

# Experimental opportunities for new physics at low transverse momentum

- some historical comments: the QGP in ALICE phase 1 and 2
- remarks on importance of low transverse momentum coverage
- focus 1: charm and multi-charm hadrons, deconfinement and universal hadronization
- focus 2: photons and di-leptons at low transverse momentum
- focus 3: ultra-soft photon measurements in ALICE 3
- outlook

pbm

student lecture QM2022  
Krakow, Poland  
Monday, April 4, 2022



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collaborators on:

multicharm production and deconfinement:

Anton Andronic, Krzysztof Redlich, Johanna Stachel +  
Bengt Friman, Pok Man Lo, Aleksas Mazeliauskas, Vytautas Vislavicius

soft photons:

the ALICE 3 soft photon working group\* plus theory input from Otto Nachtmann  
and Stefan Floerchinger

\* pbm, Henner Buesching, Klaus Reygers, Tim Rogoschinski, Kai Schweda,  
Georgijs Skorodumovs, Johanna Stachel, Martin Voelkl

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

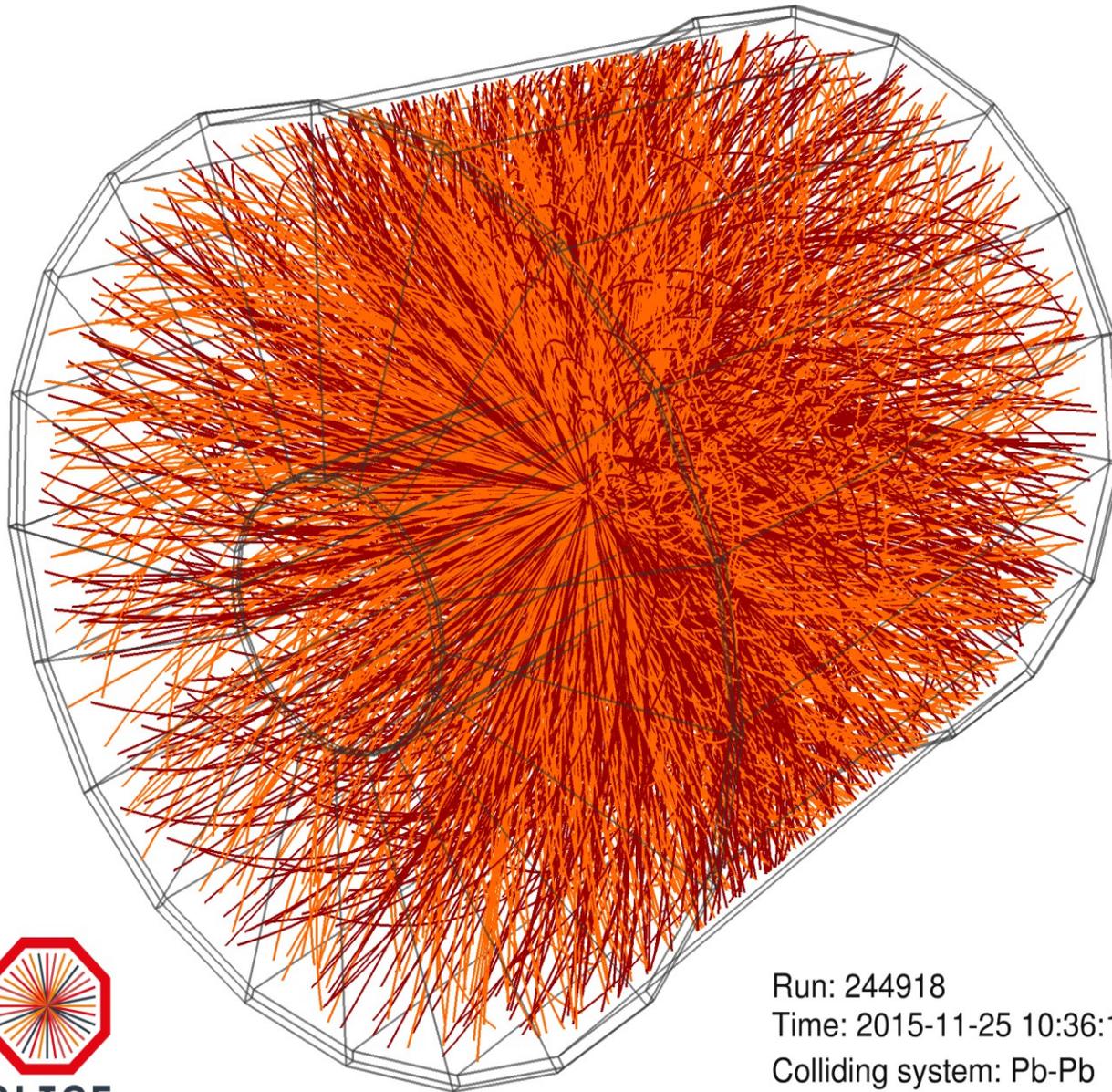
Run1: 3 data taking campaigns  
pp, pPb, Pb—Pb  
> 170 publications

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!



Run: 244918  
Time: 2015-11-25 10:36:18  
Colliding system: Pb-Pb  
Collision energy: 5.02 TeV

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:

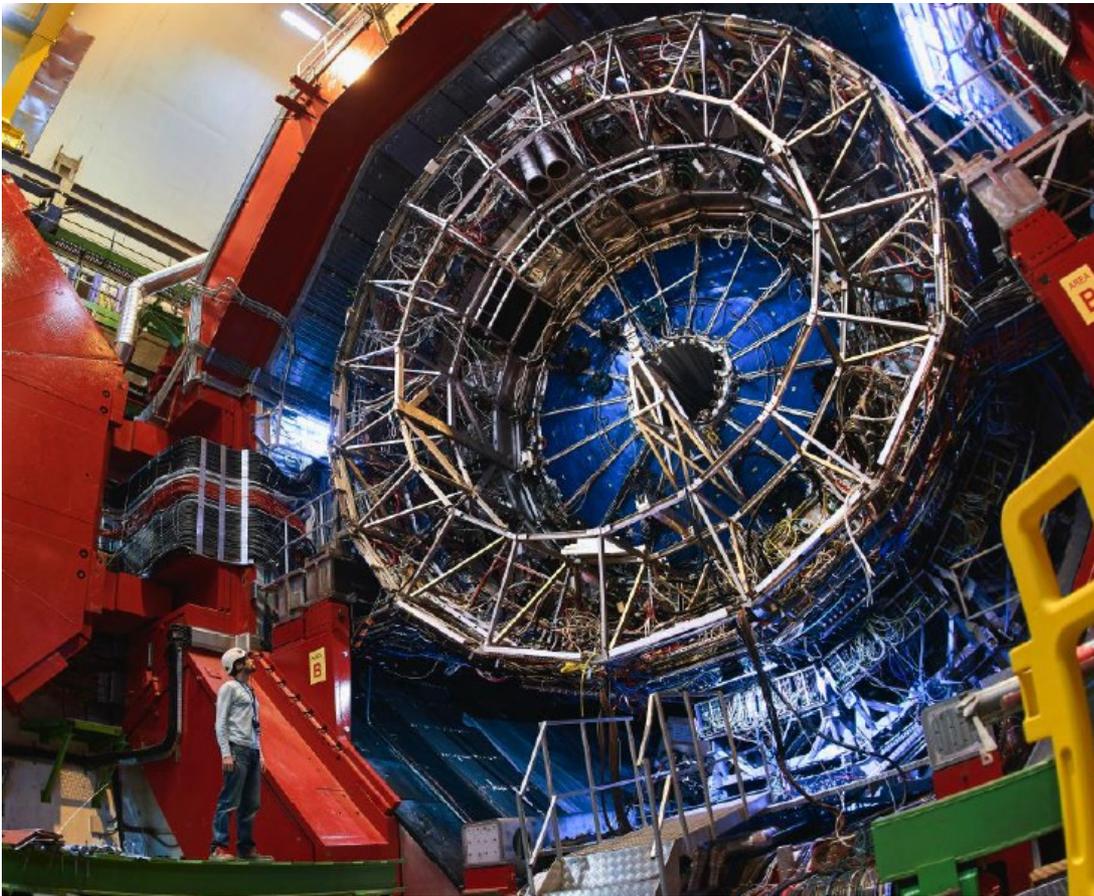
GEM based read-out chambers for the TPC  
new inner tracker with ultra-thin Si layers  
continuous read of (all) subdetectors

**increase of data rates by factor >50**

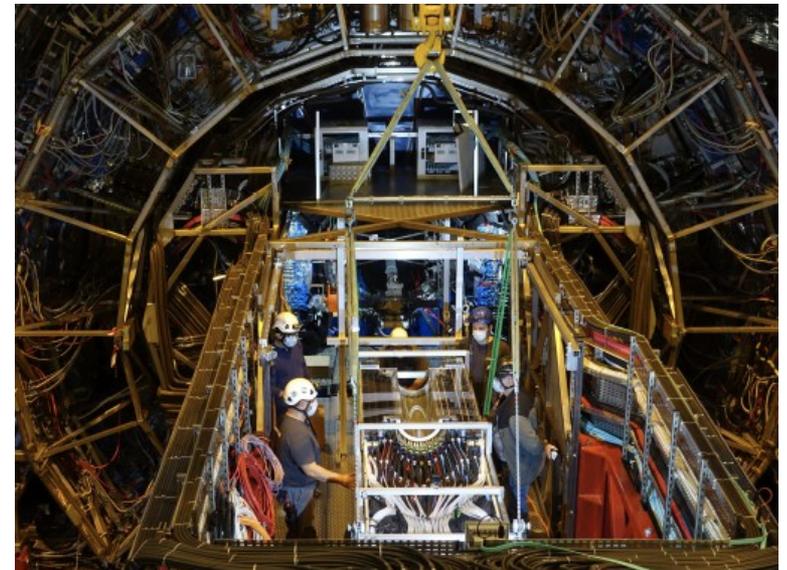
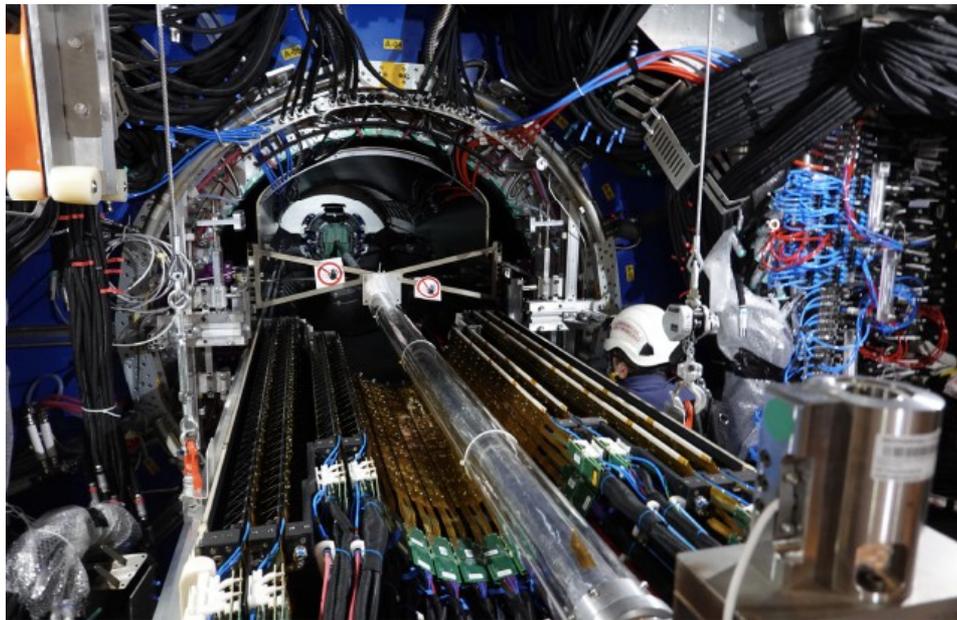
focus on rare objects, exotic quarkonia, single (and possibly double) charm hadrons to address a number of fundamental questions and issues such as:

- 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



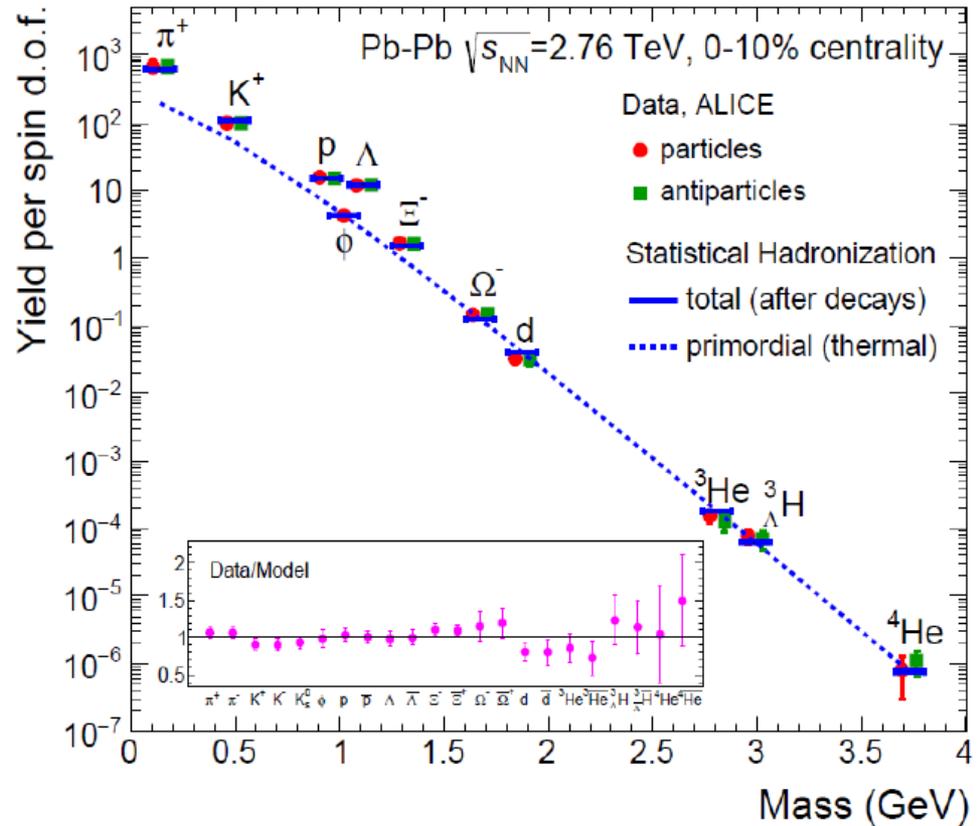
# Production of hadrons and (anti-)nuclei at LHC

1 free parameter: temperature T  
 $T = 156.5 \pm 1.5 \text{ MeV}$

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  $\sim M^{3/2} \exp(-M/T)$  (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  $\mu_b < 300$  MeV:**  
 **$T_c = 156.5 \pm 3$  MeV for  $\mu_b = 0$**   
**new insight into hadronization**

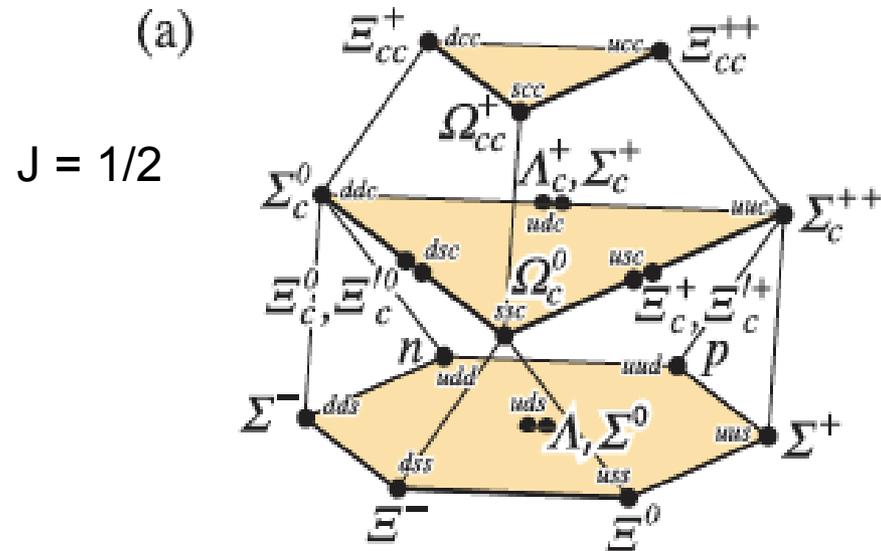
## why emphasis on low transverse momenta $p_T$ ?

