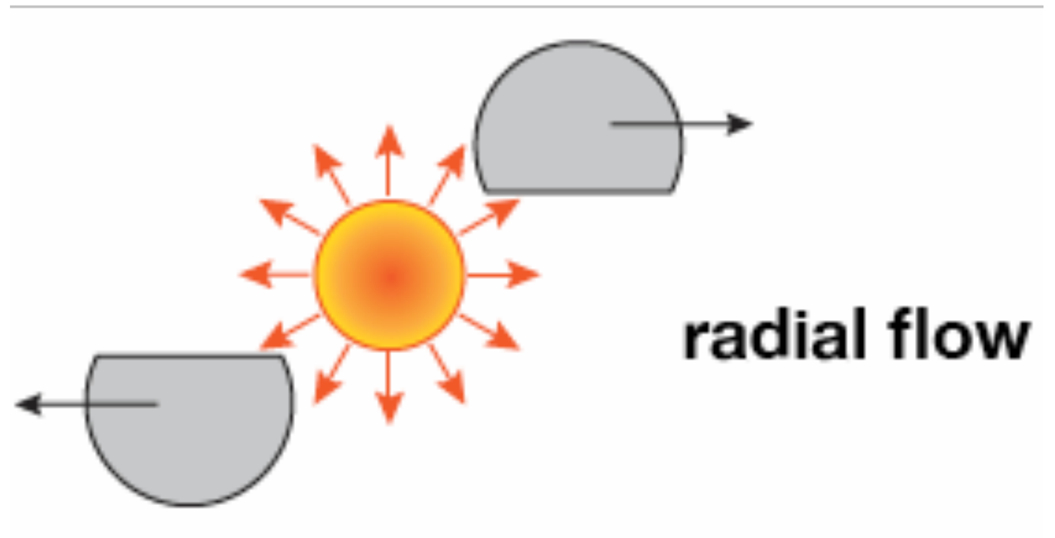
Heavy quarks: the QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of the collisions before the QGP creation



Collective expansion

➡ Radial flow



➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

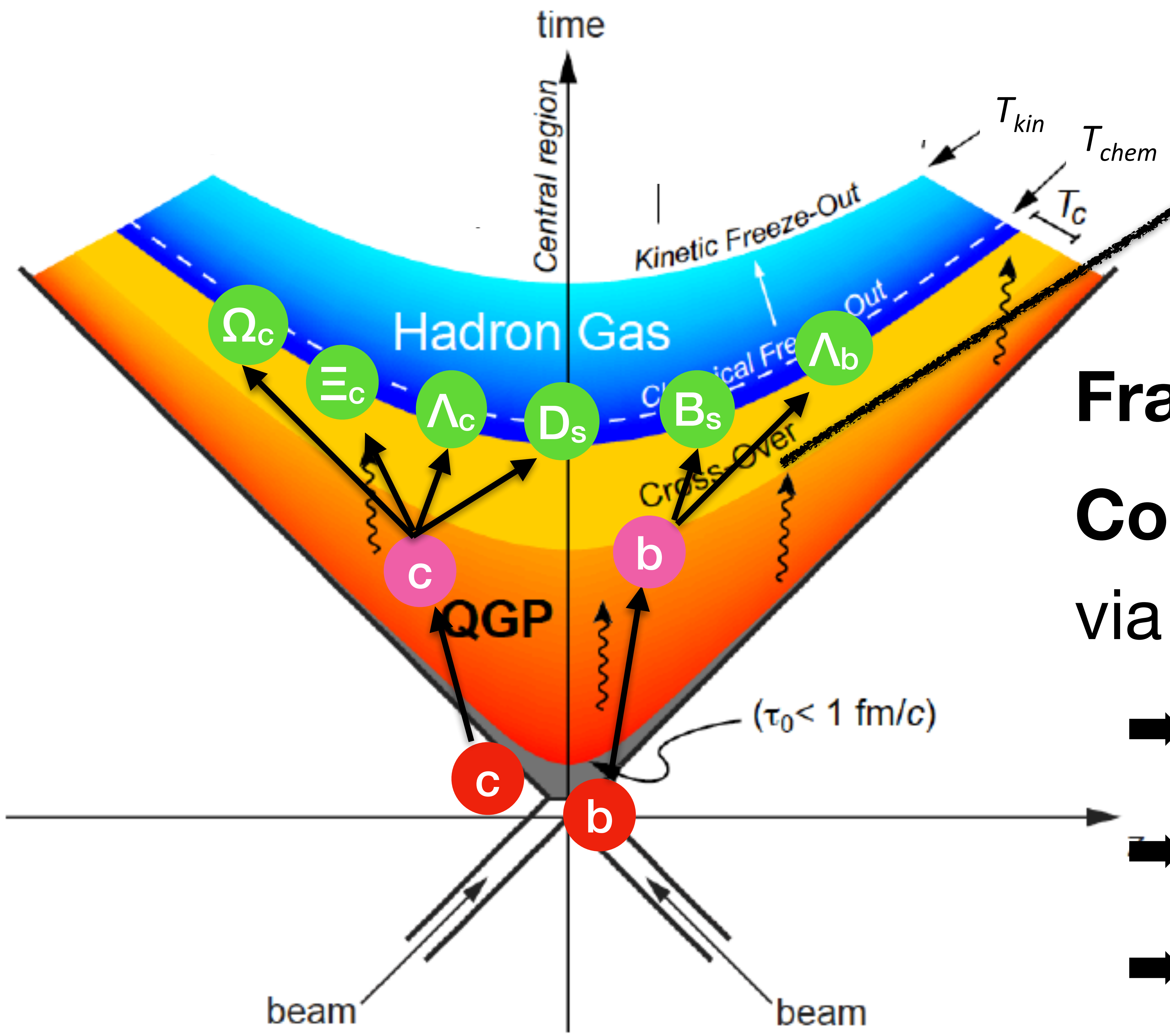
p_0: initial momentum
β: flow velocity
m: particle mass

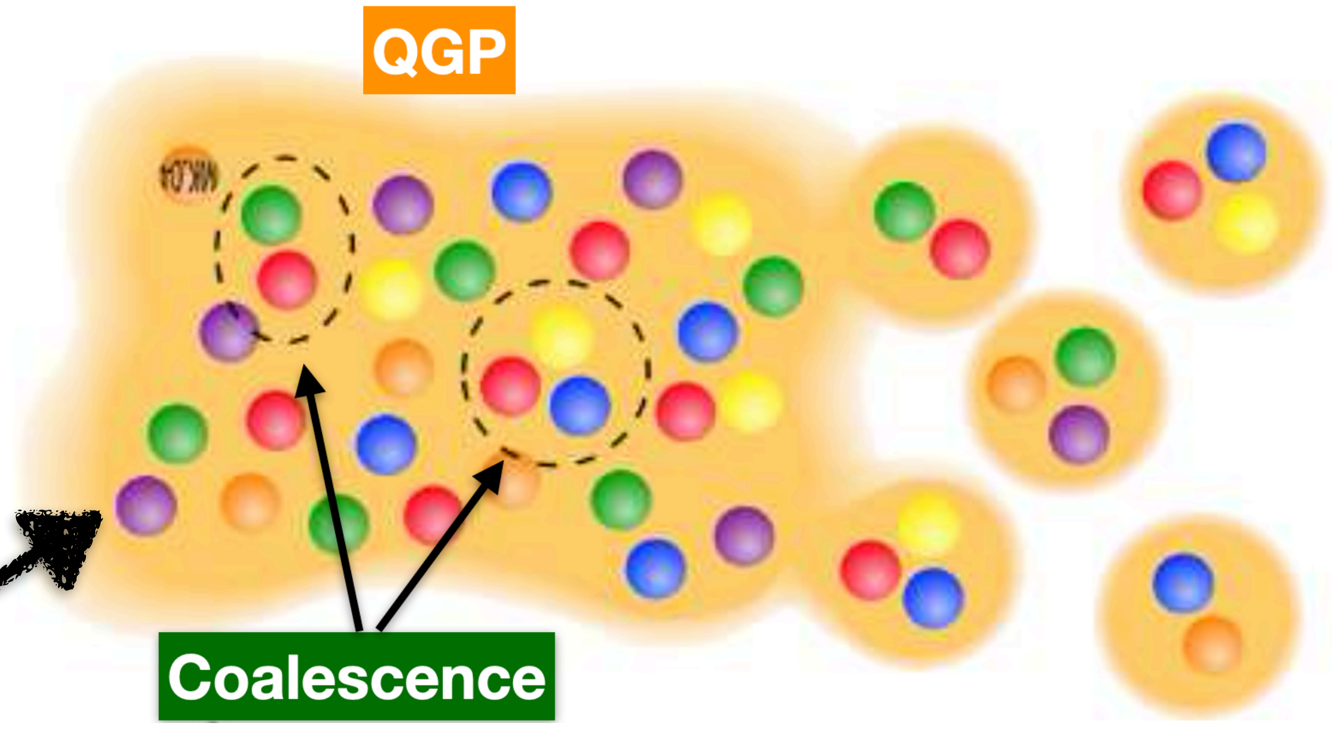
➡ More pronounced in central collisions

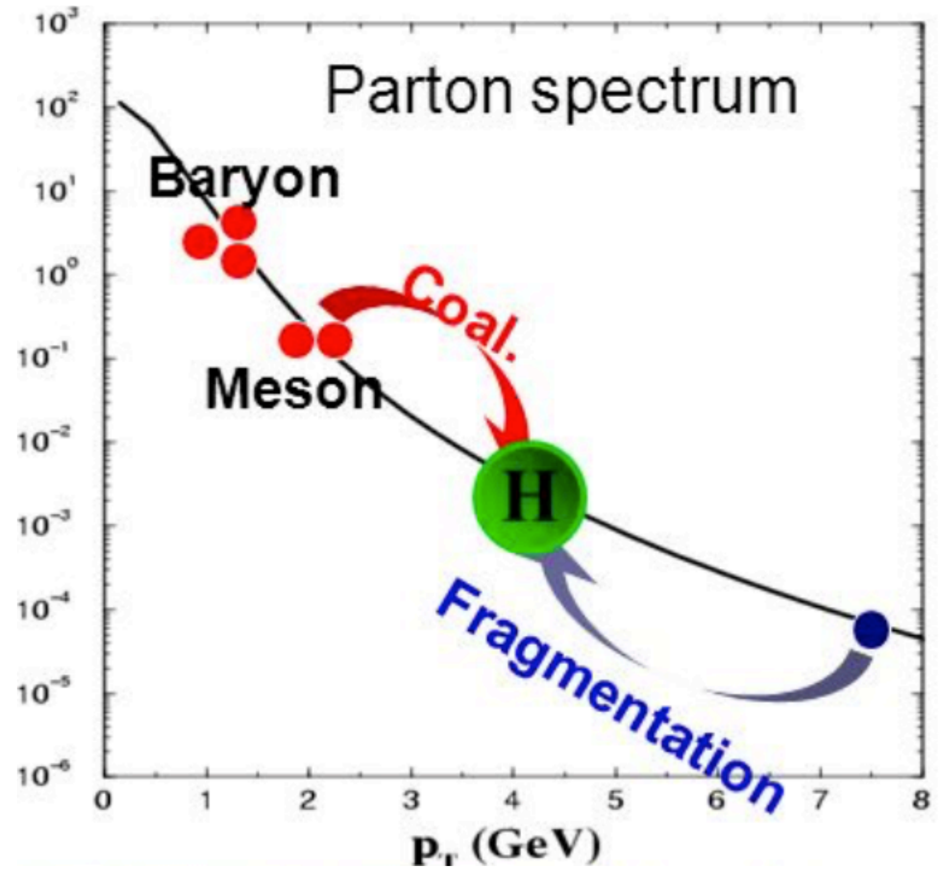
➡ Mass dependence

Heavy quarks: the QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of the collisions before the QGP creation







Fragmentation — hadrons from high $p_T$partons

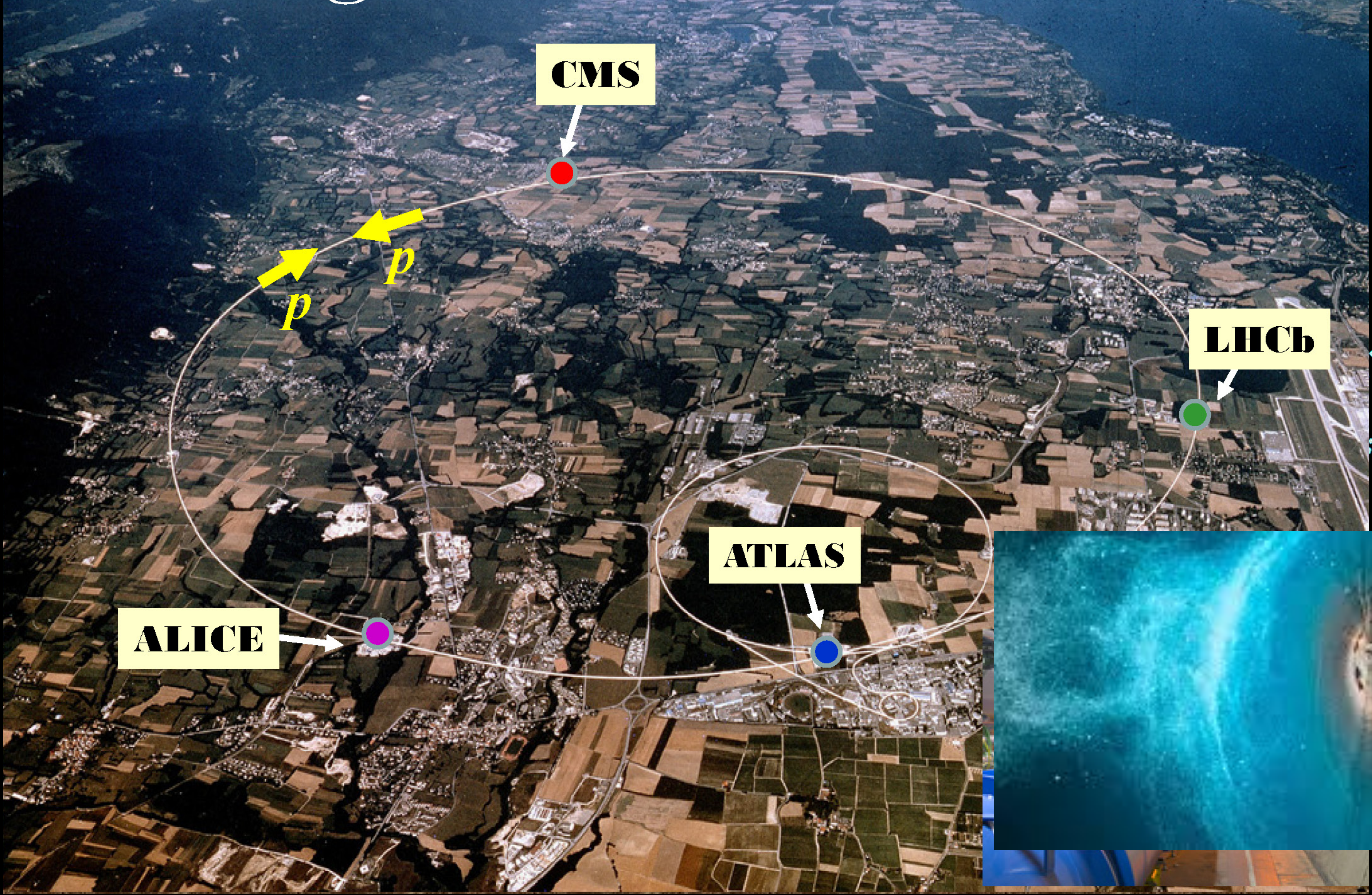
Coalescence/recombination — hadron formation via (di-)quark combination in the QGP medium

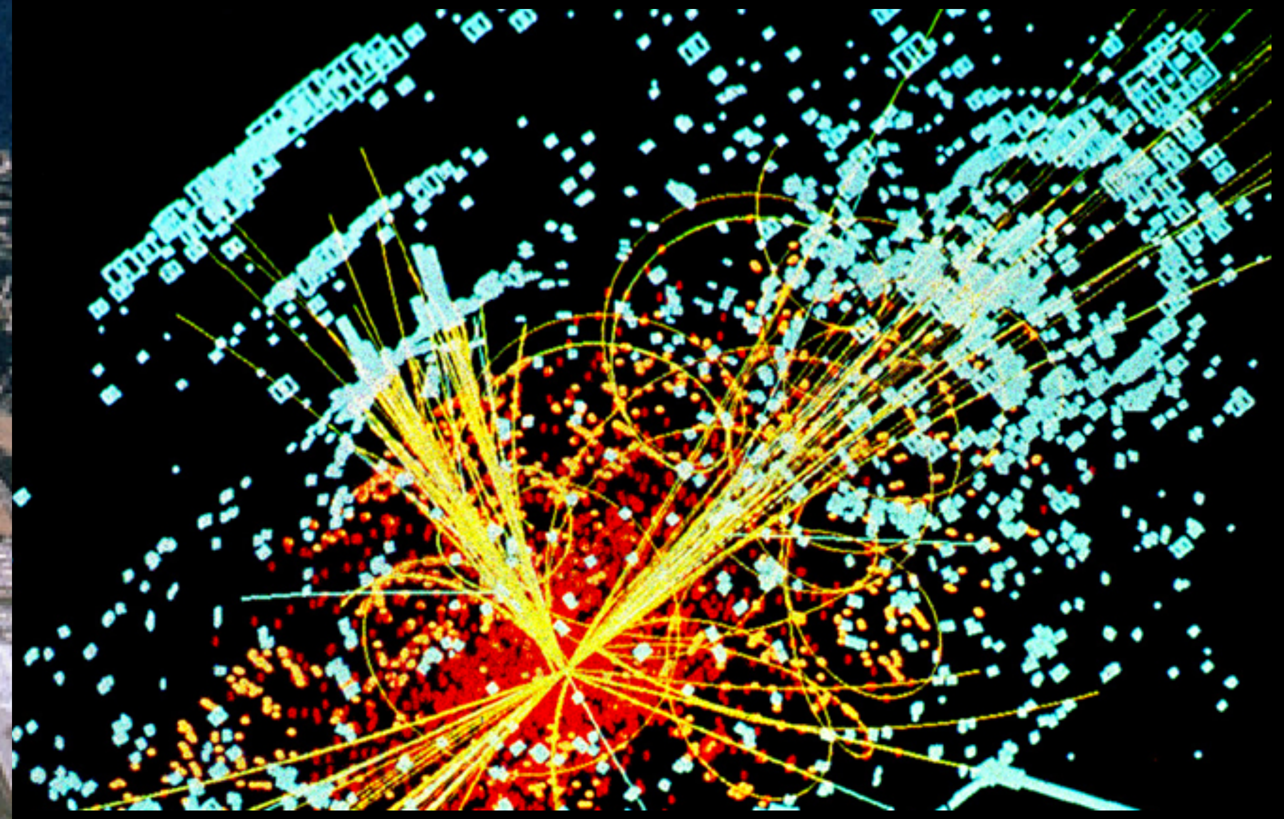
➡ $p_{T,hadron} \simeq n\, p_{T,parton}$, n = 2 (meson), 3 (baryon)

➡ Sensitive to baryon and meson species

➡ Baryons from lower momenta partons (denser)

Large Hadron Collider

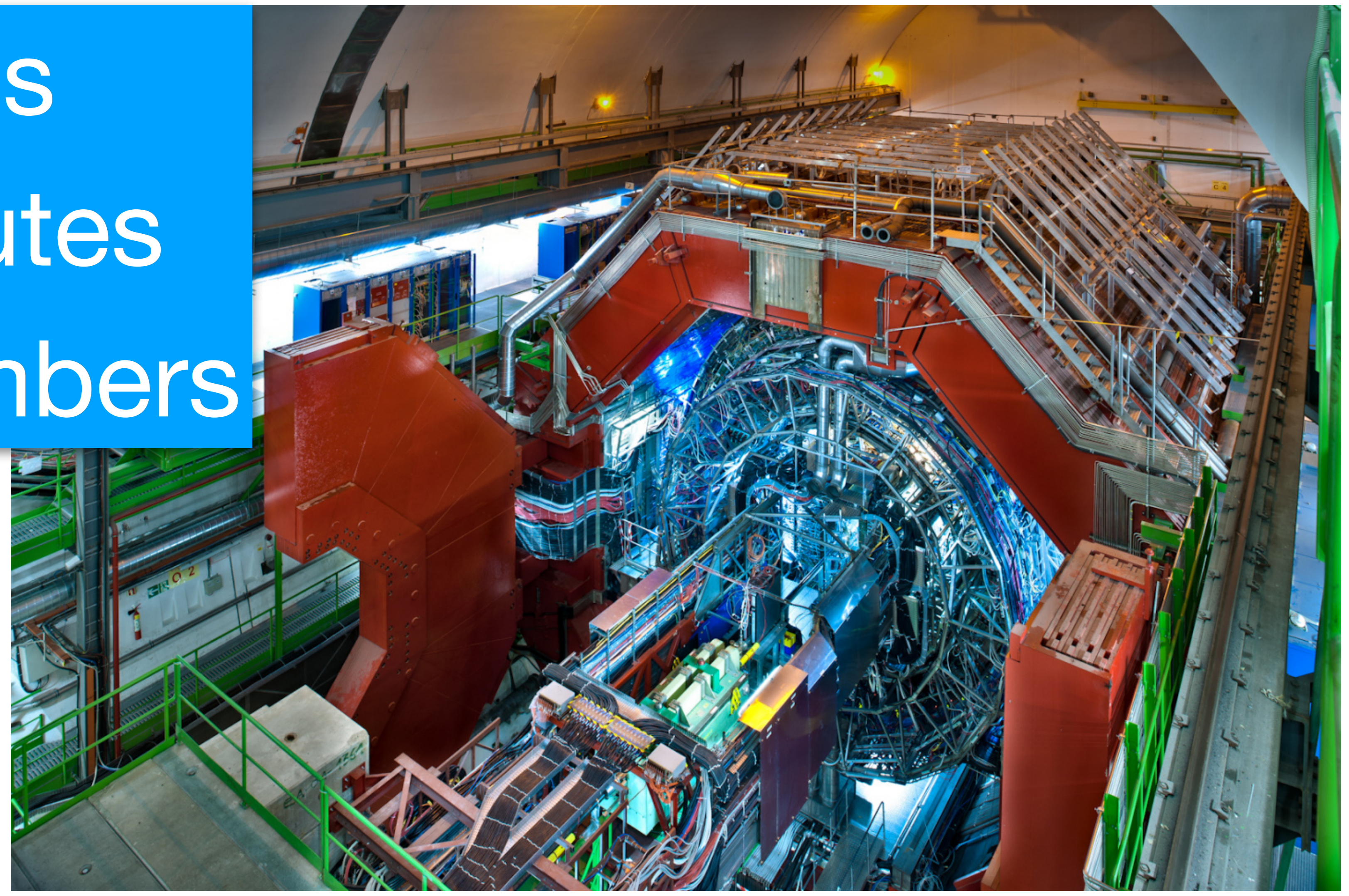


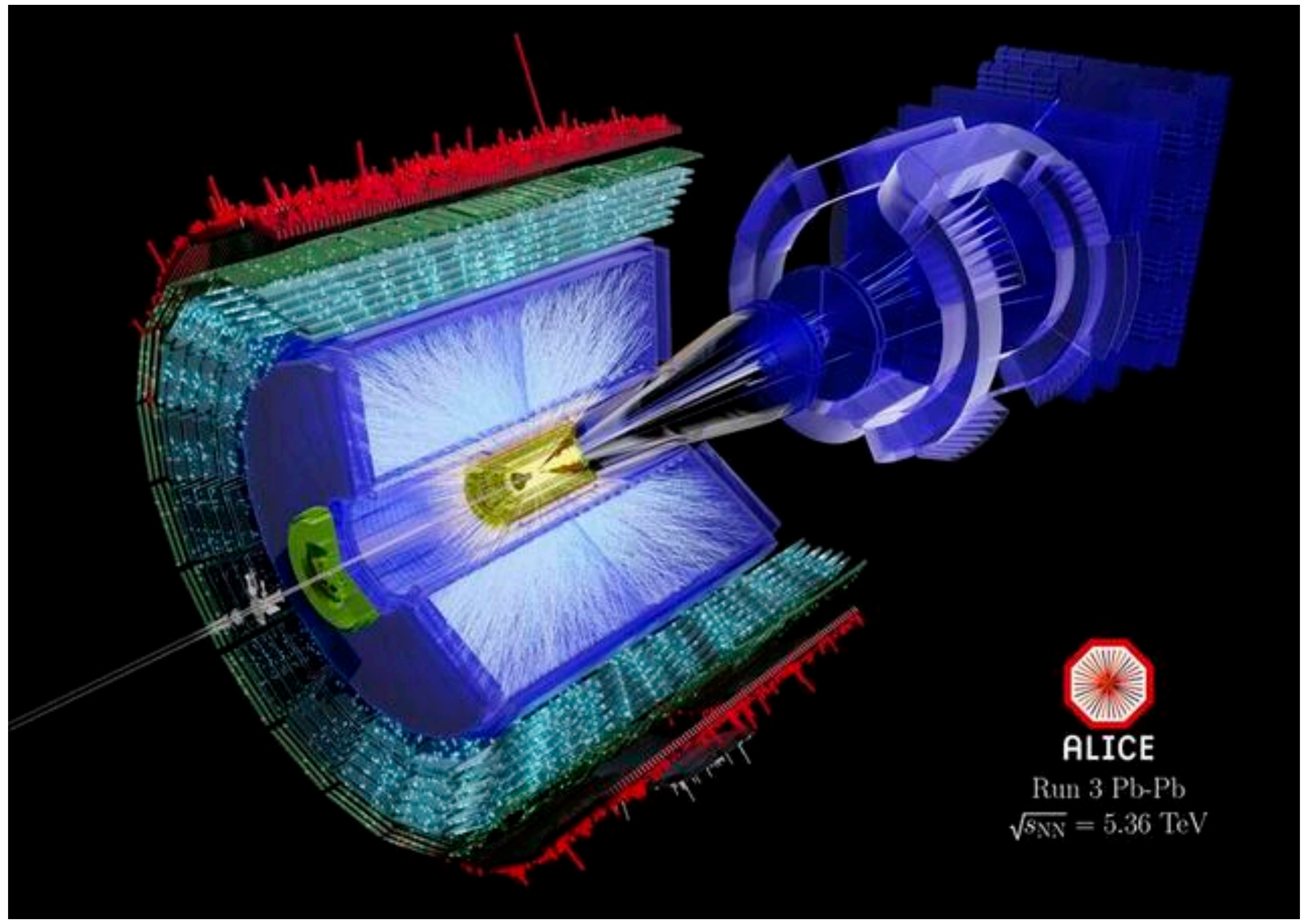


ALICE Collaboration

A large ion collider experiment — ALICE

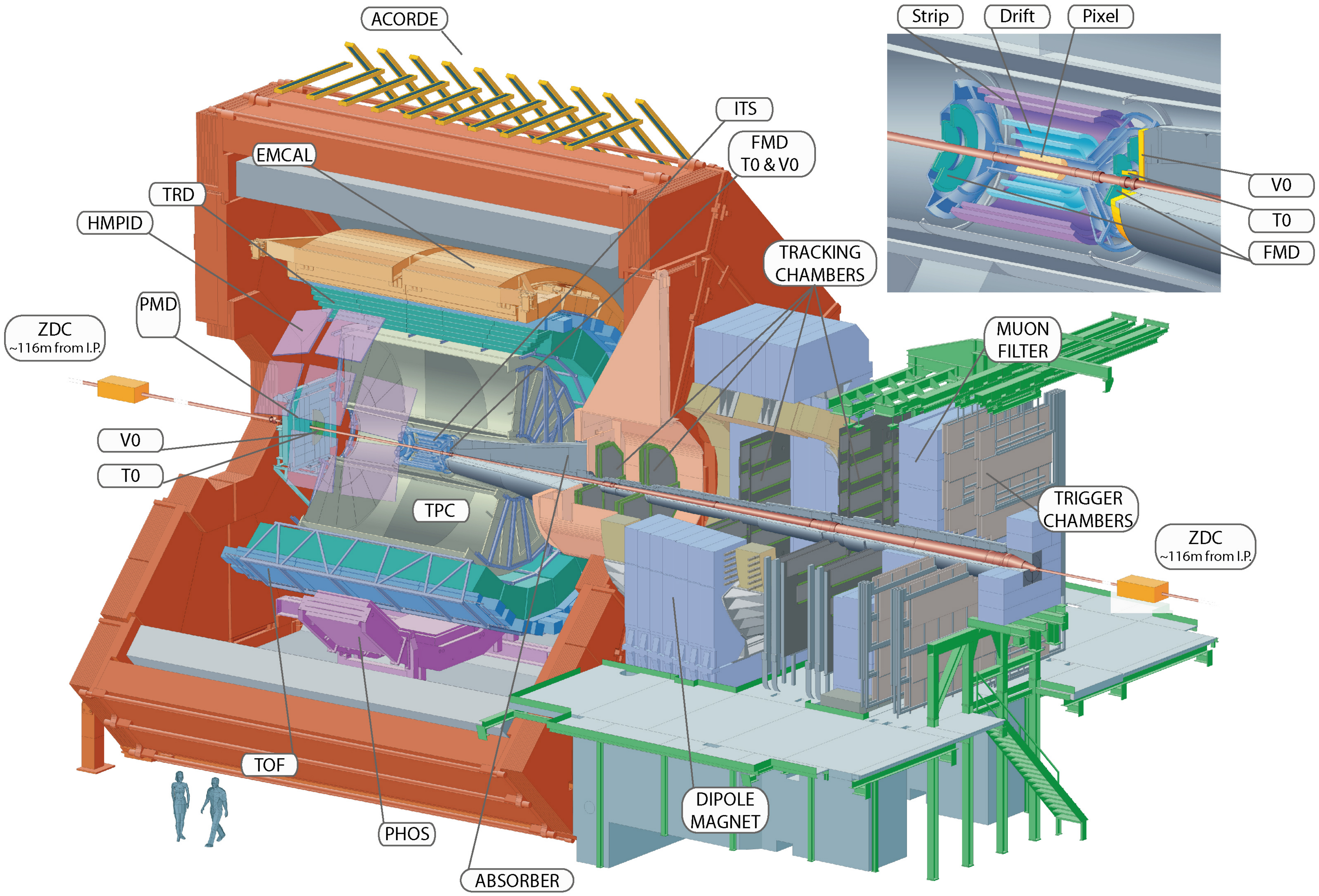
- 40 contries
- 170 institutes
- 1991 members





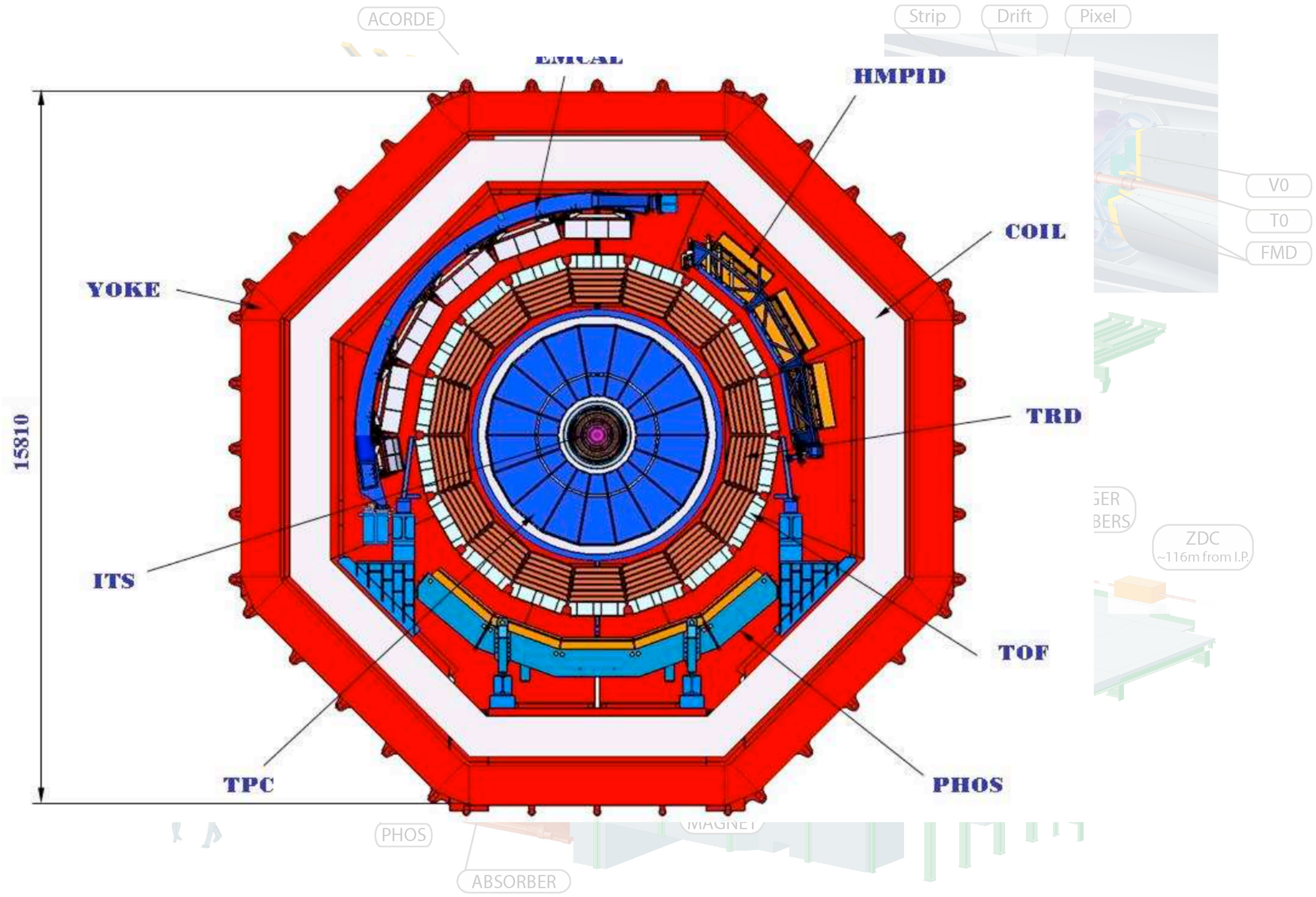
Study the primordial matter existed after the Big Bang via ultra-relativistic heavy-ion collision “little bang”

ALICE apparatus

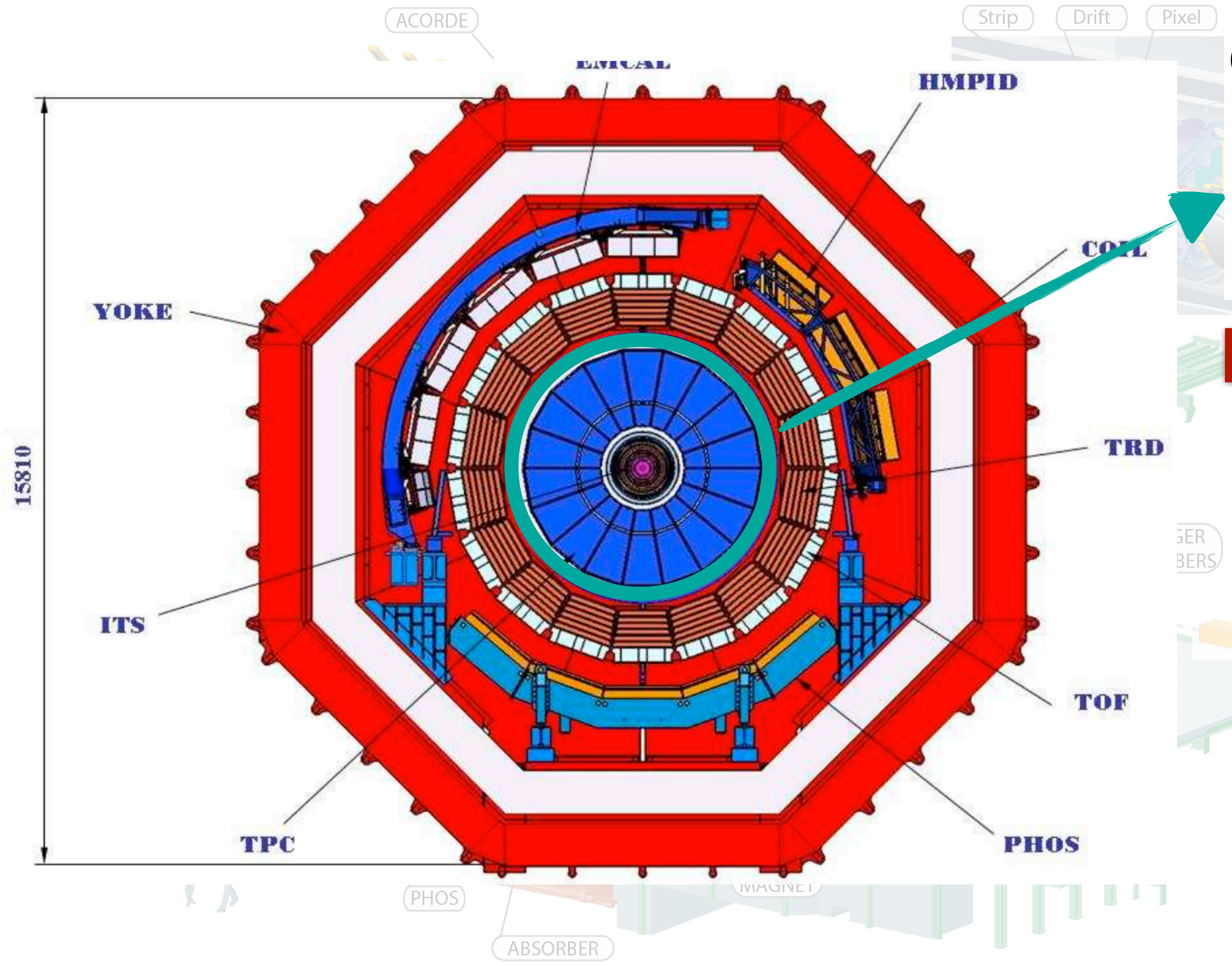


- Took 17 years to design and build
- Costing 180 M CHF
- High 16m, long 26 m
- Weight 10,000 tons
- Located 50–100 m underground

ALICE apparatus



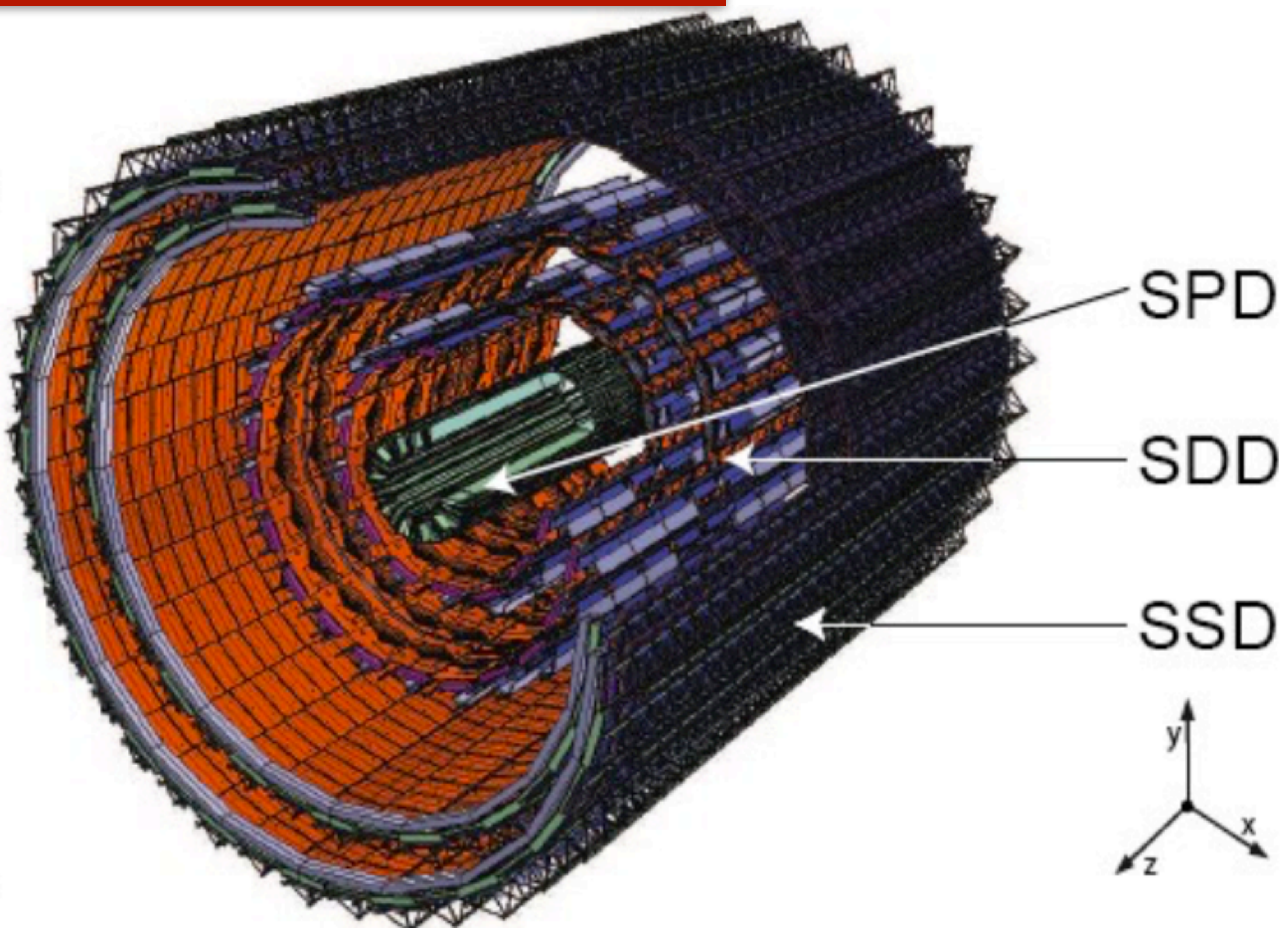
ALICE apparatus



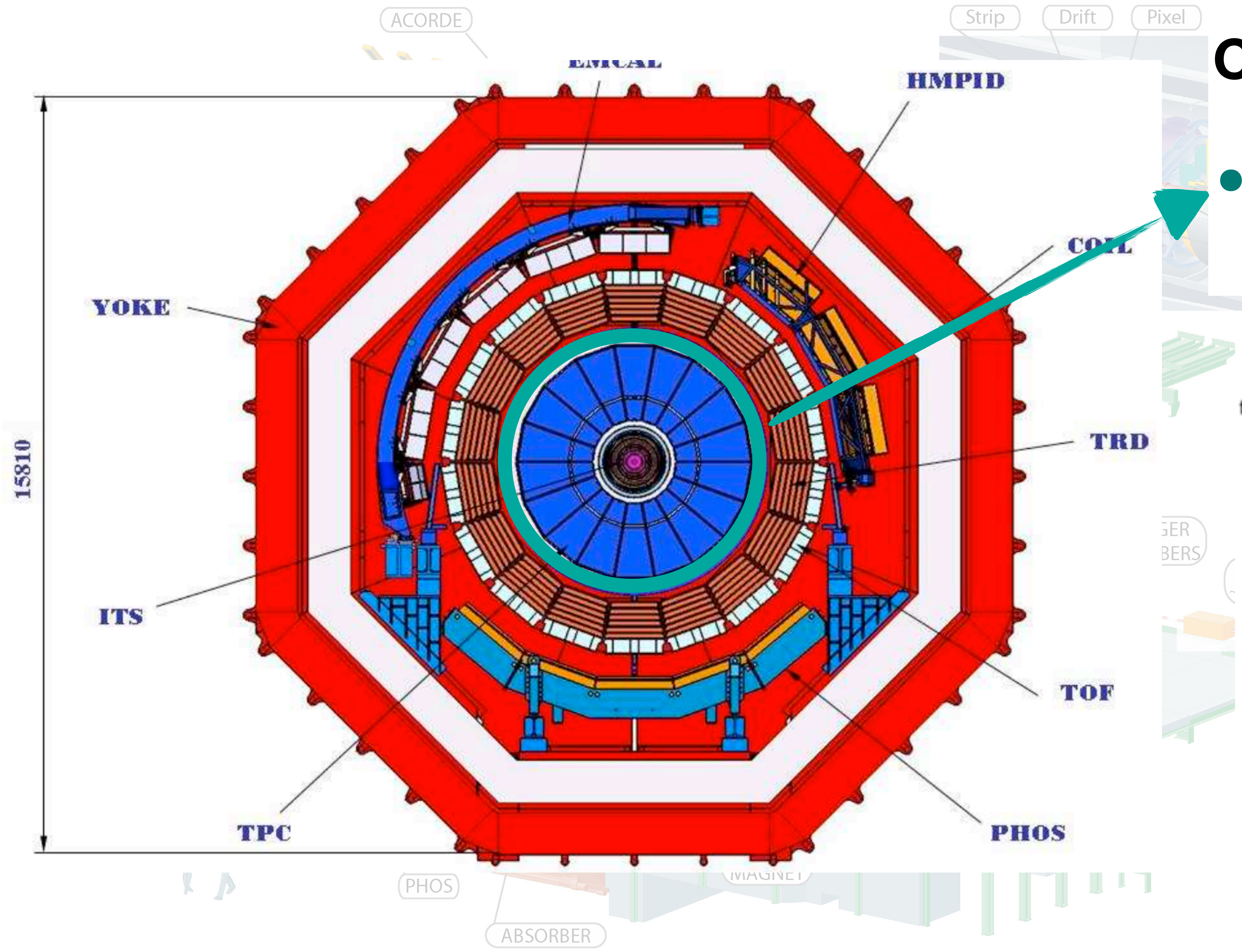
Central barrel detectors ($|\eta| < 0.9$)

- ITS, TPC: vertexing, tracking and particle identification (PID)

Inner tracking system (ITS)



ALICE apparatus



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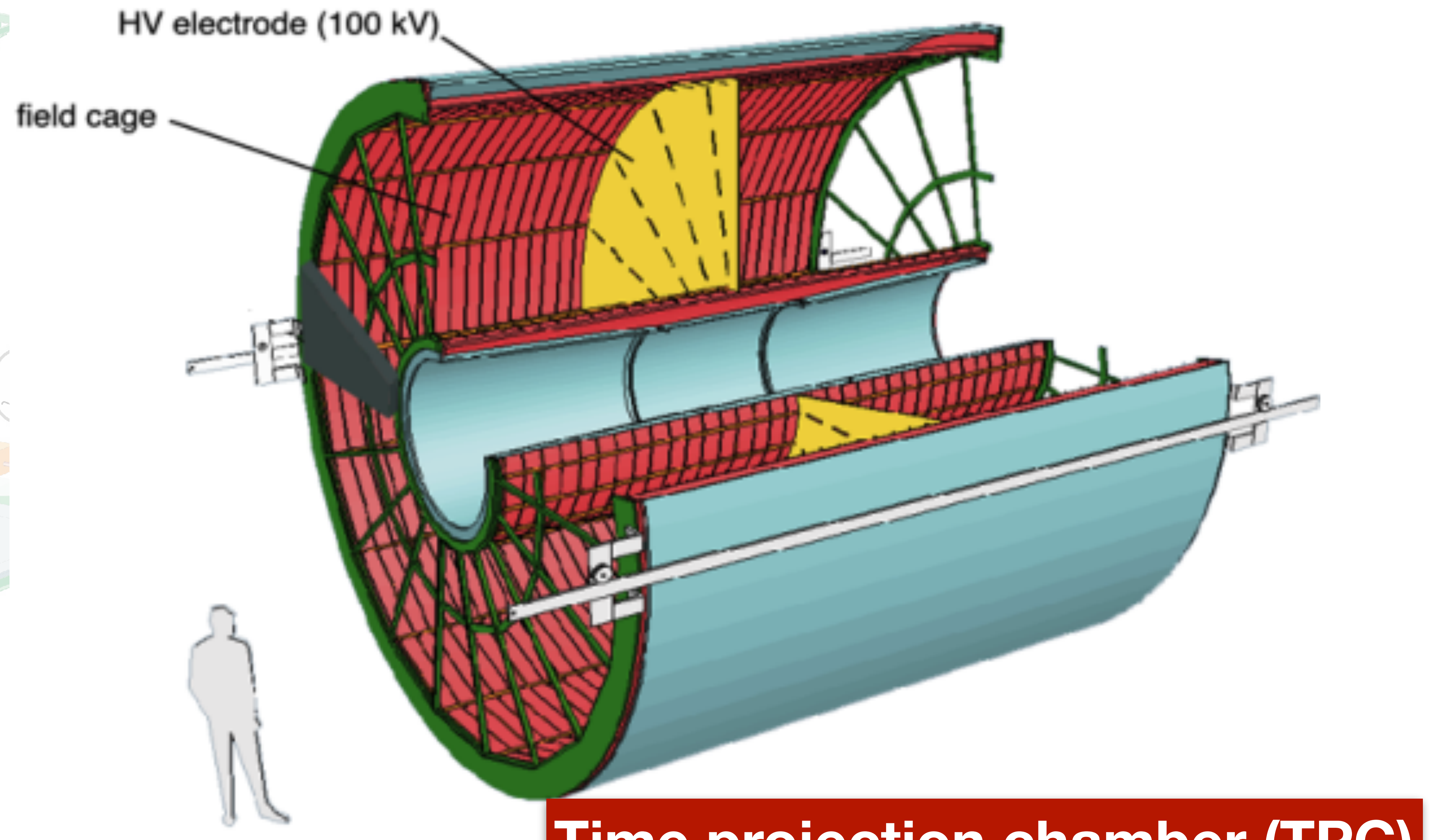
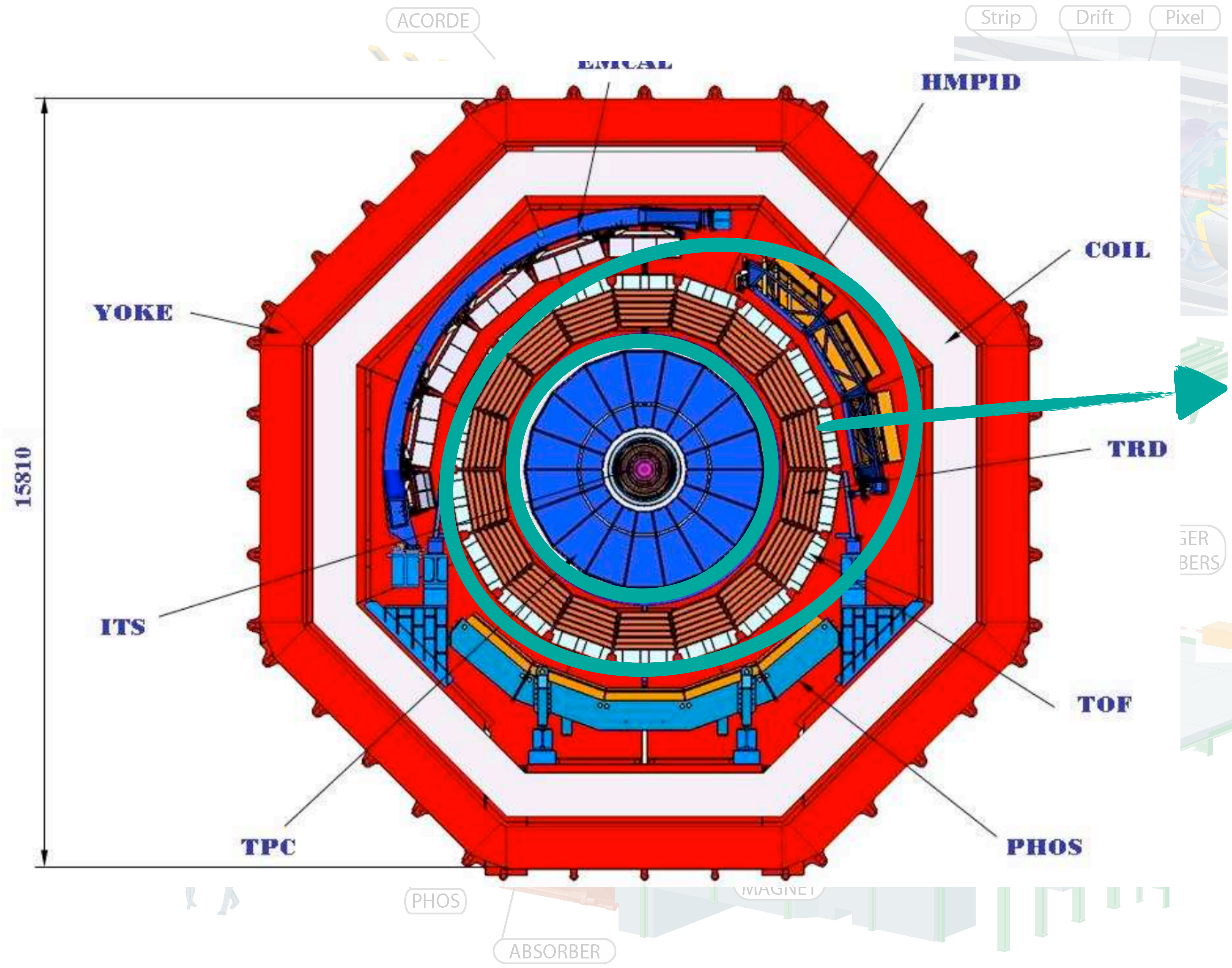


Time projection chamber (TPC)

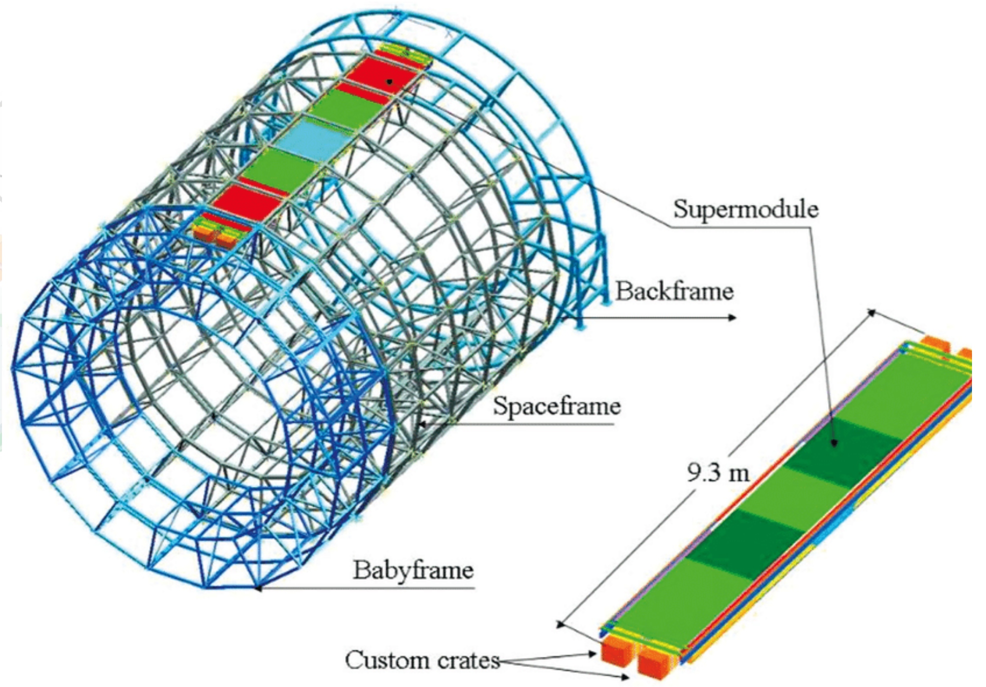
ALICE apparatus



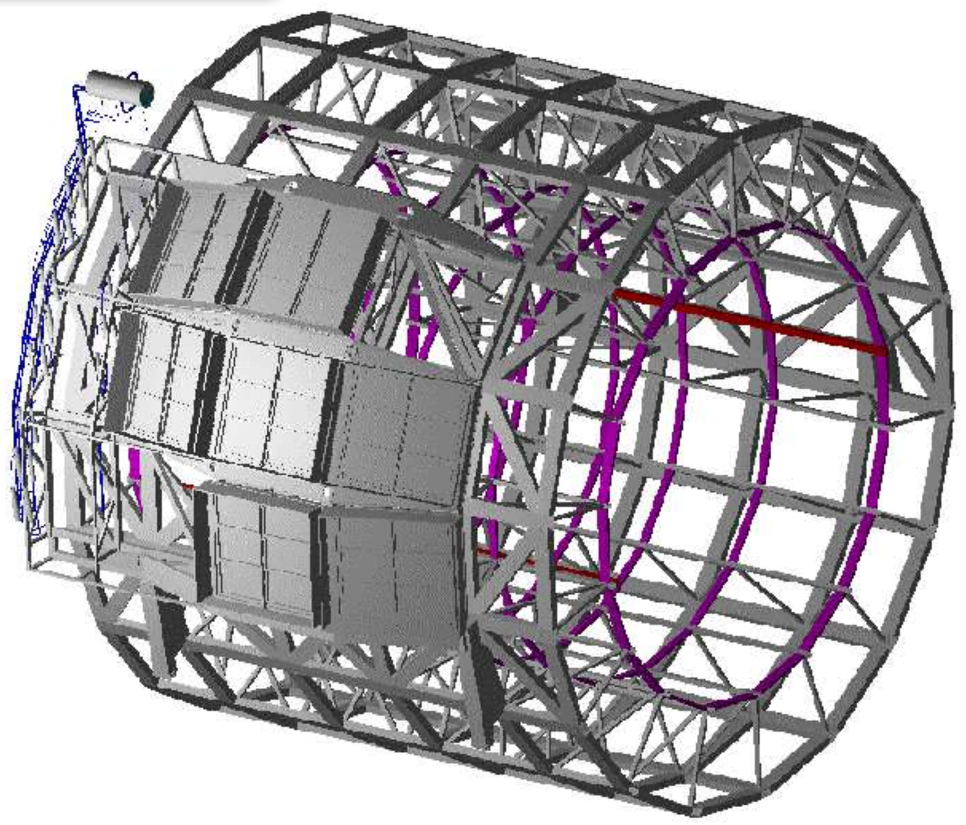
Central barrel detectors ($|\eta| < 0.9$)

- ITS, TPC: vertexing, tracking and particle identification (PID)
- TRD, TOF, HMPID: PID

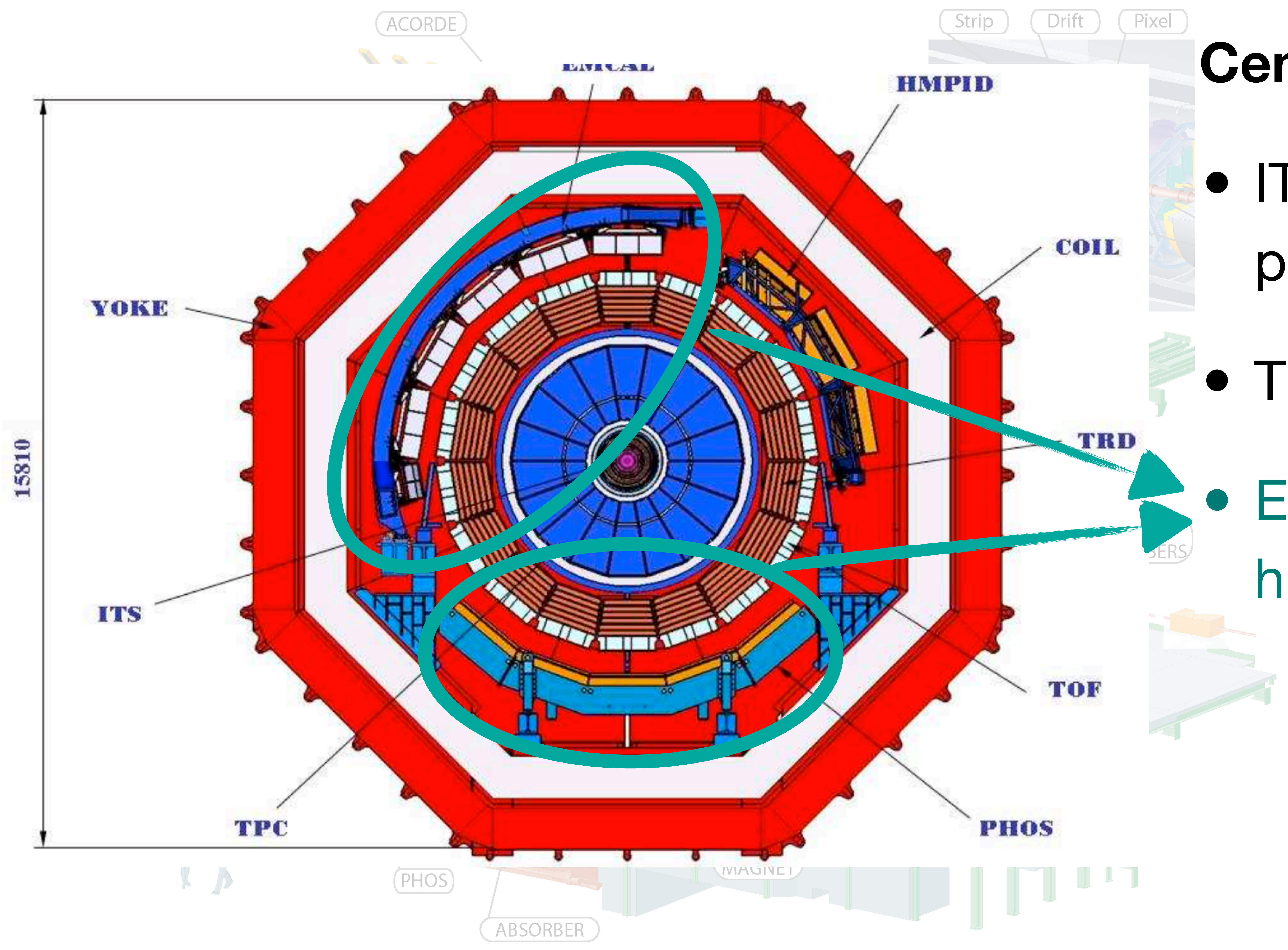
Time of flight (TOF)



HMPID

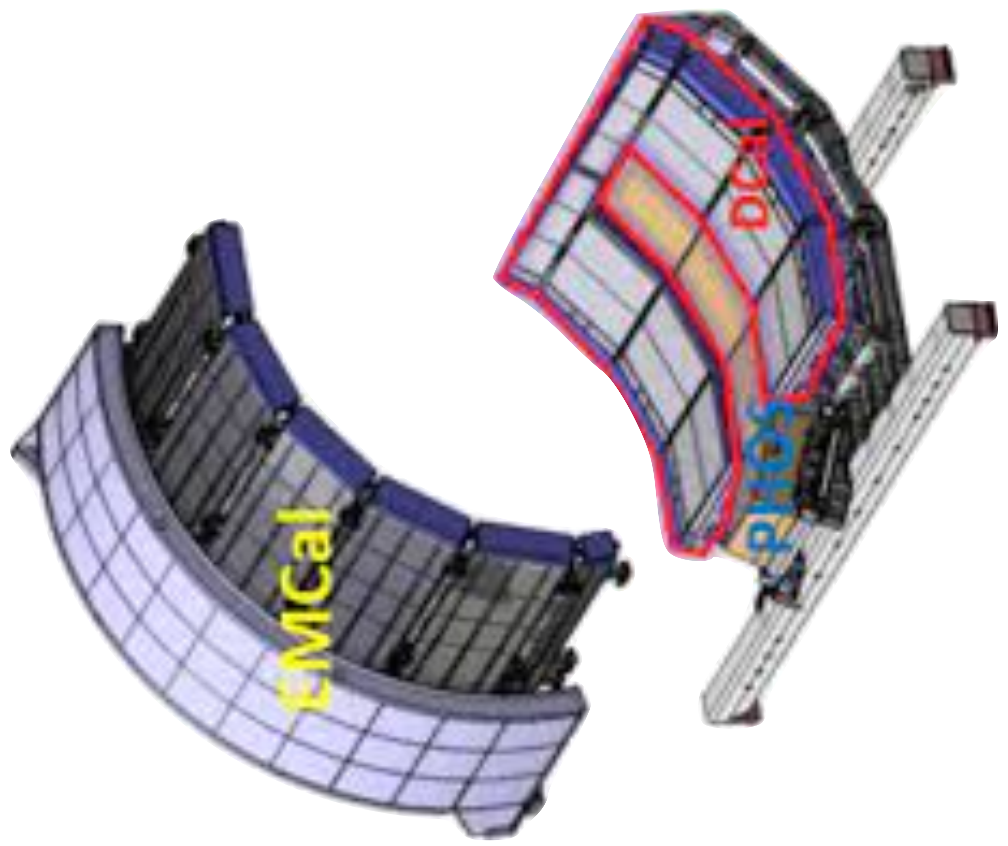


ALICE apparatus

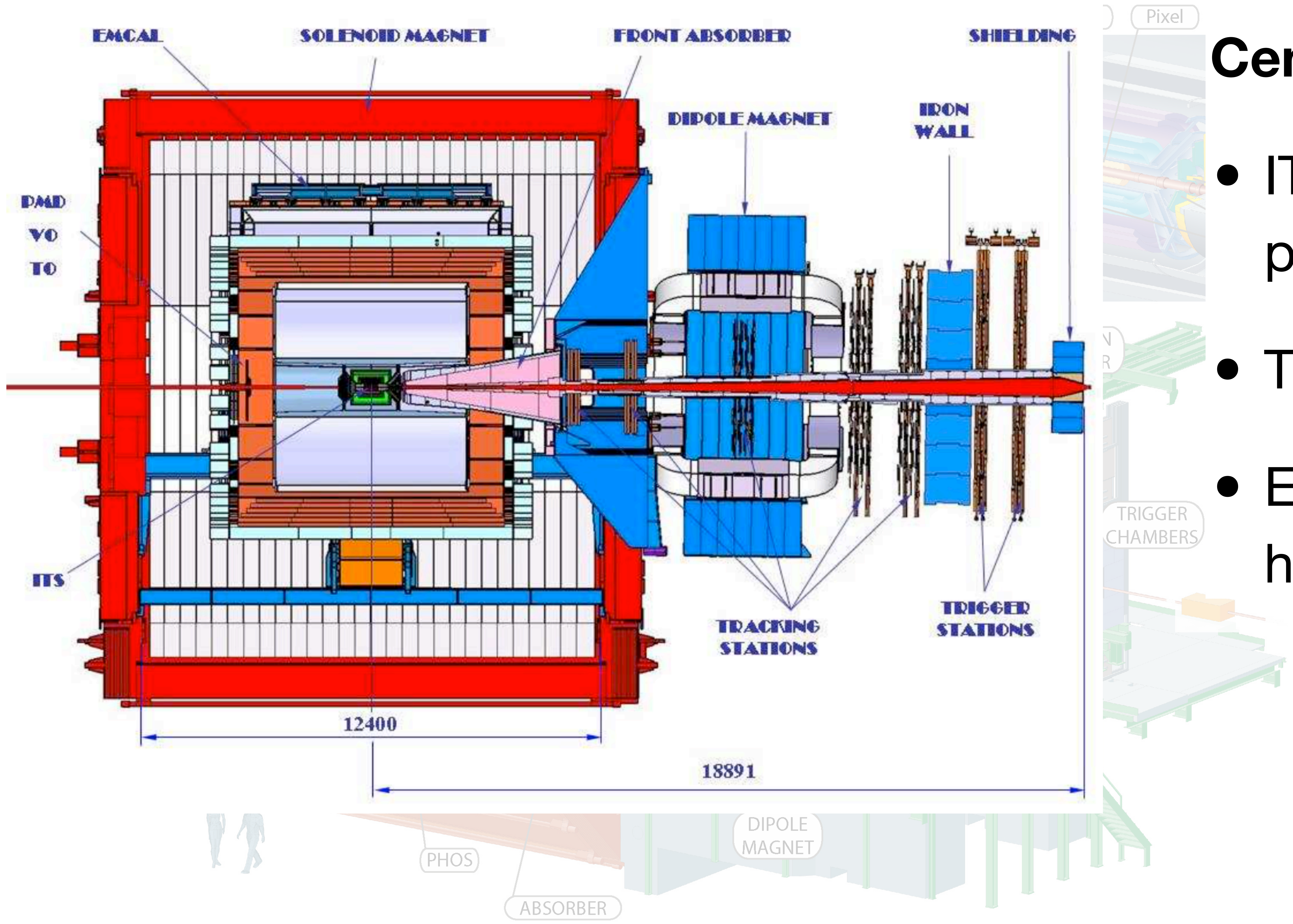


Central barrel detectors ($|\eta| < 0.9$)

