Lectures 25 – 26
Experimental opportunities for new physics at low transverse momentum

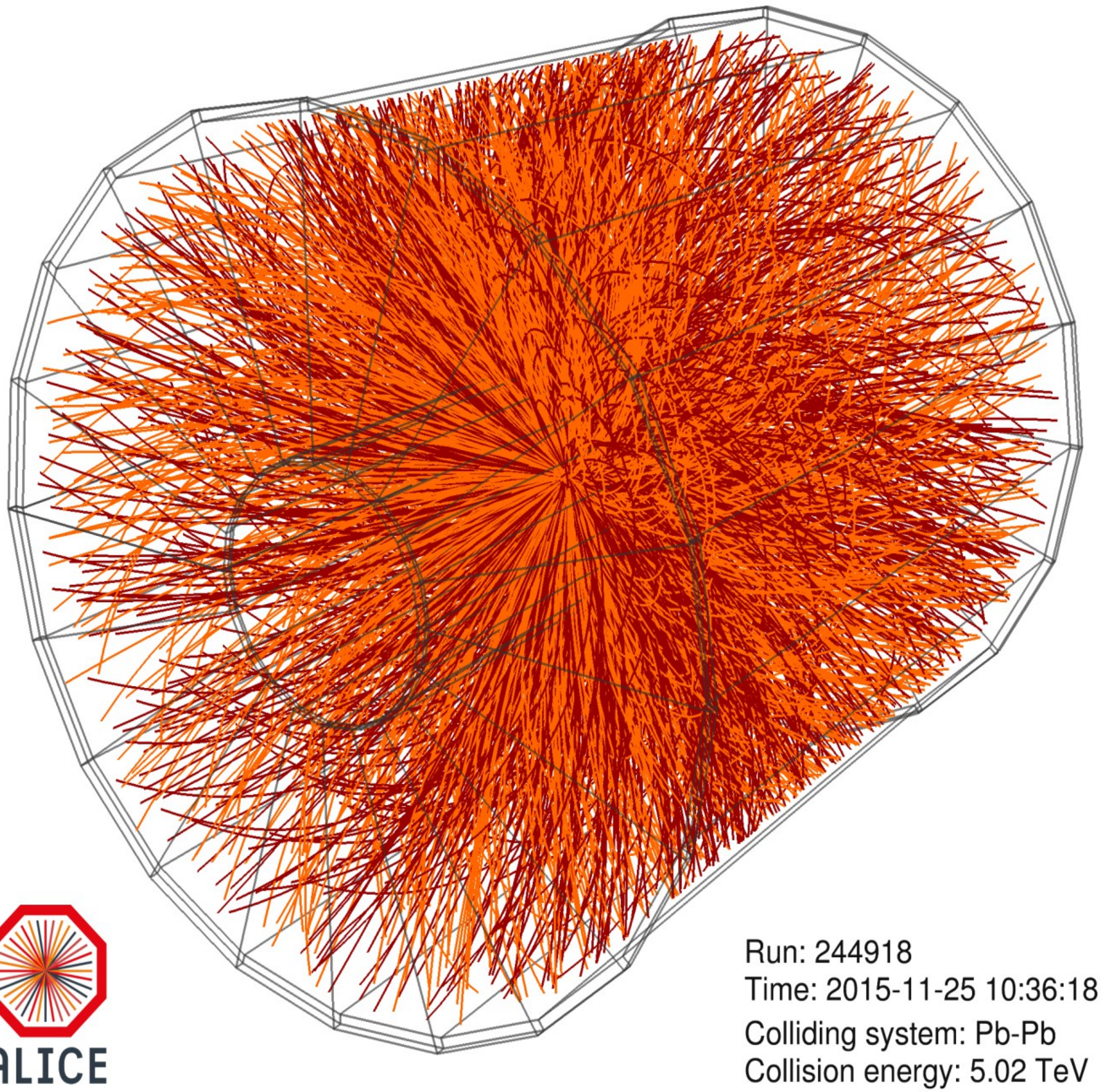
Lecture 25

- some historical comments: the QGP in ALICE phase 1 and 2
- remarks on importance of low transverse momentum coverage
- charm and multi-charm hadrons, deconfinement and universal hadronization

Lecture 26

- photons and di-leptons at low transverse momentum
- ultra-soft photon measurements and the infrared limit of Quantum Field Theories
- outlook

PbPb collisions at LHC at $\sqrt{s}$ = 5.02 A TeV



ALICE

Run1: 3 data taking campaigns
pp, pPb, Pb—Pb
> 170 publications

Run2-1 with 13 TeV pp
Pb—Pb run 5 TeV/u
p-Pb Run at 5 and 8 TeV

Run2-2 Pb--Pb 5 TeV/u
> 190 publications
Snapshot taken with the ALICE TPC

March 2022: Run1 and Run2 combined: > 380 publications

as of March 24, 2022, LHC Run3 has started!

central Pb-Pb collisions:
more than 32000
particles produced per collision
at top LHC energy
fireball size > 10 fm

ALICE plans for the coming decade 2022 – 2030
LHC Run3 and Run4

ALICE has just been upgraded:

GEM based read-out chambers for the TPC
new inner tracker with ultra-thin Si layers
continuous read of (all) subdetectors

increase of data rates by factor >50

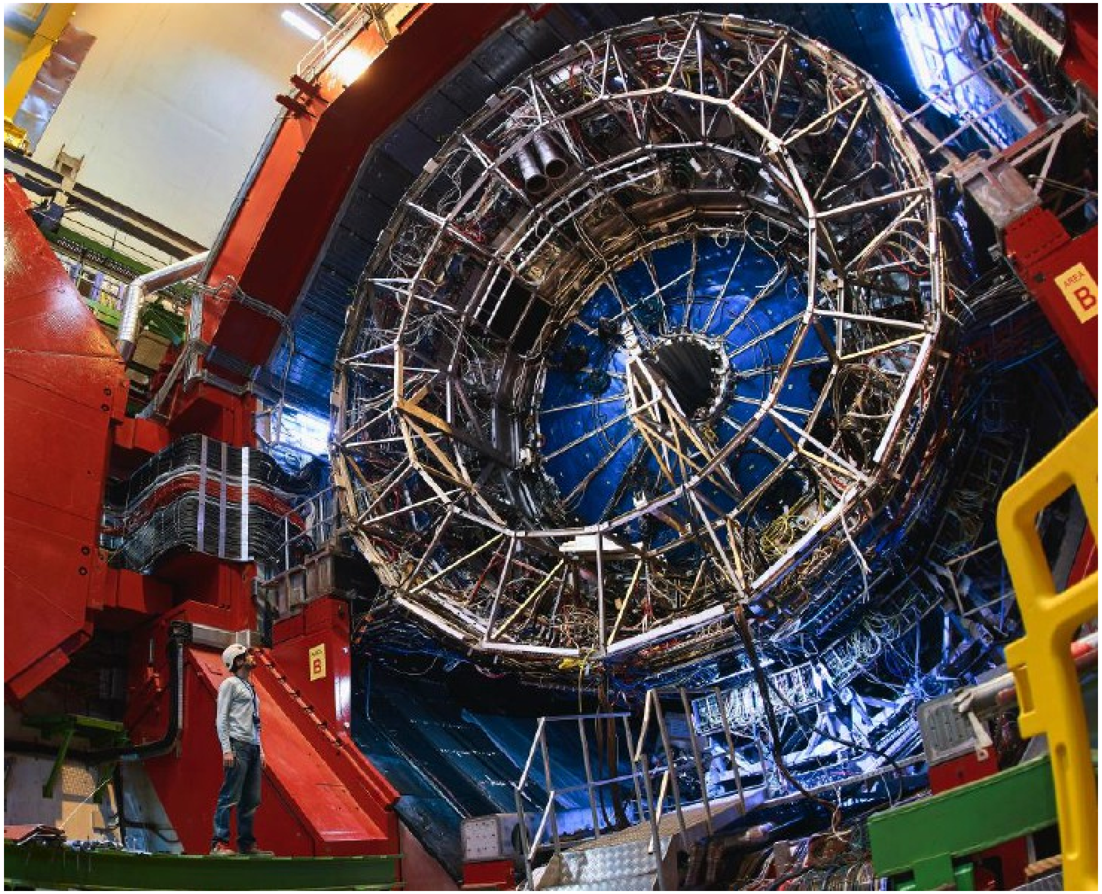
focus on rare objects, exotic quarkonia, single (and possibly double) charm hadrons to address a number of fundamental questions and issues such as:

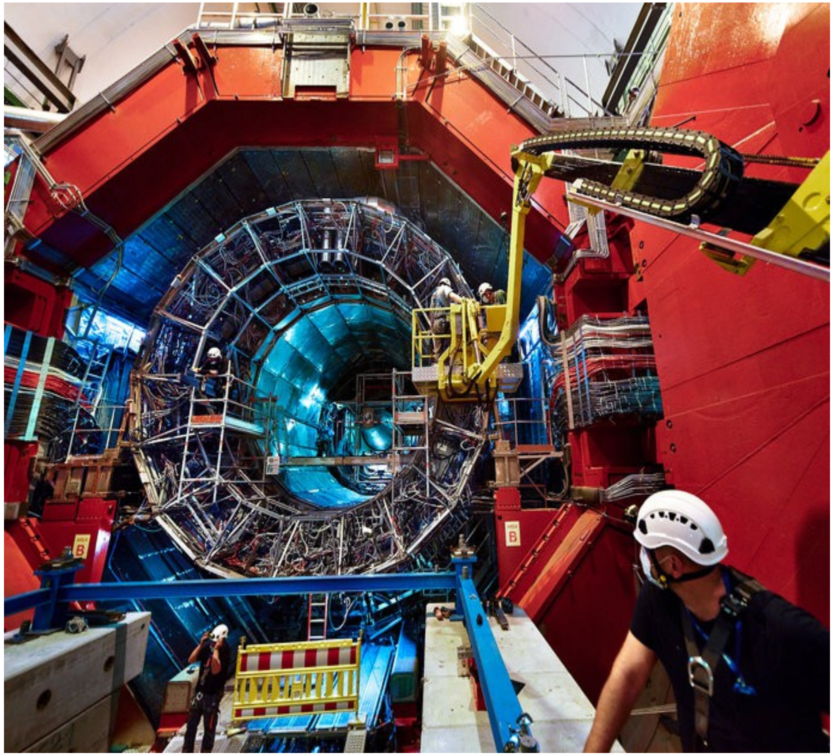
- what is the deconfinement radius for charm quarks
- are there colorless bound states in a deconfined medium?

- are complex, light nuclei and exotic charmonia (X,Y,Z) produced as compact multi-quark bags?

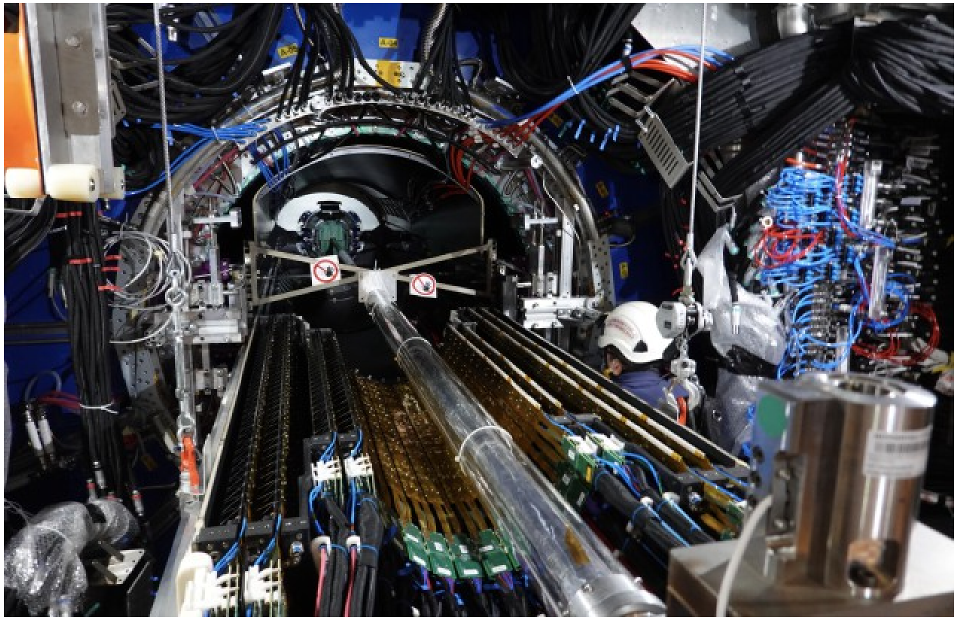
- can fluctuation measurements shed light on the mechanism of baryon production and critical behavior near the phase boundary?

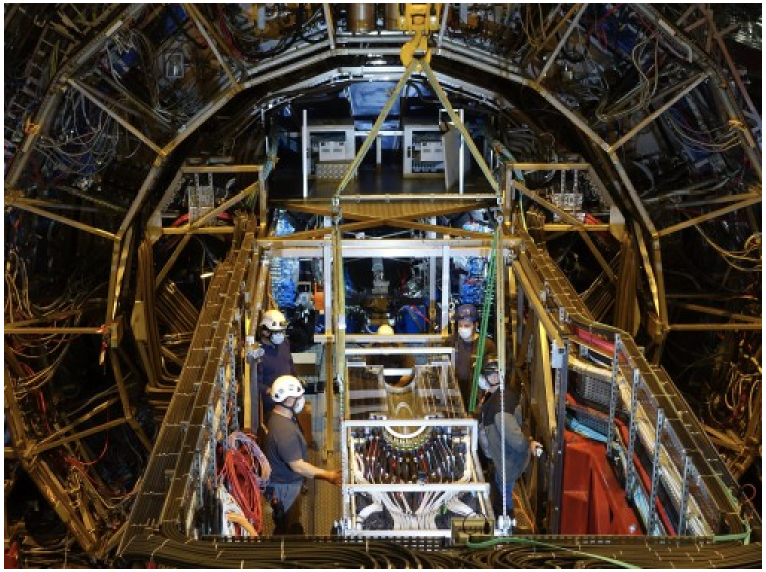
deciphering QCD in the strongly coupled regime





installation of upgraded detectors
TPC and (new) ITS
March 25, 2021





reminder: particle production and SHM

Production of hadrons and (anti-)nuclei at LHC

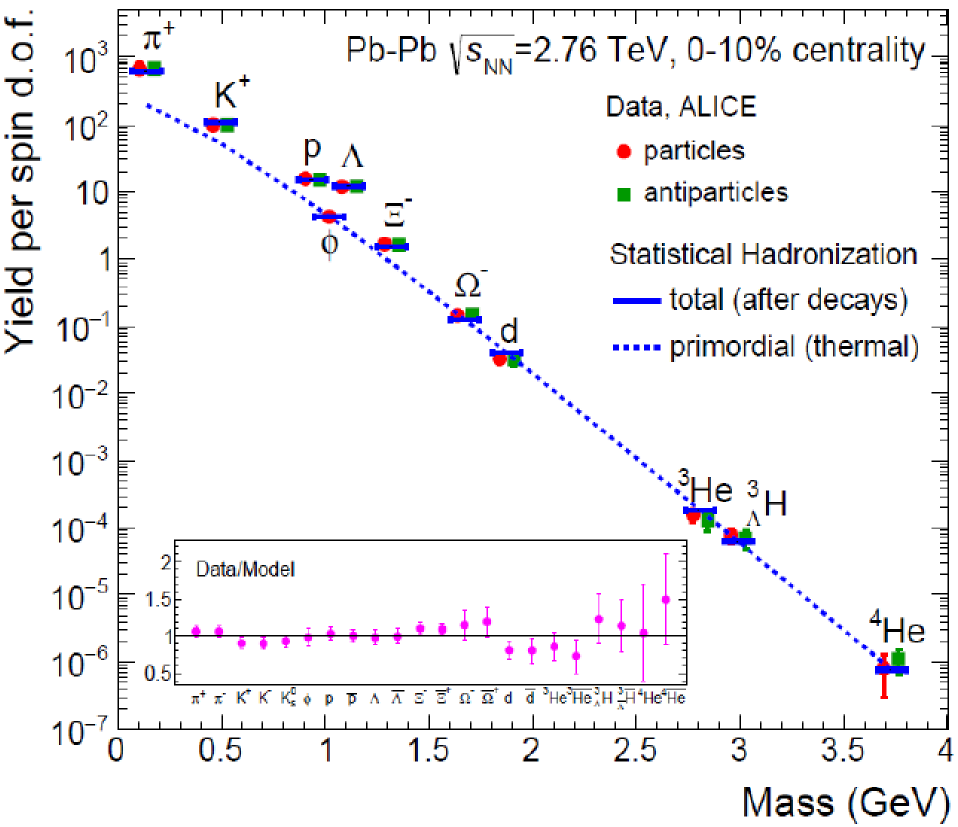
1 free parameter: temperature T

T = 156.5 ± 1.5 MeV

agreement over 9 orders of magnitude with QCD statistical operator prediction (- strong decays need to be added)

