

QCD & QGP at the LHC & Prospects with heavy ions with LHCb detector.

Ginés MARTINEZ,
Research Director at CNRS

Subatech (IMT Atlantique, CNRS/IN2P3, Nantes Université)

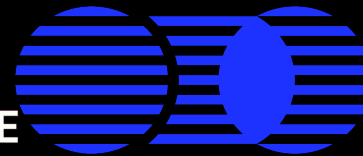
January 6 – February 2 2026, Visiting Researcher at IGFAE



Nantes
Université



NUCLÉAIRE
& PARTICULES



IGFAE

INSTITUTO GALEGO
DE FÍSICA
DE ALTAS ENERXÍAS

II CURSO TEORICO-PRACTICO "INTRODUCCION A LA FUSION POR CONFINAMIENTO MAGNETICO" CONVOCATORIA DE 14 ESTANCIAS BECADAS

Dirigido a:

Estudiantes de cuarto curso de la licenciatura de Ciencias Físicas y de quinto curso de la Escuela Técnica Superior de Ingenieros Industriales y de Ingenieros de Telecomunicaciones.
El estudiante, tras un breve periodo de clases teóricas, se integrará a un grupo de investigación ya existente donde le será asignada una tarea concreta. En la solicitud deberá declarar un orden de preferencia de los temas de trabajo siguientes:

Temas teóricos:

- 1) Estudios de equilibrio en plasmas.
- 2) Estudios de estabilidad en sistemas de eje magnético helicoidal.
- 3) Cálculos analíticos del tensor dieléctrico relativista.
- 4) Estudios teóricos de calentamiento en plasma de fusión.
- 5) Estudios de configuraciones magnéticas en el Heliac TJ - II.

Temas experimentales:

- 6) Determinación experimental de modos MHD en tokamak TJ - I.
- 7) Estudios de espectros de rayos X duros en el TJ - I.
- 8) Calibración de detectores de amplia banda y optimización de colimadores variables para bolómetros.
- 9) Estudio de fluctuaciones en el borde del plasma del TJ - I.
- 10) Interacción plasma - pared por espectroscopia y espectrómetro de masas en el TJ - I.
- 11) Medidas comparativas de la temperatura electrónica del plasma en el TJ - I.

Temas de ingeniería:

- 12) Test frío de componentes de alta potencia mediante la técnica del campo lejano.
- 13) Algoritmos de análisis de componentes en guía de ondas para calentamiento a la frecuencia de la resonancia electrónica.
- 14) Diseño detallado del sistema de alimentación eléctrica para el toratrón STORM.

Duración: Tres meses (Julio - Septiembre de 1.989)

Lugar: Instituto de Investigación Básica, Unidad de Fusión por Confinamiento Magnético (CIEMAT)

Inscripciones:

- Enviar solicitud adjuntando:
- Declaración jurada de las notas obtenidas en la carrera.
 - Orden de prioridad de los temas elegidos
 - Carta de presentación de un profesor de la facultad donde cursan sus estudios

INSTITUTO DE ESTUDIOS DE LA ENERGIA
CIEMAT
Avda. Complutense, 22 - 28040 Madrid
Telefax: 3466005 - Telex: 23595 CIEMAT - Telef.: 3466407

Condiciones: Los alumnos recibirán una beca de 180.000.-pts. integras para la realización del curso.

Edita: Secretaría General Técnica del CIEMAT
Ministerio de Industria y Energía

Becario CIEMAT
Grupo de fusión
Junio - Septiembre 1989
60000 pts/mes
360€/mes

Caveats

This is my **personal** view. I am **experimentalist**.

I have been member of **PHENIX** collaboration 1990-2004 and of **ALICE** collaboration 1998-2024. I am member as technical associate of **LHCb** collaboration since 2025.

Subatech will ask for full membership this year.

I have been **director of Subatech** from September 2018 until end 2025.

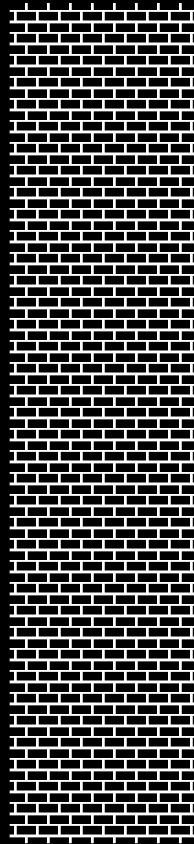
Since 1st January, I am **director of the French GdR (Recherche group) of QCD**. About 250 researchers and PhD in France are members of this GdR, covering all the topics related to Quantum Chromodynamics.

Quantum Chromodynamics “Drama”

Quark and Gluon discovery is discombobulating :

An experimentalist has to accept that we will never measure in the laboratory the four-momentum of a quark, neither for a gluon.

QCD is beautiful theory, conceptually similar to QED, but extremely different theory



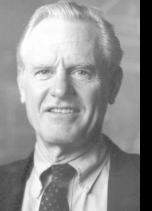
Mathematical model for describing hadrons quantum numbers

Nobel Prize 1969 M. Gell-Mann

Properties of the proton form factors that can be interpreted as point like quark and gluon particles: PDFs, Nobel Prize 1990 J. Friedmann, H. Kendall, R. Taylor

The confinement wall

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a} (i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t_{ab}^C A_\mu^C - m_q \delta_{ab}) \psi_{q,b} - \frac{1}{4} F_{\mu\nu}^A F^{A\mu\nu}$$



Studying strong interaction properties

QCD bound states and lifetime:

- two different worlds when dealing with light quarks

QCD interactions studies are conditioned by confinement:

- Mono-quarks or mono-gluons beams are simply inaccessible
- Lepton-hadron interactions: the hadron form factors → parton distribution functions. From EW to QCD
- Hadron-hadron interactions: parallel (coherent and incoherent) interactions. A big mess! Several modelling, MC generators ,...

QCD matter:

- Heavy-ion collisions: increasing the number of parallel interactions → QCD (deconfined) matter

QCD Bound States and lifetime

QCD bound states and their decay times : The Confinement Wall

Nuclear Theory

World

- Nucleus
- Proton
- Other hadrons
- Heavy hadrons
- Exotic hadrons

Hadronic Theory

EFT partons dof

Quark Model

Lattice QCD

NRQCD

AdS/CFT duality

QCD World

- Quarks & Gluons
- Quark masses
- Quark flavours
- Coupling constant close to unity
- Colour charge SU(3)
- Gluon colour octet

New Exotic QCD bound states

- Exotic hadrons : more than 3 quarks
- They are not excluded by the Quark Model
- Tetraquarks, hadron-molecules, pentaquarks and glueballs, ...
- Impressive experimental (also theory) progress during the last 25 years
- X(3872) state observed by Belle Experiment in 2003 (most cited Belle paper)
- The charged states are unanimously accepted as tetraquarks.
- Dubbed X(mass), or Y(mass), or Z(mass), referred as XYZ states. PDG proposed a naming scheme base on the quantum numbers
- Impressive amount of data.

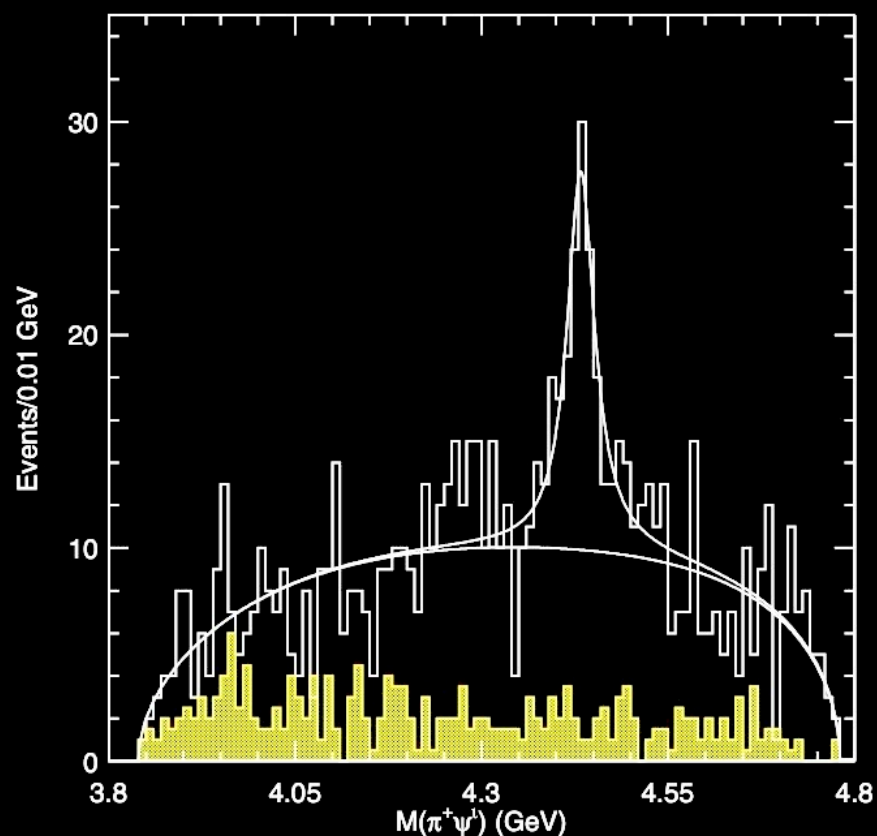
 $\bar{q}q\bar{q}q$
 $\bar{q}qqq$
 $\bar{q}\bar{q}qqq$

N. Brambilla et al, Phys. Rep. 873 (2020) 1
 Belle Collaboration Phys. Rev. Lett. 91 (2003) 262001

Beauty Physics experiments have played a leading role in the discovery of exotic hadrons, and this is still the case today!