- ITS, TPC: vertexing, tracking and particle identification (PID)
- TRD, TOF, HMPID: PID
- EMCal, DCal, PHOS: EM probes, high-p_T π^0 and electrons



ALICE apparatus



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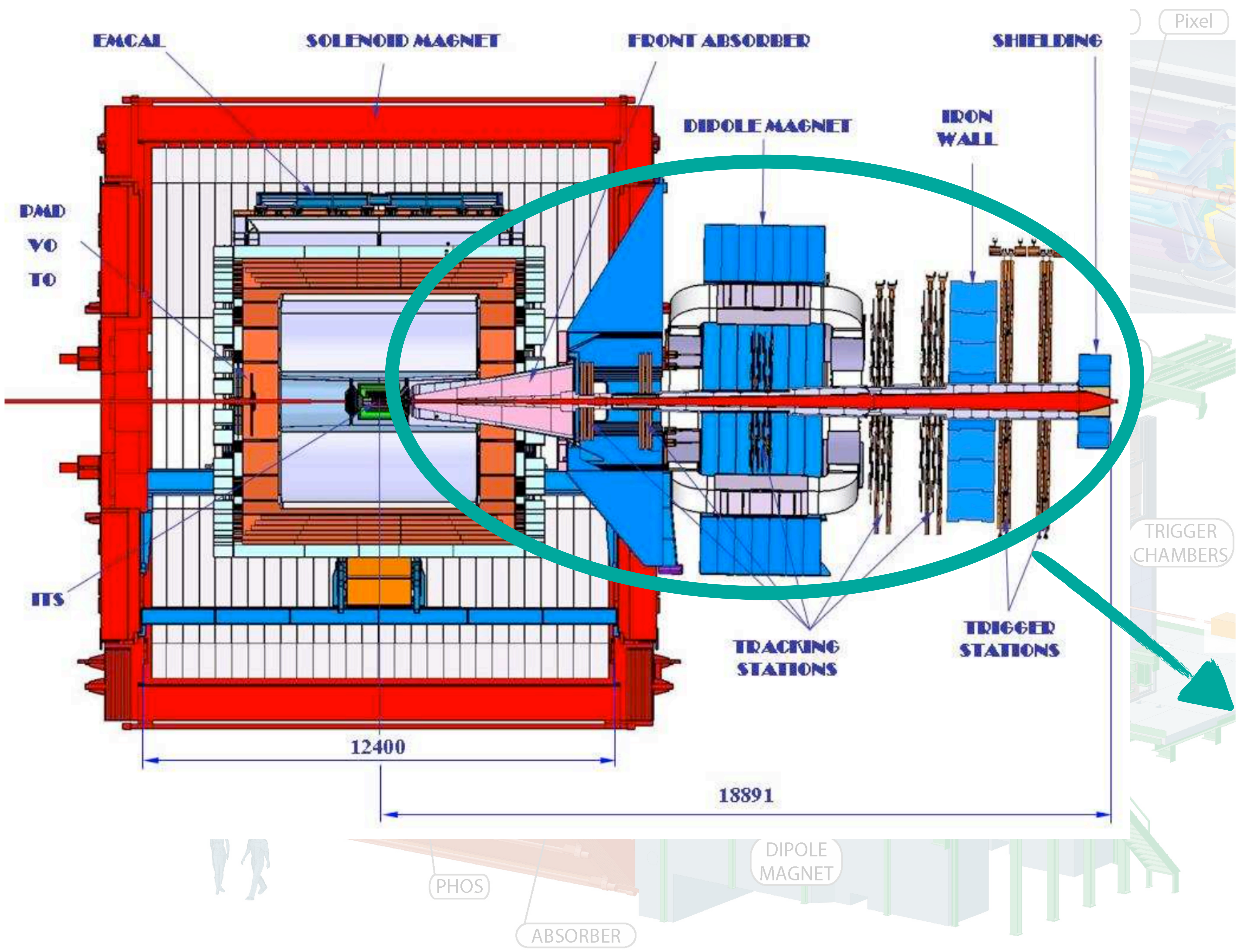

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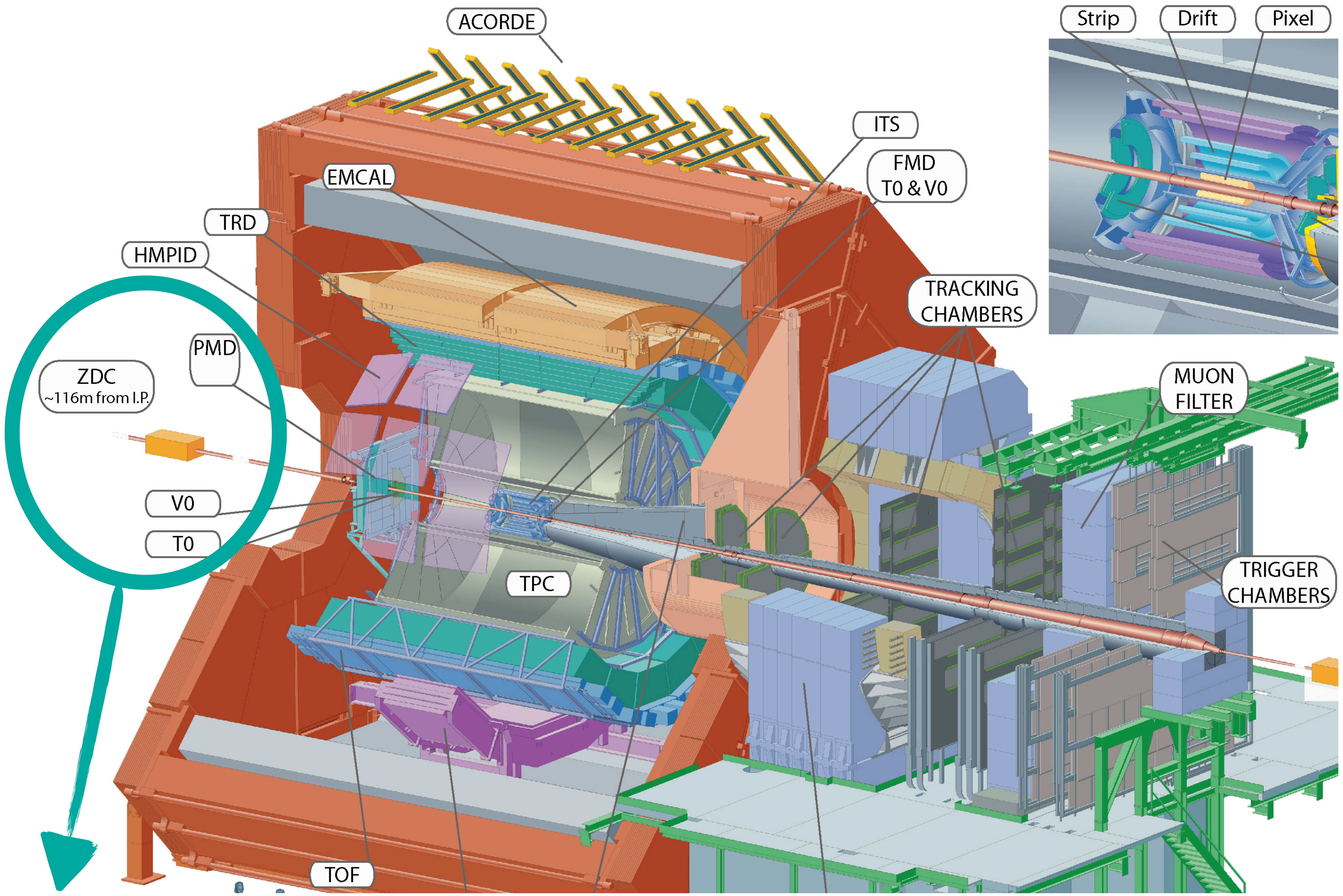
Forward MUON: open and hidden heavy-flavor hadrons and $W^{\pm}/Z^0$ muonic decays

ALICE apparatus



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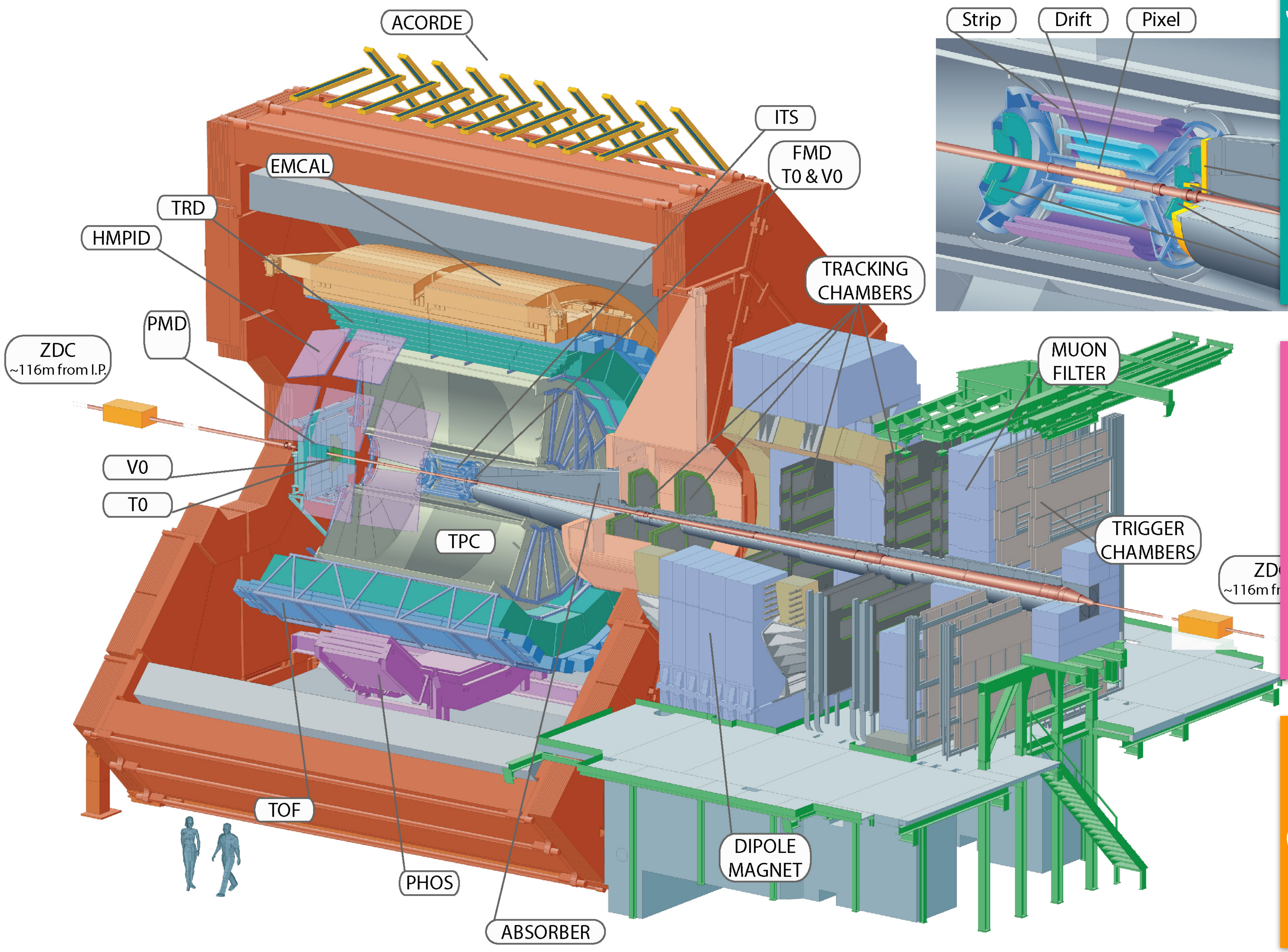
Forward muon: open and hidden heavy-flavor hadrons and $W^{\pm}/Z^0$ muonic decays

Small detectors (V0, T0, PMD, ZDC…)

- Event triggering and characterization

ALICE shopping list



Soft physics

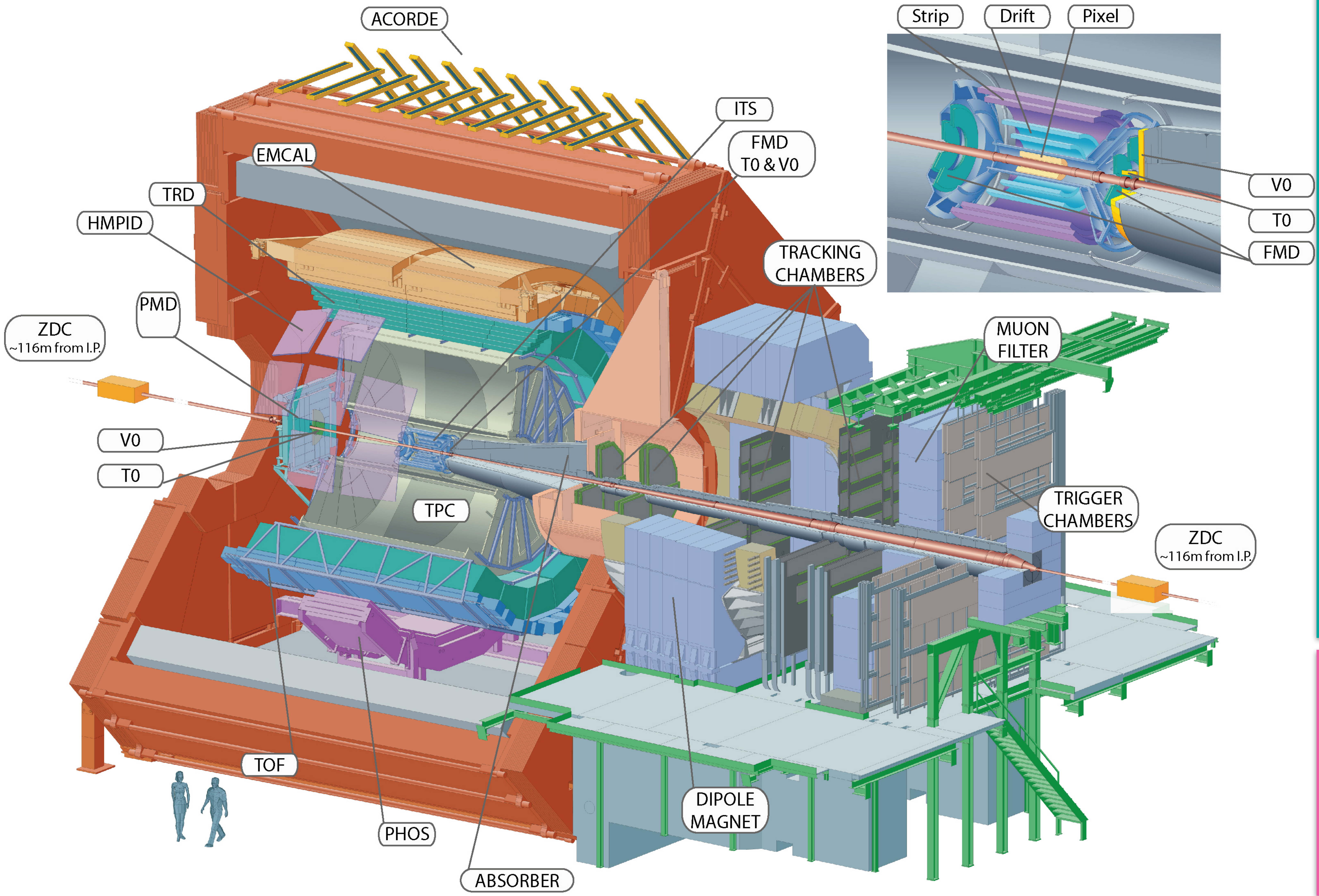
- Event multiplicity and particle production
- Correlations and fluctuations

Hard probes

- Heavy quarks, jets and high-p_T photons
- Ultra-peripheral collisions

New physics: magnetic file effects, exotic particles, light nuclei, antimatter…

ALICE heavy quark programme



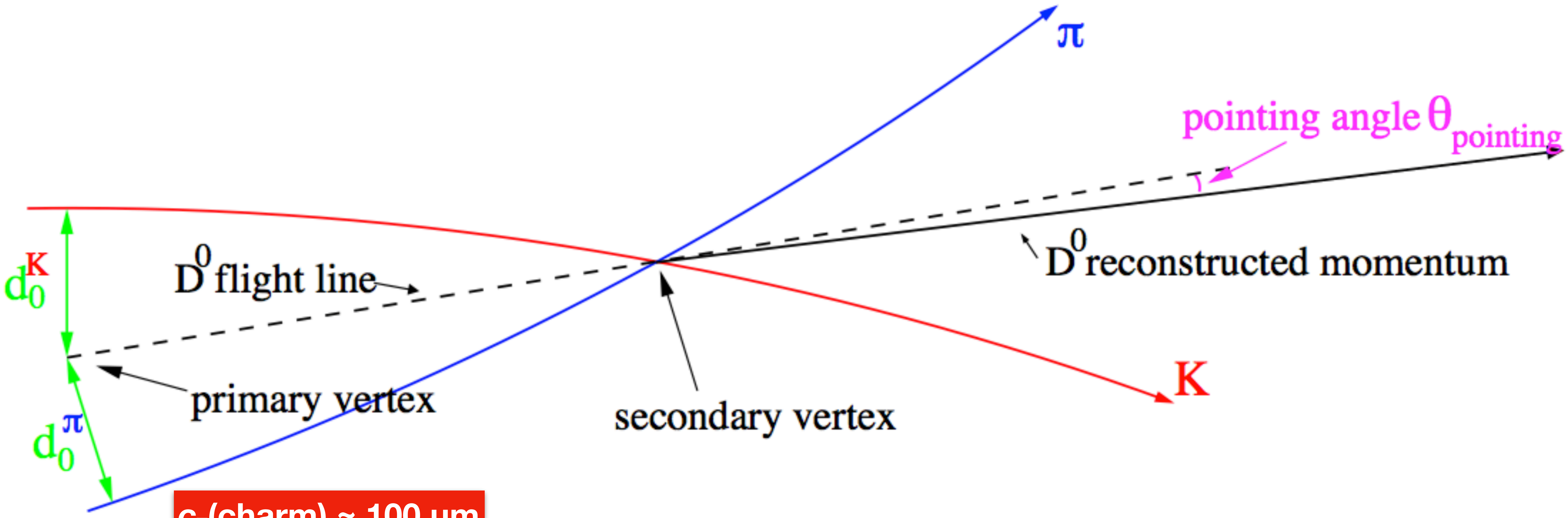
Hadronic decays ($|y| < 0.8$)

- $D^0 \rightarrow K^-\pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+$
- $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$
- $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$
- $\Lambda_c^+ \rightarrow pK^-\pi^+$
- $\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^\mp$
- $\Xi_c^{0(+)} \rightarrow \Xi^-\pi^+(\pi^+)$
- $\Omega_c^+ \rightarrow \Omega^0\pi^+$

Semi-leptonic decays

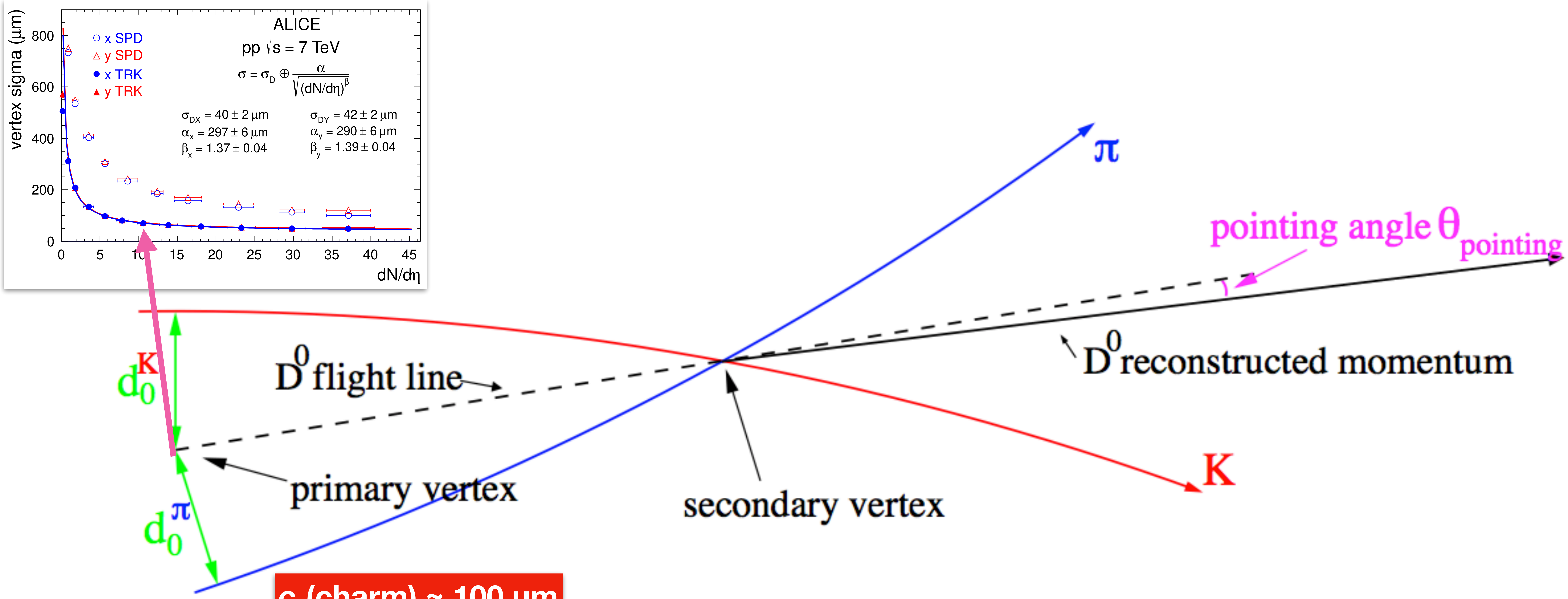
- c, b $\rightarrow e^\pm$ ($|y| < 0.7$)
- c, b $\rightarrow \mu^\pm$ ($2.5 < y < 4$)

$D^0 \to K^-\pi^+$ reconstruction



$c\tau$(charm) ~ 100 μm

$D^0 \rightarrow K^- \pi^+$ reconstruction



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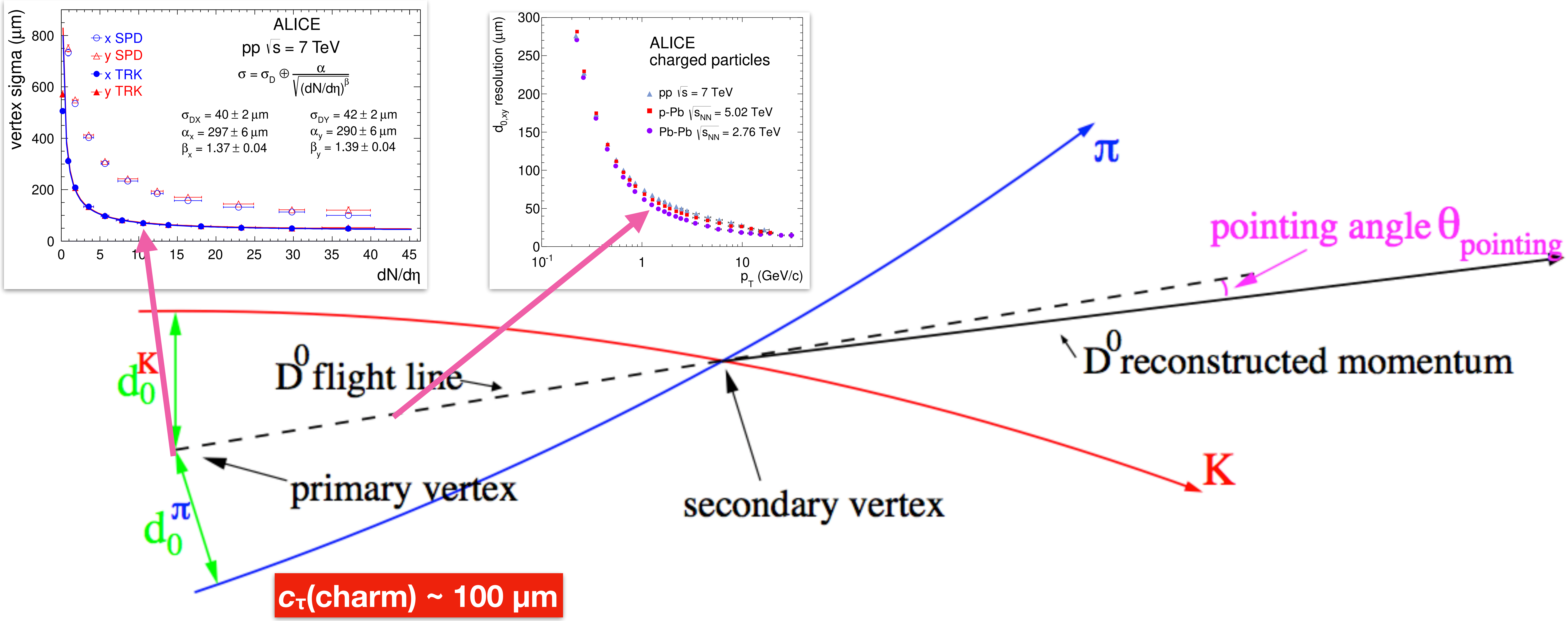
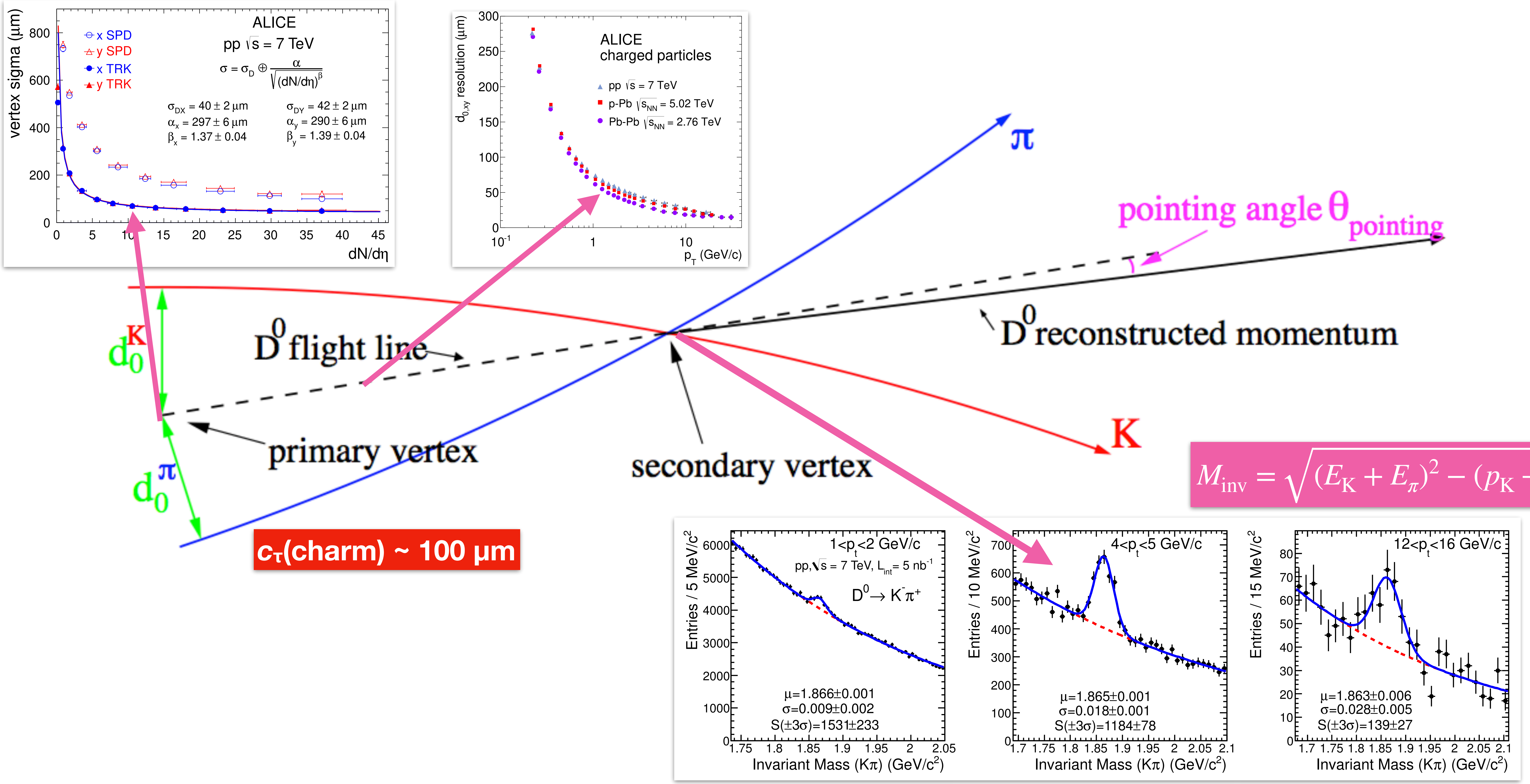


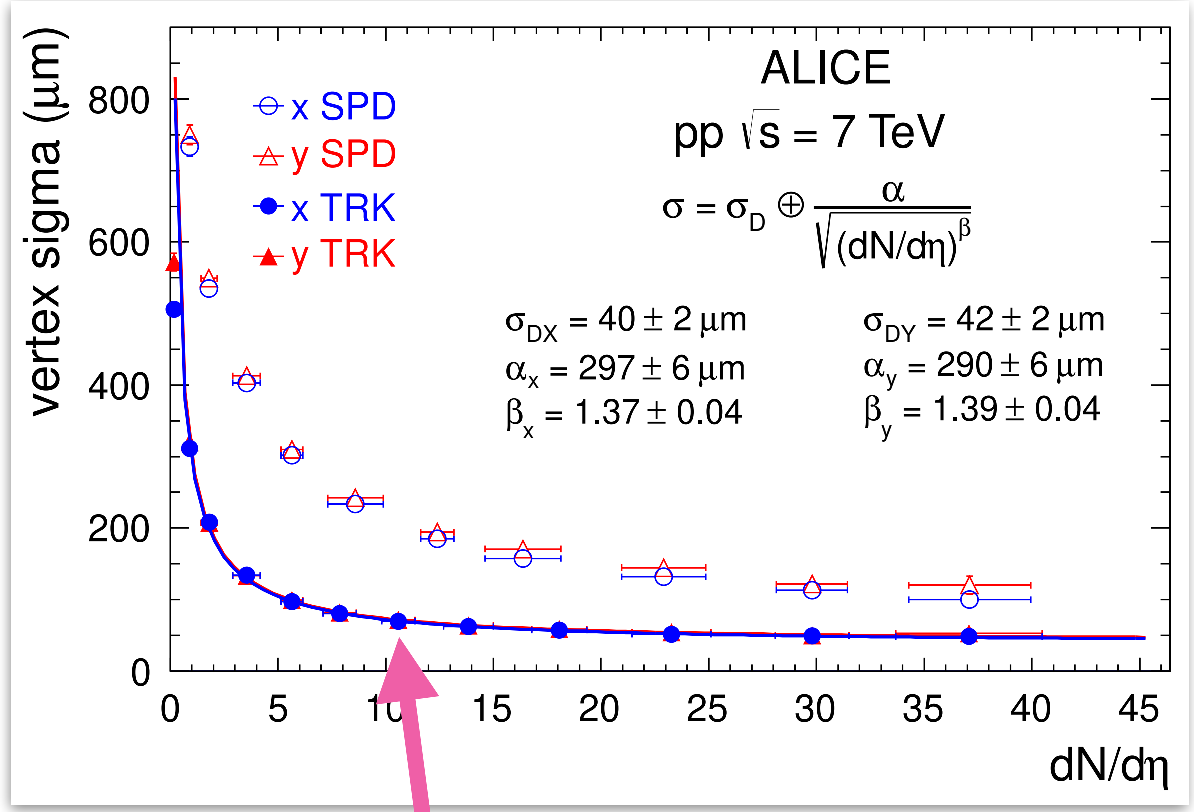
$D^0 \to K^- \pi^+$ reconstruction

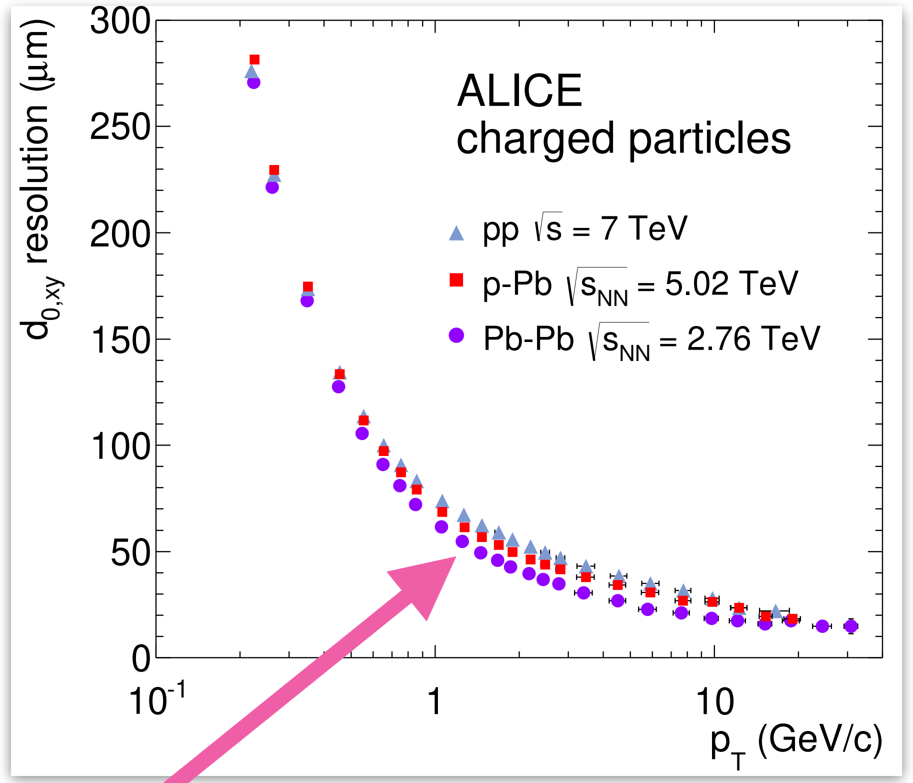


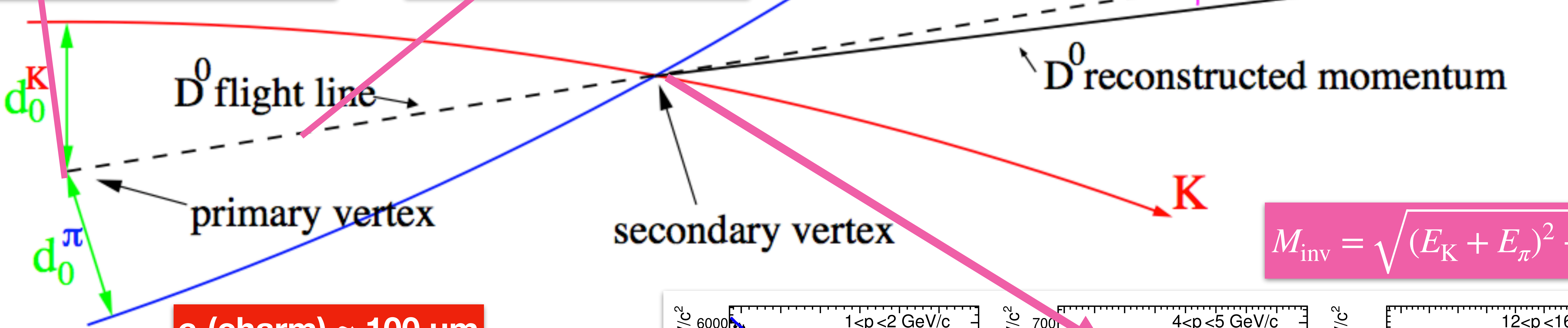
$c\tau$(charm) ~ 100 μm

$$M_{\rm inv} = \sqrt{(E_K + E_\pi)^2 - (p_K + p_\pi)^2}$$

$D^0 \to K^- \pi^+$ reconstruction







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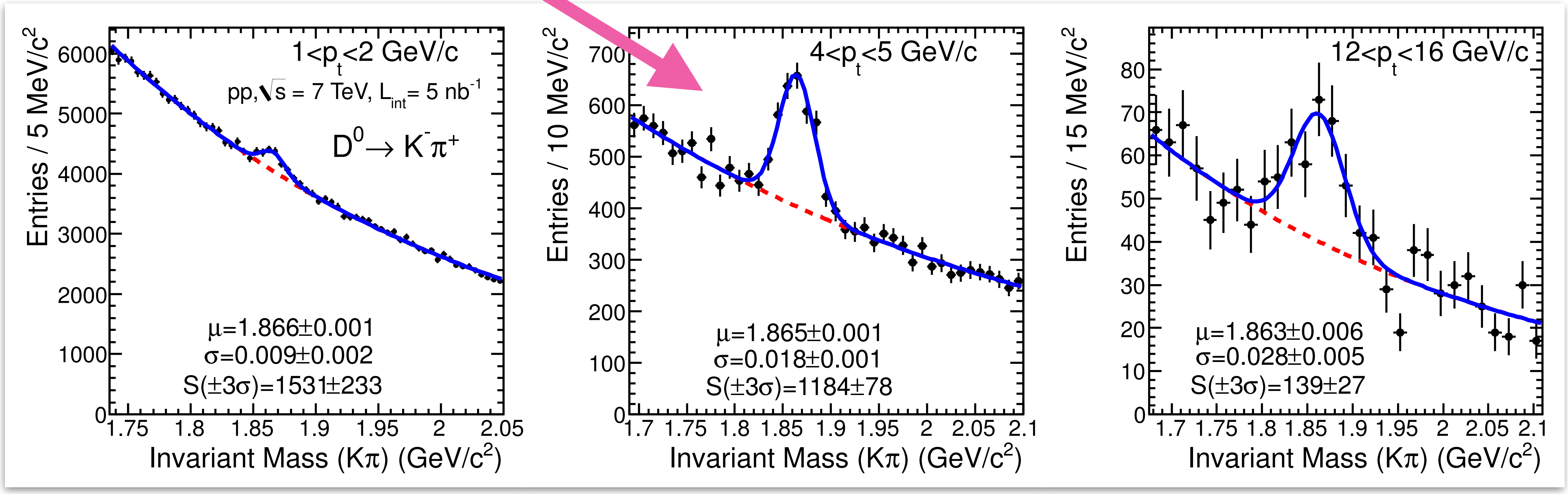
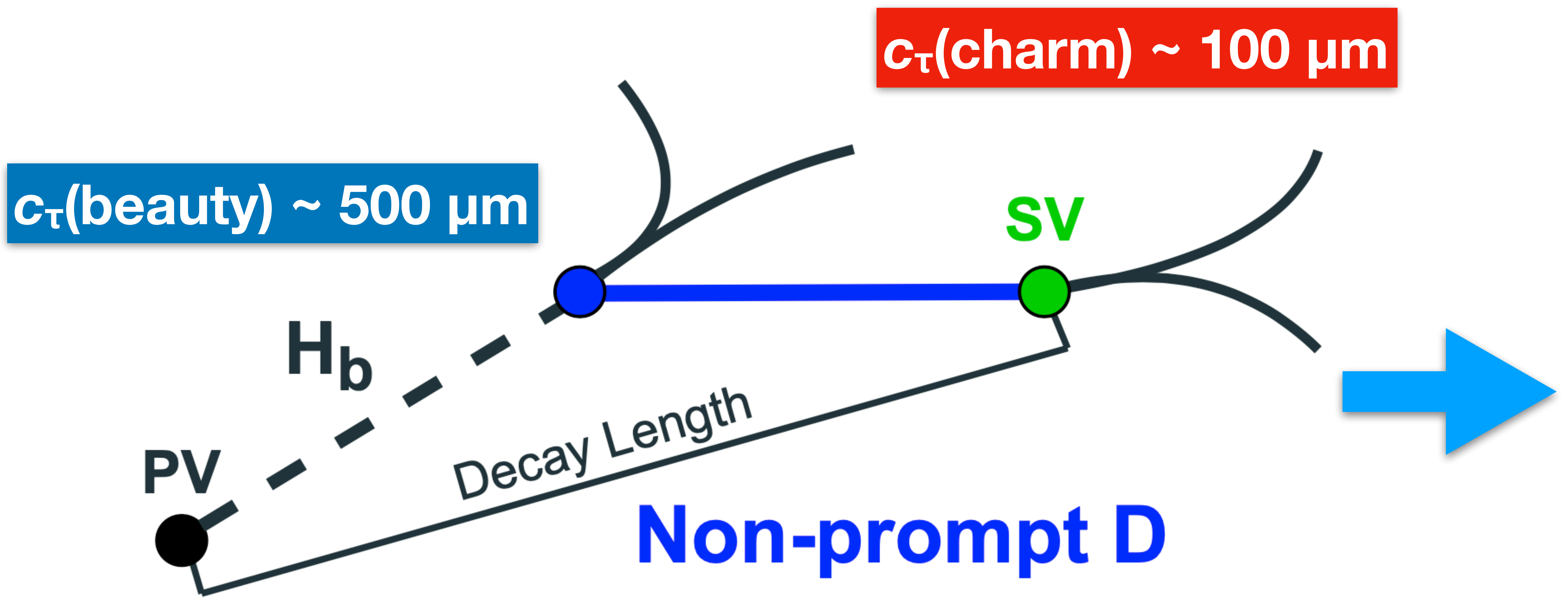
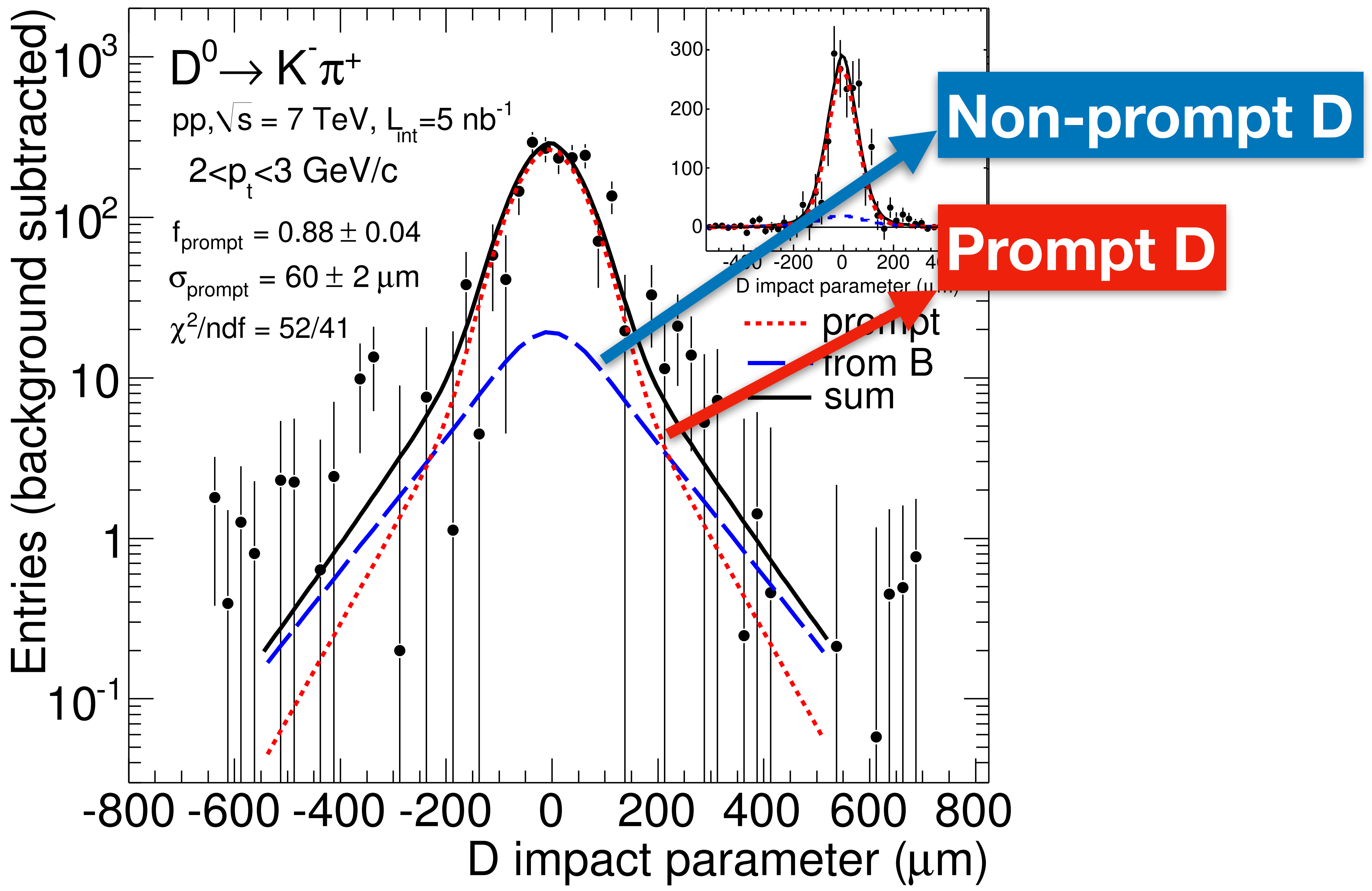


Similar procedure apply to $D^\pm$, $D^{*\pm}$ and $D_s^\pm$

Non-prompt D^0 signal extraction





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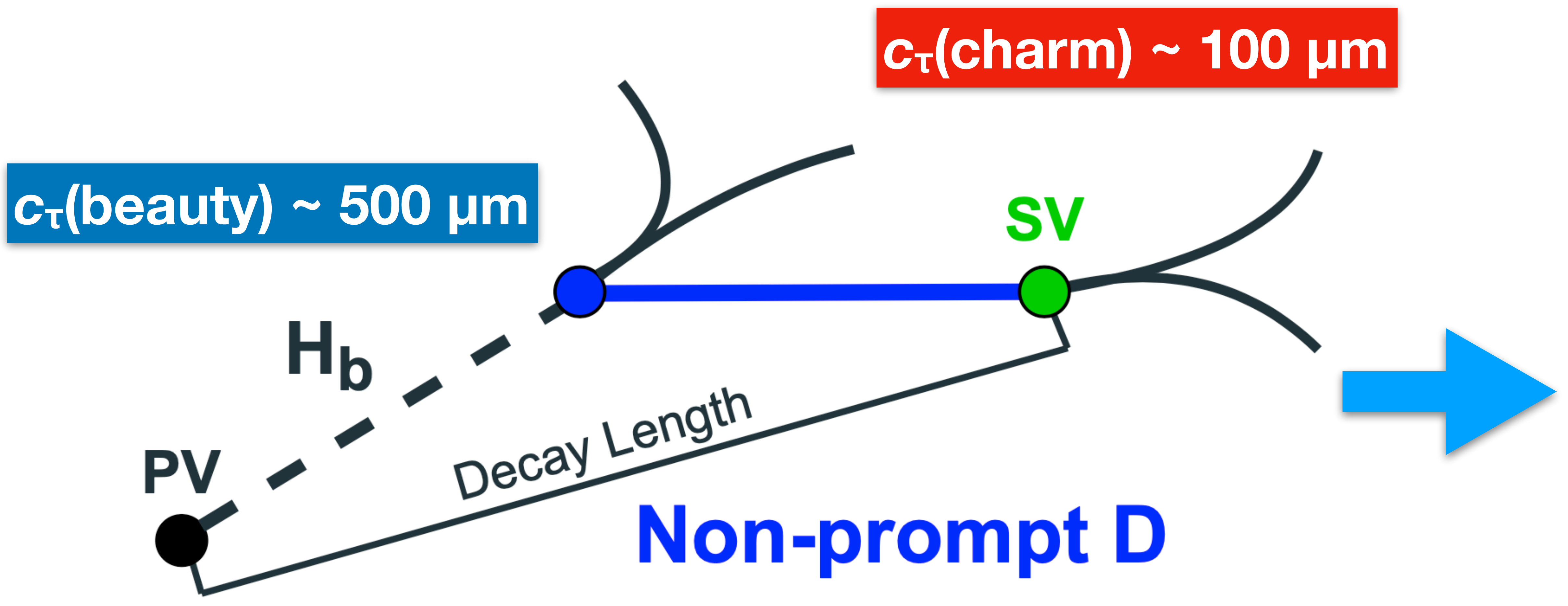
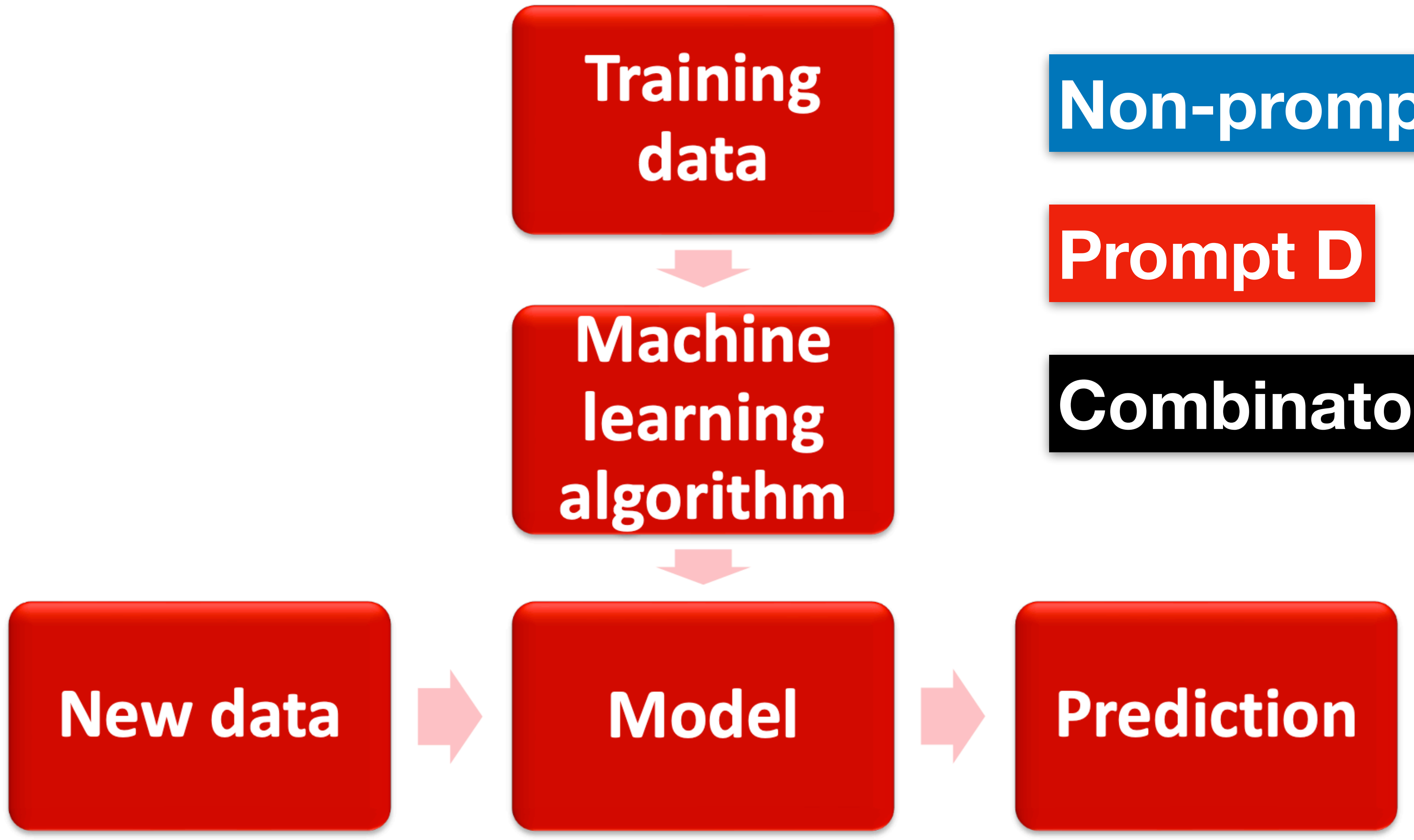


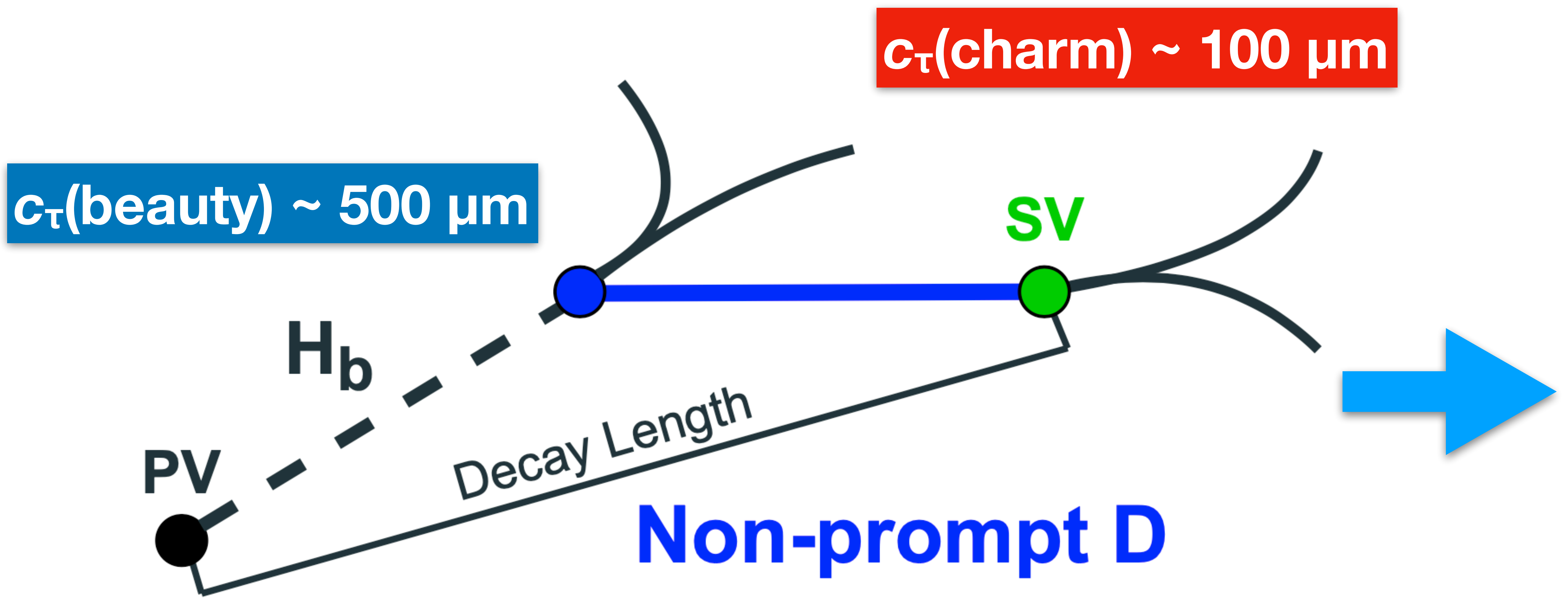


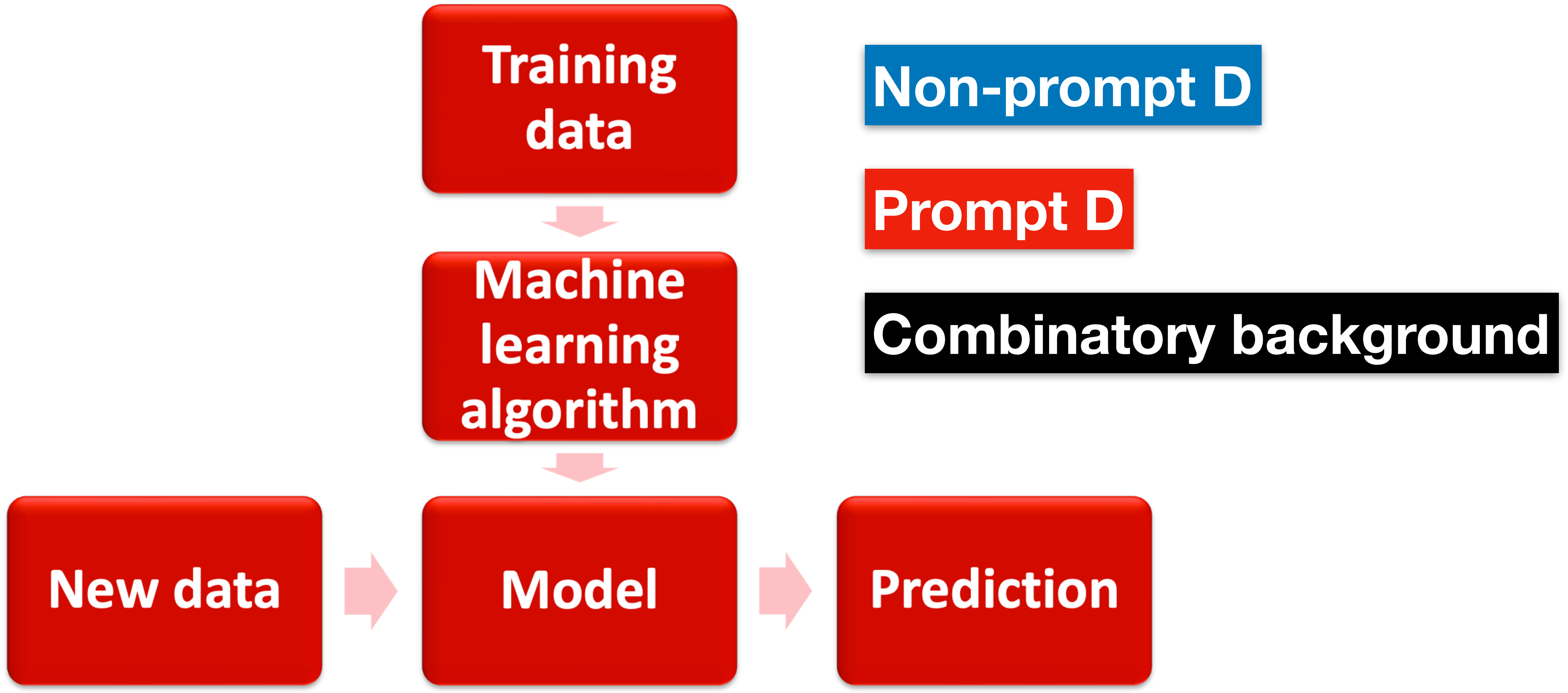
Non-prompt D

Prompt D

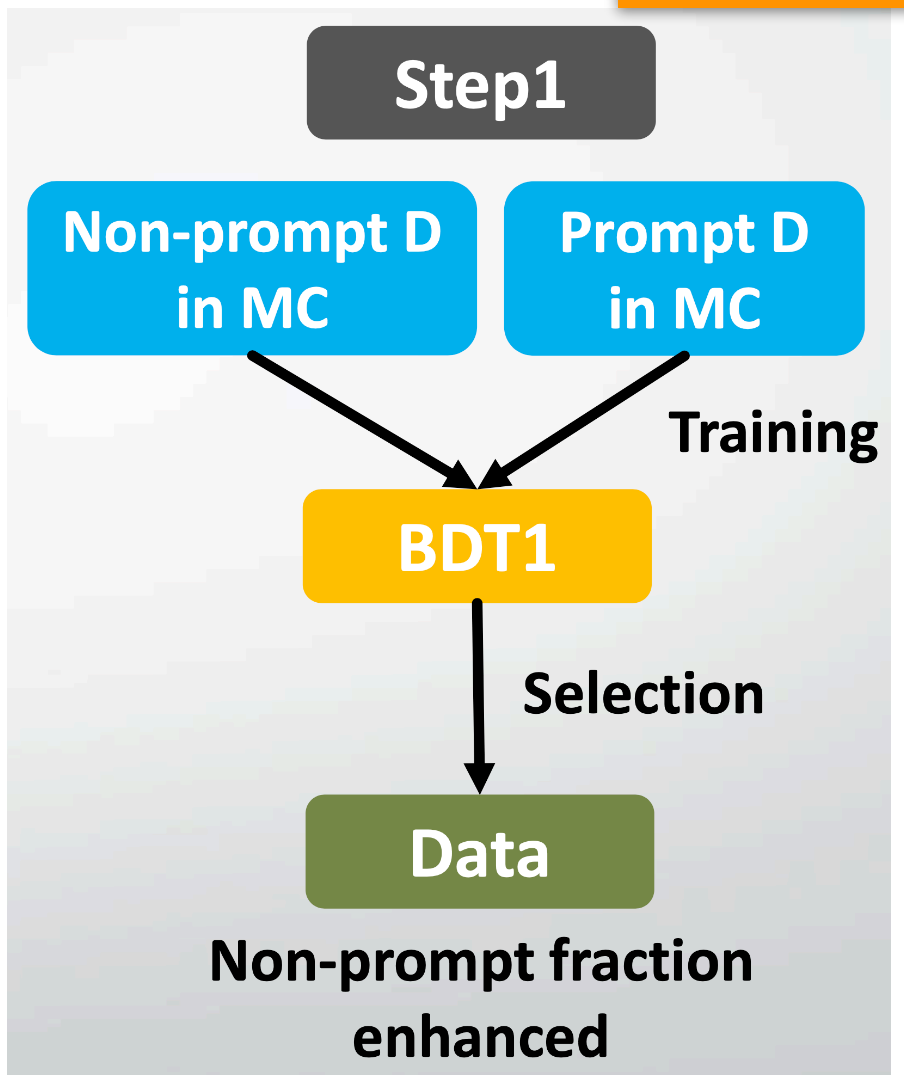
Combinatorial background

Non-prompt D^0 signal extraction





Select significant



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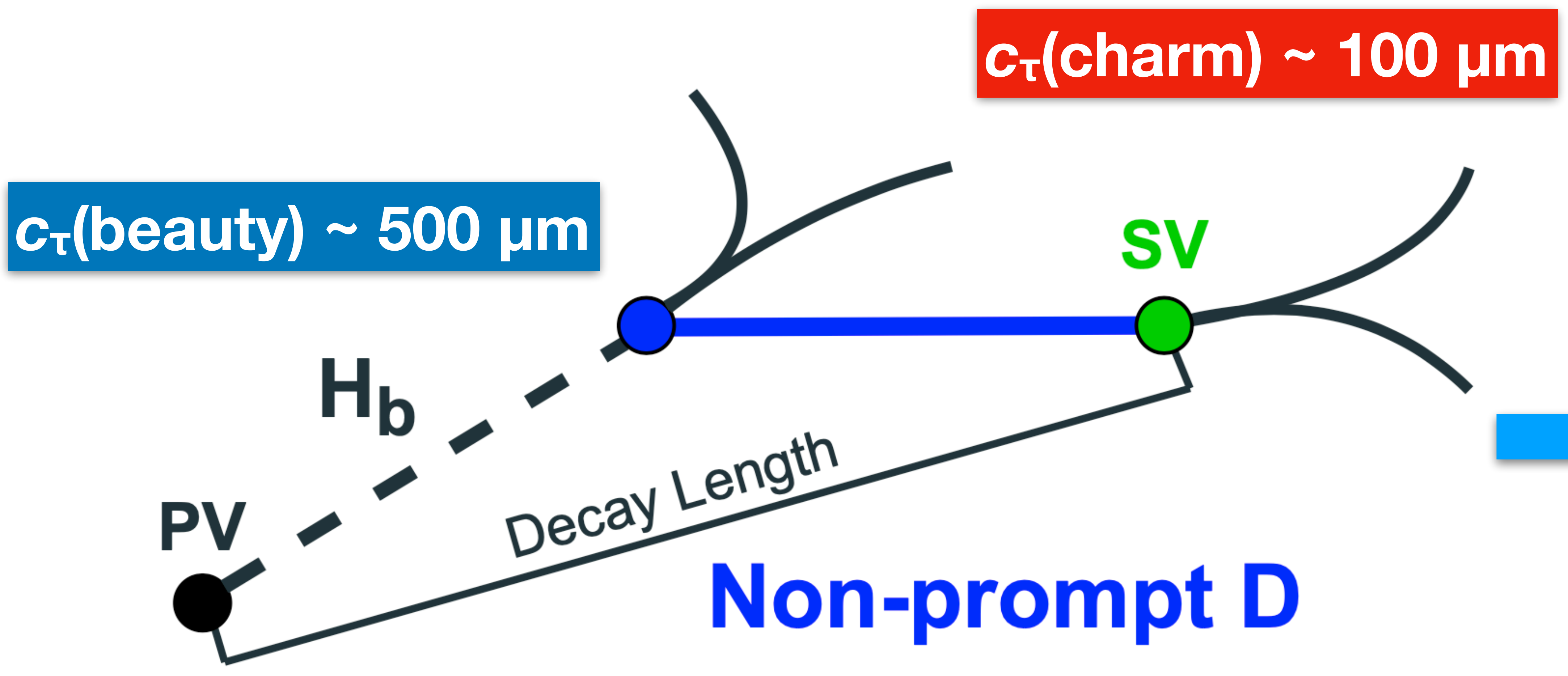