- matter and antimatter are formed in equal portions at LHC
- even large very fragile hypernuclei follow the same systematics

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) 321



at LHC energy, all chemical potentials vanish, so strangeness is immaterial for particle production, particle yields ~ $M^{3/2}$ exp(-M/T)
(no 'strangeness enhancement')

summary so far (2022) – production of (u,d,s) hadrons

- statistical hadronization model is an effective tool to understand the phenomenology of hadron production in relativistic nuclear collisions from SIS to LHC energy with predictive power for future facilities

- deeply rooted in duality 'hadrons – quarks' near QCD phase boundary

- present precision is mostly limited by incomplete knowledge of hadron mass spectrum and related branching ratios for decays

- first measurements from ALICE at the 5% accuracy level showed deviations for protons, now quantitatively understood by using experimental pion-nucleon phase shifts

- yields of light nuclei and hyper-nuclei successfully predicted
  → maybe produced as quark bags?

- works also for hadrons with charm quarks → charmonium enhancement in QGP, direct proof of deconfinement for charm quarks

key results:
experimental location of QCD phase boundary for μ_b < 300 MeV:
T_c = 156.5 ± 3 MeV for μ_b = 0
new insight into hadronization

why emphasis on low transverse momenta p_T?

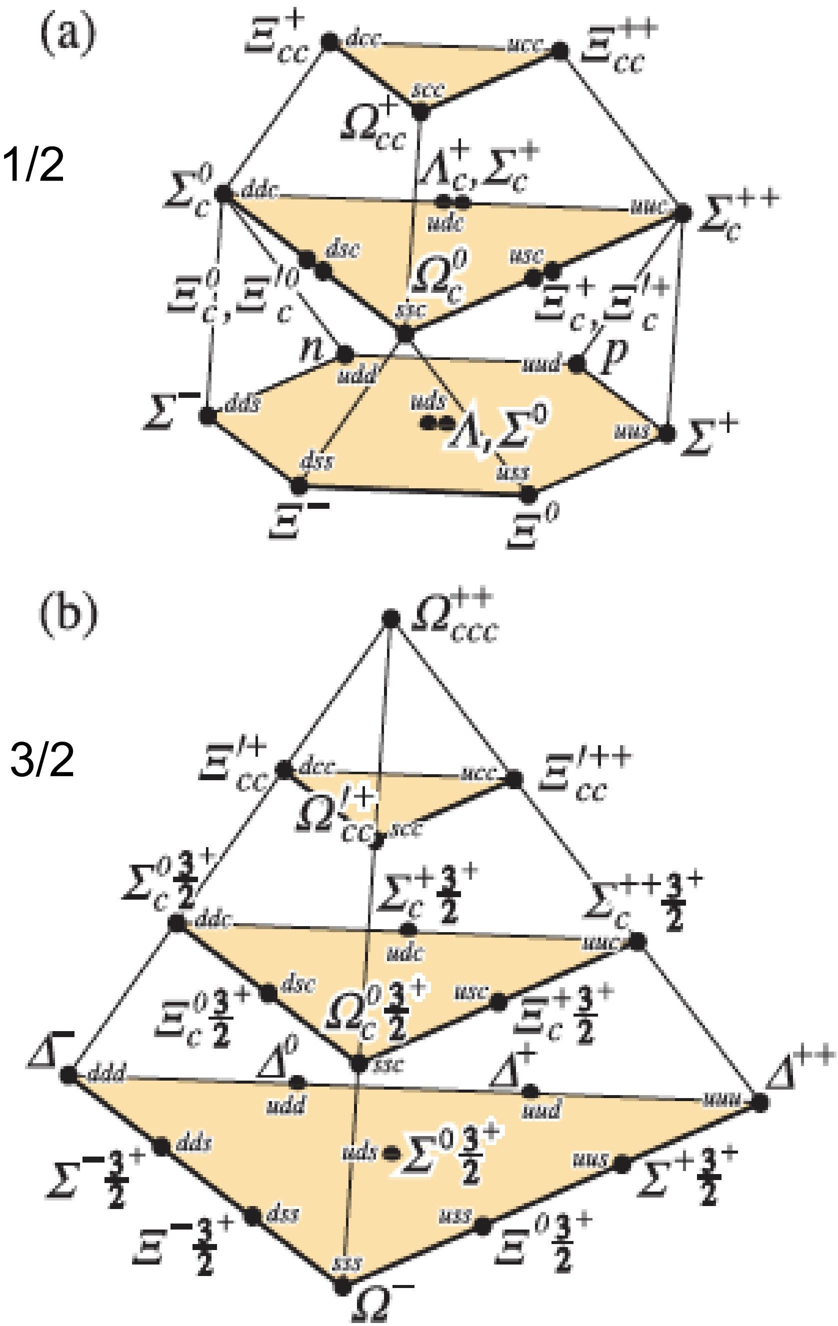
- the bulk of particles produced in hadronic and nuclear collisions takes place at $p_T < 1$ GeV
- typical sizes of the interaction region range from 1 fm (pp collisions) to > 10 fm (Pb—Pb collisions)
- our main emphasis is to create matter (such as the quark-gluon plasma) in such collisions and study its properties
- matter (in contrast to a weakly or non-interacting gas of hadrons) implies some degree of thermalization; thermalization takes place predominantly where the bulk of particles is
- larger systems emit particles at low transverse momenta: $p_T < 1$ GeV implies spatial size $r_T > 0.2$ fm, $p_T < 100$ MeV implies $r_T > 2$ fm, $p_T < 20$ MeV implies $r_T > 10$ fm (note that $\hbar c = 197$ MeV fm)
- all produced particles are accompanied by photons with characteristic $1/p_T$ spectrum, the majority of these photons is at very low p_T (see below)

charm sector

- production of hadrons with charm in relativistic nuclear collisions
- brief review of quark model of baryons and mesons
- focus on baryons containing charm quarks
- the multiple charm hierarchy
- deconfinement and hadronization of a fireball containing charm quarks

the charm baryons in the quark model

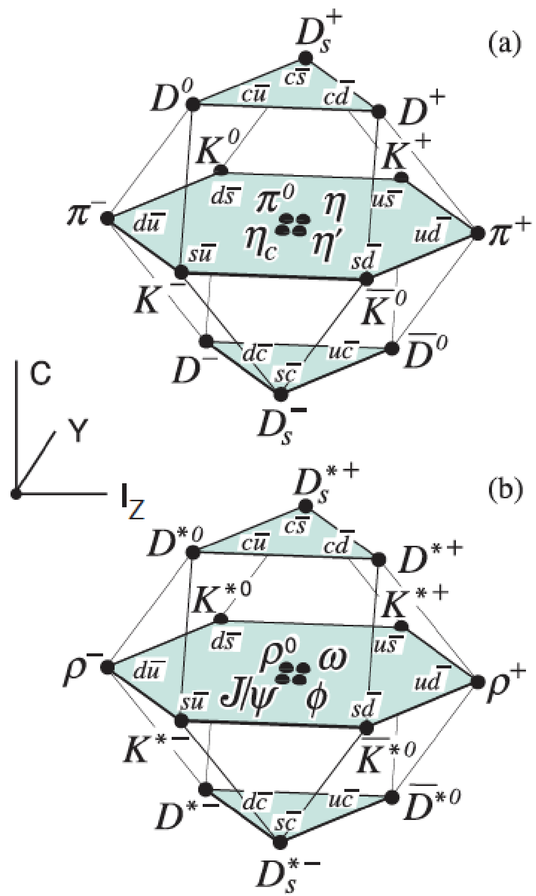
J = 1/2



J = 3/2

note: baryons with 2 or 3 charm quarks cannot be produced in a single (hard) collision

charm mesons in the quark model



the mechanism for statistical hadronization with charm (SHMc)

[Braun-Munzinger and Stachel, PLB 490 (2000) 196]
[Andronic, Braun-Munzinger and Stachel, NPA 789 (2007) 334]

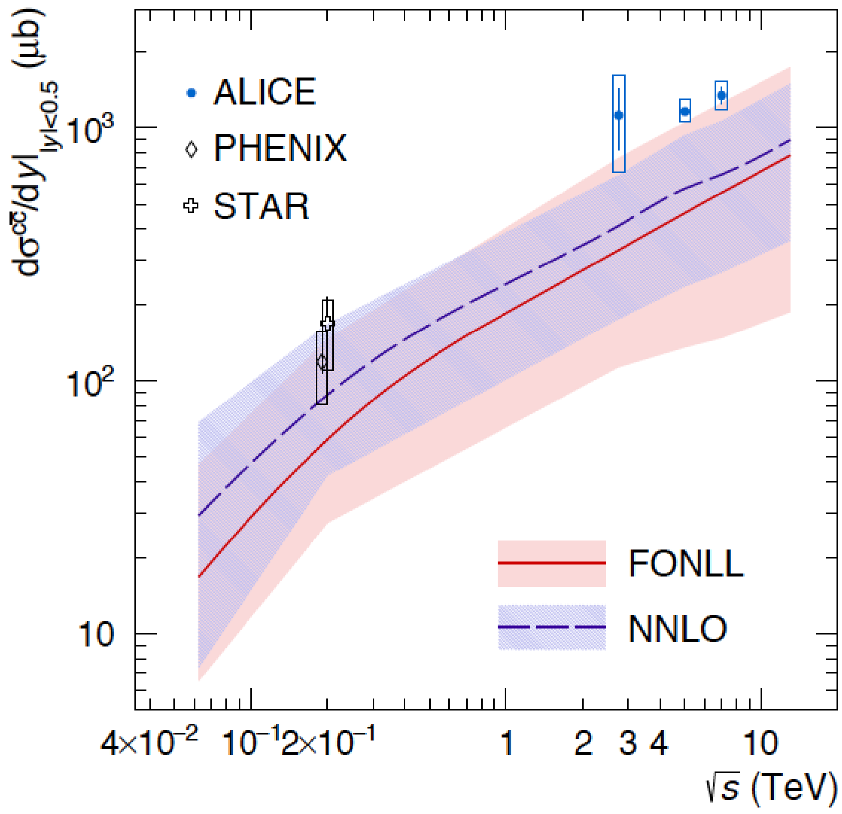
- Charm quarks are produced in initial hard scatterings ($m_{c\bar{c}} \gg T_{\mathrm{c}}$) and production can be described by pQCD ($m_{c\bar{c}} \gg \Lambda_{\mathrm{QCD}}$)
- Charm quarks survive and *thermalise* in the QGP
- Full screening before T_{CF}
- Charmonium is formed at phase boundary (together with other hadrons)
- Thermal model input ($T_{\mathrm{CF}}, \mu_{\mathrm{b}} \rightarrow n_X^{\mathrm{th}}$)

$$N_{c\bar{c}}^{\mathrm{dir}} = \underbrace{\frac{1}{2} g_c V \left(\sum_i n_{D_i}^{\mathrm{th}} + n_{\Lambda_i}^{\mathrm{th}} + \cdots \right)}_{\text{Open charm}} + \underbrace{g_c^2 V \left(\sum_i n_{\psi_i}^{\mathrm{th}} + n_{\chi_i}^{\mathrm{th}} + \cdots \right)}_{\text{Charmonia}}$$

- Canonical correction is applied to $n_{\mathrm{oc}}^{\mathrm{th}}$
- Outcome $N_{\mathrm{J}/\psi}, N_D, \ldots$

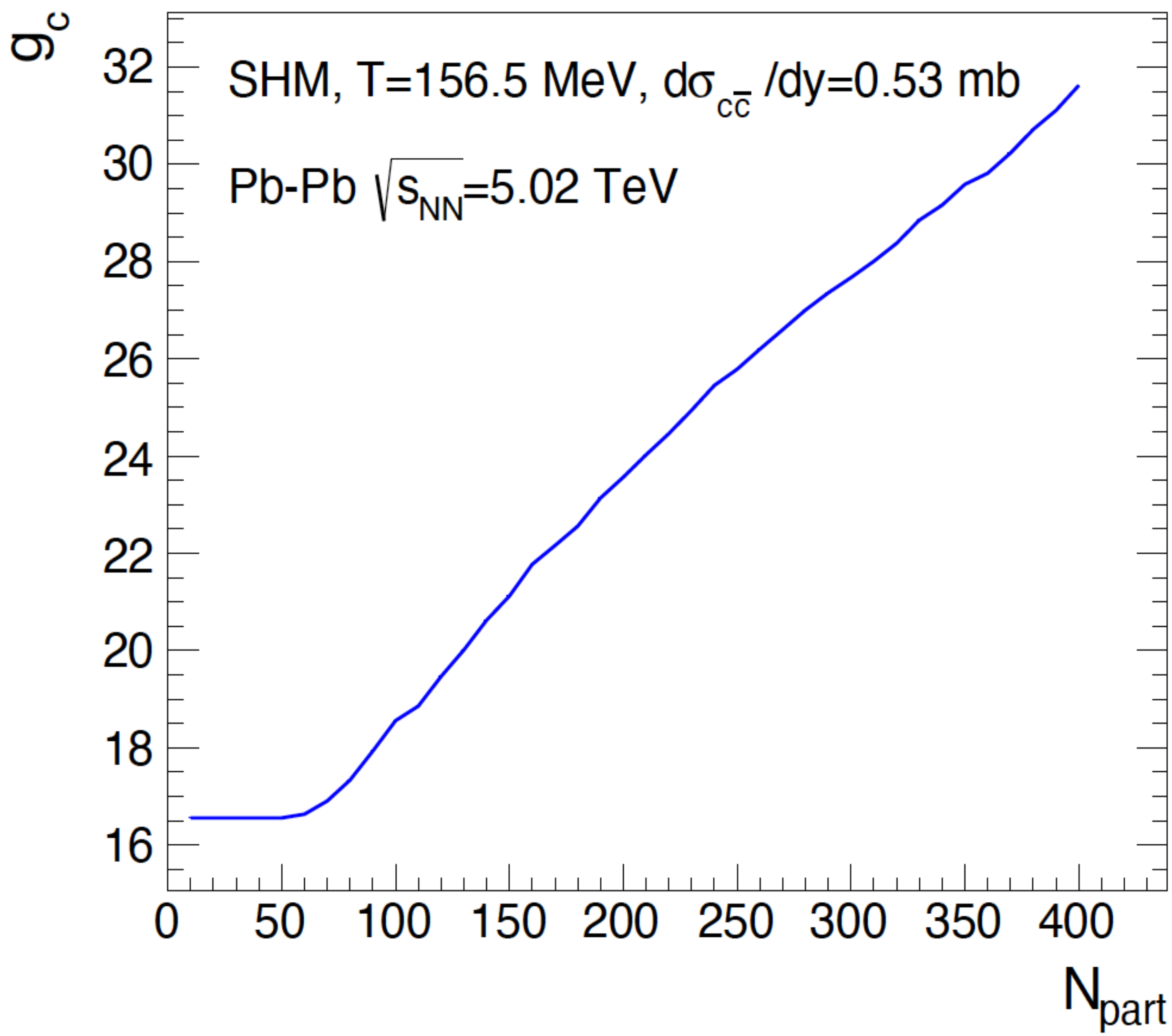
core-corona picture: treat low density part of nuclear overlap region, where a nucleon undergoes 1 or less collisions as pp collisions, use measured pp cross section scaled by $T_{AA} = N_{coll}/\sigma_{inel}^{pp}$ with N_{coll} the number of (hard) collisions as obtained in the Glauber approach

energy dependence of charm production cross section at mid-rapidity



ALICE collaboration, arXiv:2105.06335

centrality dependence of charm fugacity g_c at LHC energy



now SHMc predictions for charmed hadrons compared with spectra and yields as measured in ALICE

importantly, in the SHMc approach, all charmed hadrons are treated uniformly
the yields of charmonia, (multi-)charm baryons, (multi-)charm mesons etc are predicted without any new parameter
T and μ_B are obtained from (u,d,s) analysis, the only additional input is total open charm cross section, now obtained from inclusive measurement of D^0 production in Pb-Pb collisions