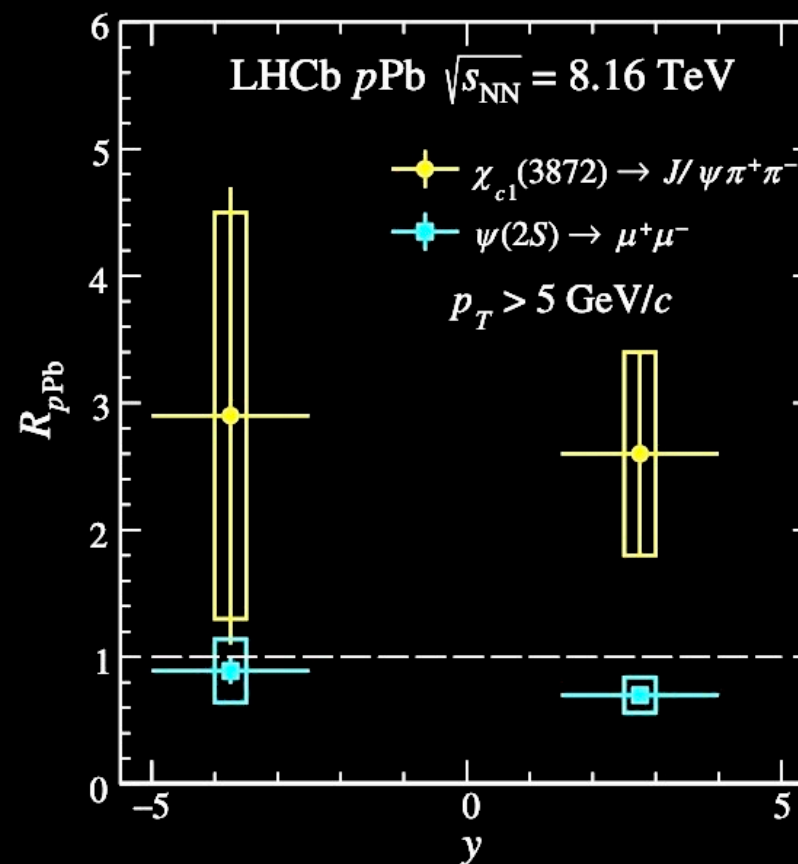
Two examples of Exotic Hadron Production

$Z_c^+(4430)$ First charged exotic hadron (2008)



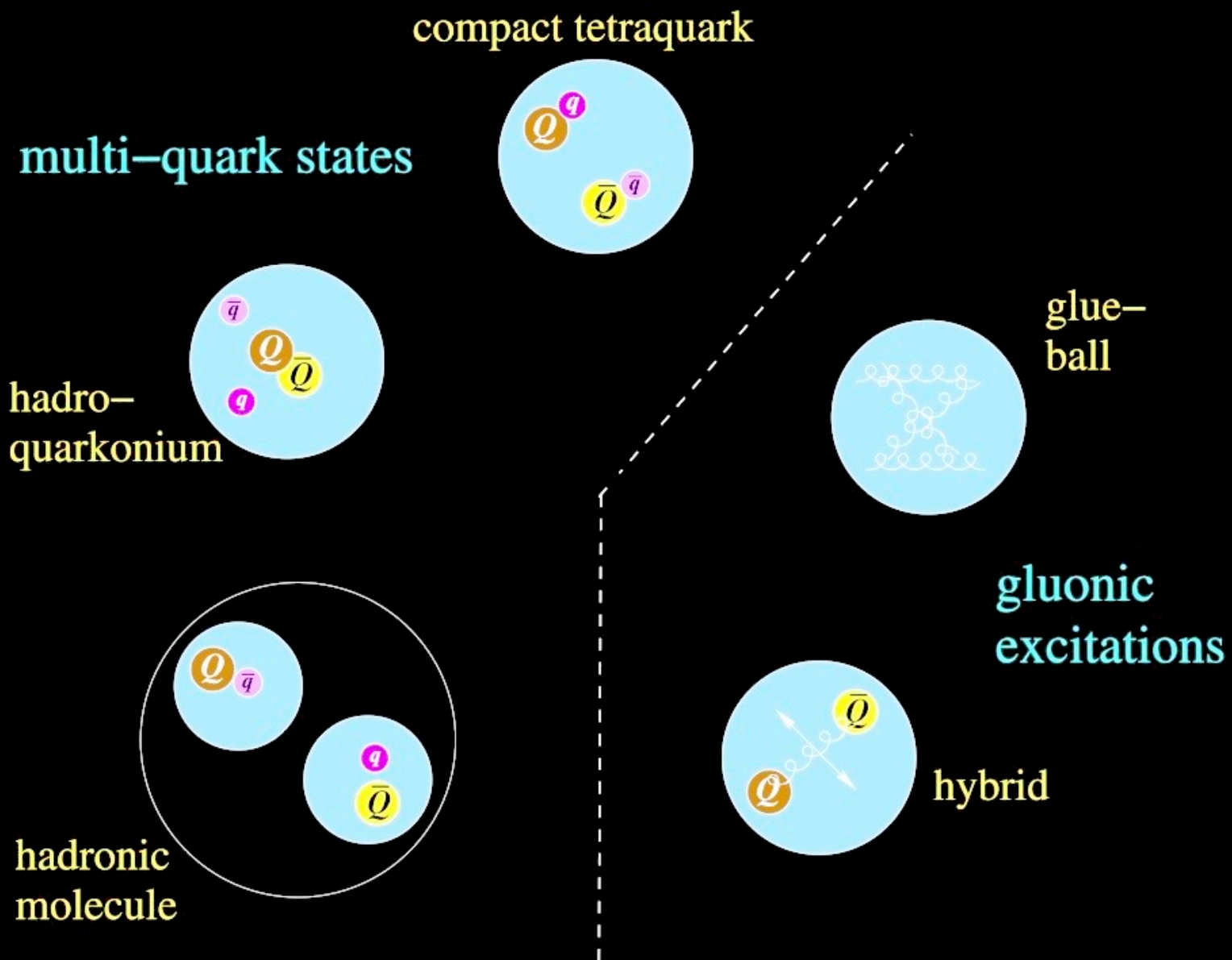
Belle Collaboration Phys. Rev. Lett. 100 (2008) 142001

$X(3872)$ Nuclear modification factor



LHCb Collaboration Phys. Rev. Lett. 132 (2024) 242301

Theoretical Pictures



QCD Interaction

Asymptotic freedom of QCD

Contrary to expectations from QED

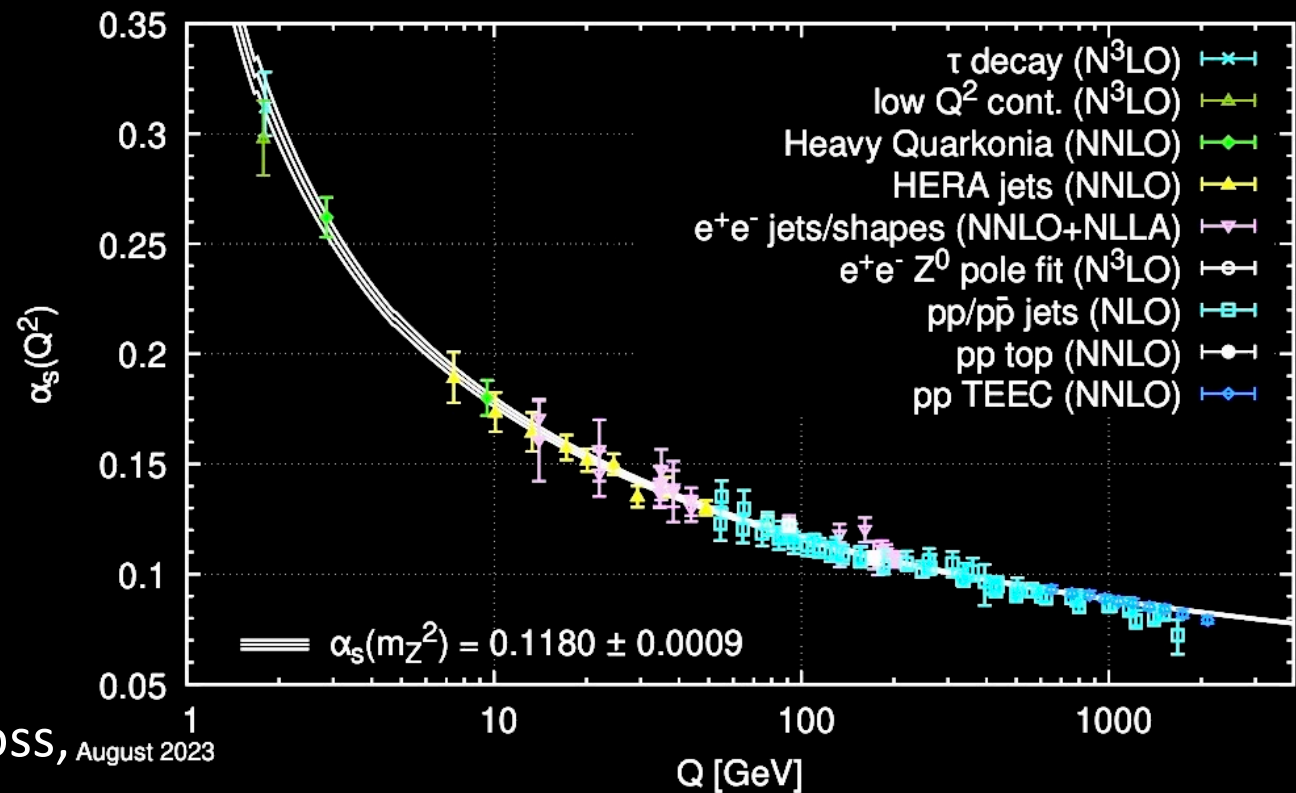
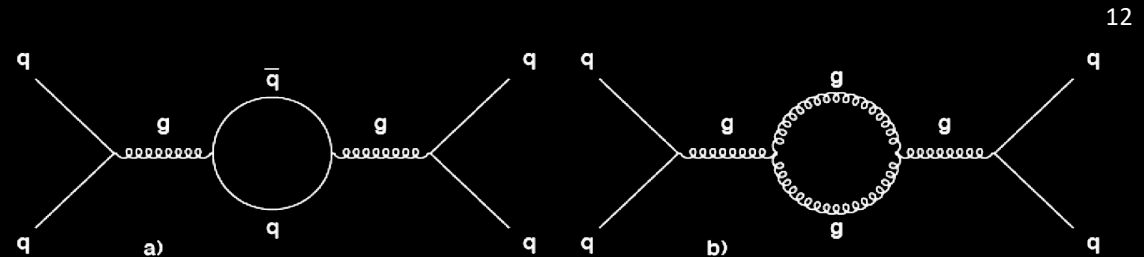
Running coupling decreasing quickly with energy