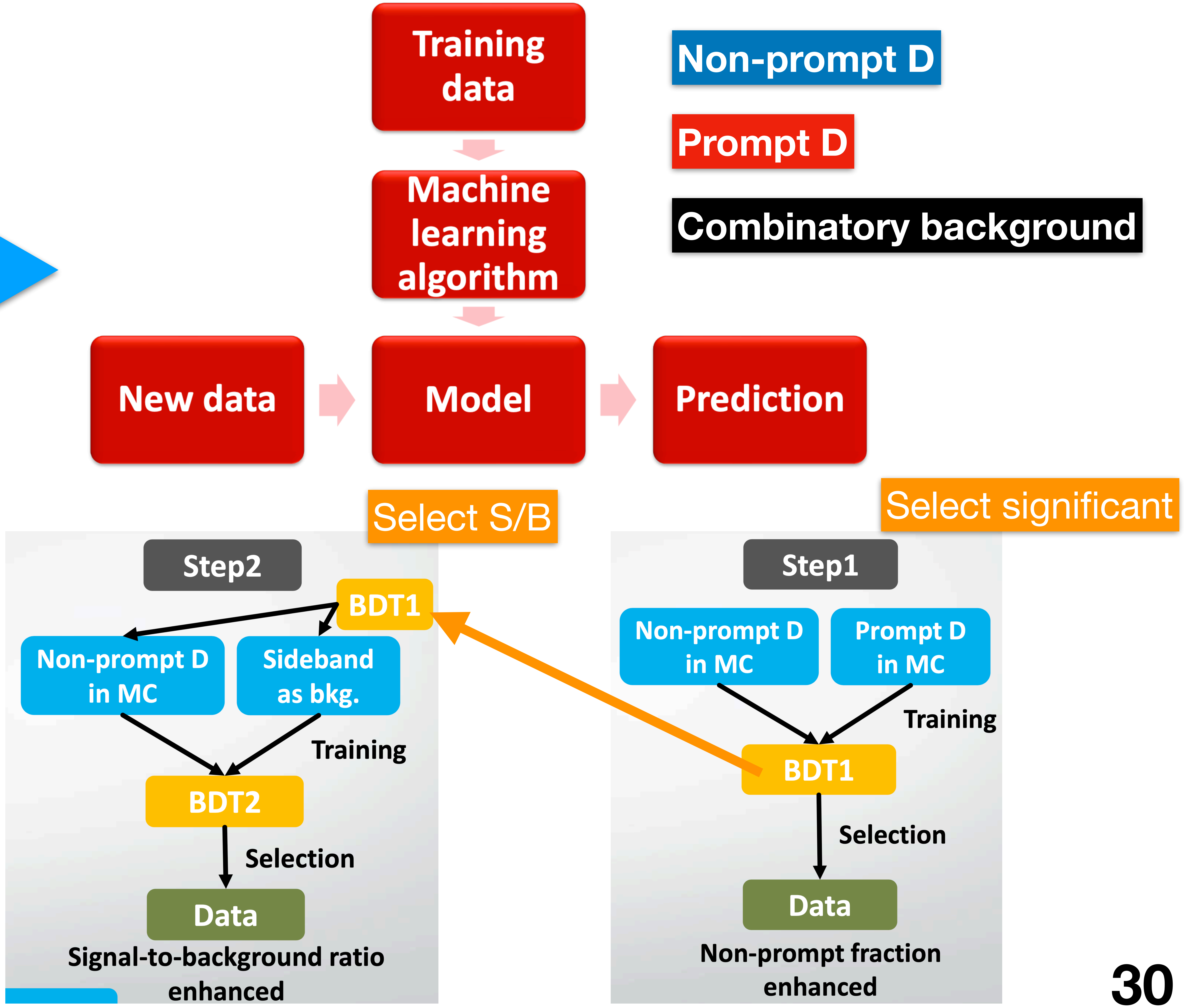

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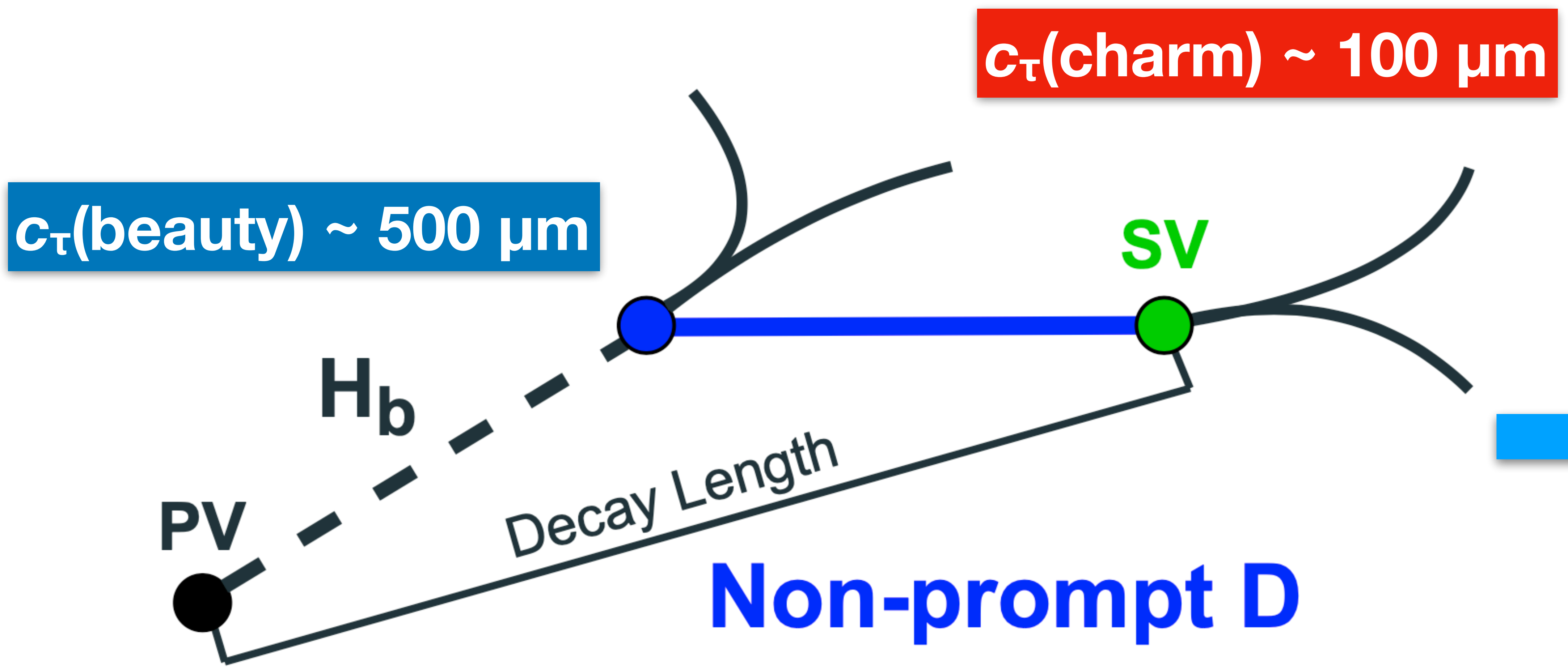

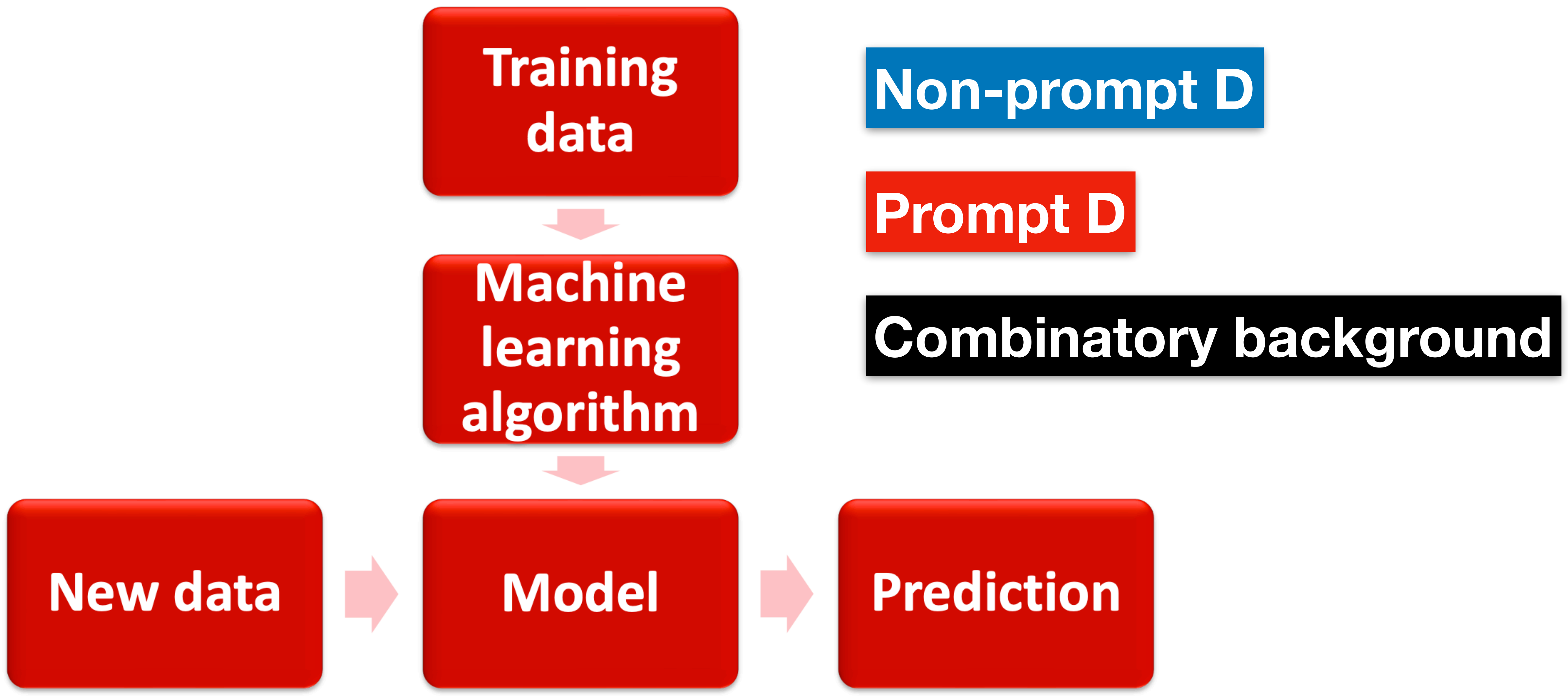

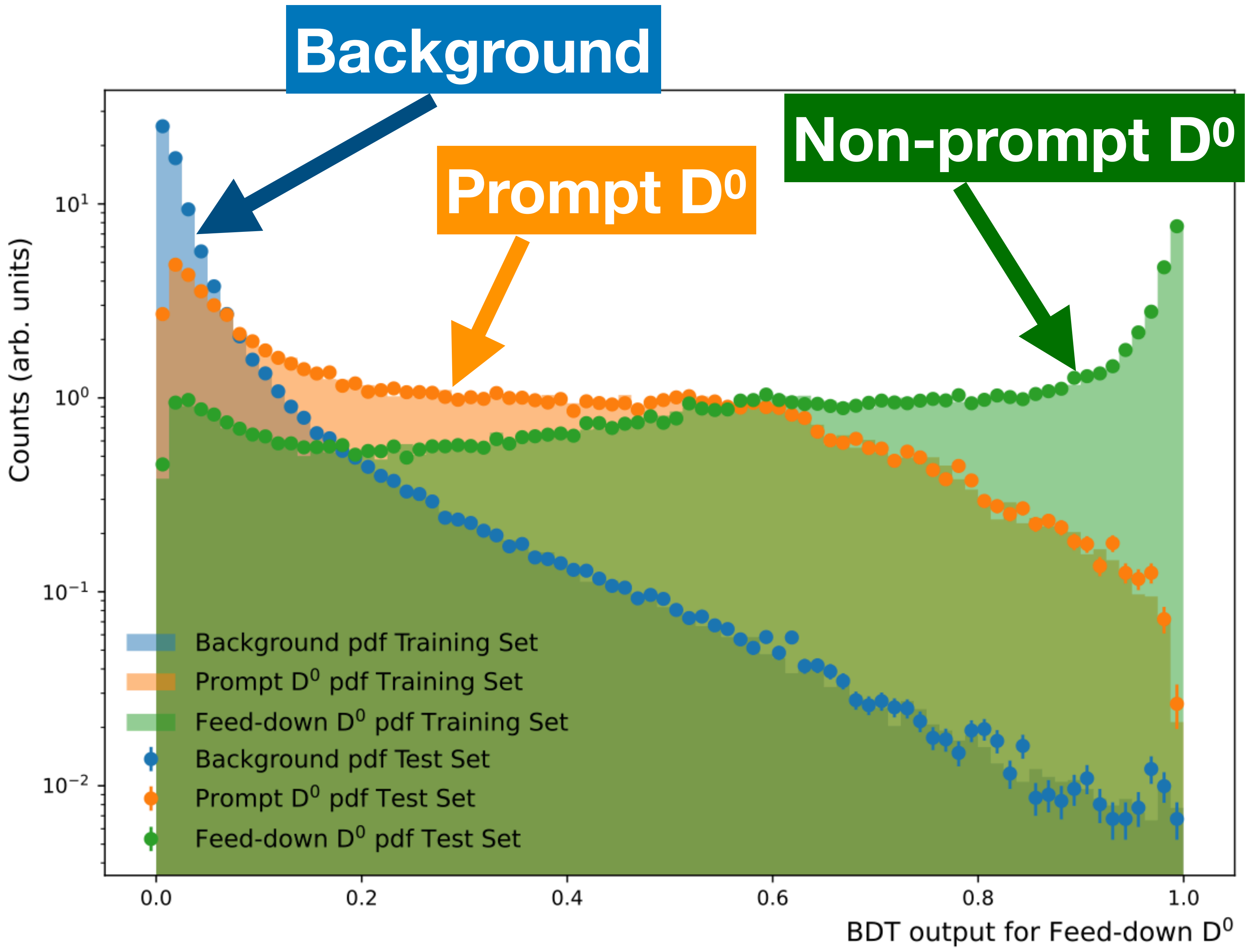

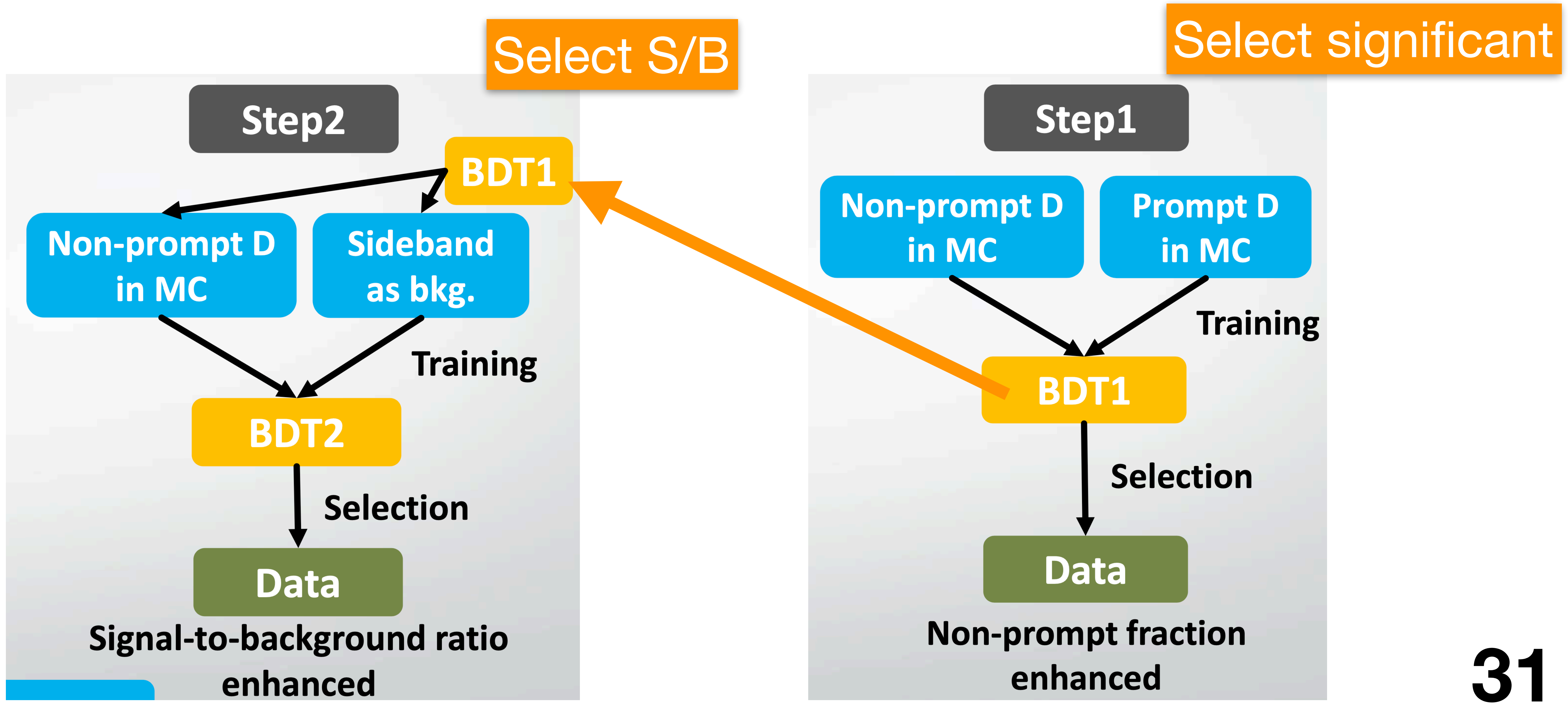

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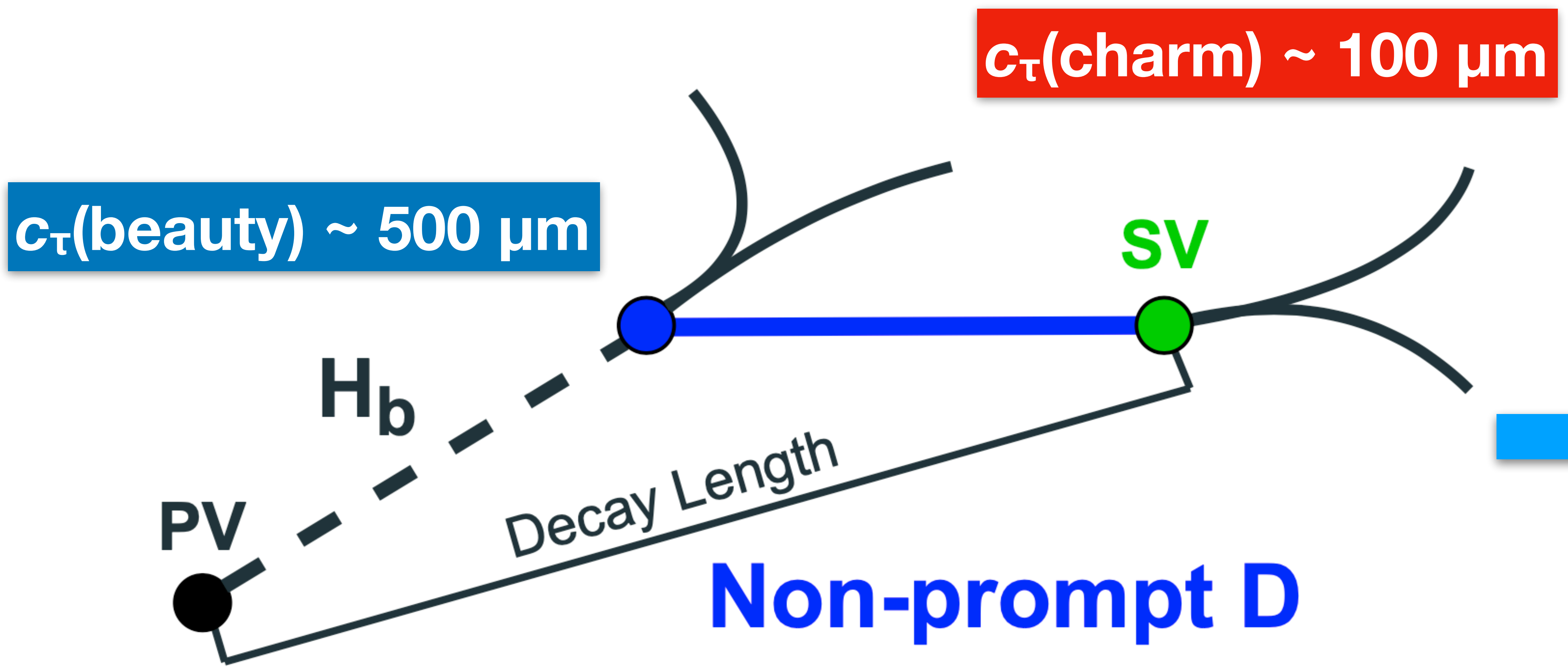

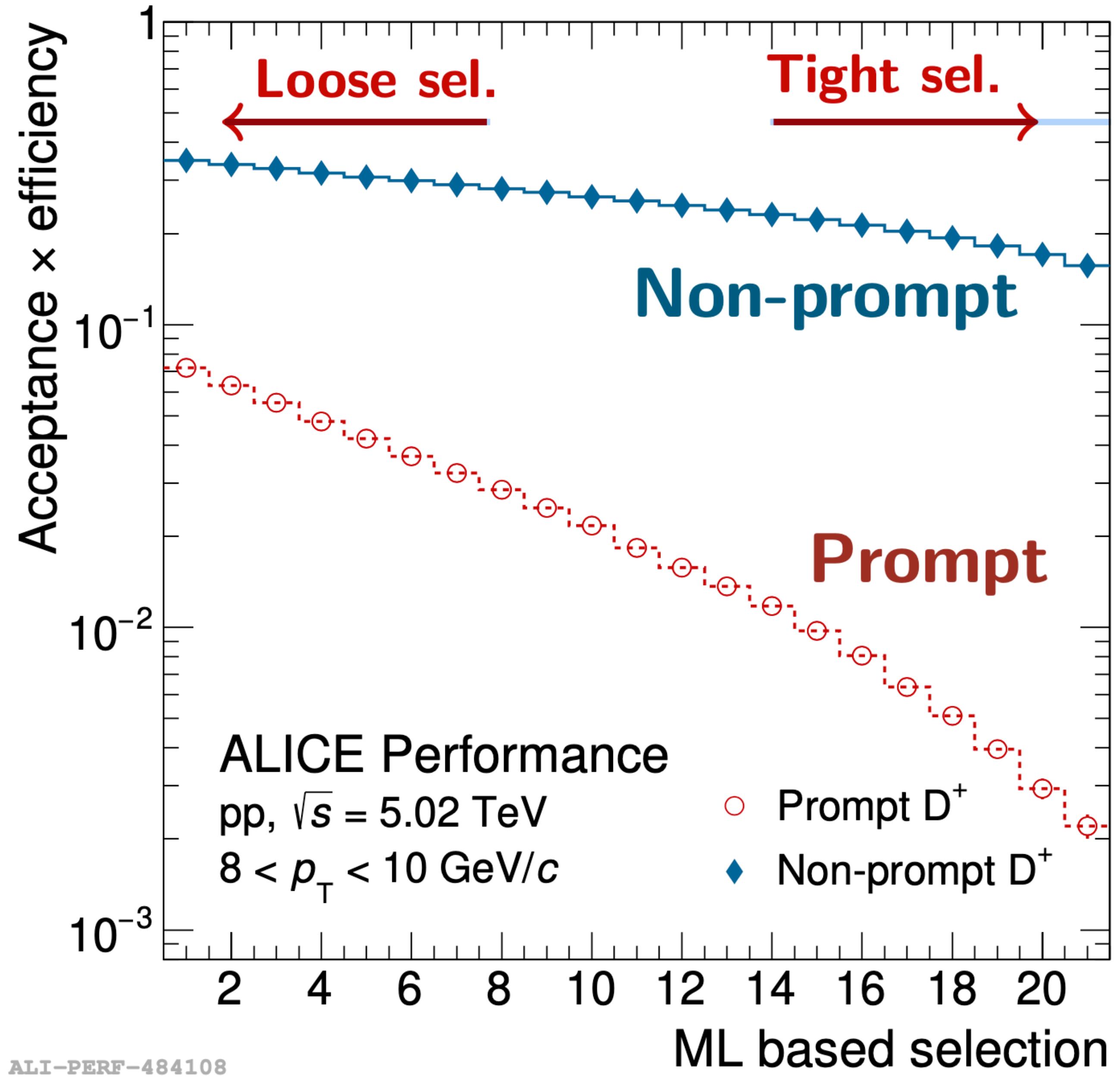

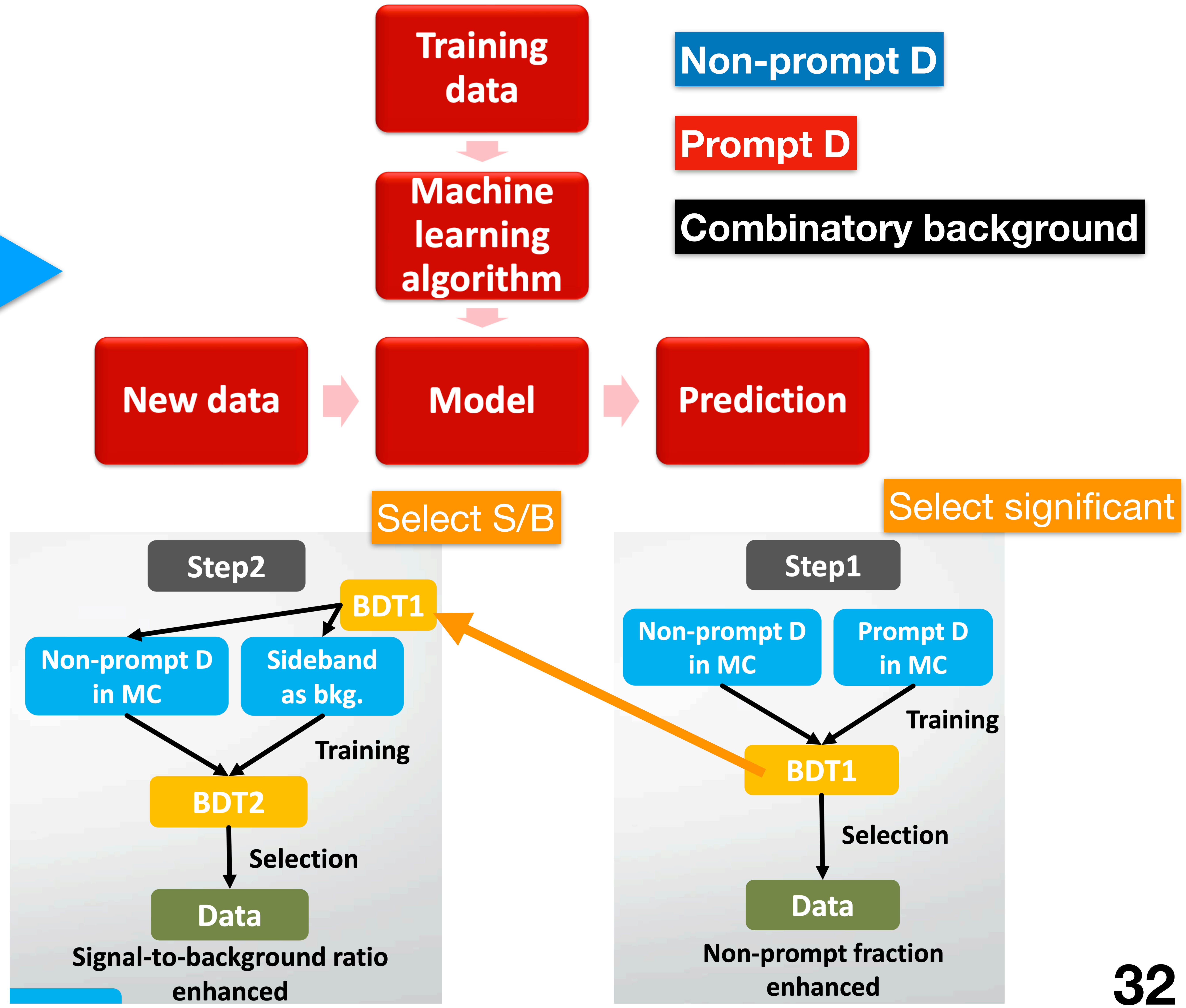

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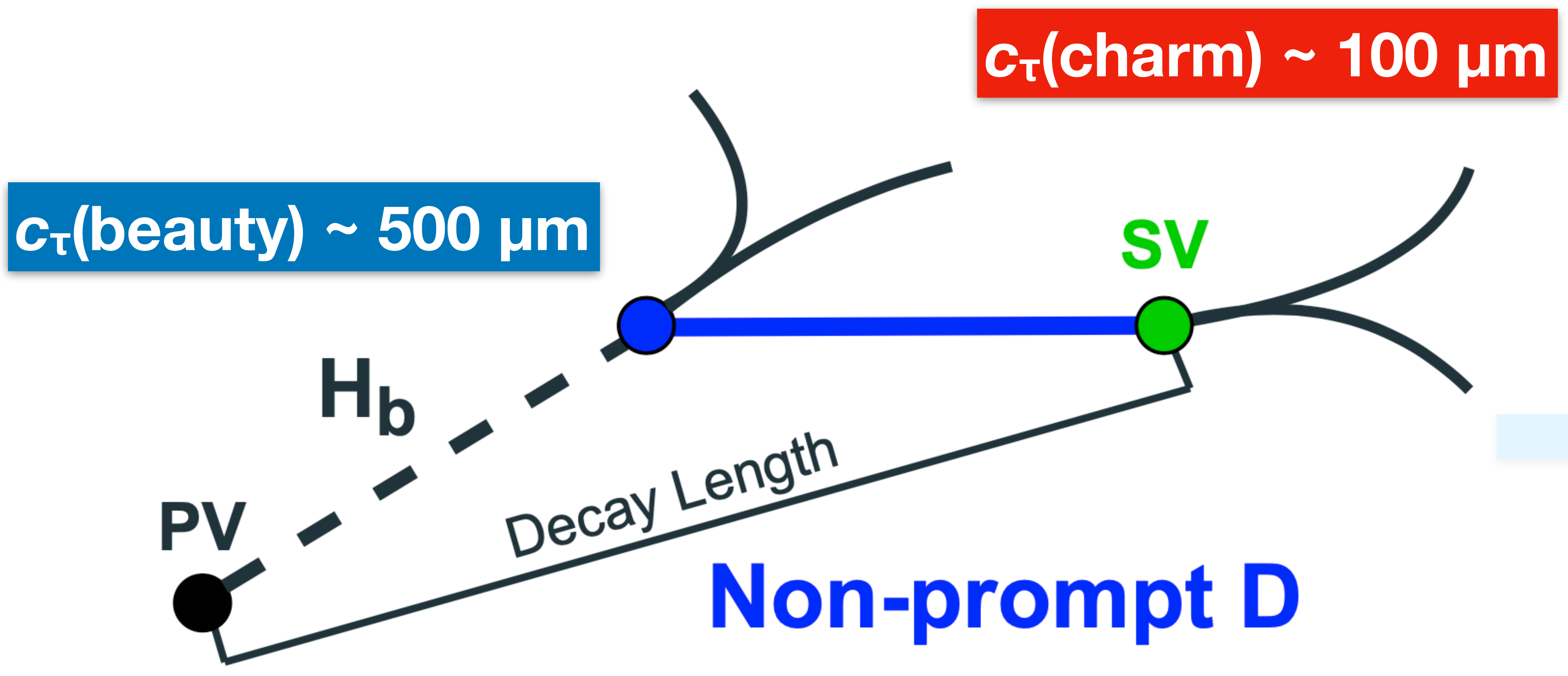
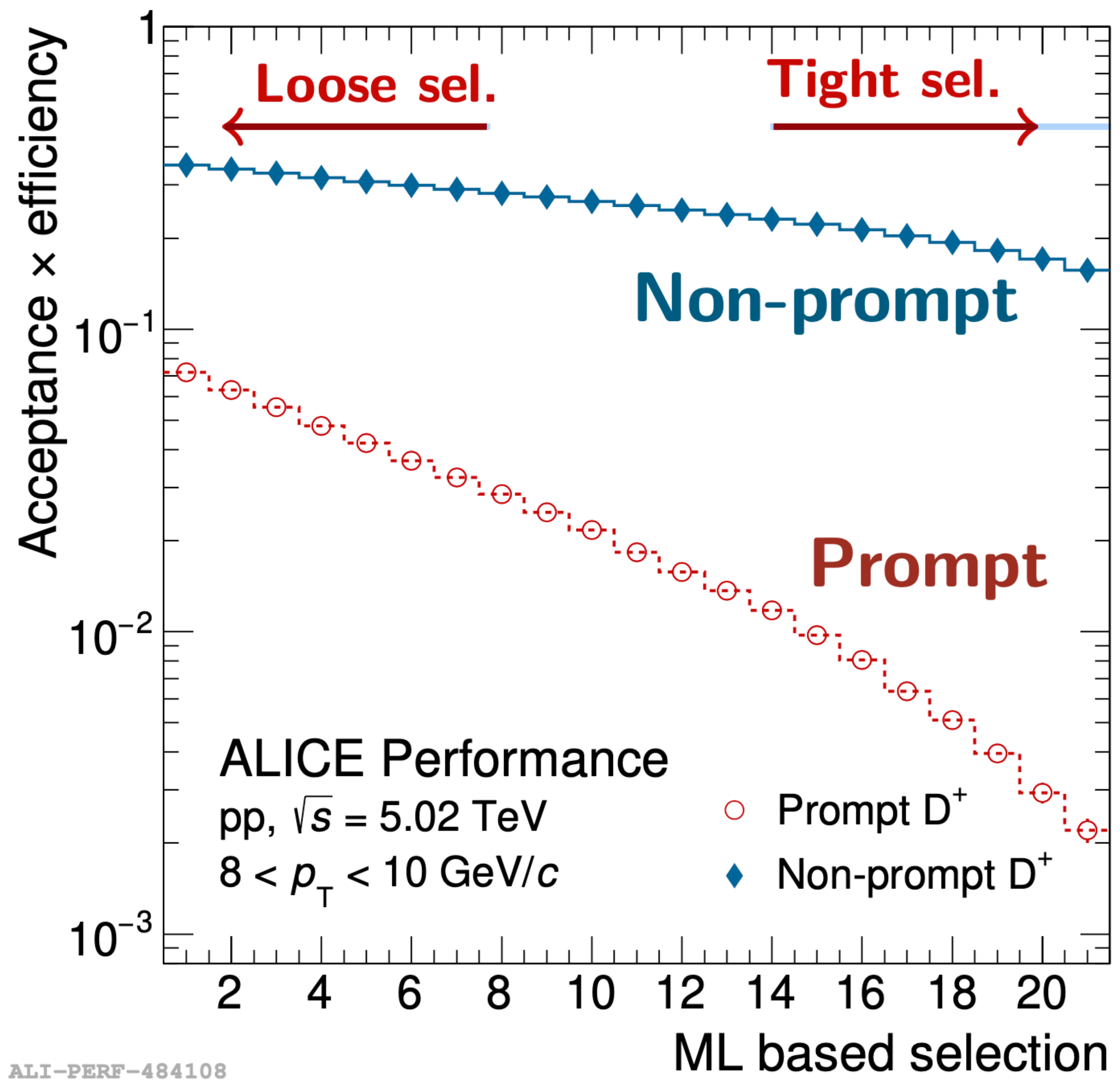
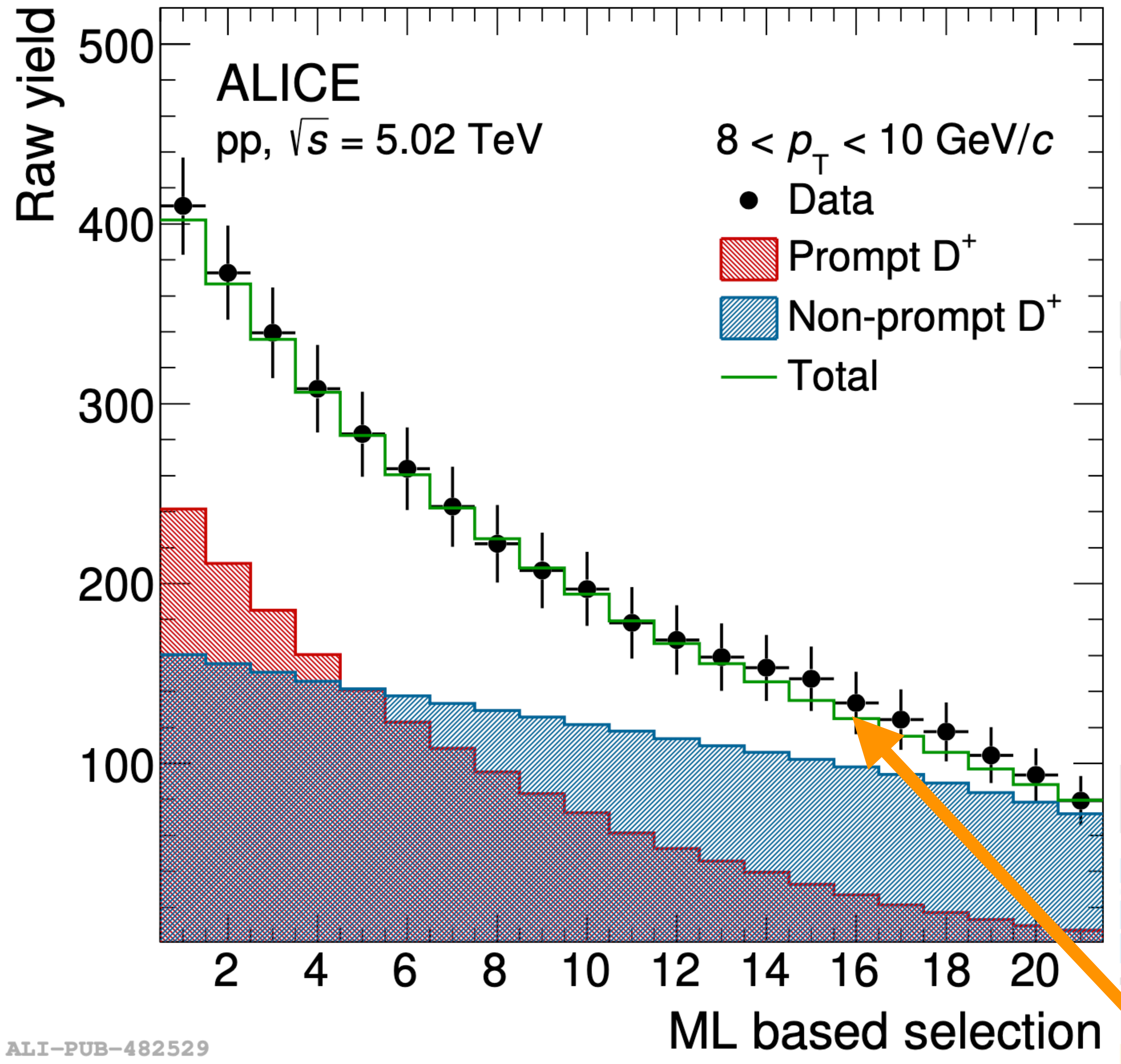
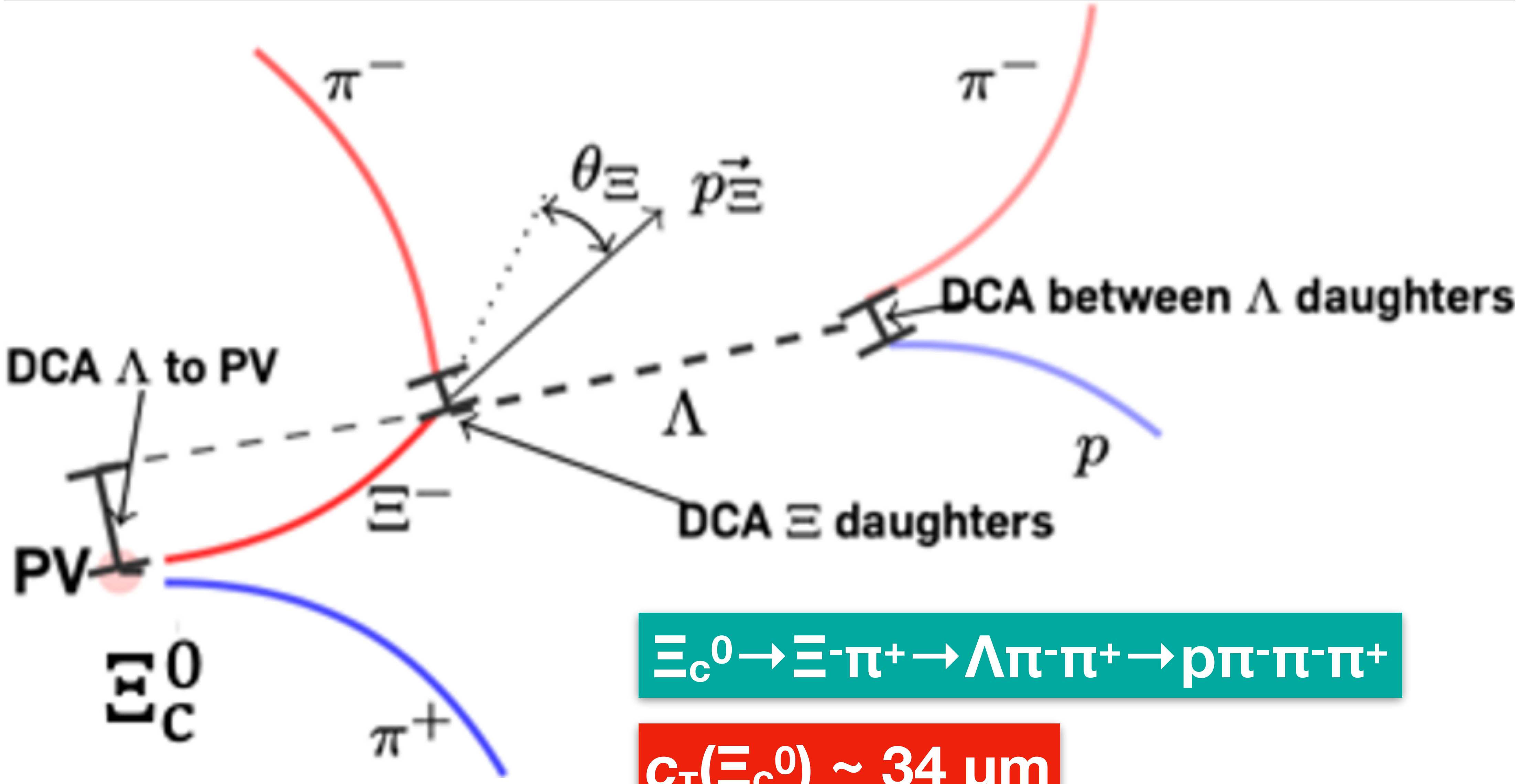






$$
\begin{cases}
(\mathrm{Acc}\times\epsilon)_1^{\mathrm{prompt}}\cdot N_{\mathrm{prompt}} + (\mathrm{Acc}\times\epsilon)_1^{\mathrm{non\text{-}prompt}}\cdot N_{\mathrm{non\text{-}prompt}} = Y_1\\
\dots\\
(\mathrm{Acc}\times\epsilon)_n^{\mathrm{prompt}}\cdot N_{\mathrm{prompt}} + (\mathrm{Acc}\times\epsilon)_n^{\mathrm{non\text{-}prompt}}\cdot N_{\mathrm{non\text{-}prompt}} = Y_n
\end{cases}
$$

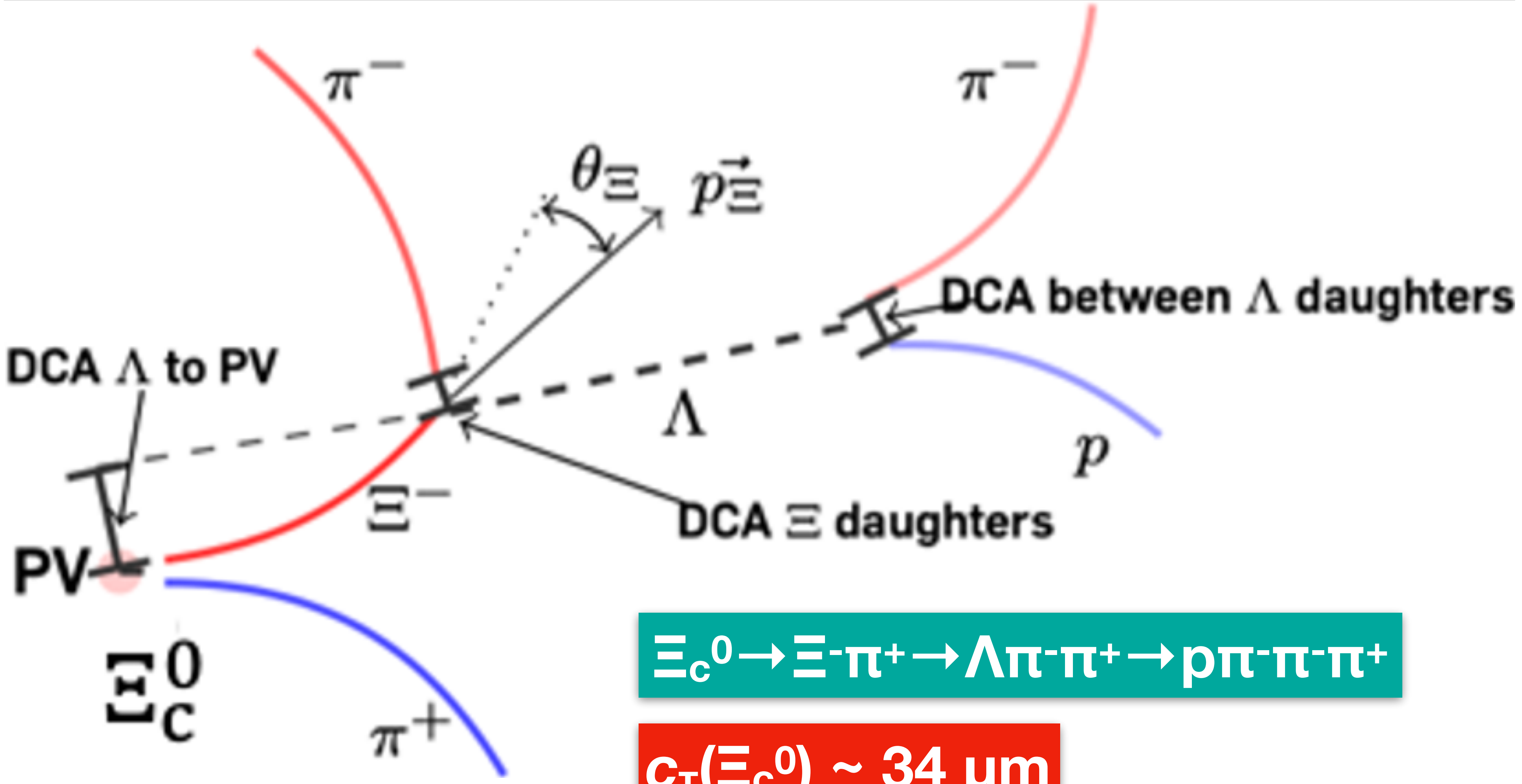
Cascade decay reconstruction



$\Xi_c^0 \rightarrow \Xi^-\pi^+ \rightarrow \Lambda\pi^-\pi^+ \rightarrow p\pi^-\pi^-\pi^+$

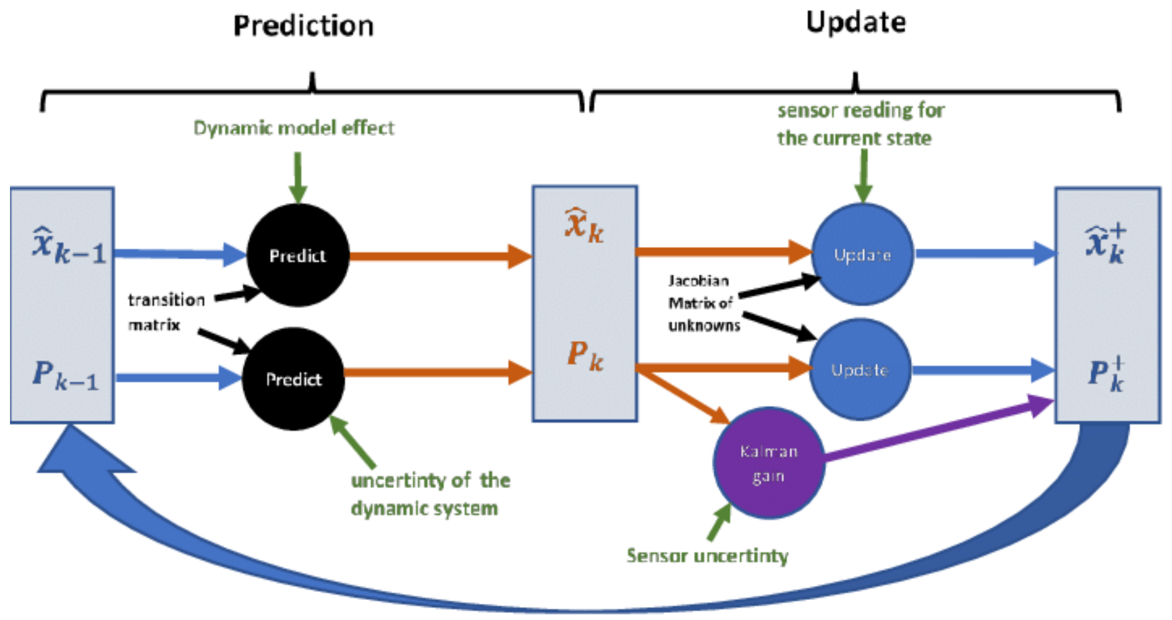
$c\tau(\Xi_c^0)$ ~ 34 μm

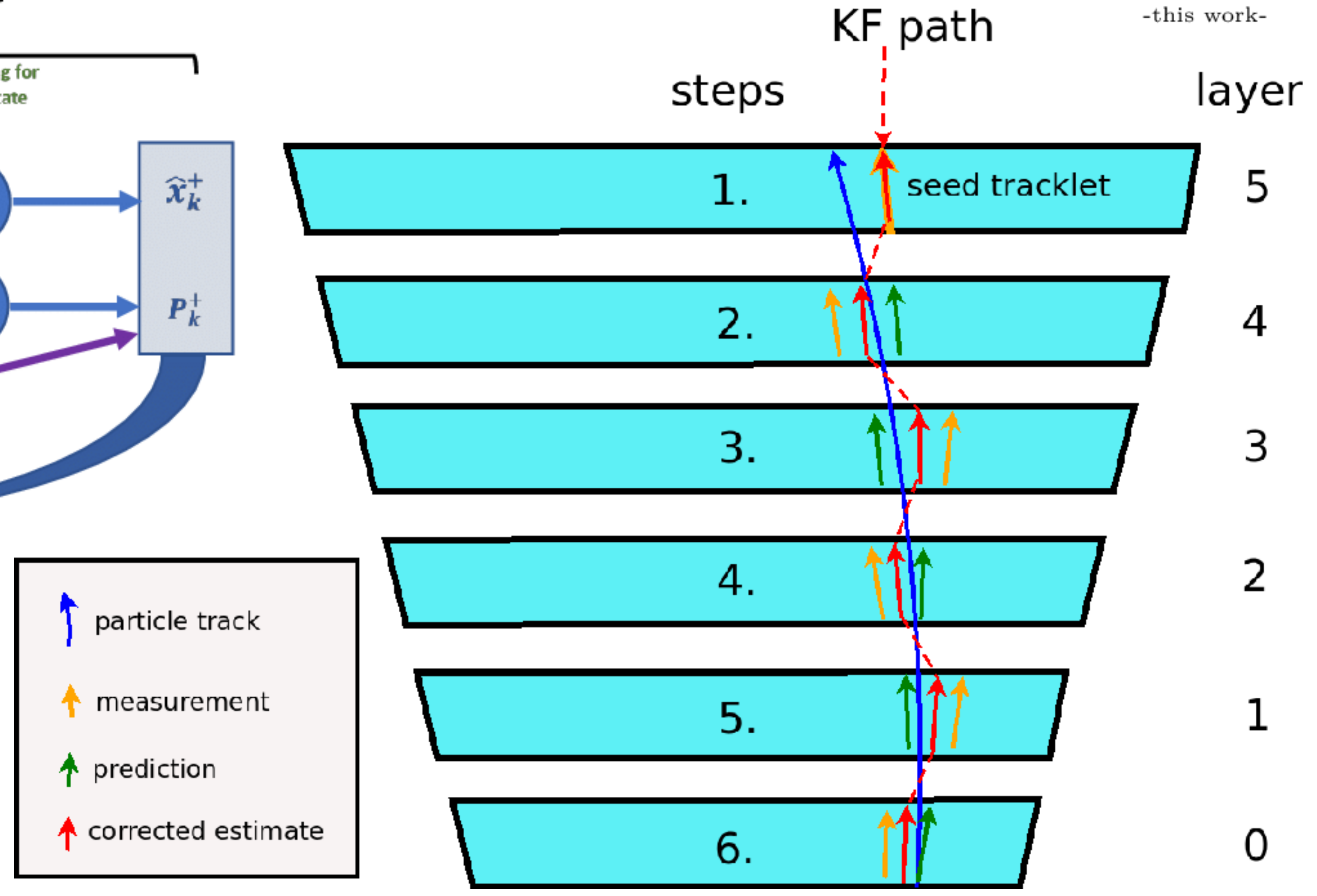
Cascade decay reconstruction

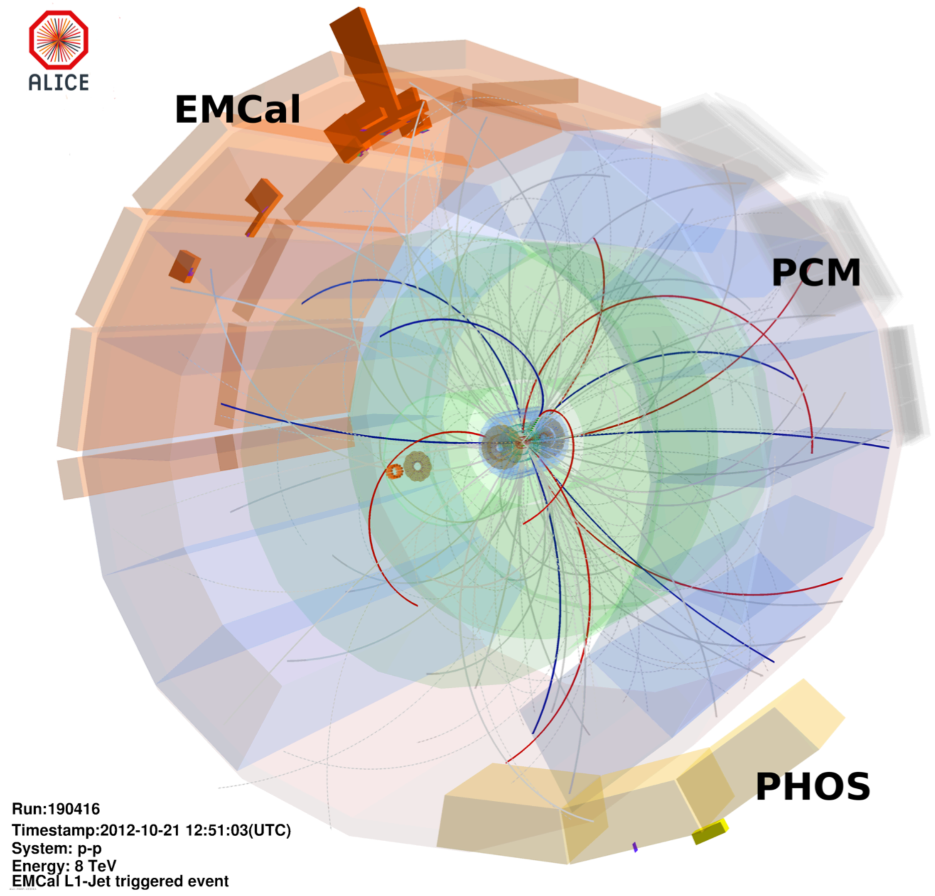


$\Xi_c^0 \rightarrow \Xi^- \pi^+ \rightarrow \Lambda \pi^- \pi^+ \rightarrow p \pi^- \pi^- \pi^+$

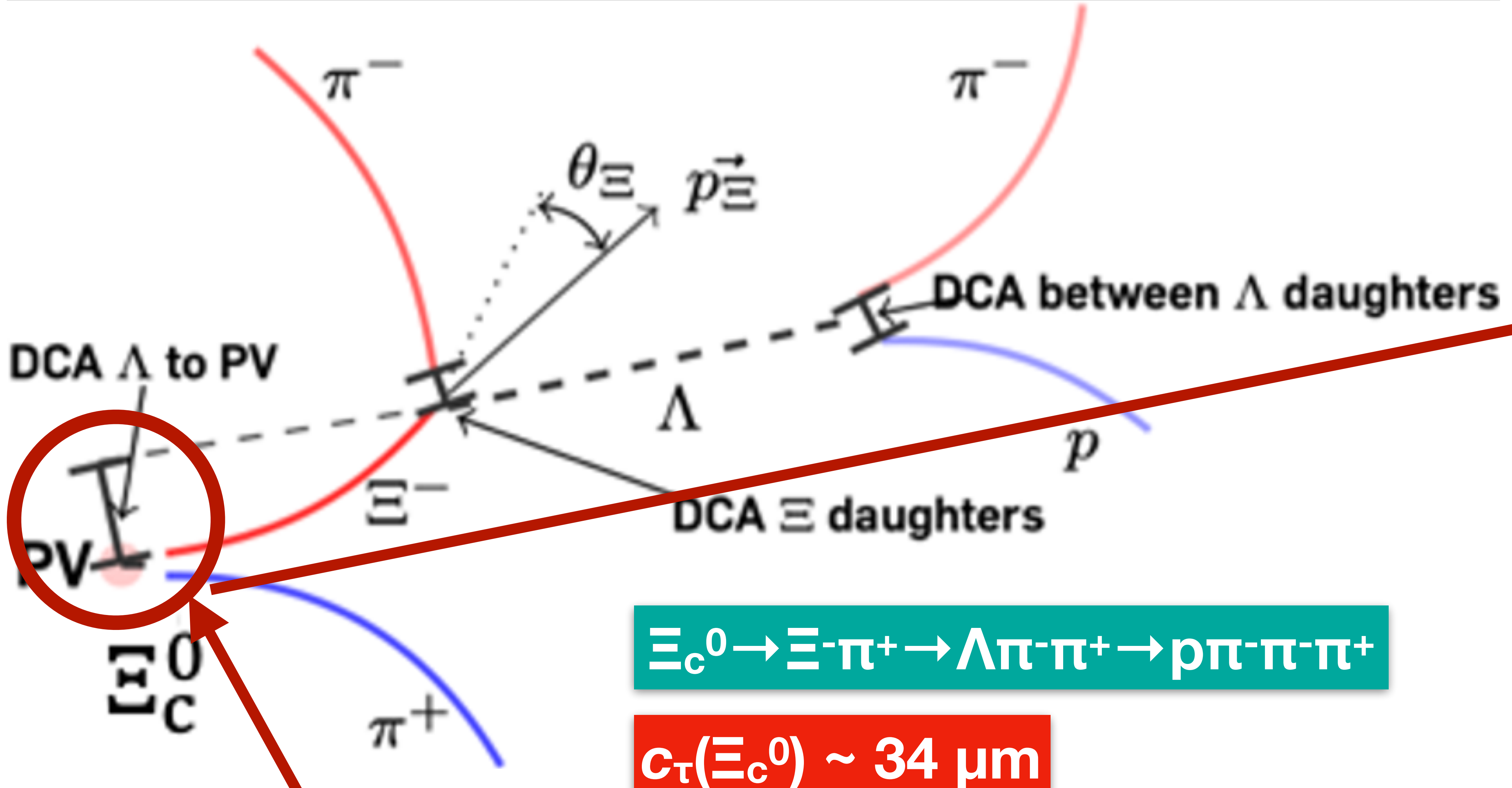
$c\tau(\Xi_c^0)$ ~ 34 μm







Cascade decay reconstruction



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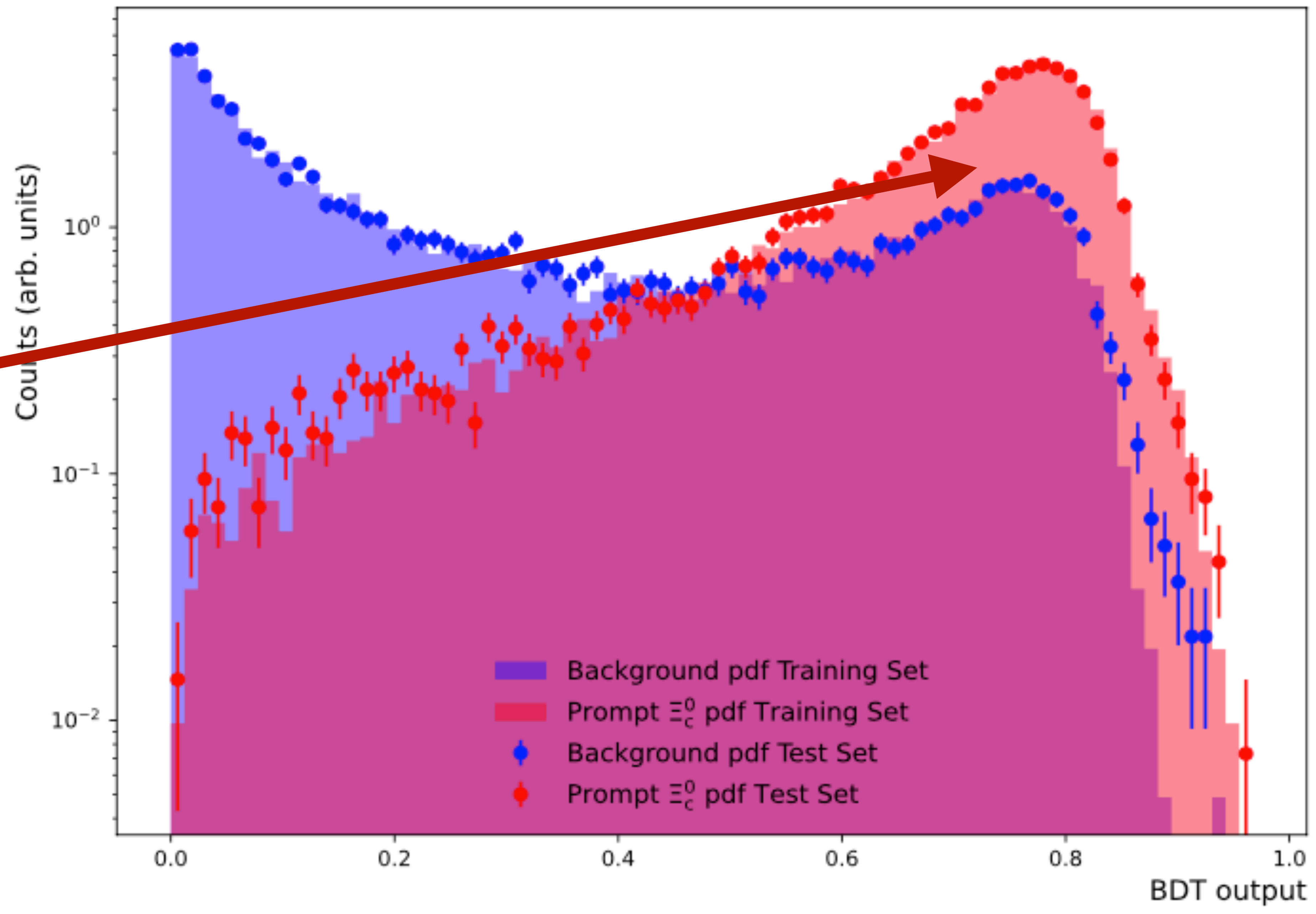
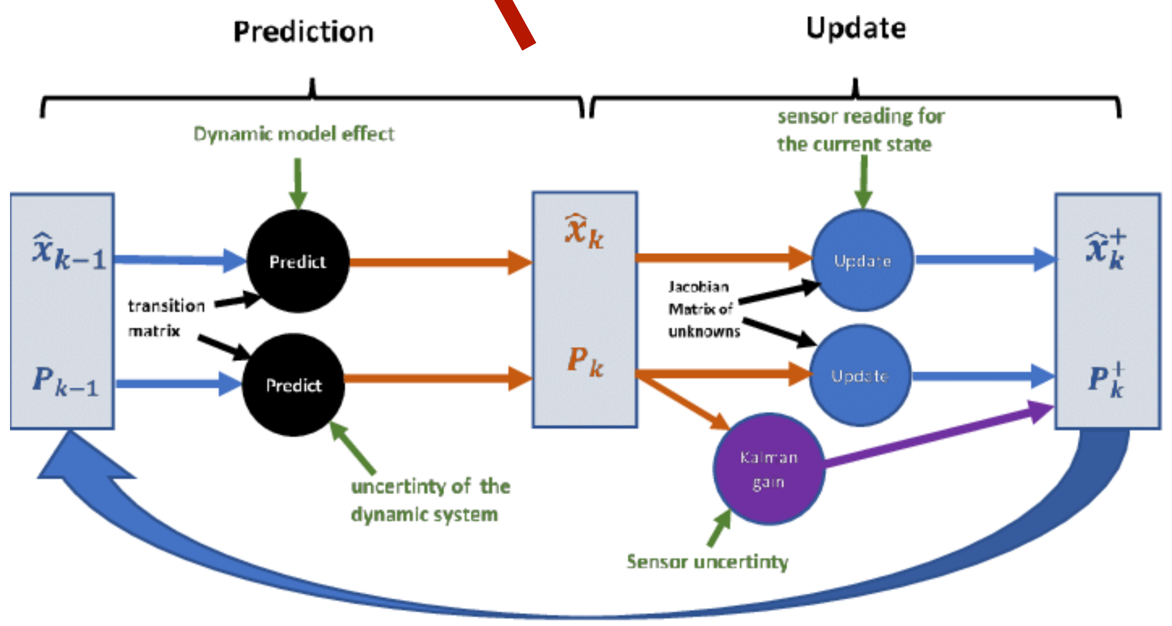
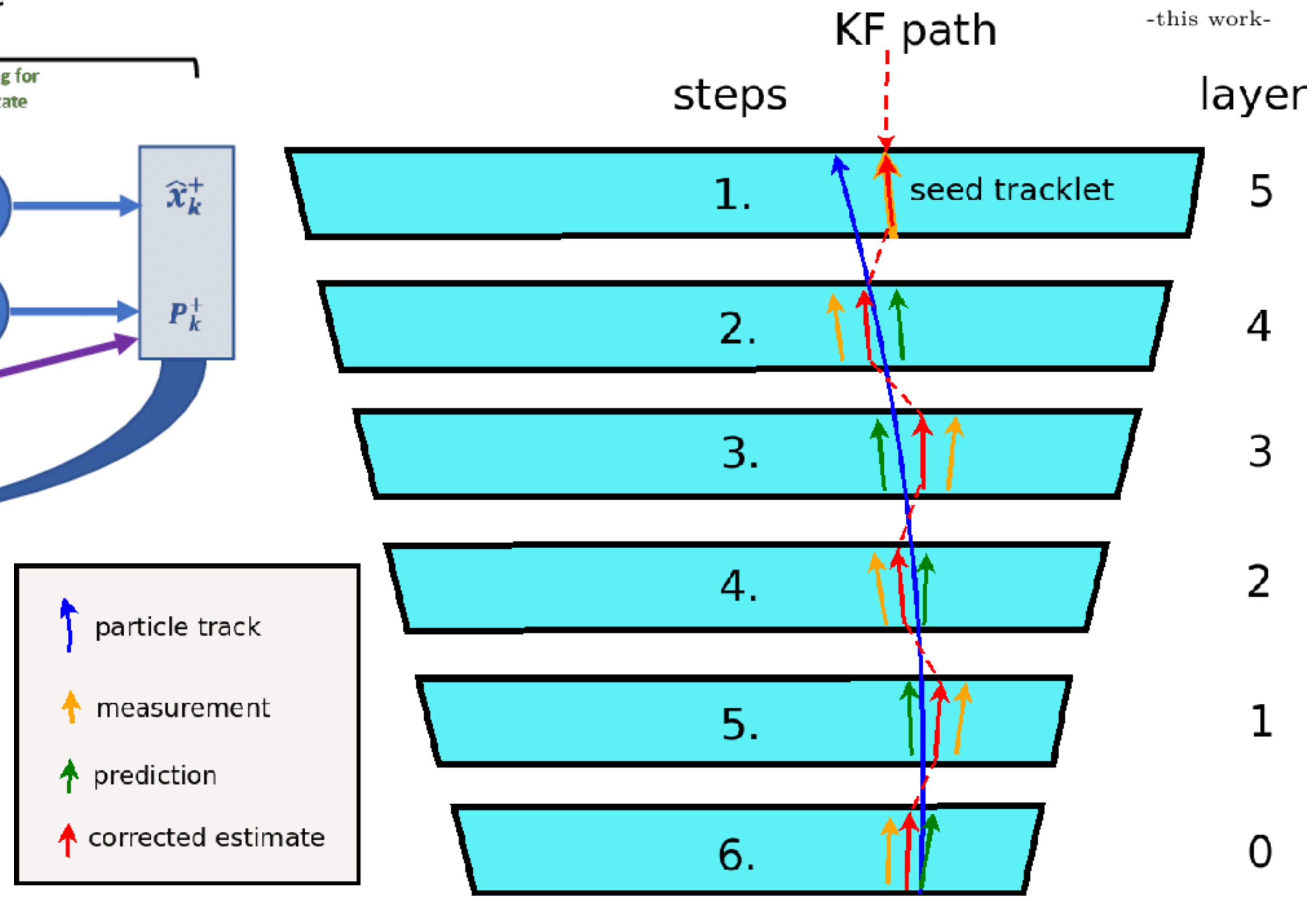
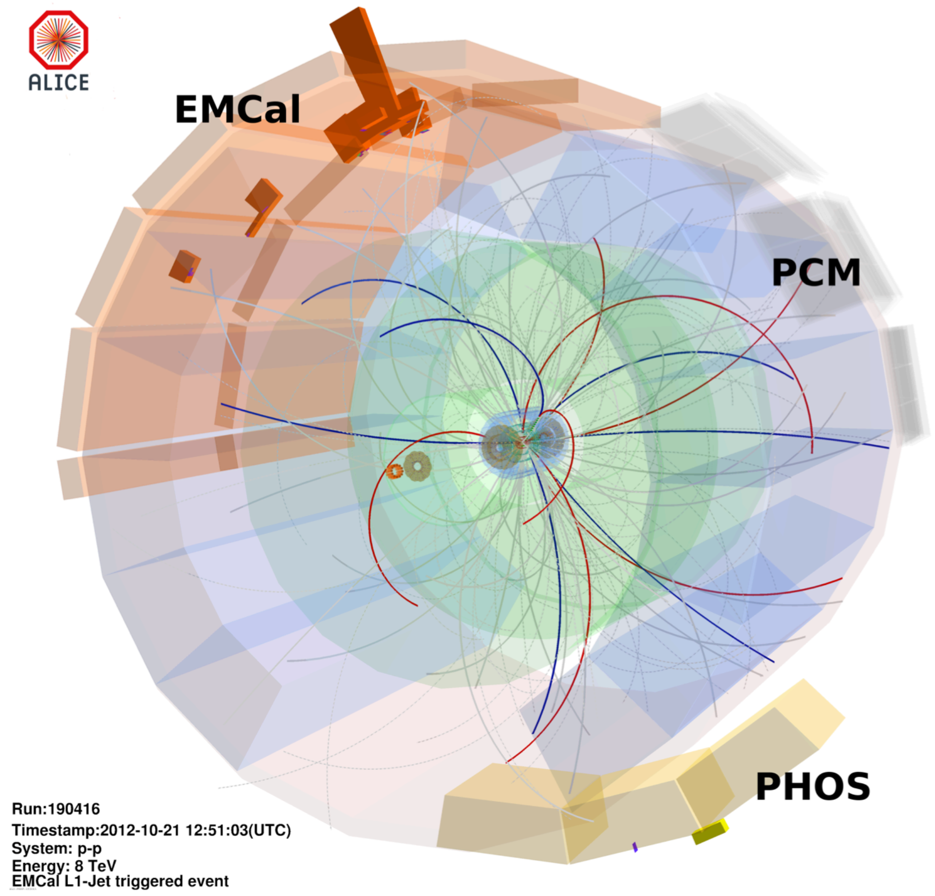
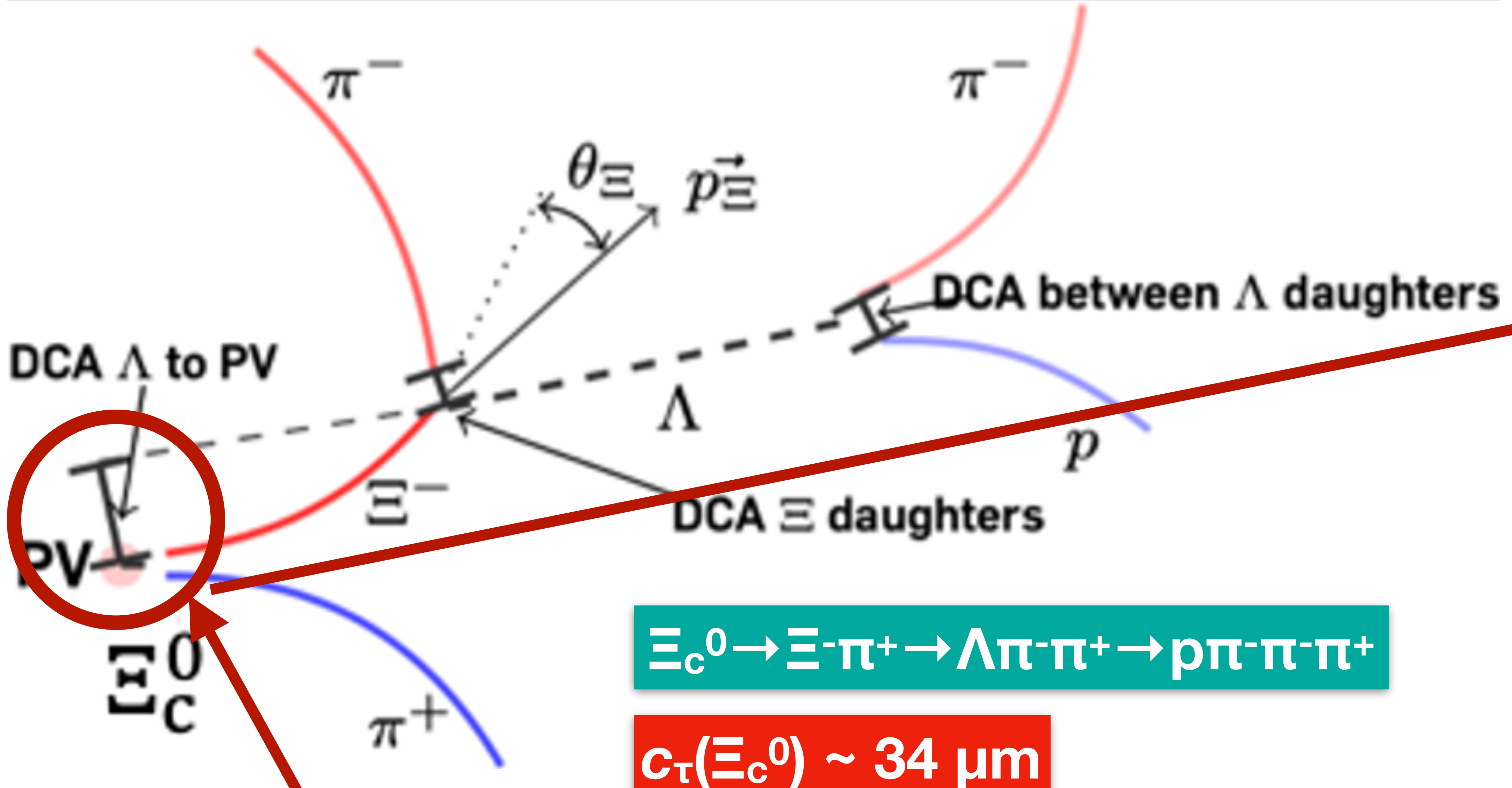