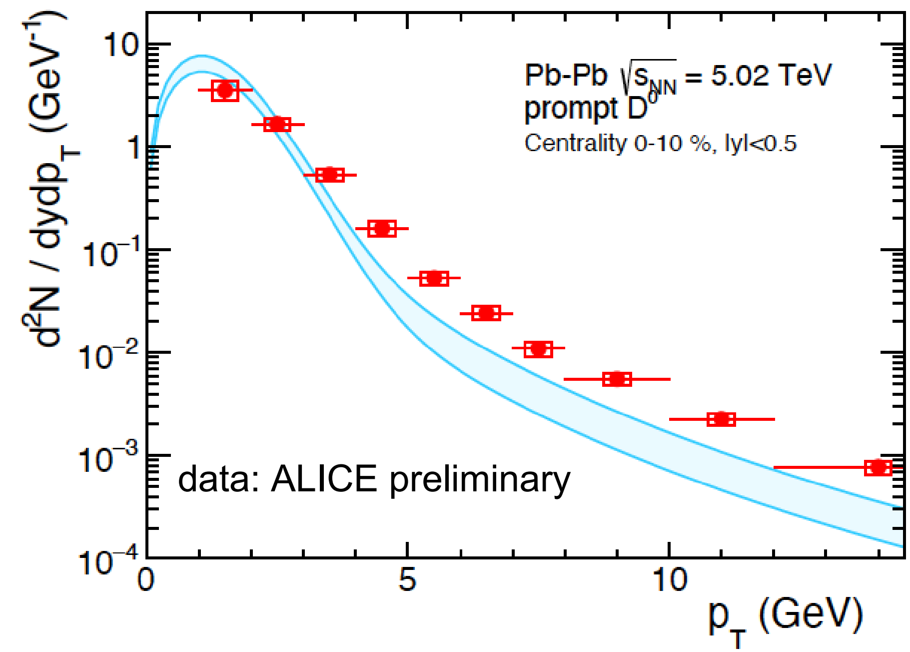
statistical hadronization for hidden and open charm

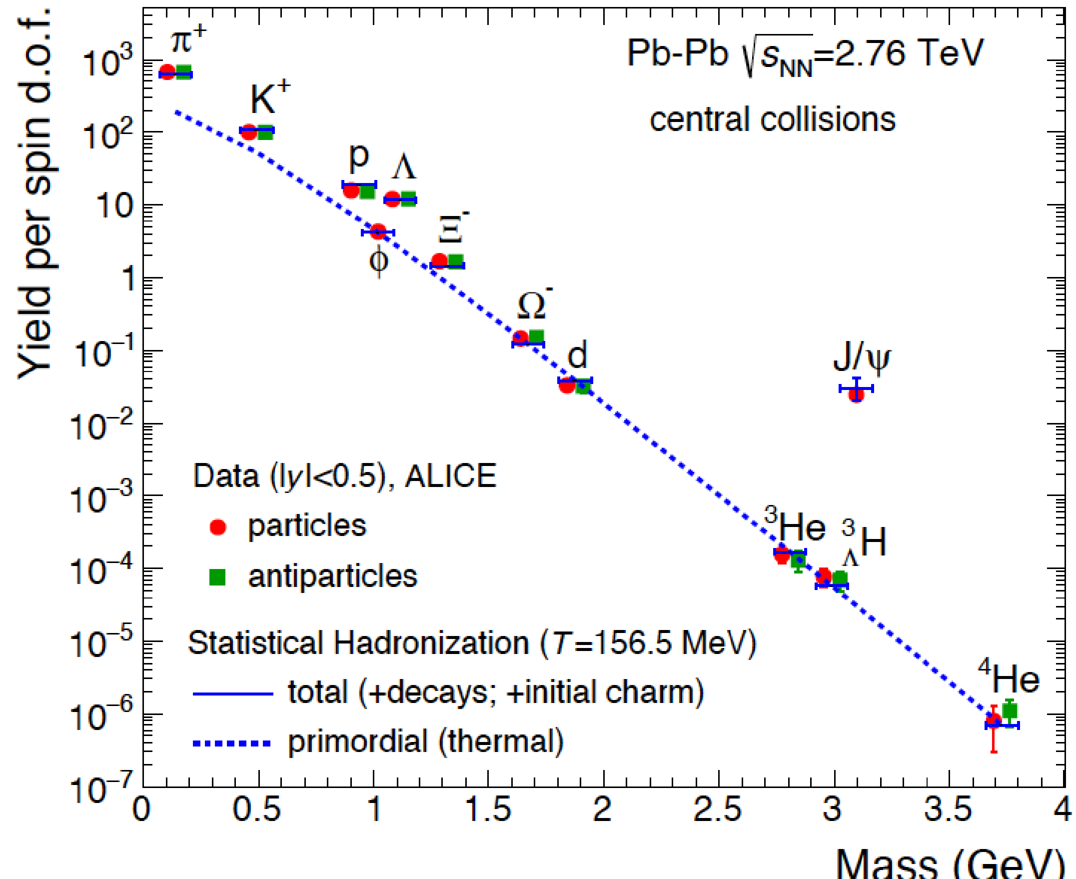
J/ψ enhanced compared to other M = 3 GeV hadrons since number of c-quarks is about 30 times larger than expected for pure thermal production at T = 156 MeV due to production in initial hard collisions and subsequent thermalization in the fireball.

production probability scales with N_{ccbar}^2

enhancement factor is 900 for J/ψ

enhancement factor is 30 for D^0





Andronic, pbm, Koehler, Redlich, Stachel PLB 792 (2019) 304 and Andronic, pbm, Koehler, Mazeliauskas, Redlich, Stachel, Vislavicius,   JHEP 07 (2021) 035

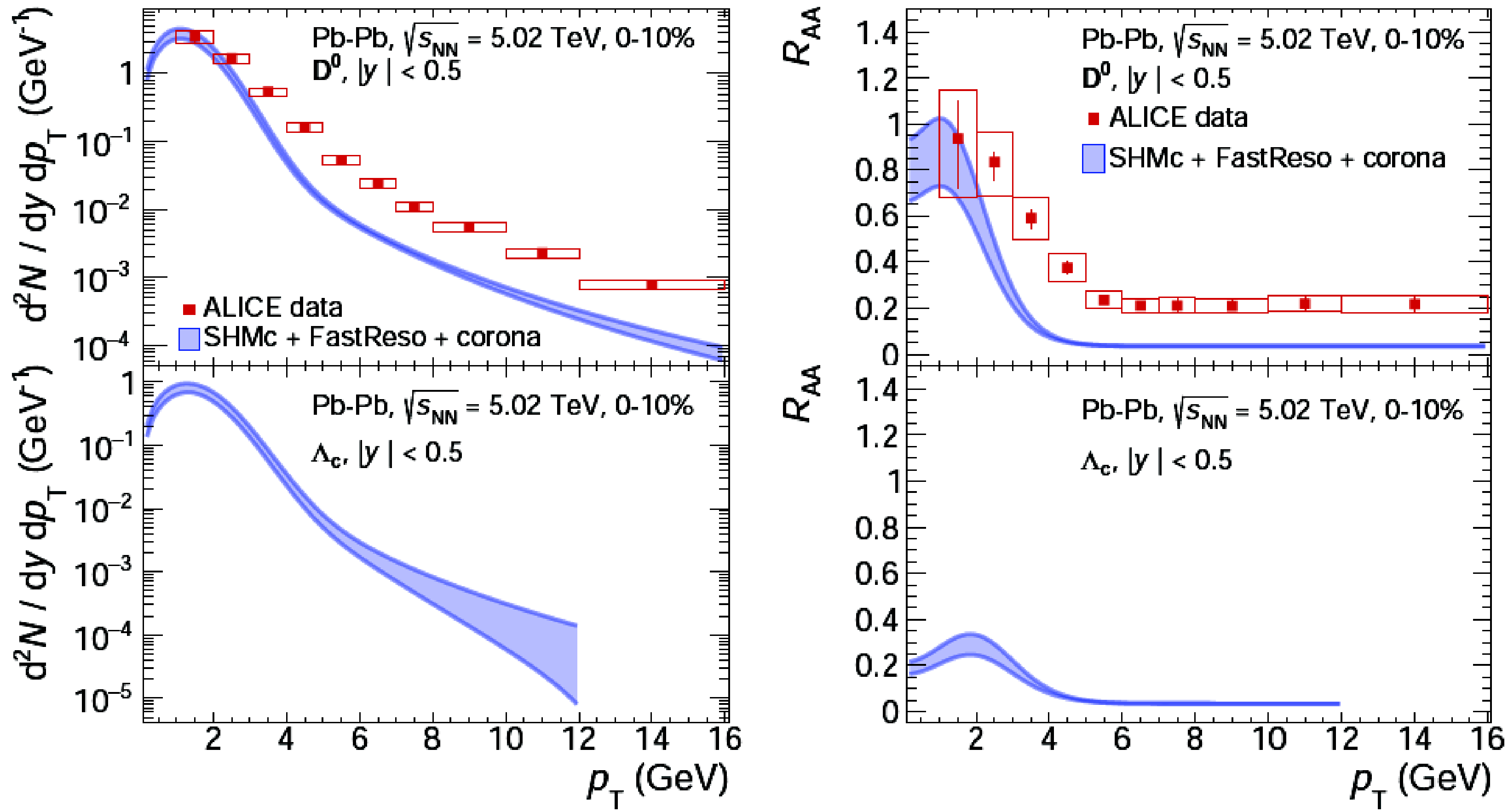
quantitative agreement for open and hidden charm hadrons, same mechanism should work for all open and hidden charm hadrons, universal hadronization mechanism
even for exotica such as Ω_{ccc} where enhancement factor is nearly 30000
quantitative tests in LHC Run3/Run4 and mainly ALICE 3

enhancement is defined relative to purely thermal value, not to pp yield

open charm hadrons and the SHMc

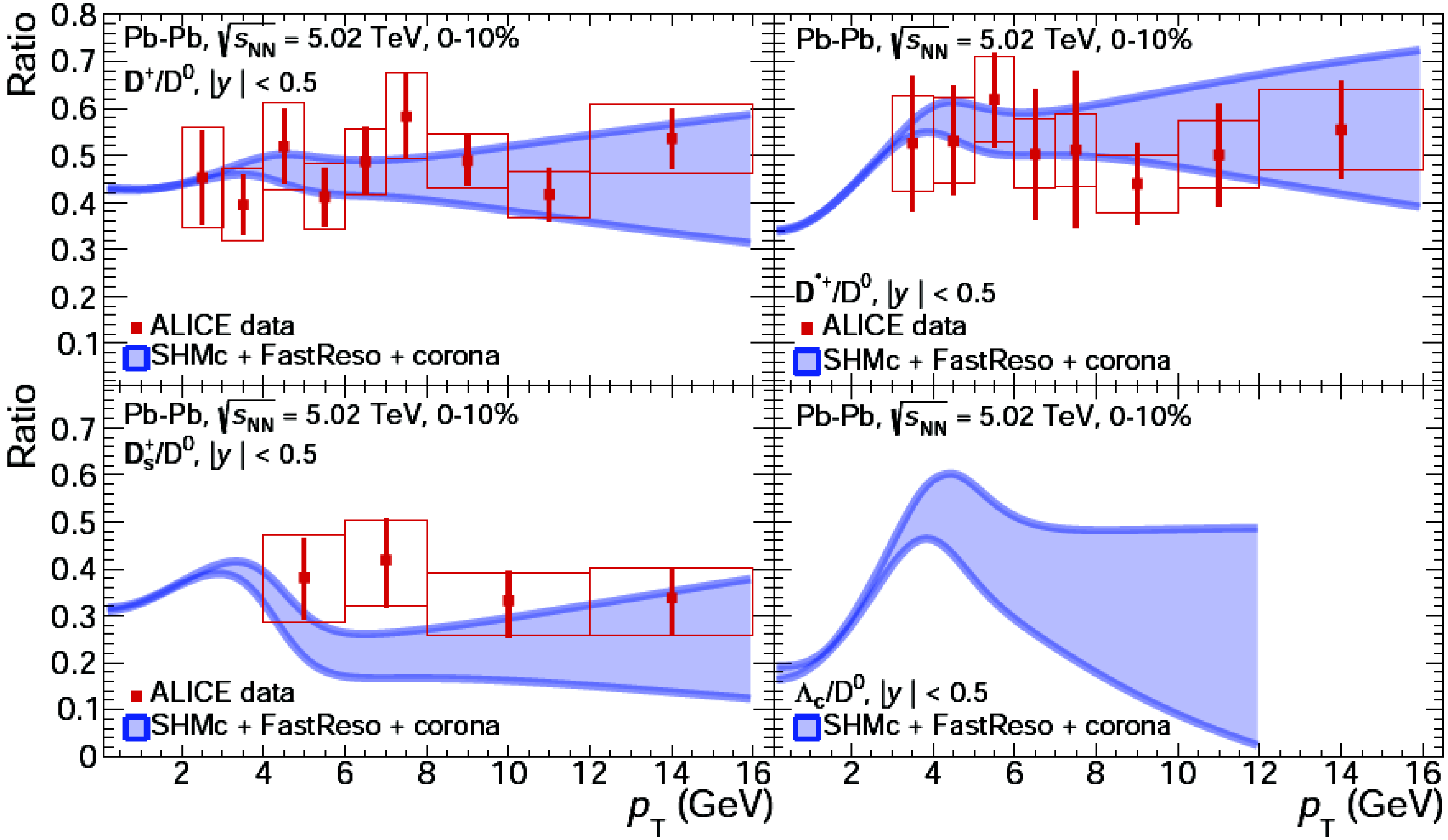
spectra and R_{AA} of D^0 mesons and Λ_c baryons

for open heavy flavor hadrons strong contribution from resonance decays
- include all known charm hadron states as of PDG2020 in SHMc
- compute decay spectra with FastReso: 76 2-body and 10 3-body decays
  (A. Mazeliauskas, S. Floerchinger, E. Grossi, D. Teaney, EPJ C79 (2019) 284 arXiv: 1809.11049)