Impressive succès of QCD theory

Perturbative QCD calculations are predictive

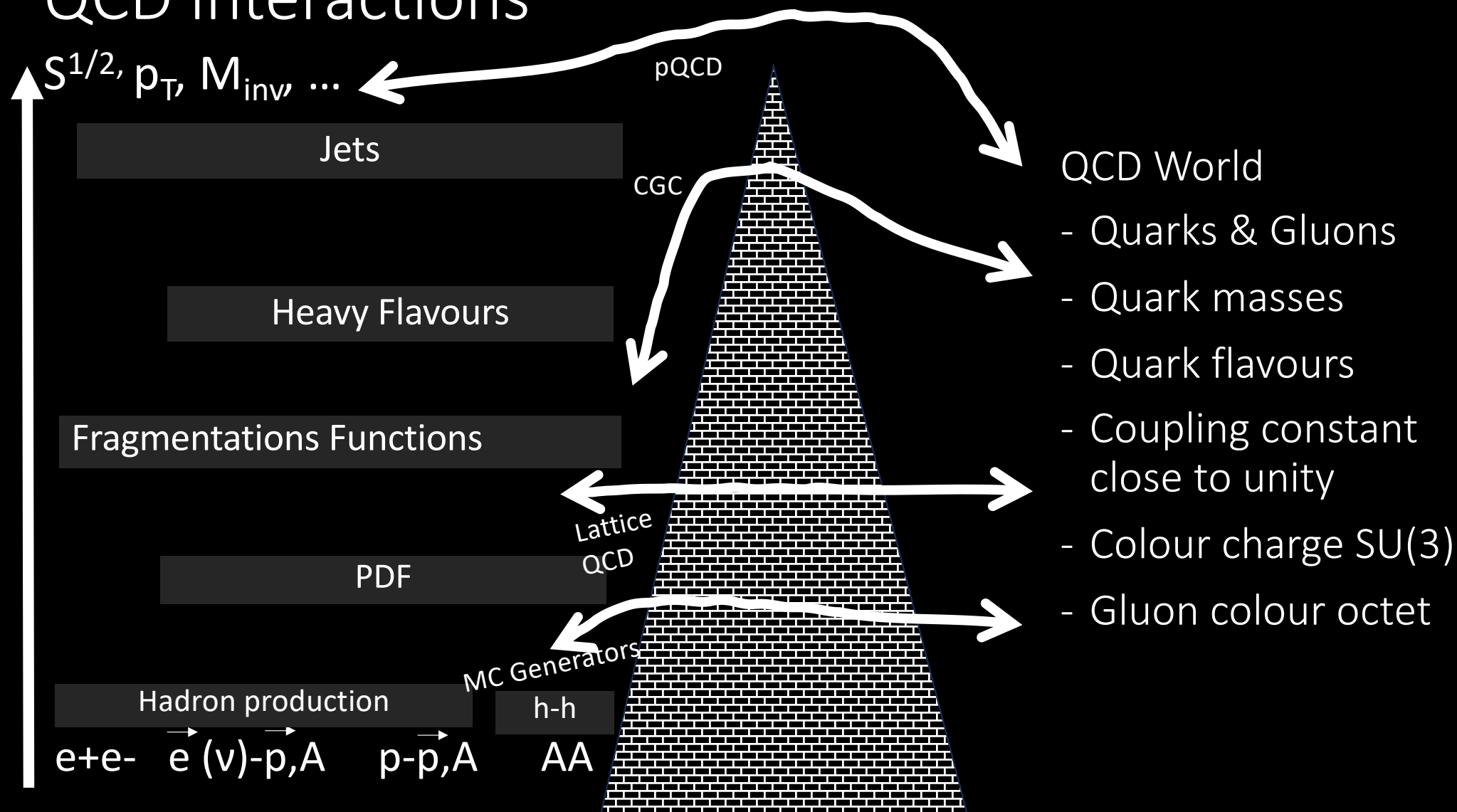


Nobel Prize
2004, FD Gross, August 2023
D. Politzer, F.
Wilczek



PDG PRD 110 (2024) 030001 & Update 2025

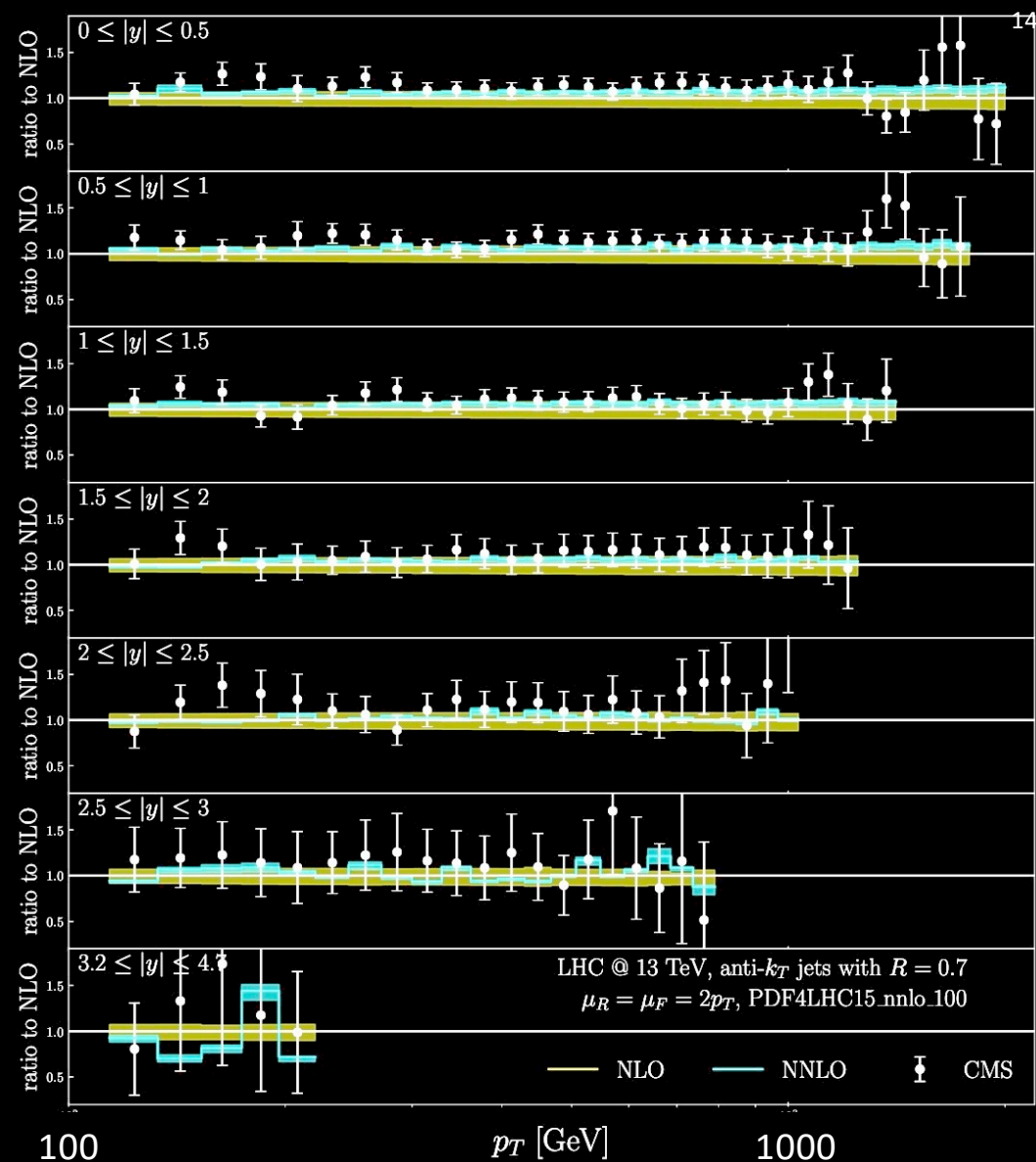
QCD interactions



Single Jet pQCD calculations

- Good agreement
- PDF remain non perturbative input
- 10% is a good prediction for pQCD calculation
- Transverse momentum range from 100 GeV to 1 TeV

M Czakon et al. JHEP10(2019)262

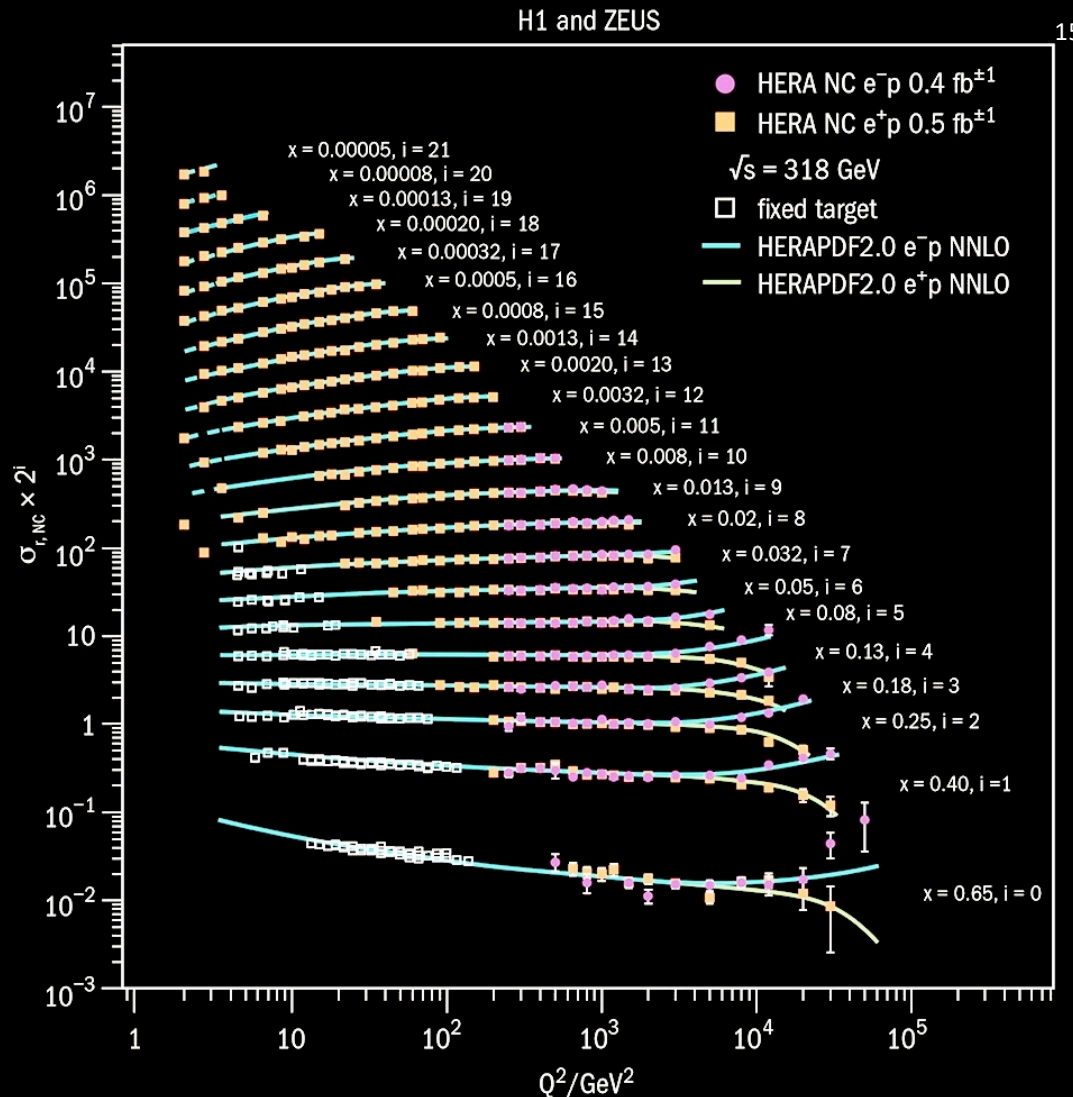


Structure Functions and Parton distribution functions: (PDFs)

But some ingredients of the perturbative QCD (pQCD) calculations remain purely non-perturbative, like PDFs or FFs.