Cascade decay reconstruction



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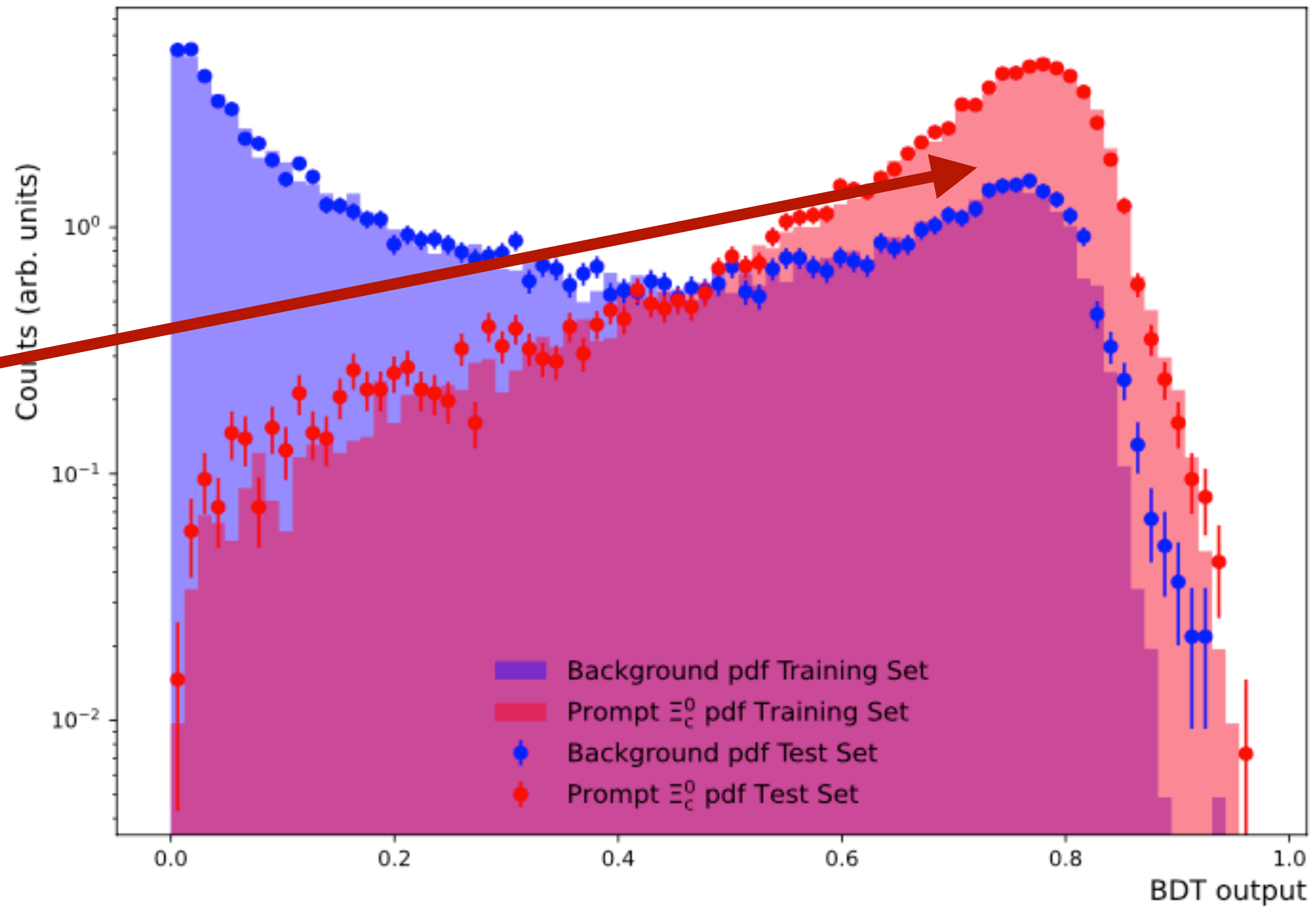
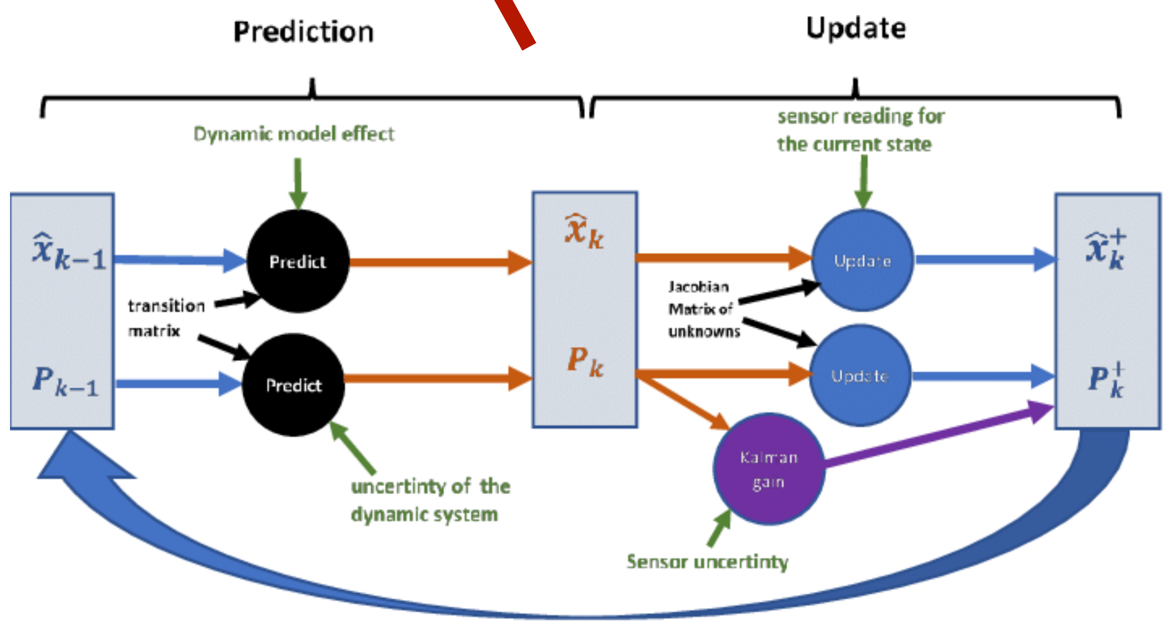
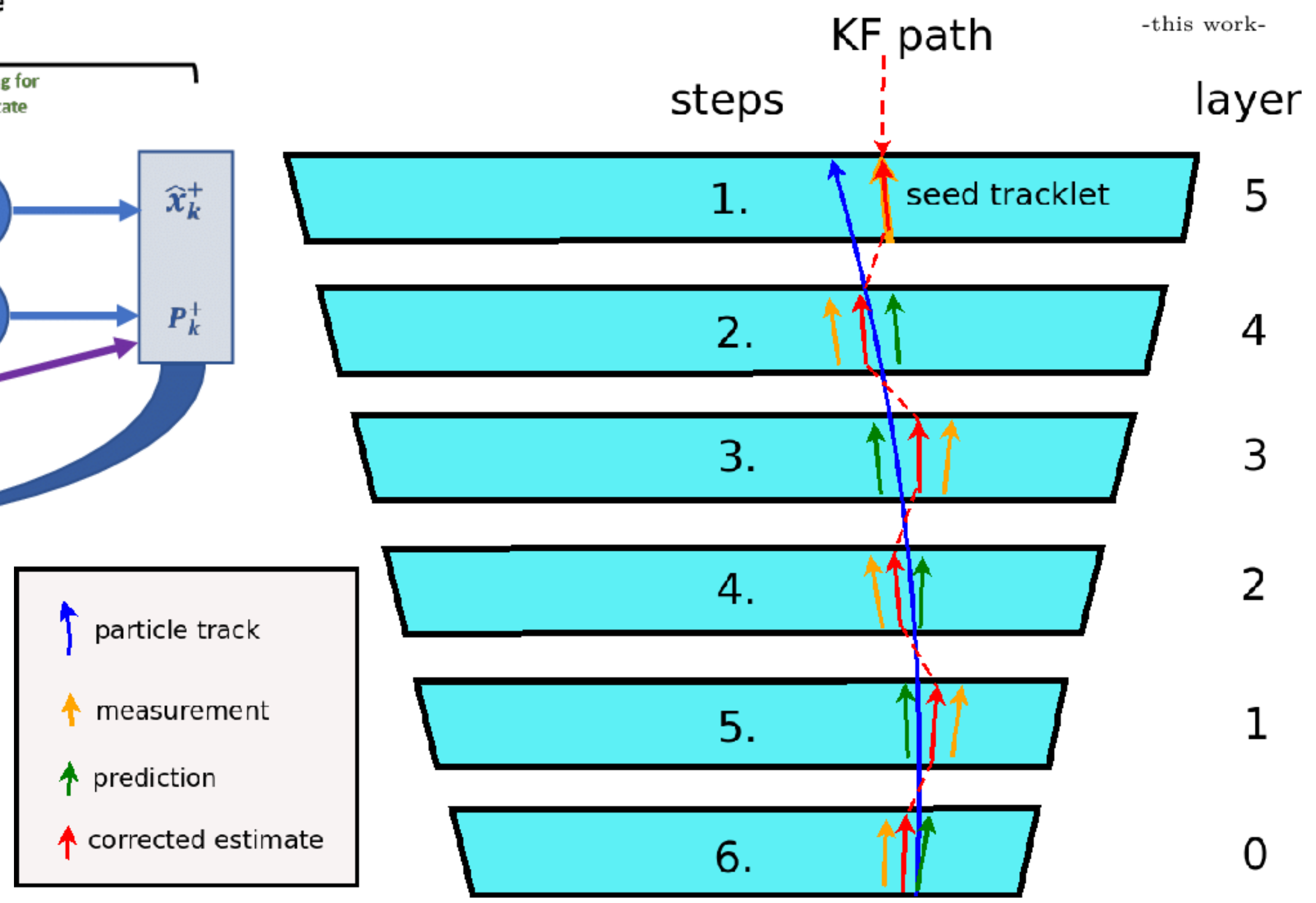
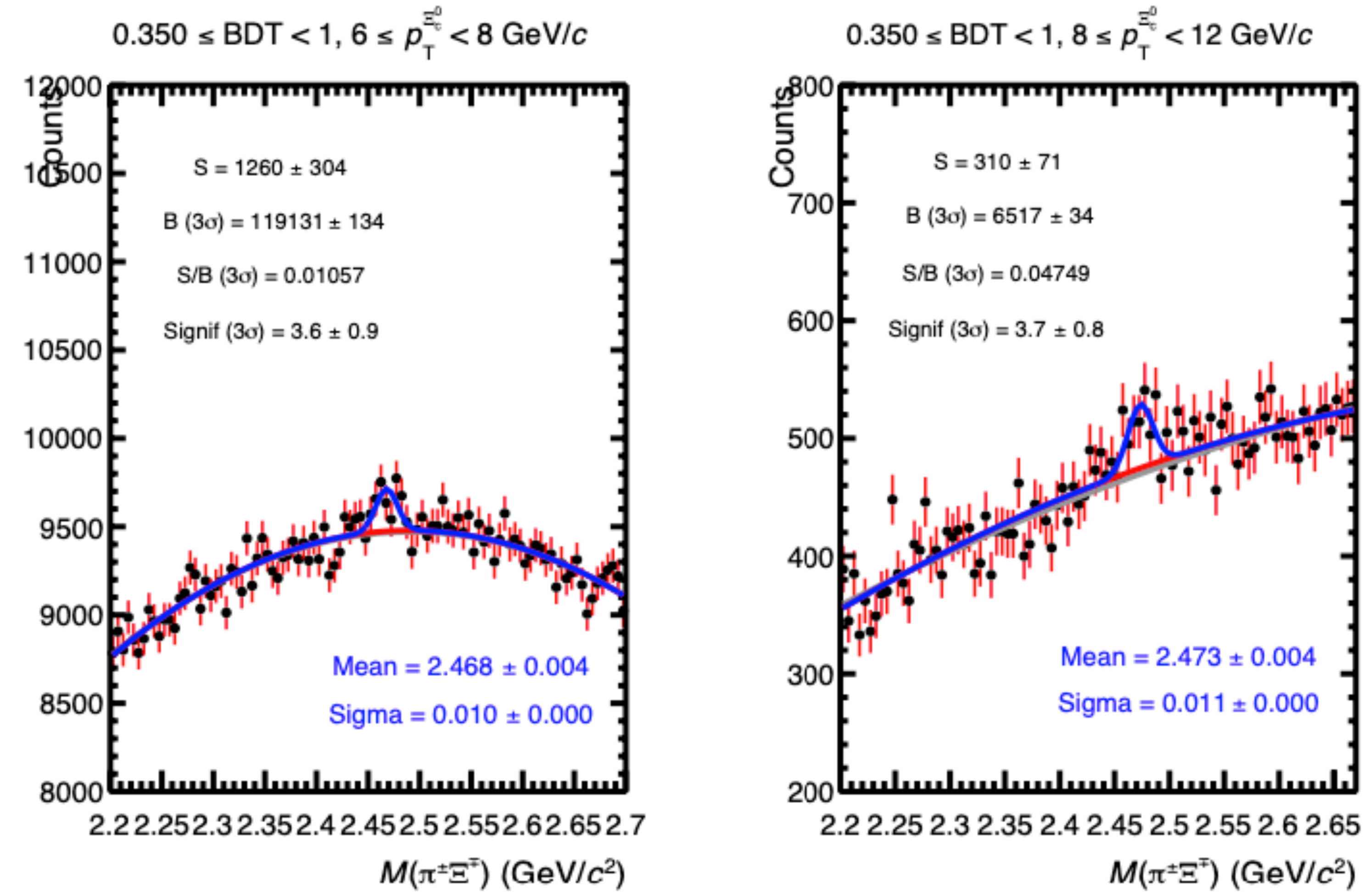
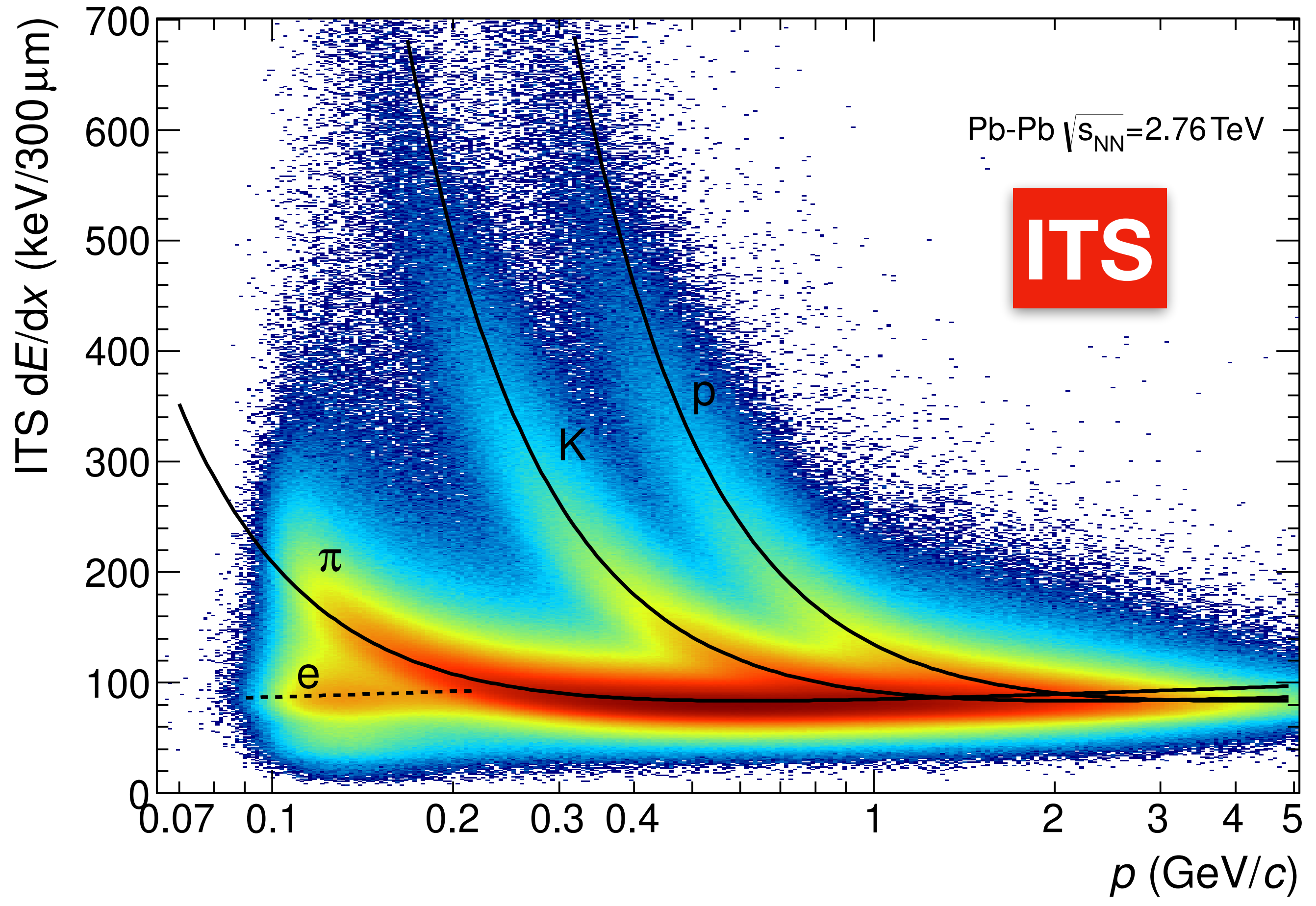


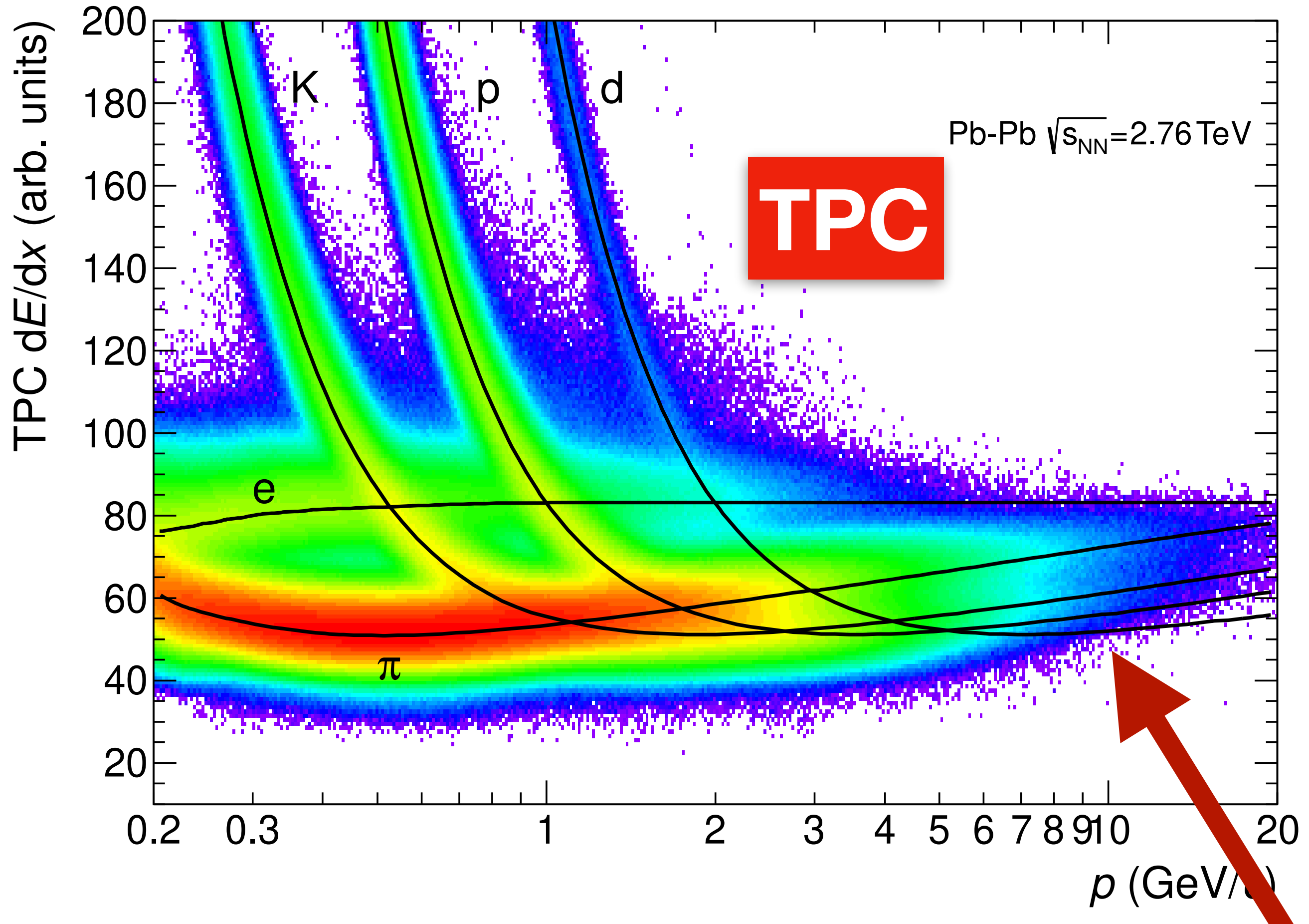


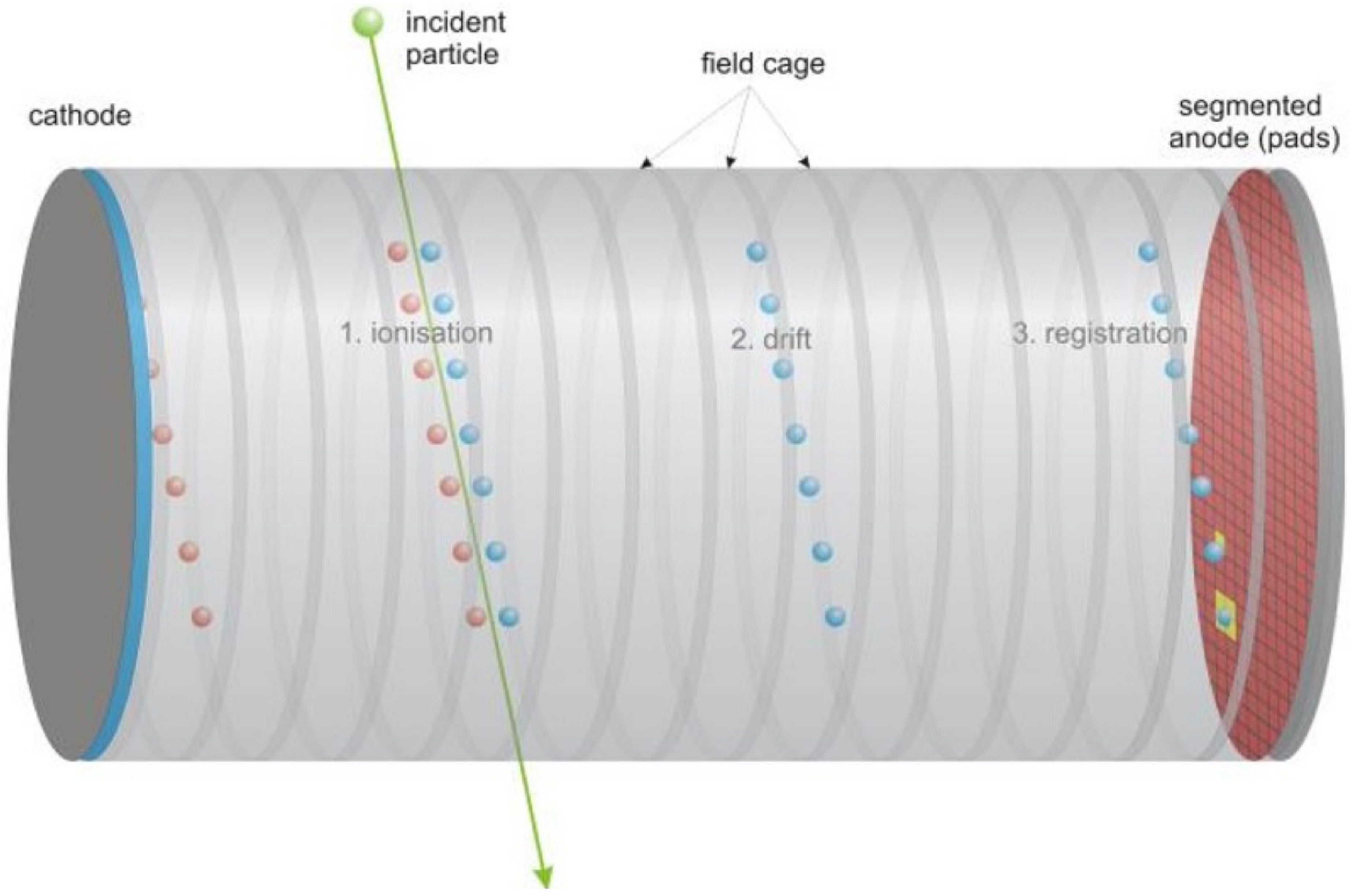


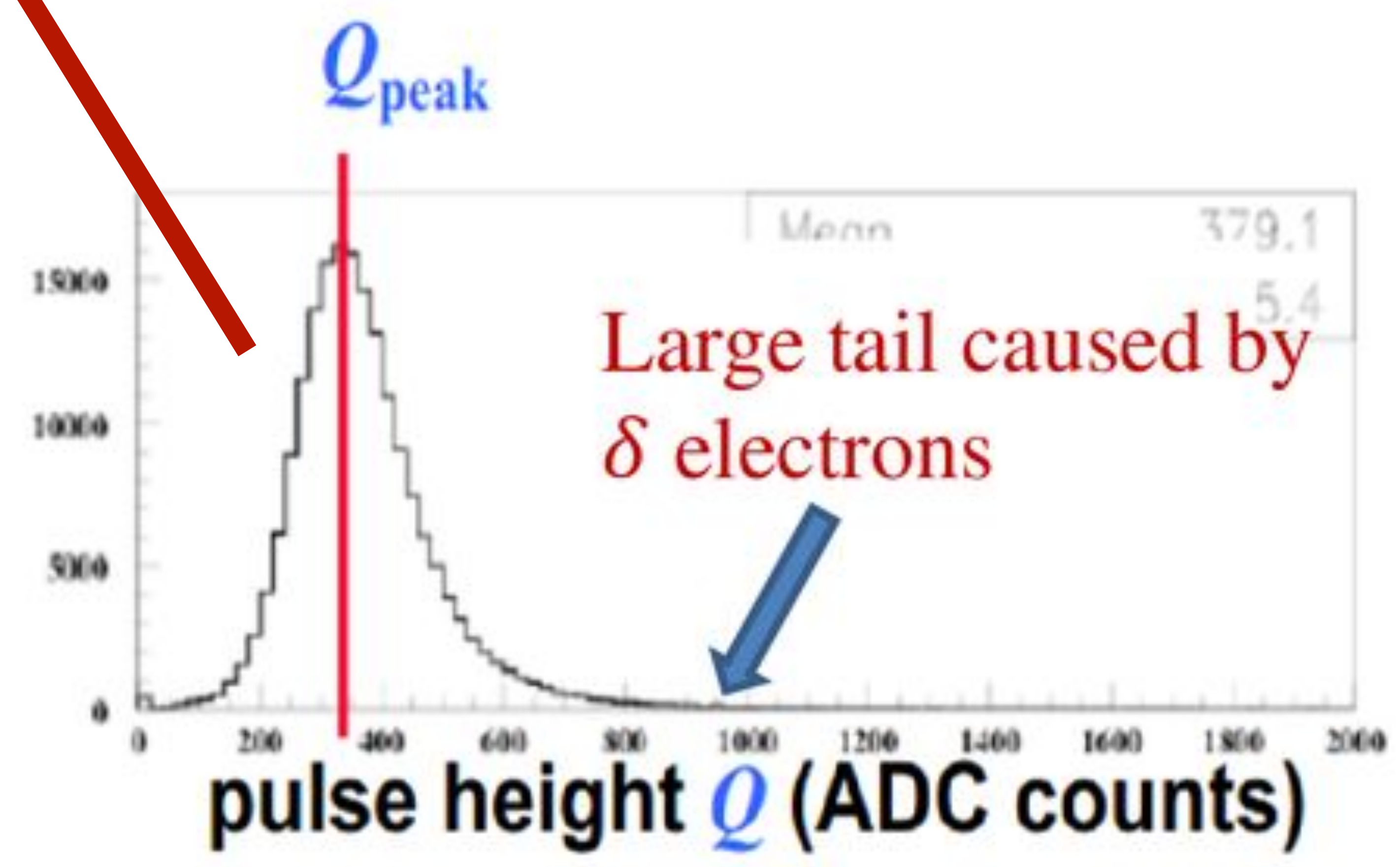


Particle identification









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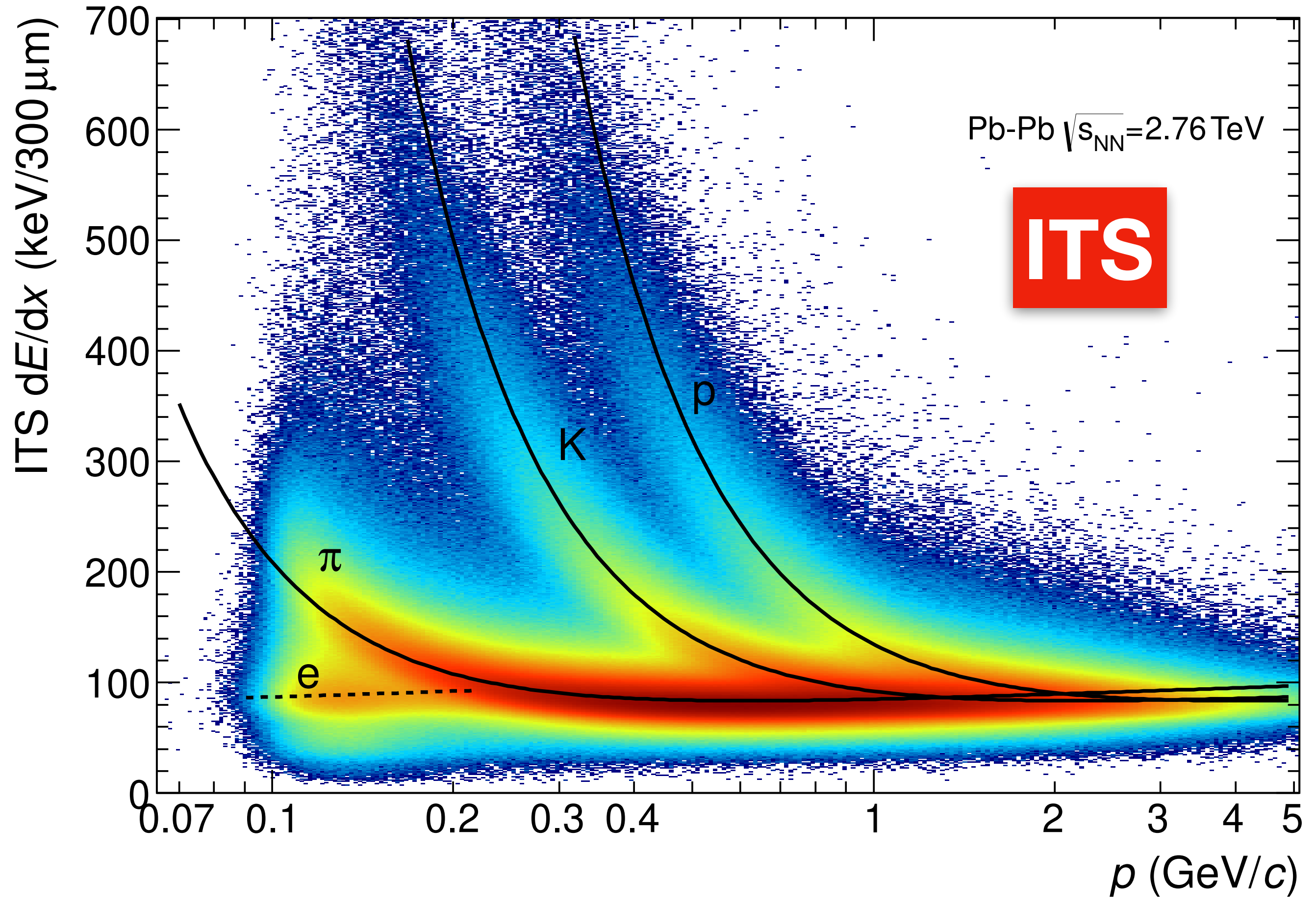

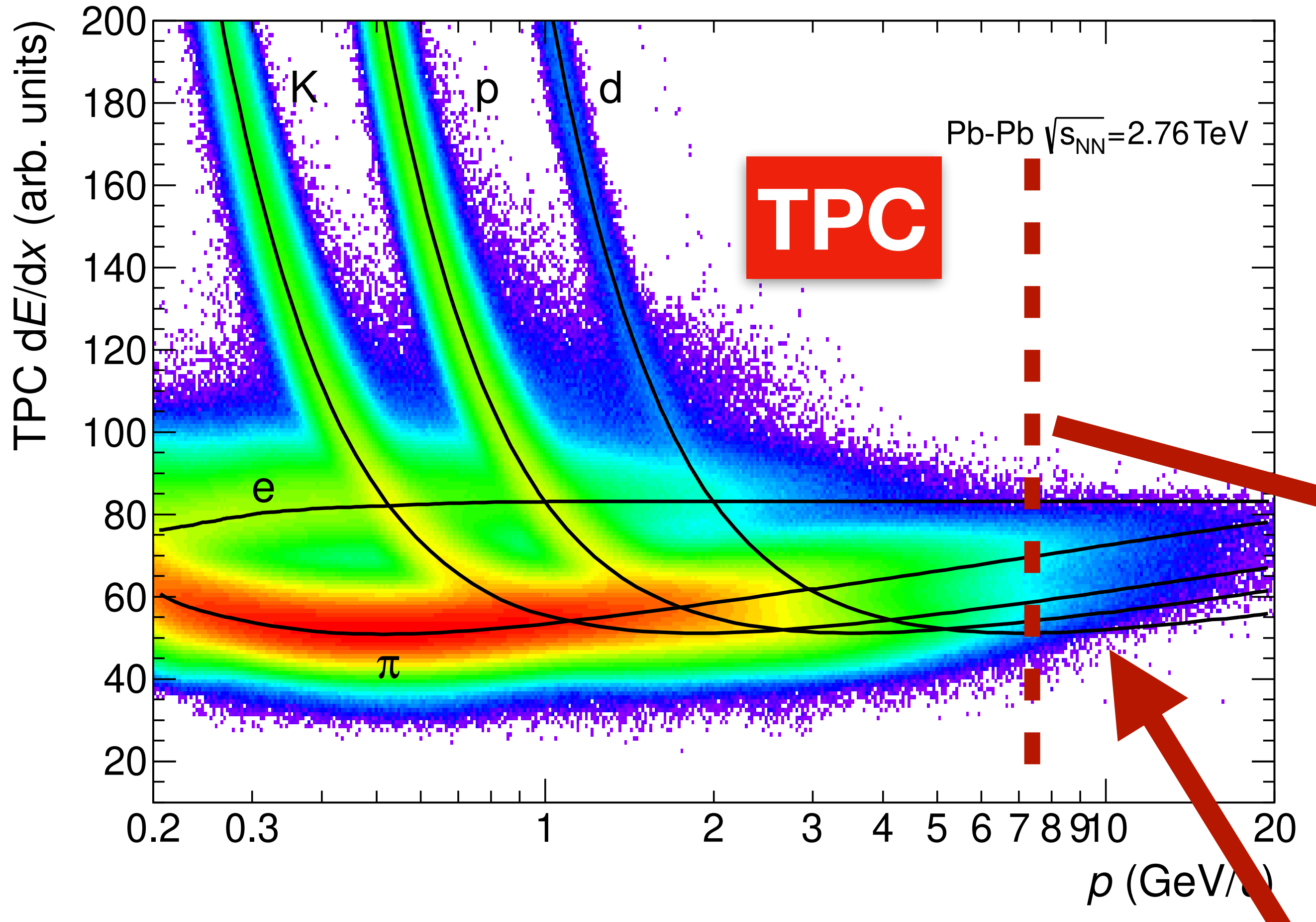

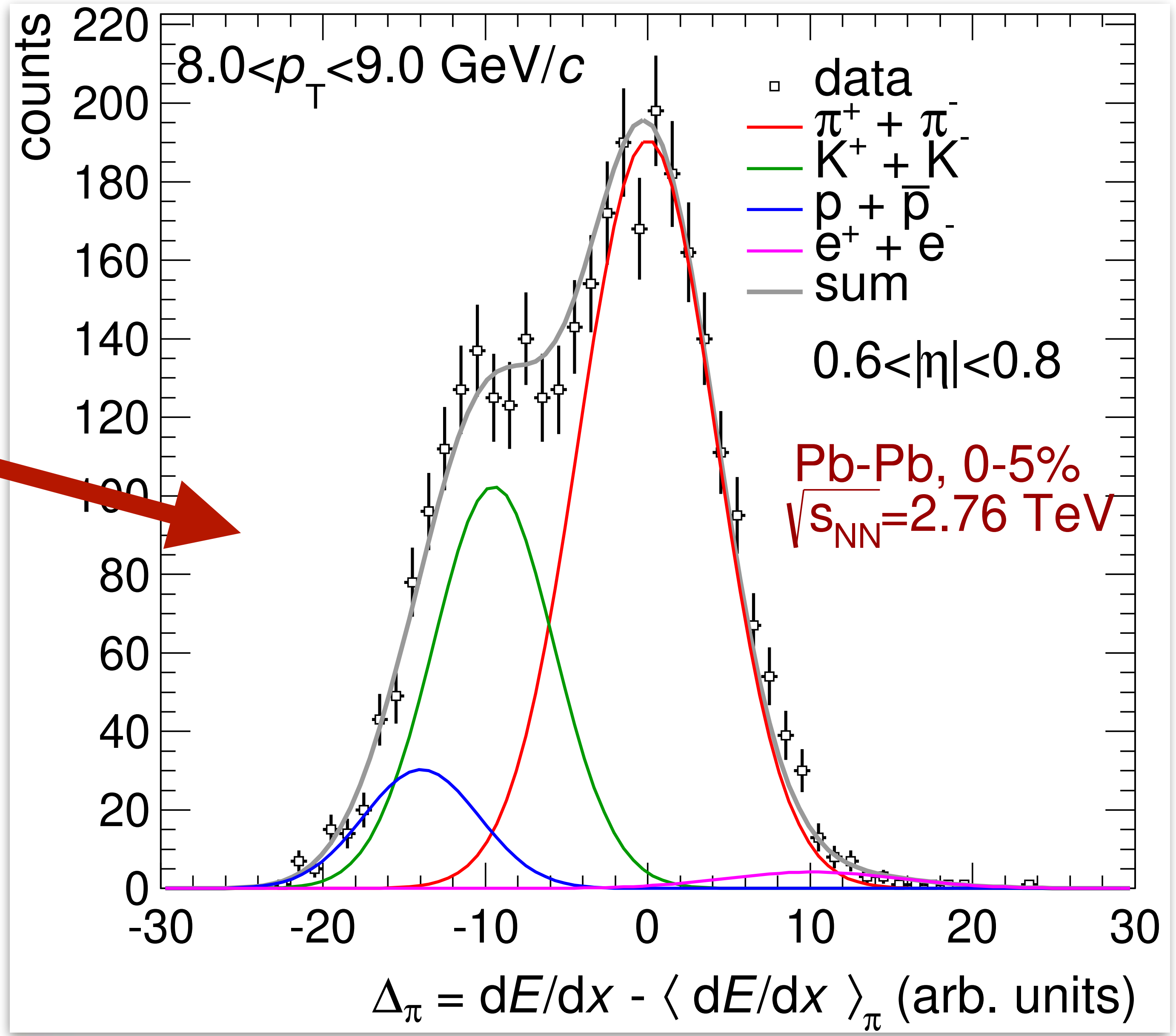

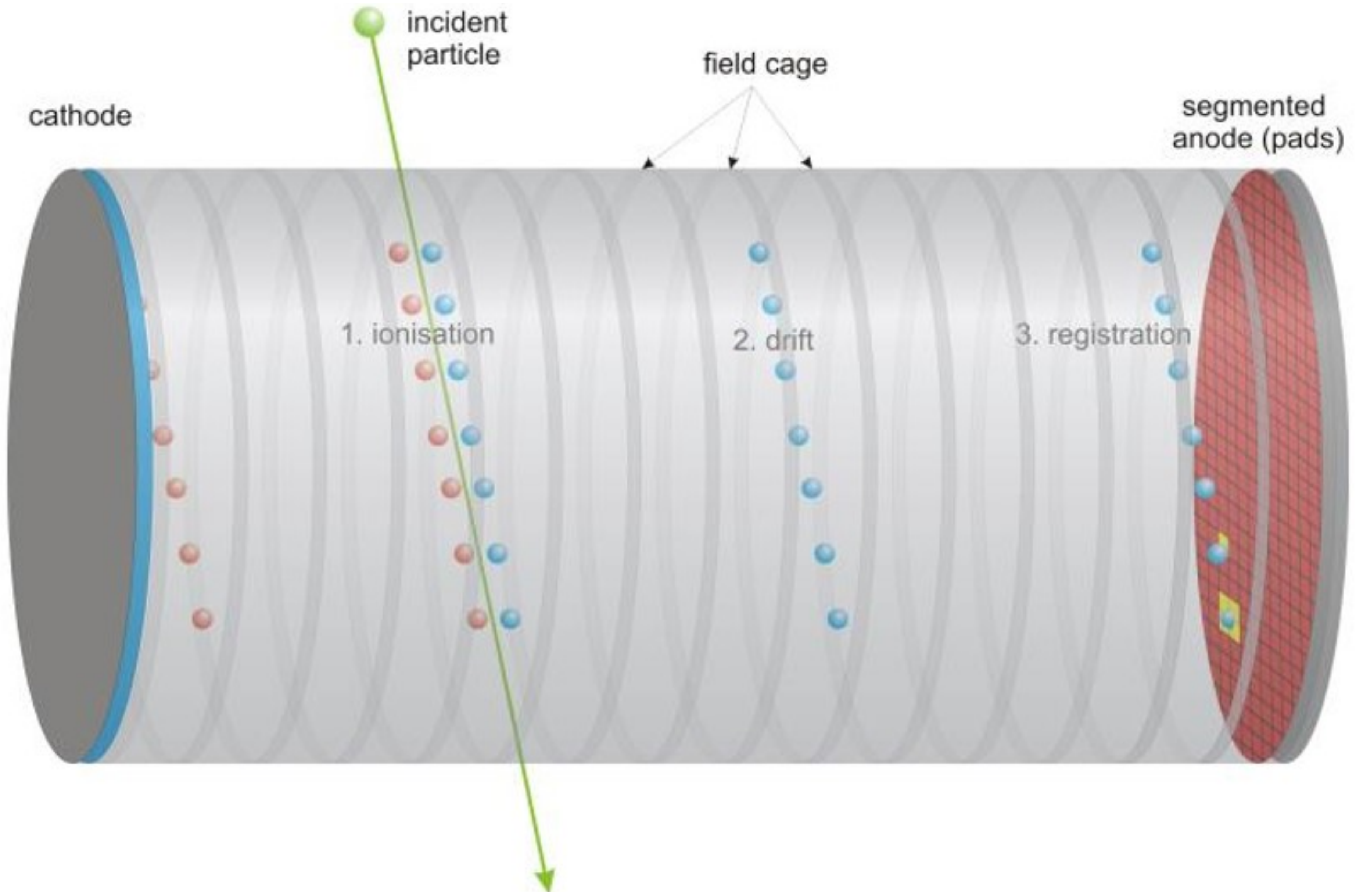

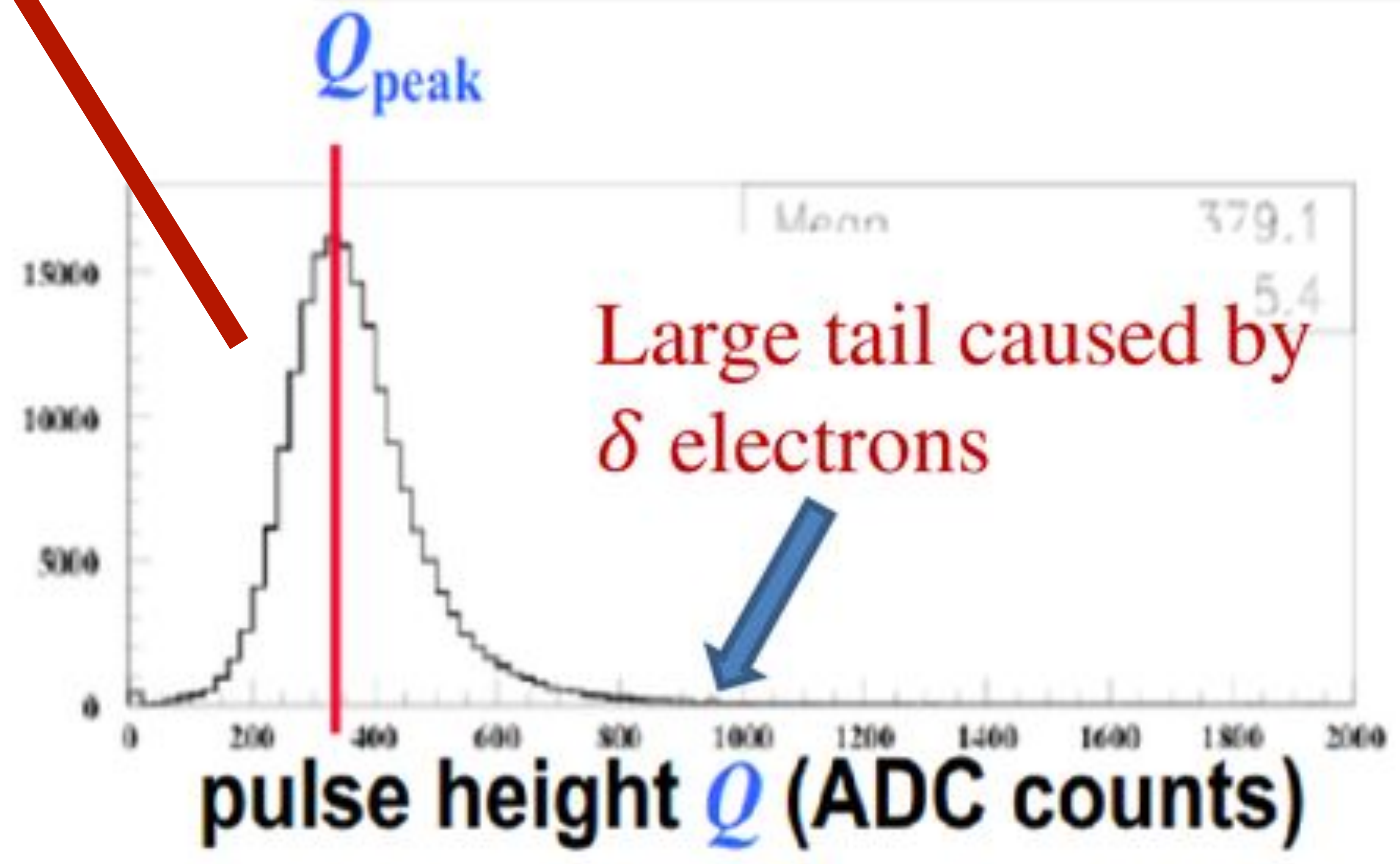

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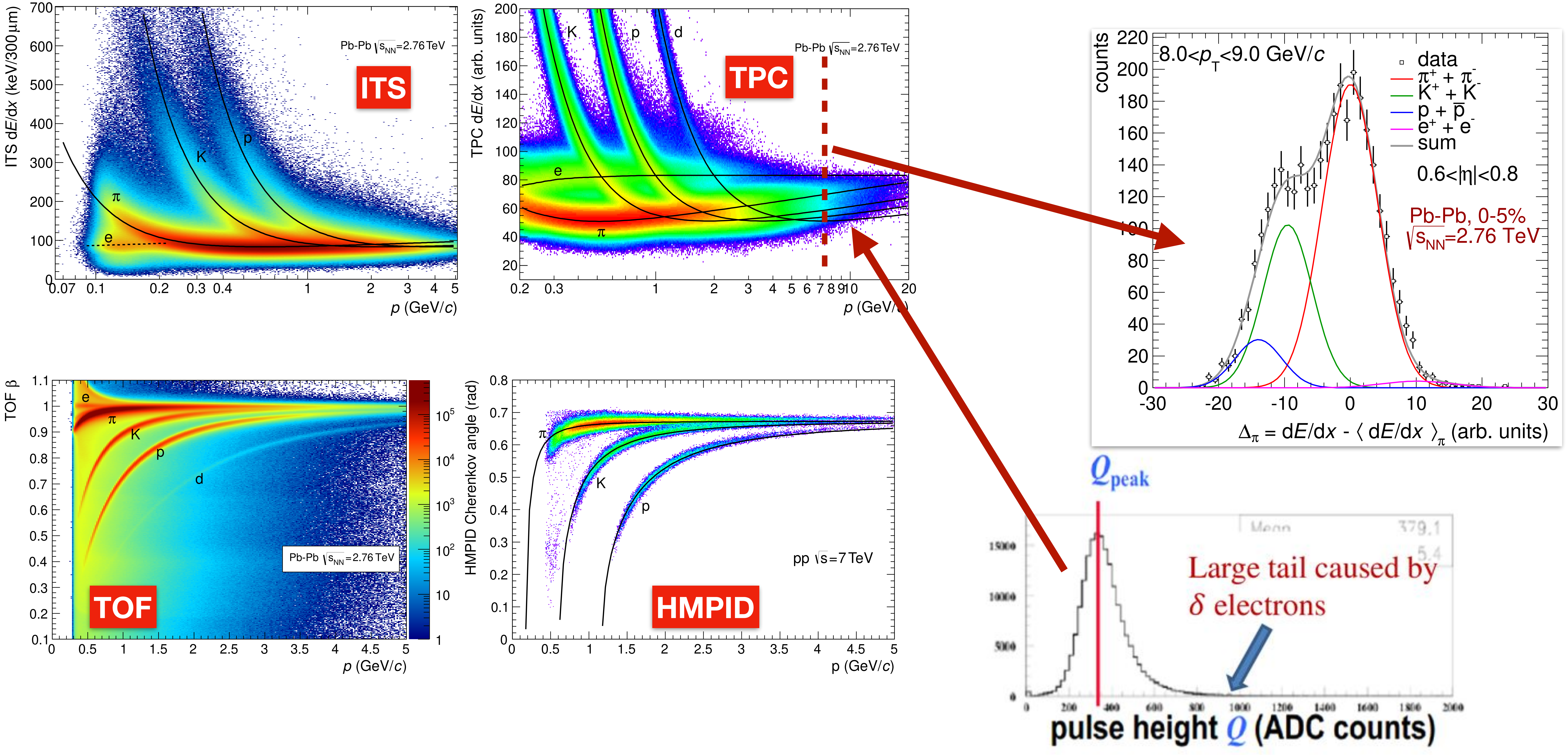
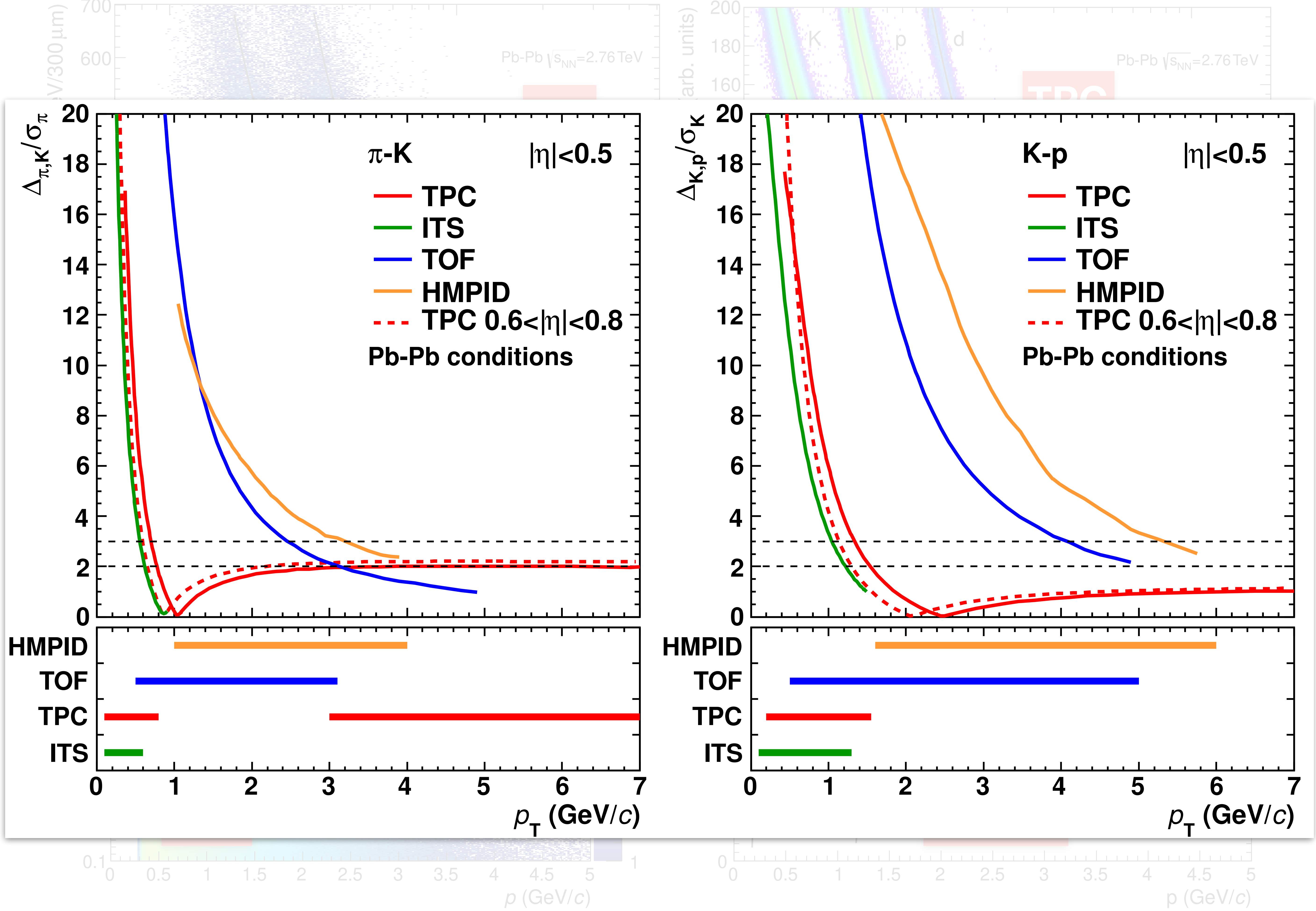
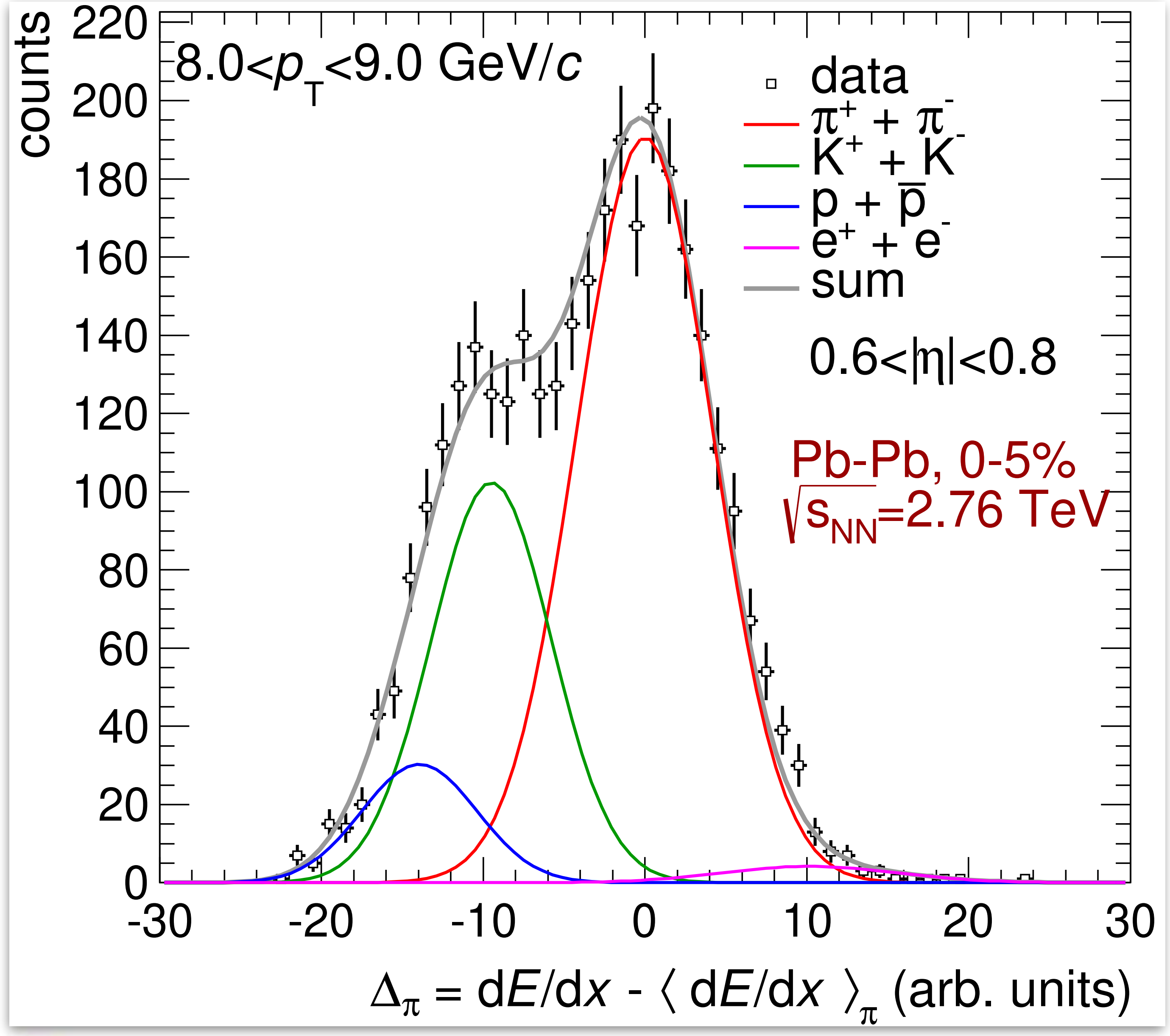
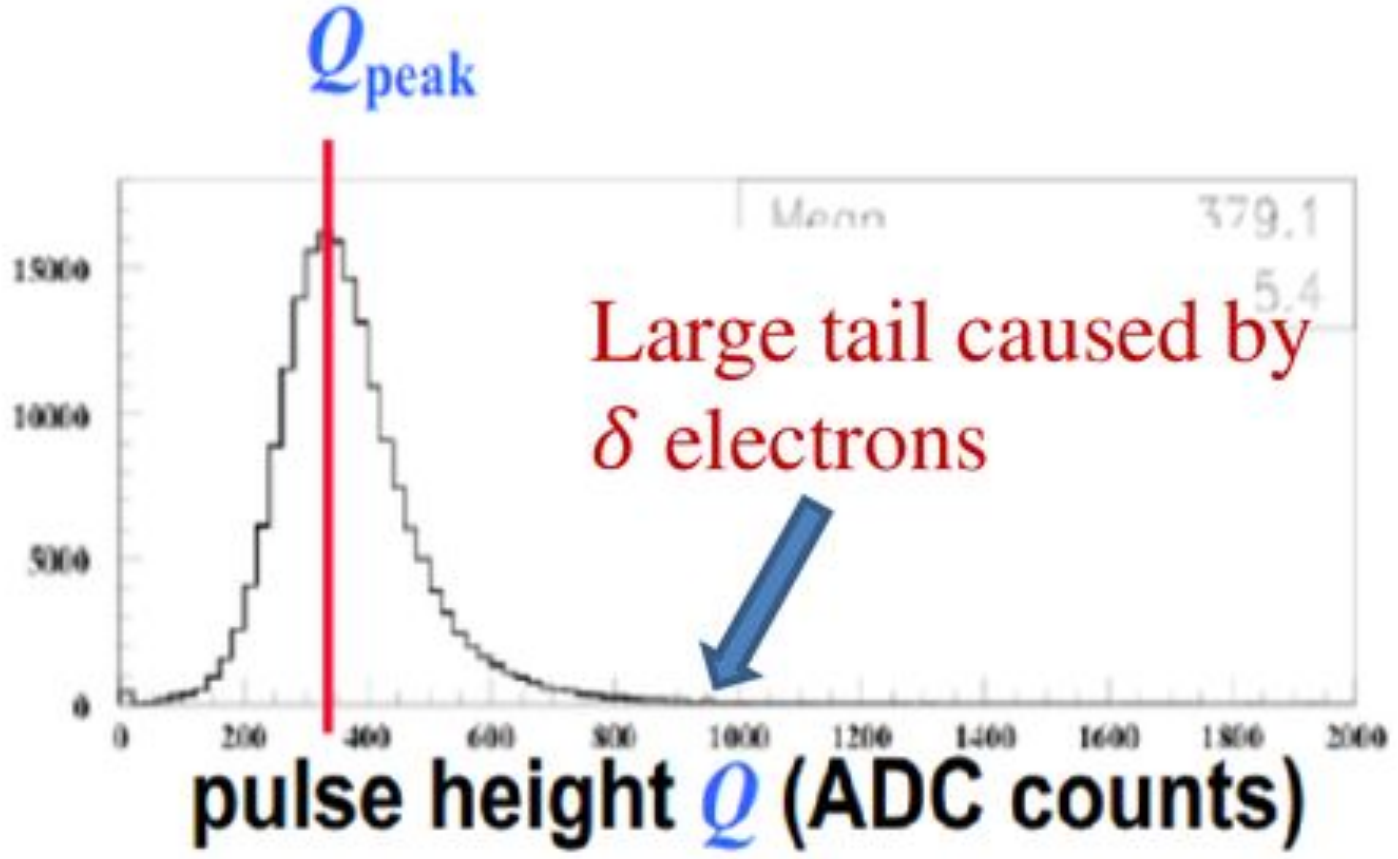