Λ_c data from ALICE exist, will be shown at QM2022

ratios of charm hadron to D^0 spectra



excellent agreement considering that there are NO free parameters

parameter-free, first indication of charm quark deconfinement

to further reduce uncertainties, need improved measurments of total open charm cross section

multi-charm hadrons, deconfinement and universal hadronization

why are multi-charm baryons important to measure?

these complex baryons are assembled at the QCD phase transition from the quarks in the fireball

in the SHMc the production probability scales as $g_c{}^{n_c}$ if charm quarks are deconfined over the volume of the fireball formed in the Pb-Pb collision, see below

it follows that the yield of the doubly charmed Ξ_{cc}^{++} should be strongly (by a factor 900, see below) enhanced

measurement of this enhancement is hence a clear proof of deconfinement of charm quarks over distances determined by the volume of the fireball

in central Pb-Pb collisions this volume is of order 5000 fm^3

this implies deconfinement over linear dimensions of order 10 fm
much larger than the size of a (confined) nucleon (size of order 0.8 fm)

the multiple-charm hierarchy in the statistical hadronization model

results shown in this lecture are based in part on the recent paper:
A. Andronic, P. Braun-Munzinger, J. Stachel, M. Koehler,
A. Mazeliauskas, K. Redlich, V. Vislavicius, JHEP 07 (2021) 035,
2104.12754 [hep-ph]

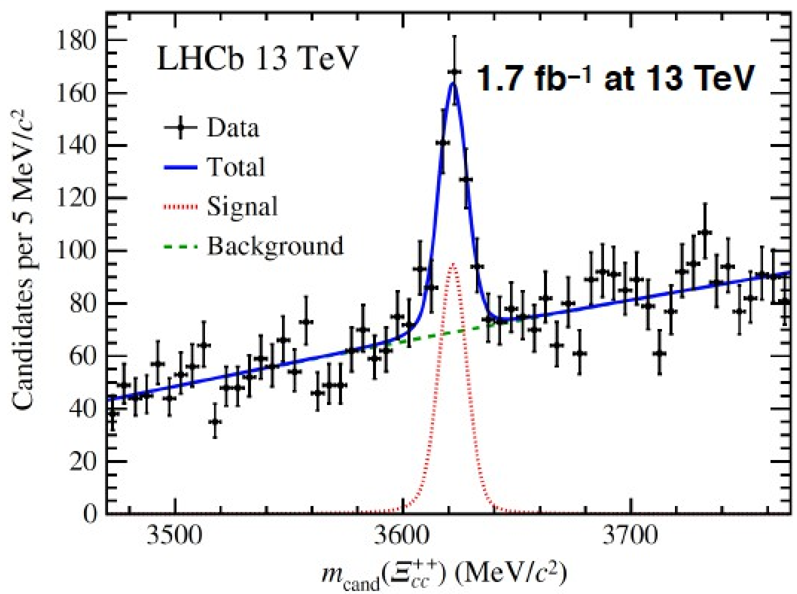
focus on production of open (multi)-charm hadrons at LHC energy
collision systems: Pb-Pb, Xe-Xe, Kr-Kr, Ar-Ar, O-O
production yields, rapidity and transverse momentum distributions

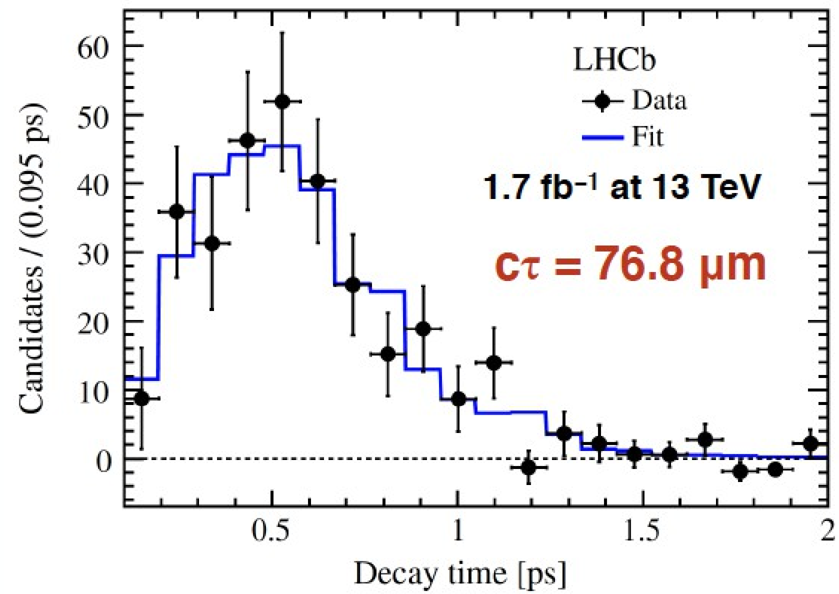
how to measure multi-charm baryons?

measurements are generally done via invariant mass analysis

but: such measurements need very sophisticated detectors since the decay chains can be very complicated

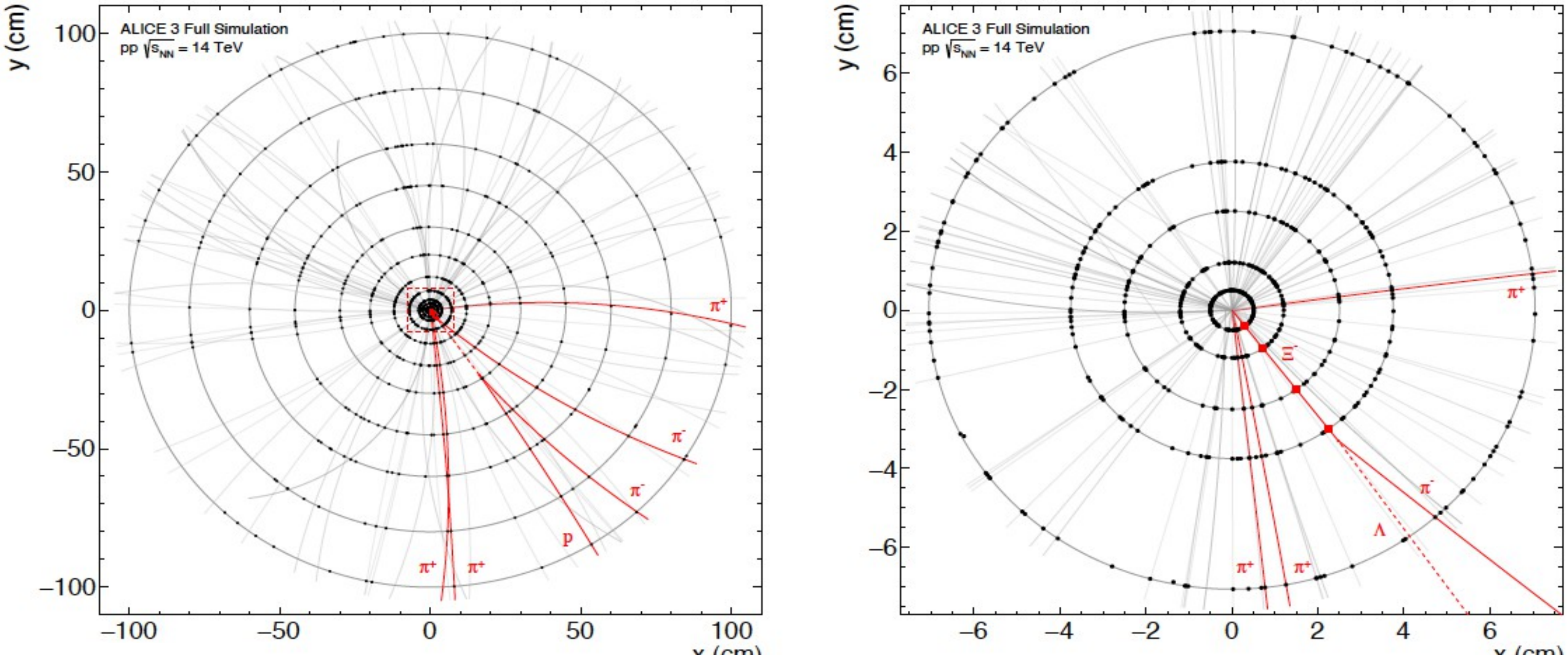
example: $$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$
$$\Lambda_c^+ \to p K^- \pi^+$$





LHCb collaboration, arXiv:1910.11316, pp collisions

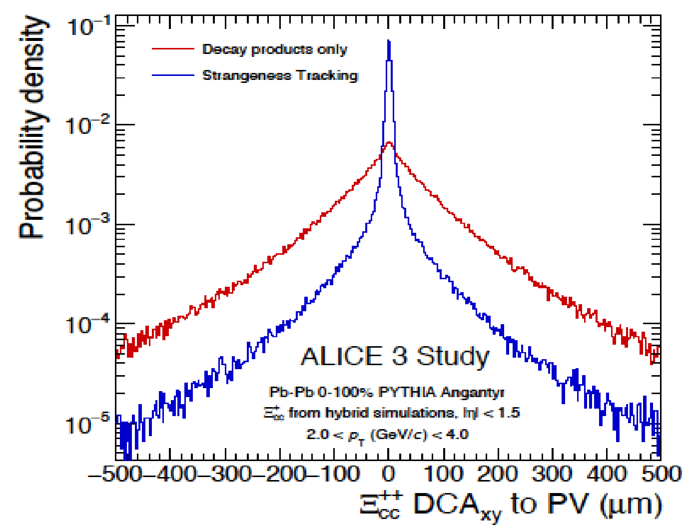
new ALICE development: strangeness tracking



(left) Illustration of strangeness tracking from full detector simulation of the Ξ_{cc}^{++} decay into $\Xi_c^+ + \pi^+$ with the successive decay $\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$. (right) Close-up illustration of the region marked with a red dashed box in the left figure, containing the five innermost layers of ALICE 3 and the hits that were added to the Ξ^- trajectory (red squares).

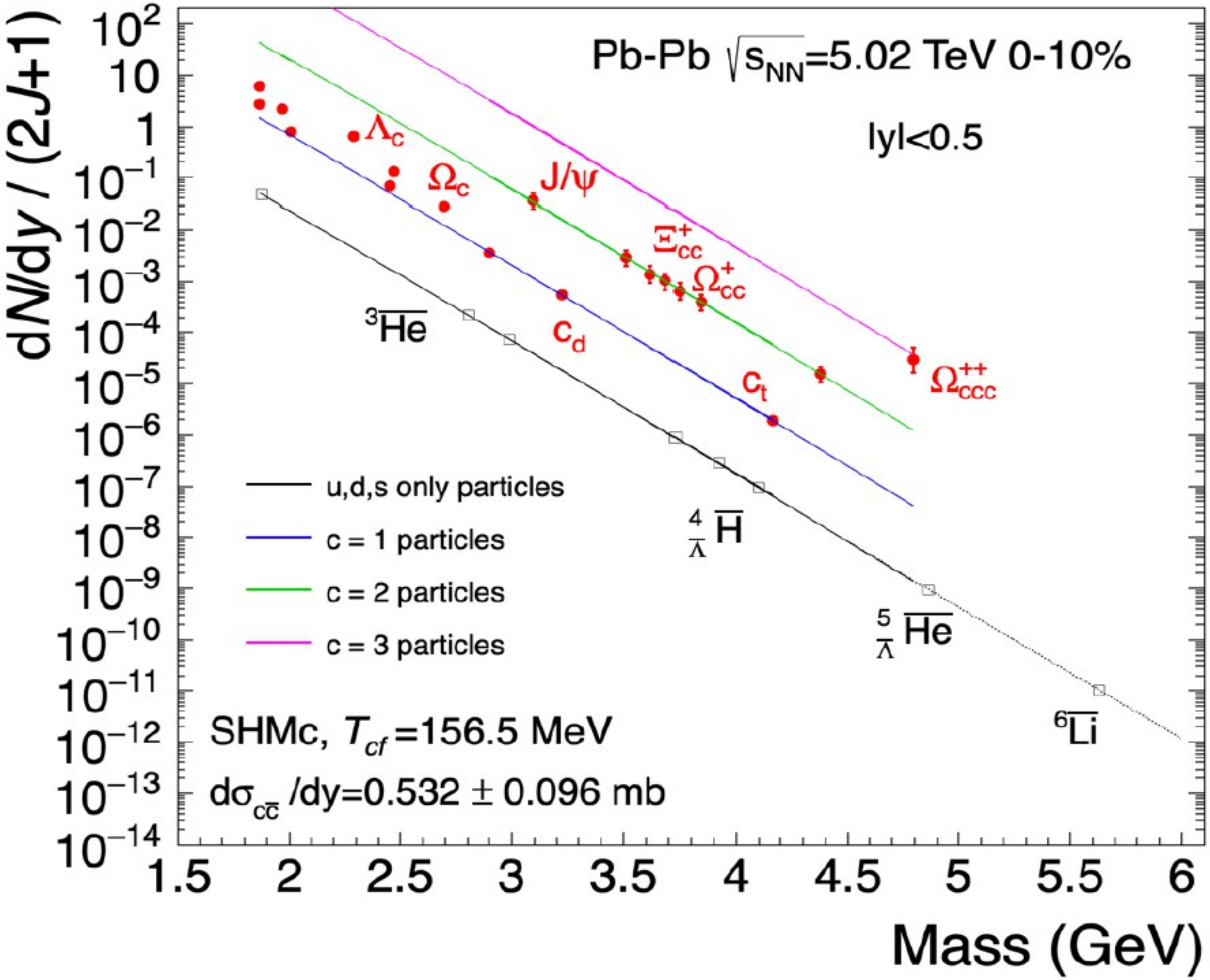
Ξ^{++}_{cc} mass spectrum without (red) and with (blue) strangeness tracking