- the bulk of particles produced in hadronic and nuclear collisions takes place at  $p_T < 1 \text{ GeV}$
- typical sizes of the interaction region range from 1 fm (pp collisions) to  $> 10 \text{ fm}$  (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:  $p_T < 1 \text{ GeV}$  implies spatial size  $r_T > 0.2 \text{ fm}$ ,  $p_T < 100 \text{ MeV}$  implies  $r_T > 2 \text{ fm}$ ,  $p_T < 20 \text{ MeV}$  implies  $r_T > 10 \text{ fm}$  (note that  $\hbar c = 197 \text{ MeV fm}$ )
- 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)

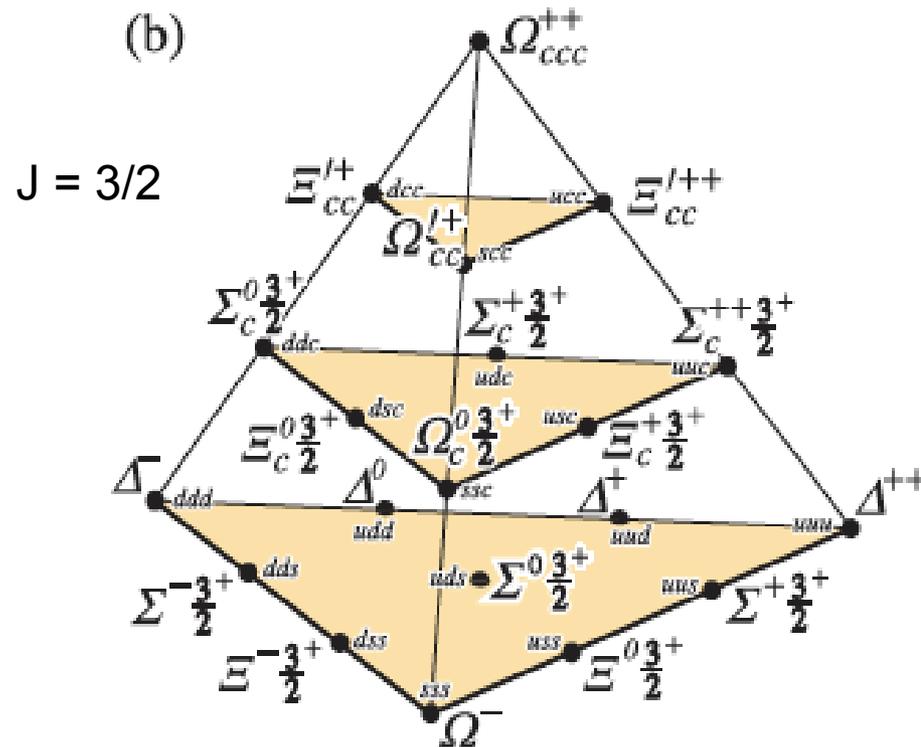
## **focus 1: charm sector**

- 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

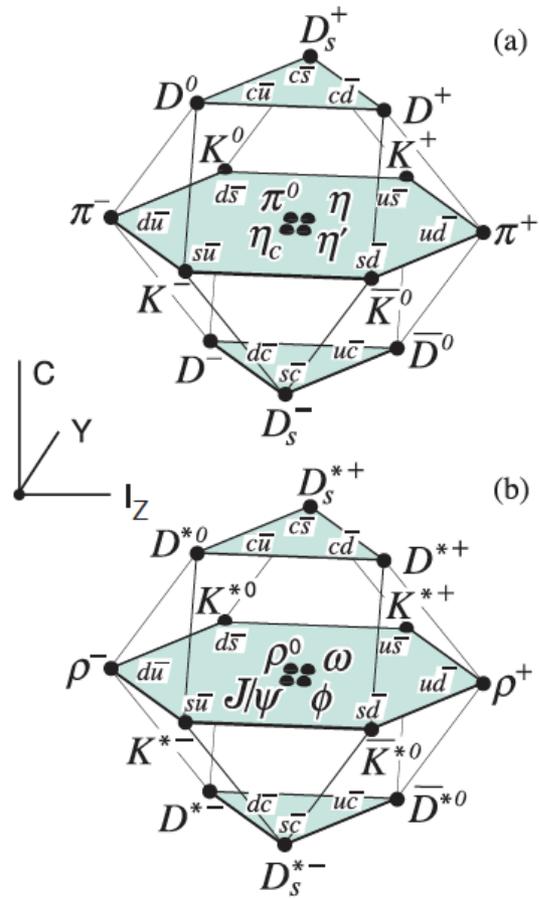
# the charm baryons in the quark model



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]

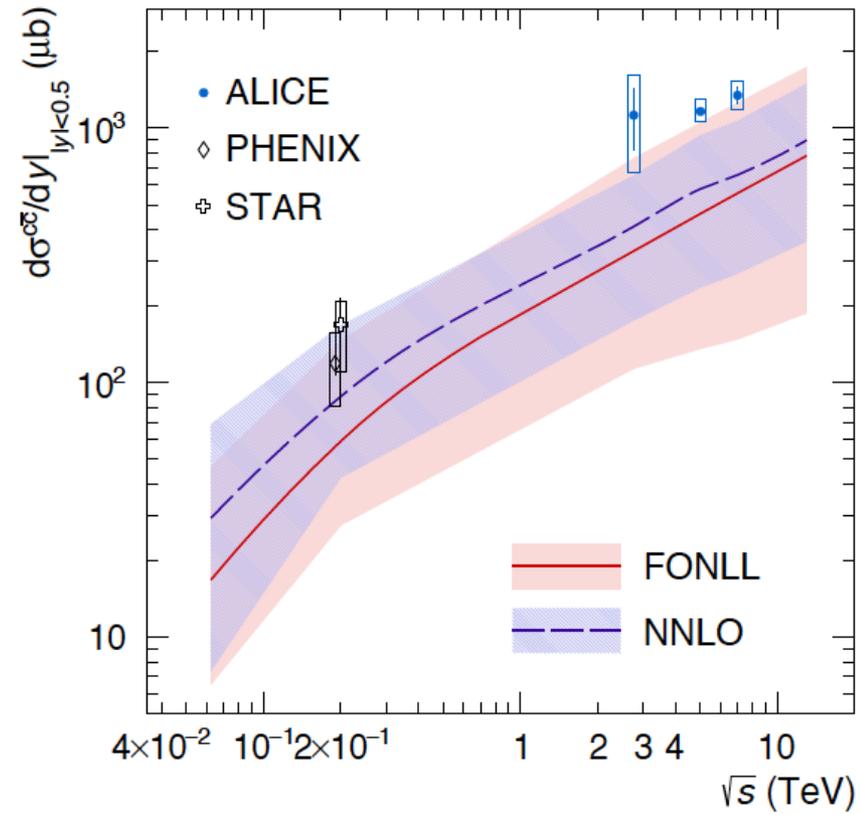
- ▶ Charm quarks are produced in initial hard scatterings ( $m_{c\bar{c}} \gg T_c$ ) and production can be described by pQCD ( $m_{c\bar{c}} \gg \Lambda_{\text{QCD}}$ )
- ▶ Charm quarks survive and *thermalise* in the QGP
- ▶ Full screening before  $T_{\text{CF}}$
- ▶ Charmonium is formed at phase boundary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

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

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

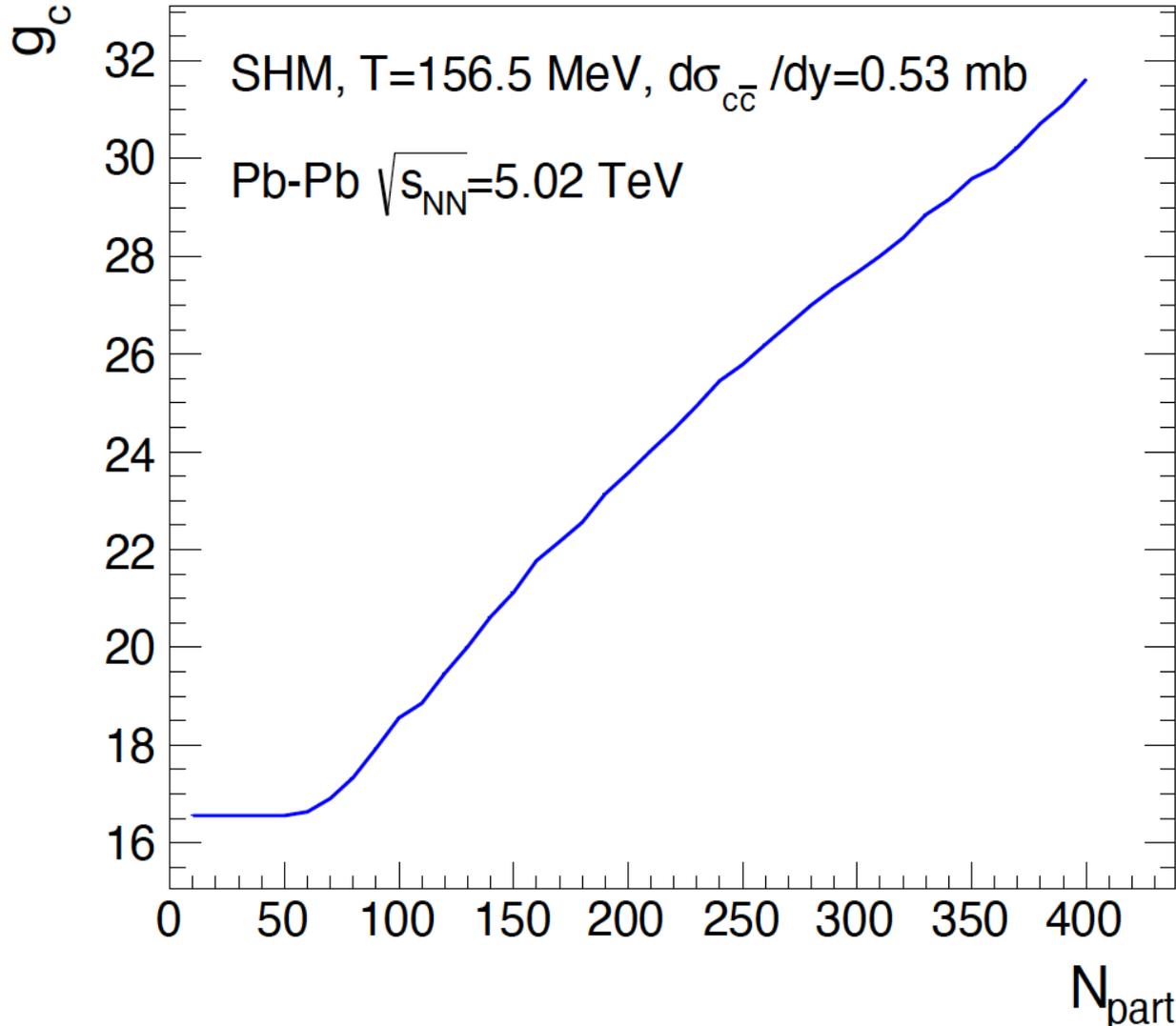
core-corona picture: treat low density part of nuclear overlap region, where a nucleon undergoes 1 or less collisions as pp collisions, use measured pp cross section scaled by  $T_{\text{AA}} = N_{\text{coll}}/\sigma_{\text{inel}}^{\text{pp}}$  with  $N_{\text{coll}}$  the number of (hard) collisions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