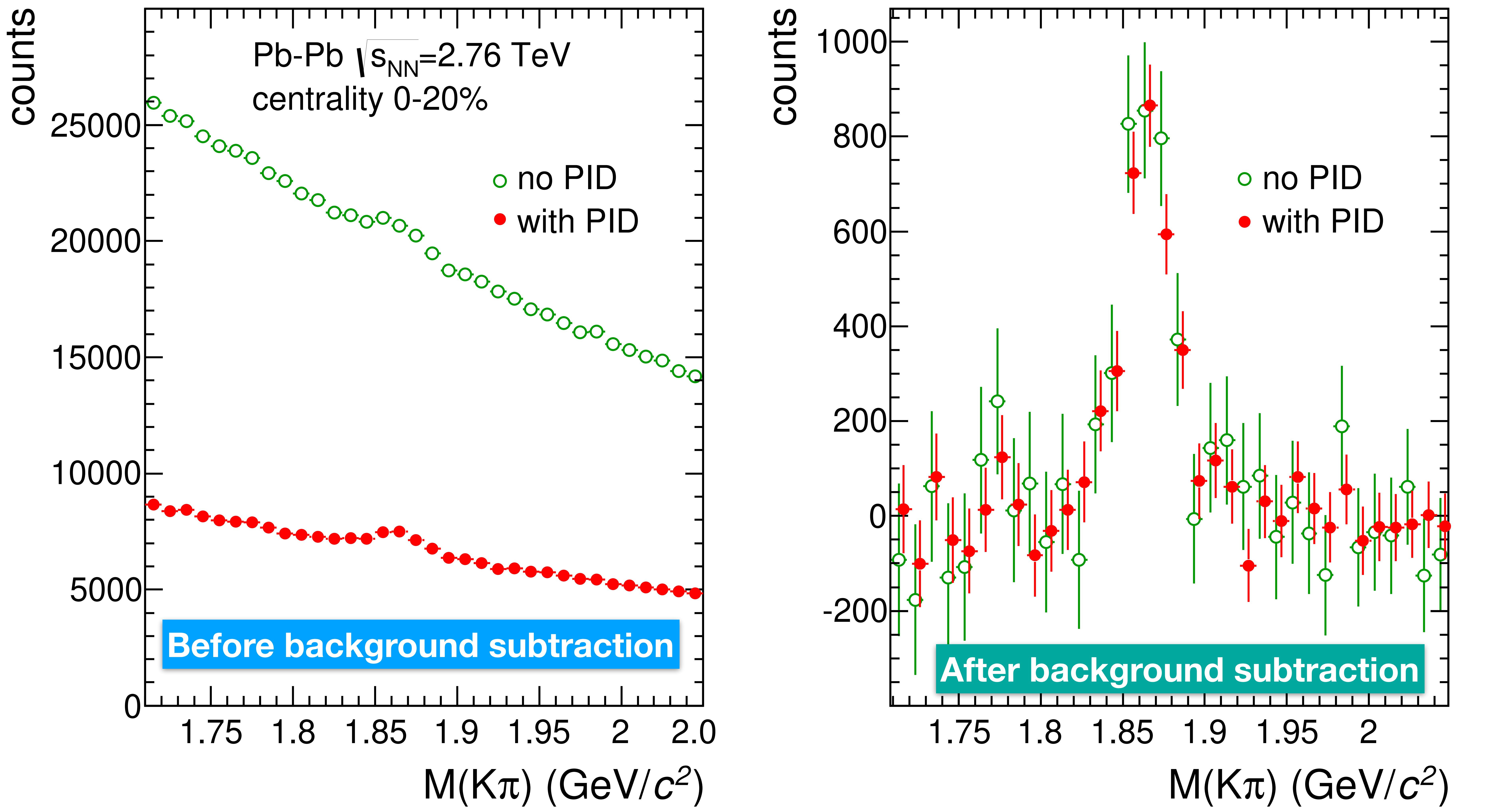
Particle identification





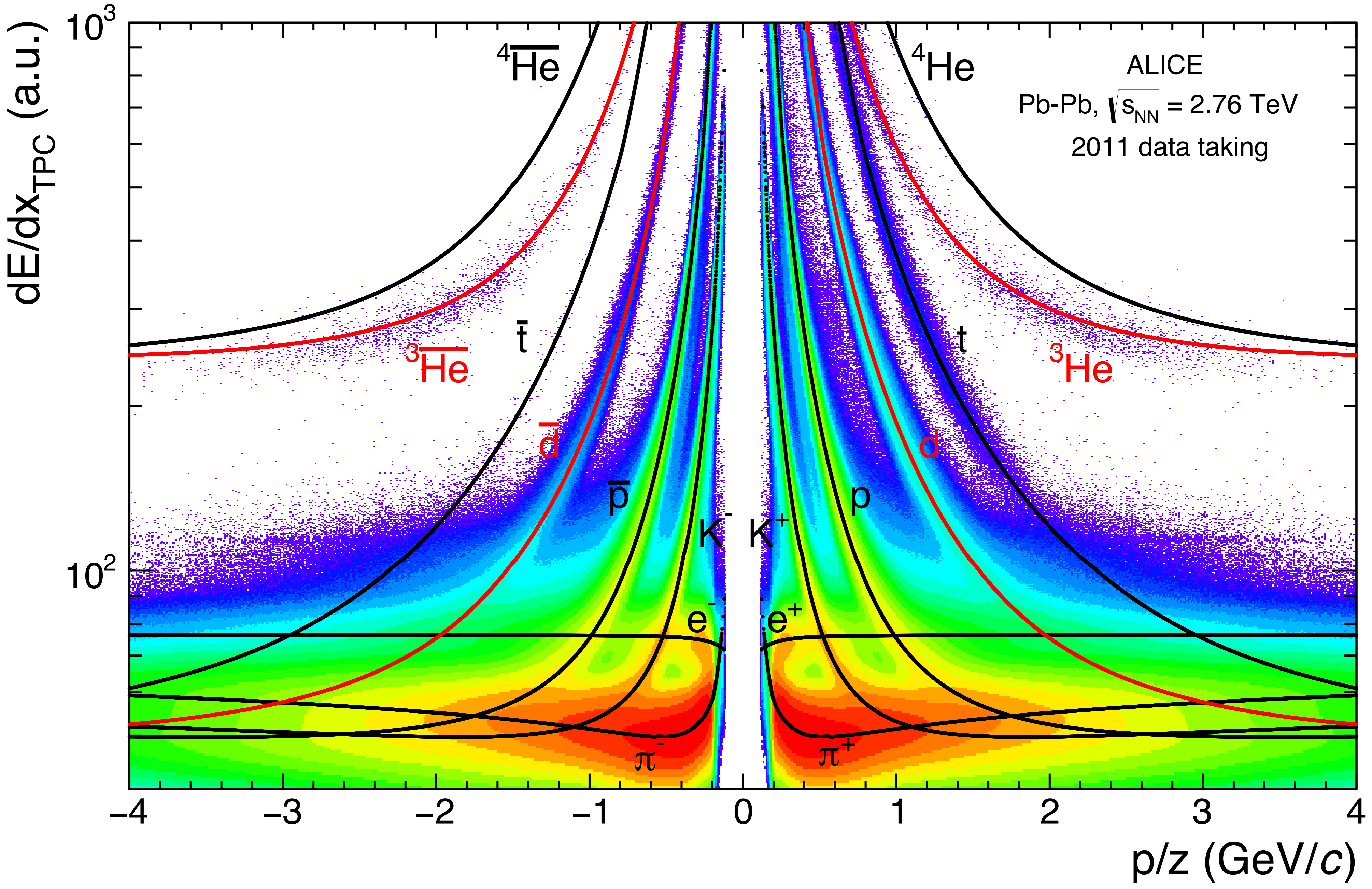


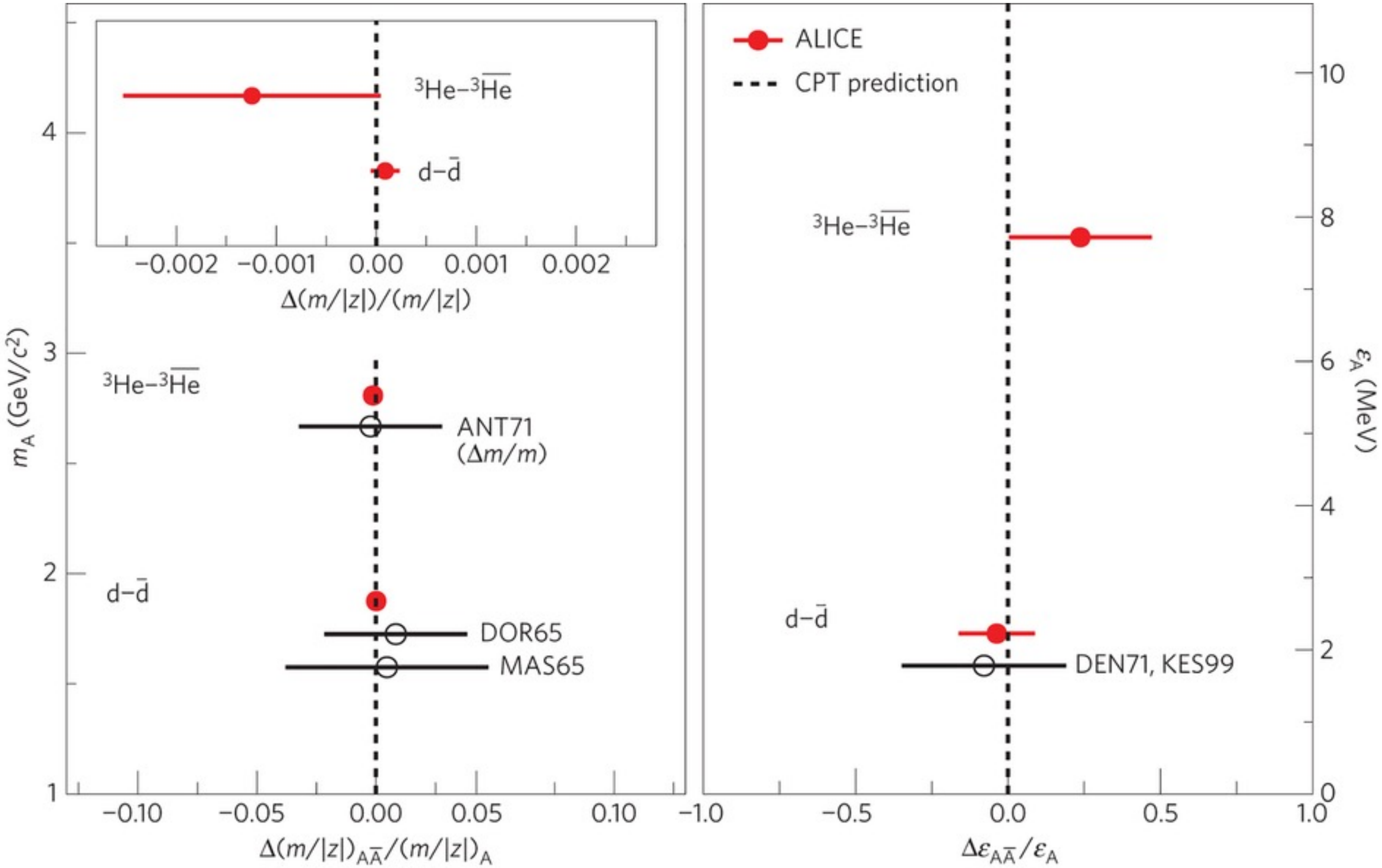
D^0 selection with PID



Mass difference of (anti)-nuclei

- Test of CPT invariance of residual nuclear force by measuring mass difference in the nuclei sector (^{3}He and deuterons)





- First measurement of binding-energy for (anti-)^{3}He
- Confirms CPT invariance for light nuclei

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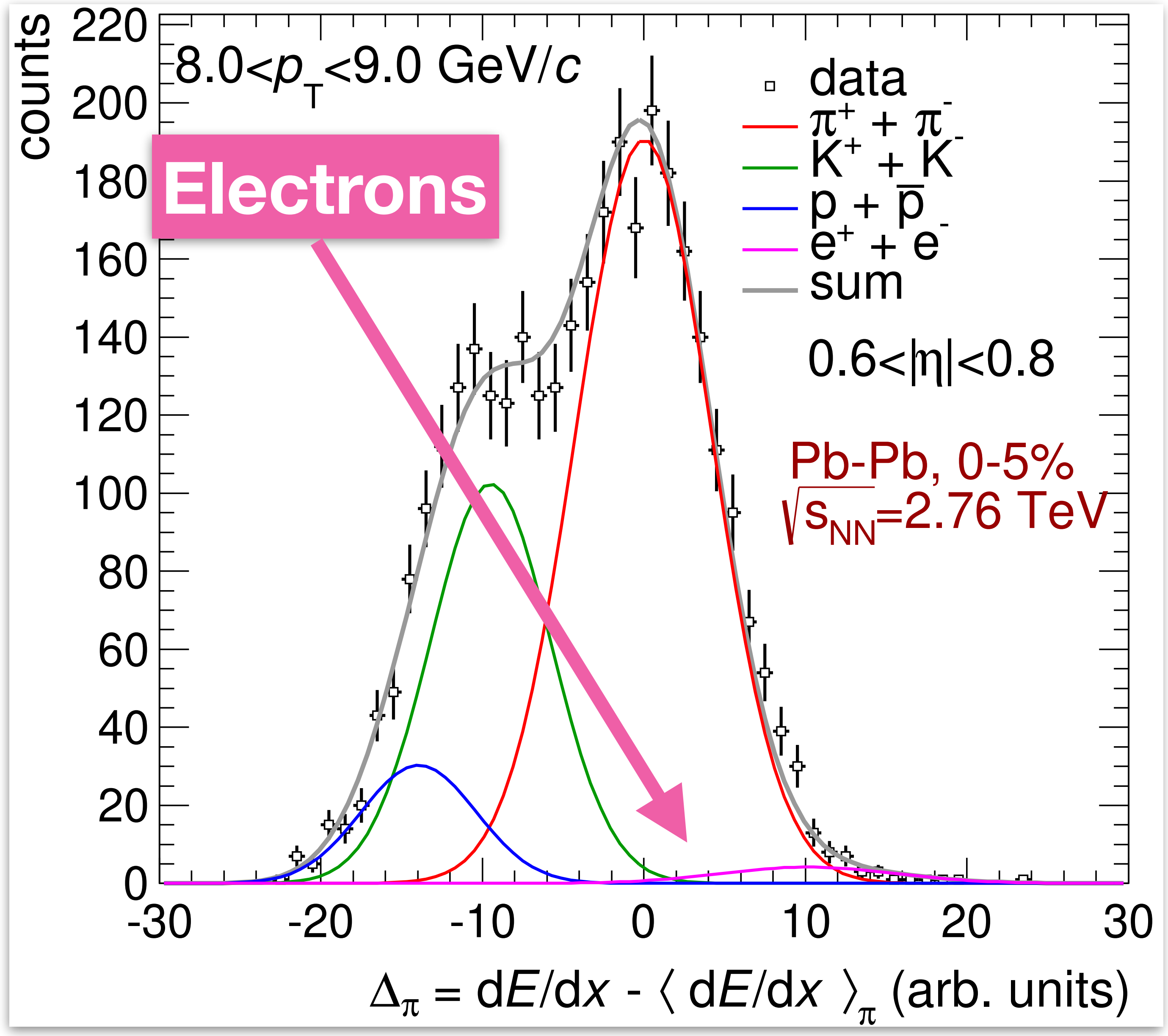
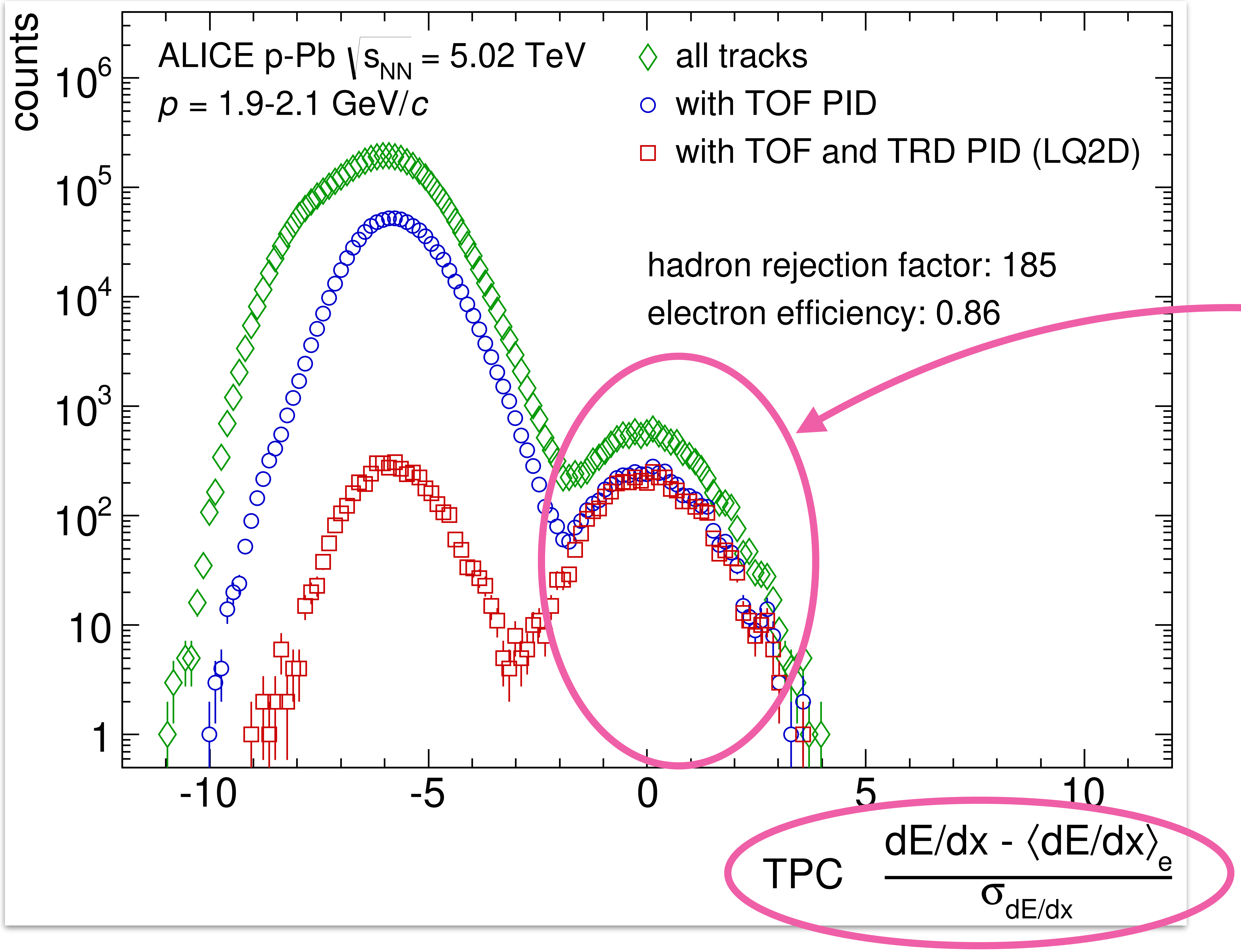
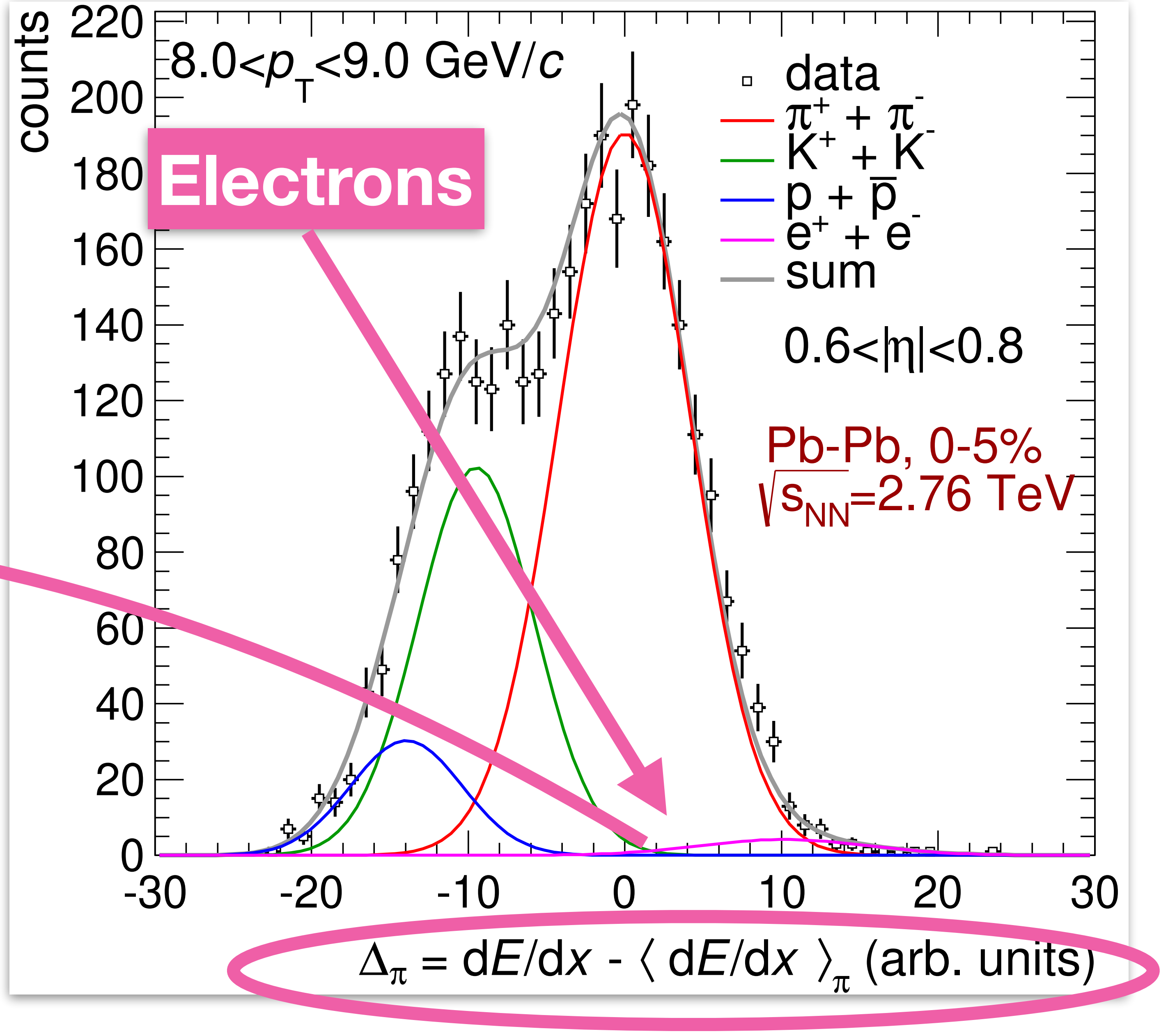
Electron identification



Electron identification





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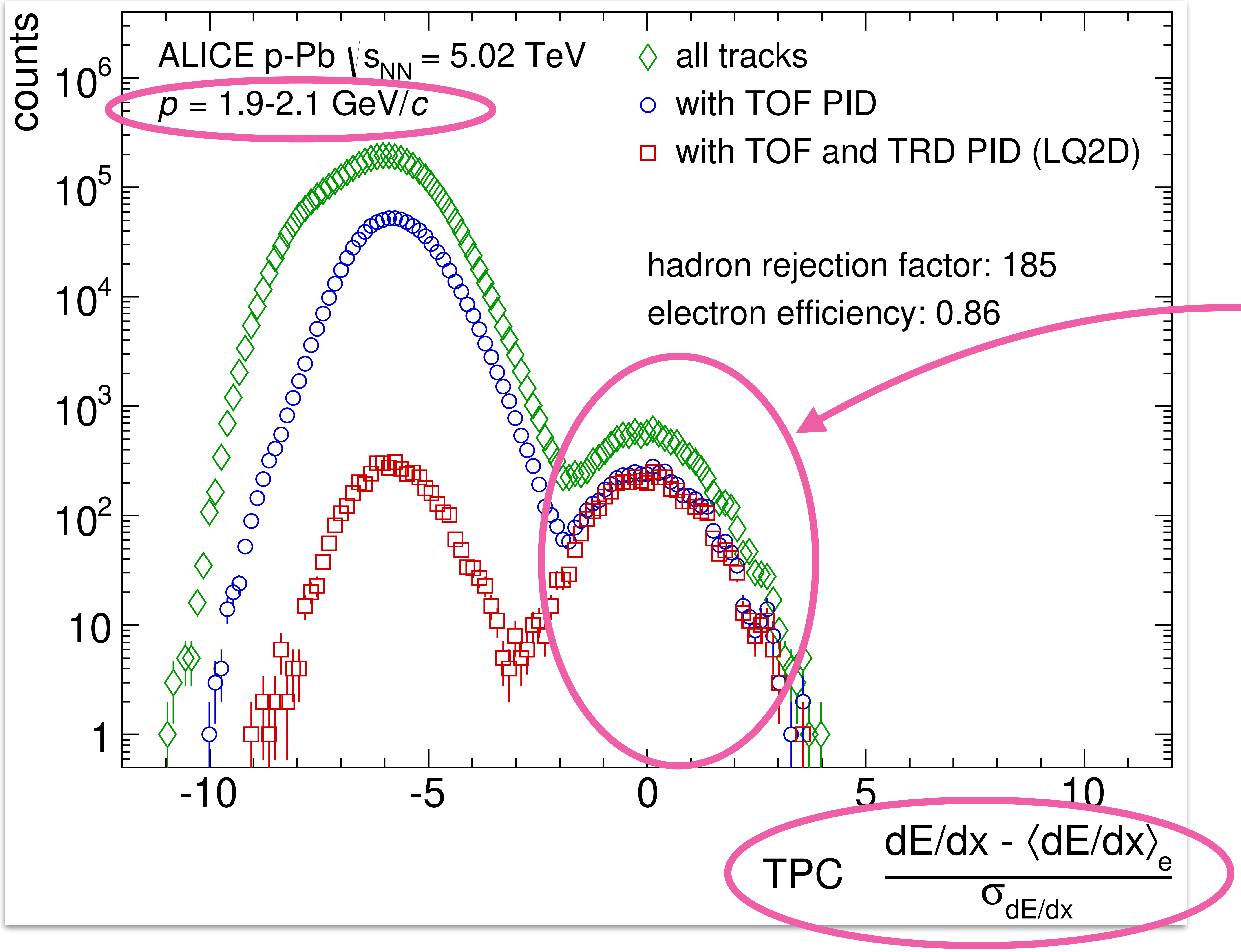

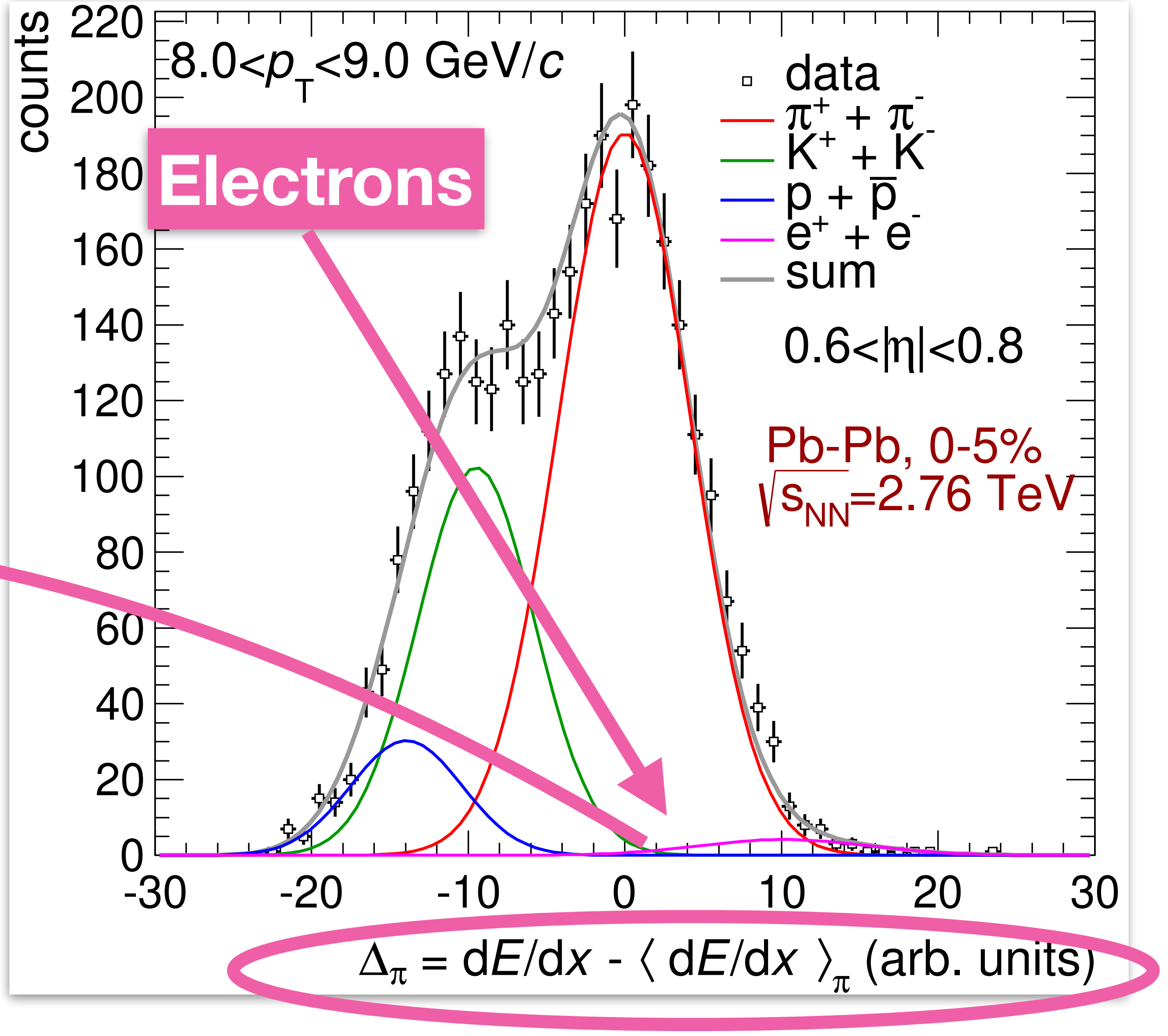

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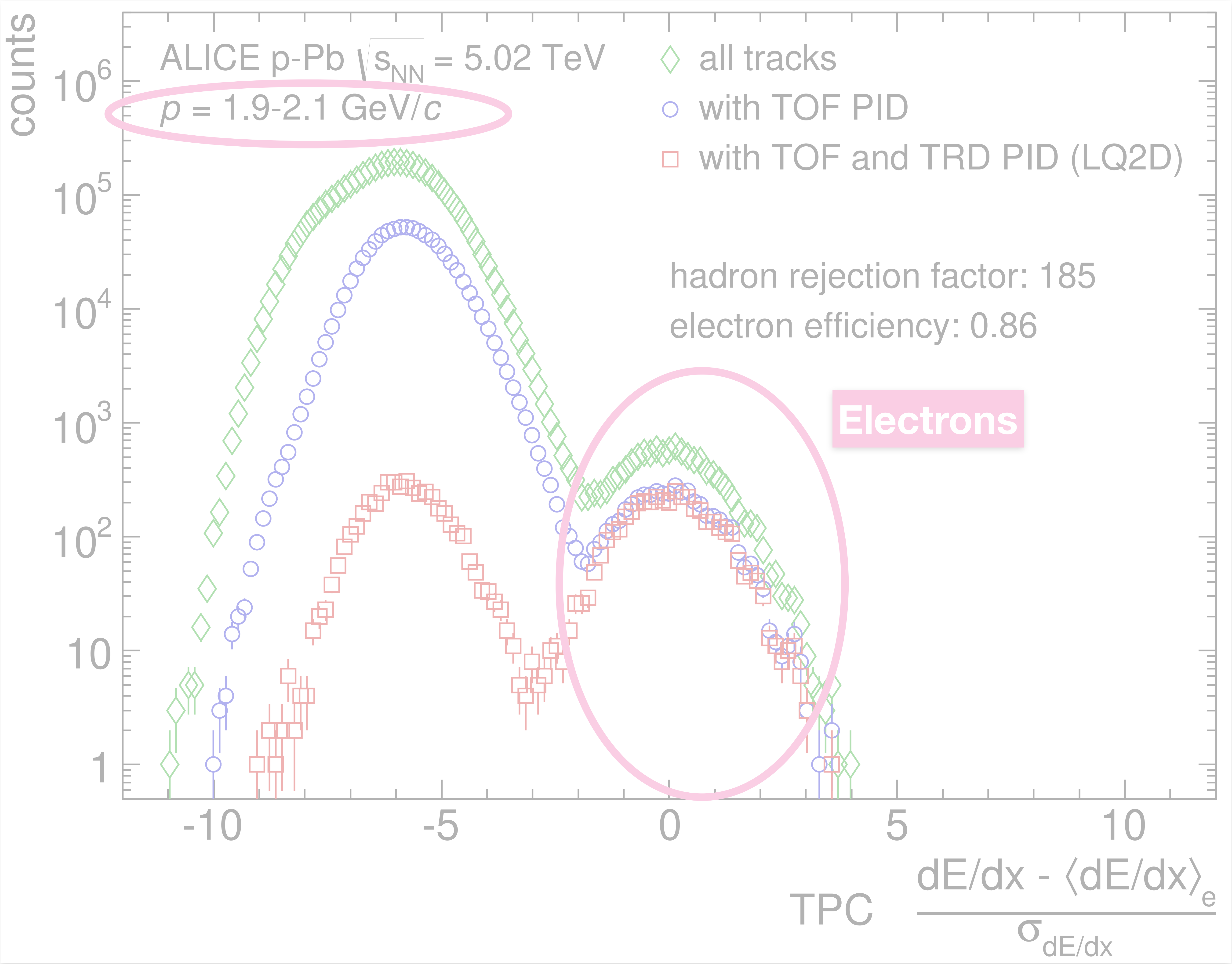

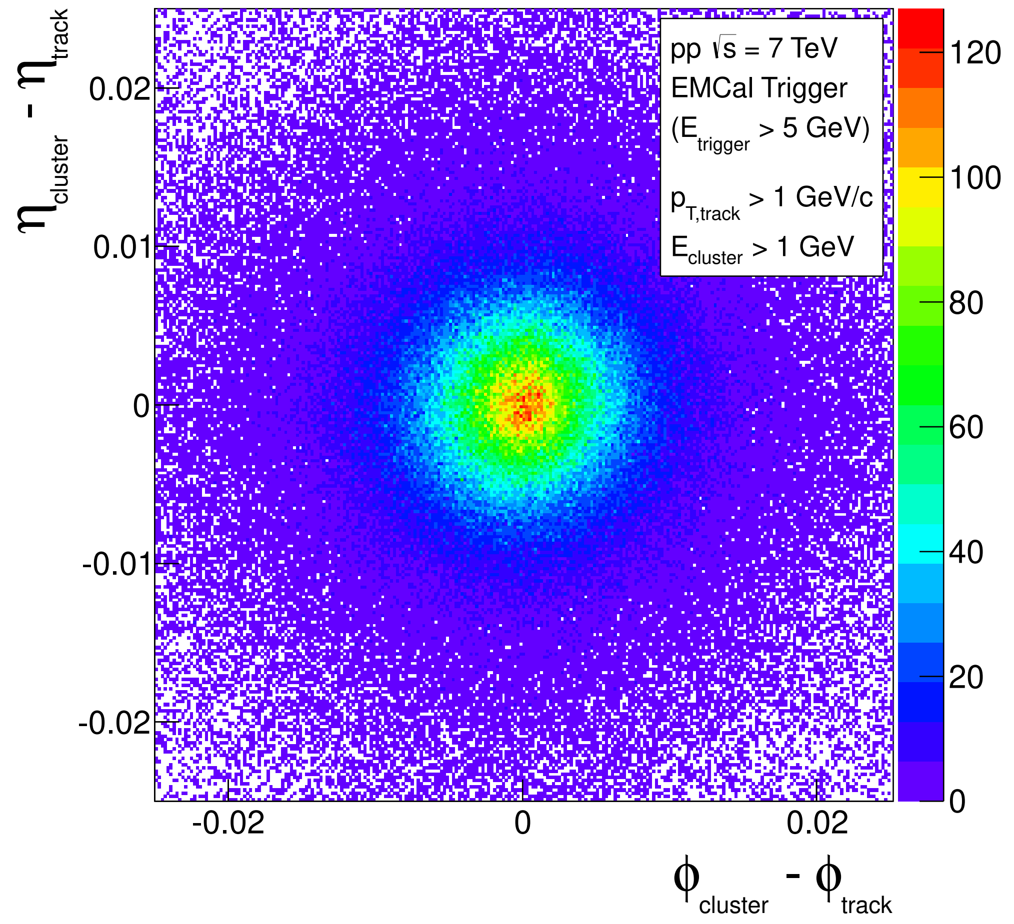

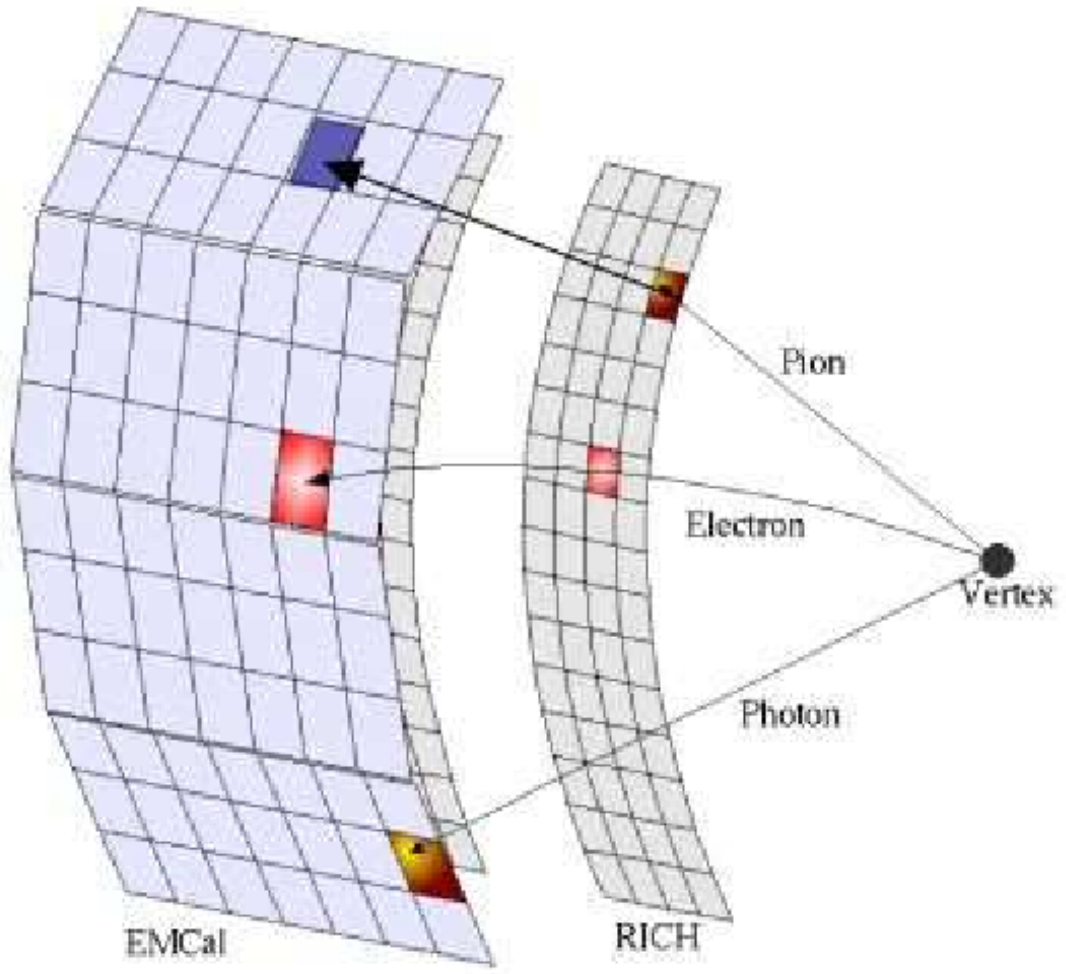

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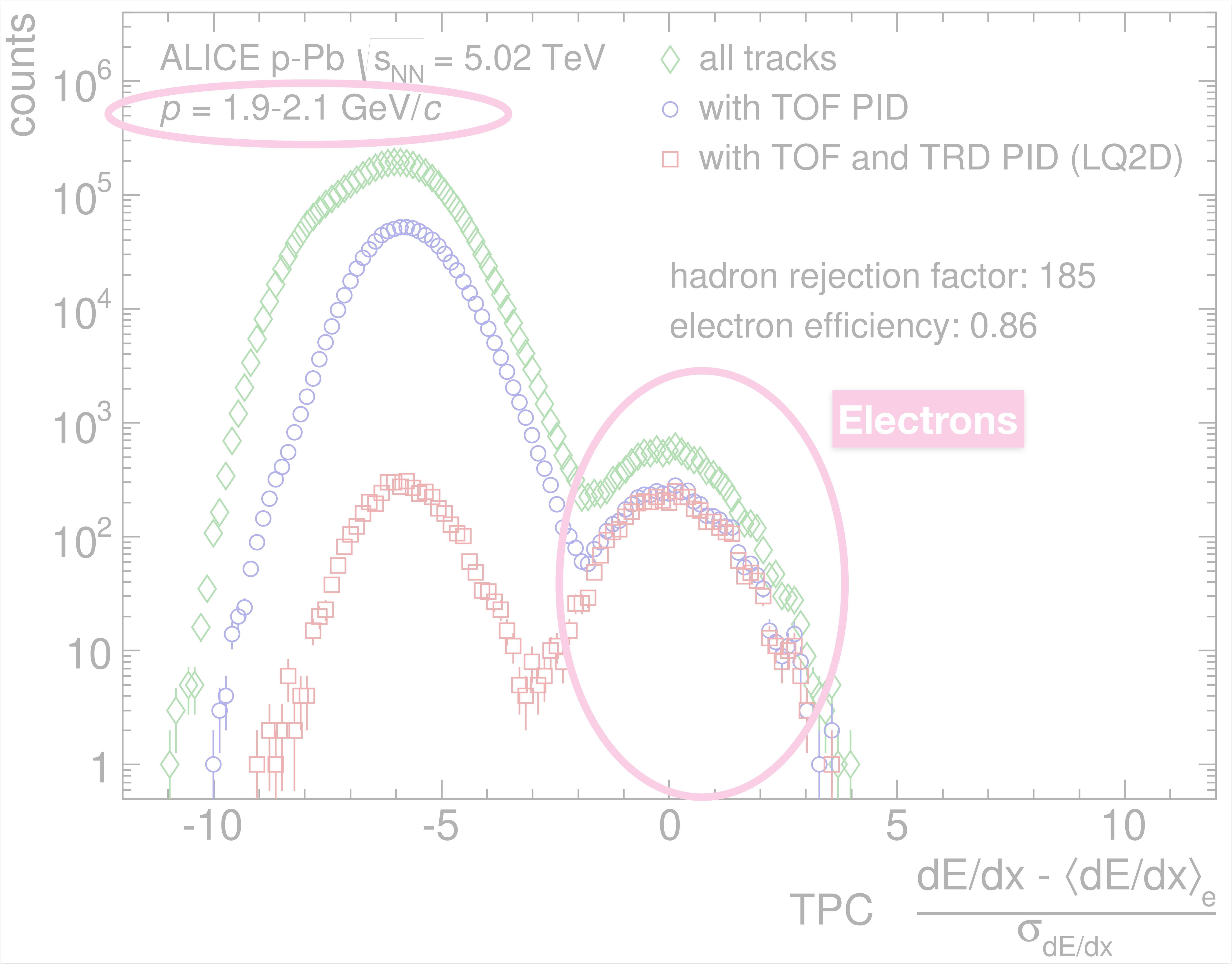

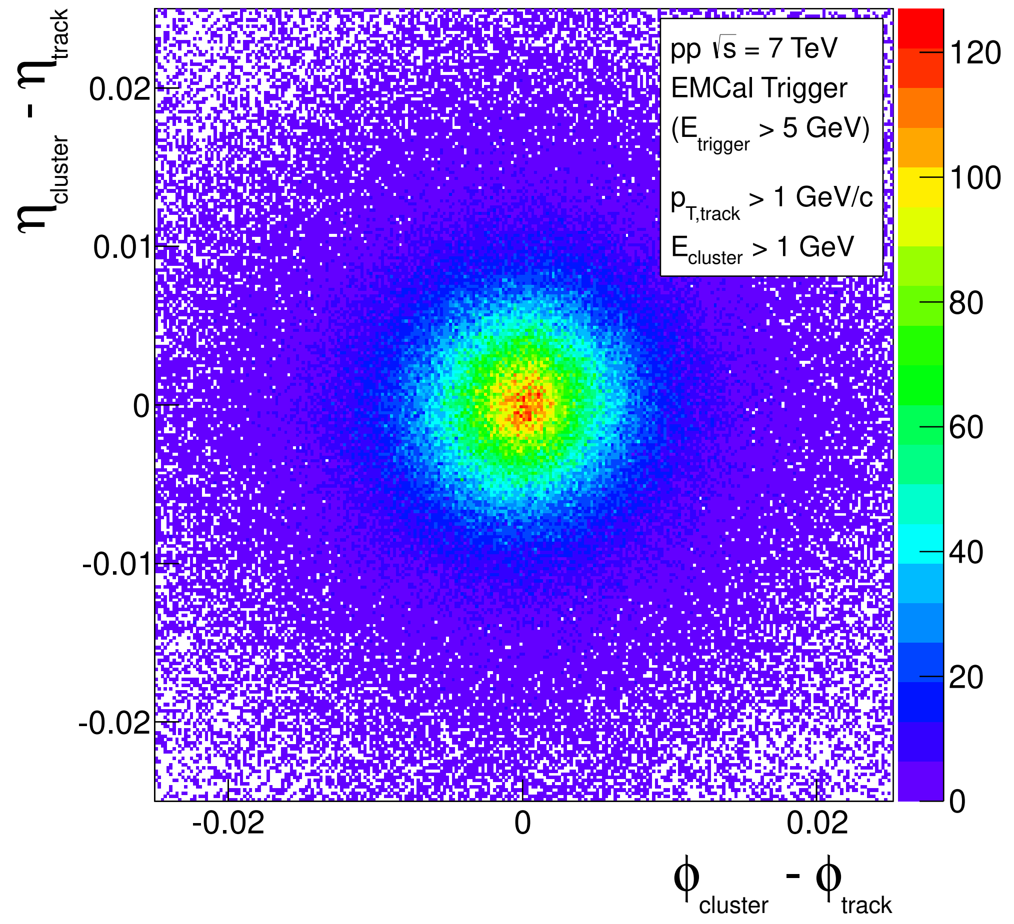

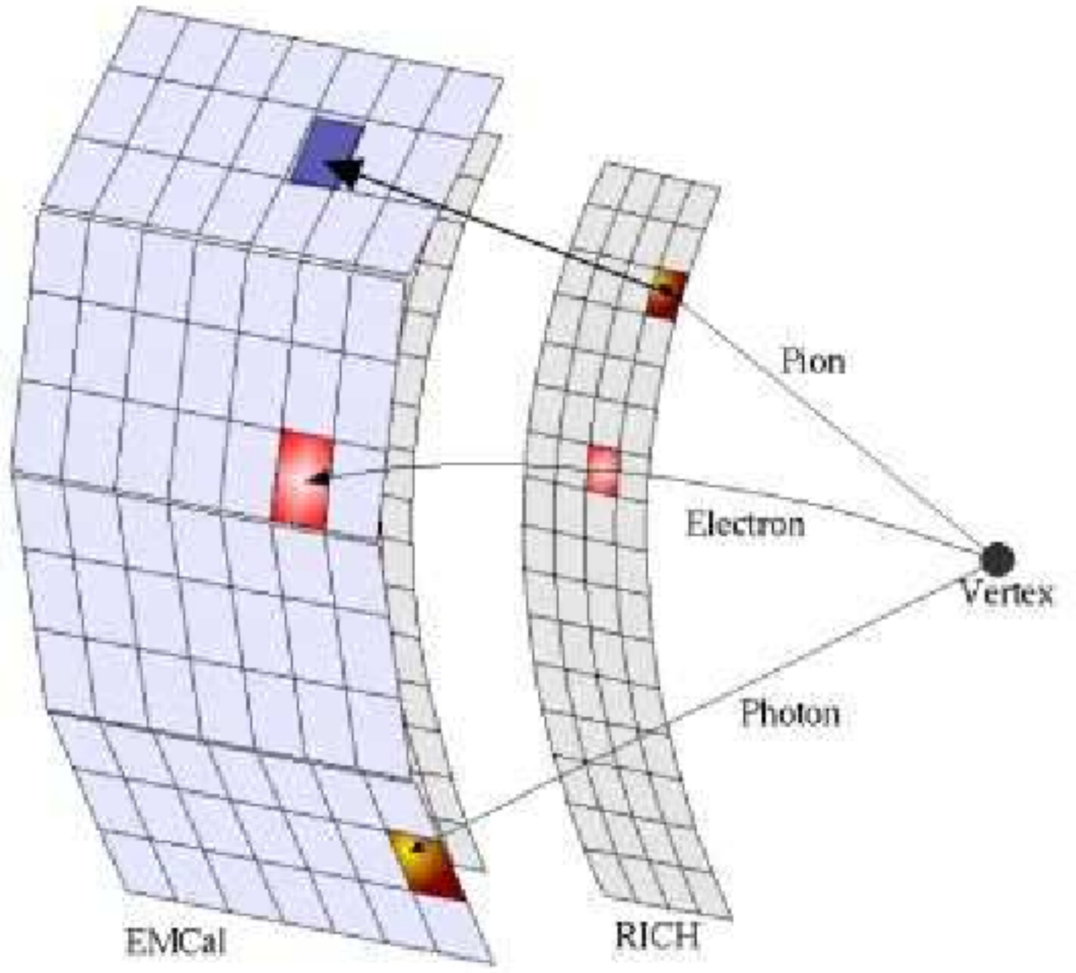

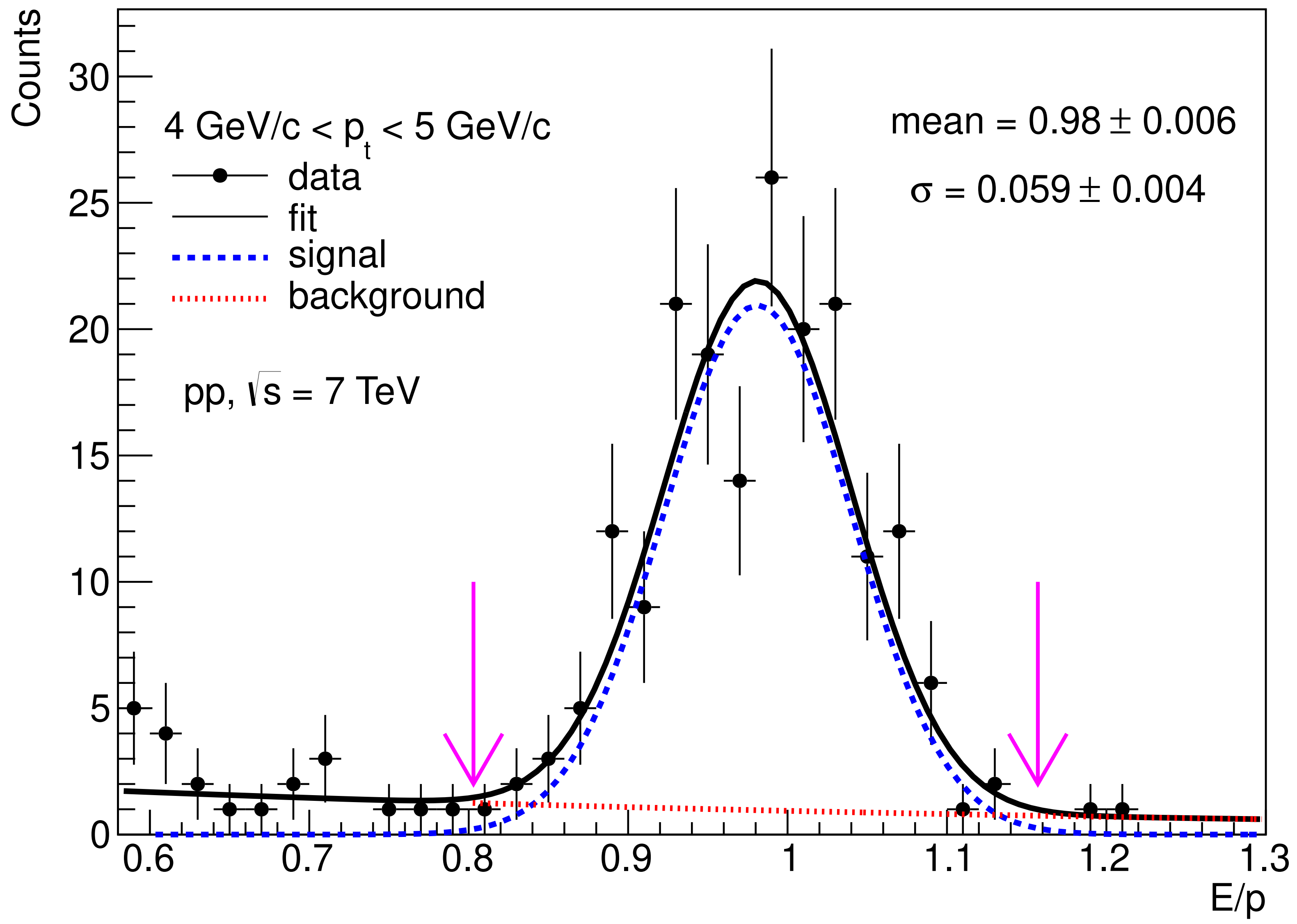

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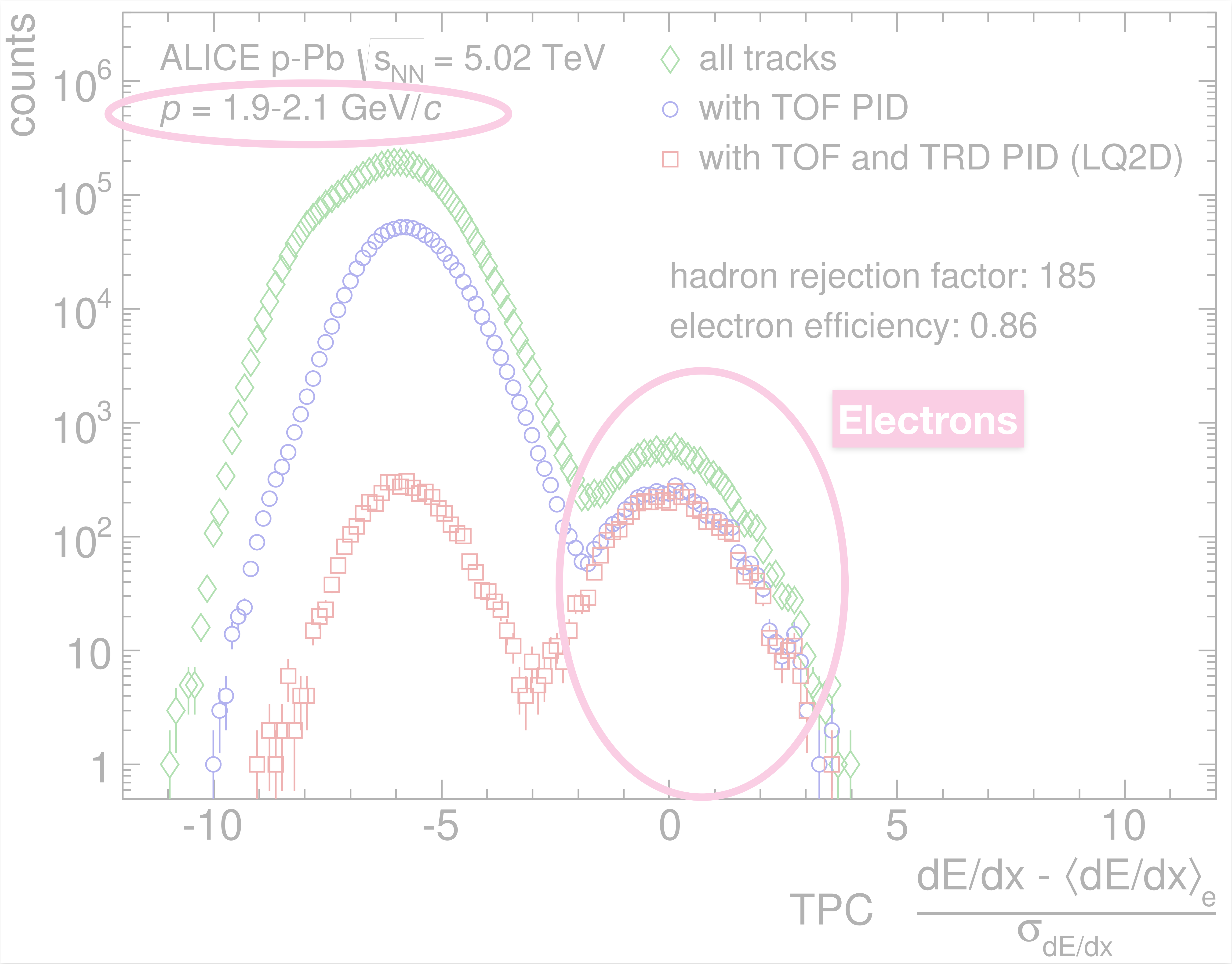
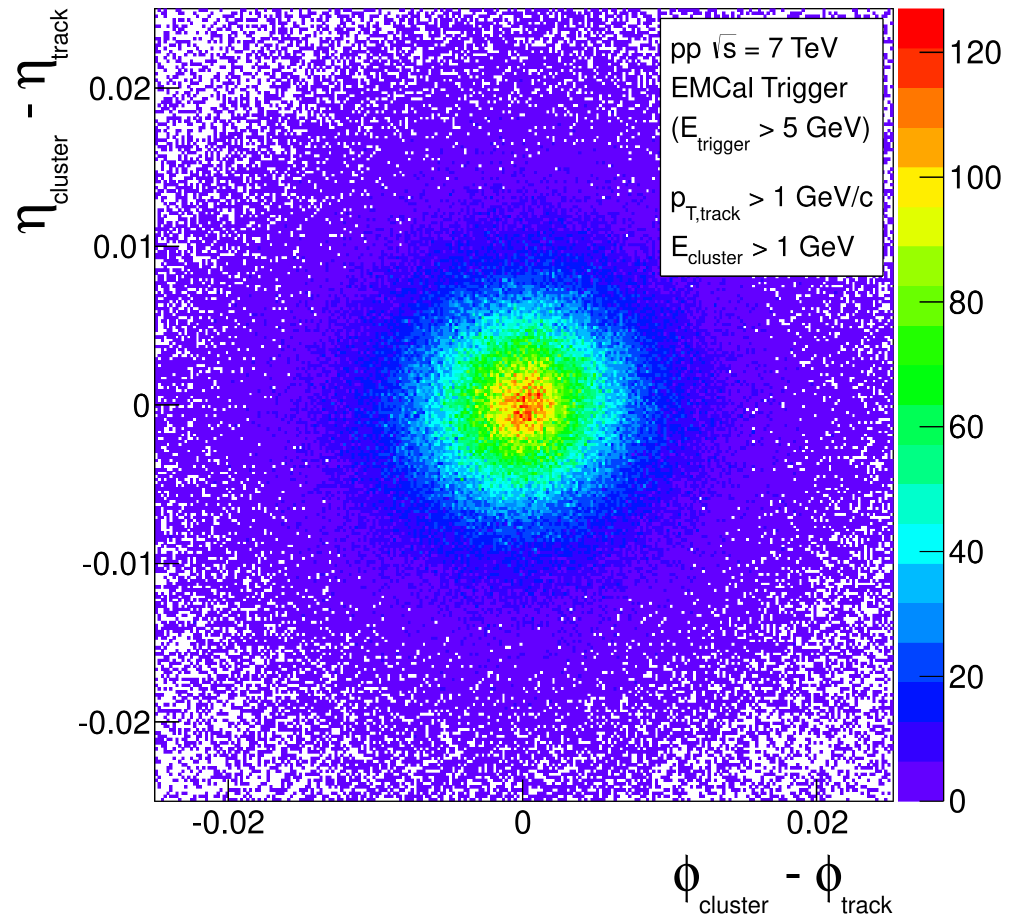
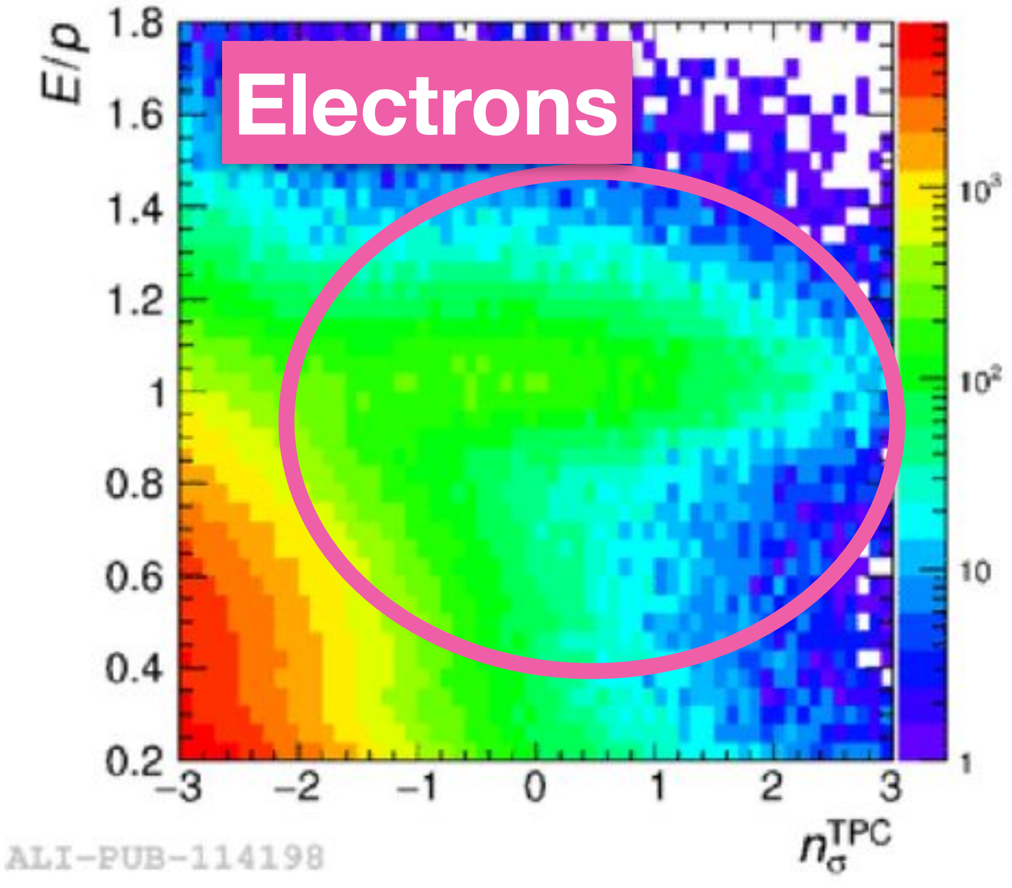
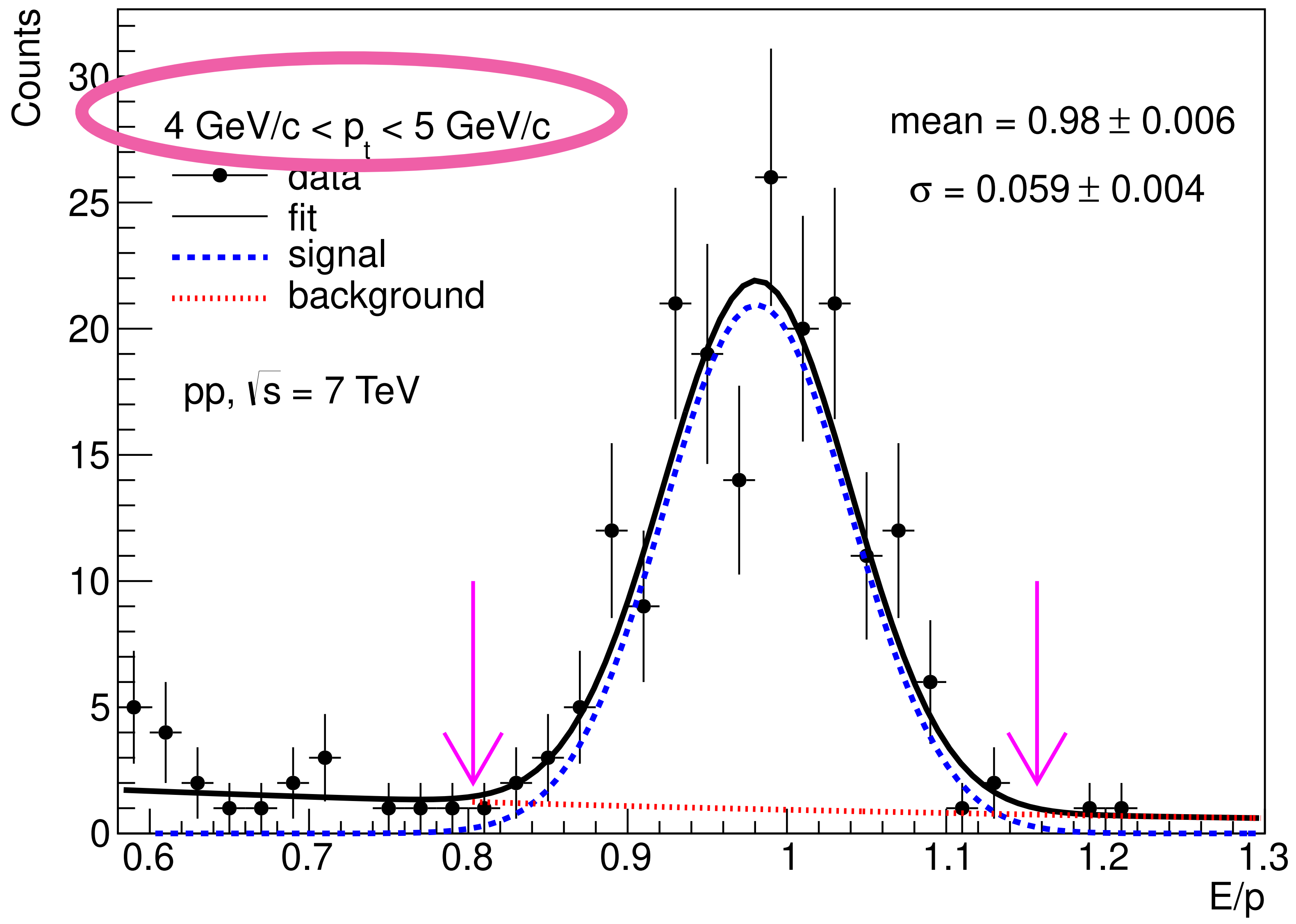
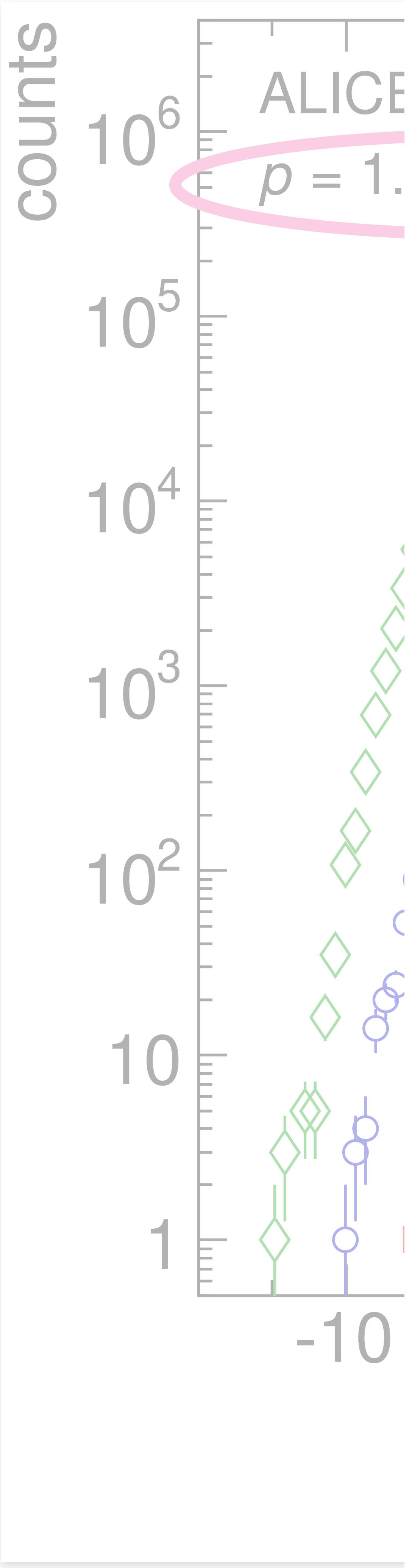