the power of ultra-thin, ultra-precise MAPS detectors for ALICE 3



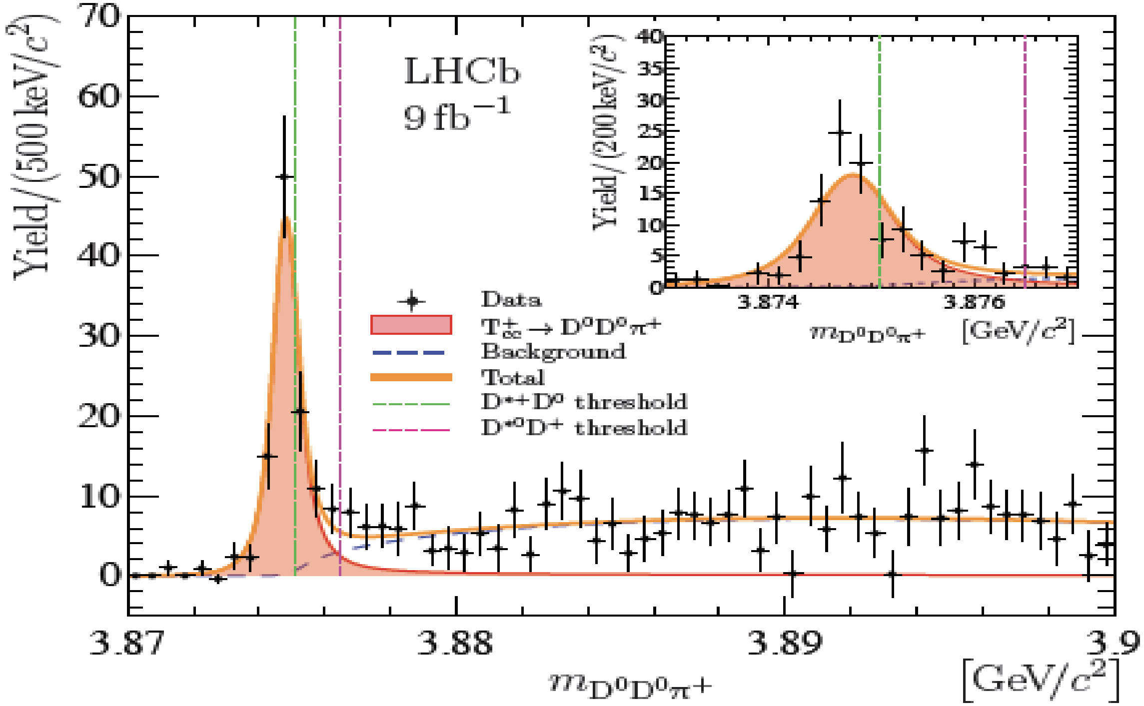
the multi-charm hierarchy

open and hidden charm hadrons, including exotic objects, such as X-states, c-deuteron, pentaquark, Ω_{ccc}



emergence of a unique pattern, due to g_c^n and mass hierarchy
perfect testing ground for deconfinement for LHC Run 3 and beyond

what about T_{cc}^{+} very recently discovered by LHC_b 2109.01038 [hep-ex]



if statistical hadronization is universal, its production cross section will fall on the 2 charm quark line at the measured mass, can be tested experimentally

to understand new aspects of discovery of T_{cc}, need reminder of charmonia

- quarkonia are heavy quark antiquark bound states, i.e. cc_{bar} and bb_{bar}
- since masses of charm and beauty quarks are high as compared to QCD scale parameter Λ_{QCD} ~ 200 MeV non-relativistic Schrödinger equation can be used to find bound states

$$(-\frac{\nabla^2}{2(m_Q/2)} + V(r))\Psi(\vec{r}) = E\Psi(\vec{r})$$

with quark-quark potential of the form

$$V(r) = \sigma r - \frac{4}{3}\frac{\alpha_s}{r} + \frac{32\pi\alpha_s}{9}\frac{\vec{s}_1\cdot\vec{s}_2}{m_Q^2}\delta(\vec{r}) + \ldots$$

confinement

color Coulomb int.

spin-spin int.

tensor, spin-orbit, higher order rel. corr.

note: the pre-factor of the 'QCD Coulomb term' results from 1 gluon exchange and contains the Casimir factor $C_F = (N_c^2 - 1)/2N_c$ with which all 2-body amplitudes in QCD are multiplied. Here, N_c is the number of colors $N_c = 3$.

and

- with the string tension **σ** ~ 0.9 GeV/fm, the strong coupling constant $\boldsymbol{\alpha}_s(m_Q)$ ~ 0.35 and 0.20 for m_c=1.5 and m_b=4.6 GeV, respectively to obtain the spectrum of quarkonia

charmonia at finite temperature

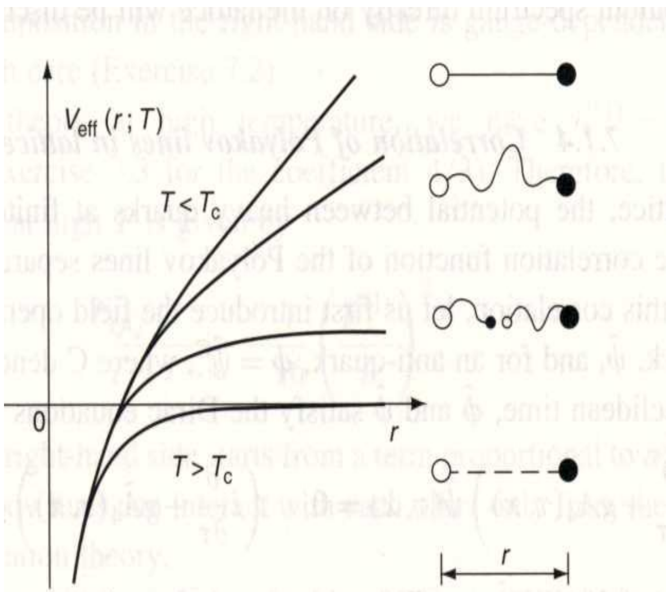
consider T« m_c so QGP of gluons, u,d,s quarks and antiquarks, no thermal heavy quarks

consider cc_{bar} in thermal environment of gluons and light quarks

$$V(r) \to V_{eff}(r,T) \quad \text{and} \quad m_Q \to m_Q(T)$$

in QGP color singlet and color octet cc_{bar} states can mix by absorption or emission of a soft gluon

→ modification of V_{eff}



- reduced string tension as T approaches T_c
- string breaking due to thermal qqbar and gluons leading to D and Dbar
- for T>T_c confining part disappears and short range Coulomb part is Debye screened to give Yukawa type potential

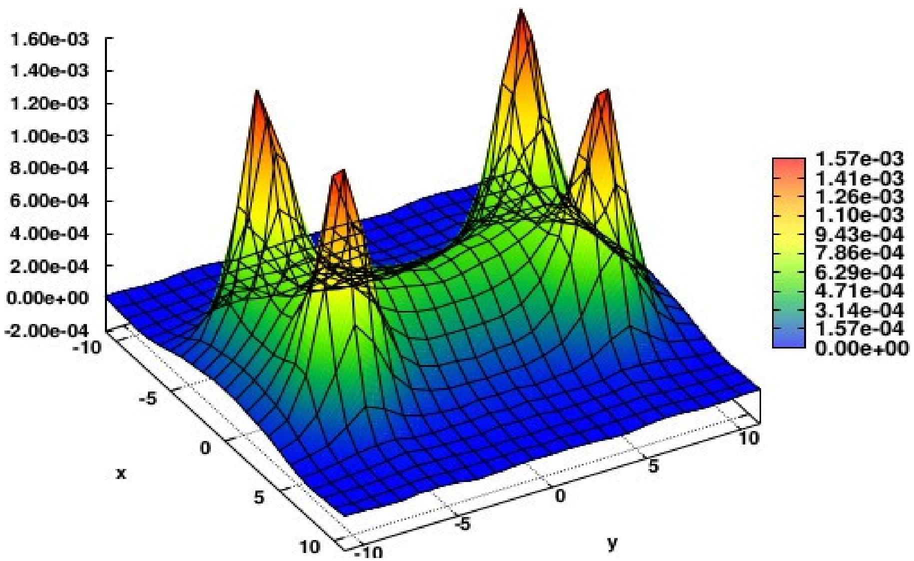
$$V_{eff}(r,T) \to -\frac{4}{3}\frac{\alpha_s}{r}e^{-r/\lambda_D}$$

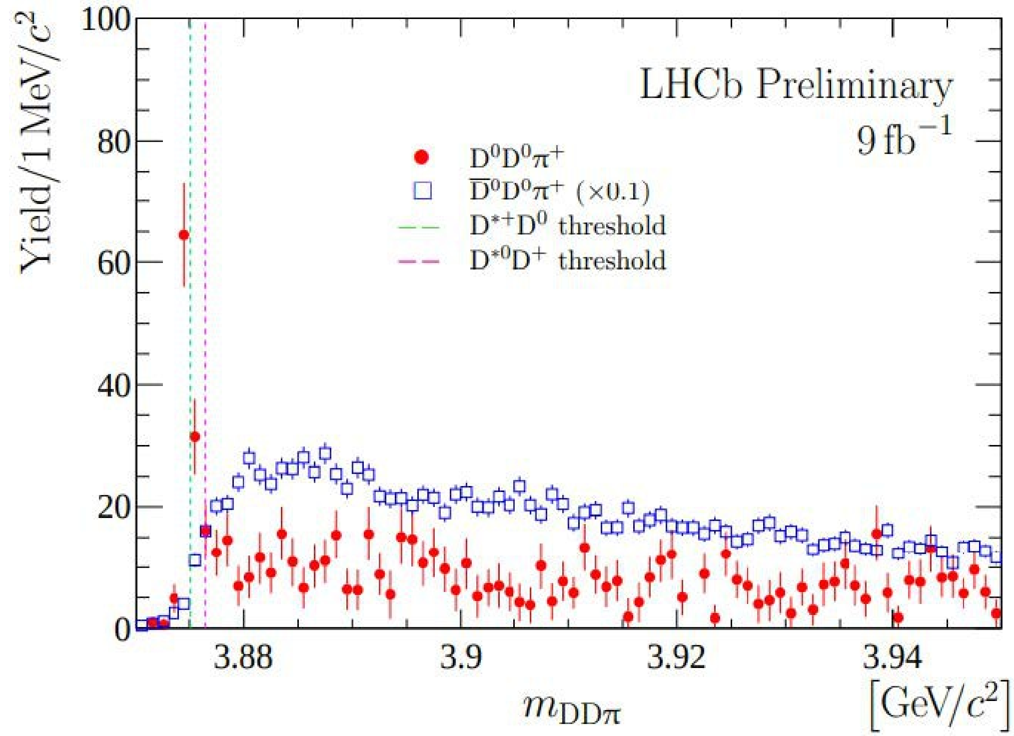
$$\omega_D = 1/\lambda_D$$

Debye screening mass and length

note: charmonia are apparently not special, see discussion about T_{cc}+ below

now tetraquarks





lQCD simulation: Cardoso et al., Phys. Rev. D84 (2011) 054508

LHCb: Nature Phys. (2022) arXiv:2109.01038 [hep-ex]

structure of T_{cc}^{+}

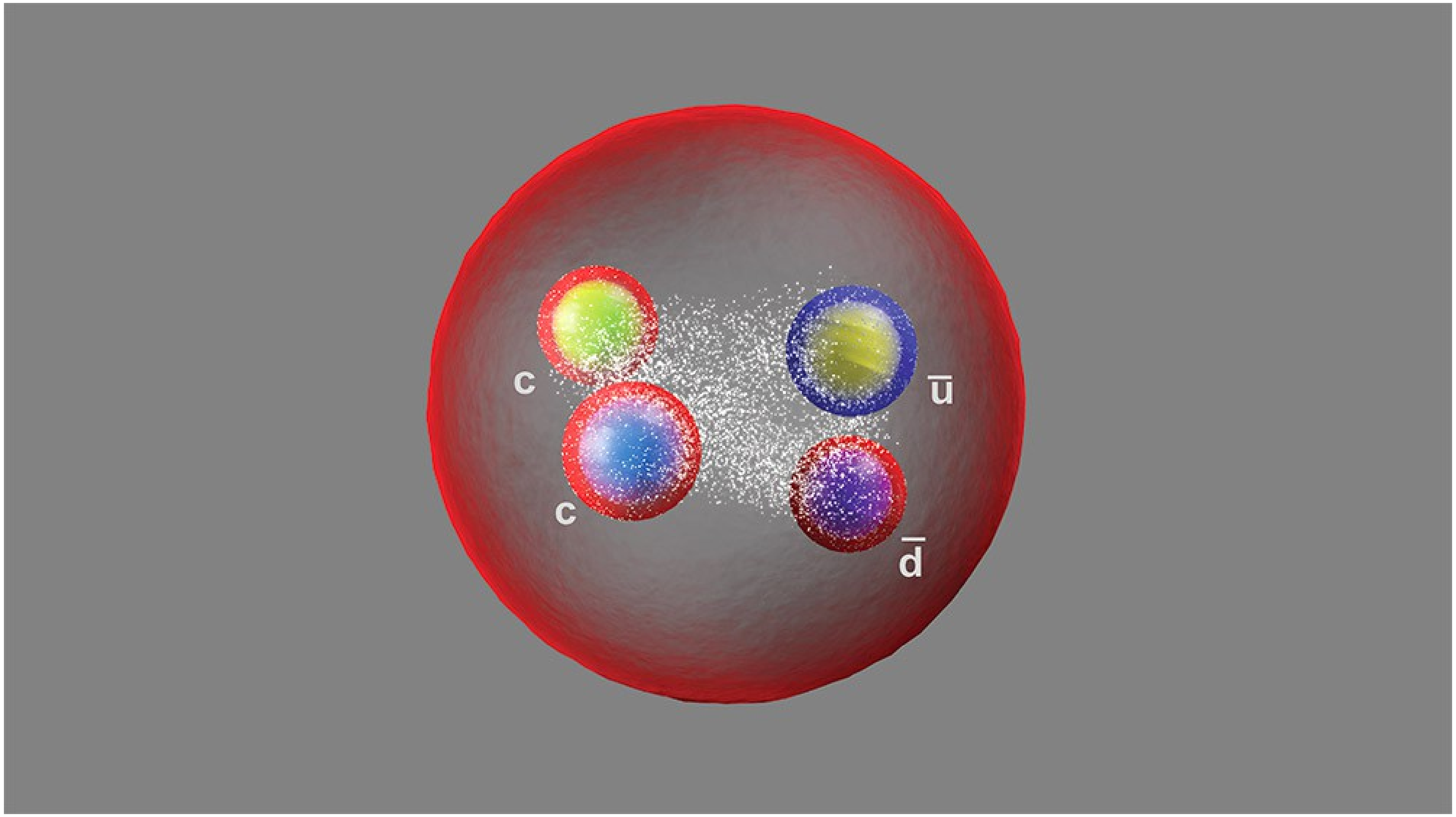


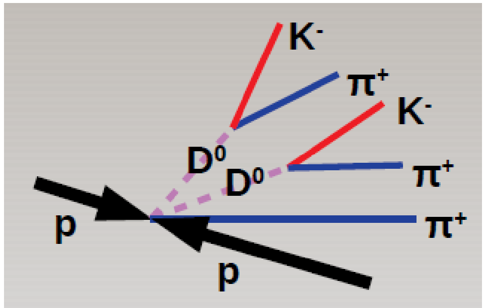
illustration: copyright CERN

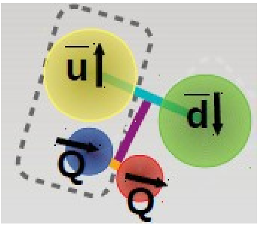
this loosely bound state has net charm 2, very different from charmonia

there is no Debye screening, but we assume that it will be formed at the phase boundary just like the other charmed hadrons

fits naturally into SHMc

predicted yield in central Pb-Pb collisions at 5.02 TeV: dN/dy = 2.8 x 10^{-3}





mass = 3874.75 ± 0.11 MeV
mass is very close to that of $D^{0*}D^{+}_{bar}$
width = 48 ± 2 + 0 - 14 keV
d(m) = - 360 ± 40 keV
binding energy: 360 ± 40 keV
T_{cc}+ → D0 D0 π+
angular momentum: J=1, isospin I = 0

see LHCb papers
2109.01038 [hep-ex]
2109.01056 [hep-ex]

summary – charm production

- statistical hadronization works quantitatively for hadrons with charm quarks
- charm quarks are not thermally produced but in initial hard collisions and subsequently thermalize in the hot and dense fireball
- predicted charmonium enhancement at low p_T established at LHC energies
- charmonium enhancement implies that charm quarks are deconfined over distances > 5 fm