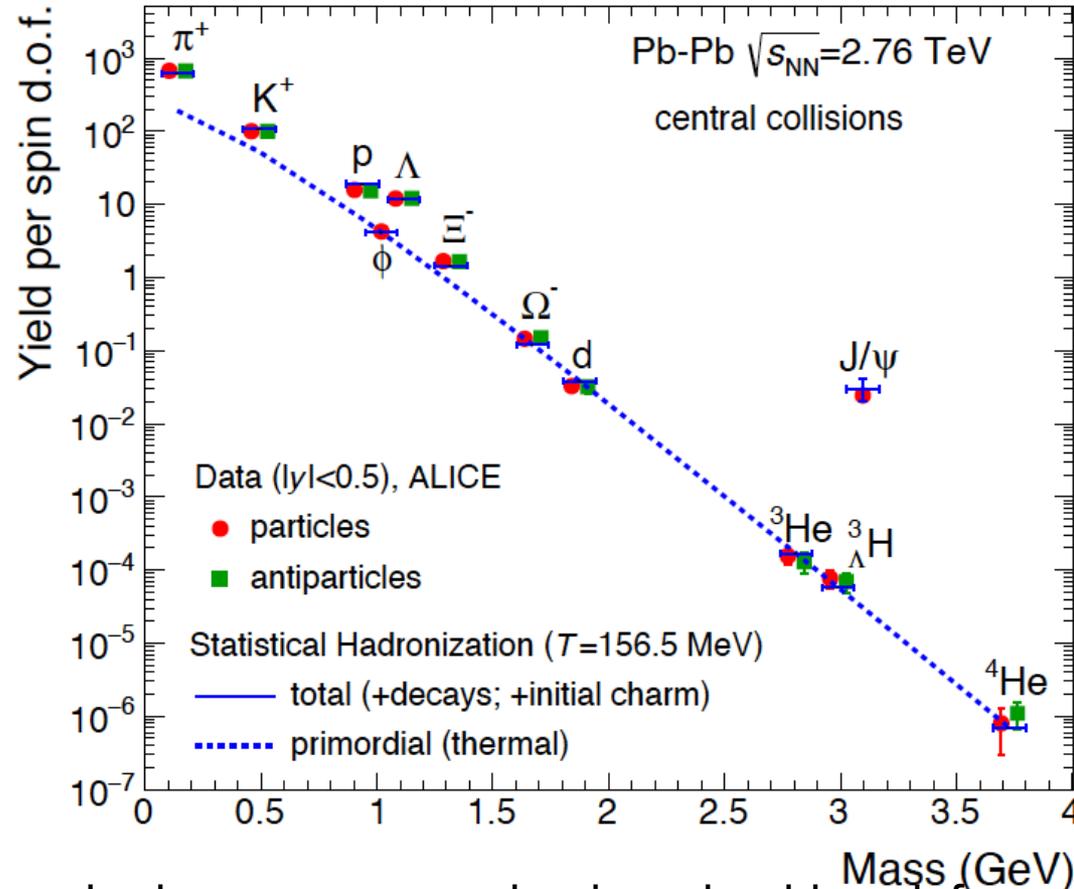
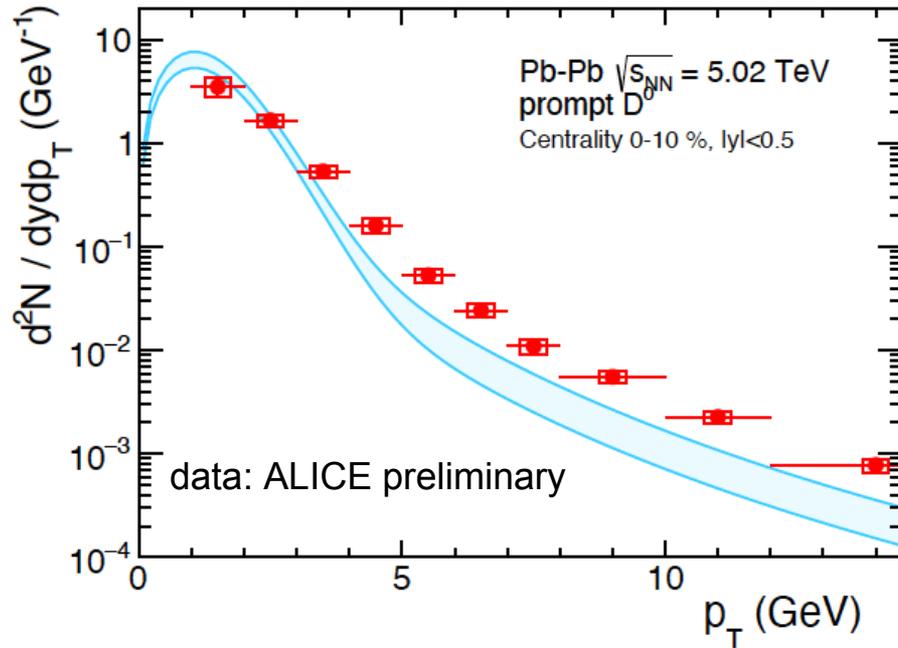
# statistical hadronization for hidden and open charm

$J/\psi$  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  $N_{c\bar{c}}$ <sup>2</sup>

enhancement factor is 900 for  $J/\psi$

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  $\Omega_{ccc}$  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

first we summarize results for hidden charm mesons ( $J/\psi$ )

- quarkonia are heavy quark antiquark bound states, i.e.  $c\bar{c}$  and  $b\bar{b}$
- since masses of charm and beauty quarks are high as compared to QCD scale parameter  $\Lambda_{\text{QCD}} \sim 200 \text{ MeV}$  non-relativistic Schrödinger equation can be used to find bound states

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

with quark-quark potential of the form

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

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  $\sigma \sim 0.9 \text{ GeV/fm}$ , the strong coupling constant  $\alpha_s(m_Q) \sim 0.35$  and  $0.20$  for  $m_c=1.5$  and  $m_b=4.6 \text{ GeV}$ , respectively to obtain the spectrum of quarkonia

## charmonia at finite temperature

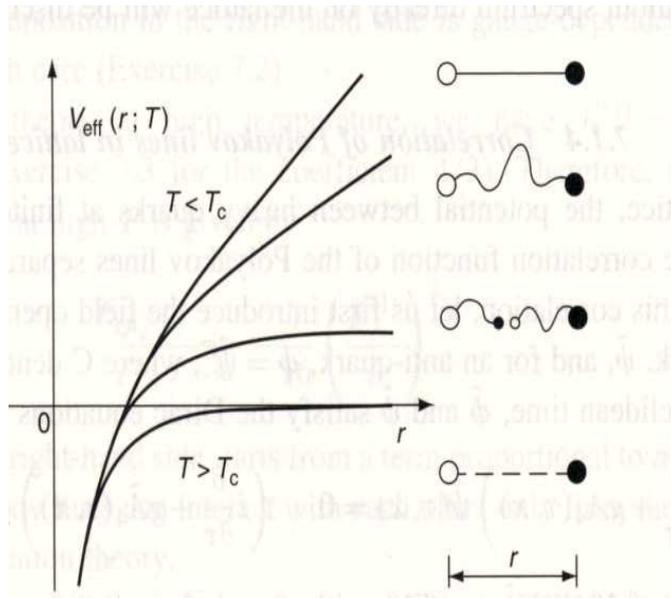
consider  $T \ll m_c$  so QGP of gluons, u,d,s quarks and antiquarks, no thermal heavy quarks

consider  $c\bar{c}$  in thermal environment of gluons and light quarks

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

in QGP color singlet and color octet  $c\bar{c}$  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  $q\bar{q}$  and gluons leading to  $D$  and  $D\bar{D}$
- for  $T > T_c$  confining part disappears and short range Coulomb part is Debye screened to give Yukawa type potential

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

$$\omega_D = 1/\lambda_D$$

Debye screening mass and length

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

# charmonium as a probe for the properties of the QGP

the original idea: (Matsui and Satz 1986) implant charmonia into the QGP and observe their modification, in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – **sequential melting (suppression)**

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – **signal for deconfined, thermalized charm quarks production probability scales with  $N(c\bar{c})^2$**

reviews: L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010

nearly simultaneous: Thews, Schroeder, Rafelski 2001

formation and destruction of charmonia inside the QGP

n.b. at collider energies there is a complete separation of time scales

$$t_{\text{coll}} \ll t_{\text{QGP}} < t_{\text{Jpsi}}$$

implanting charmonia into QGP is an inappropriate notion

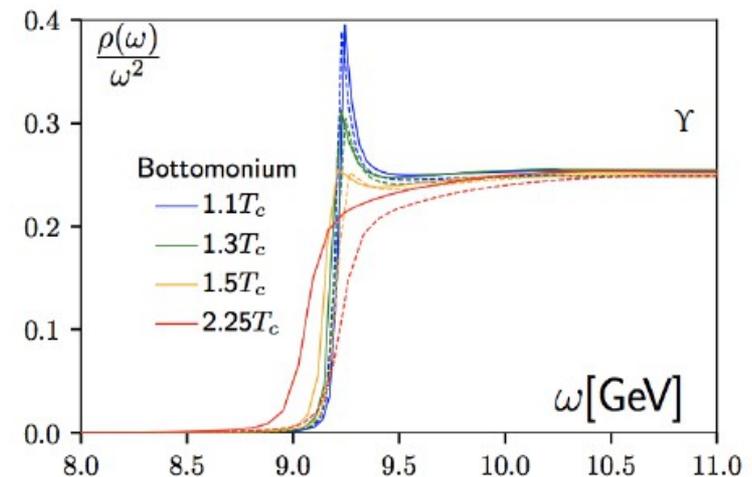
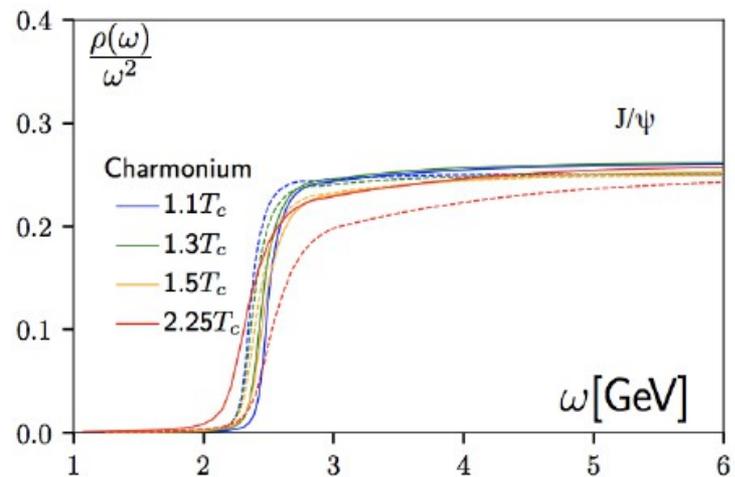
this issue was already anticipated by Blaizot and Ollitrault in 1988

also charm quark production increases strongly with collision energy

**an aside: charmonium melts at  $T_c$**   
**newest result from the Bielefeld/BNL/Wuhan lattice group**  
arXiv:2002.00681

little modification of quarkonia in QGP:  
charmonia and (presumably) all charm hadrons melt at  $T_c$   
bottomonia melt at  $< 1.5 T_c$

Thermal modification of spectral functions for  
charmonium and bottomonium at high temperature



A.L. Lorenz, H.T. Ding, O. Kaczmarek et al., arXiv:2002.00681

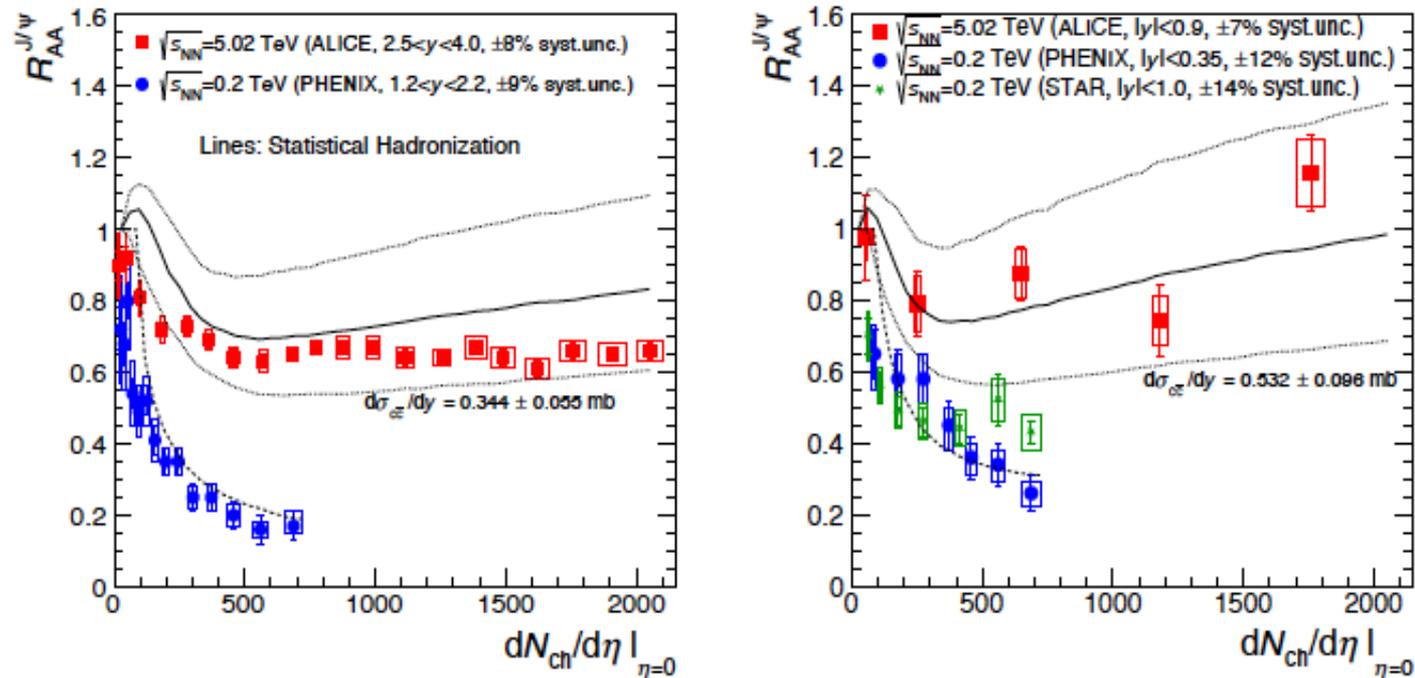
No evidence of survival of  
charmonium bound states above  $T_c$

Survival of bottomonium  
significantly above  $T_c$

-> Consistent with picture of statistical (re-)generation of  $J/\psi$  at freeze-out

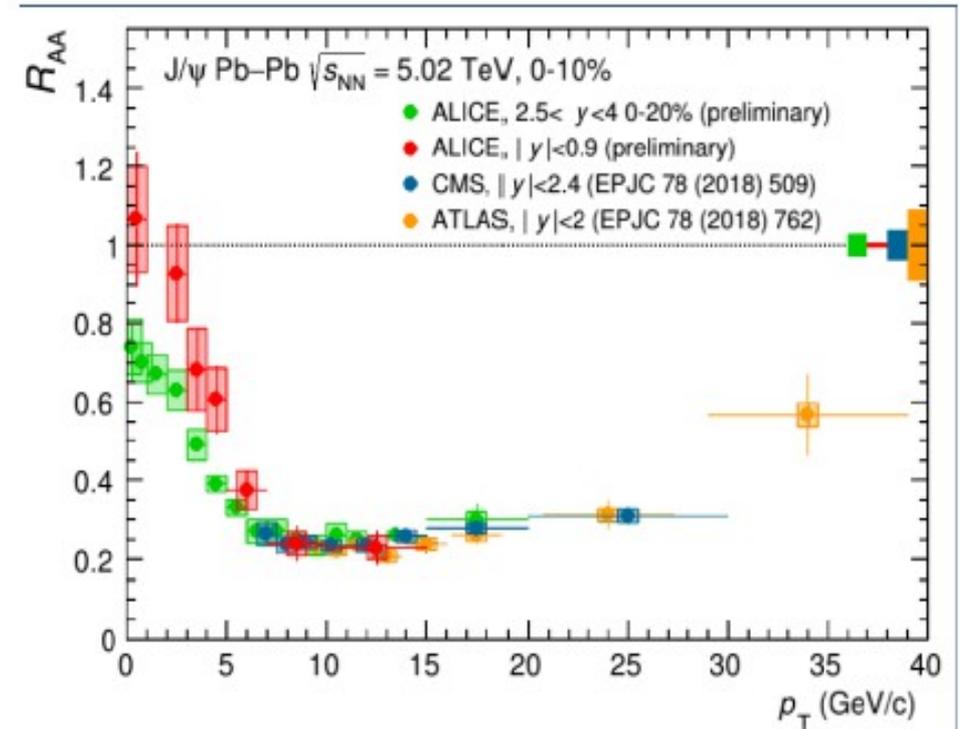
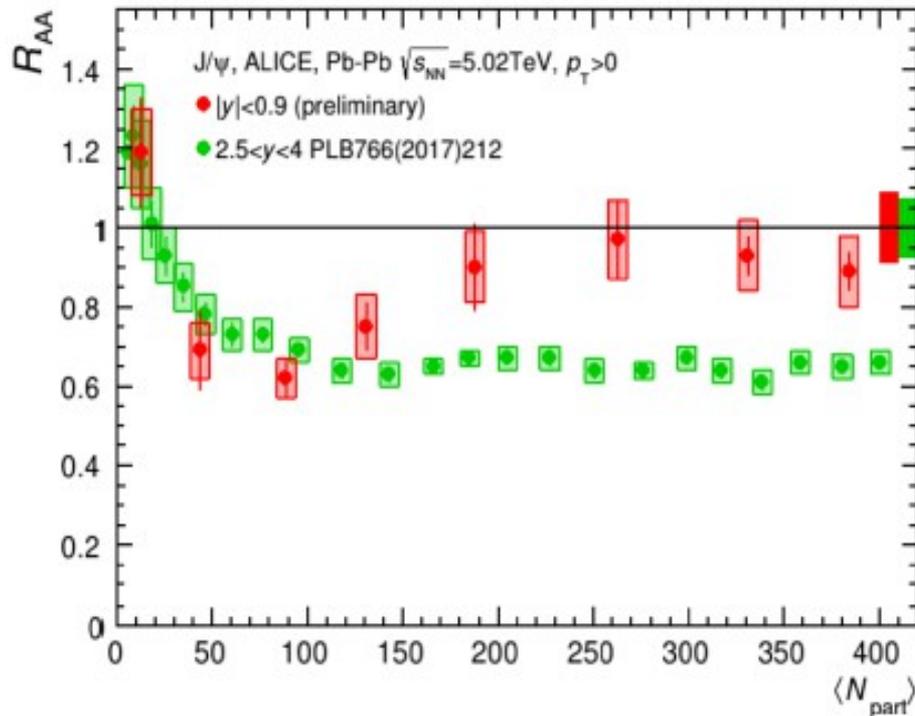
# RHIC and LHC data compared to SHM predictions