Experimental data are mandatory to access to the nucleon PDFs : lepton-hadron collisions.

Beyond the PDFs, there is the question of the structure of hadrons, and in particular de structure of the proton

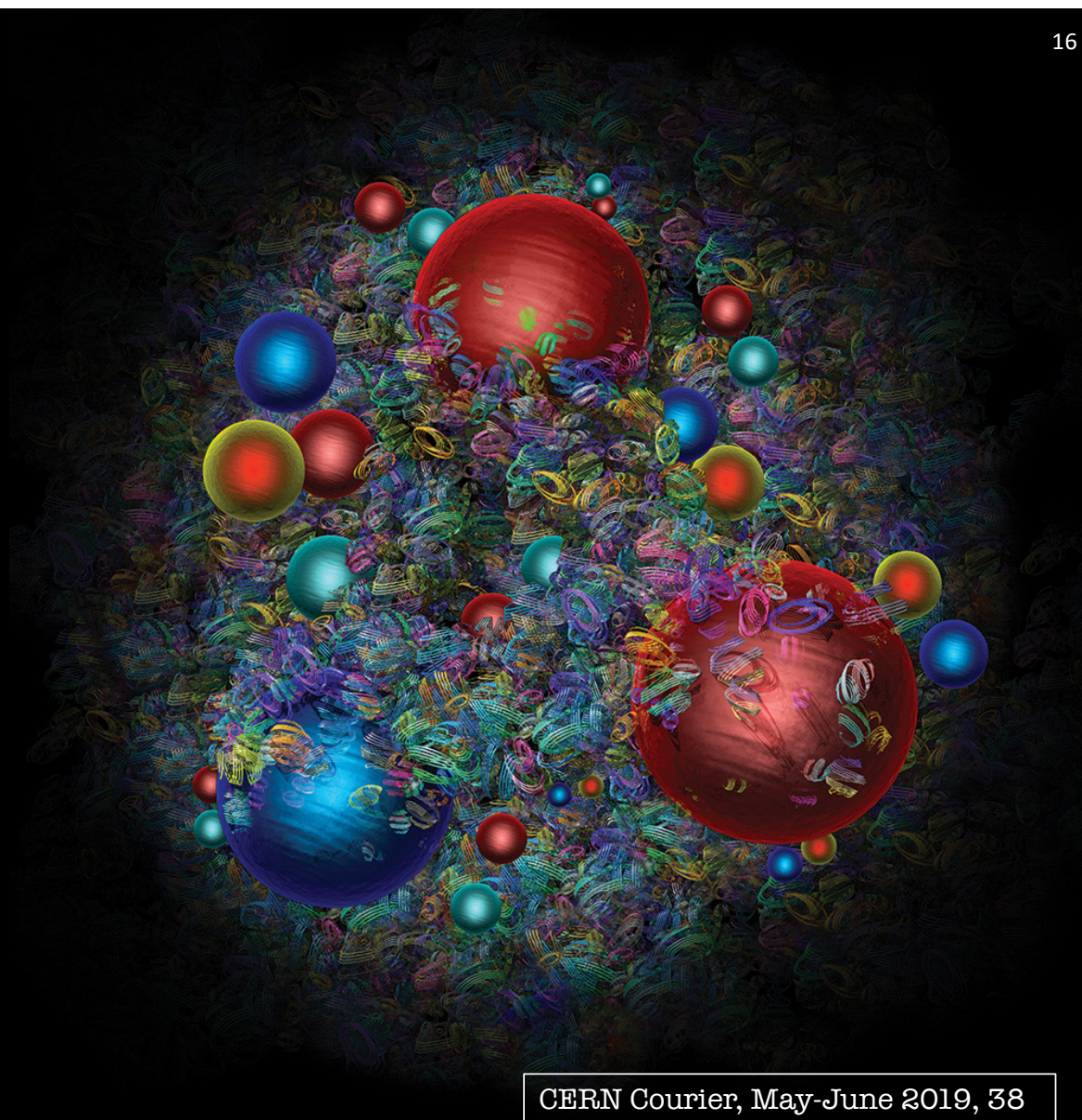


The proton structure

Open questions :

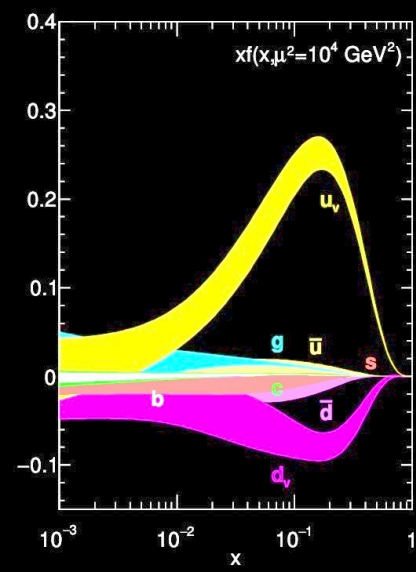
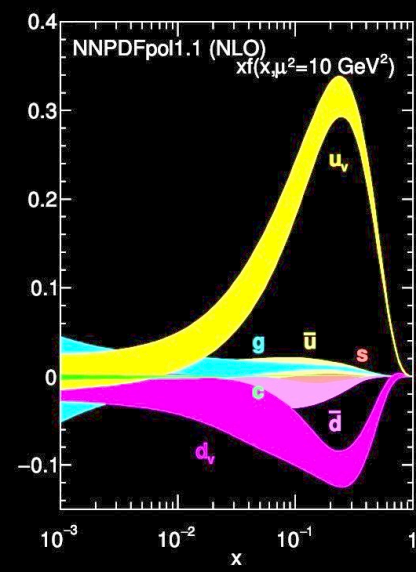
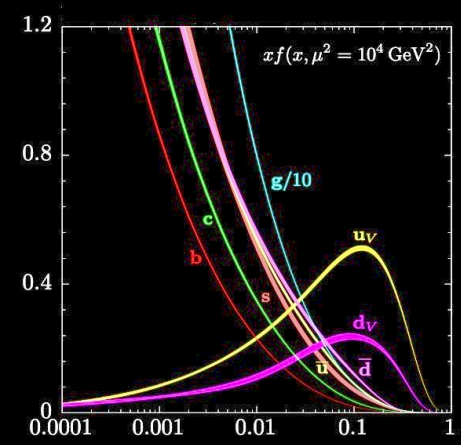
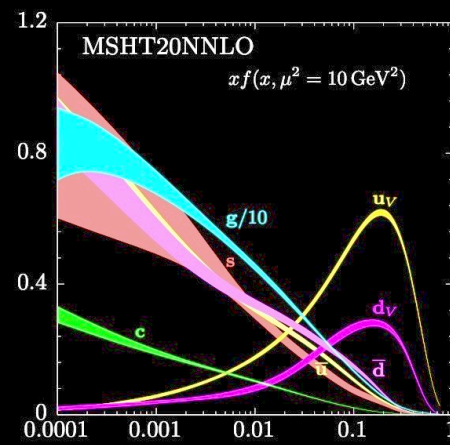
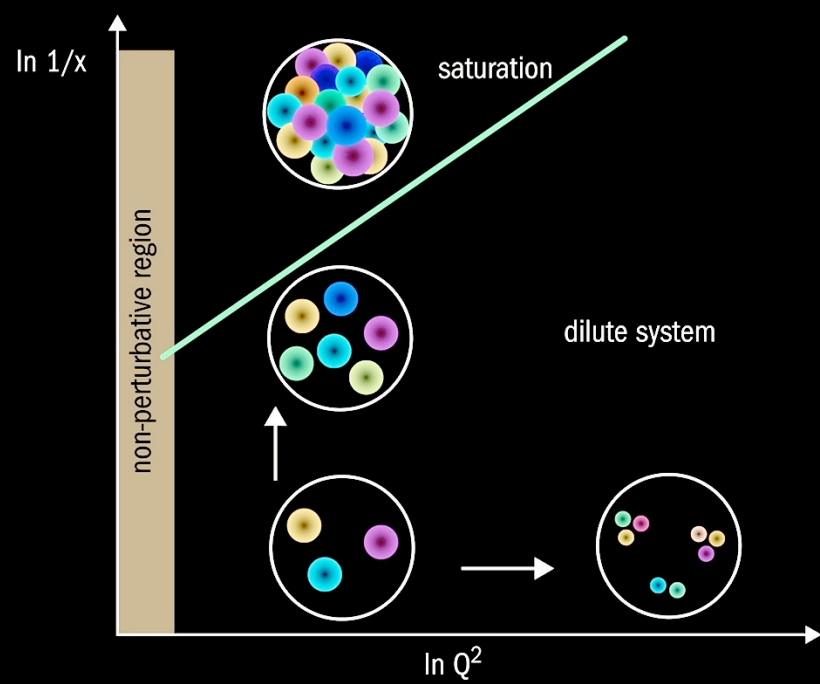
- Spin origine
- Mass origin and its distribution (GFF, the QCD trace anomaly)
- 3D parton distribution functions (GPD, TMD) $\rightarrow$ averaged transverse momentum and positions of partons
- Nucleons in the nucleus (nPDF)