- the study of open charm hadron production has just begun
- predict dN/dy for hierarchy of multi-charm states, very large (> 5000) enhancement expected
- precision study of such hadrons → further insight into confinement, deconfinement and hadronization

Lecture 26 – real and virtual photons

low mass lepton pairs – status and expectations

see also: sect. 8 of CERN Yellow Rep. Monogr. 7 (2019) 1159-1410, 1812.06772 [hep-ph]

main goal: measure electromagnetic radiation emitted by the hot QGP fireball

experimental problem: signal S very small, backgrounds B very large

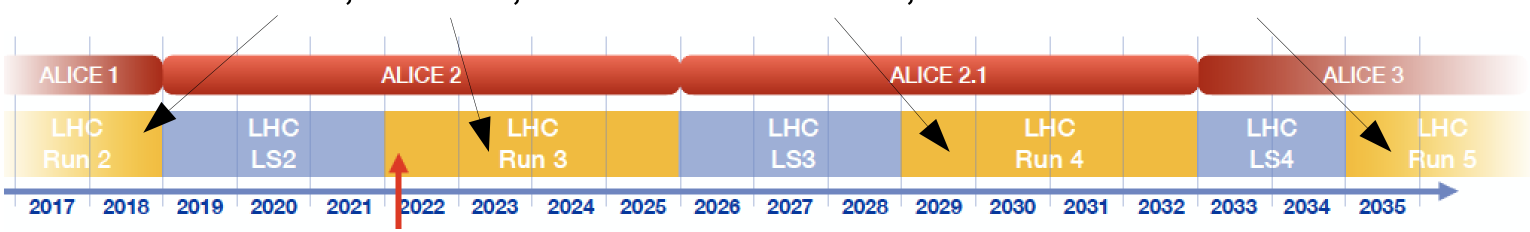
we will focus on di-lepton measurements, no strong interactions in QGP, $S_l \sim \alpha^2 S_h$ relative to hadronic background B, S/B ~ 10^{-4} (B = Dalitz decays of hadrons, photon conversions, di-leptons from charm and beauty decays)

B can be reduced by :

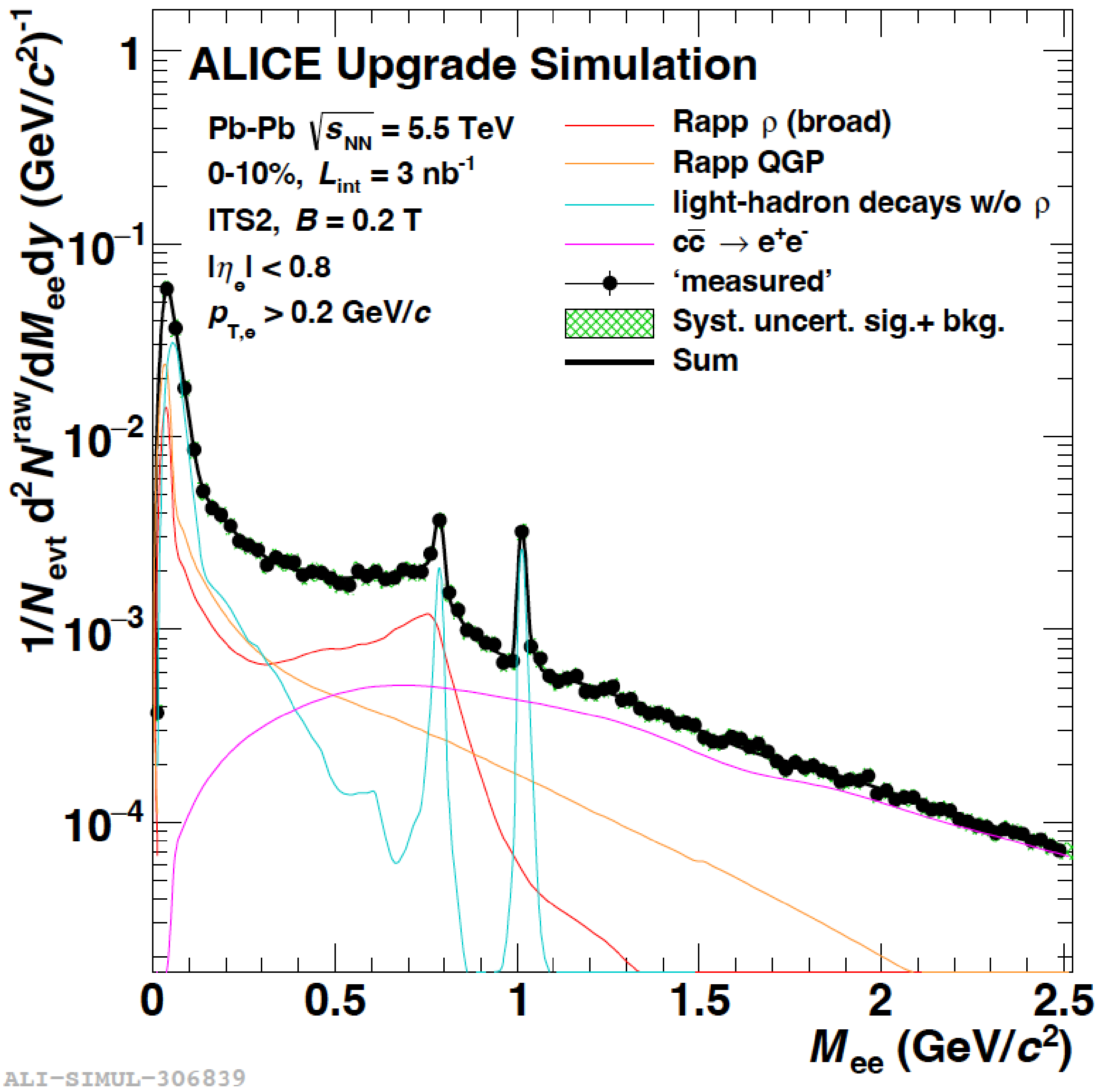
– an improved vertex resolution, which leads to a better separation of electrons from prompt sources, like thermal radiation, and electrons from the decays of heavy-flavour hadrons, for which $c\tau$ is about 150 μm (open-charm hadrons) or 400 μm (open-beauty hadrons),

– a reduced material budget and improved tracking efficiency at low transverse momentum p_T, which leads to a smaller background of electrons and positrons from photon conversion in the detector material,

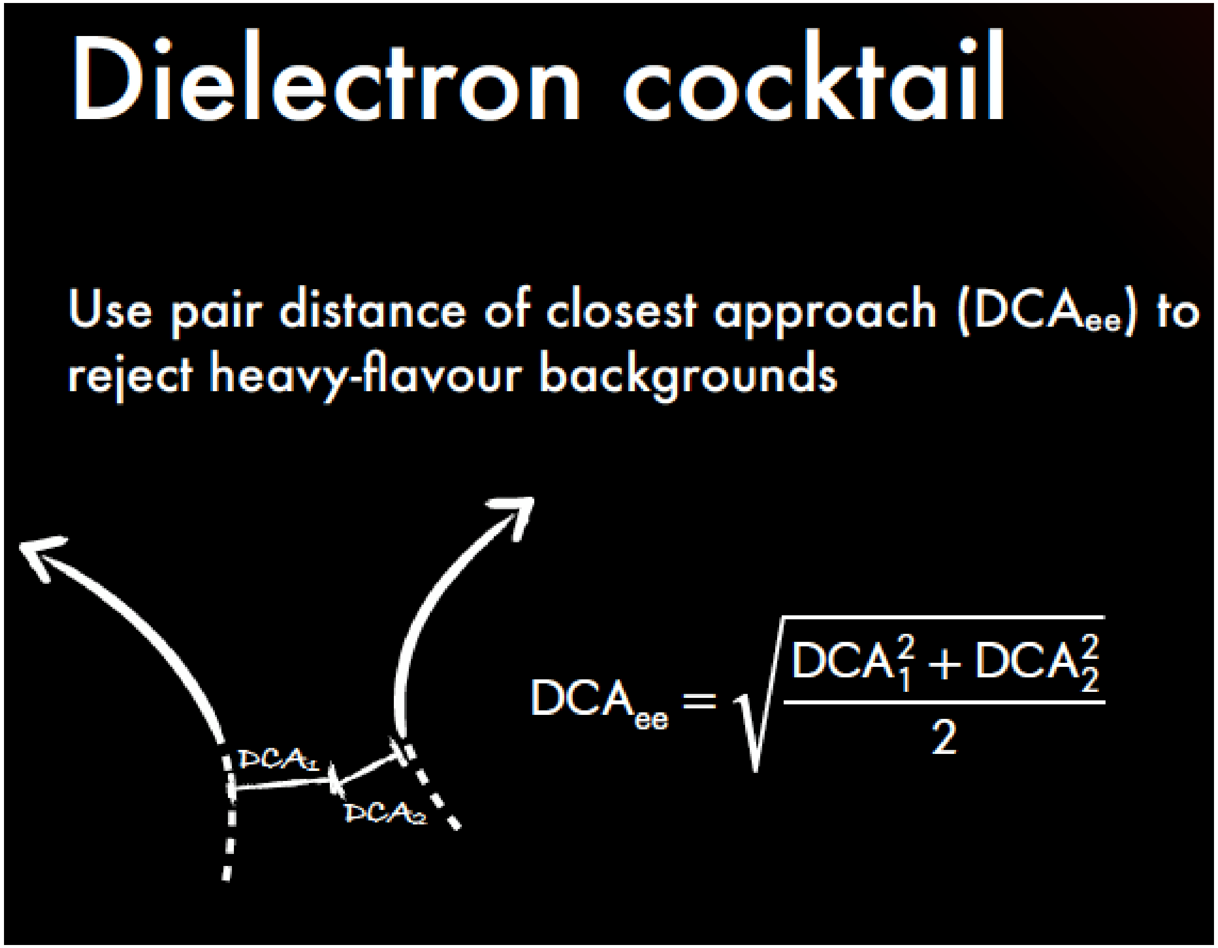
sequence of improvements from better and better inner tracking systems:
for ALICE: ITS, ITS2, ITS3, ALICE 3



expected signal and backgrounds based on 1st 10 years of ALICE running and on new inner tracking system ITS2 built for ALICE Run 3

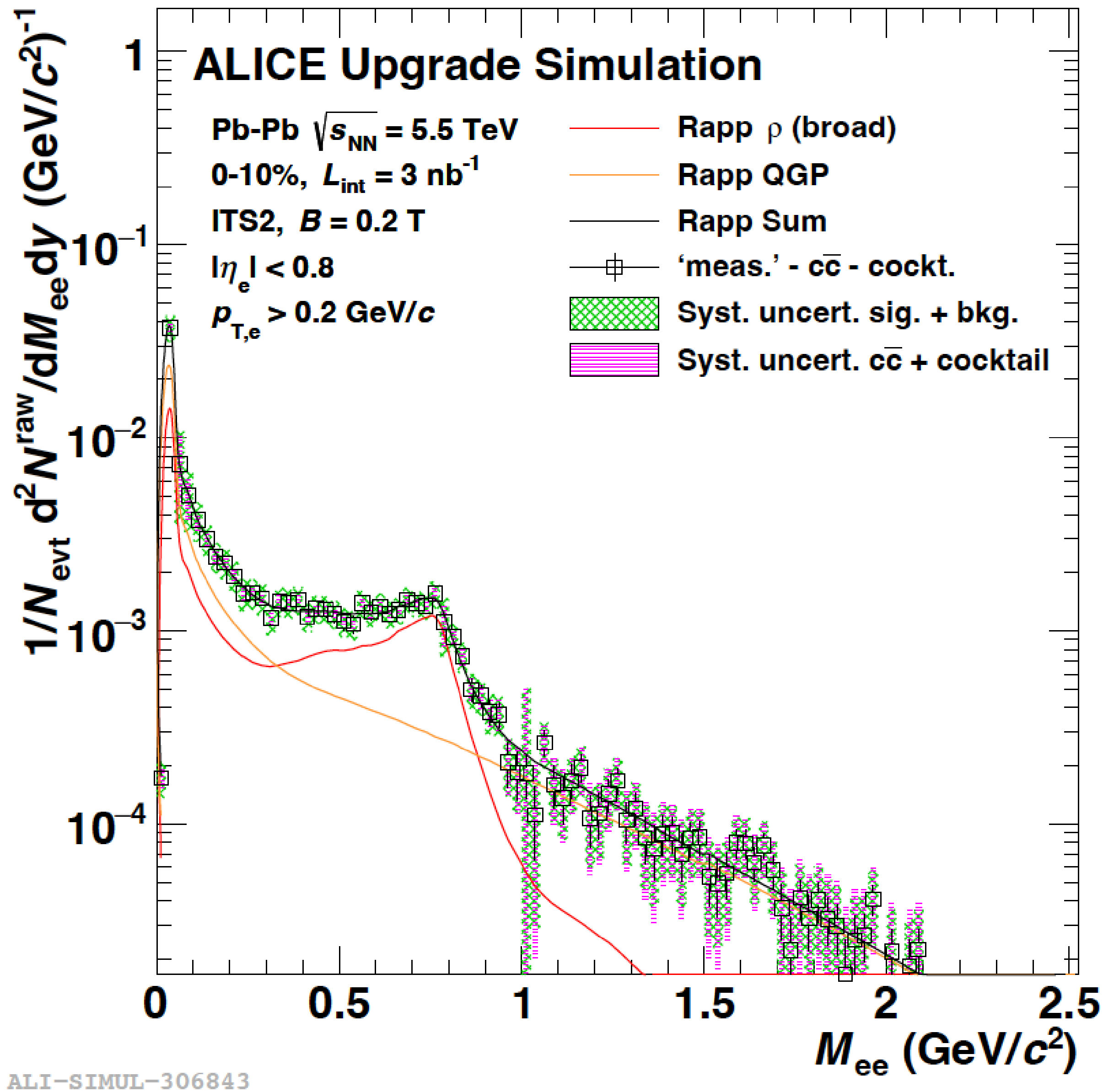


the DCA (distance of closest approach) technique based on precision tracking and very good vertexing with ITS2