note the energy dependence of the nuclear modification factor  $R_{AA}$



the band with the model predictions at LHC energy is due to the uncertainties in the pp open charm cross section and the necessary shadowing corrections

enhancement is at low (transverse) momentum and at angles perpendicular to the beam direction, as expected for a thermal, nearly isotropic source



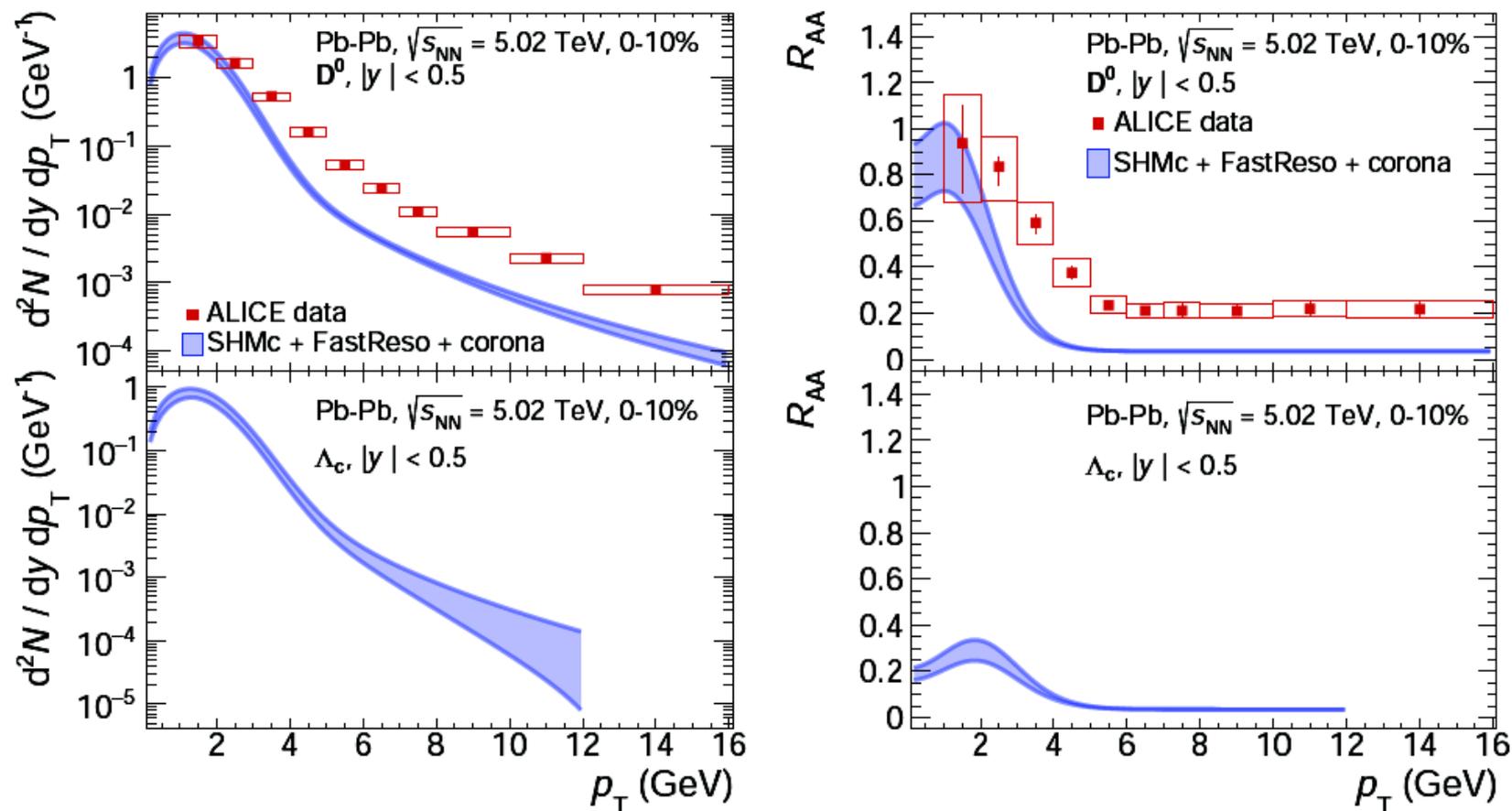
enhancement is due to statistical combination of charm- and anti-charm quarks these heavy quarks have masses  $O(1 \text{ GeV})$  and are not produced thermally since  $T_{cf} = 156 \text{ MeV} \ll 1 \text{ GeV}$ . Interactions in the hot fireball bring the charm quarks close to equilibrium  $\rightarrow$  production probability scales with  $N_{ccbar}^2$

**now open charm hadrons and the SHMc**

# spectra and $R_{AA}$ of $D^0$ mesons and $\Lambda_c$ baryons

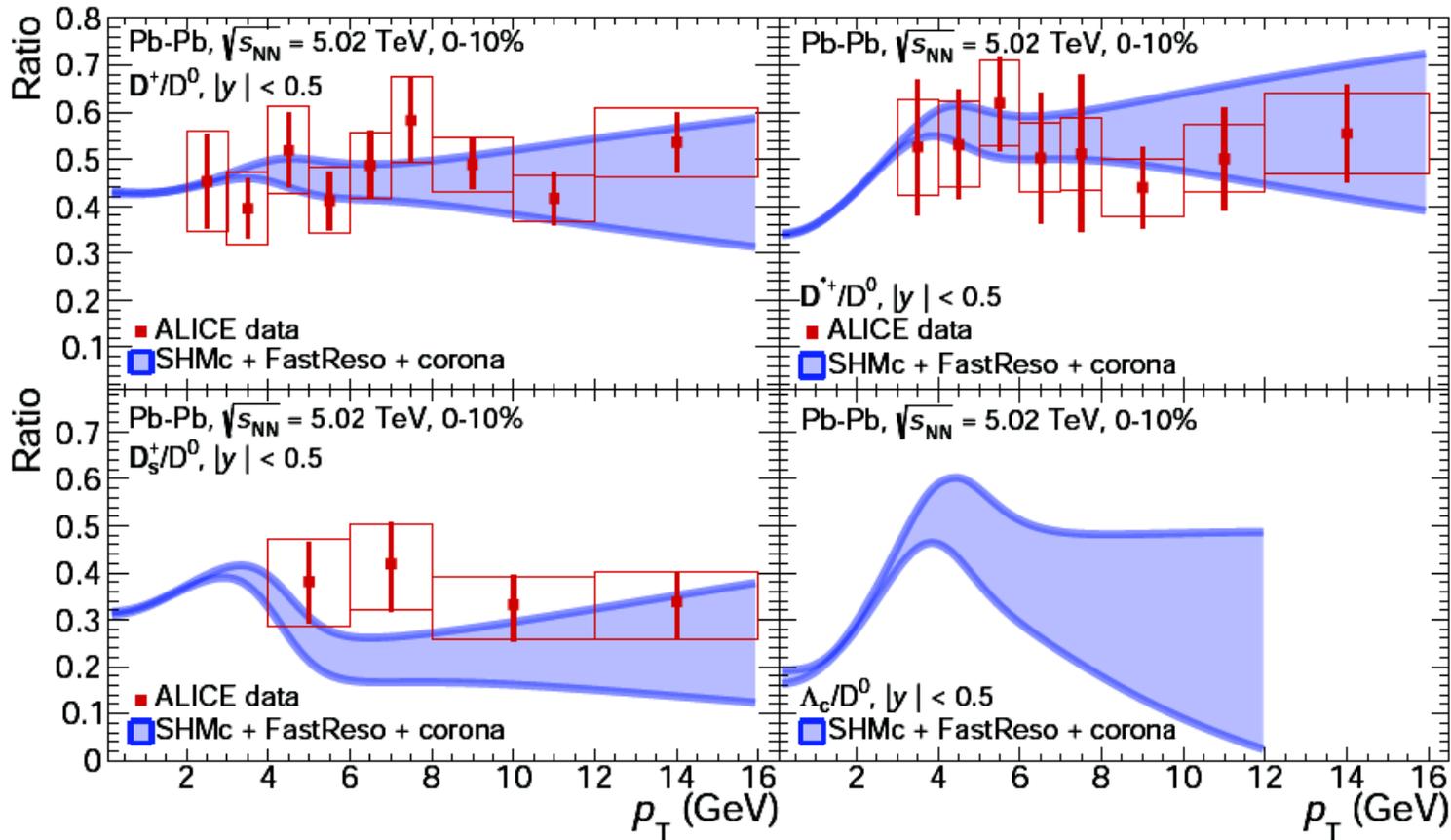
for open heavy flavor hadrons strong contribution from resonance decays

- 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)



$\Lambda_c$  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 measurements 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  $\Xi_{cc}^{++}$  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  $5000 \text{ fm}^3$

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?

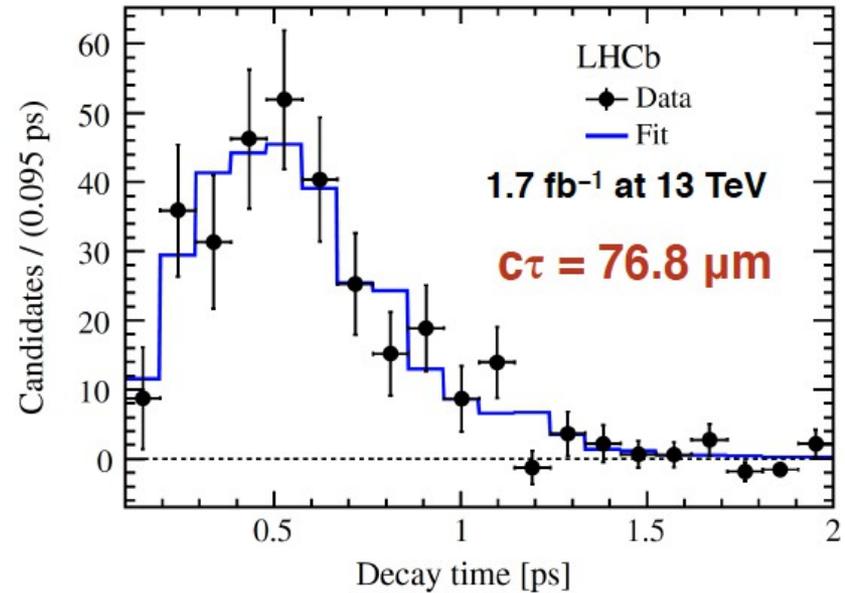
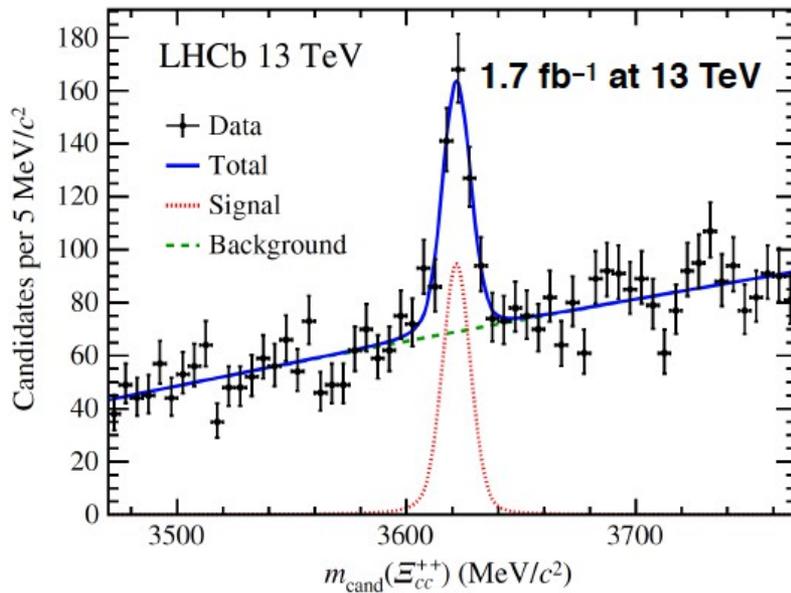
measurements are generally done via invariant mass analysis

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

example:

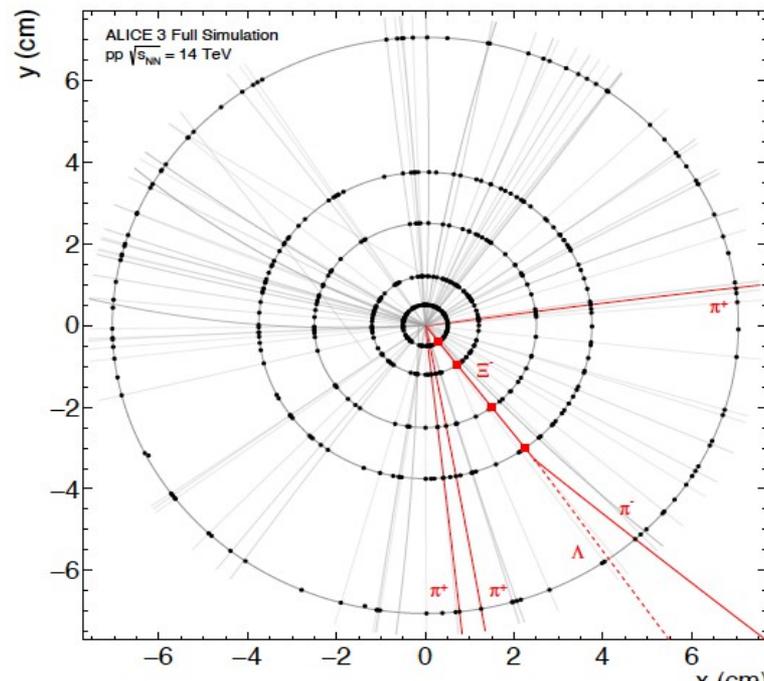
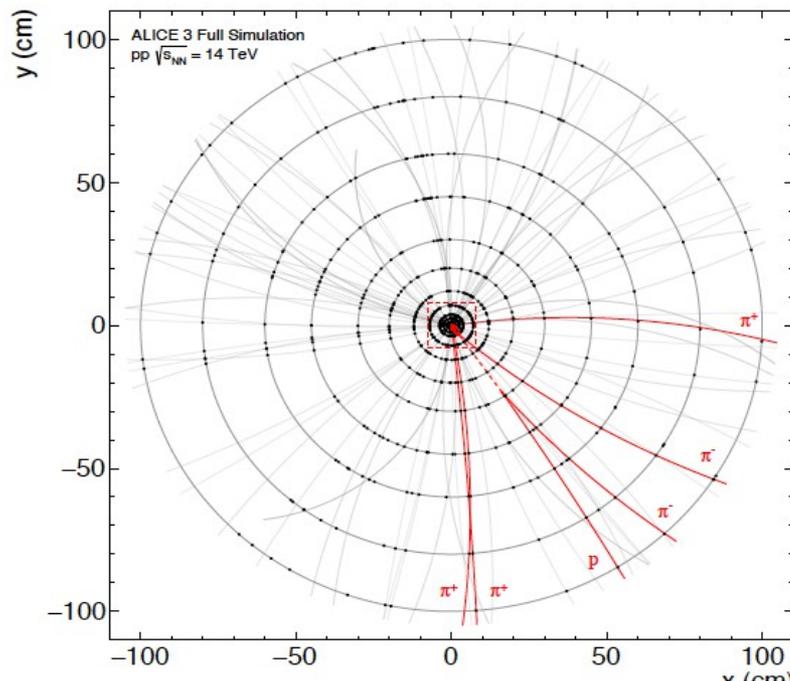
$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$$

$$\Lambda_c^+ \rightarrow p K^- \pi^+$$



LHCb collaboration, arXiv:1910.11316, pp collisions

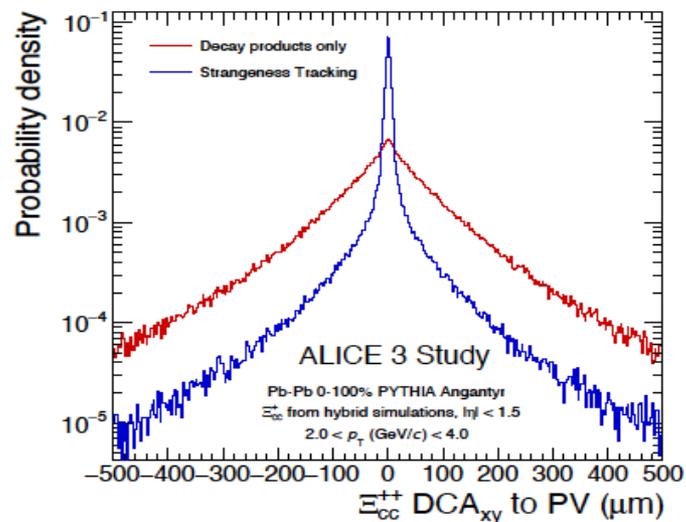
# new ALICE development: strangeness tracking



(left) Illustration of strangeness tracking from full detector simulation of the  $\Xi_{cc}^{++}$  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  $\Xi^-$  trajectory (red squares).

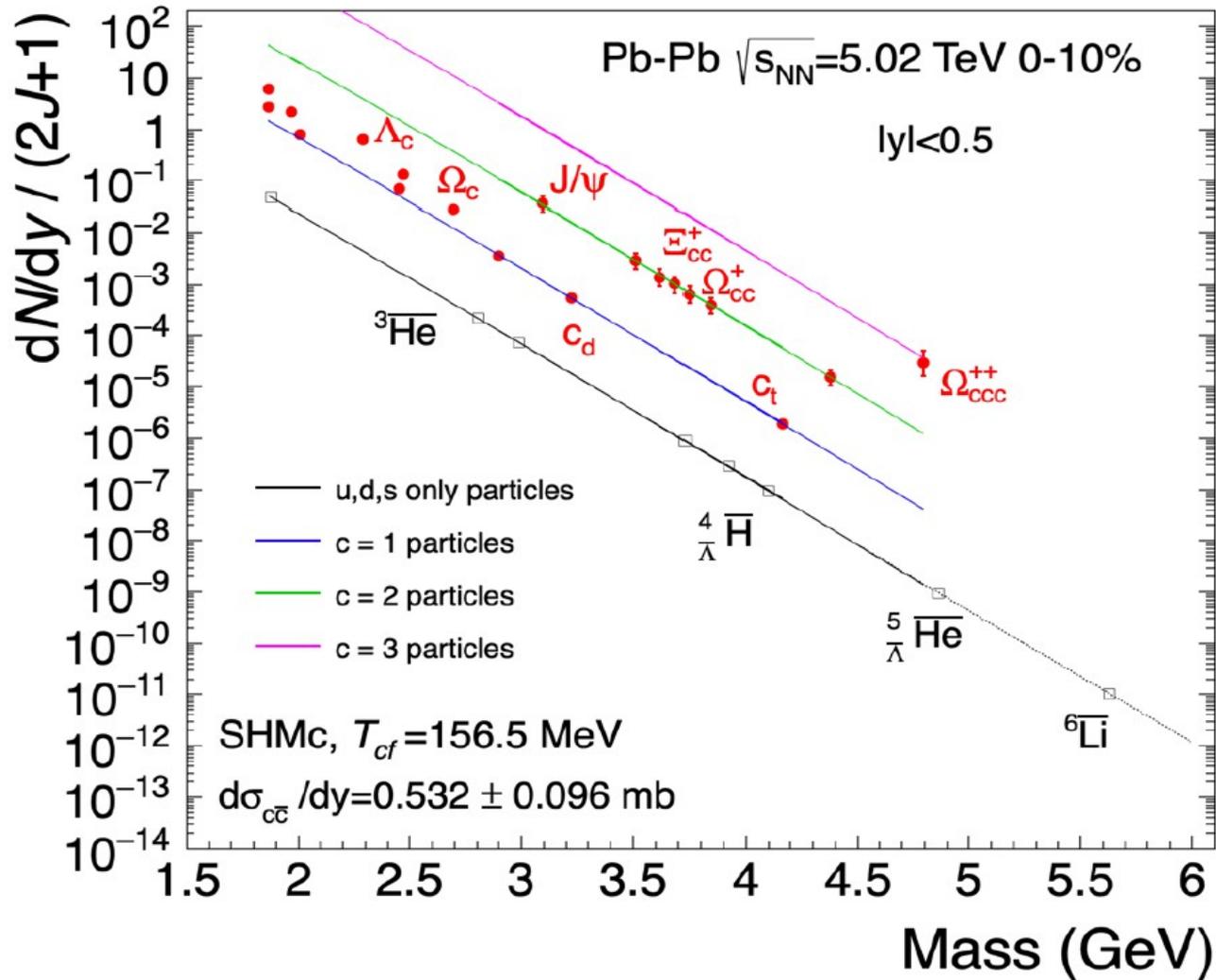
$\Xi_{cc}^{++}$  mass spectrum without (red) and with (blue) strangeness tracking

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



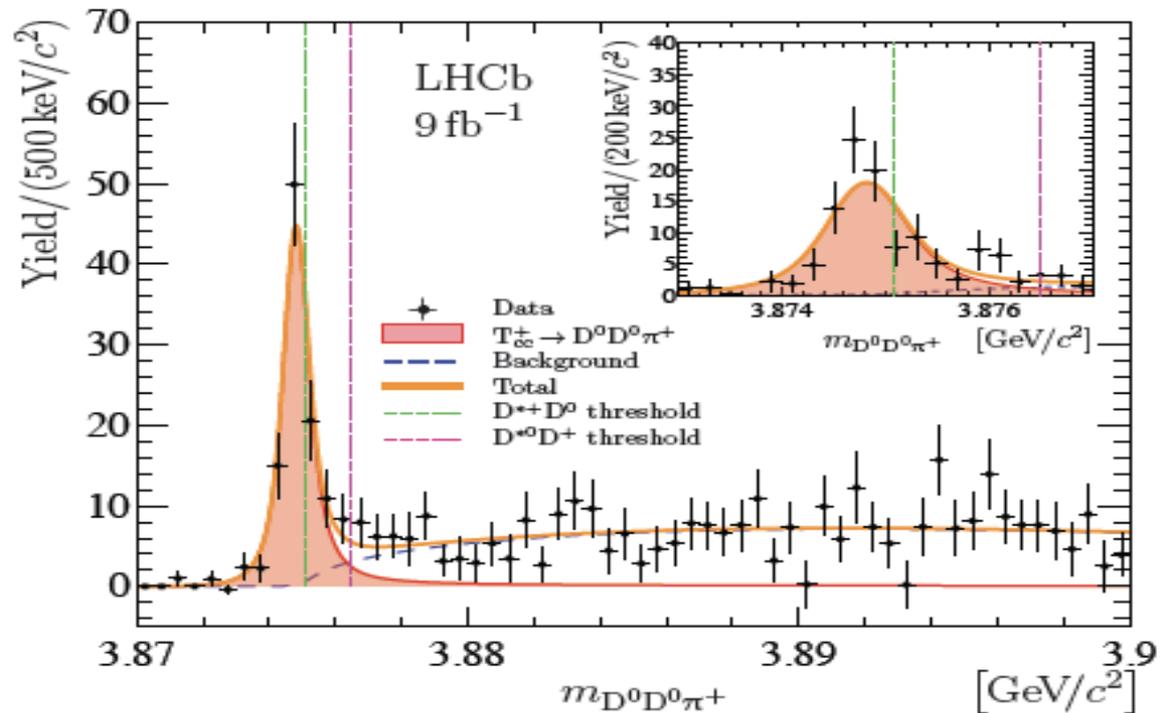
# the multi-charm hierarchy

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



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 LHCb  
 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

## 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  $\rightarrow$  further insight into confinement, deconfinement and hadronization

## focus 2: 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

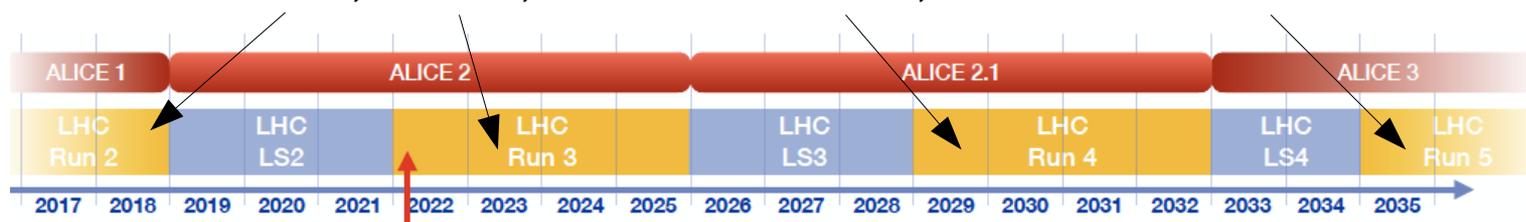
experimental problem: signal  $S$  very small, backgrounds  $B$  very large

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

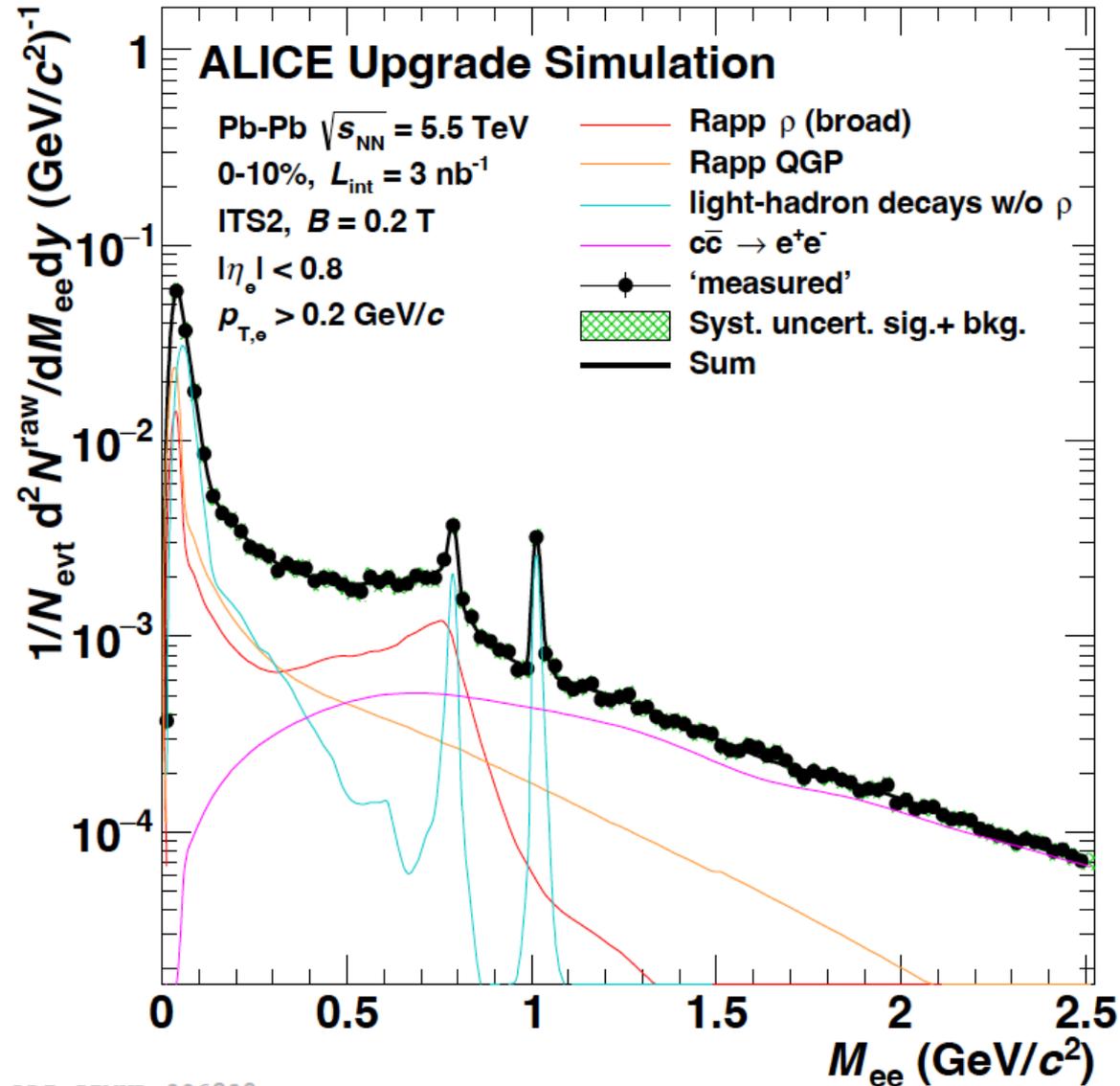
$B$  can be reduced by :