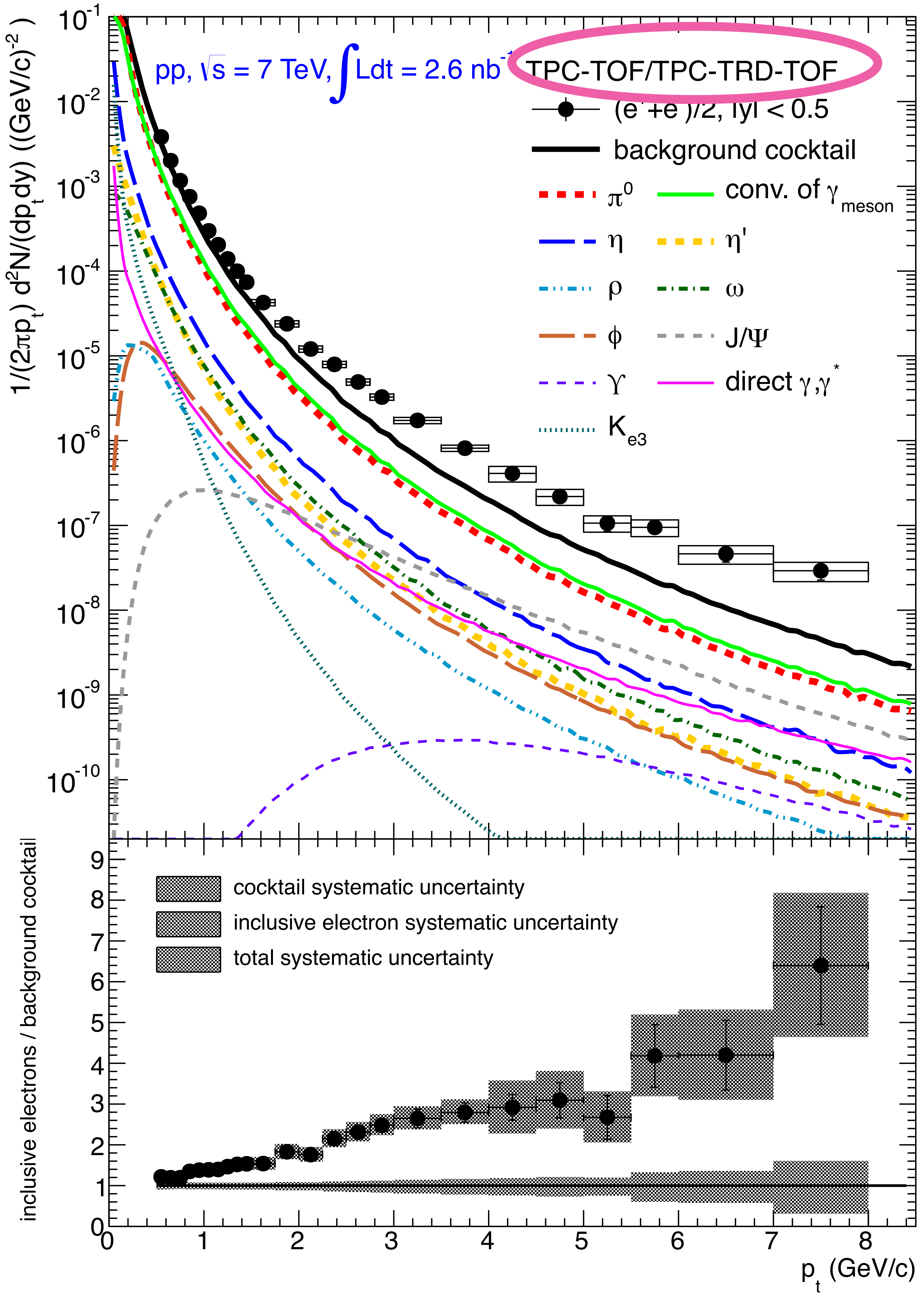


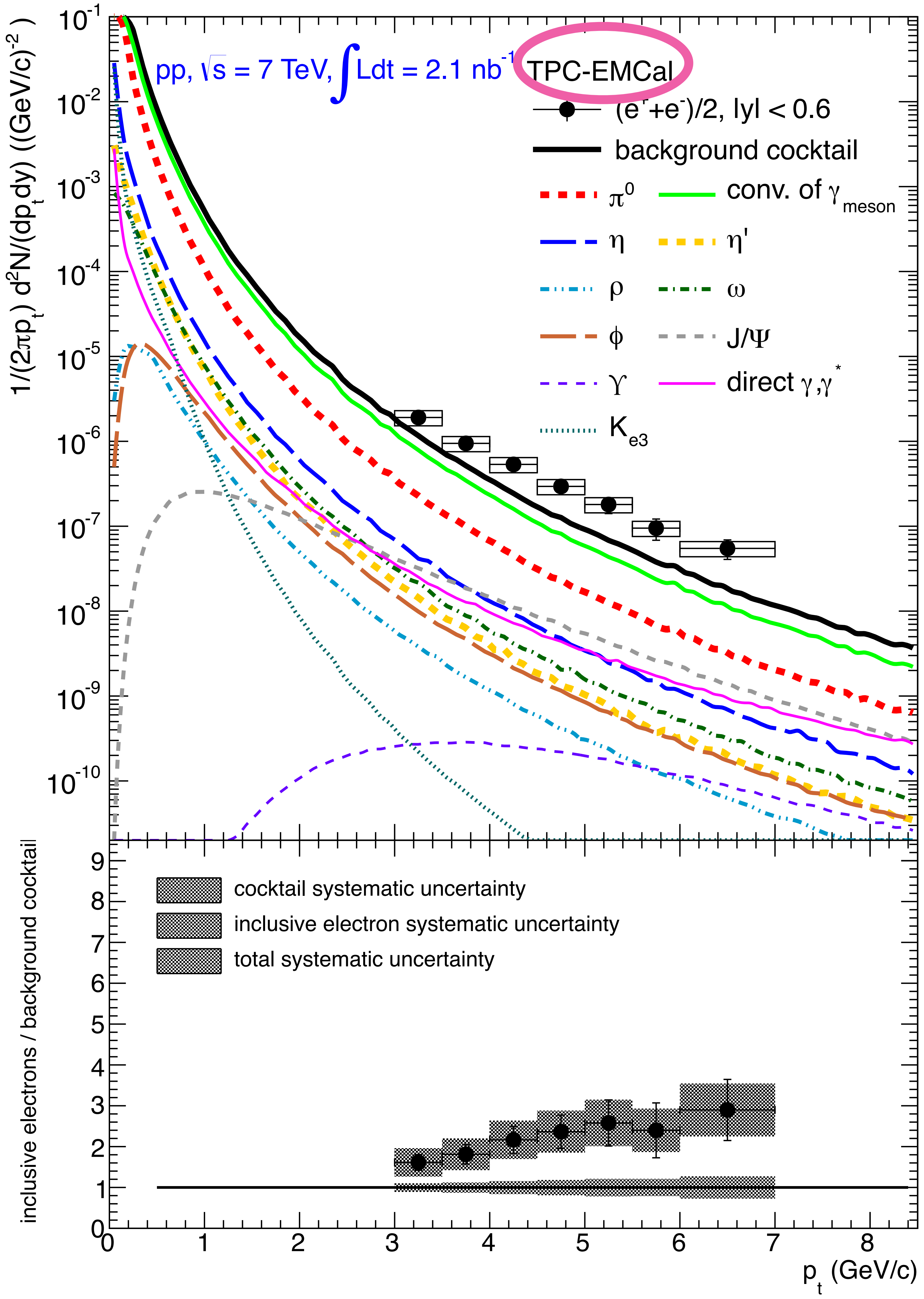


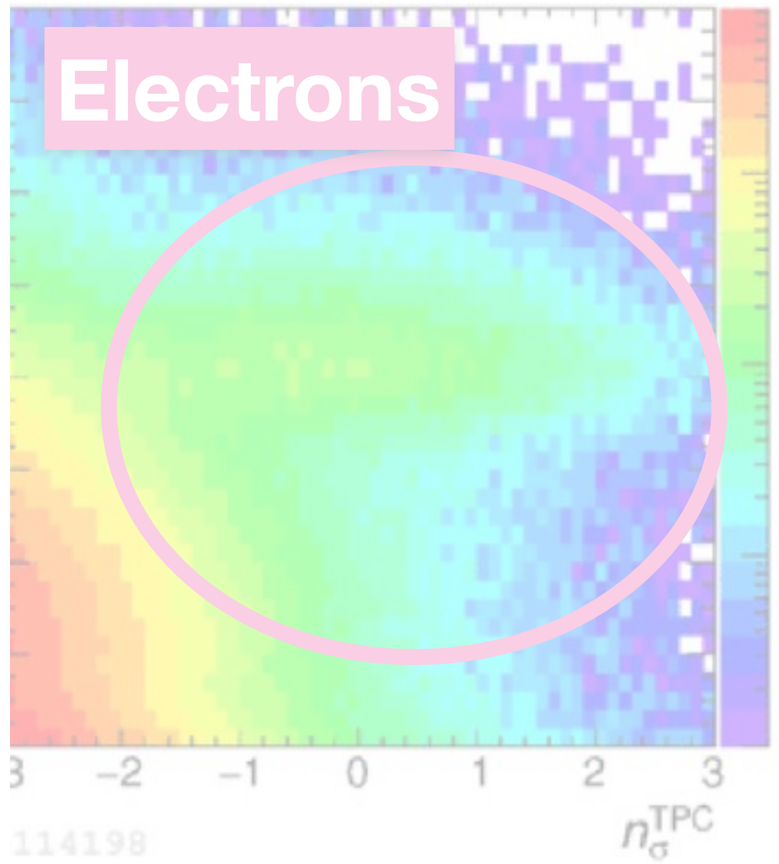


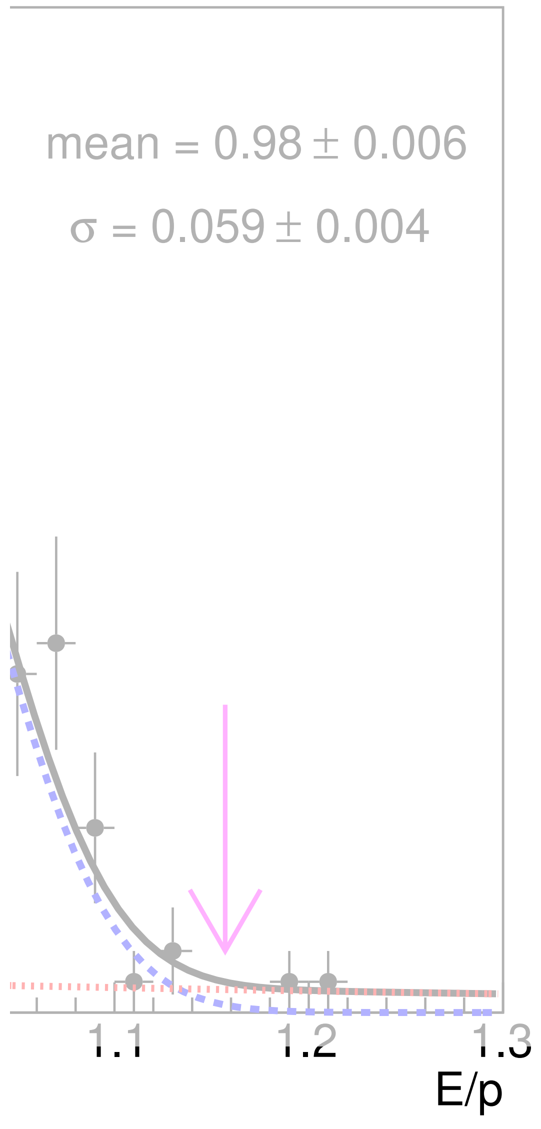
Heavy flavour decay electrons



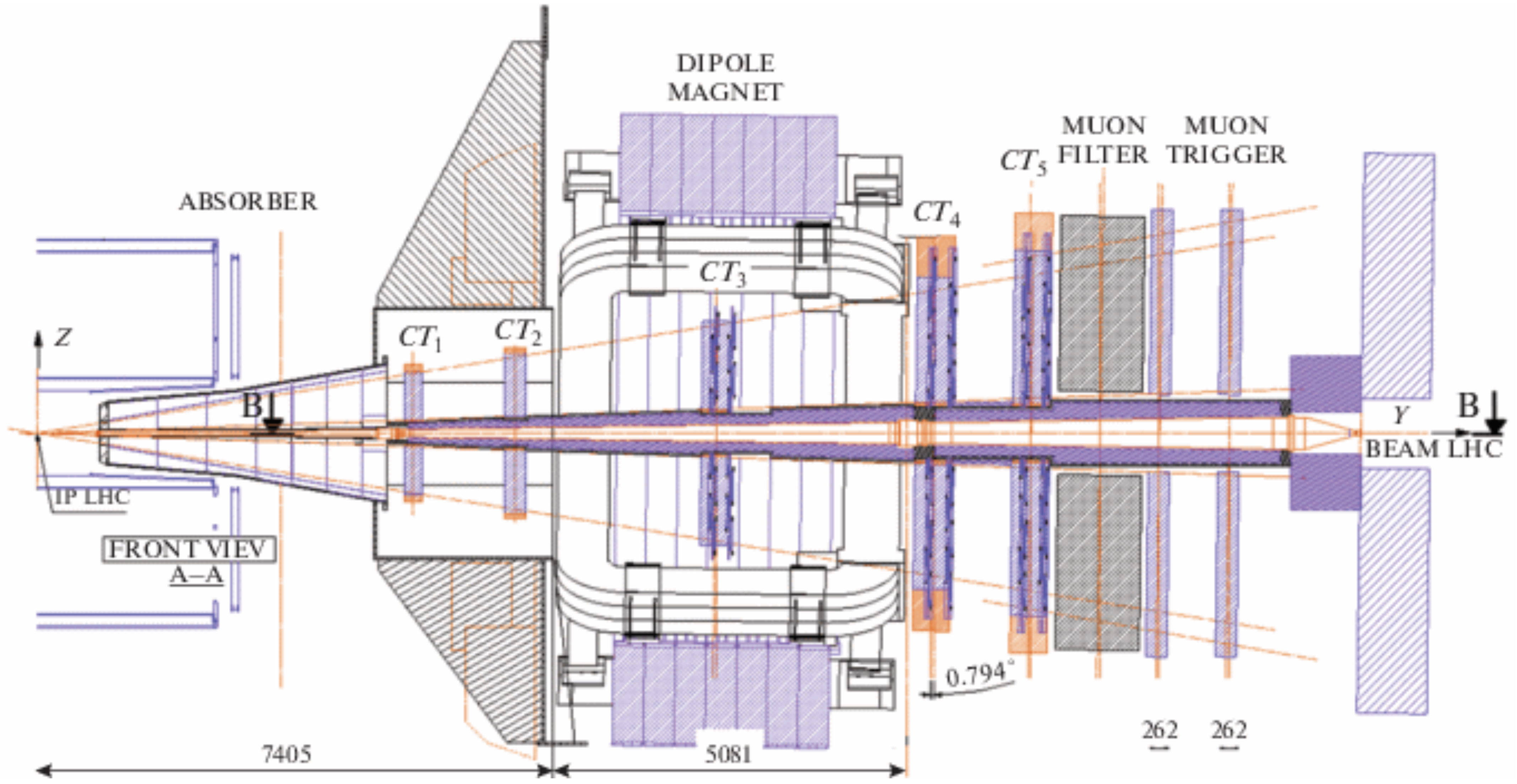




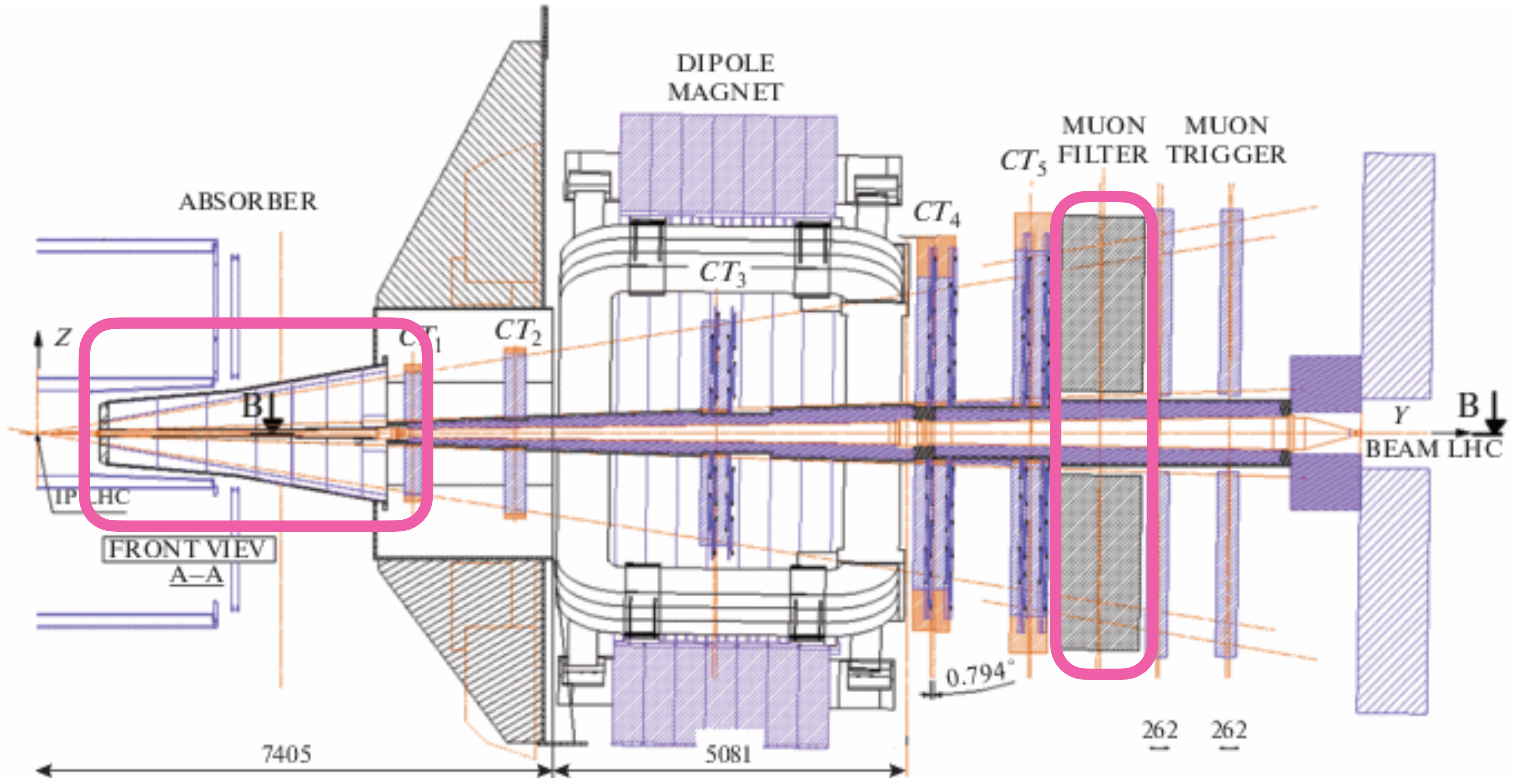




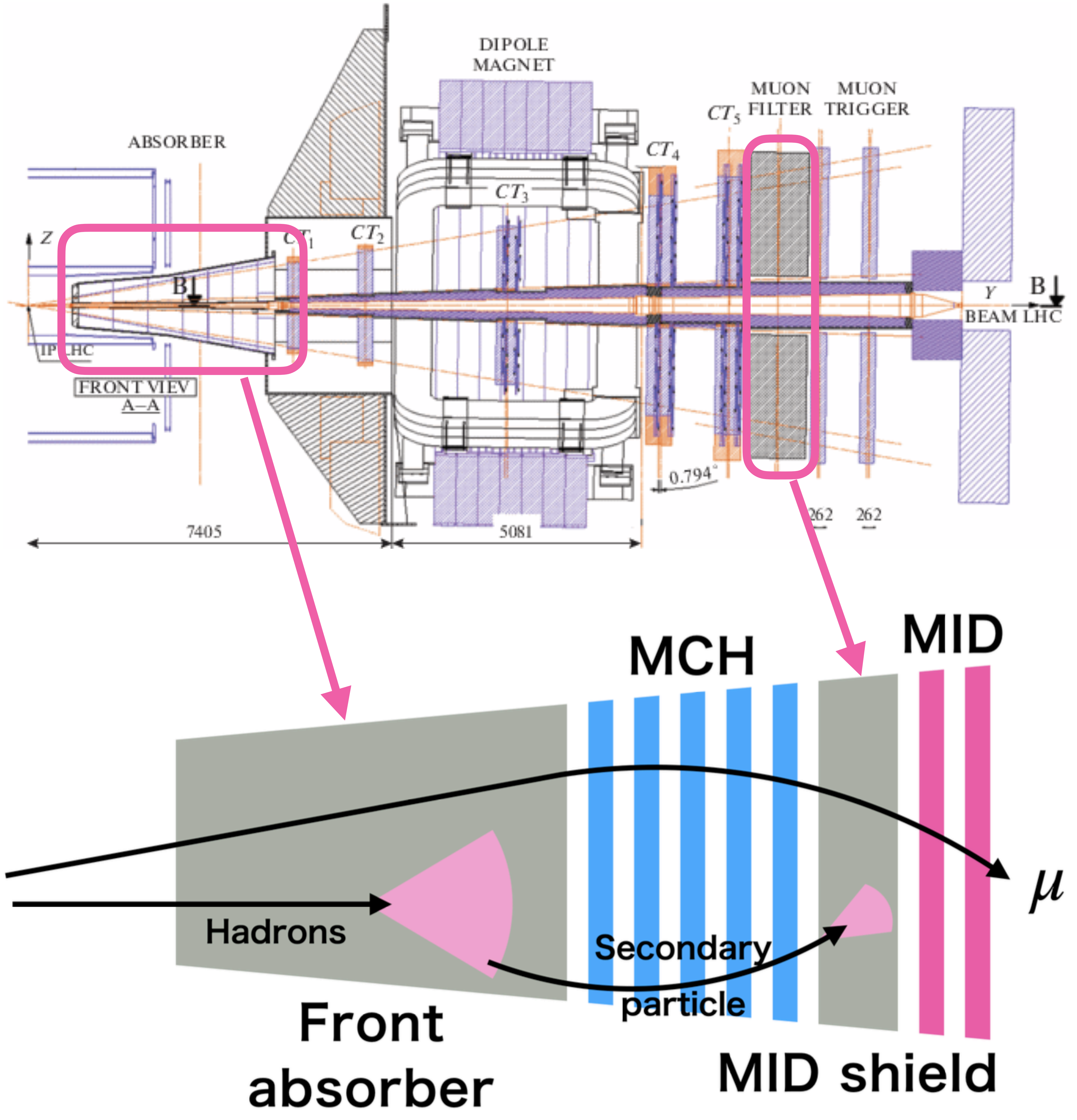
Heavy flavour decay muons



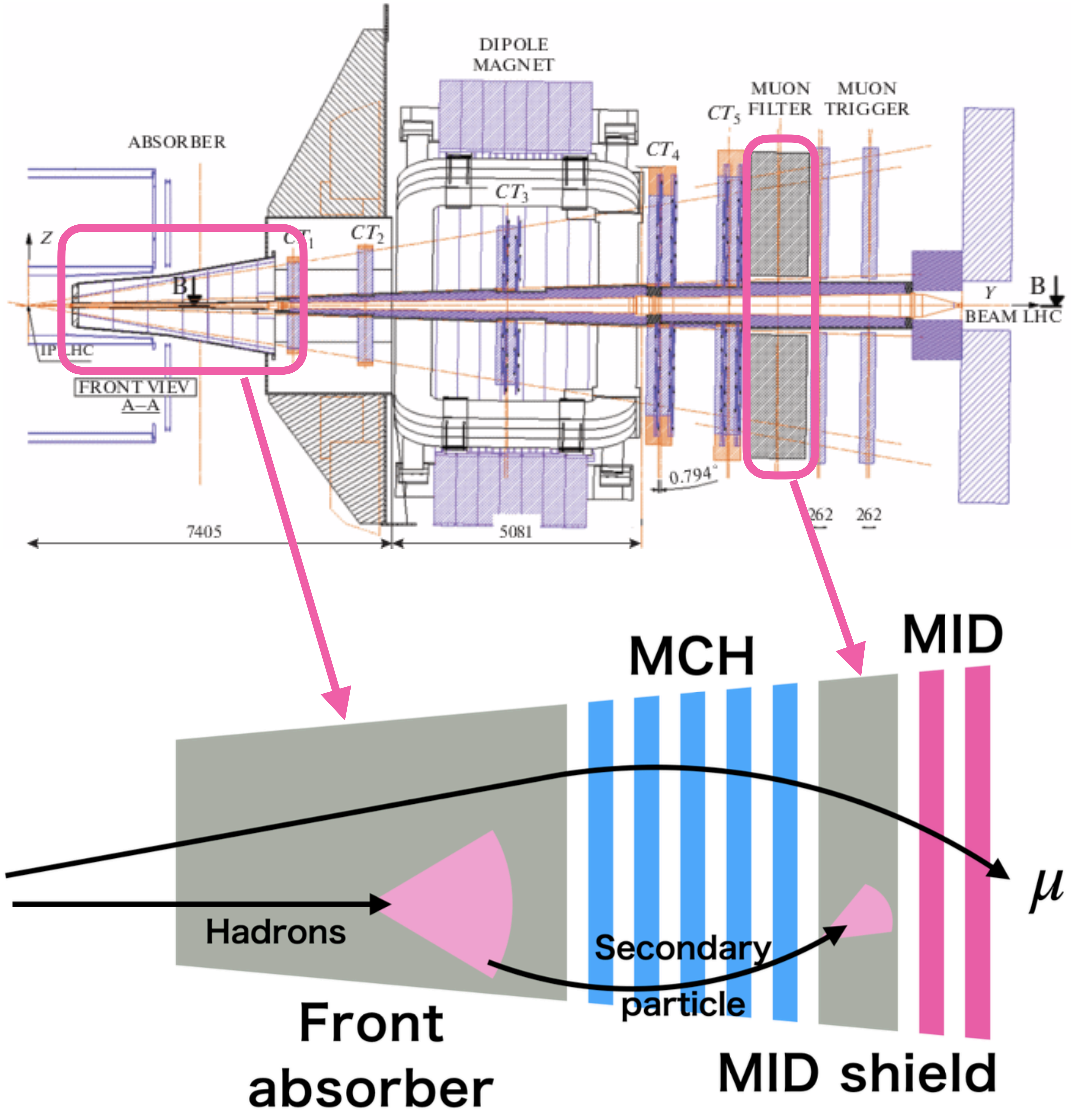
Heavy flavour decay muons

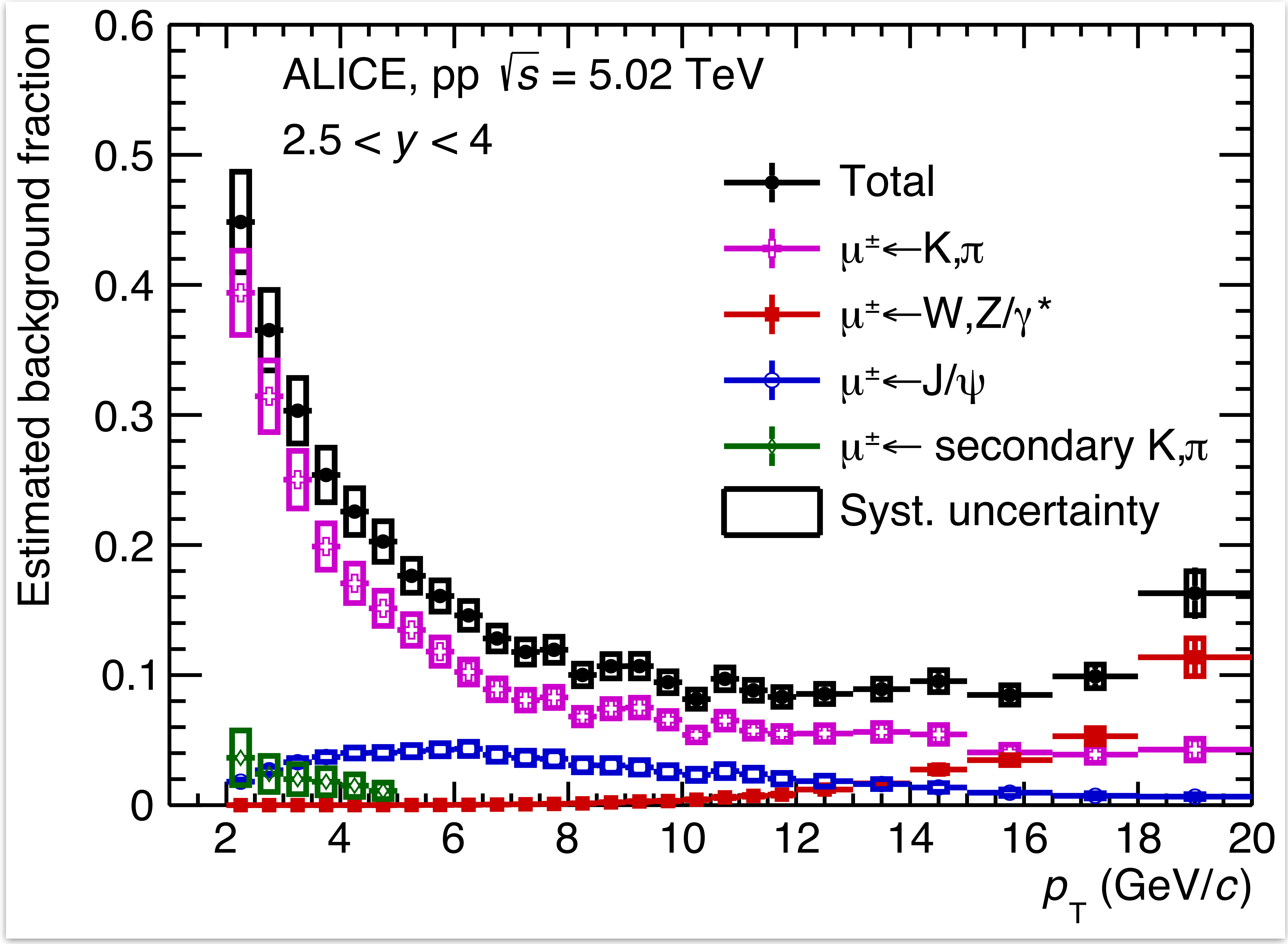


Heavy flavour decay muons

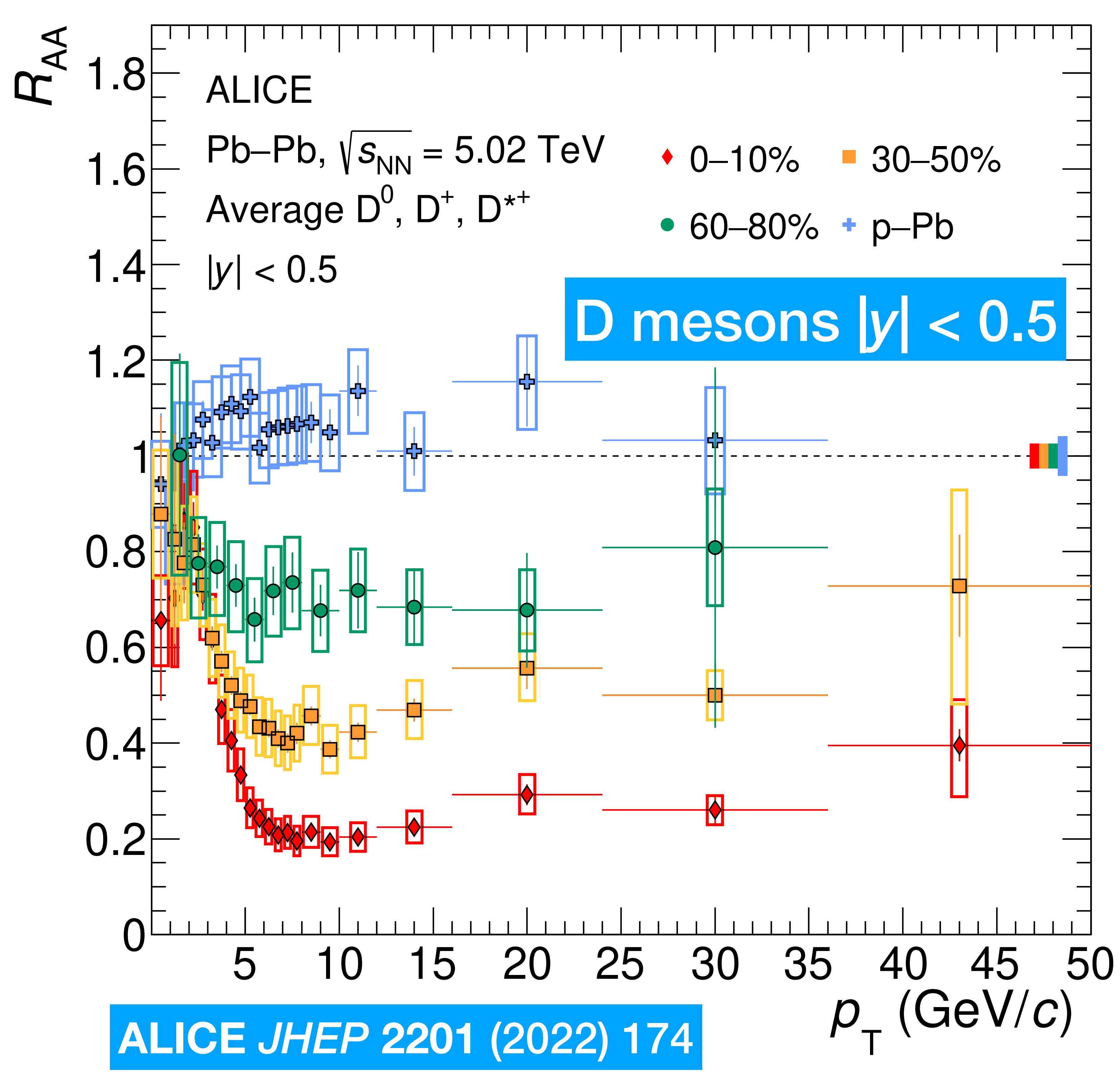


Heavy flavour decay muons





Charmed particle R_{AA}



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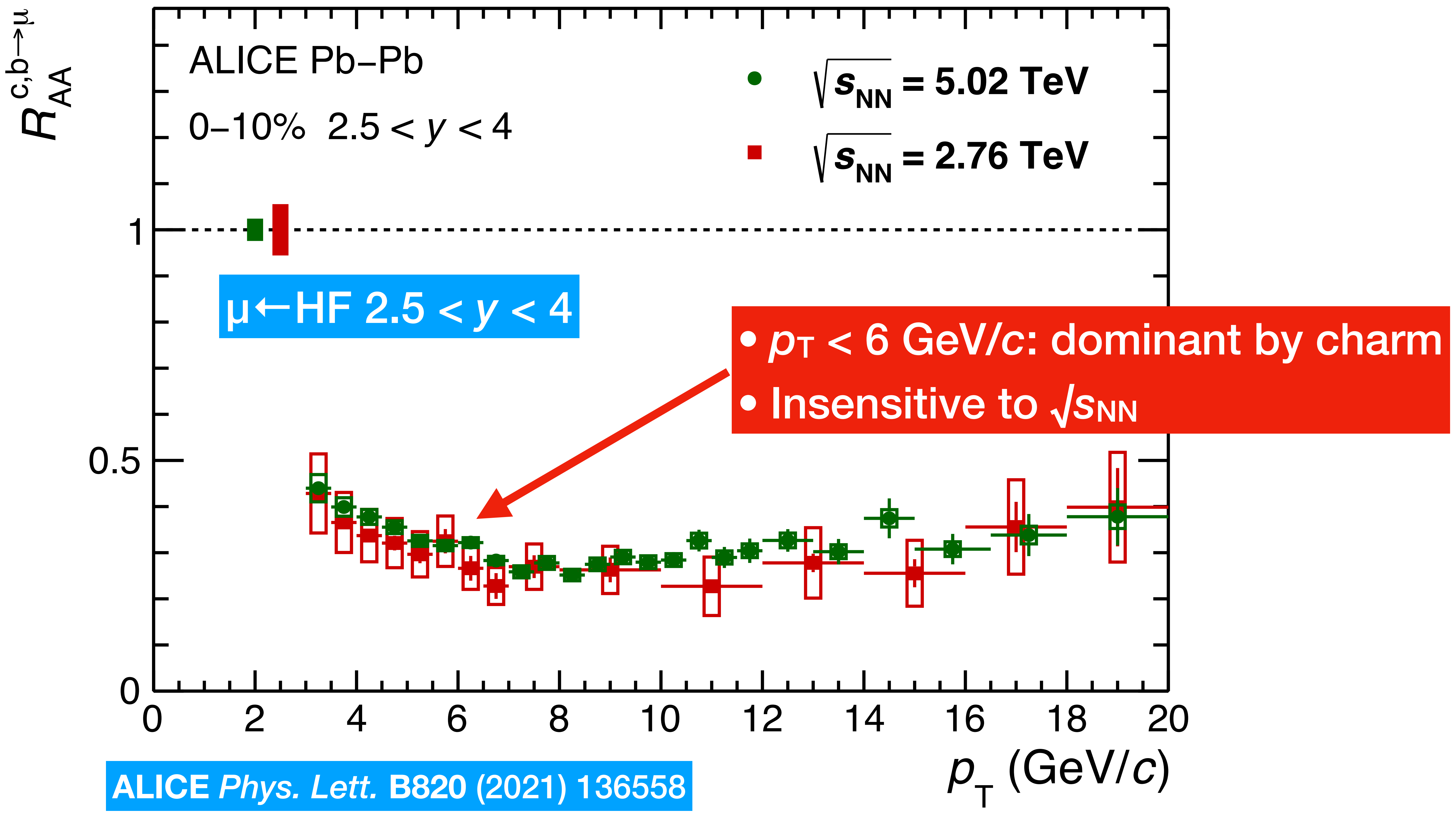
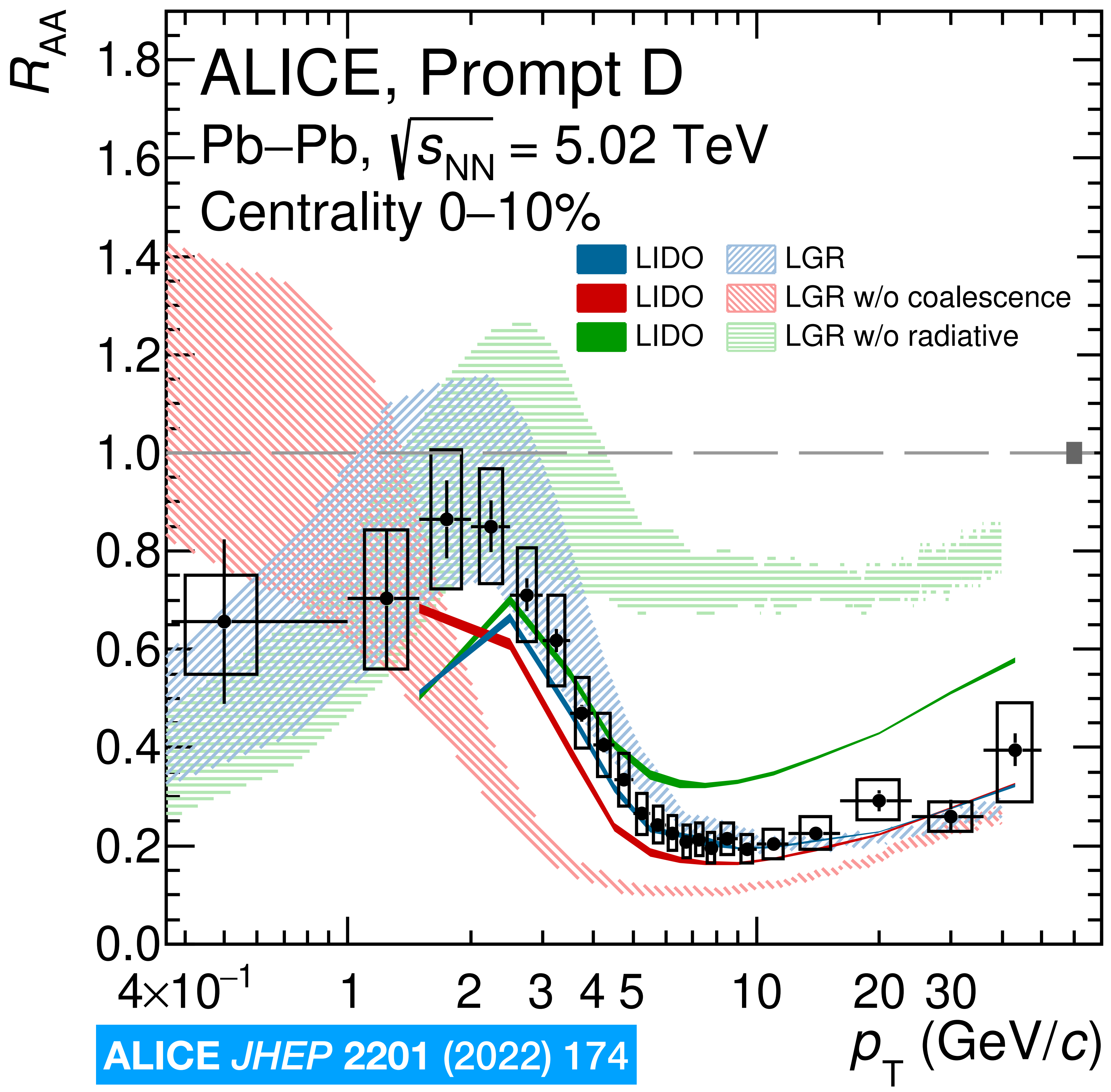


ALICE *Phys. Lett.* B820 (2021) 136558

- Suppression increases from peripheral to central collisions
- Similar suppression in the most central collisions between mid- and forward-rapidity

➡ Charm quarks undergo strong energy loss in a wide rapidity range

Charm quark energy loss



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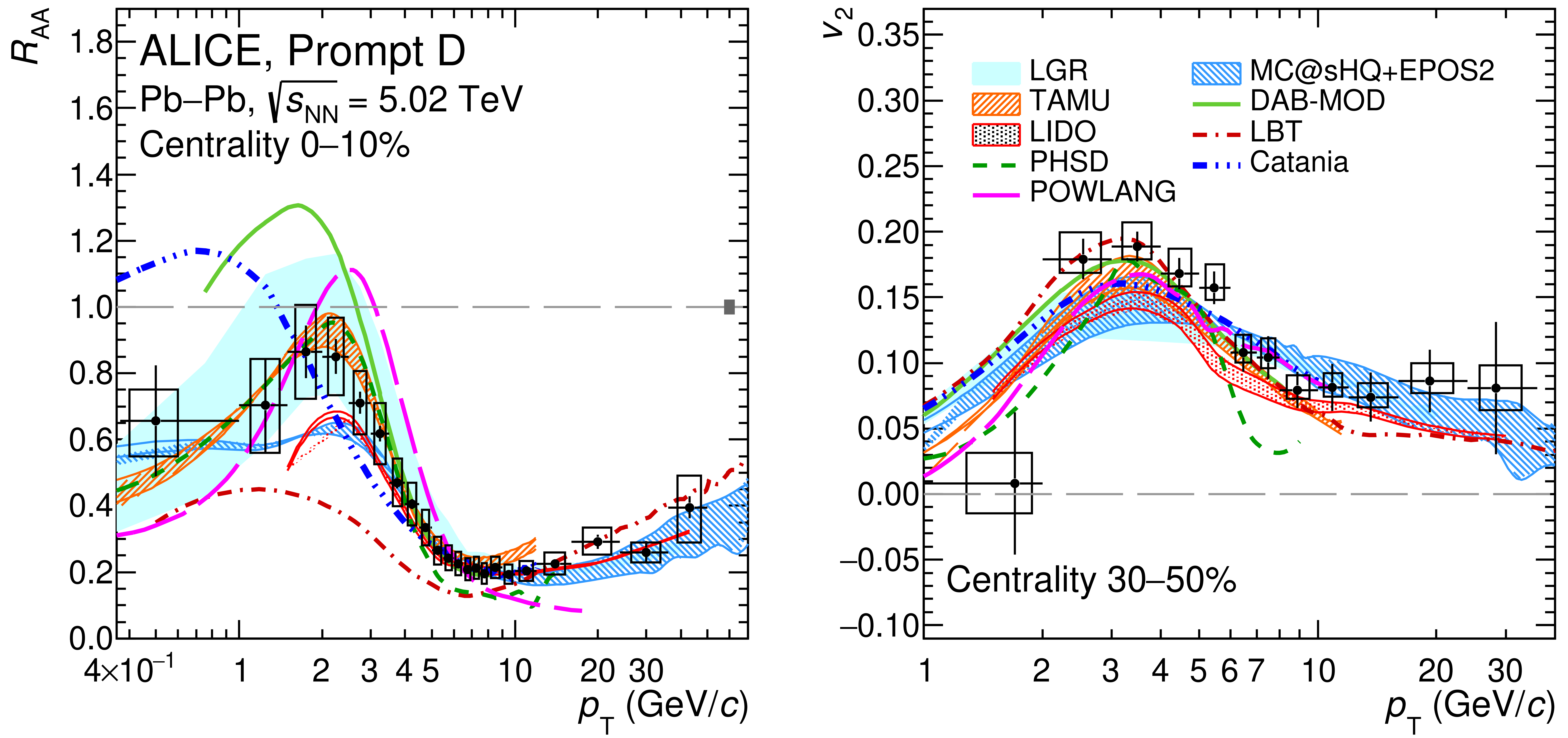
W/o coalescence: large deviation from data

➡ Hadronization via coalescence is important to interpret data

W/o radiative energy loss: reasonably describe data in p_T < 5 GeV/c, but largely overestimate data at high p_T

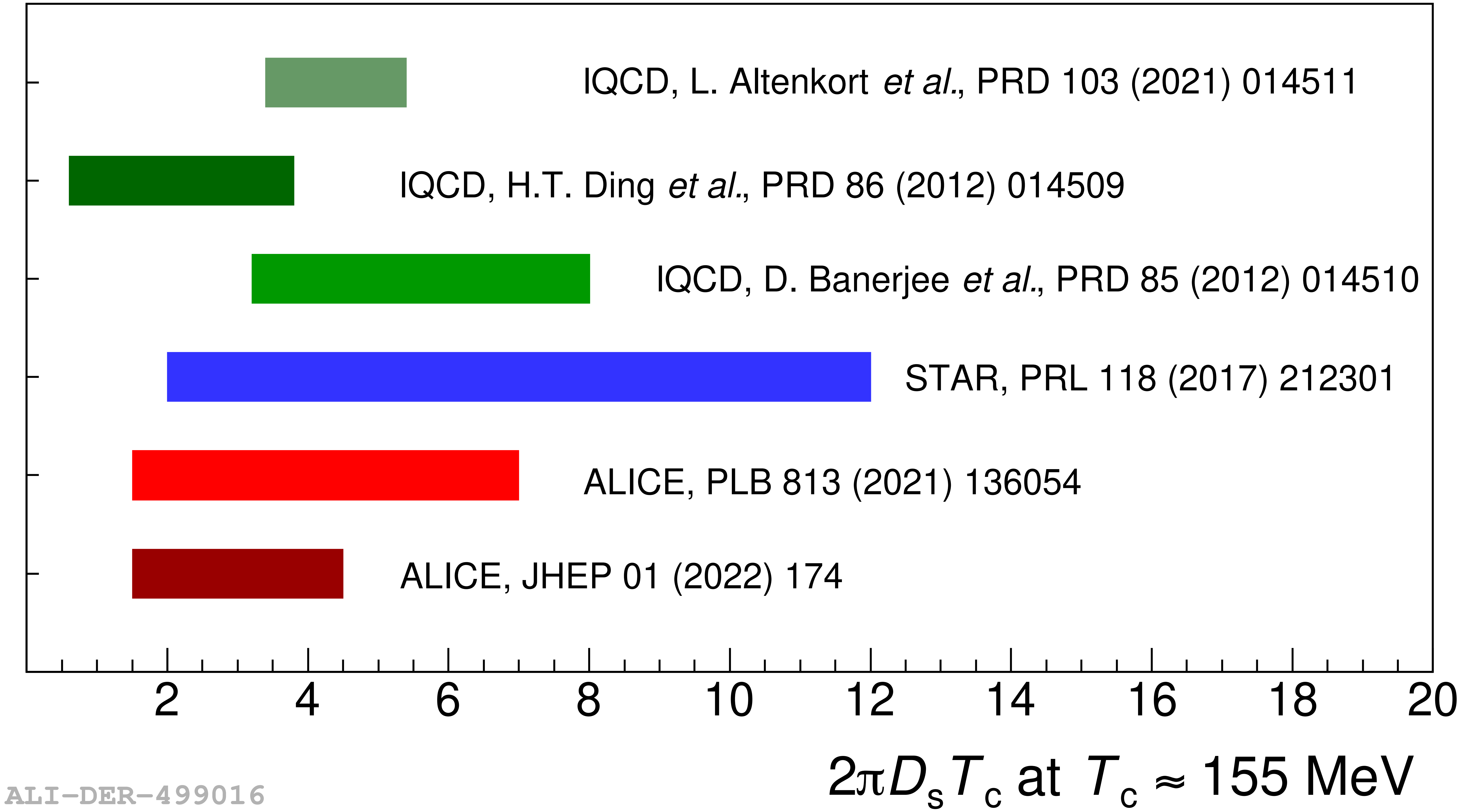
➡ Radiative energy loss is dominant at high p_T, while collisional energy loss is predominant at low and intermediate p_T

Charm quark transport



- Most charm quark transport models able to describe both the R_{AA} and v_2
- Use to estimate the spatial diffusion coefficient *Ds*

Charm quark transport



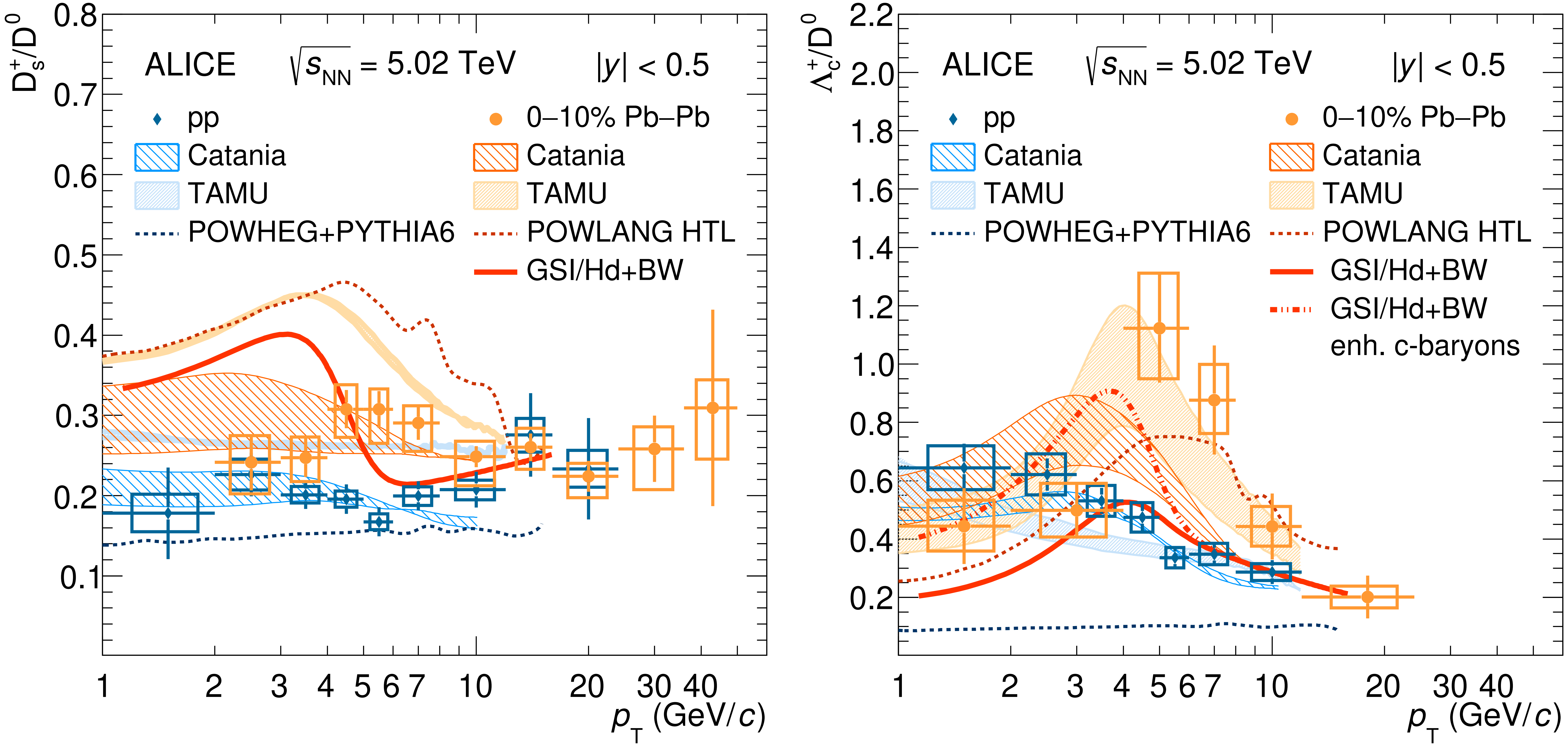
Diffusion coefficient D_s

- Almost independent of quark mass
- Characterization of the transport properties of the medium
- Constrains the specific shear viscosity η/s

The newest constraints from ALICE by combining D meson R_{AA} and v_2

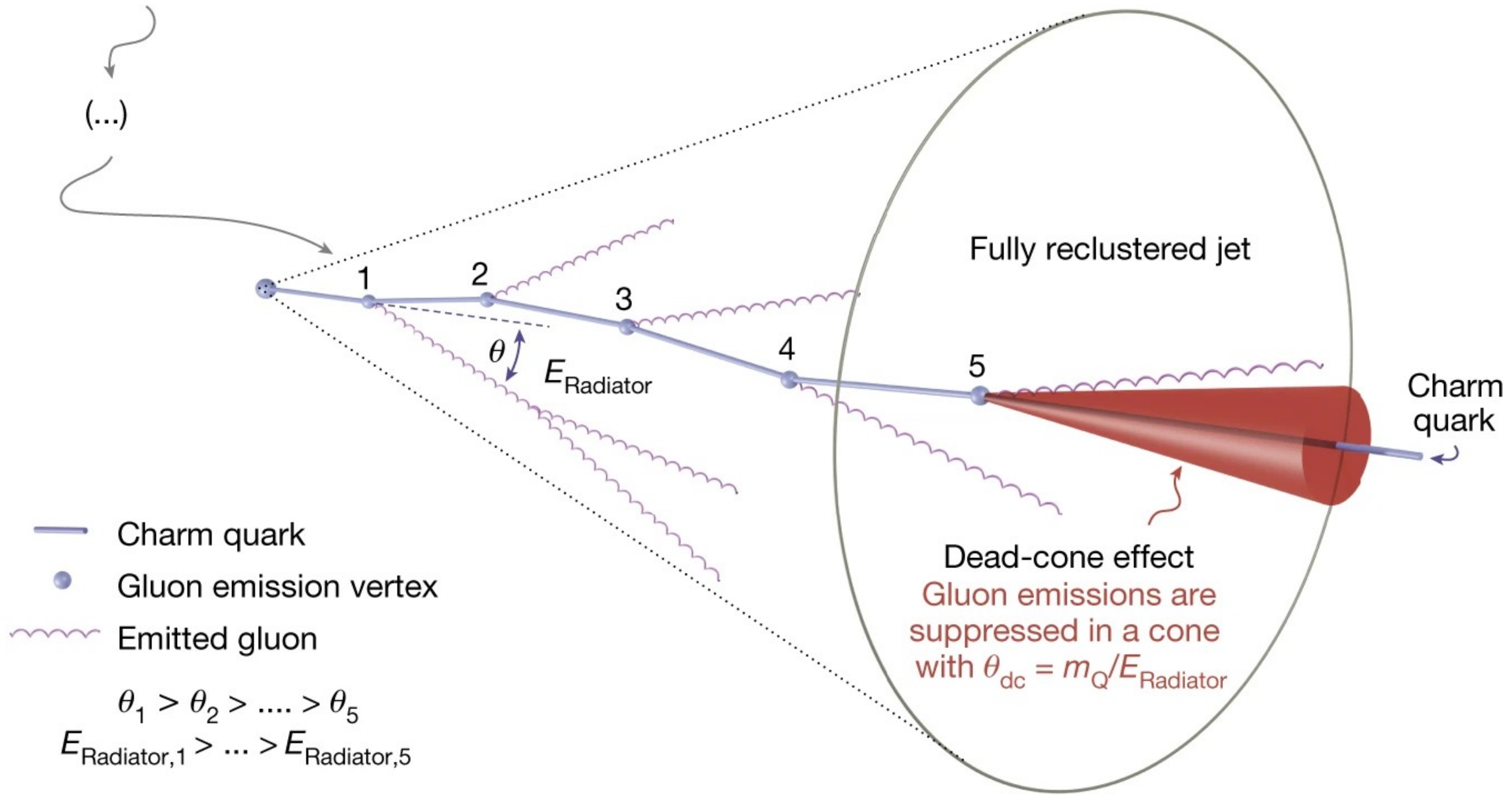
- $1.5 < 2\pi D_s(T) < 4.5$, $\tau_{charm} = (m_{charm} / T)\, D_s(T) = 3–9$ fm/c $< \tau_{medium} \approx 10$ fm/c
- Indicate charm may thermalize in the medium

Charm quark hadronization



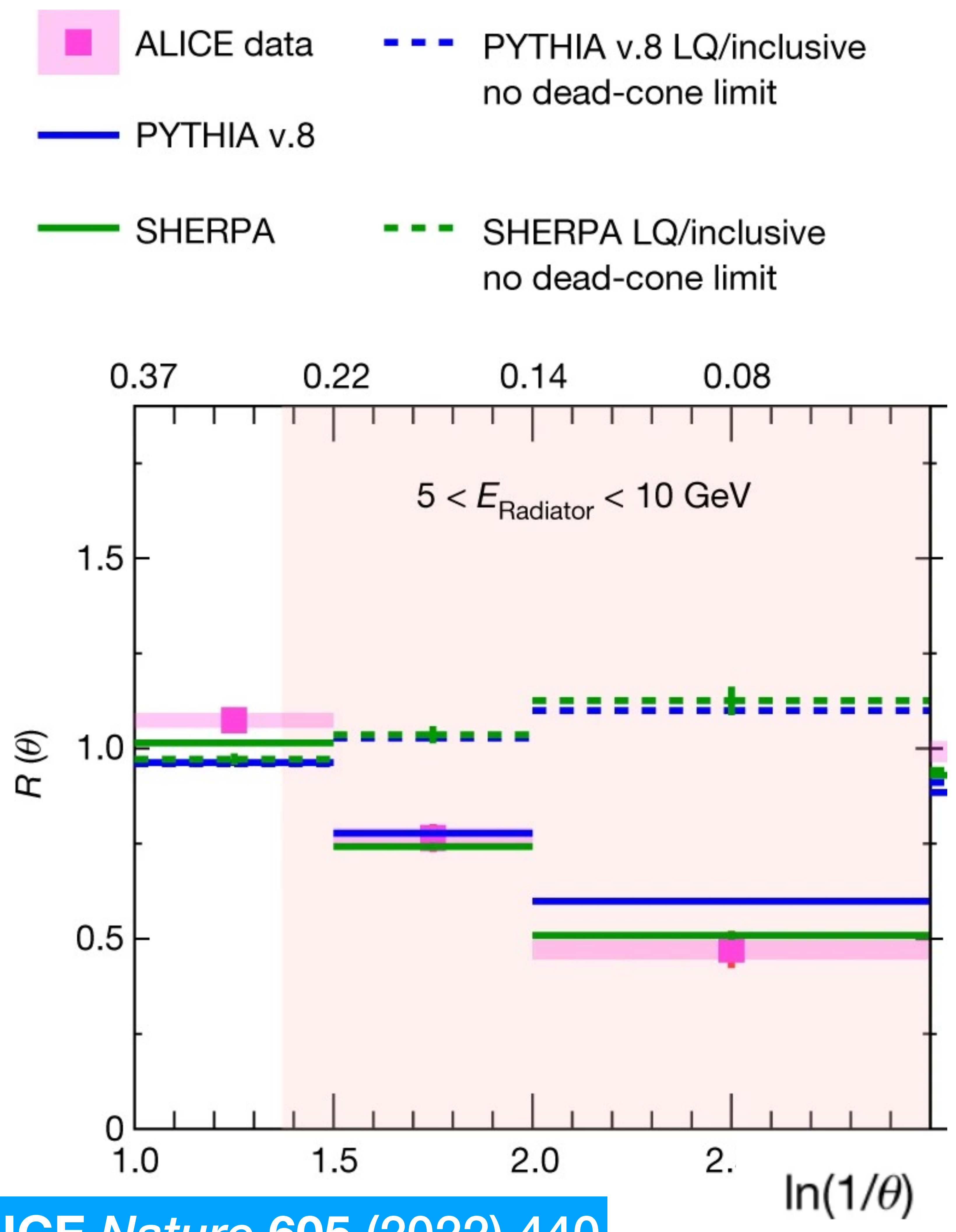
- Hints of enhanced D_s^+/D^0 ratio at intermediate p_T in Pb–Pb w.r.t. pp — support charm hadronization via recombination
- Enhanced Λ_c/D^0 ratio in Pb–Pb w.r.t. pp — suggest interplay between recombination and radial flow

Dead-cone of charm radiation



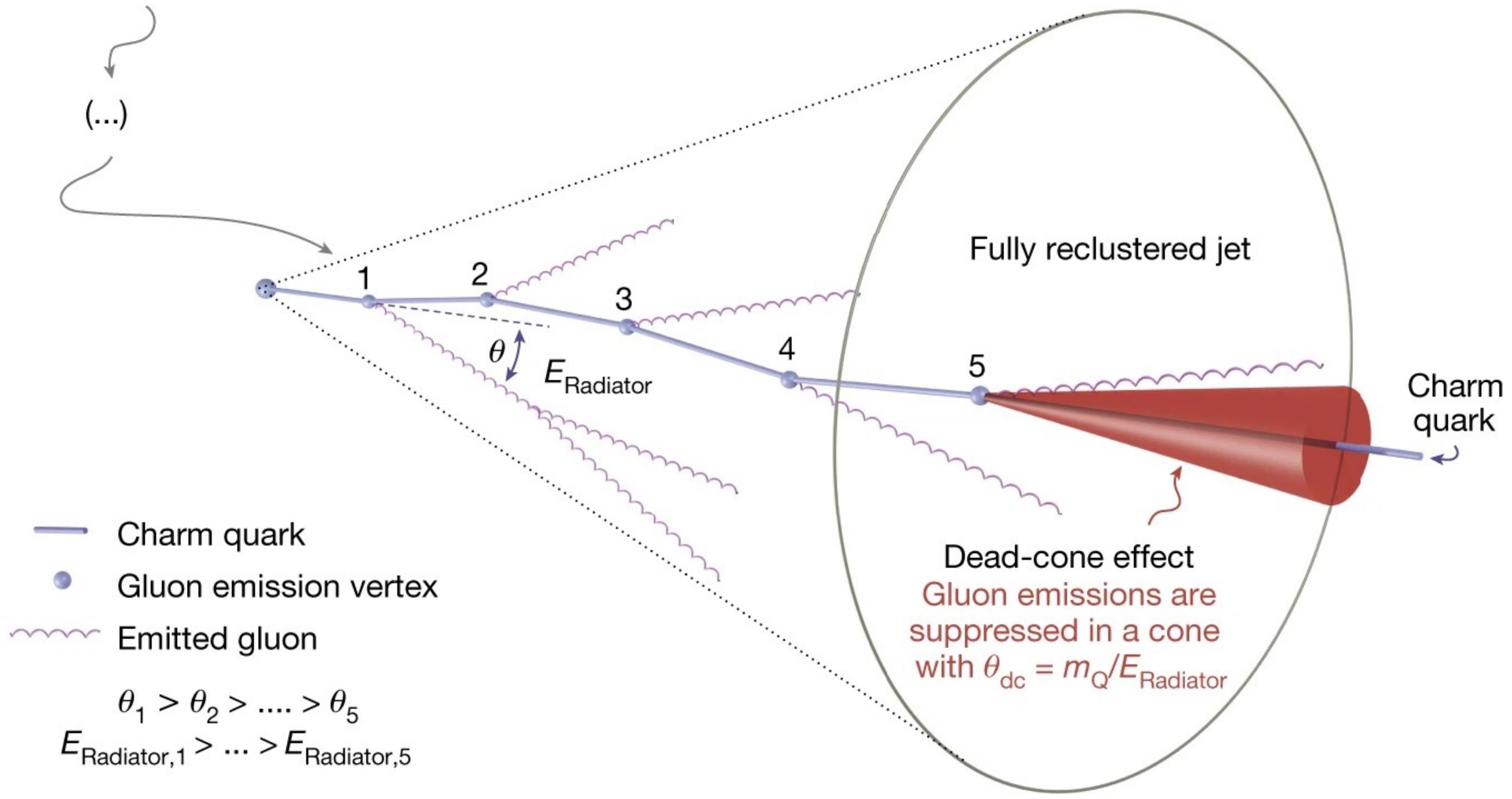
One of fundamental properties of QCD: suppression of gluon emissions within cone $\theta < m_Q / E$ — dead-cone effect

- Direct observation for charm quarks in pp — QCD vacuum



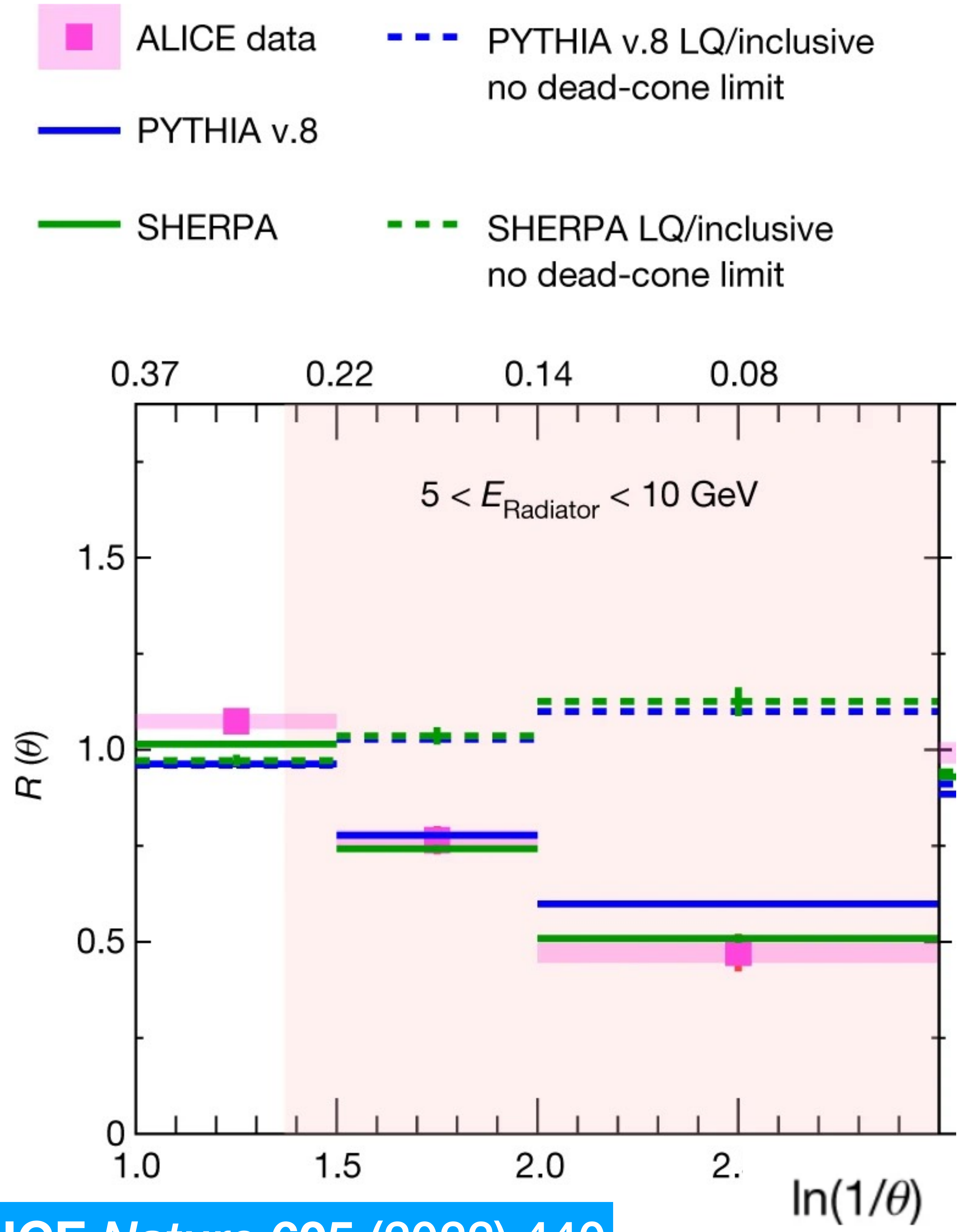
ALICE *Nature* 605 (2022) 440

Dead-cone of charm radiation



One of fundamental properties of QCD: suppression of gluon emissions within cone $\theta < m_Q / E$ — dead-cone effect

- Direct observation for charm quarks in pp — QCD vacuum



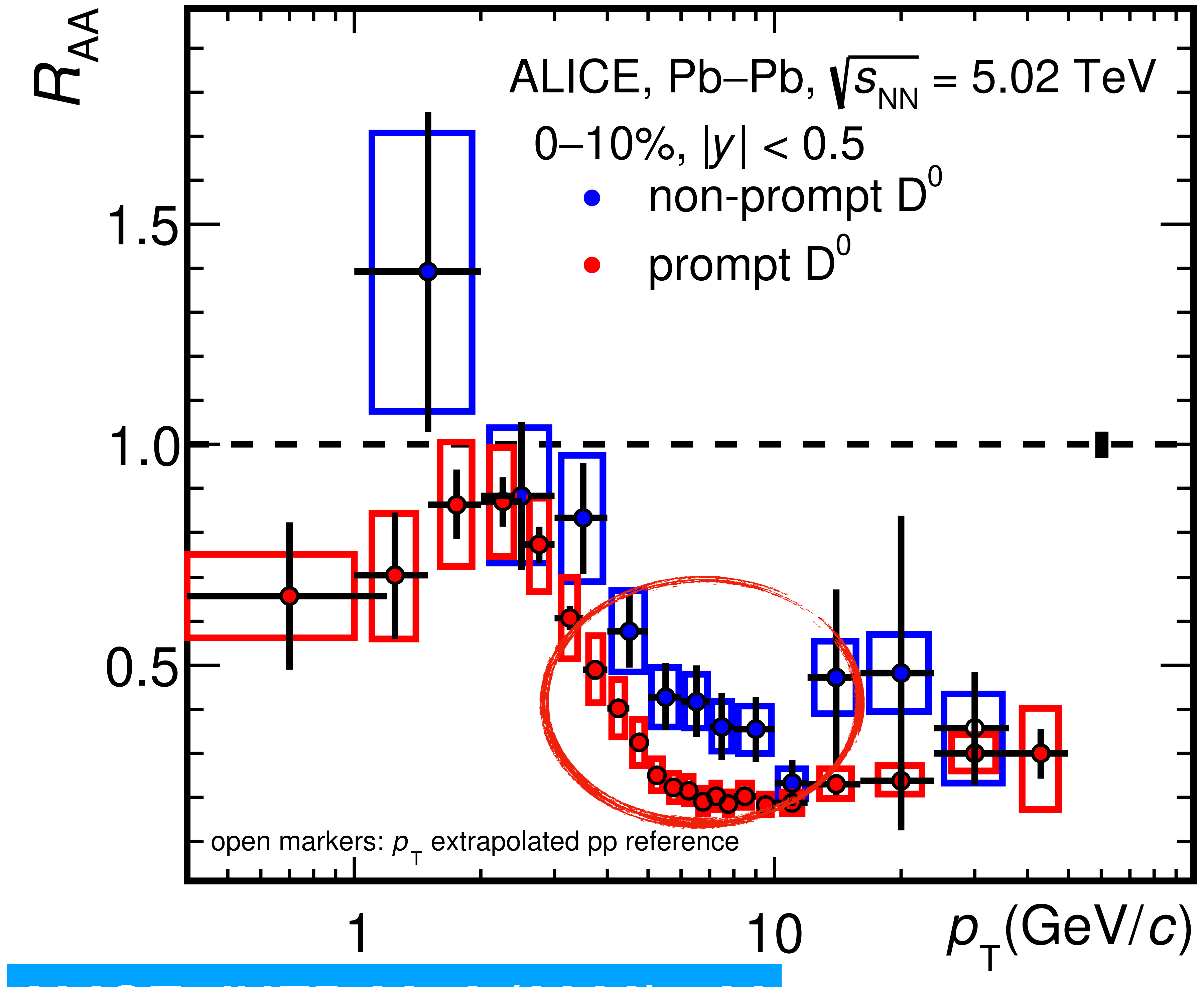
ALICE *Nature* 605 (2022) 440

- Whether is it still validated in QCD medium?