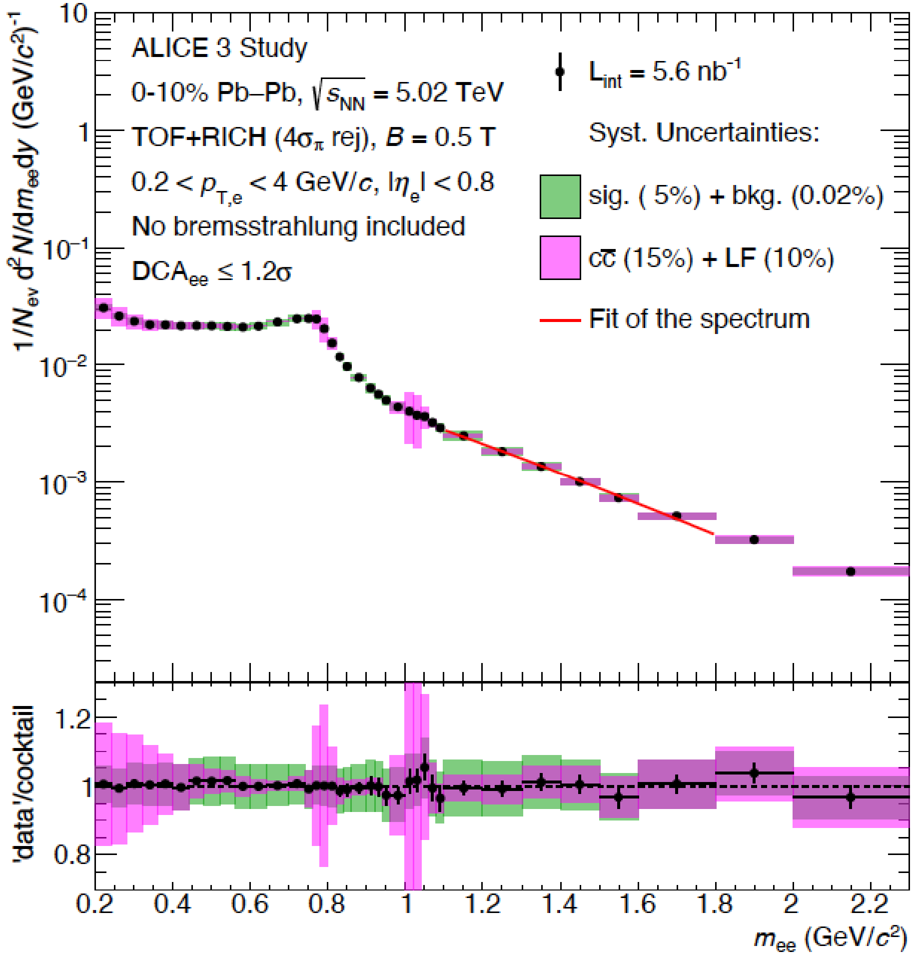
project charged particle tracks onto plane perpendicular to direction of beams. in this 'xy' direction, the quantity DCA$_{ee}$ is evaluated to reject tracks not originating from the primary vertex

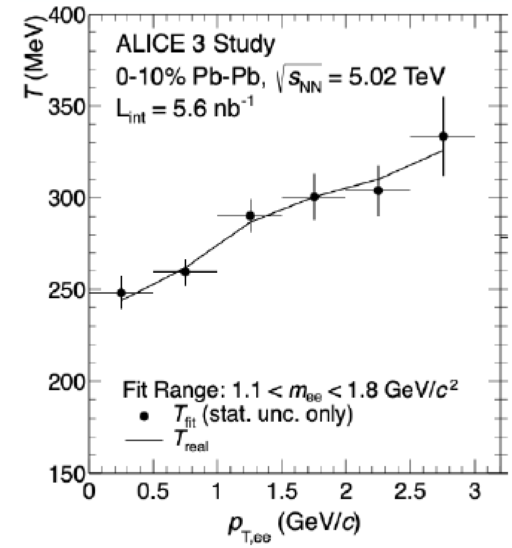
expected signal after subtraction of 'hadronic cocktail' and backgound from correlated charm decays via the DCA technique



spectrum expected at the end of Run 3, i.e. by 2026

... finally, measuring the direct electromagnetic radiation from the QGP fireball with ALICE 3





note: fit of the mass spectrum yields average temperature
fit of the mass spectrum for different p_T windows yields information on the time dependence of temperature

soft photons, the Low theorem, and ALICE 3

In 1958, Francis Low wrote a seminal paper* on how to relate hadron momenta produced in a high energy collision to the number of soft photons produced. The predictions from the resulting theorem have been repeatedly tested experimentally. In most cases, significant discrepancies were found between predictions and experimental measurements. Clearly, the measurement of very soft (MeV scale in transverse momentum) photons presents formidable difficulties. Nevertheless, the disrepancies are striking, and no agreement exists on their possible origin, despite > 40 years of research.

We present ideas how to make a precision test of the Low predictions in the framework of ALICE 3

*F. Low,
Bremsstrahlung of very low-energy quanta in elementary particle collisions,''
Phys. Rev. 110 (1958), 974-977

Background

In all collisions among elementary particles, soft photons can be produced at any stage and without limits on their number by conservation laws etc. This was realized in the 1930ties when first QED calculations were performed, by Weisskopf, Bethe and Heitler and others. The consequences were worked out in systematic fashion in the by now famous paper by Bloch and Nordsieck,

F. Bloch and A. Nordsieck,
Note on the Radiation Field of the electron, Phys. Rev. 52 (1937), 54-59

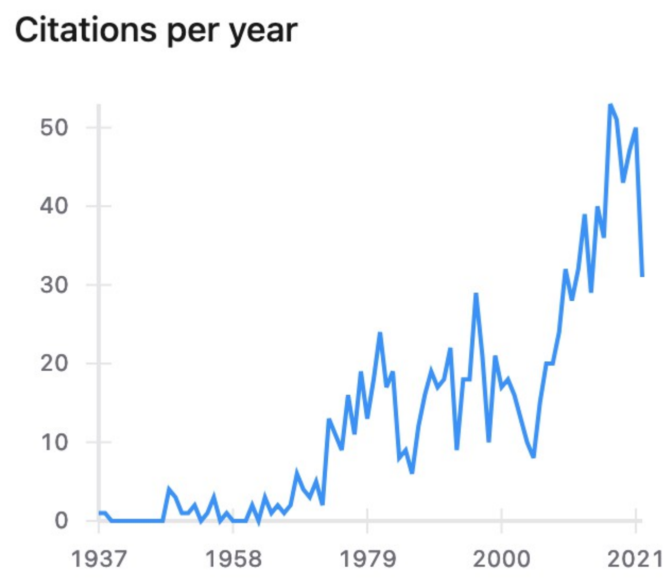
the conclusion by Bloch and Nordsieck is that, in the infrared limit, the mean total number of light quanta radiated diverges, but the mean total energy radiated stays finite. see also H. Bethe and W. Heitler, Proc. Roy. Soc. A146 (1934) 83

This led to the work by Francis Low in the context of collisions between elementary particles.

an aside on Arnold Nordsieck

a man of many talents

- 1911 born in Marysville, Ohio
- 1935 PhD with Robert Oppenheimer, UCB, 'scattering of radiation by an electric field'
- 1935 – 1937 Guggenheim Fellow, worked in Leipzig, Germany with W. Heisenberg, paper with Felix Bloch
- 1947 – 1961 Prof. Physics UIUC, Urbana-Champaign
- 1950 built 1st analog computer out of WW2 surplus worth 700$, later copy was 1st computer at LLNL
- 1953 designed and built the 1st inertial Electrostatic Gyroscope System (EGS), served as inertia navigation system for US nuclear submarines
- 1950ties proposed the CORNFIELD system, a computer-based decision-making system for the air defense of ships using radar
- 1961 head of physics at General Research Corp., Santa Barbara, CA
- 1962 paper ' On numerical integration of ordinary differential equations ' Mathematics of Computation, vol.16 (1962) 22
- 1967 1st numerical solution of the full Boltzmann equation, with B.L Hicks
- 1971 died in St. Barbara



F. Bloch, A. Nordsieck
1116 citations
(July 7, 2022)

Outline

1. a derivation of the Low formula in y and k_t space

2. comments on implementation and application in the experimental context

3. ALICE 3
   - short overview
   - soft photon measurements

4. remarks

5. outlook

The Low theorem:
F.E. Low,
Bremsstrahlung of very low-energy quanta in elementary particle collisions,
Phys. Rev. 110 (1958), 974-977

The 'standard' derivation is based on the original article plus:

1. S. Weinberg, Phys. Rev. 140 (1965) B516 -- particularly clear exposition based on QED and gravitation theory,
see also S. Weinberg, The quantum theory of fields vol. 2
Cambridge University press, 2005

2. A.T. Goshaw et al., PRL 43 (1979) 1065, -- 1st experimental application

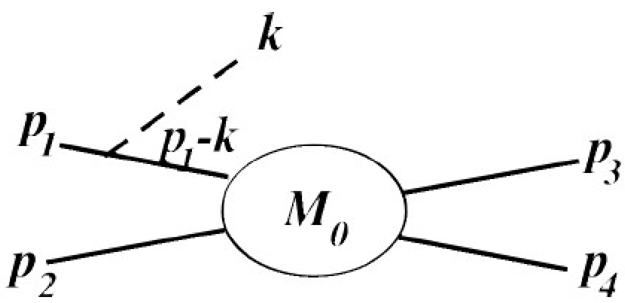
3. Delphi coll., Eur. Phys. J. C67 (2010) 343 -- measurement in jets

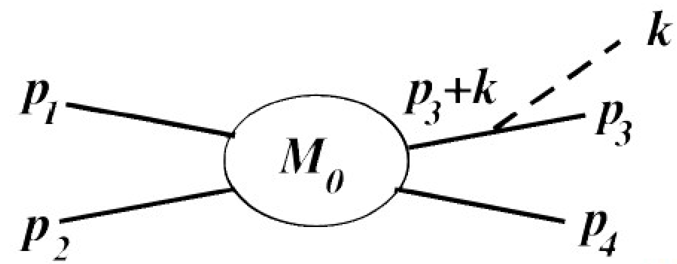
4. C.Y. Wong, arXiv:1404.0440, -- pedagogical introduction

5. A. Strominger, arXiv:1703.05448, -- introduction to soft theorems in general

6. see also recent talks in the Oct. ALICE 3 meeting by Stefan Floerchinger and by Klaus Reygers, available from the authors

Feynman diagrams in leading order for a 'two body collision with soft photons' at high energy





note: the soft photon part is independent of particle identity

$$M(p_1 p_2; p_3 p_4 k) \quad = M_0(p_1 p_2; p_3 p_4) \left(\sum_i^{\text{all charged particles}} \frac{\eta_i e_i p_i \cdot \varepsilon}{2 p_i \cdot k} \right)$$

amplitude 2-body part photon part

all momenta are 4-vectors, ε is the 4-vector polarization of the photon
e_i is the charge of particle i and η_i = -1 for an incoming hadron,
η_i = + 1 for an outgoing hadron
note the presence of interference terms between incoming and outgoing particles

a note on the propagator of the emitted photon

for real photons, the propagator contains (since $p^2 - m^2 = 0$) a factor:

$$[(p \pm k)^2 - m^2]^{-1} = (\pm 2pk)^{-1}$$

this is derived in : Steven Weinberg, Phys. Rev. 140 (1965) B516, see eq. 2.1 and 2.2 and beware of the sign convention explained in footnote 7

this implies that the amplitude of a process with a bremsstrahlung photon has a divergence (pole) whenever $p\,k \rightarrow 0$. Since $p\,k$ is a Lorentz invariant, this implies that, for vanishing photon energy E_γ (in any reference frame), the amplitude for soft photon production diverges as $1/E_\gamma$.

In experiments, one usually goes to forward rapidity y, where $E_\gamma = k_T \cosh y$, and in the reference frame determined by rapidity y, the divergence is in $1/k_T$

in the soft photon limit, all Feynman diagrams where the soft photon line is connected to an internal line, i.e. a virtual charged particle with p^2 not equal to m^2 , yield a non-diverging and, hence, negligible contribution to the soft photon production cross section, as already noted by Weinberg. Consequently, it is not necessary to evaluate the contribution of all possible internal diagrams.

two versions of the Low formula

(a) original version

$$\frac{dN_\gamma}{d^3\vec{k}} = \frac{\alpha}{(2\pi)^2}\frac{1}{E_\gamma}\int d^3\vec{p}_1 ... d^3\vec{p}_N \sum_{i,j}\eta_i\eta_j \frac{-(P_iP_j)}{(P_iK)(P_jK)}\frac{dN_{hadrons}}{d^3\vec{p}_1...d^3\vec{p}_N}$$

(b) Haissinski version

J. Haissinski, How to Compute in Practice the Energy Carried away by Soft Photons to all Orders in α, LAL 87-11, 1987; http://ccdb4fs.kek.jp/cgi-bin/img−index?8704270

$$\frac{dN_\gamma}{d^3\vec{k}} = \frac{\alpha}{(2\pi)^2}\frac{1}{E_\gamma}\int d^3\vec{p}_1 ... d^3\vec{p}_N \sum_{i,j}\eta_i\eta_j \frac{(\vec{p}_{i\perp}\cdot\vec{p}_{j\perp})}{(P_iK)(P_jK)}\frac{dN_{hadrons}}{d^3\vec{p}_1...d^3\vec{p}_N}$$

$$\vec{p}_{i\perp} = \vec{p}_i - (\vec{n}\cdot\vec{p}_i)\cdot\vec{n} \text{ and } \vec{n} \text{ is the photon unit vector, } \vec{n} = \vec{k}/k$$

both formulas are mathematically equivalent, but (b) is much preferred for e+e- collisions because of strong interference between incoming and outgoing particles

for pp or AA collisions with many outgoing particles the interference term between ingoing and outgoing particles is very small but for numerical applications (b) is more stable

why test these 'divergencies' experimentally?

when the photon transverse momentum becomes very small, $k_t^{-1} >> d_{trans}$ the maximum conceivable transverse dimensions d_{trans}, then the structure of the system does not matter anymore

note: k_t = 1 MeV corresponds to k_t^{-1} = 200 fm

any deviation between between Low theorem predictions and experimental results for soft photon spectrum indicates:

a) a loophole in the theory argument

b) an experimental problem

or

c) something fundamentally not understood

a loophole in the theory?

the Low theorem has now been intensively studied by many scientists, for an exhaustive discussion see the review by A. Strominger, arXiv:1703.05448

the theorem has been derived in various ways and is considered, in the soft photon limit, tree-level exact, i.e. there are no loop corrections
see also 2107.10829 [hep-ph] for a recent update, also discussed below

are there possibly non-perturbative corrections?