- 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  $\mu\text{m}$  (open-charm hadrons) or 400  $\mu\text{m}$  (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



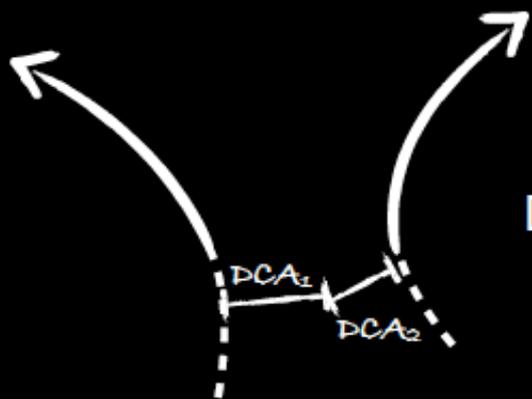
# expected signal and backgrounds based on 1<sup>st</sup> 10 years of ALICE running and on new inner tracking system ITS2 built for ALICE Run 3



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

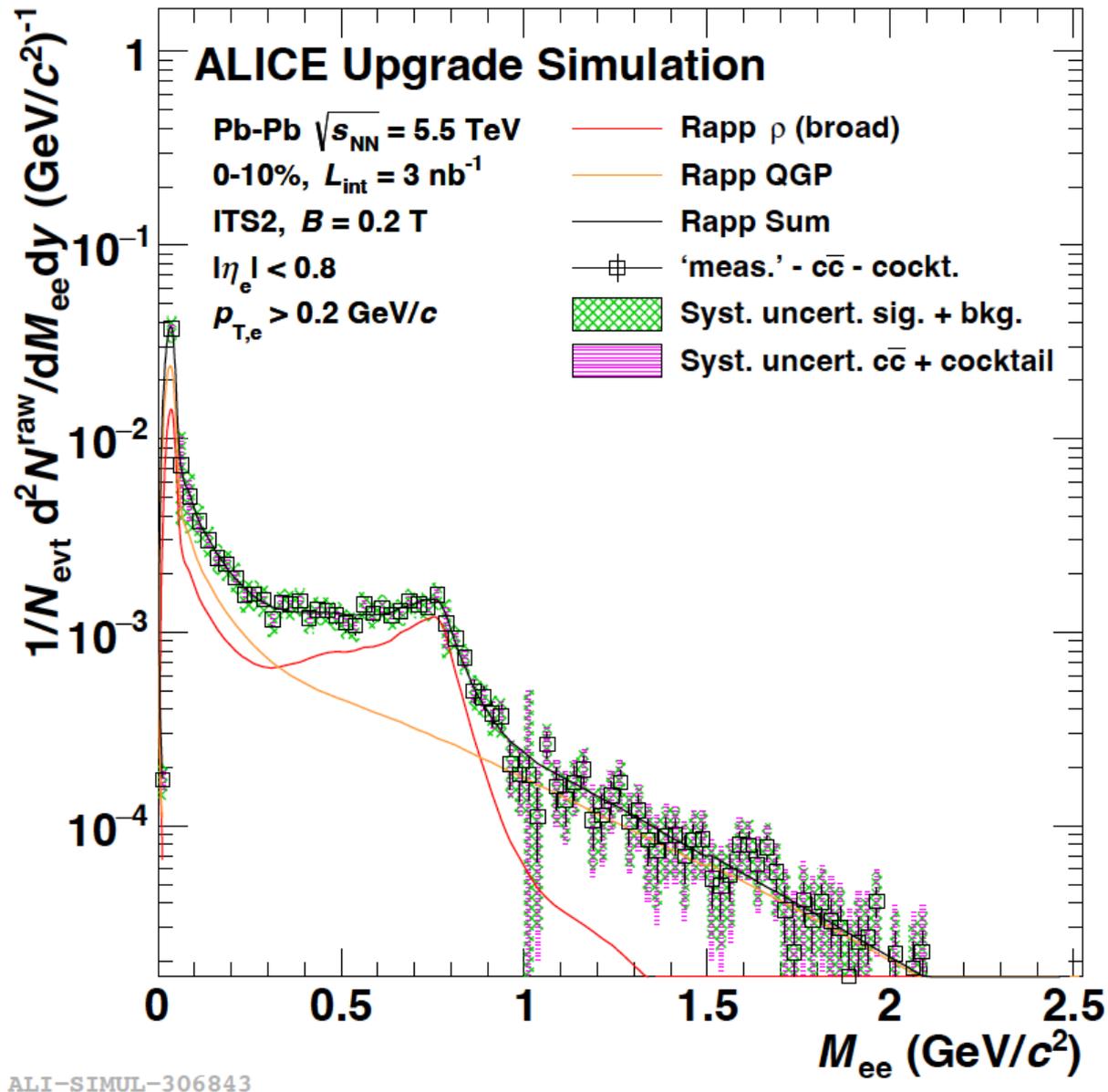
# Dielectron cocktail

Use pair distance of closest approach ( $DCA_{ee}$ ) to reject heavy-flavour backgrounds


$$DCA_{ee} = \sqrt{\frac{DCA_1^2 + DCA_2^2}{2}}$$

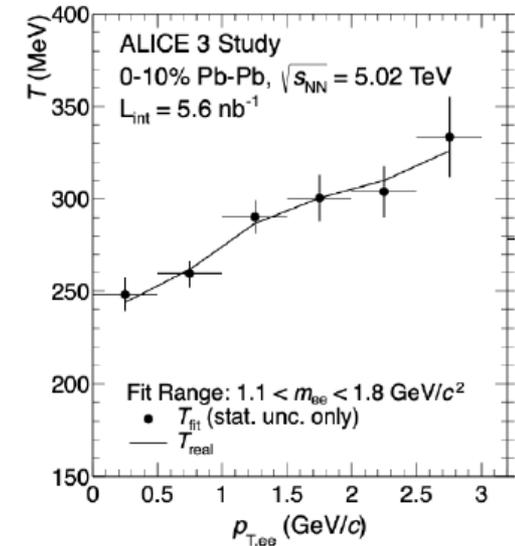
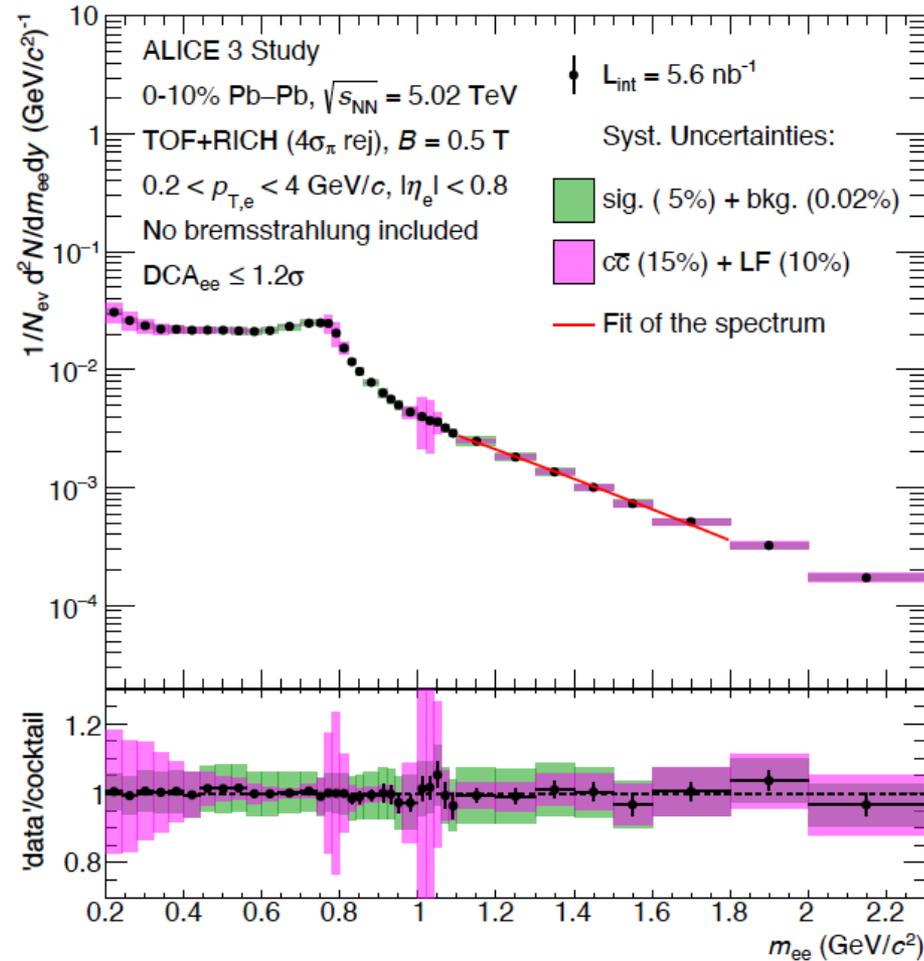
project charged particle tracks onto plane perpendicular to direction of beams. in this 'xy' direction, the quantity  $DCA_{ee}$  is evaluated to reject tracks not originating from the primary vertex

# expected signal after subtraction of 'hadronic cocktail' and background 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

## focus 3: 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 discrepancies 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

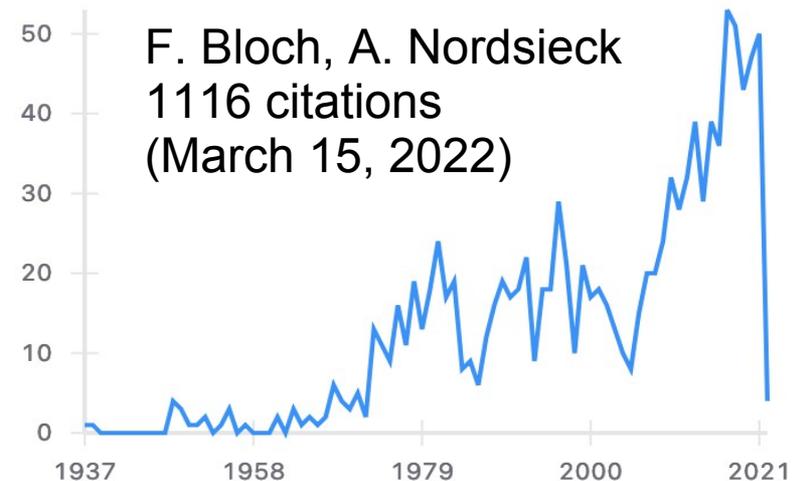
This led to the work by Francis Low in the context of collisions between elementary particles.

# 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 inertial 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 1<sup>st</sup> numerical solution of the full Boltzmann equation, with B.L Hicks
- 1971 died in St. Barbara

Citations per year



# Outline

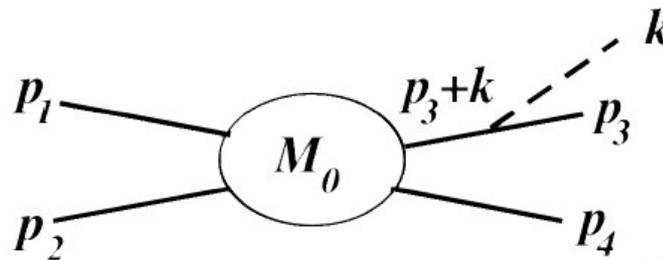
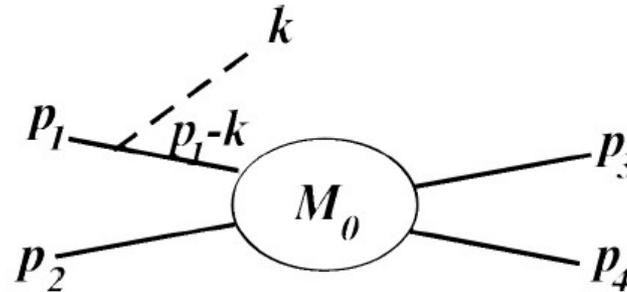
1. a derivation of the Low formula in  $y$  and  $k_t$  space
2. comments on implementation and application in the experimental context
3. ALICE 3
  - short overview
  - soft photon measurements
4. remarks
5. outlook

**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, -- 1<sup>st</sup> 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

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

amplitude

2-body part

photon part

all momenta are 4-vectors,  $\varepsilon$  is the 4-vector polarization of the photon

$e_i$  is the charge of particle  $i$  and  $\eta_i = -1$  for an incoming hadron,

$\eta_i = +1$  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  $p \cdot k \rightarrow 0$ . Since  $p \cdot k$  is a Lorentz invariant, this implies that, for vanishing photon energy  $E_\gamma$  (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. <sup>45</sup>

## two versions of the Low formula

(a) original version

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

(b) Haissinski version

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

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

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

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,  $k_t^{-1} \gg d_{\text{trans}}$  the maximum conceivable transverse dimensions  $d_{\text{trans}}$ , then the structure of the system does not matter anymore

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

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 ( $E_{\text{photon}} \ll 100 \text{ MeV}$ ) 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  $(k_{\text{T}}, y)$  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  $k_{\text{T}}$ , the photon energy becomes boosted to  $E_{\text{photon}} = k = k_{\text{T}} \cosh(y)$ . for rapidity  $y = 4.5$ ,  $\cosh(y) = 45$ , so at  $k_{\text{T}} = 10 \text{ MeV}$ ,  $E_{\text{photon}} = 450 \text{ MeV}$