Collisions : $\vec{e}(v) - \vec{p}, A$ $p - \vec{p}, A$



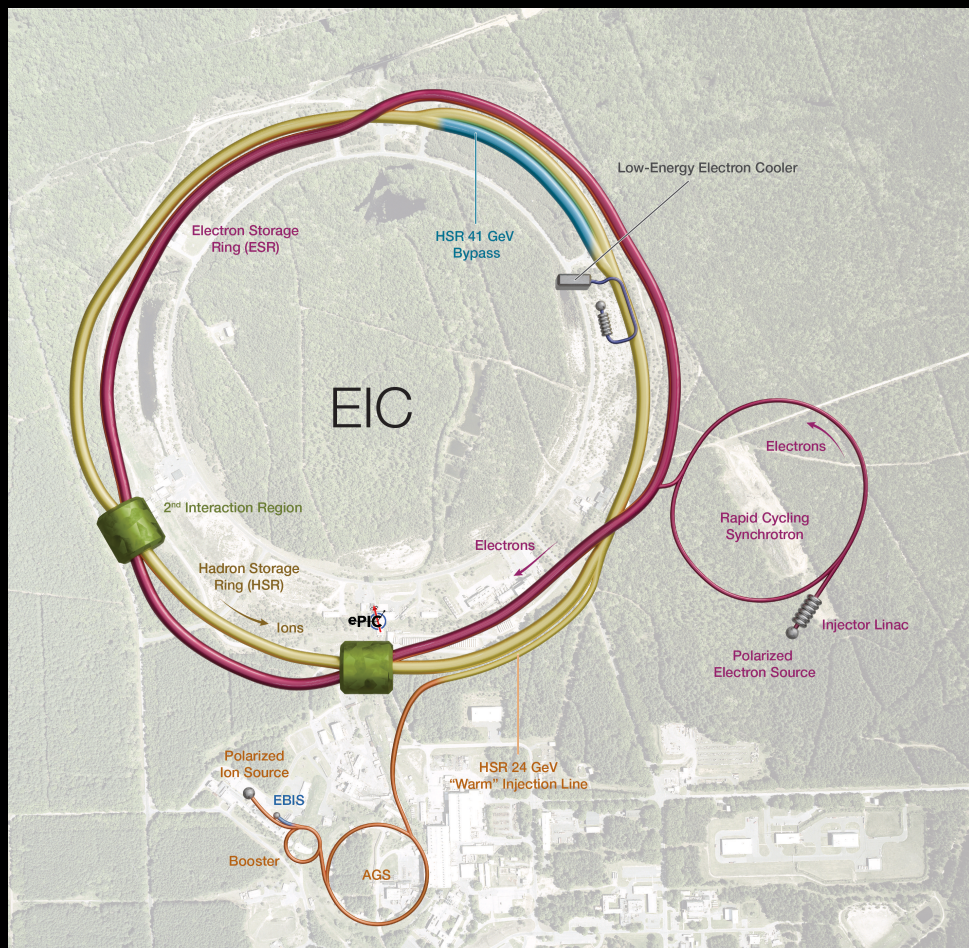
New QCD regime

Small x domain, high density of gluons (CGC, Saturation)
Density higher ($A^{1/3}$) in the nucleus



CERN Courier, May-June 2019, 38
PDG Phys. Rev. D110 (2025) 030001

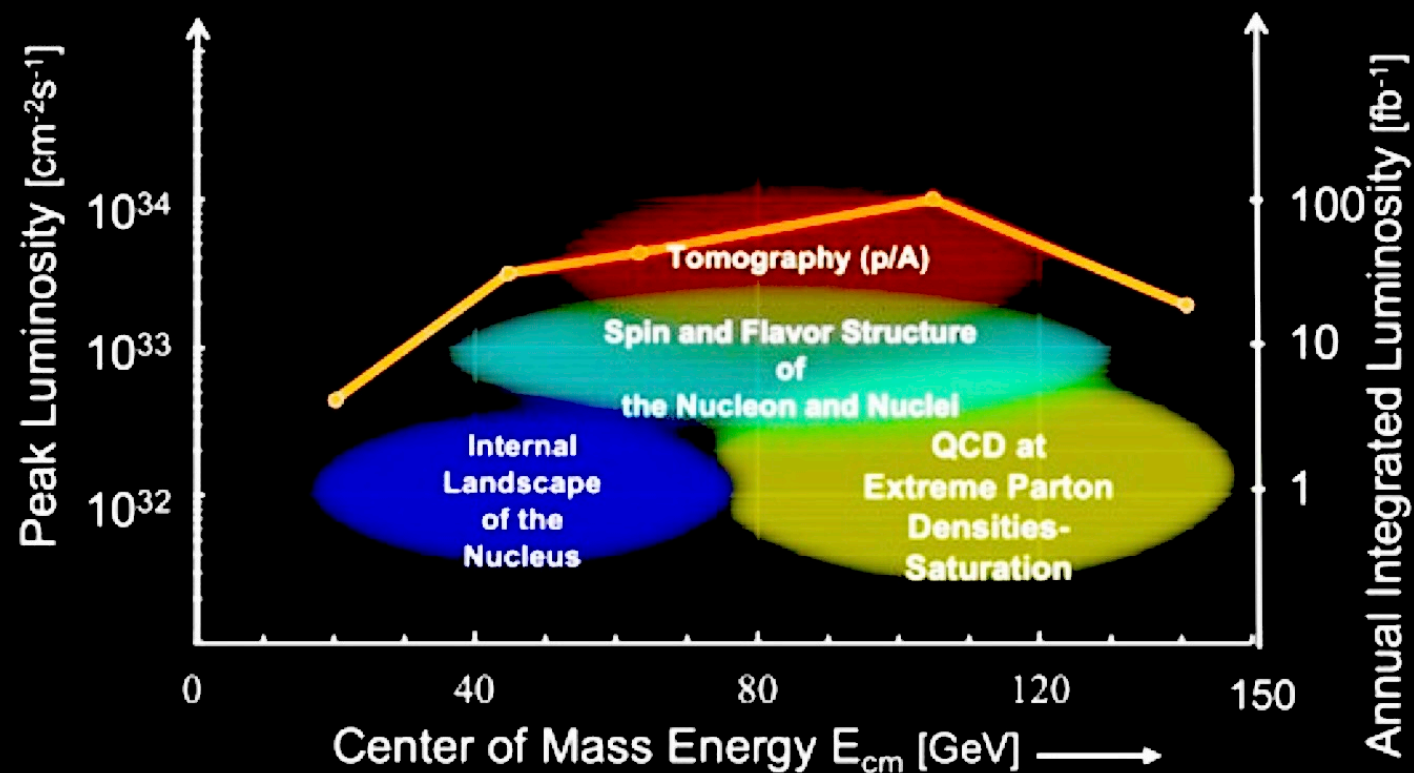
The Electron Ion Collider

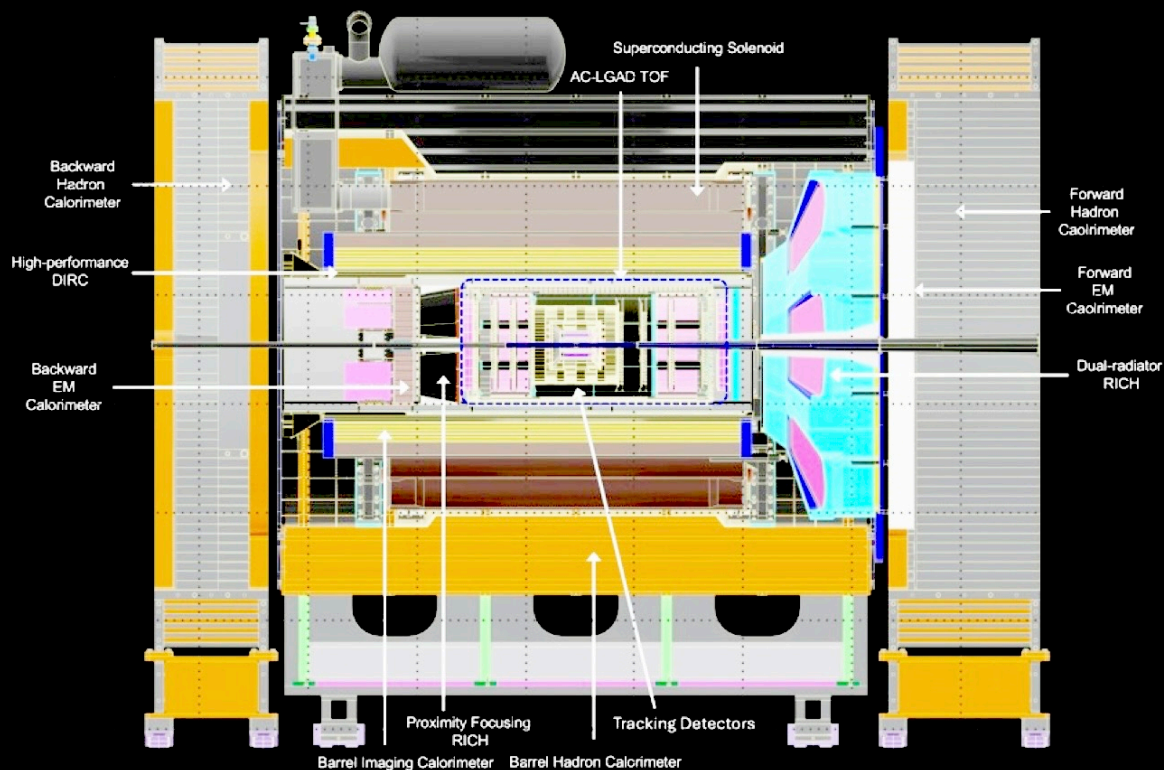
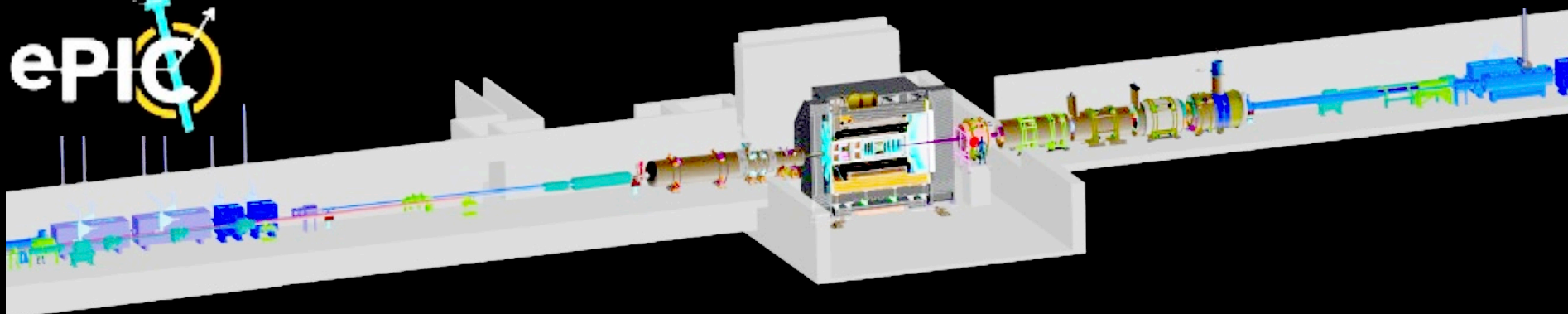