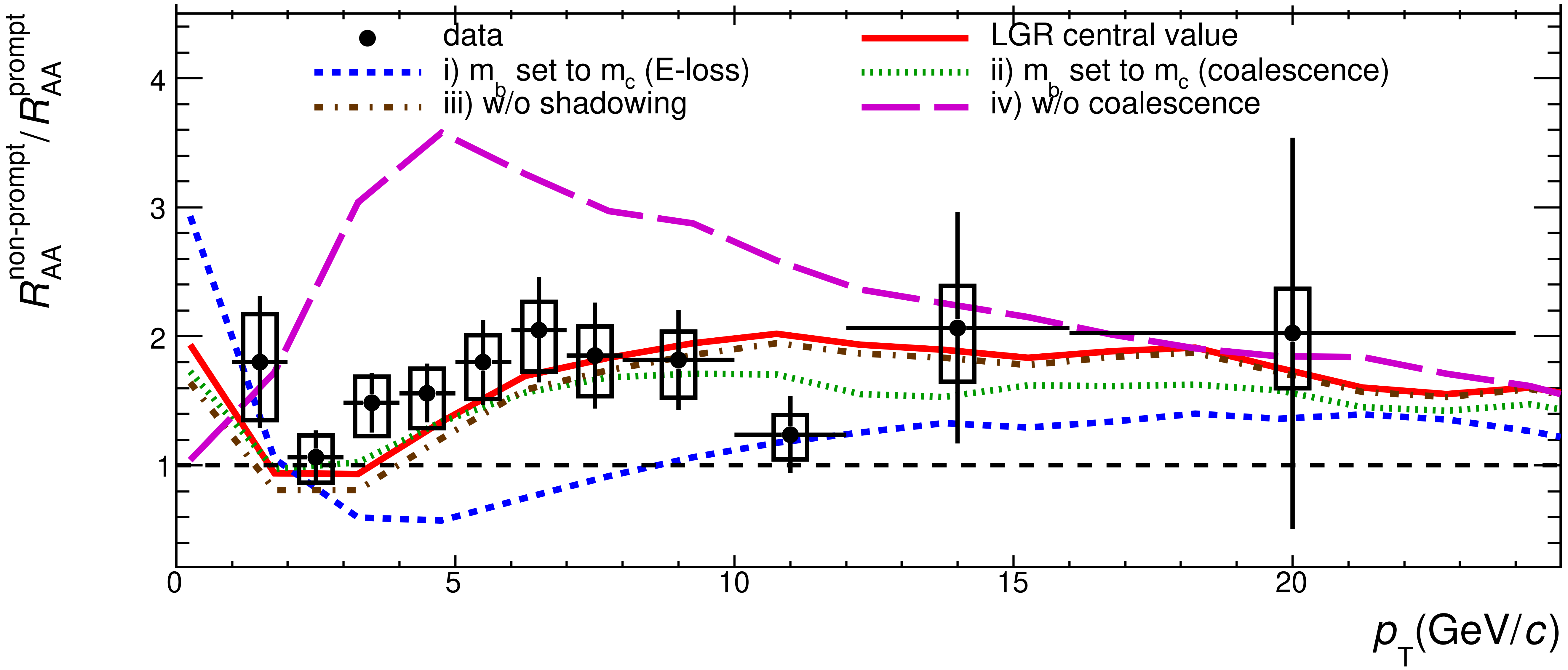
➡ Mass dependent heavy quark radiative energy loss

$\Delta E_{beauty} < \Delta E_{charm} \Rightarrow R_{AA}(\text{beauty}) > R_{AA}(\text{charm})$

Beauty quark energy loss



ALICE *JHEP* 2212 (2022) 126

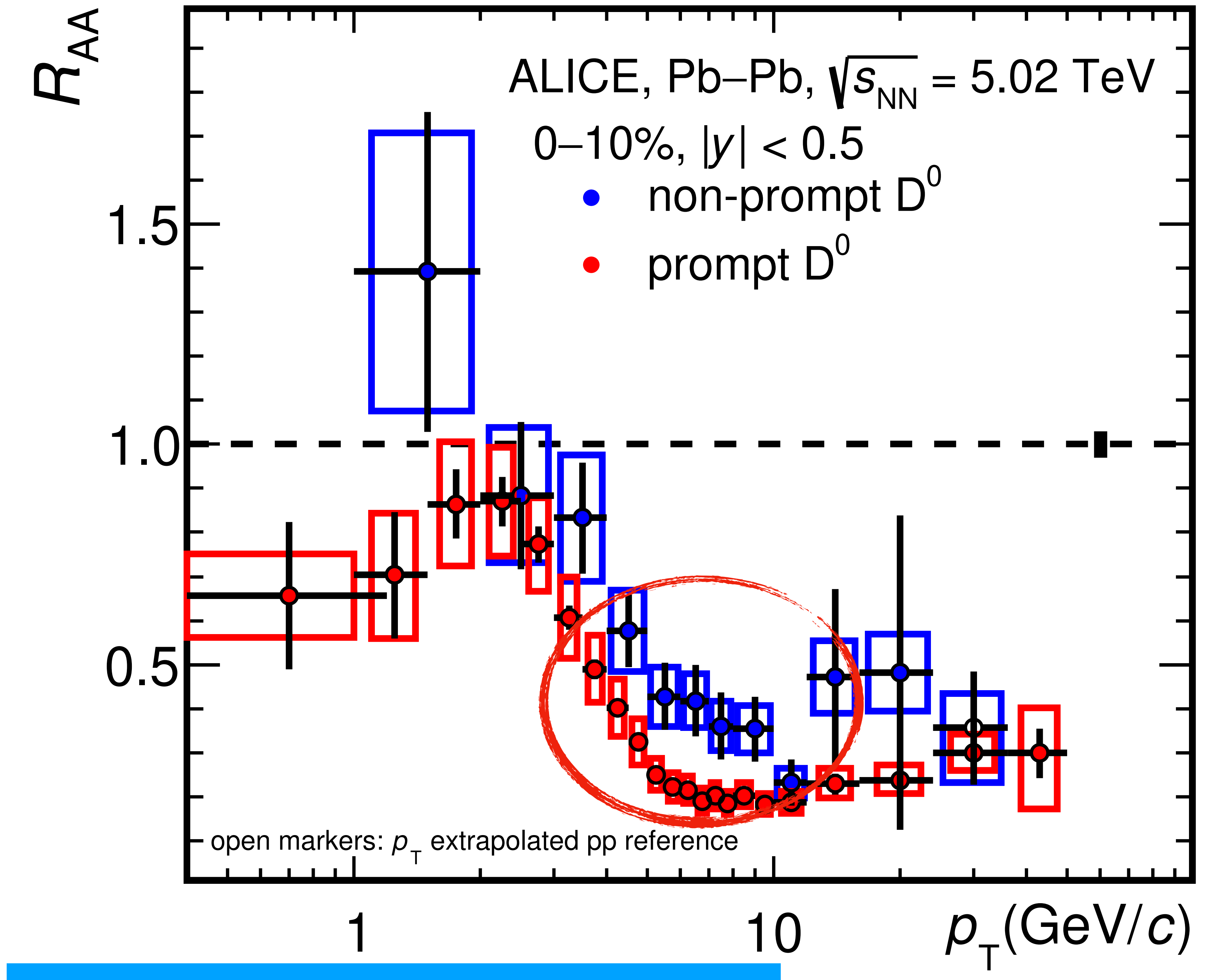


- Mass effect is important to describe data
- However, coalescence is more critical

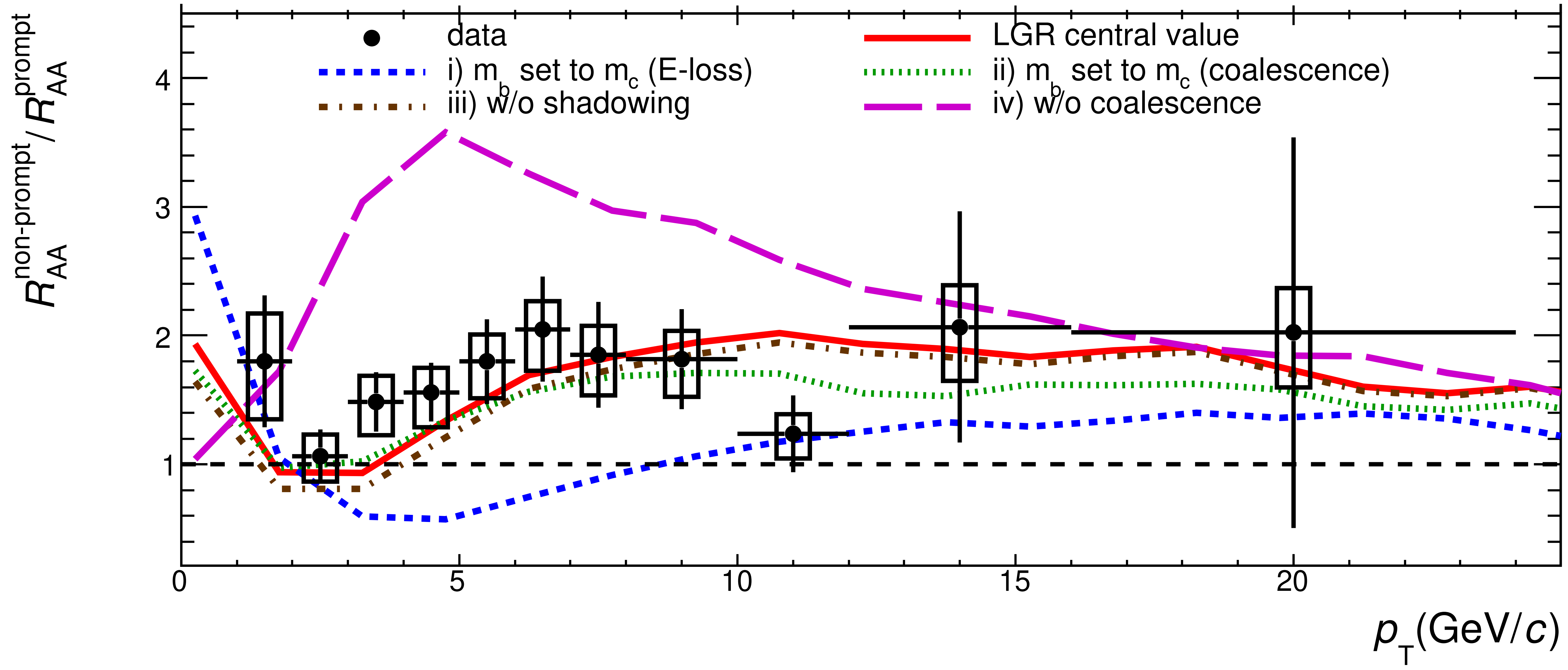
Non-prompt D mesons are less suppressed than prompt D mesons

$R_{AA}(\text{beauty}) > R_{AA}(\text{charm}) \Rightarrow \Delta E_{\text{beauty}} < \Delta E_{\text{charm}}$ (?)

Beauty quark energy loss



ALICE *JHEP* 2212 (2022) 126



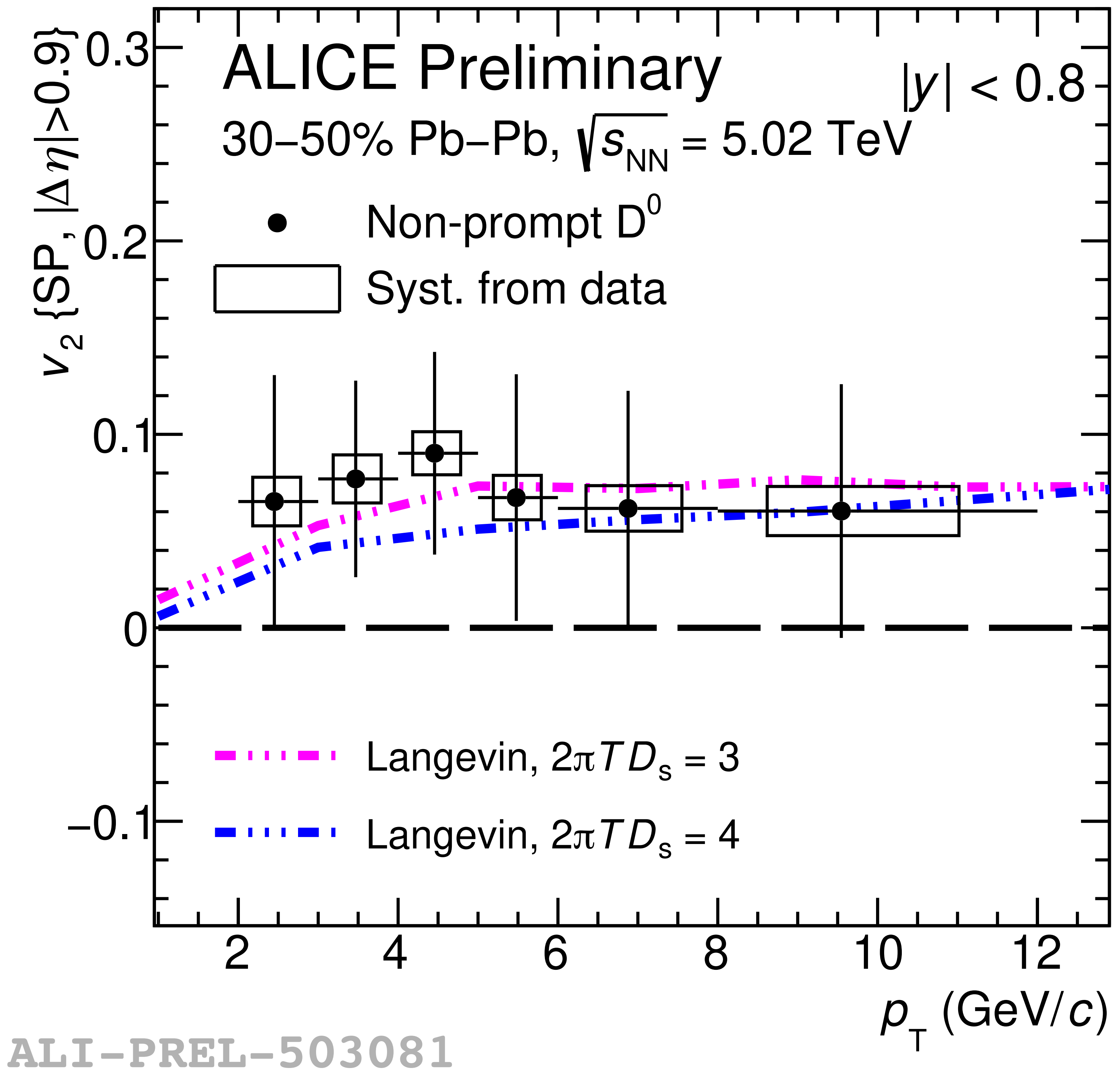
- Mass effect is important to describe data
- However, coalescence is more critical

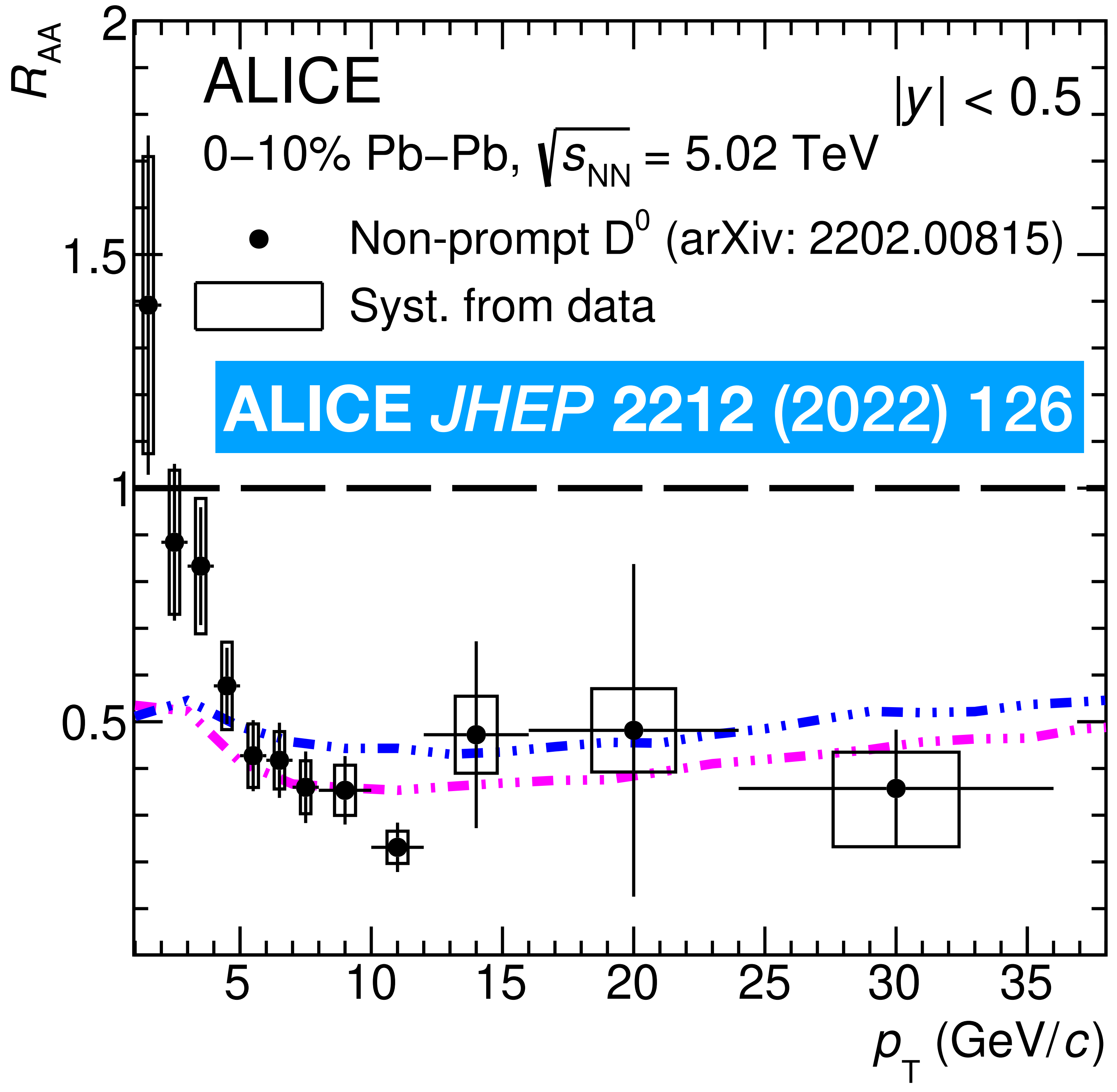
Non-prompt D mesons are less suppressed than prompt D mesons

R_{AA}(beauty) > R_{AA} (charm) ⇒ $\Delta E_{beauty} < \Delta E_{charm}$ (?)

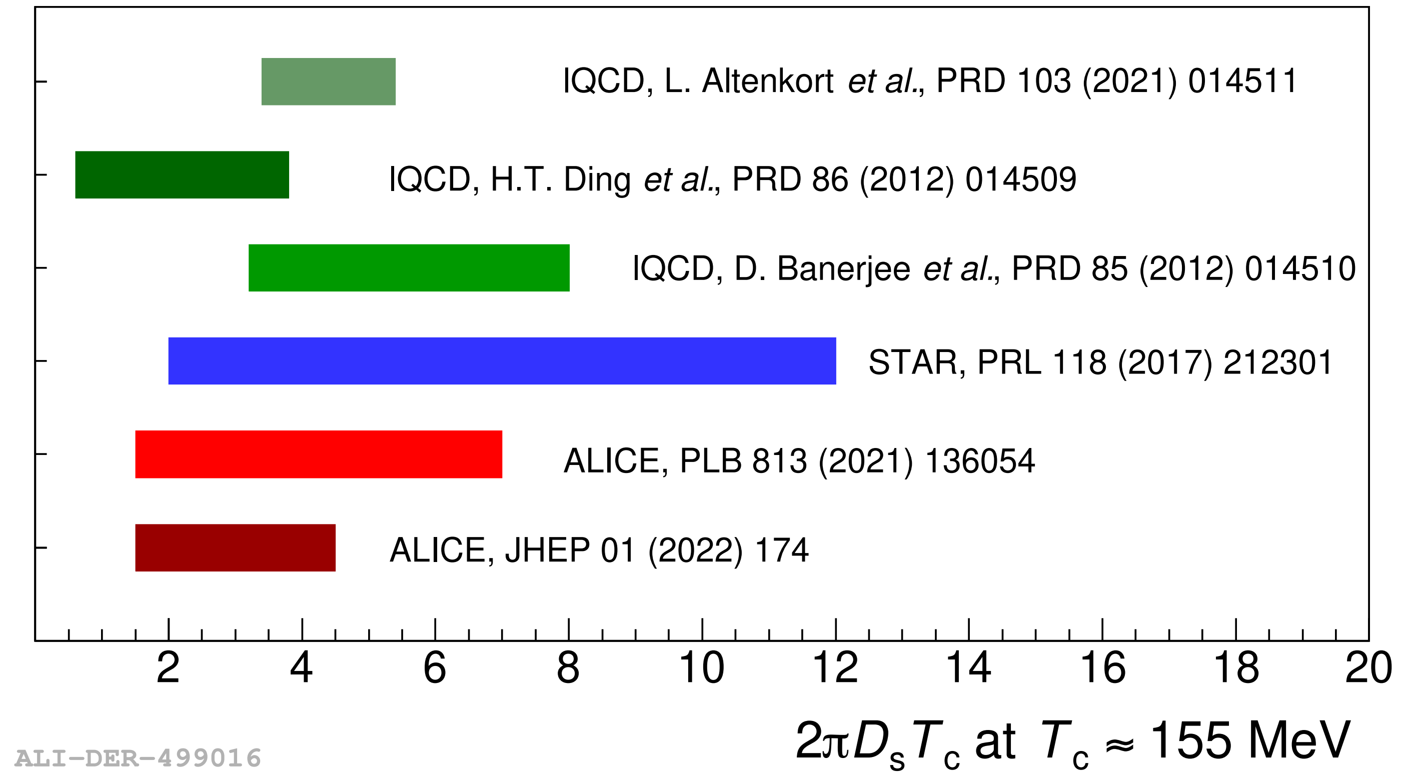
Open question: Can the dead-cone effect be explored directly in the QCD medium?

Beauty quark transport





- Beauty particle R_{AA} and v_2 measured via non-prompt D^0 by ALICE
- Conclusion is similar to the measurements of B mesons, non-prompt J/Ψ and B meson semileptonic decays by ATLAS and CMS



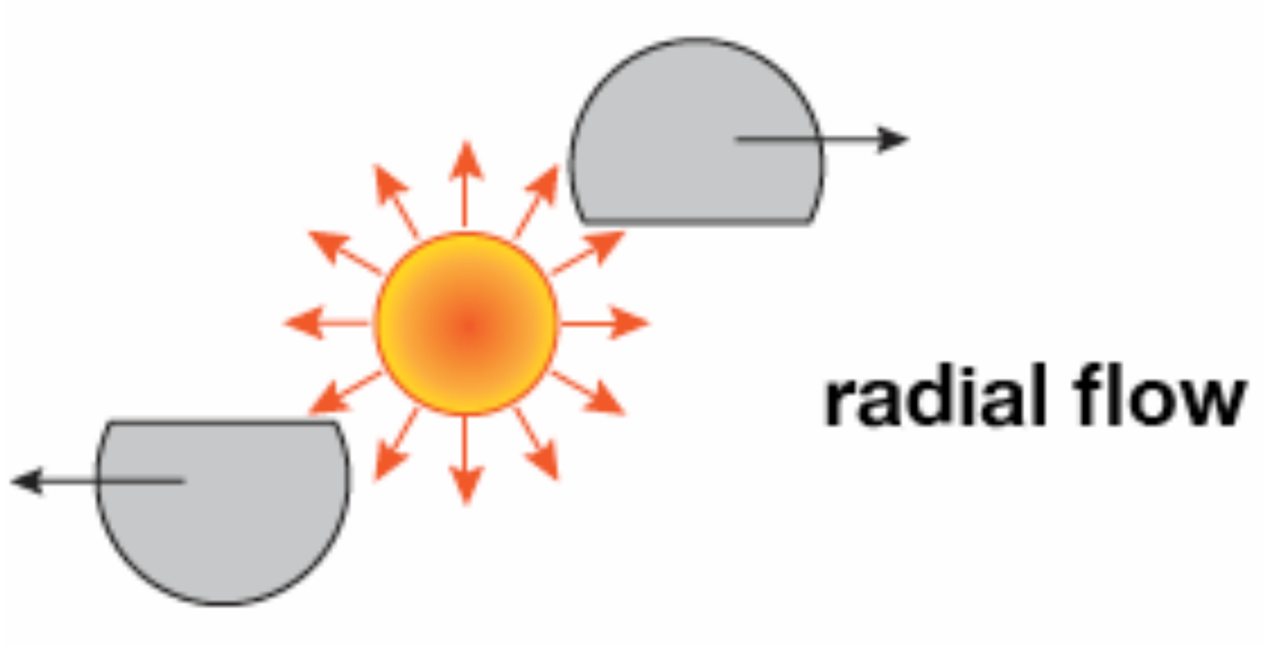
- D_s obtained in beauty sector is similar to that in charm sector ($2\pi D_s \approx 1.5$–4.5 for charm)
- Indicate $\tau_{beauty} \propto m_{beauty} D_s \gtrsim \tau_{medium}$ ($m_{beauty} \approx 3\, m_{charm}$)

➡ What is thermalization DOF of beauty in the QGP medium?

Radial flow

Collective expansion

➡ "Zero order" — radial flow

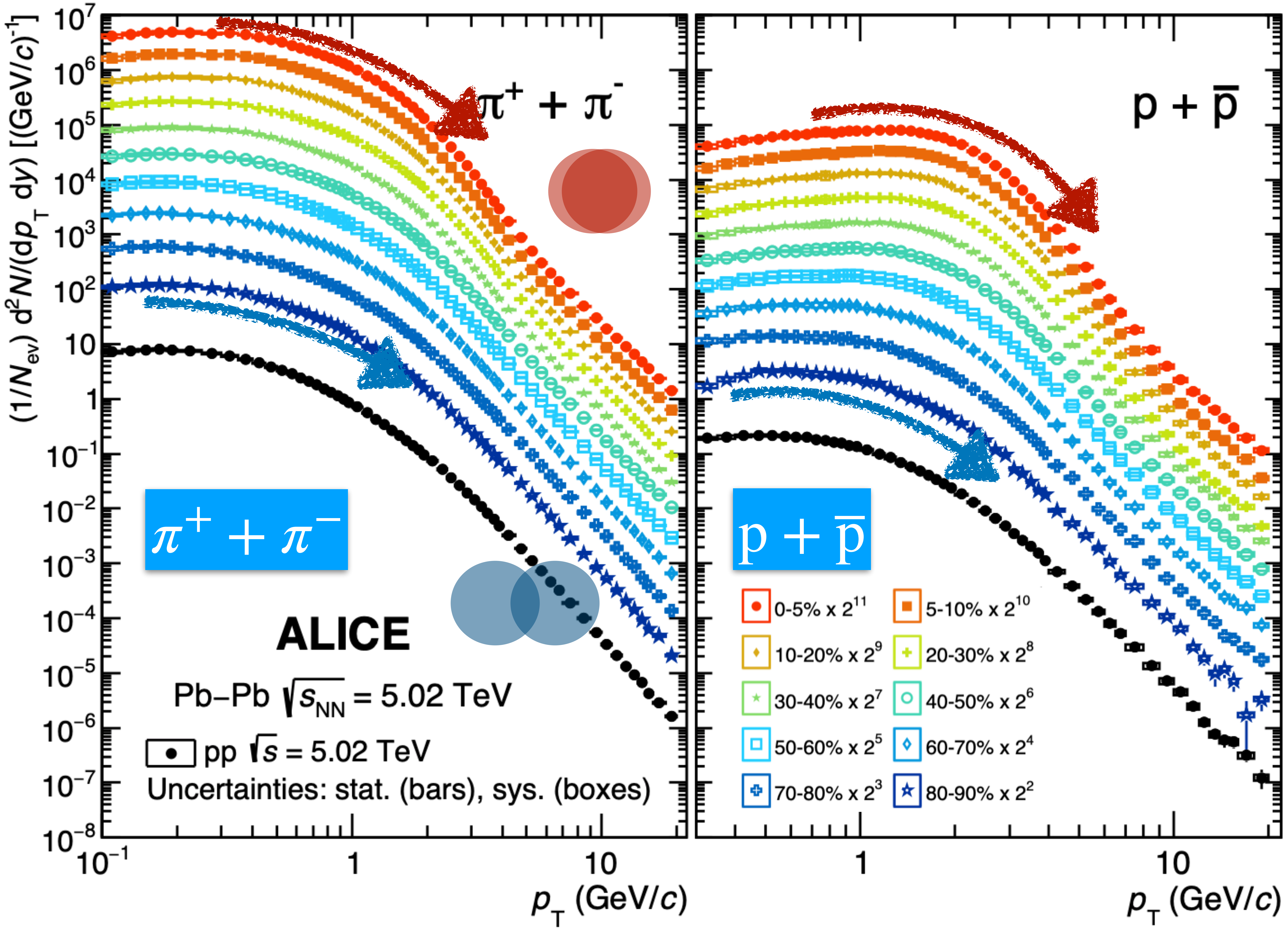


➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

p_0: initial momentum
β: flow velocity
m: particle mass

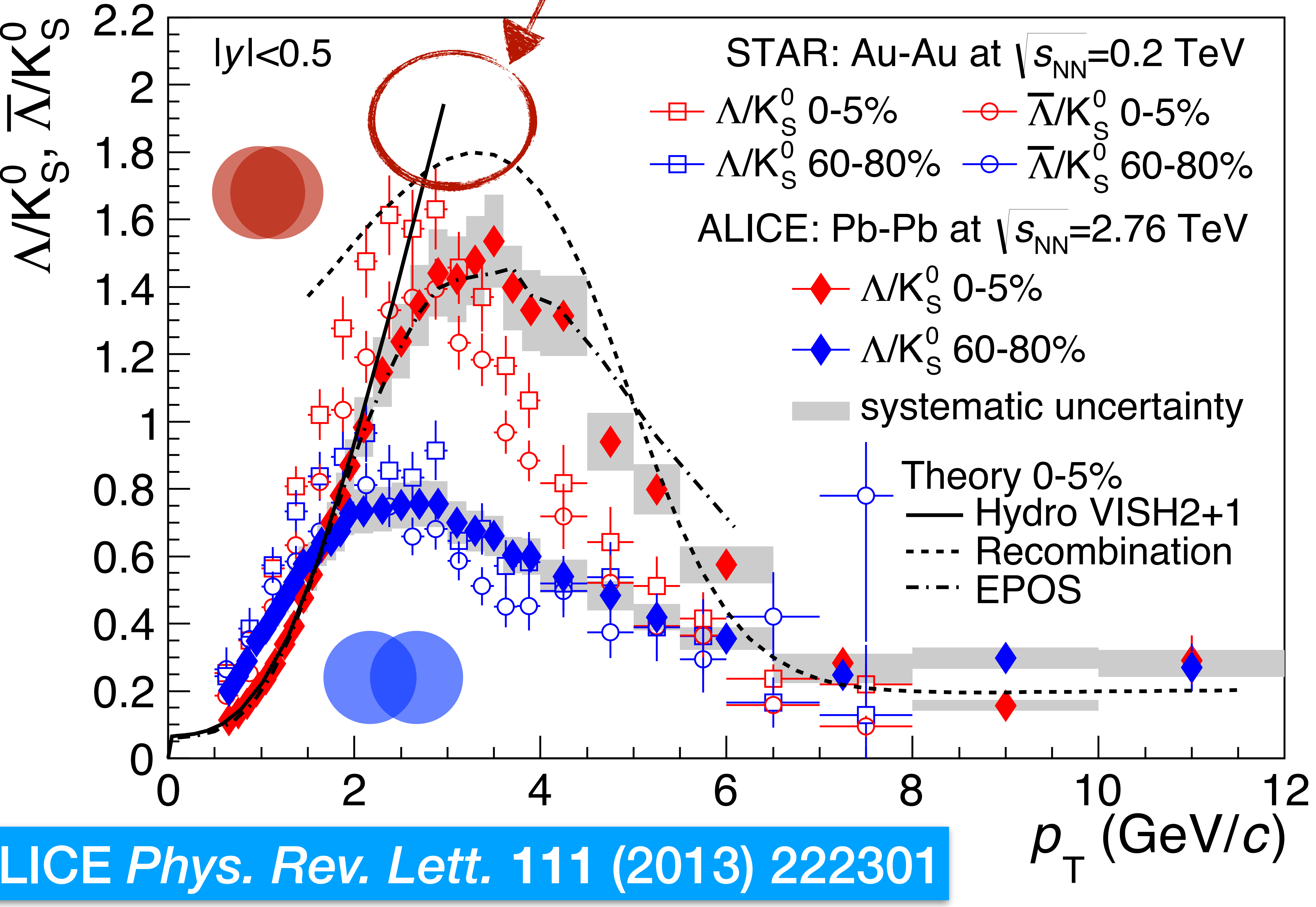
➡ More pronounced in central collisions



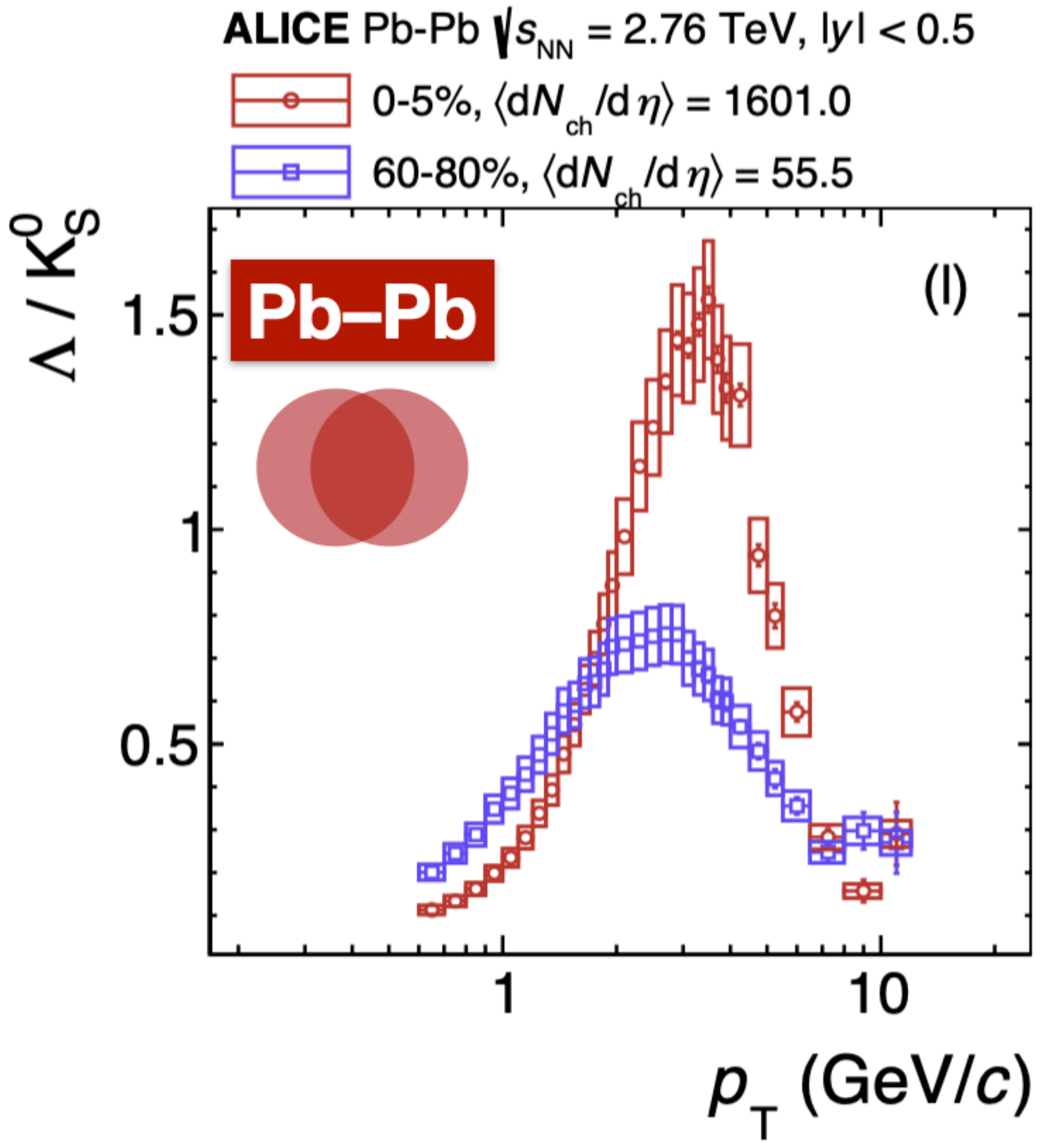
ALICE *Phys. Rev.* C101 (2020) 044907

Baryon-to-meson enhancement

It leads large deviation from data if consider the soft component only

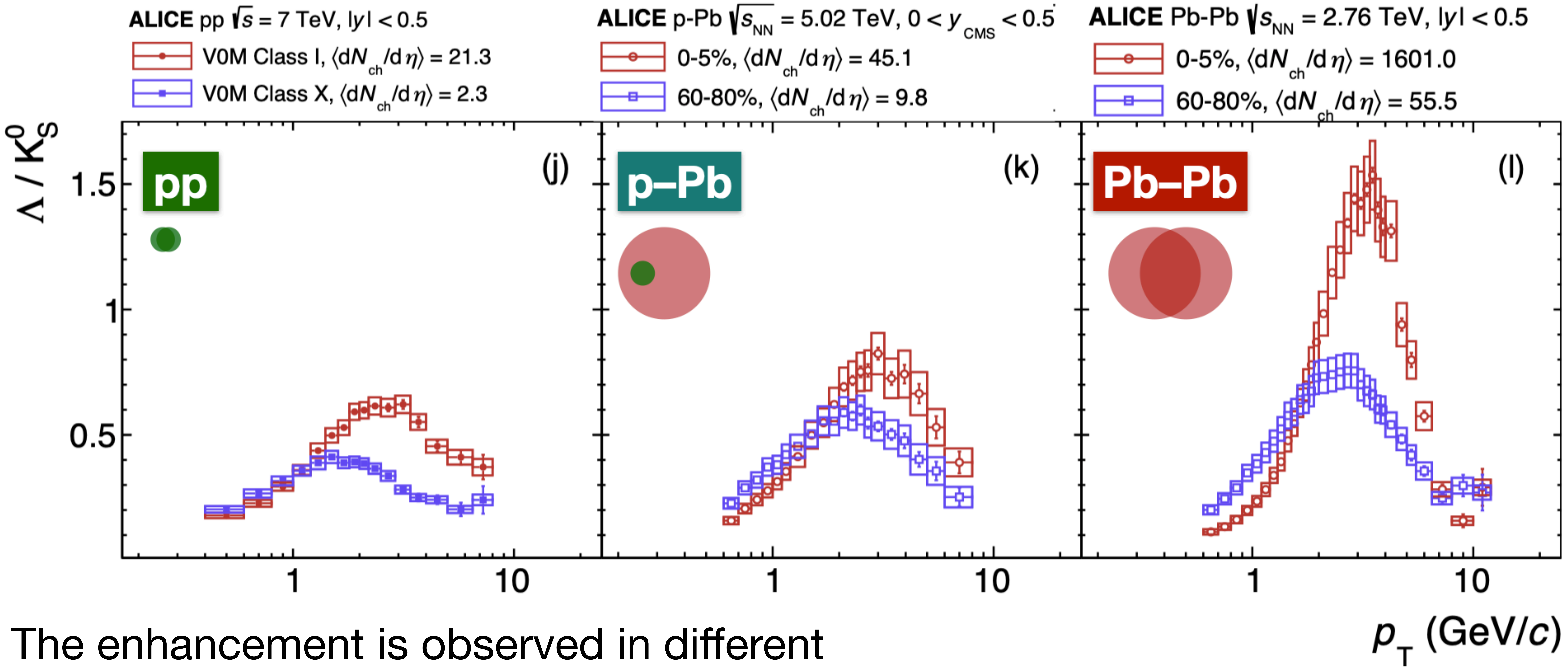


ALICE *Phys. Rev. Lett.* 111 (2013) 222301



ALICE *Phys. Rev.* C99 (2019) 024906

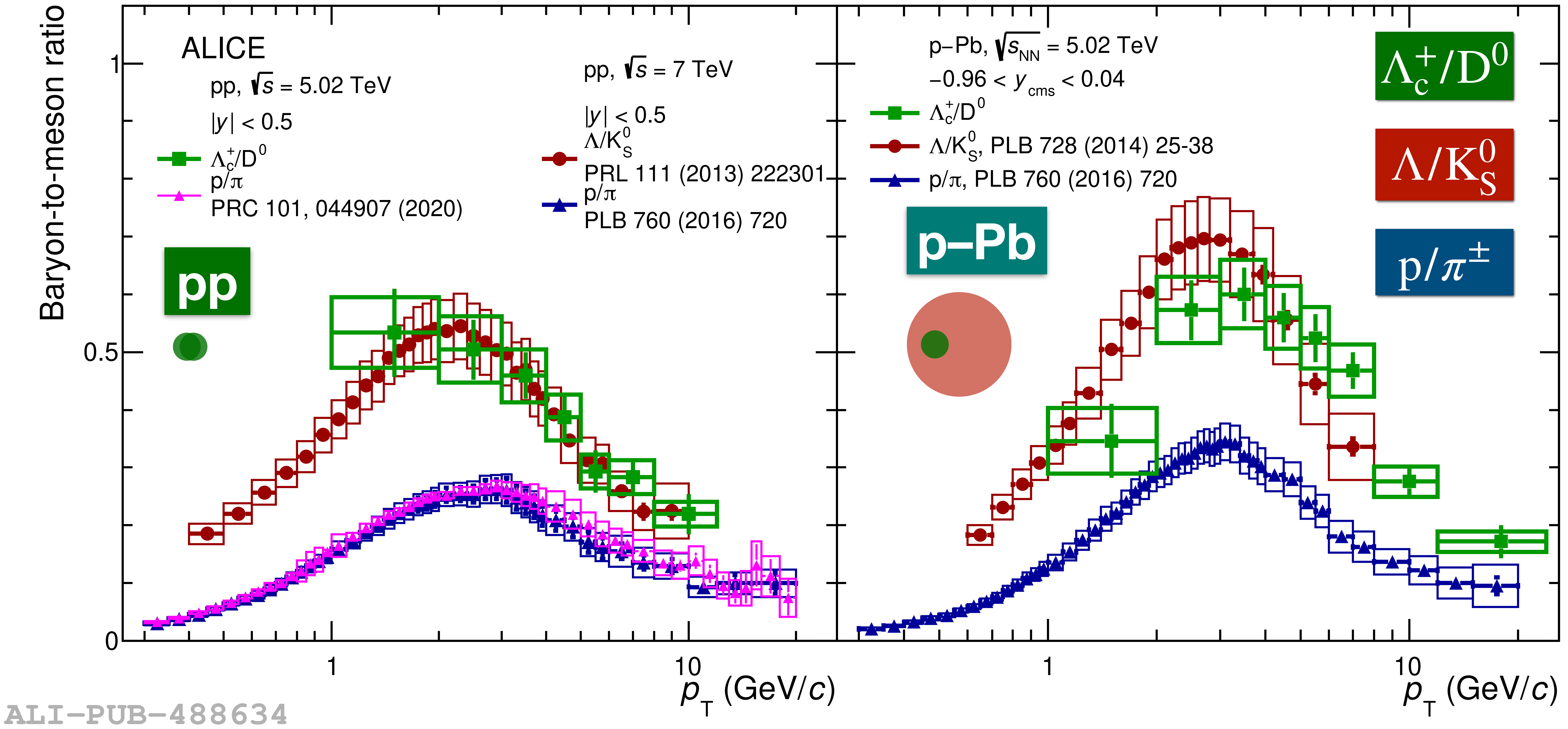
Baryon-to-meson enhancement



The enhancement is observed in different collision systems (Pb–Pb, p–Pb and pp) at high multiplicities

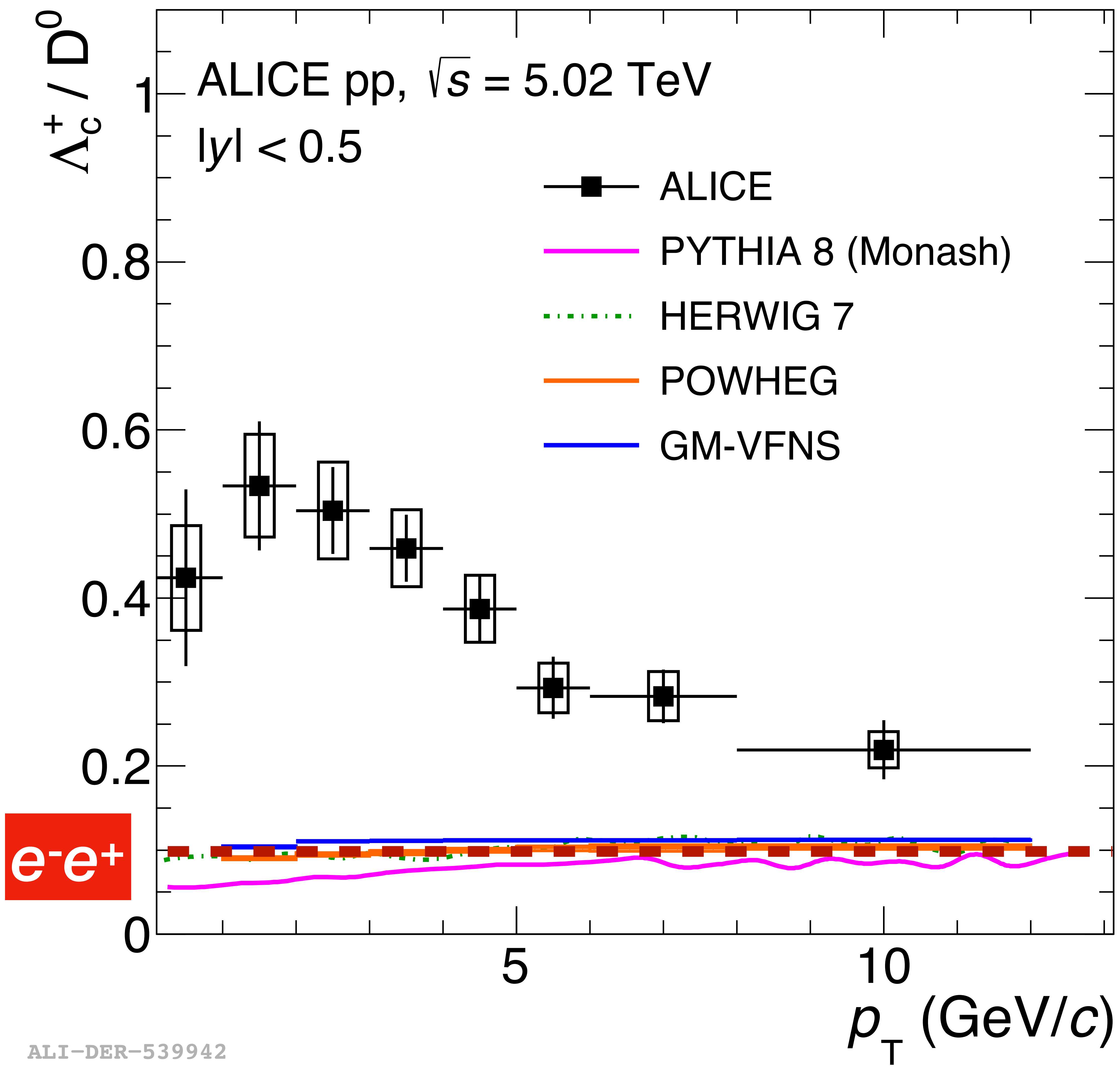
ALICE *Phys. Rev.* C99 (2019) 024906

Baryon-to-meson enhancement



Similar behavior observed also in **charm sector** in small system (pp and p–Pb) collisions

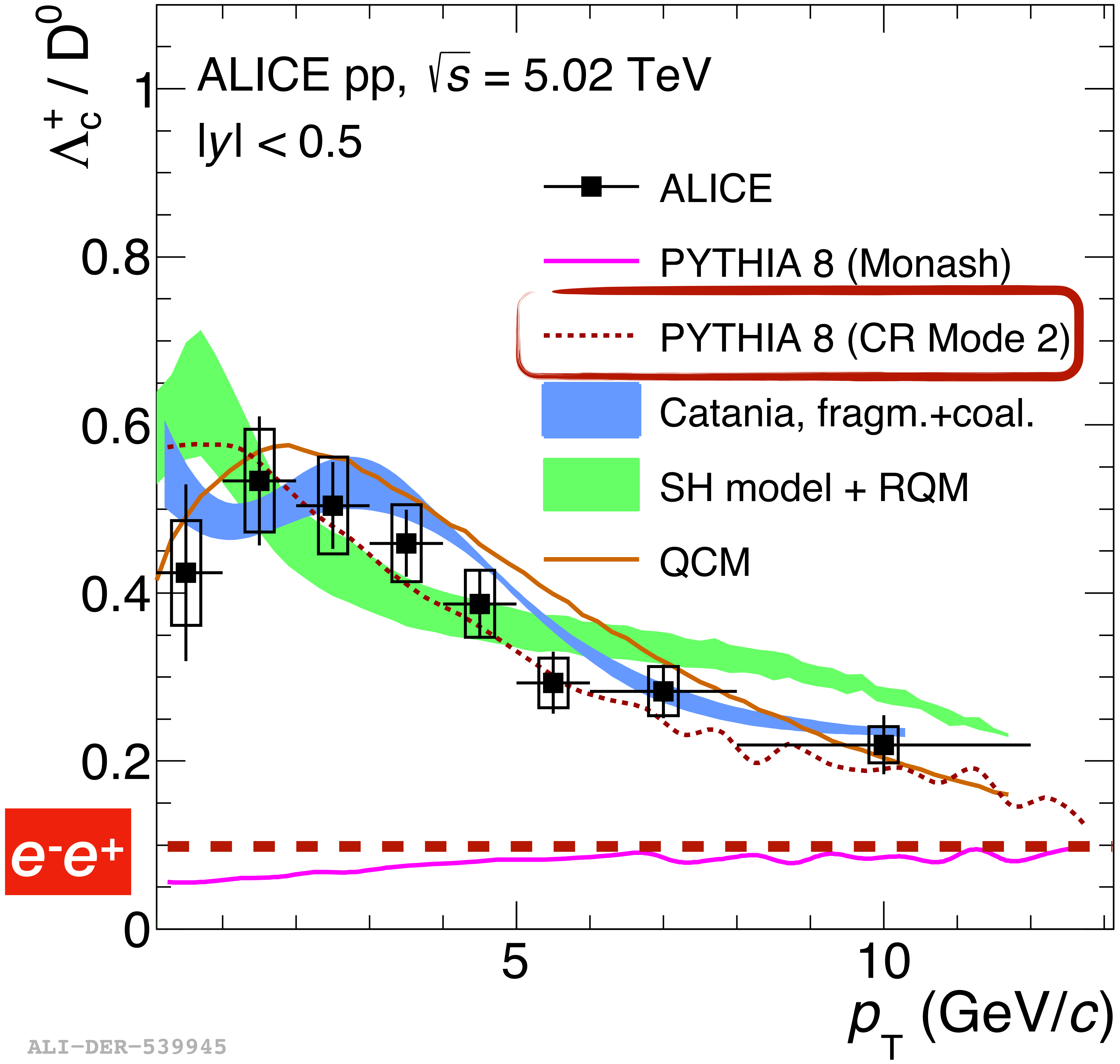
Λ_c^+/D^0 ratio in pp collisions



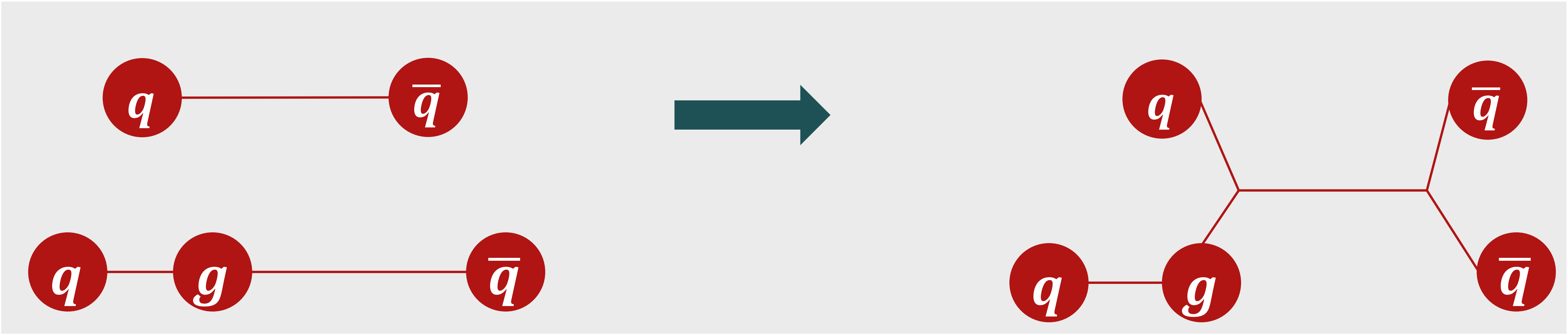
ALICE *Phys. Rev.* C107 (2023) 064901

- Λ_c/D^0 ratios significantly higher than e^-e^+, p_T dependence observed

Λ_c^+/D^0 ratio in pp collisions

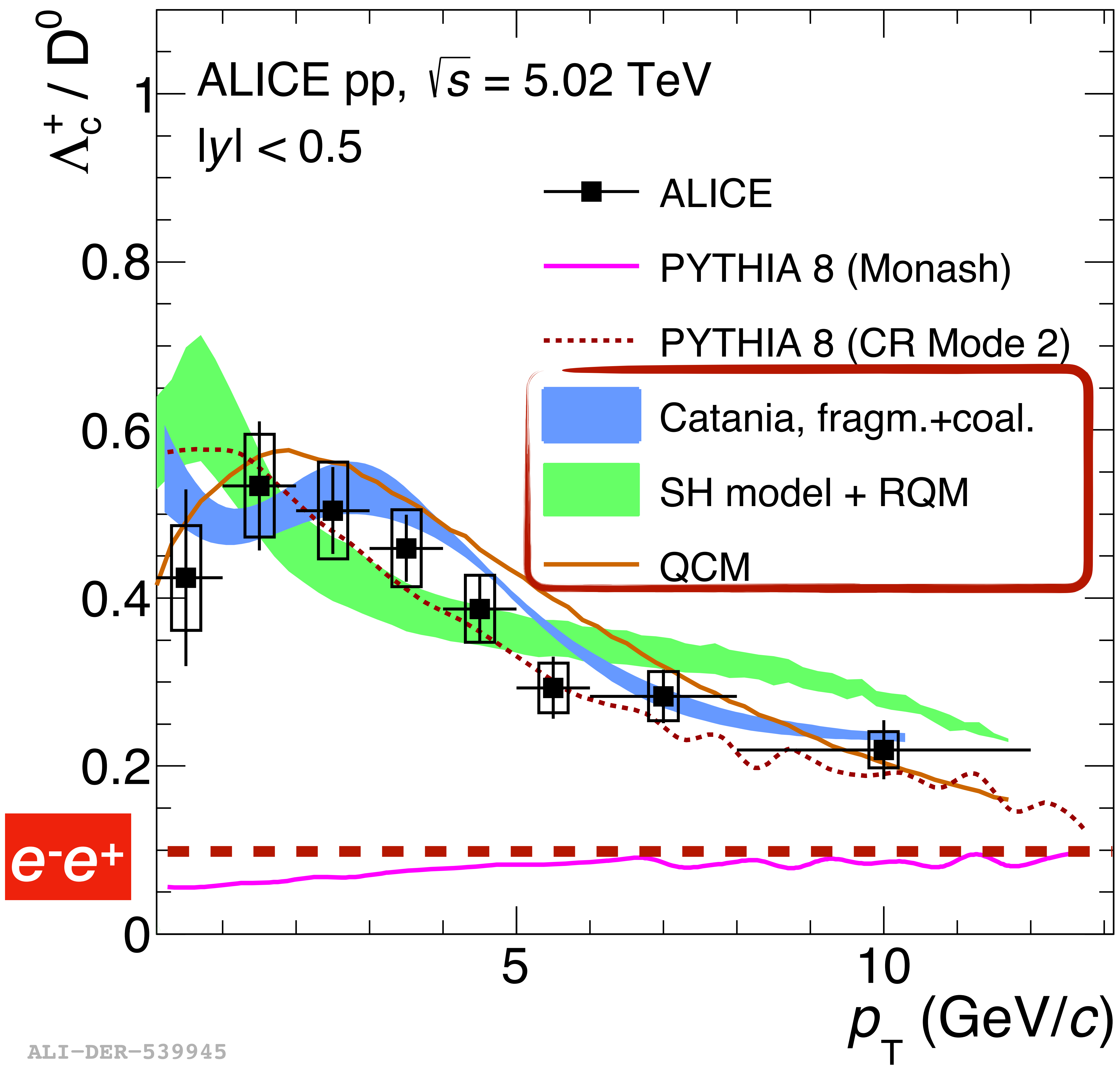


- Λ_c/D^0 ratios significantly higher than e^-e^+, p_T dependence observed
- PYTHIA8 color-reconnection Allowing "junction" topologies in multiparton interactions, which enhance the charm baryon production