## **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 Weinberg's paper presented above

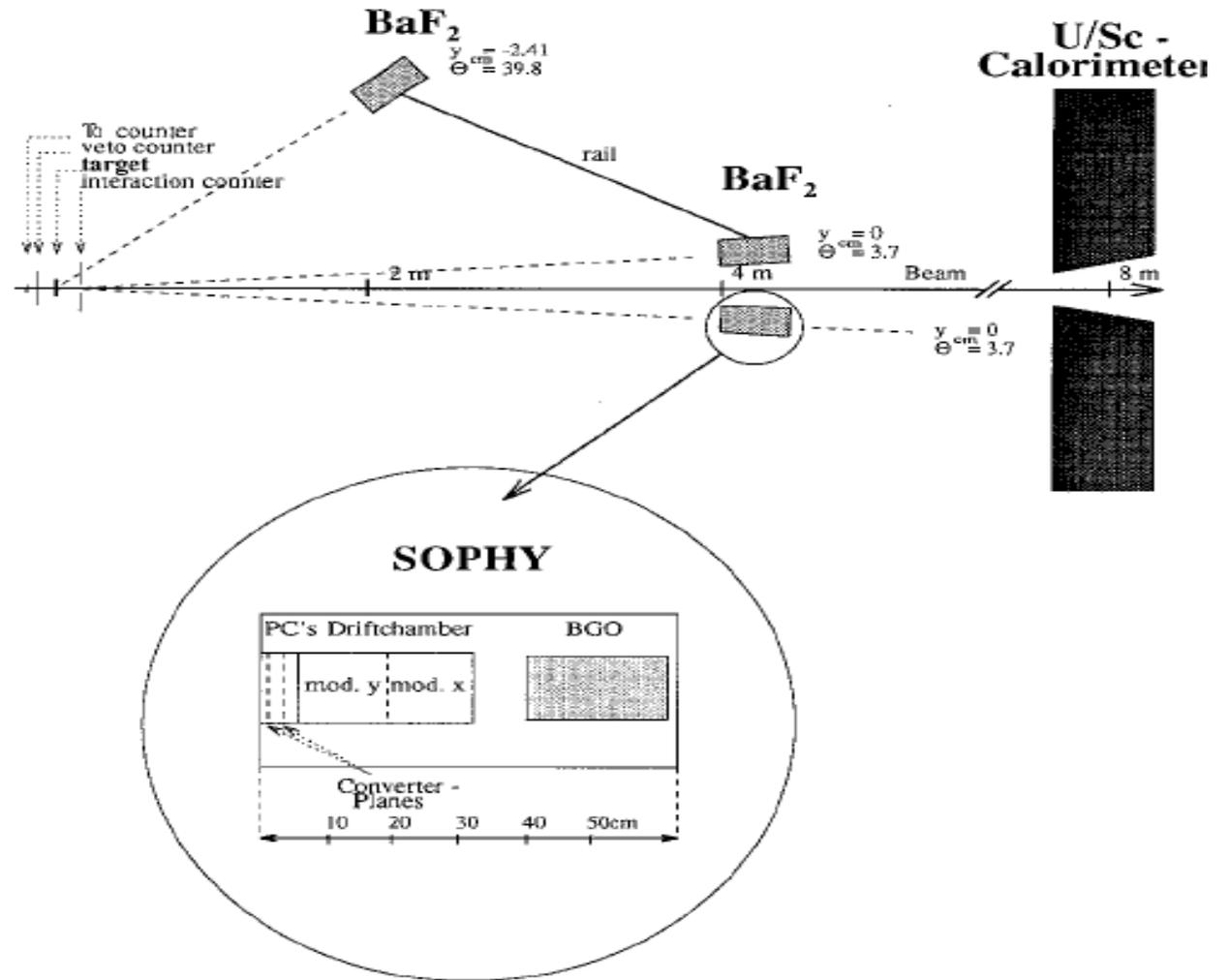
# thoughts about experimental approaches to test the Low theorem

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<sup>st</sup> 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 multiplicity 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.

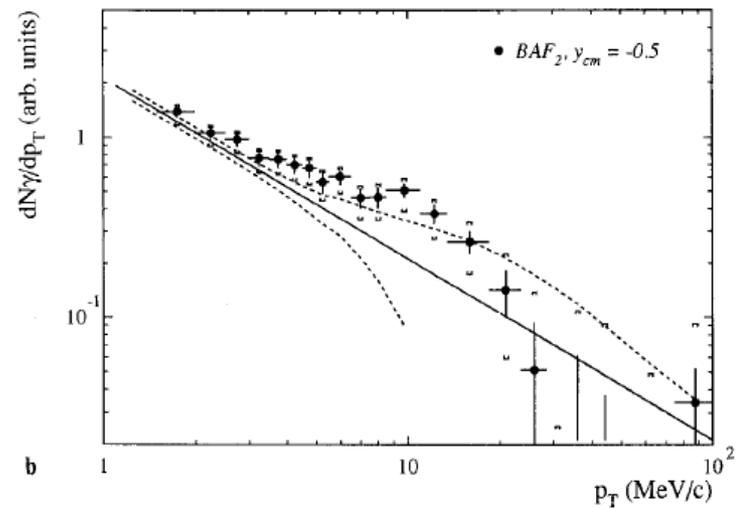
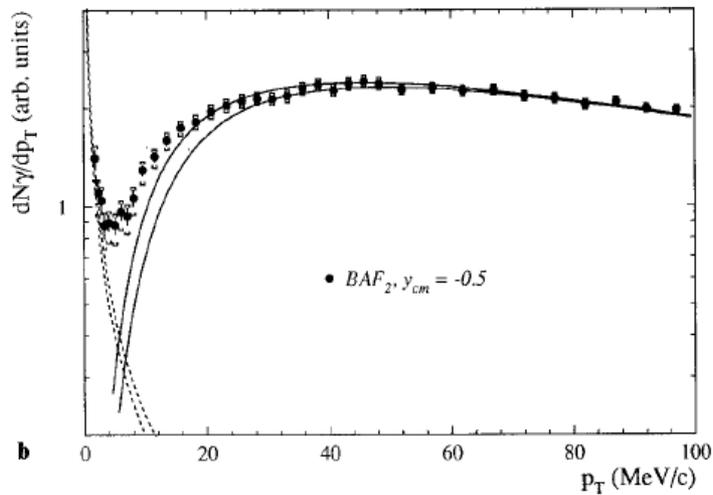
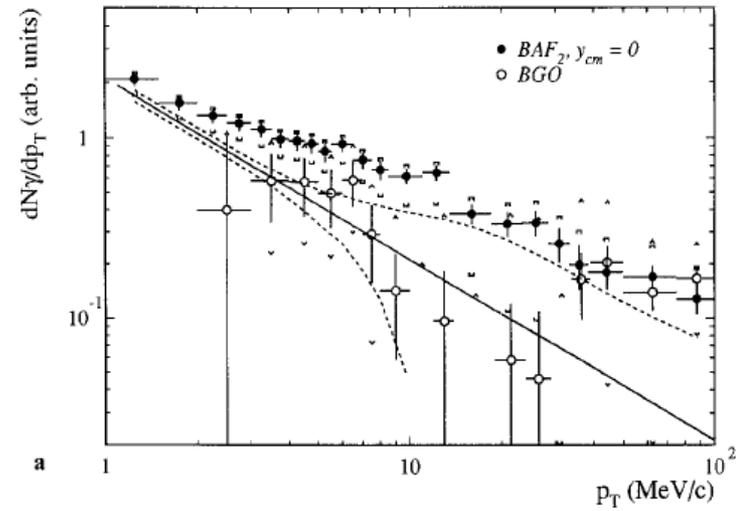
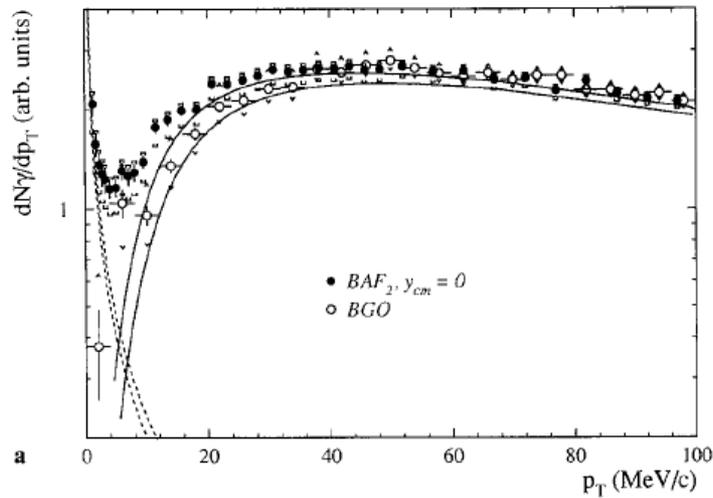
# **brief survey of experimental situation**

**see also: K. Reygers, ALICE 3 workshop Oct. 13 – 15, 2020**

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



## ... there is life beyond the Jacobian peak



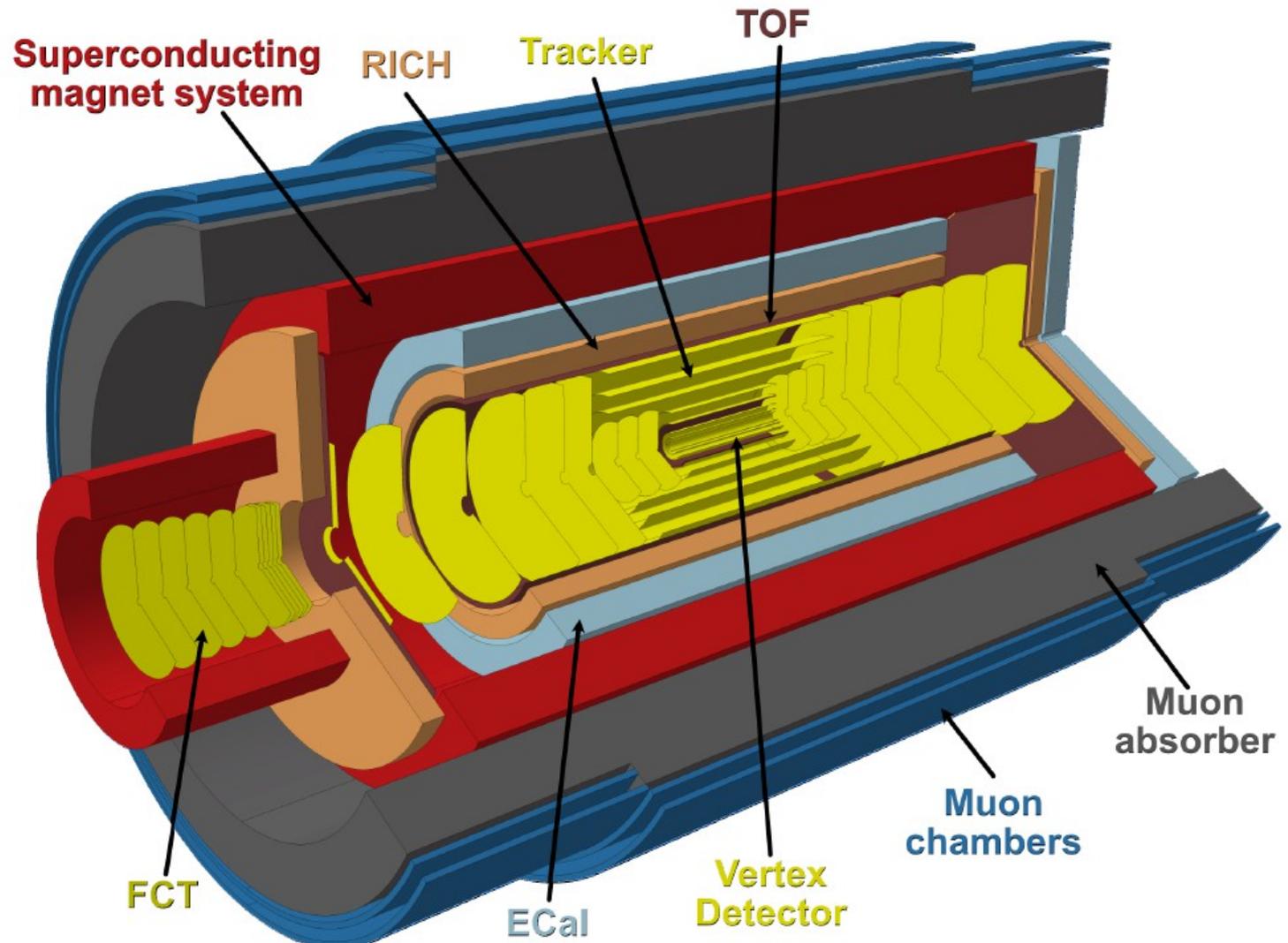
real photons down to the MeV scale, bremsstrahlung rise towards low  $k_T$  ( $p_T$ ) clearly observed, smaller than but still consistent with Low theorem predictions, charged particles were not measured, only simulated

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

large discrepancies between Low predictions and measurements

# ALICE 3 and ultra-soft photons



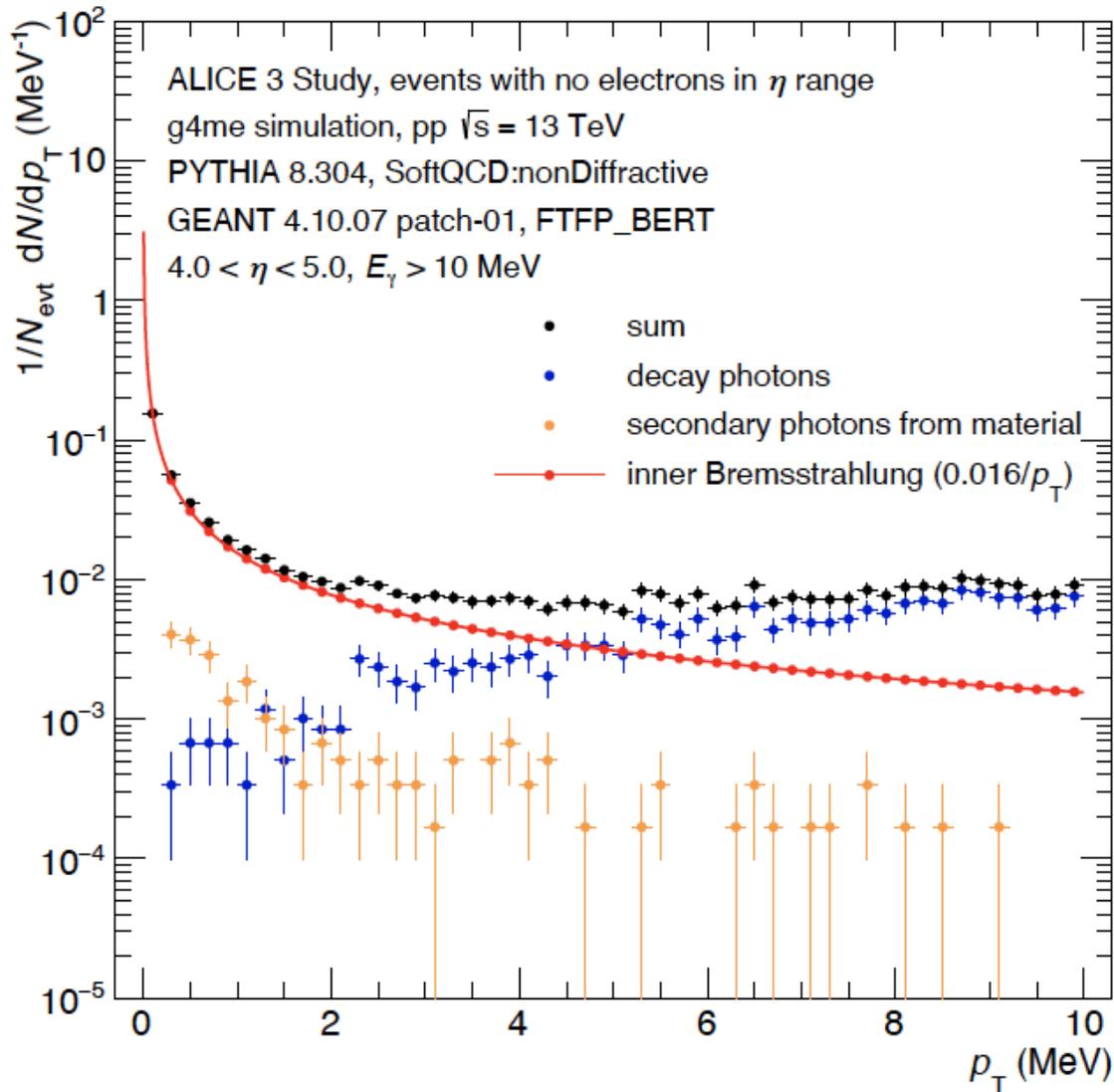
FCT:  
forward conversion  
tracker for soft photon  
measurements

## 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.

# 1<sup>st</sup> feasibility studies with FCT



conservatively, the bremsstrahlung spectrum can be measured with better than 20% accuracy

this should settle the 'ultra-soft photon puzzle'

see also the measurement of ultra-soft photons in exclusive collisions

for pp collisions at 13 TeV, bremsstrahlung spectrum is well identified at very low  $p_T$  provided that material in front of FCT is strongly reduced and that electrons in the acceptance are identified and removed

## soft photon production in exclusive collisions, an alternative

use pp collisions at  $E_{\text{cm}} = 13.5$  TeV and study exclusive collisions\* such as  $pp \rightarrow pp \pi\pi \gamma$  where the two outgoing protons are unobserved

the soft photons will be detected with transverse momenta down to  $k_{\text{T}} =$  a few MeV in a photon conversion tracker placed at rapidities  $3.5 < y < 5$

this will allow the Low theorem to be studied in a theoretically controlled region and with little experimental background

\* 2107.10829 [hep-ph]

in the course of these studies the authors found a mistake in the original Low paper. While the leading order  $1/k_{\text{T}}$  term is correct, the next order term needs a correction given in the above reference. For our purposes this is only relevant if one wants to make a precision study in the  $p_{\text{T}}$  region above the Low divergence.