- Major technological developments (cooler, by-pass, injections, ...)
- Centre of mass energy 29 -141 GeV
 - electron beam 5-18 GeV,
 - proton beam 41, 100 – 275 GeV
 - Ions beam $Z/A \times E_p$, up to Uranium
- Luminosity $10^{33} - 10^{34} \text{ cm}^{-2}/\text{s}$
- Polarisation up to 70%
- Up to 2 interaction regions with (almost) complete coverage
- EPIC Collaboration

The Electron Ion Collider

Start of the Physics Program 2035, 10 years from now





26 subsystems over ± 40 m

- to measure particle momenta, energy and particle type
- 3 electromagnetic calorimeters
- 3 hadronic calorimeters
- Silicon and Multi-pattern gas detectors
- 3 RICH detector + time-of-flight
- 7 Auxiliary detectors (Si + HCal + ECals)
- electron and hadron polarimetry
- Integration, Installation and Infrastructure

Bulk properties of pp collisions at the LHC

$dN_{ch}/d\eta$ about 5 @ LHC (5 TeV)

Average transverse energy about 0.5 GeV

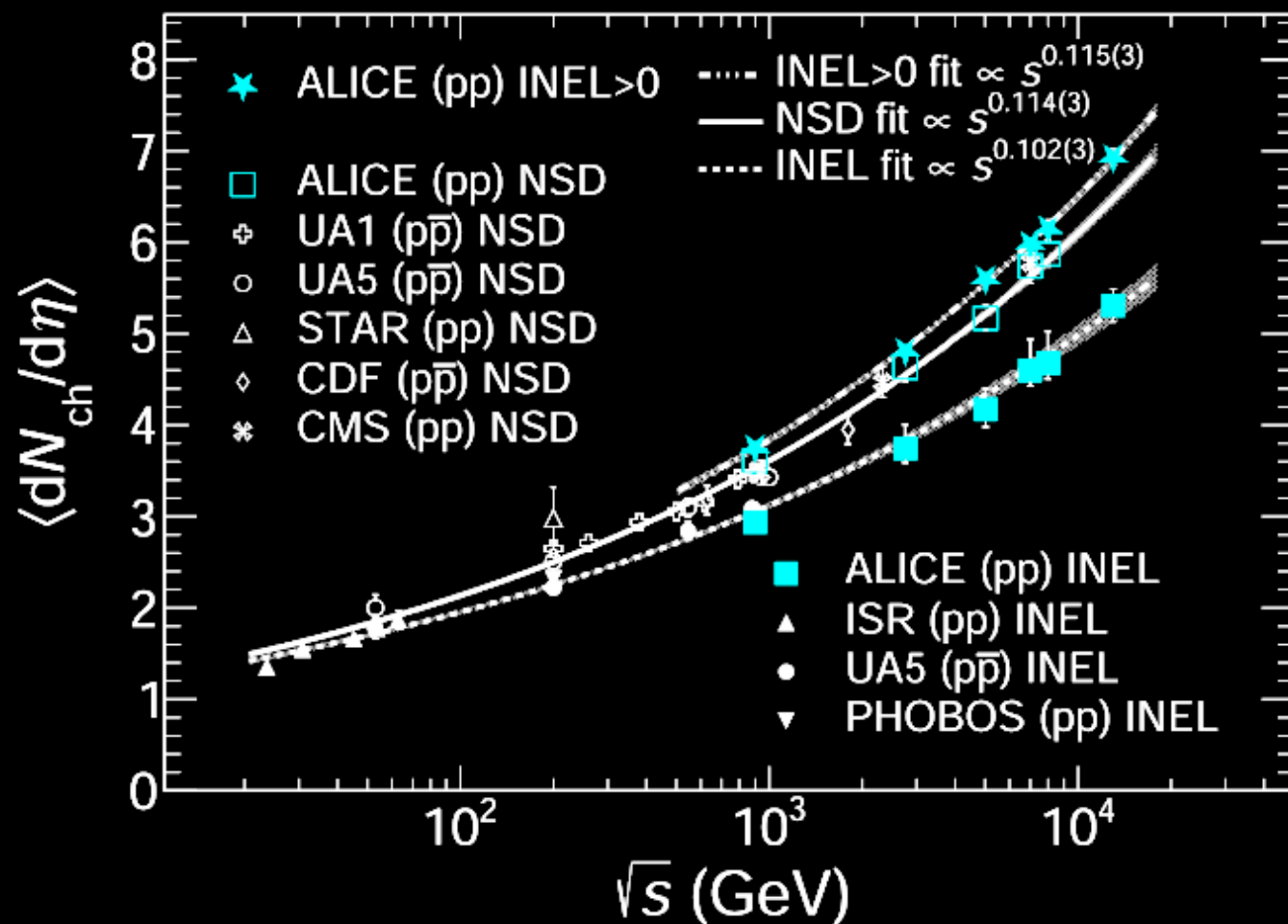
x Bjorken about $2\langle E_T \rangle / \sqrt{s} = 2 \times 10^{-4}$

Gluons balls colliding

$\gamma_{beam} = 8.5$

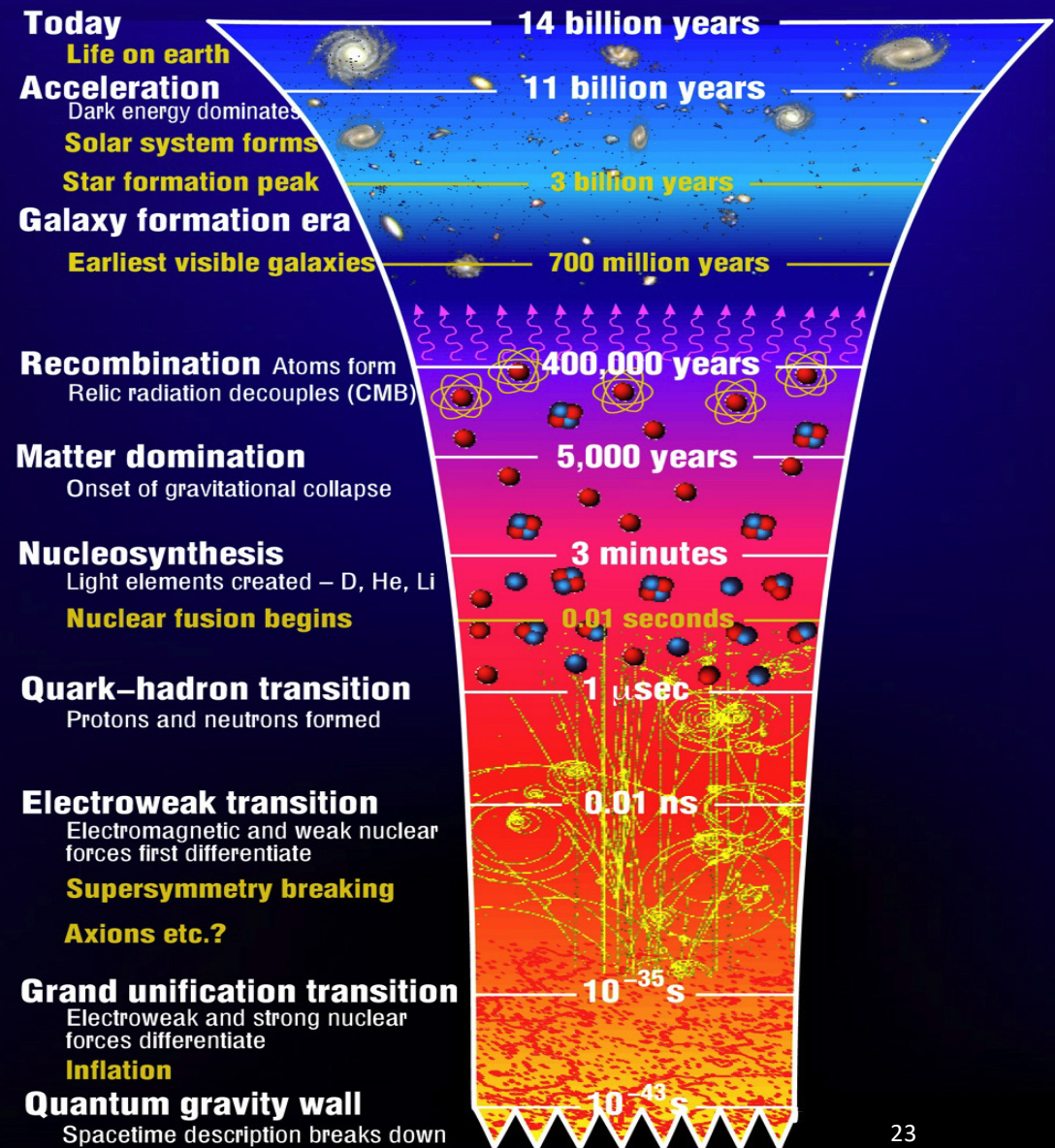
Total average energy in the transverse plane about 25 GeV, 0.5% of the total available energy in the cm