I quote here again Andrew Strominger:

> To even talk about nonperturbative contributions to the soft theorem, one first needs a theory that exists nonperturbatively. QED — the theory of photons and electrons — does not exist due to the Landau pole. It must be embedded in some bigger theory — maybe one that is asymptotically free — that does exist nonperturbatively. To the best of my knowledge, all examples of such bigger theories contain magnetic monopoles.

clearly it is important to test the predictions of the Low theorem as best we can

experimental problems?

soft photons (E_{photon} << 100 MeV) are very difficult to measure in a collider environment

one also needs precise measurement of the momenta of all primary charged particles, over what phase space needs to be discussed

nearly all experimental tests so far have found large discrepancies between theoretical prediction and data, see below

since we can express all quantities in (k_T, y) space it helps to move to very small angles relative to the direction of one of the colliding beams, i.e. to large rapidities y. then for very small k_T, the photon energy becomes boosted to $E_{photon} = k = k_T \cosh(y)$. for rapidity y = 4.5, cosh(y) = 45, so at k_T = 10 MeV, E_{photon} = 450 MeV

an aside: what is the nature of an 'elementary' particle

- the Low divergence implies that there are no isolated particles but rather each particle is in fact accompanied ('dressed') by an infinite cloud of soft photons
- since the soft photon factor is independent of the particle's identity, the photon cloud should be universal
- same is true for soft gravitons – see Steven Weingerg's paper presented above

thoughts about experimental approaches to test the Low theorem

1. currently, the direct photon spectrum in pp to Pb-Pb collisions is largely unknown for transverse momenta below 1 GeV

2. measurements in this kinematic region are exceedingly difficult because of the huge decay photon background

3. the soft photon spectrum in the very low k_t region can be computed with precision if one has an excellent measurement of the momenta of all charged primary particles with the least possible cut-offs

4. 1^{st} focus should be on pp collisions at the highest available energy, both for exclusive channels and inclusive production

5. new at LHC energies is that one can make the number of outgoing charged particles large. this is a direct test of the multipicity dependence of soft photon production. It also will significantly change the interference pattern between incoming and outgoing particles, a unique possibility at high energy

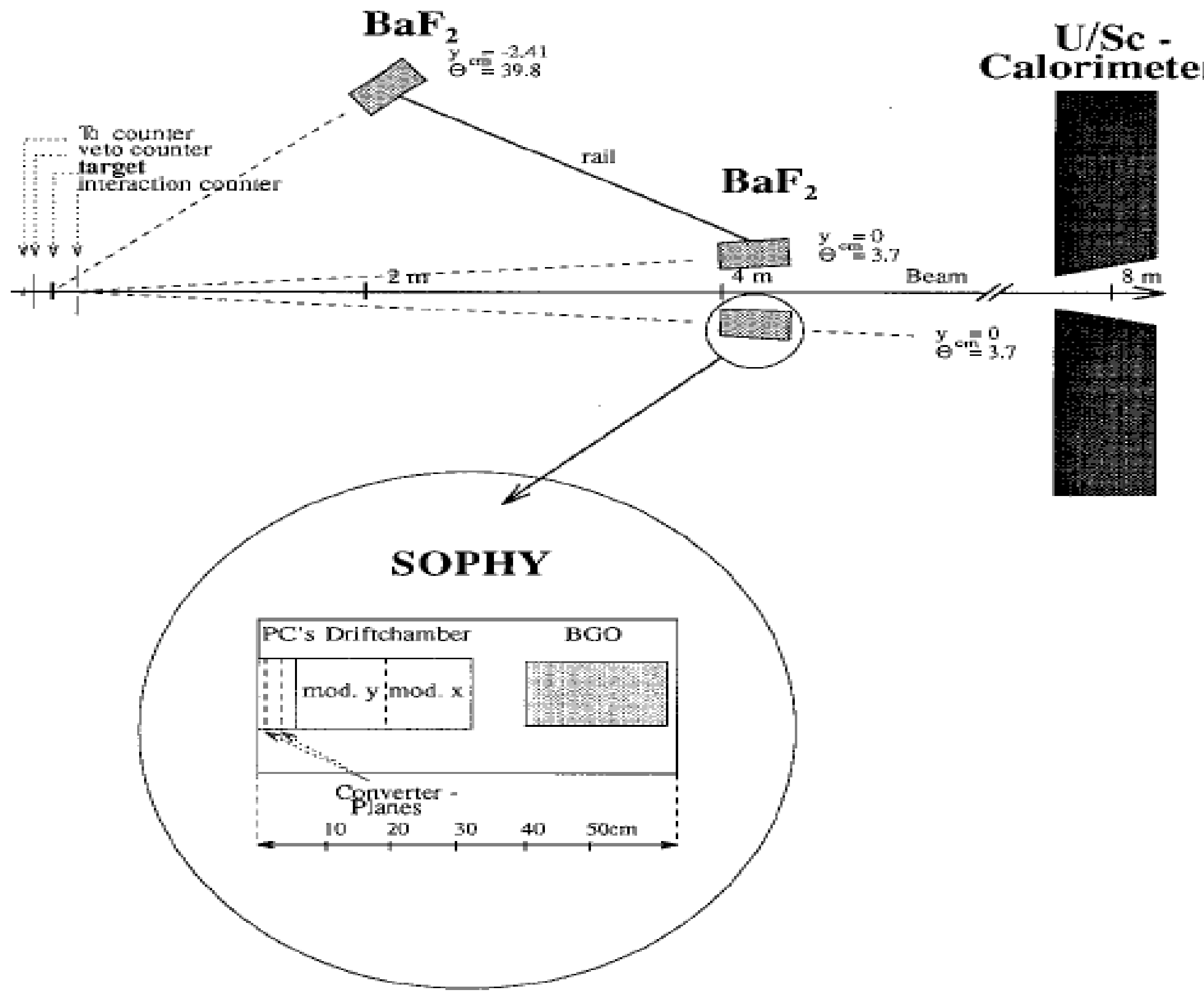
6. to understand what is going on one needs to measure the range between 100 MeV and 10 MeV as well as possible before attempting to go into the MeV region

7. maybe the region below 20 – 30 MeV becomes simpler because of the suppression of meson decay photons via the Jacobi factor, see below

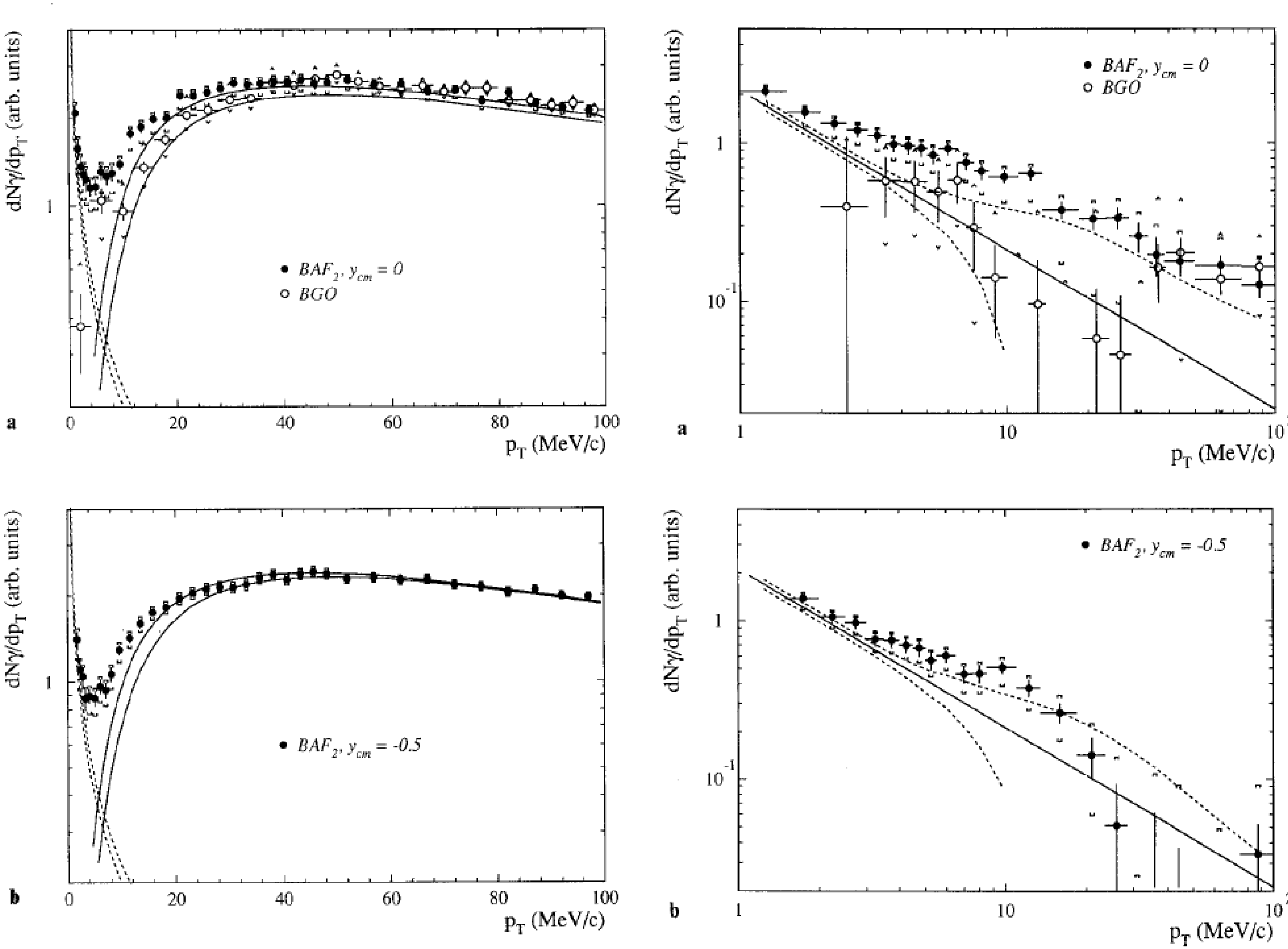
8. simultaneous measurement of low mass low p_t di-electrons is very important, although and especially because it is clear that there is nothing like a Low theorem and a divergence for virtual photons. their total energy cannot be less than $2\ m_e = 1.02$ MeV.

Z. Phys. C 59, 547–553 (1993)

Soft photon production in 450 GeV/c *p*-Be collisions



... there is life beyond the Jacobian peak

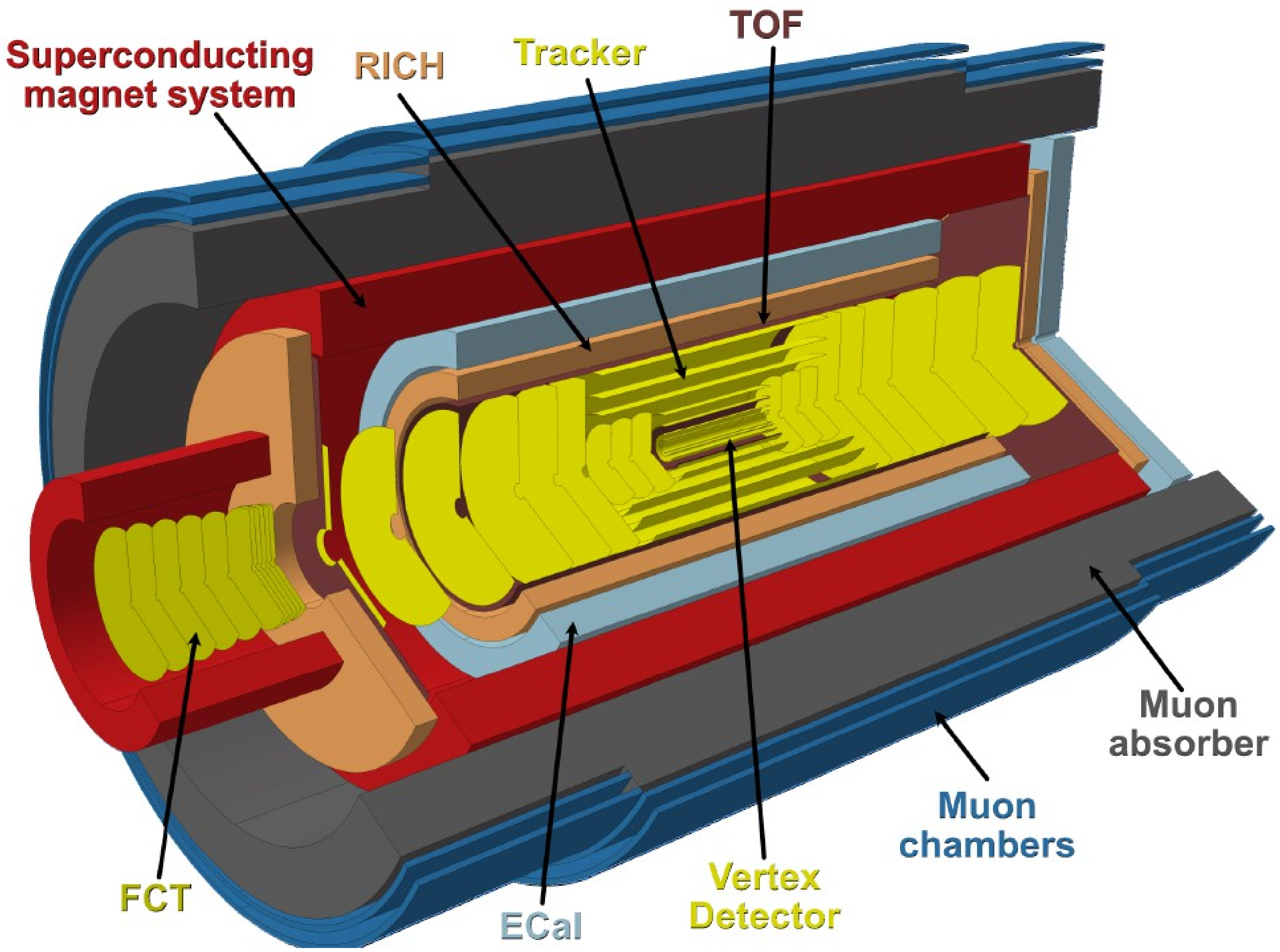


real photons down to the MeV scale, bremsstrahlung rise towards low k_T (p_T) clearly observed, smaller than but still consistent with Low theorem predictions, charged particles were not measured, only simulated summary of most existing soft photon results, taken from K. Reygers, ALICE 3 workshop , Oct. 2020

Experiment	Year	Collision energy	Photon p_T	Photon / Brems Ratio	Detection method	Reference (click to go to paper)
π^+p	1979	10.5 GeV	p_T < 30 MeV/c	1.25 ± 0.25	bubble chamber	Goshaw et al., Phys. Rev. Lett. 43, 1065 (1979)
K^+p WA27, CERN	1984	70 GeV	p_T < 60 MeV/c	4.0 ± 0.8	bubble chamber (BEBC)	Chliapnikov et al., Phys. Lett. B 141, 276 (1984)
π^+p CERN, EHS, NA22	1991	250 GeV	p_T < 40 MeV/c	6.4 ± 1.6	bubble chamber (RCBC)	Botterweck et al., Z. Phys. C 51, 541 (1991)
K^+p CERN, EHS, NA22	1991	250 GeV	p_T < 40 MeV/c	6.9 ± 1.3	bubble chamber (RCBC)	Botterweck et al., Z. Phys. C 51, 541 (1991)
π^-p, CERN, WA83, OMEGA	1993	280 GeV	p_T < 10 MeV/c (0.2 < E_γ < 1 GeV)	7.9 ± 1.4	calorimeter	Banerjee et al., Phys. Lett. B 305, 182 (1993)
p-Be	1993	450 GeV	p_T < 20 MeV/c	< 2	pair conversion, calorimeter	Antos et al., Z. Phys. C 59, 547 (1993)
p-Be, p-W	1996	18 GeV	p_T < 50 MeV/c	< 2.65	calorimeter	Lissauer et al., Phys.Rev. C54 (1996) 1918
π^-p, CERN, WA91, OMEGA	1997	280 GeV	p_T < 20 MeV/c (0.2 < E_γ < 1 GeV)	7.8 ± 1.5	pair conversion	Belogianni et al., Phys. Lett. B 408, 487 (1997)
π^-p, CERN, WA91, OMEGA	2002	280 GeV	p_T < 20 MeV/c (0.2 < E_γ < 1 GeV)	5.3 ± 1.0	pair conversion	Belogianni et al., Phys. Lett. B 548, 122 (2002)
pp, CERN, WA102, OMEGA	2002	450 GeV	p_T < 20 MeV/c (0.2 < E_γ < 1 GeV)	4.1 ± 0.8	pair conversion	Belogianni et al., Phys. Lett. B 548, 129 (2002)
$e^+e^- \to$ 2 jets CERN, DELPHI	2006	91 GeV (CM)	p_T < 80 MeV/c (0.2 < E_γ < 1 GeV)	4.0 ± 0.3 ± 1.0	pair conversion	DELPHI, Eur. Phys. J. C 47, 273 (2006)
$e^+e^- \to \mu^+\mu^-$ CERN, DELPHI	2008	91 GeV (CM)	p_T < 80 MeV/c	~ 1	pair conversion	DELPHI, Eur. Phys. J. C57, 499 (2008)

large discrepancies between Low predictions and measurements

ALICE 3 and ultra-soft photons



FCT:
forward conversion
tracker for soft photon
measurements

ALICE 3
the future (and futuristic) ALICE detector to study novel QCD phenomena in the low transverse momentum region $p_T < 10$ GeV
for colliding systems pp, pPb, OO, KrKr, XeXe, PbPb at LHC energies.