# High-energy $\pi\pi$ scattering without and with photon radiation

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Radzikowskiego 152, PL-31342 Kraków, Poland*

<sup>2</sup>*Institut für Theoretische Physik, Universität Heidelberg,  
Philosophenweg 16, D-69120 Heidelberg, Germany*

**Abstract** Phys.Rev.D 105 (2022) 1, 014022, 2107.10829 [hep-ph]

We discuss the processes  $\pi\pi \rightarrow \pi\pi$  and  $\pi\pi \rightarrow \pi\pi\gamma$  from a general quantum field theory (QFT) point of view. In the soft-photon limit where the photon energy  $\omega \rightarrow 0$  we study the theorem due to F.E. Low. We confirm his result for the  $1/\omega$  term of the  $\pi\pi \rightarrow \pi\pi\gamma$  amplitude but disagree for the  $\omega^0$  term. We analyse the origin of this discrepancy. Then we calculate the amplitudes for the above reactions in the tensor-pomeron model. We identify places where “anomalous” soft photons could come from. Three soft-photon approximations (SPAs) are introduced. The corresponding SPA results are compared to those obtained from the full tensor-pomeron model for c.m. energies  $\sqrt{s} = 10$  GeV and 100 GeV. The kinematic regions where the SPAs are a good representation of the full amplitude are determined. Finally we make some remarks on the type of fundamental information one could obtain from high-energy exclusive hadronic reactions without and with soft photon radiation.

conclusion of the authors

From the results of our present paper we know that the terms of order  $1/\omega$  and  $\omega^0$  in the expansion of the standard amplitude are strict results from QFT without approximations, given the on-shell  $\pi\pi \rightarrow \pi\pi$  amplitudes. Therefore, if QFT describes experiment we must have (see Appendix B for a detailed discussion)

$$\lim_{\omega \rightarrow 0} R_{\text{exp}}(\omega) = 1, \quad \lim_{\omega \rightarrow 0} \frac{dR_{\text{exp}}(\omega)}{d\omega} = 0. \quad (6.2)$$

A violation of these relations would mean a terrible crisis for QFT!

## summary ultra-soft photons

- the study of ultra-soft photon production promises, via the Low theorem, insight into the infrared limit of quantum field theories such as QED and QCD
- in the past, a number of experimental tests have been performed at relatively low center of mass energies  $E_{\text{cm}} = 10 - 100 \text{ GeV}$
- nearly all tests in collisions with hadrons in the final state have resulted in large (2 – 8 fold) enhancements compared to the predictions based on the Low theorem
- at the LHC, with a factor 100 larger energies, soft photon production will be studied in a comprehensive and dedicated way with ALICE 3
- the planned tests will mostly use pp collisions at  $E_{\text{cm}} = 13.5 \text{ TeV}$  and will be based on exclusive collisions\* such as  $pp \rightarrow pp \pi\pi \gamma$  where the two outgoing protons are unobserved as well as on multi-hadron production collisions such as  $pp \rightarrow (n \text{ charged hadrons}) \gamma + X$  where  $X$  is in the beam fragmentation region
- the soft photons will be detected with transverse momenta down to  $k_{\perp} = \text{a few MeV}$  in a photon conversion tracker placed at rapidities  $3.5 < y < 5$

\* arXiv:2107.10829

exciting times are ahead of us

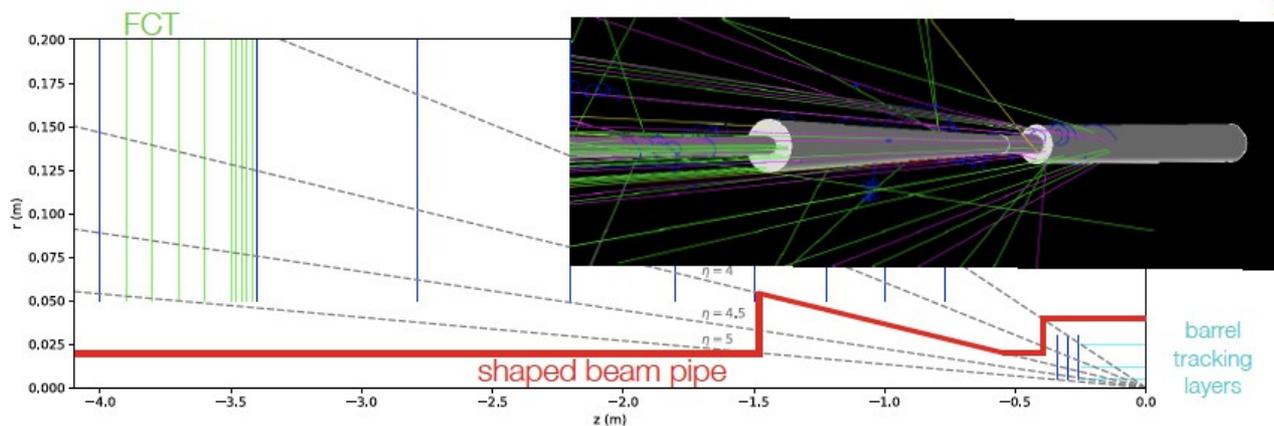
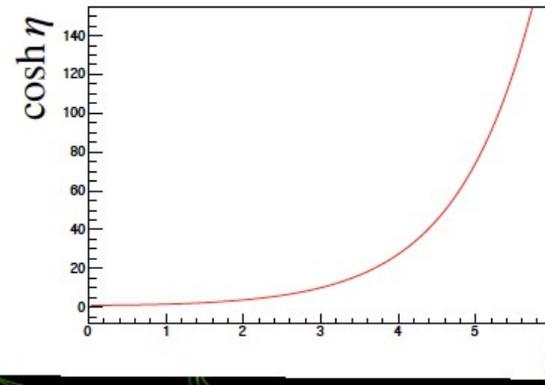
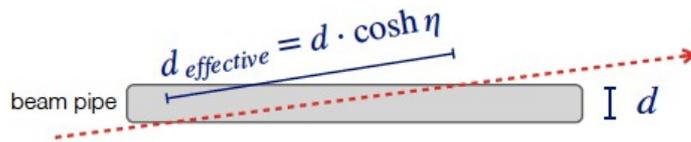
additional slides

minimisation of material in front of FCT due to the beam pipe

suggestion: **shaped beam pipe optimised for FCT**

minimisation of detector material in front of FCT:

- ▶ avoid material crossing at shallow angles, e.g.: shape beam pipe for FCT measurement



slide courtesy T. Rogoschinski, Univ. Frankfurt

## main assumptions and results

In the soft photon limit,  $k \rightarrow 0$ , the matrix element  $M$  can be factorized into the hadron part  $M_0$  and the photon emission part

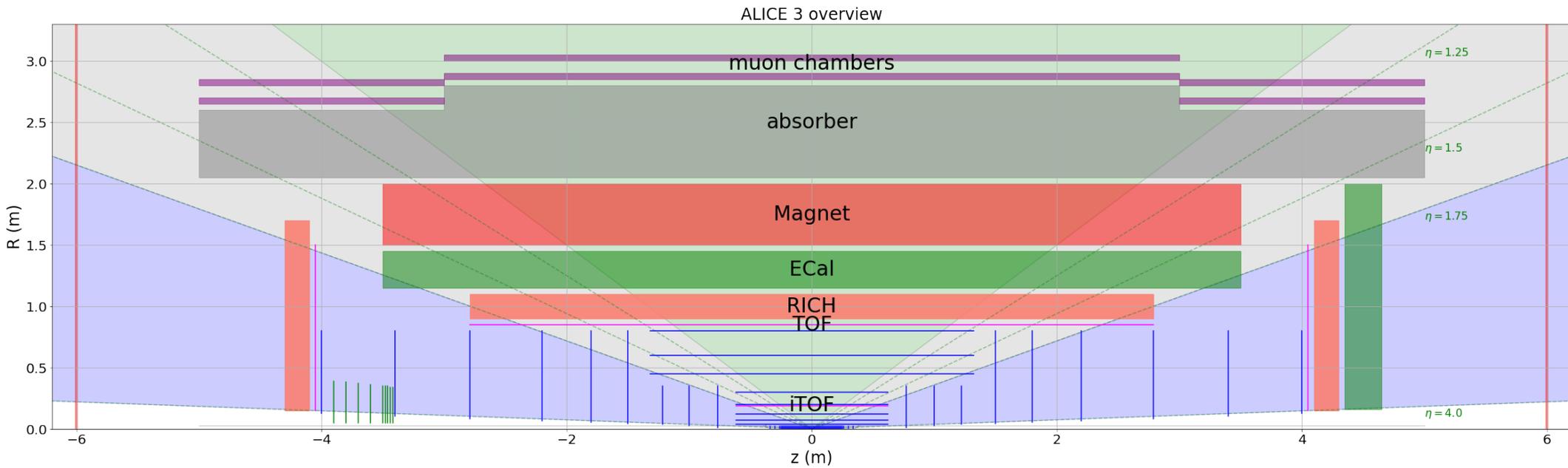
$$\sum_i^{\text{all charged particles}} \frac{\eta_i e_i p_i \cdot \varepsilon}{2p_i \cdot k}$$

underlying this is the recognition that, for  $k \rightarrow 0$ , and with the colliding hadrons in the GeV to TeV range, the following equality holds:

$$M_0(p_1 - k, p_2; p_3, p_4) \sim M_0(p_1, p_2; p_3 + k, p_4) \sim M_0(p_1, p_2; p_3, p_4)$$

since  $M_0$  is just the amplitude for 'elastic' scattering, or in the general case, the amplitude for multi-hadron production, the number of soft photons is precisely predicted from the (measured) cross section for multiple production of charged hadrons

# current view of ALICE 3 detectors – under development



the inner part, up to radial distance  $R < 1$  m, is essentially massless

note the distance and pseudo-rapidity scale

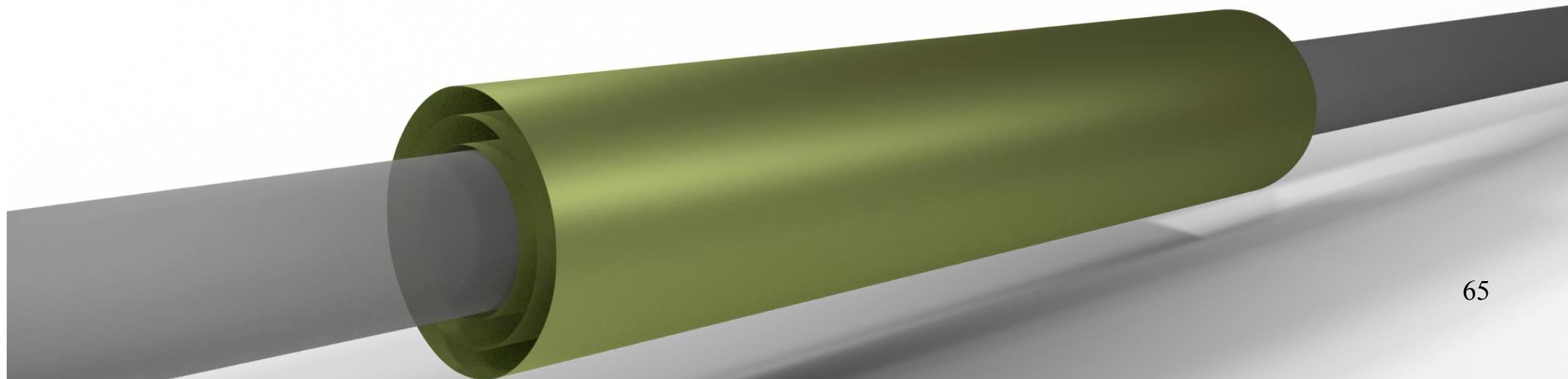
## ALICE 3: a (nearly) massless detector for ALICE after LHC Run4 (2030+)

principle: surround the beam pipe by very thin ( $< 40 \mu\text{m}$ ) Si pixel-chips bent into cylindrical shape

1<sup>st</sup> application: the ITS3 detector with 3 cylindrical layers, to be inserted into the current ALICE experiment after LHC Run3 (2026), see sketch below

baseline: monolithic active pixel (MAPS) sensors fabricated in the commercially available CMOS process

sensor and detector development currently underway in the framework of ITS3



# transverse momentum coverage for selected observables in ALICE 3

<b>Observables</b>	<b>Kinematic range</b>
Heavy-flavour hadrons	$p_T \rightarrow 0,$ $ \eta  < 4$
Dielectrons	$p_T \approx 0.05$ to $3 \text{ GeV}/c,$ $M_{ee} \approx 0.05$ to $4 \text{ GeV}/c^2$
Photons	$p_T \approx 0.1$ to $50 \text{ GeV}/c,$ $-2 < \eta < 4$
Quarkonia and exotica	$p_T \rightarrow 0,$ $ \eta  < 1.75$
Ultrasoft photons	$p_T \approx 1$ to $50 \text{ MeV}/c,$ $3 < \eta < 5$
Nuclei	$p_T \rightarrow 0,$ $ \eta  < 4$