ALICE *Phys. Rev.* C107 (2023) 064901

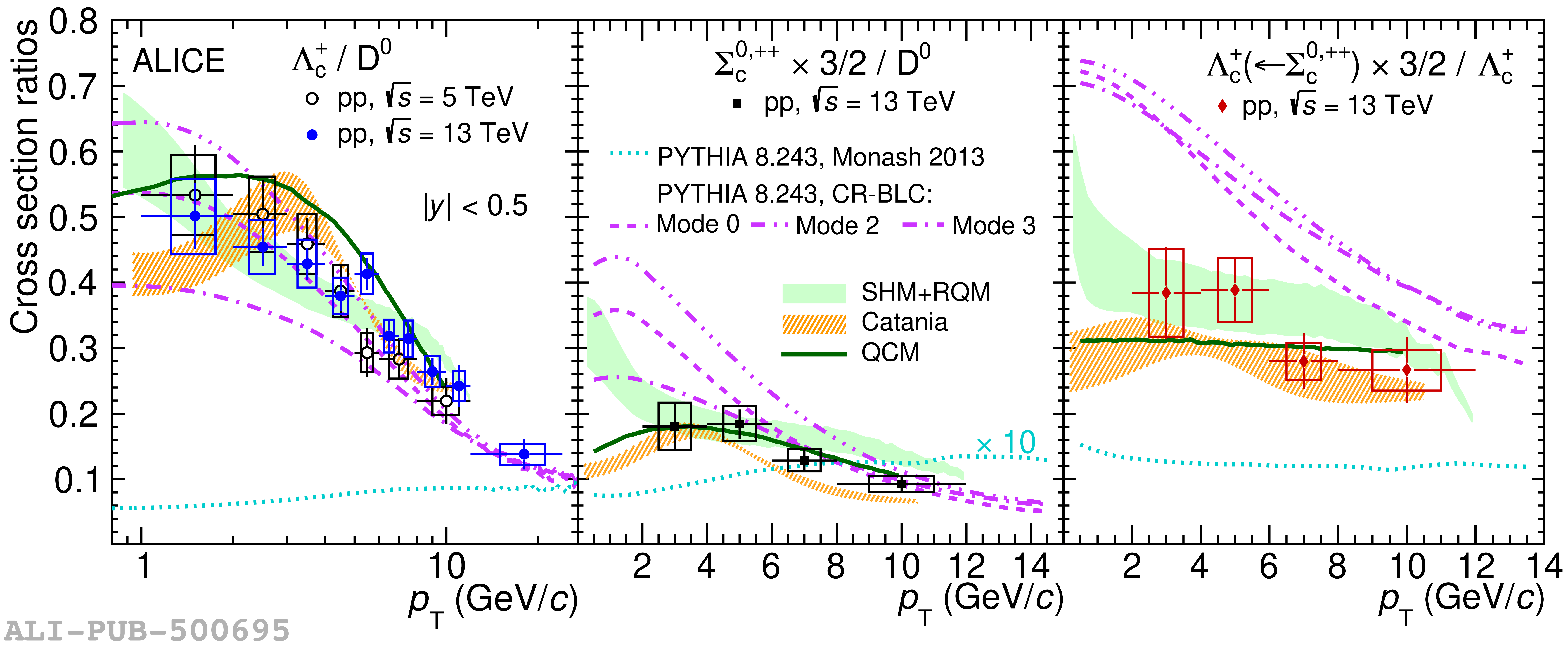
Λ_c^+/D^0 ratio in pp collisions



- Catania Thermalised system of gluons, light quarks and antiquarks (QGP), hadronisation via coalescence and fragmentation
- SH model + RQM Hadronisation driven by statistical weights govern by hadron masses, feed-down from excited baryon states predicted by RQM
- QCM Pure coalescence model, charm is combined with co-moving light antiquark or two quarks

ALICE *Phys. Rev.* C107 (2023) 064901

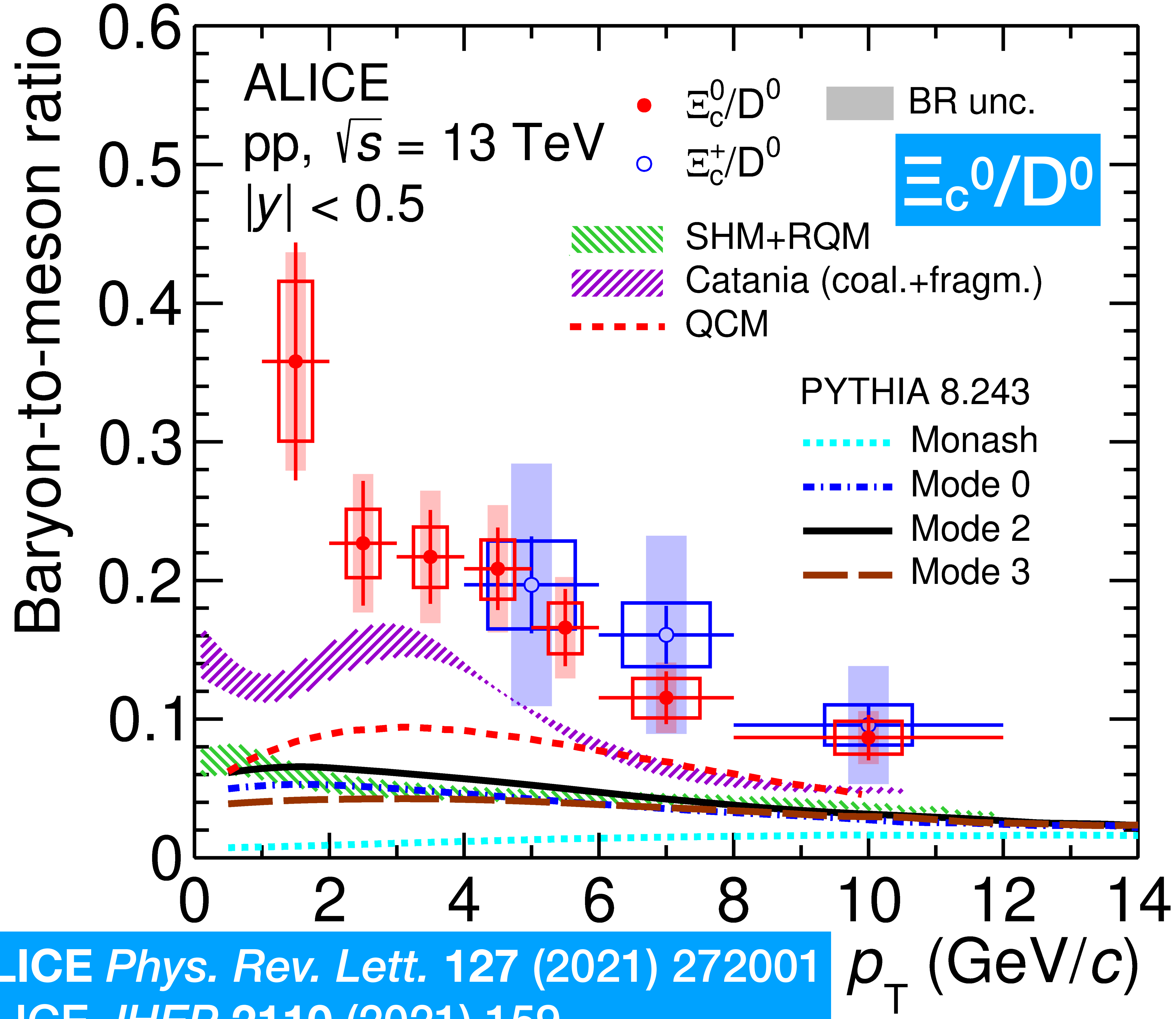
$\Sigma_c^{0,++}$ production in pp collisions



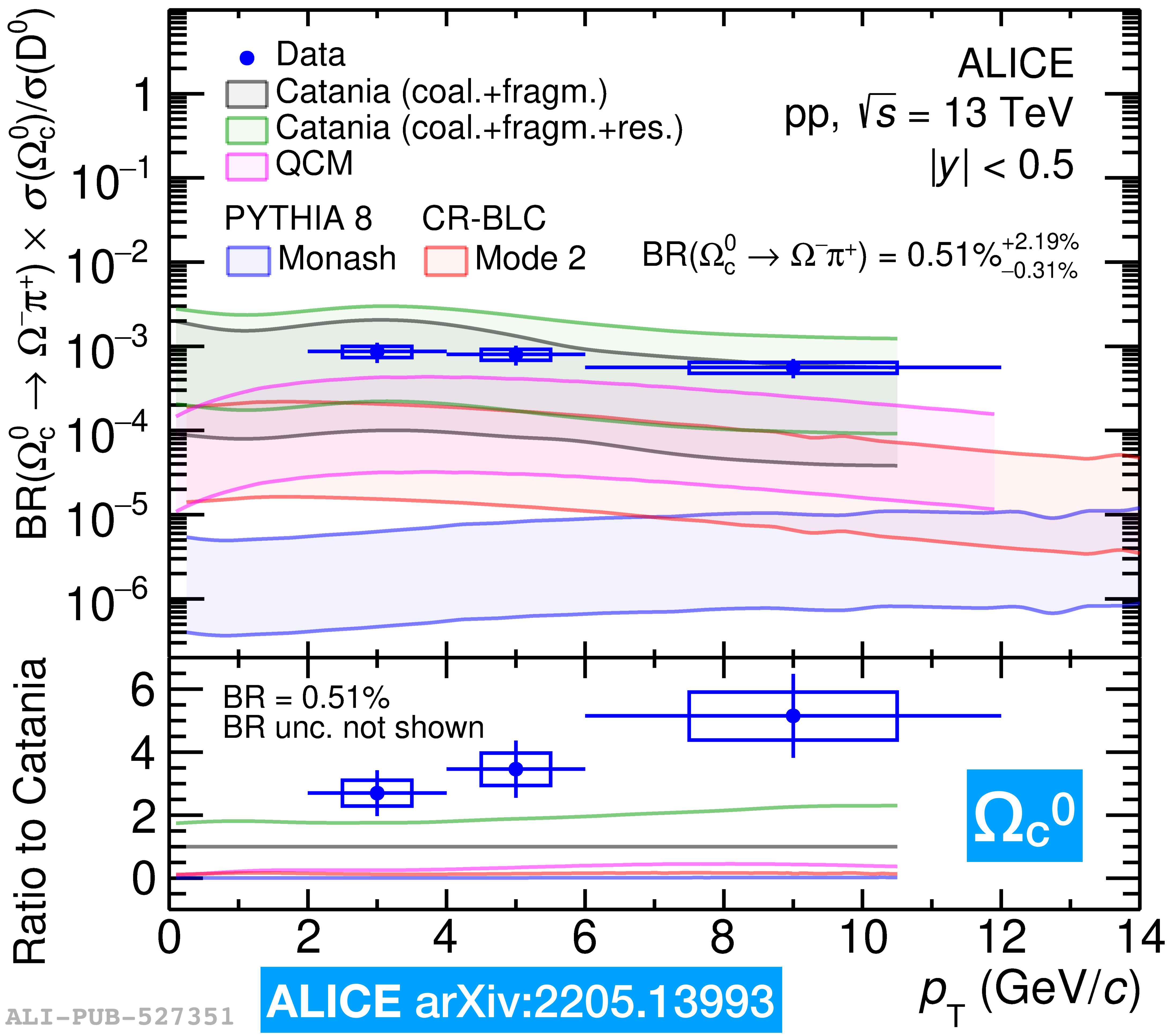
ALICE *Phys. Rev. Lett.* 128 (2022) 012001

- SHM+RQM, Catania, and QCM describe the $\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})/\Lambda_c^+$ ratio while PYTHIA8 with CR-BLC overestimates the data

Strange charmed baryon in pp



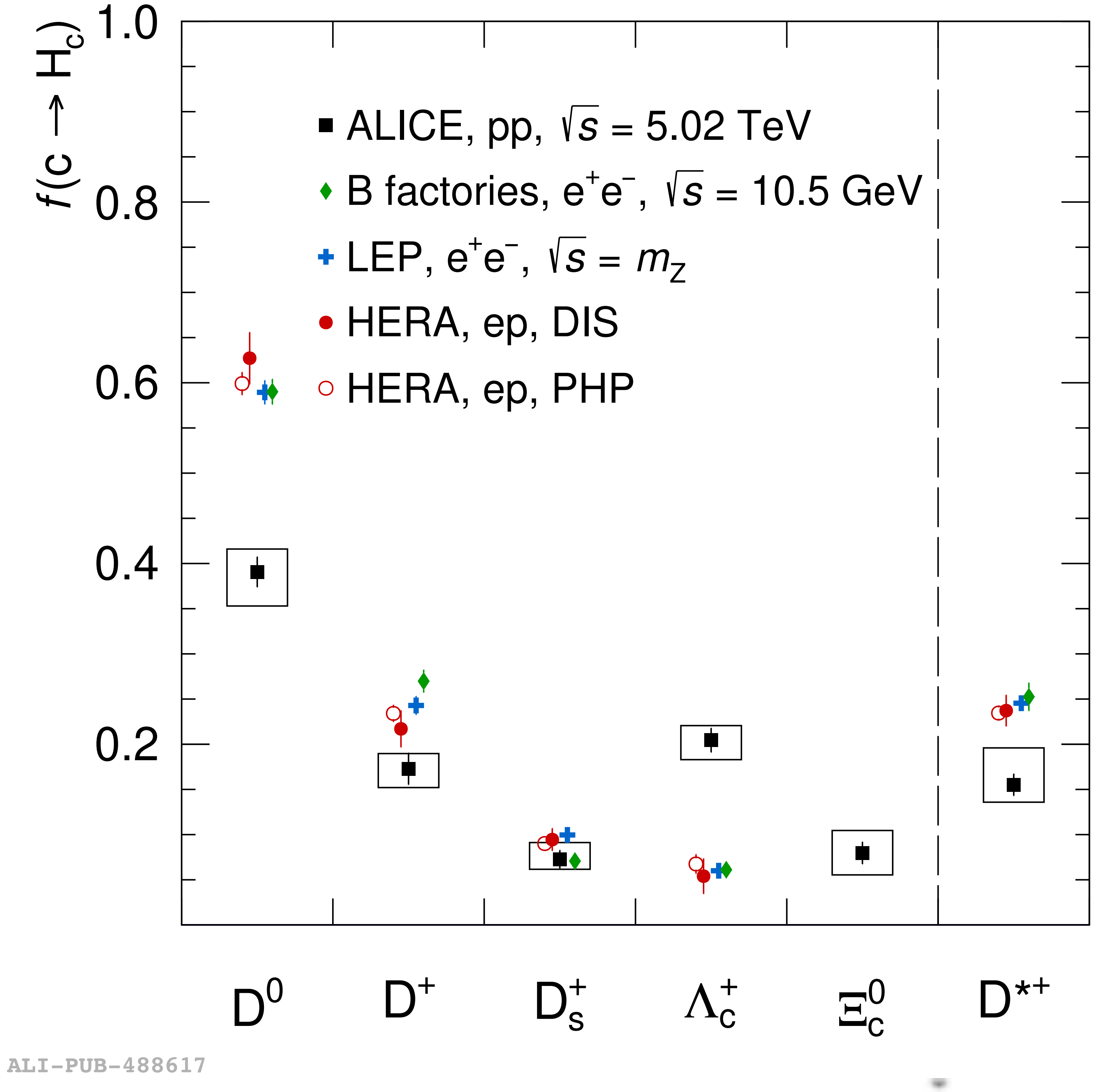
ALICE *Phys. Rev. Lett.* **127** (2021) 272001
ALICE *JHEP* **2110** (2021) 159

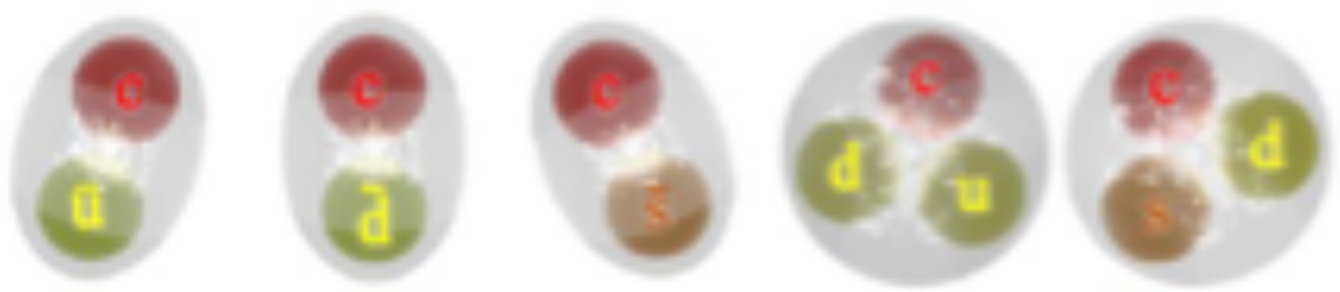


ALICE arXiv:2205.13993

- Catania model closer to the measurement when decays from additional higher-mass resonances are considered

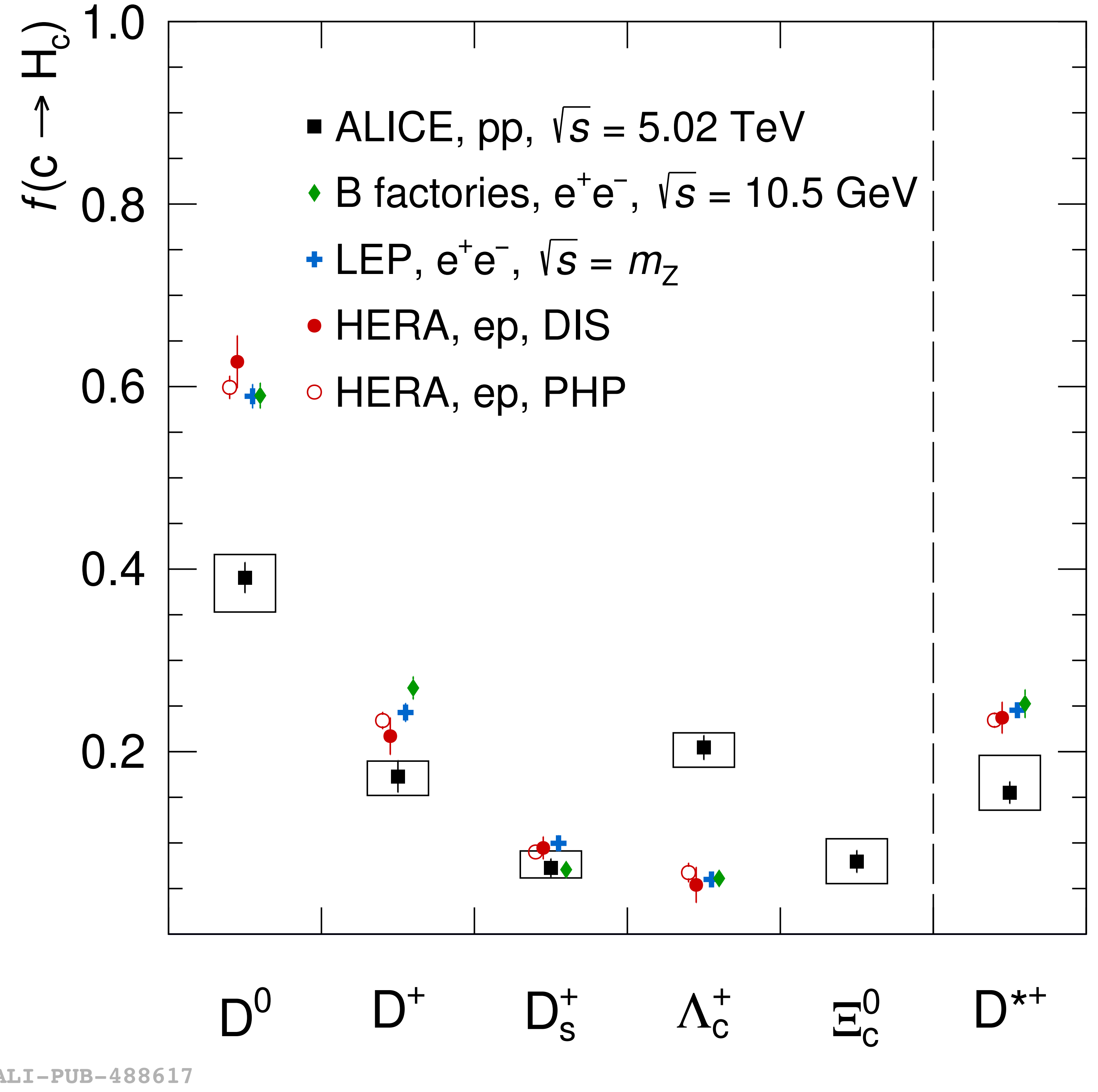
Charm quark hadronizaton





- Hadronization non-universal between e-e+/ ep and pp collisions
- Additional constraint to hadronization — heavy quarks created in hard scatterings
- Important to calibrate heavy-quark observables for QCD matter studies

Charm quark hadronizaton



- Hadronization non-universal between e^-e^+/ ep and pp collisions
- Additional constraint to hadronization — heavy quarks created in hard scatterings
- Important to calibrate heavy-quark observables for QCD matter studies

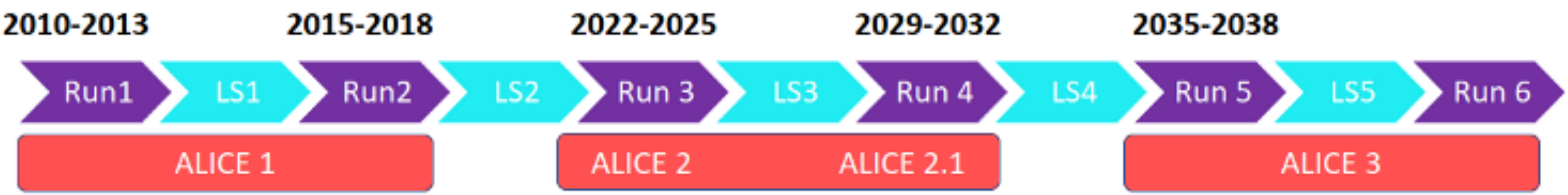
$$\frac{d\sigma^{pp\to H_Q}}{dp_T} = \sum_{ij} f_i(x_1,\mu_F) f_j(x_2,\mu_F) \otimes \frac{d\sigma^{ij\to Q}}{dp_T}(x_1 x_2, \mu_F, \mu_R) \otimes D_{Q\to H_Q}\left(z_Q = \frac{p_{H_Q}}{p_Q}, \mu_F\right)$$

Parton distribution functions (PDF)

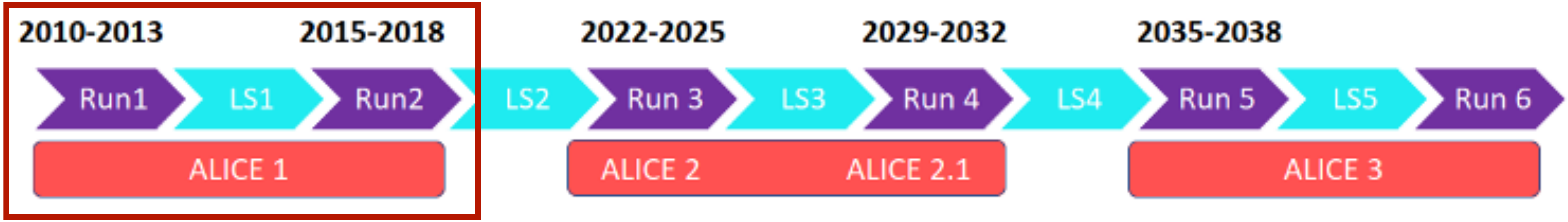
Hard scattering cross section (pQCD)

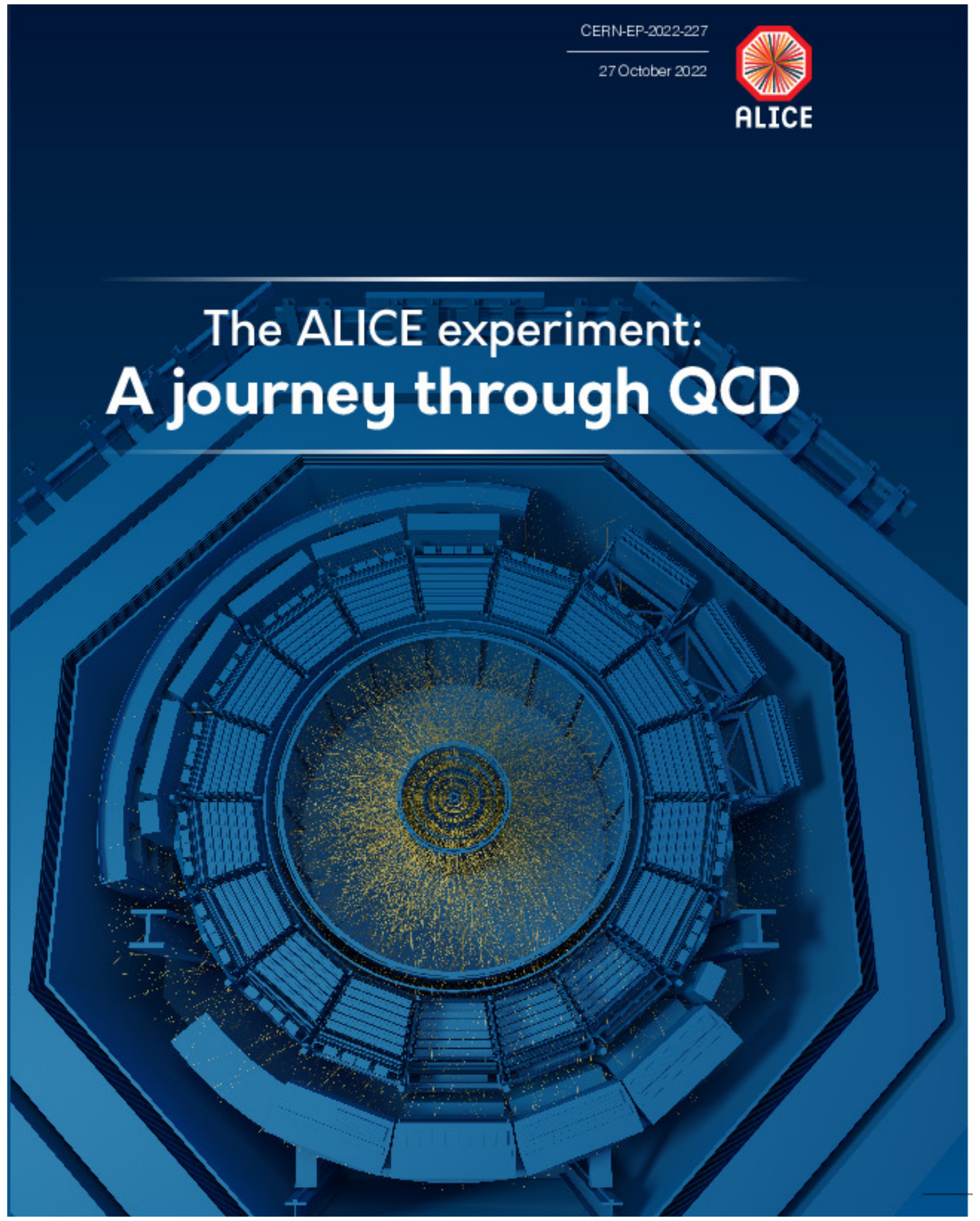
Fragmentation function (Hadronization)

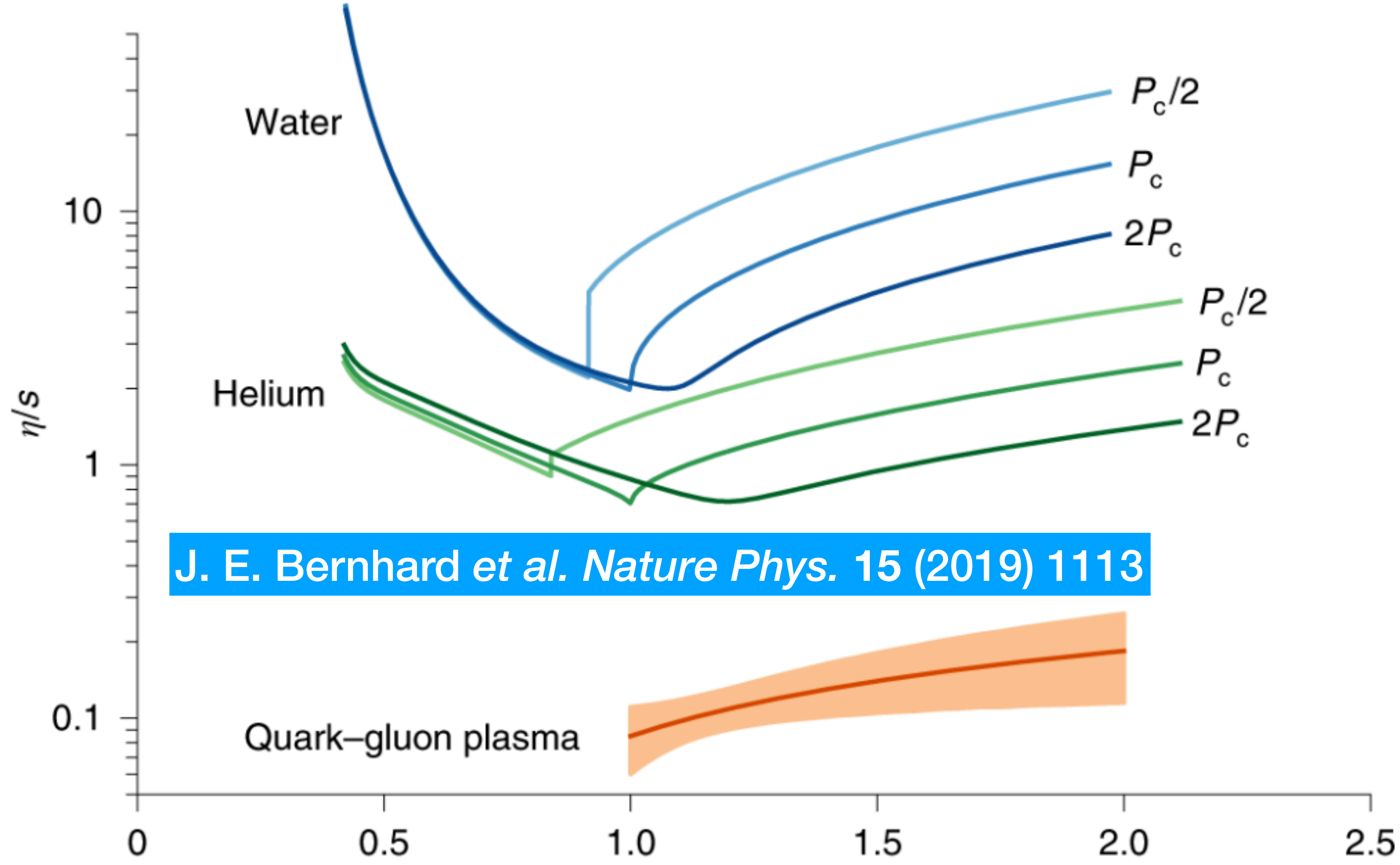
ALICE schedule



A journey through QCD





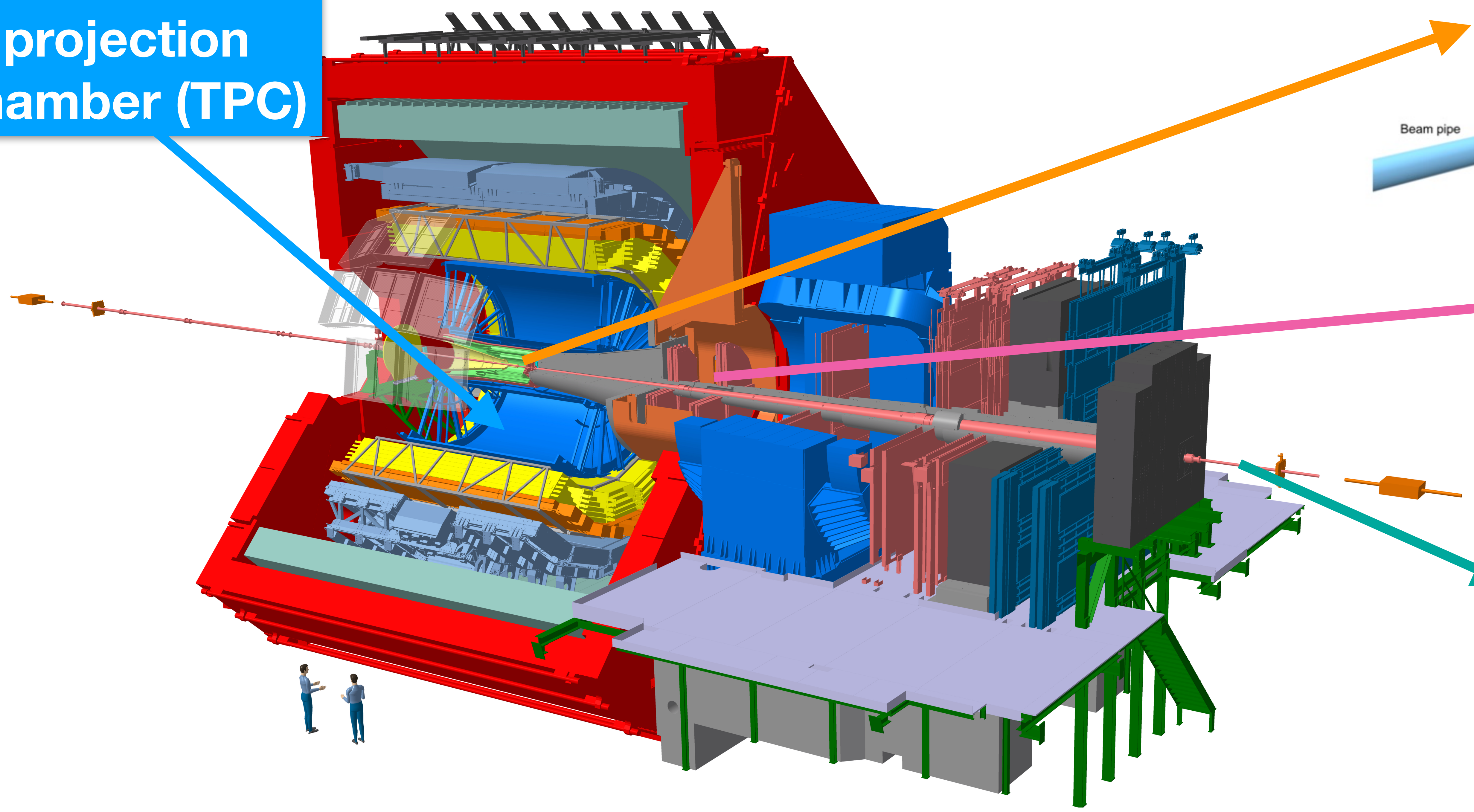


J. E. Bernhard *et al. Nature Phys.* 15 (2019) 1113

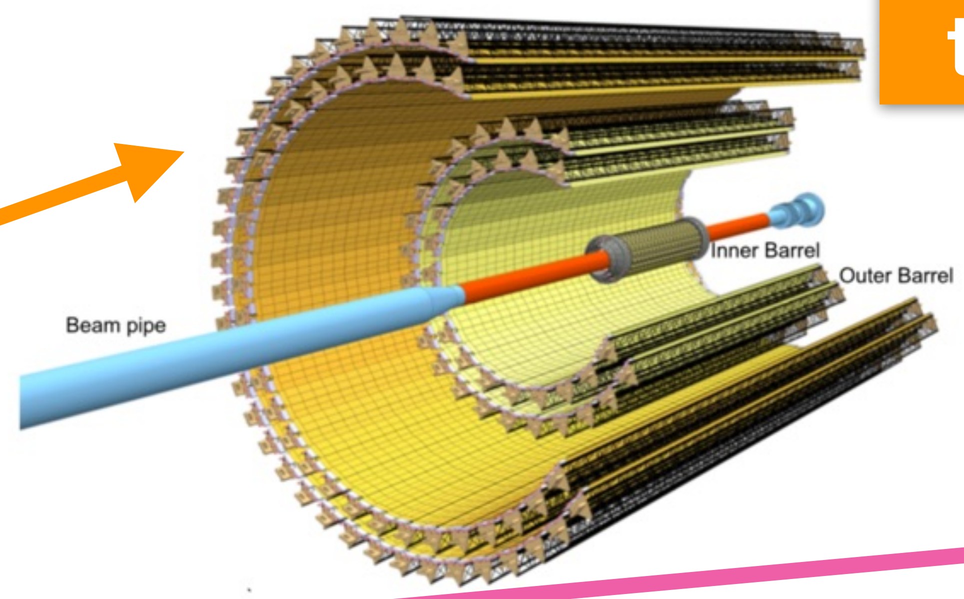
Microscopic of the QCD

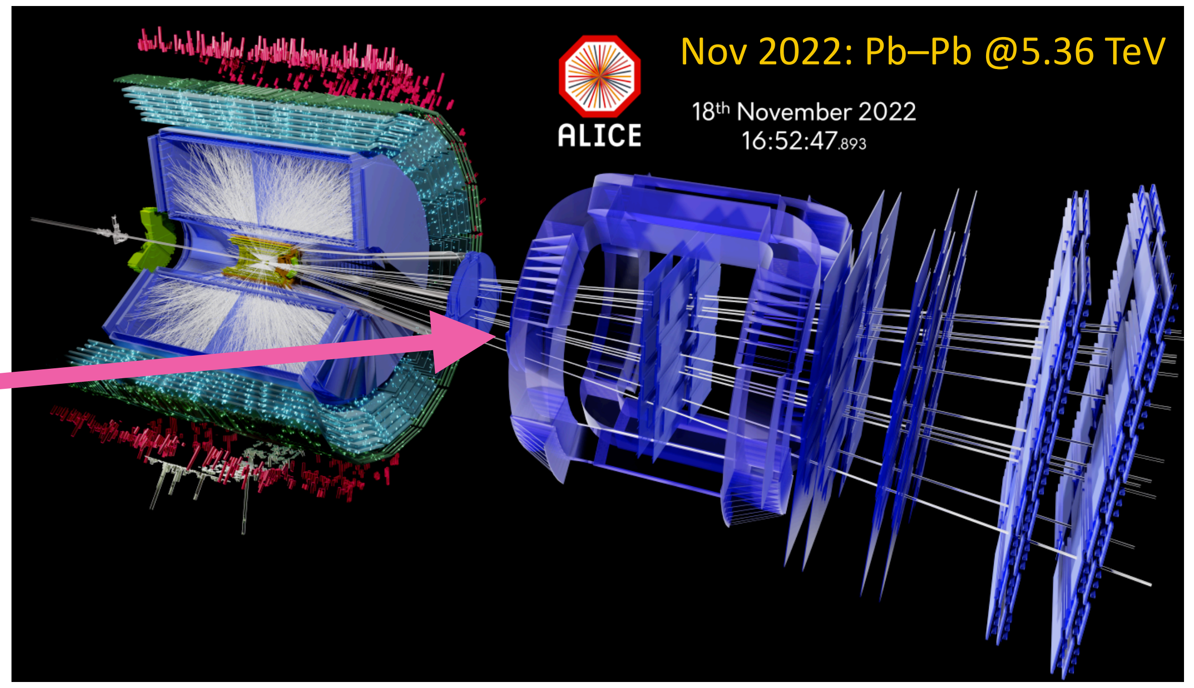
2010-2013		2015-2018		2022-2025		2029-2032		2035-2038		
Run1	LS1	Run2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
ALICE 1				ALICE 2		ALICE 2.1		ALICE 3		

Upgraded readout of time projection chamber (TPC)

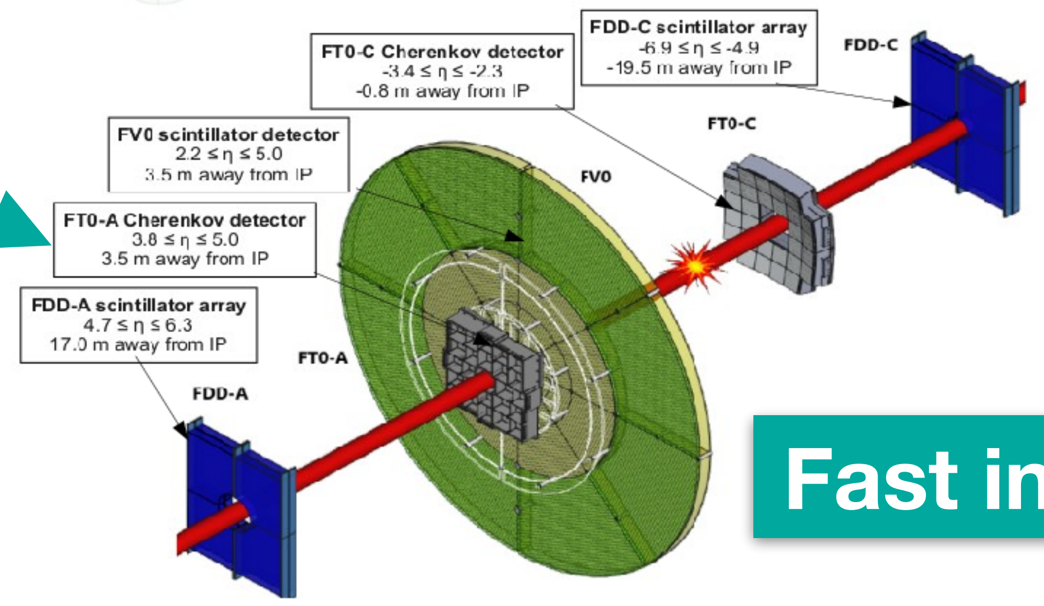


The 2nd generation inner tracking system (ITS2)





Muon forward tracker (MFT)



Fast integrated trigger (FIT)

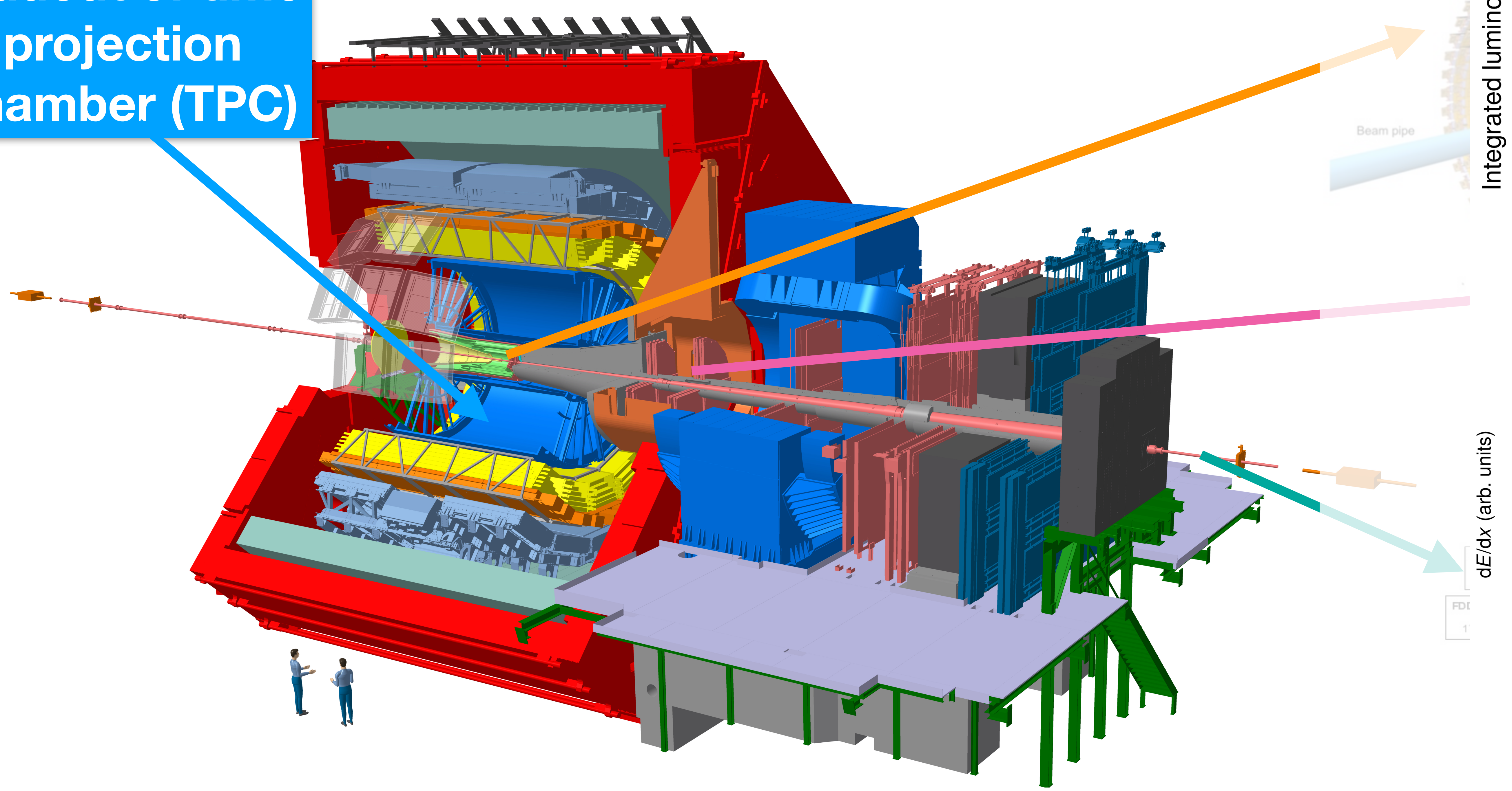
Microscopic of the QCD

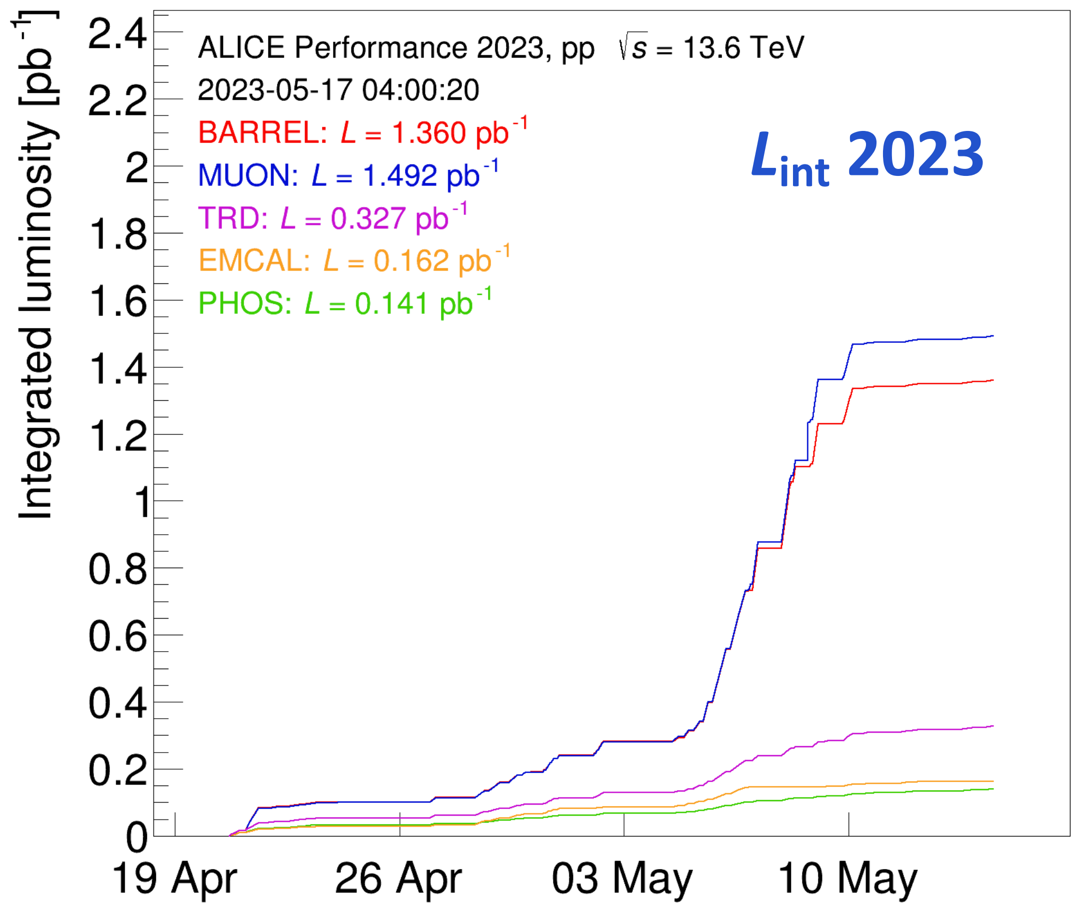
2010-2013 | 2015-2018 | 2022-2025 | 2029-2032 | 2035-2038

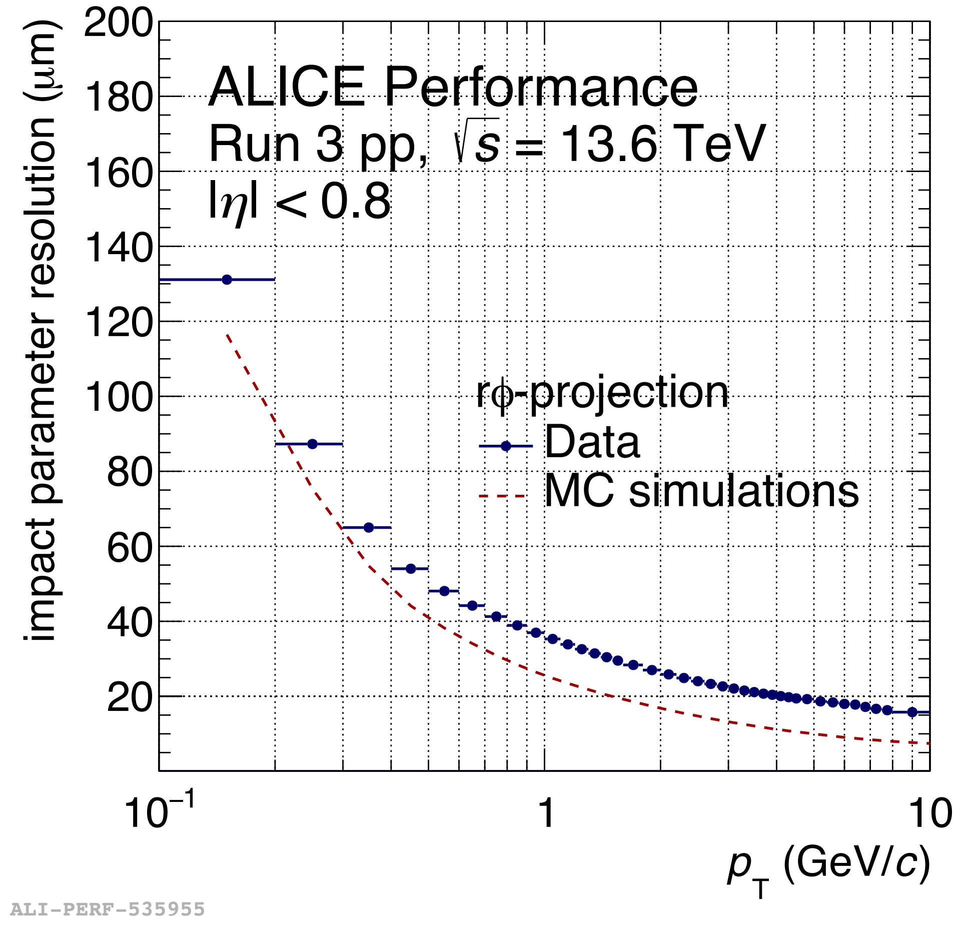
Run1 → LS1 → Run2 → LS2 → Run 3 → LS3 → Run 4 → LS4 → Run 5 → LS5 → Run 6

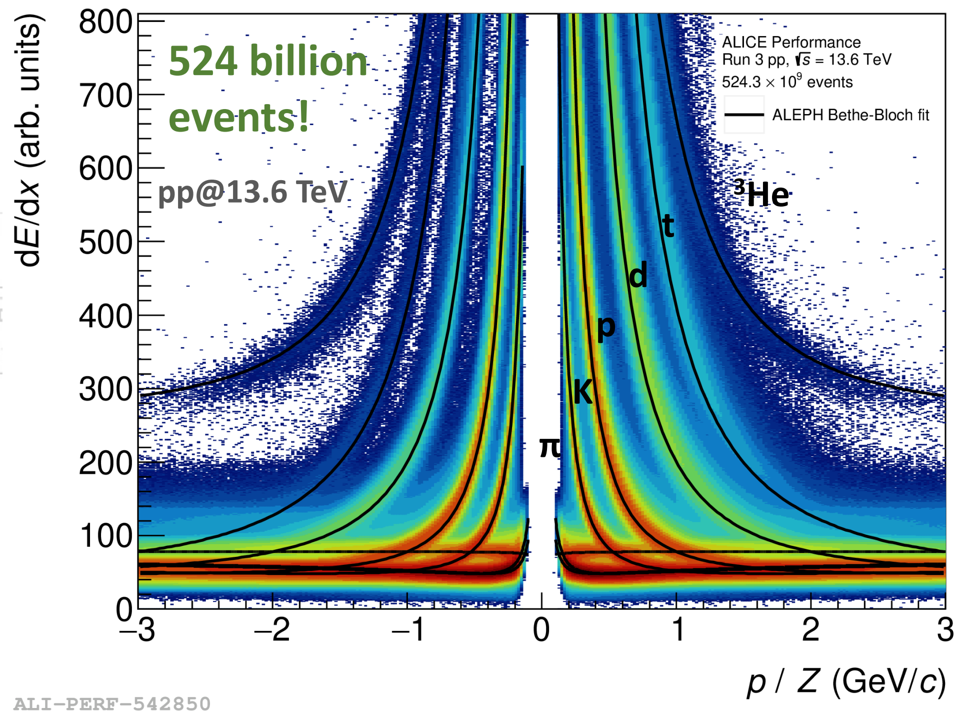
ALICE 1 | ALICE 2 | ALICE 2.1 | ALICE 3

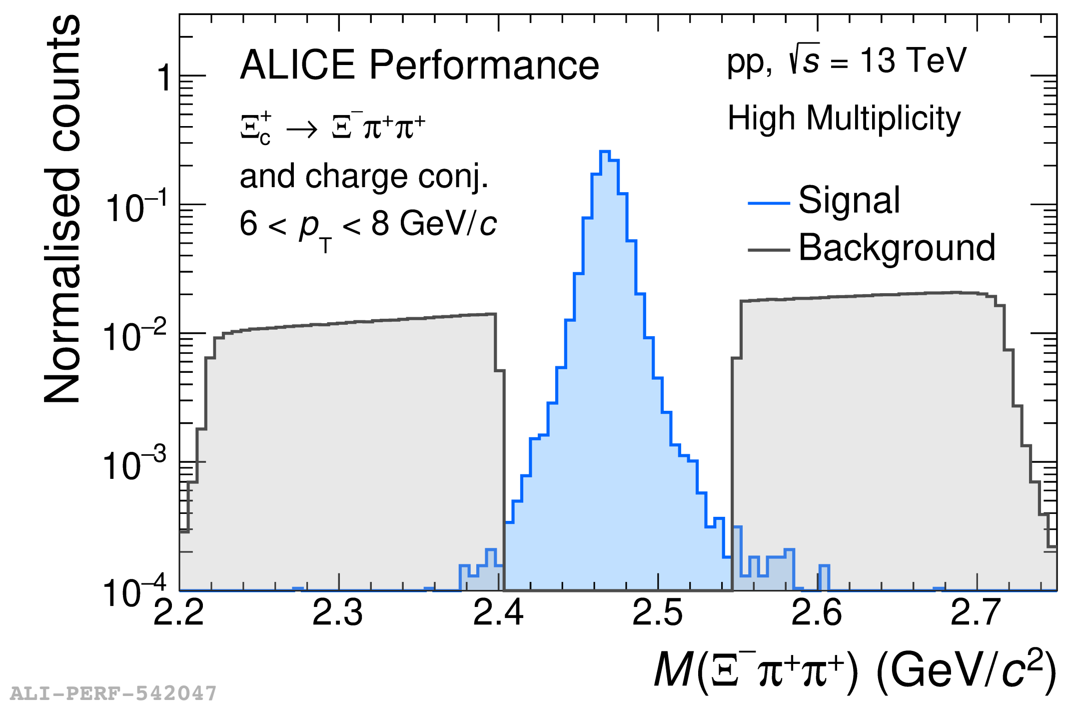
Upgraded readout of time projection chamber (TPC)



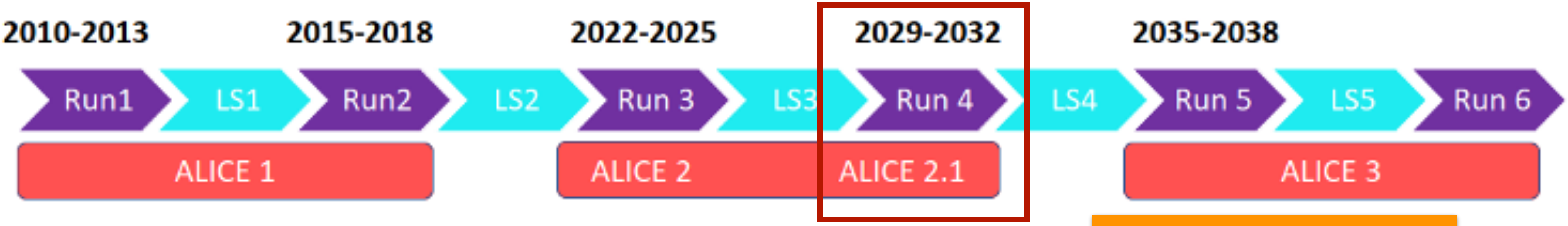


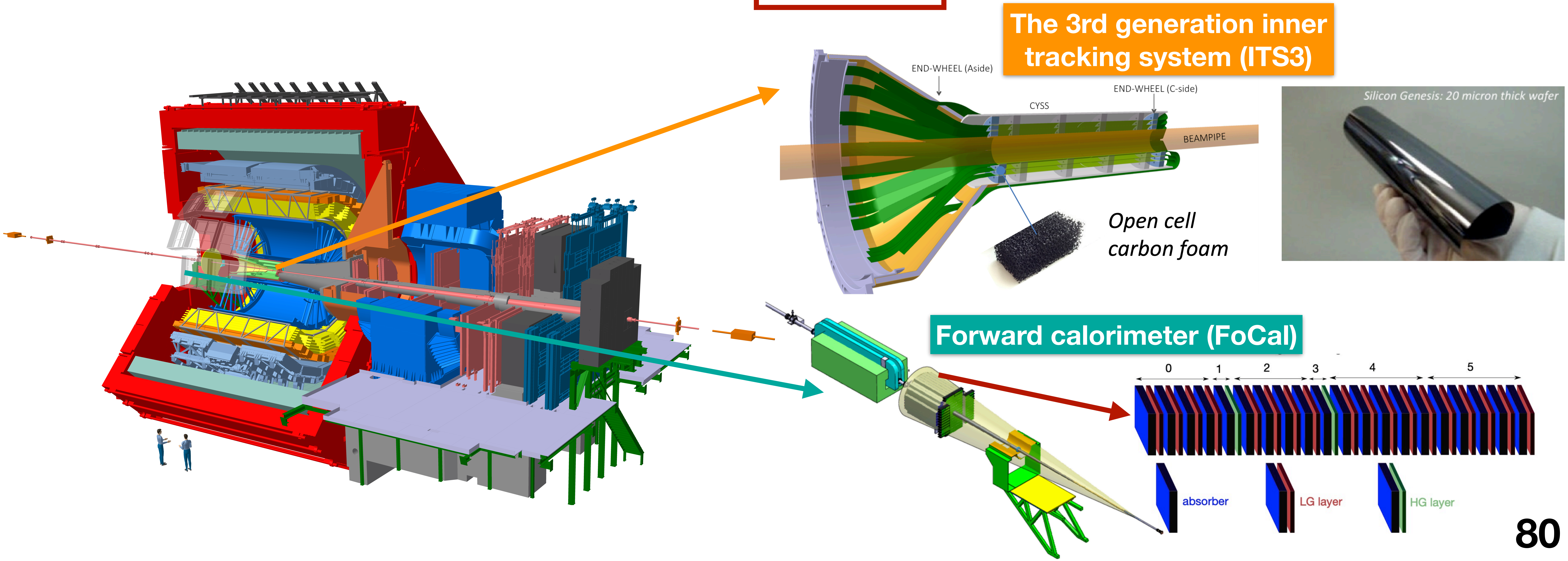




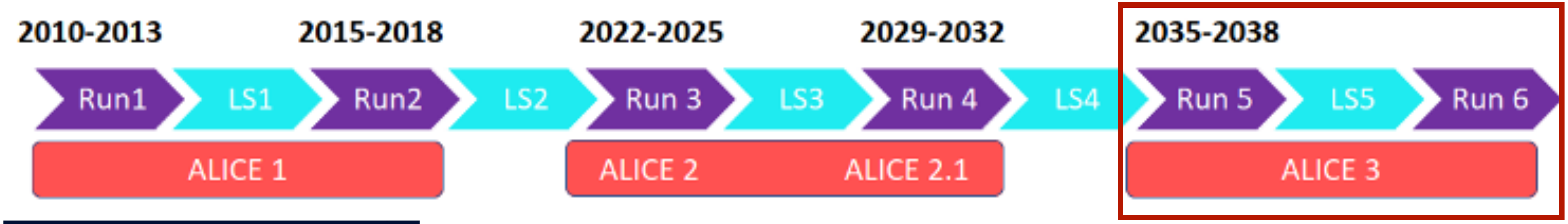


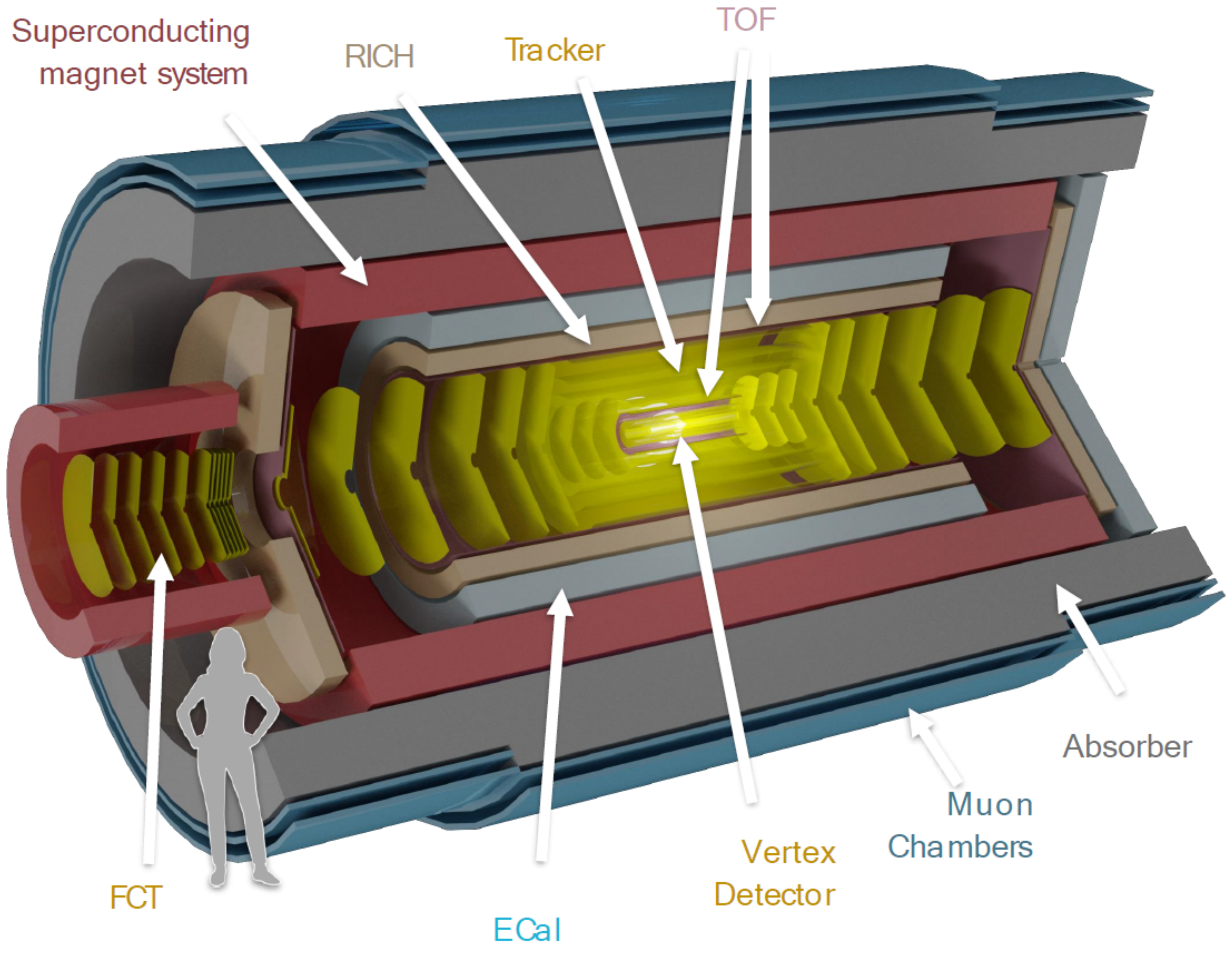
Femtoscopic of the QCD

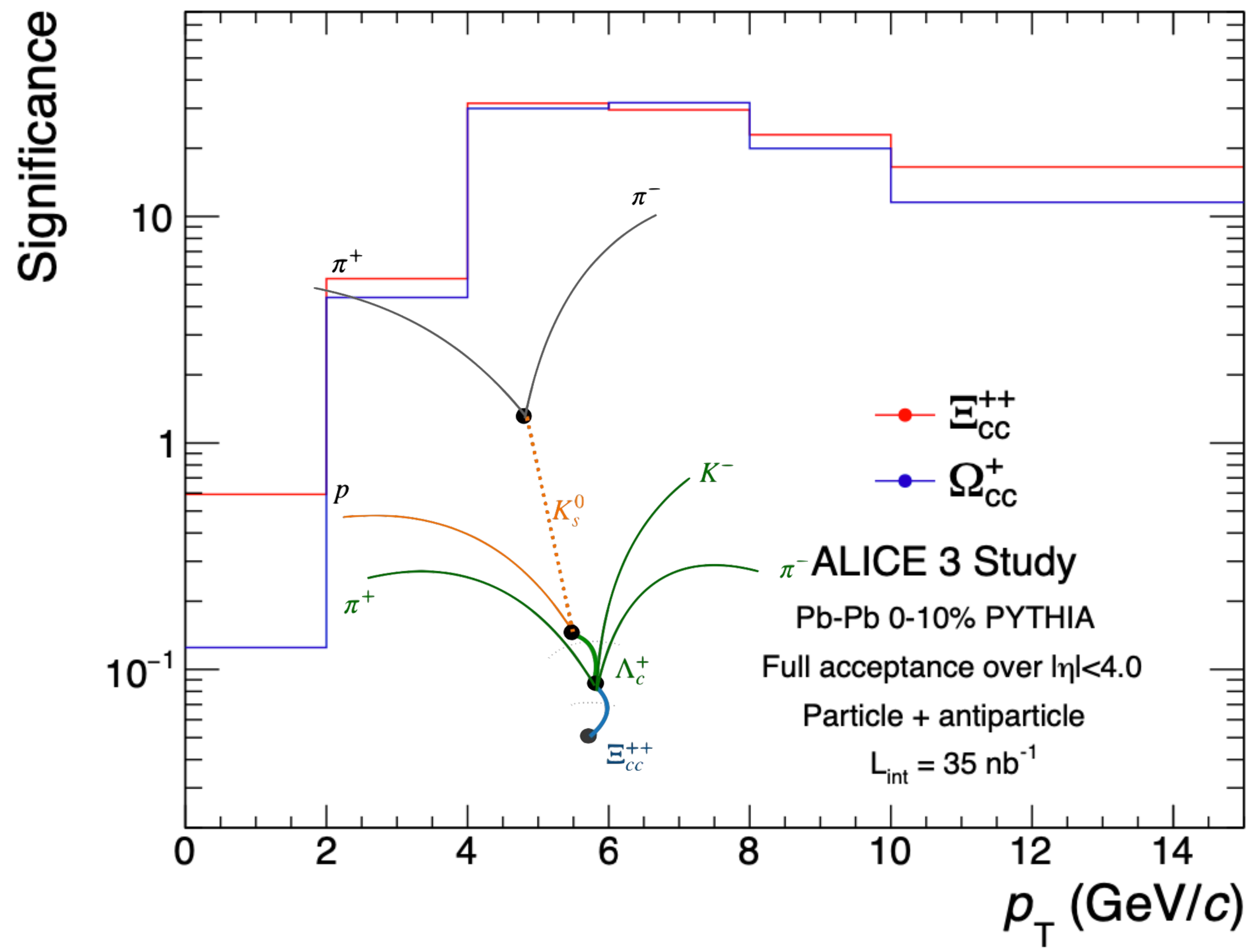




Next-generation HI experiment







What is experimental physics?