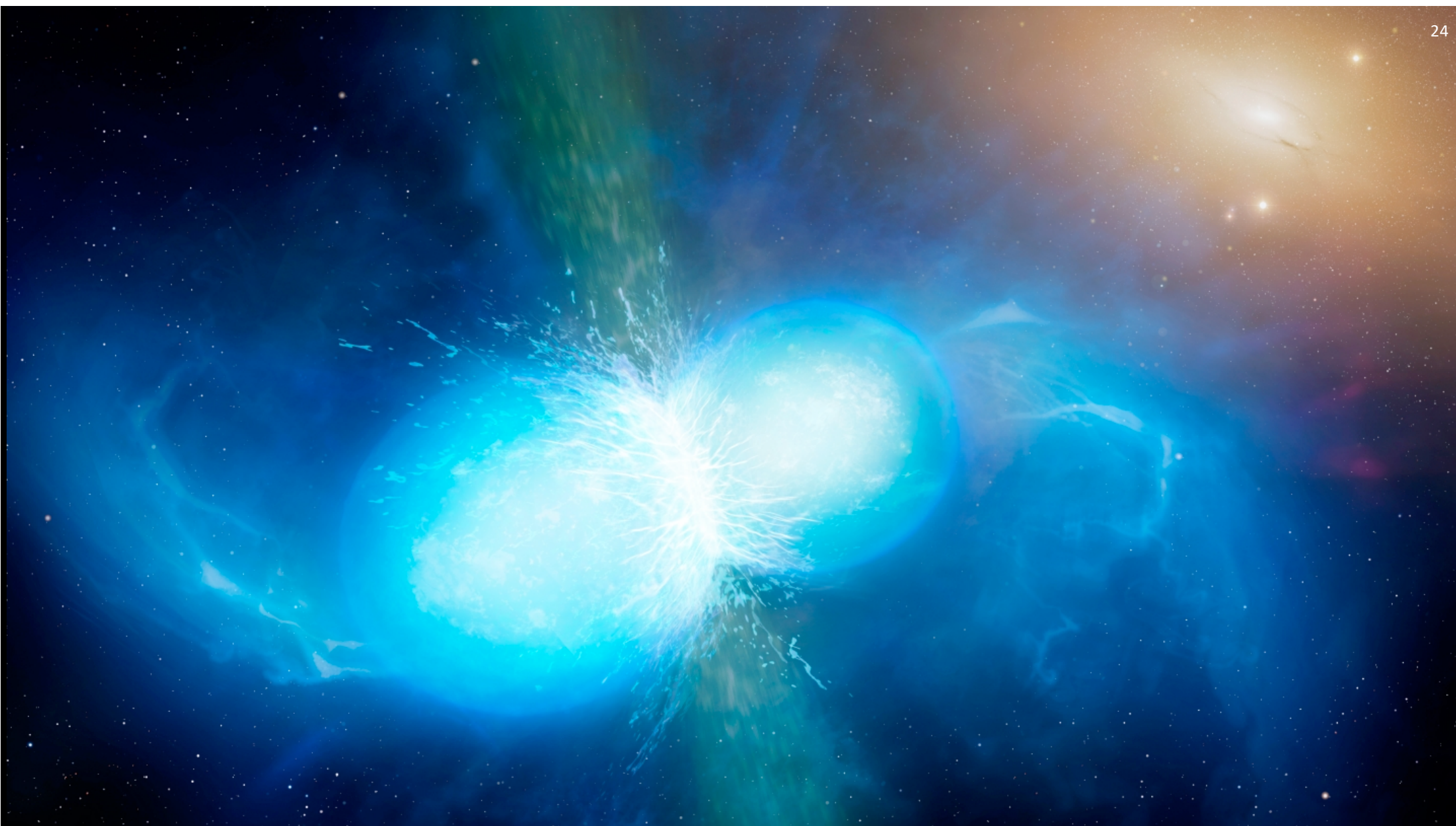
75% pions, 20% kaon, ...



QCD Matter

Transition at t about 1
microseconds after
the Big Bang

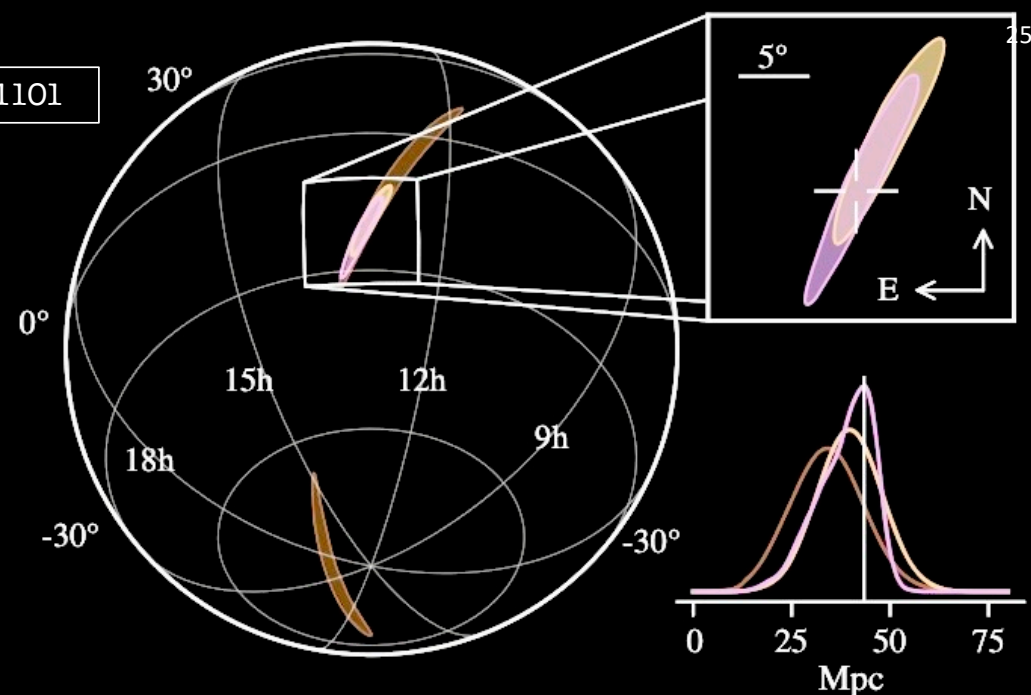




GW170817

LIGO & Virgo PRL 119 (2017) 161101

- NS-NS merger
- Gamma-ray burst GRB 170817A observed
- Agreement with General Relativity
- Sensibility to EoS of QCD matter
- Tidal deformability (incompressibility): upper limit



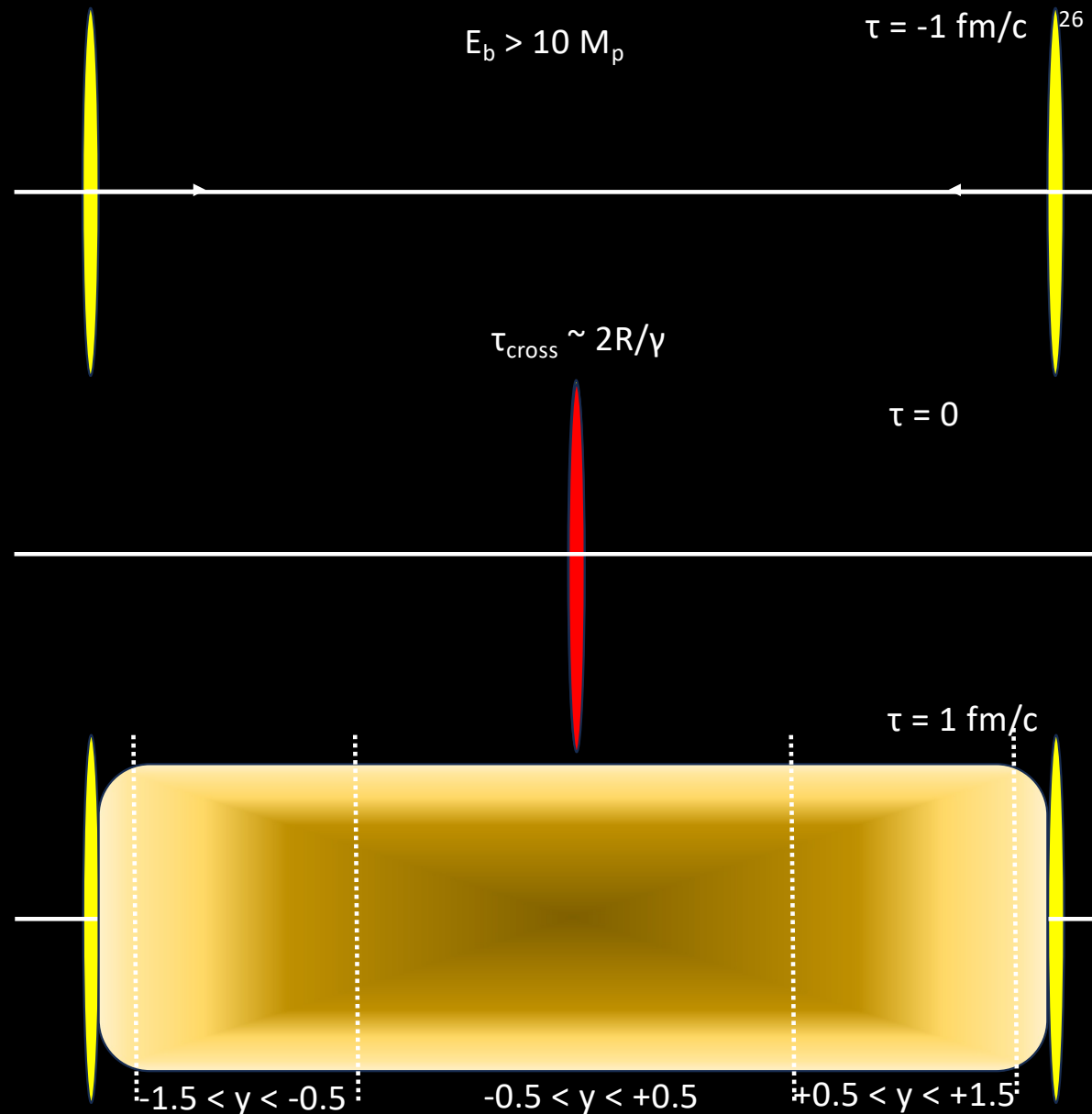
	Low-spin priors ($ \chi \leq 0.05$)	High-spin priors ($ \chi \leq 0.89$)
Primary mass m_1	$1.36\text{--}1.60 M_\odot$	$1.36\text{--}2.26 M_\odot$
Secondary mass m_2	$1.17\text{--}1.36 M_\odot$	$0.86\text{--}1.36 M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	$0.7\text{--}1.0$	$0.4\text{--}1.0$
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	$40^{+8}_{-14} \text{ Mpc}$	$40^{+8}_{-14} \text{ Mpc}$
Viewing angle Θ	$\leq 55^\circ$	$\leq 56^\circ$
Using NGC 4993 location	$\leq 28^\circ$	$\leq 28^\circ$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

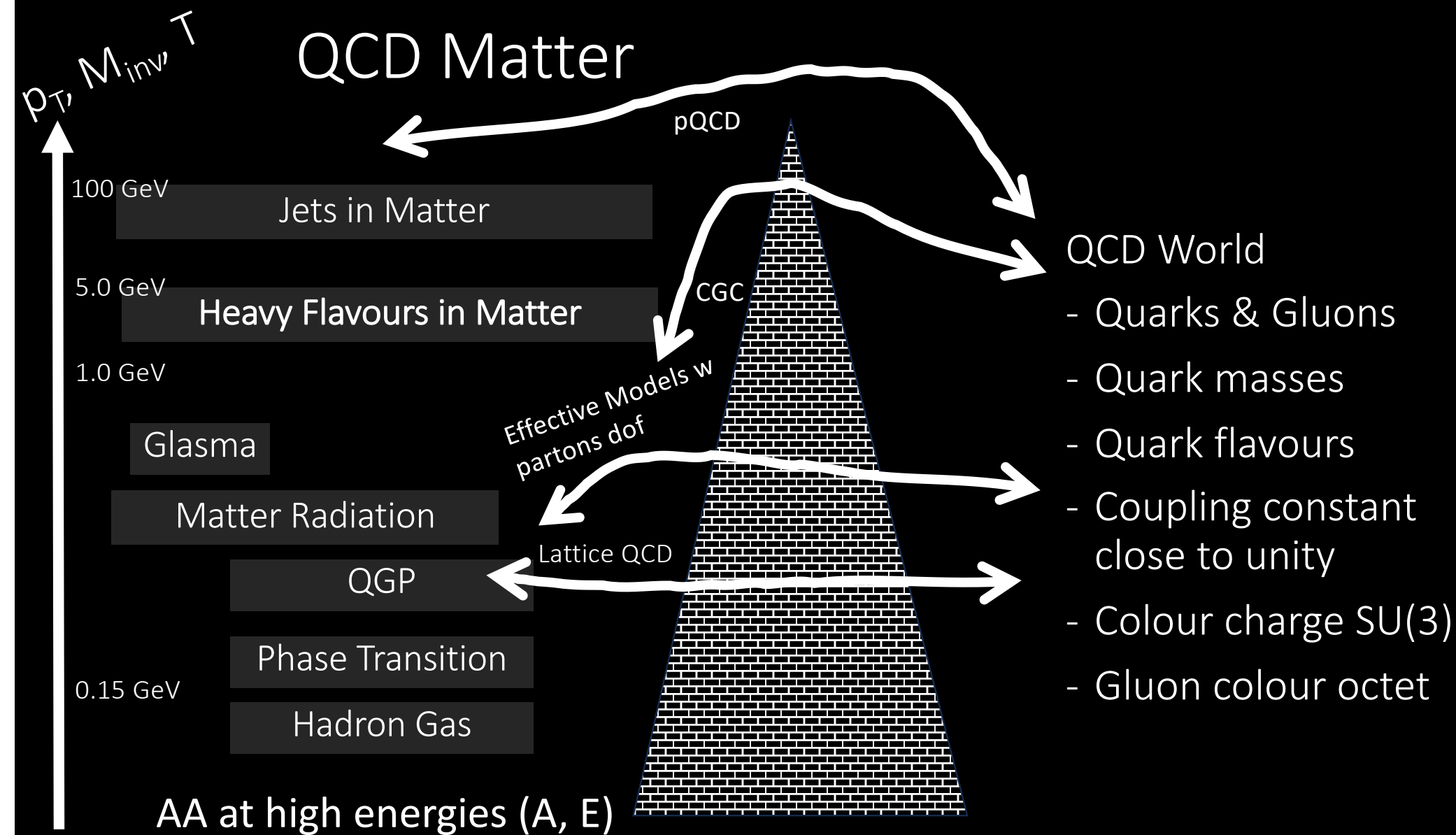
Bjorken Model

- Heavy Ion at ultra relativistic energies $E_b > 10 M_p$. Crossing time : $\tau_{\text{cross}} < 1/\Lambda_{\text{QCD}}$
- Typical x-Bjorken at mid-rapidity : Λ_{QCD}/E_b : Gluon cloud collision.
- @LHC : About 5 charged particle per unit of rapidity and per NN collision
- About 1000 N_{coll} in central Pb-Pb collisions
- $2 \times 5 \times 1000 / 1 \text{ fm} / (\pi R^2) = 63$ “hadrons” per $\text{fm}^3 \rightarrow$ Hydrodynamical expansion of QCD matter should work fine.

$$\beta_z = \tanh(y)$$

Bjorken PRD27 (1983) 140 (1983)





QCD Phase Diagram Lay-out

	$\sqrt{s_{NN}}$	$dE_t/d\eta$	ϵ_{BJ}	T
	[GeV]	[GeV]	[GeV/fm ³]	[GeV]
AGS	4.8	200	1.9	0.180
SPS	17.2	400	3.5	0.212
RHIC	200	600	5.5	0.239
LHC	2760	2000	14.5	0.307

F Gross et al. Eur. Phys. J. C83 (2023) 1125

Chiral symmetry spontaneous breaking

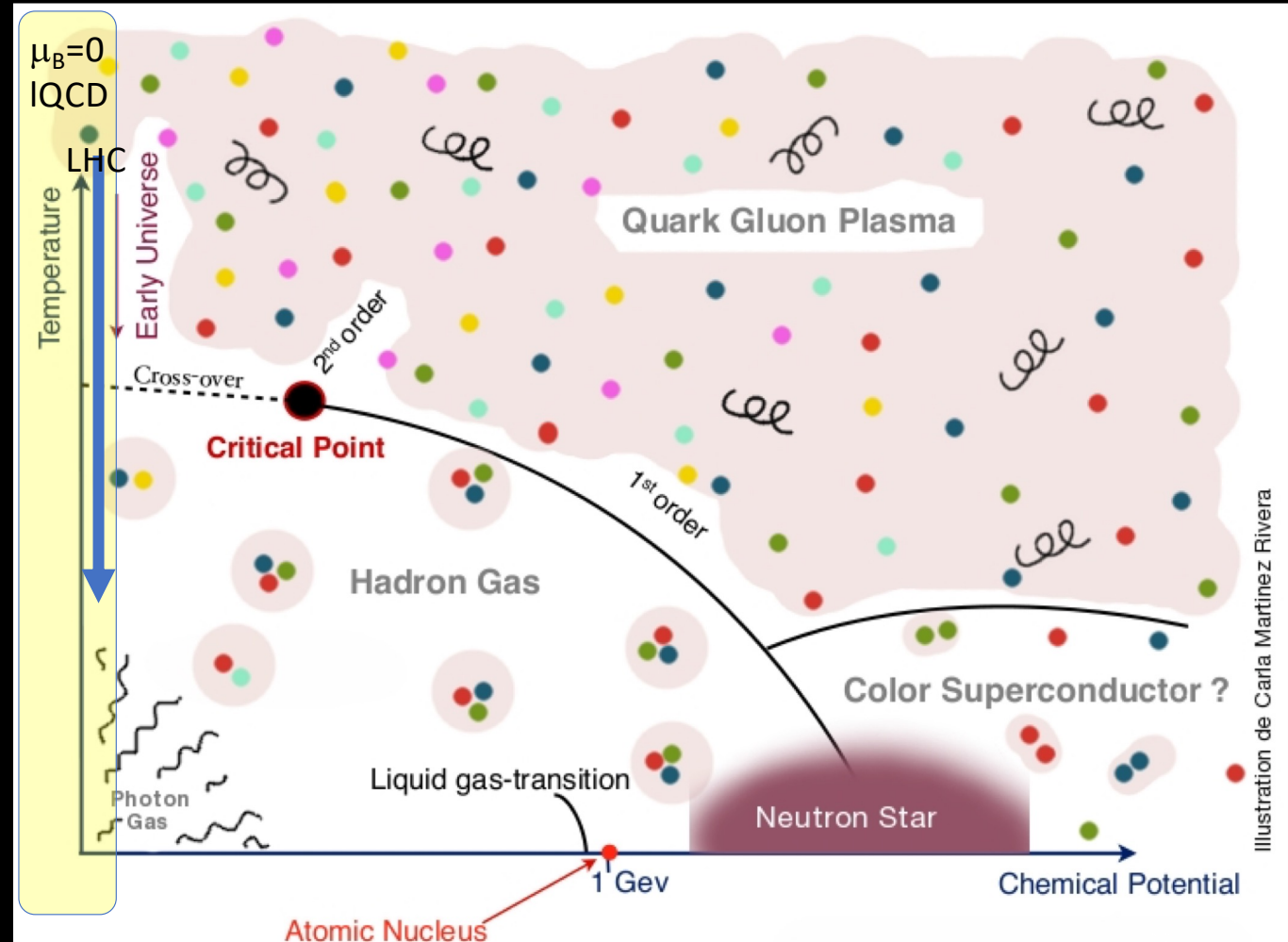
Deconfinement transition

Other transitions?

Existence of the critical point?

Huge IQCD progress in the last decades

Gines MARTINEZ Habilitation Tesis (2006)
tel-00370481v1



Experimental study of the quark
gluon plasma in heavy ion
collisions at relativistic energies

Heavy ion facilities

- SPS Heavy Ion accelerator (1986-) $\sqrt{s}$ 20 GeV per nucleon:
 - Pb, In at 158A GeV, O, S at 200A GeV on fixed target:
 - NA35, WA80, CERES, WA98, NA50, NA49, NA57, NA60, ..
- RHIC, BNL (2000 - ?) $\sqrt{s}$ 10-200 GeV per nucleon:
 - Au-Au, d+Au, Cu-Cu, U-U, ...
 - PHENIX, sPHENIX, STAR, PHOBOS, BRAHMS;
- LHC, CERN (2010 - ?) $\sqrt{s}$ 2-5.5 TeV per nucleon
 - PbPb, XeXe, pPb, pO, OO, NeNe, ...
 - LHCb Fixed target at RHIC energies pHe, pAr, pNe, PbNe, ...
 - LHCb ALICE, CMS, ATLAS;

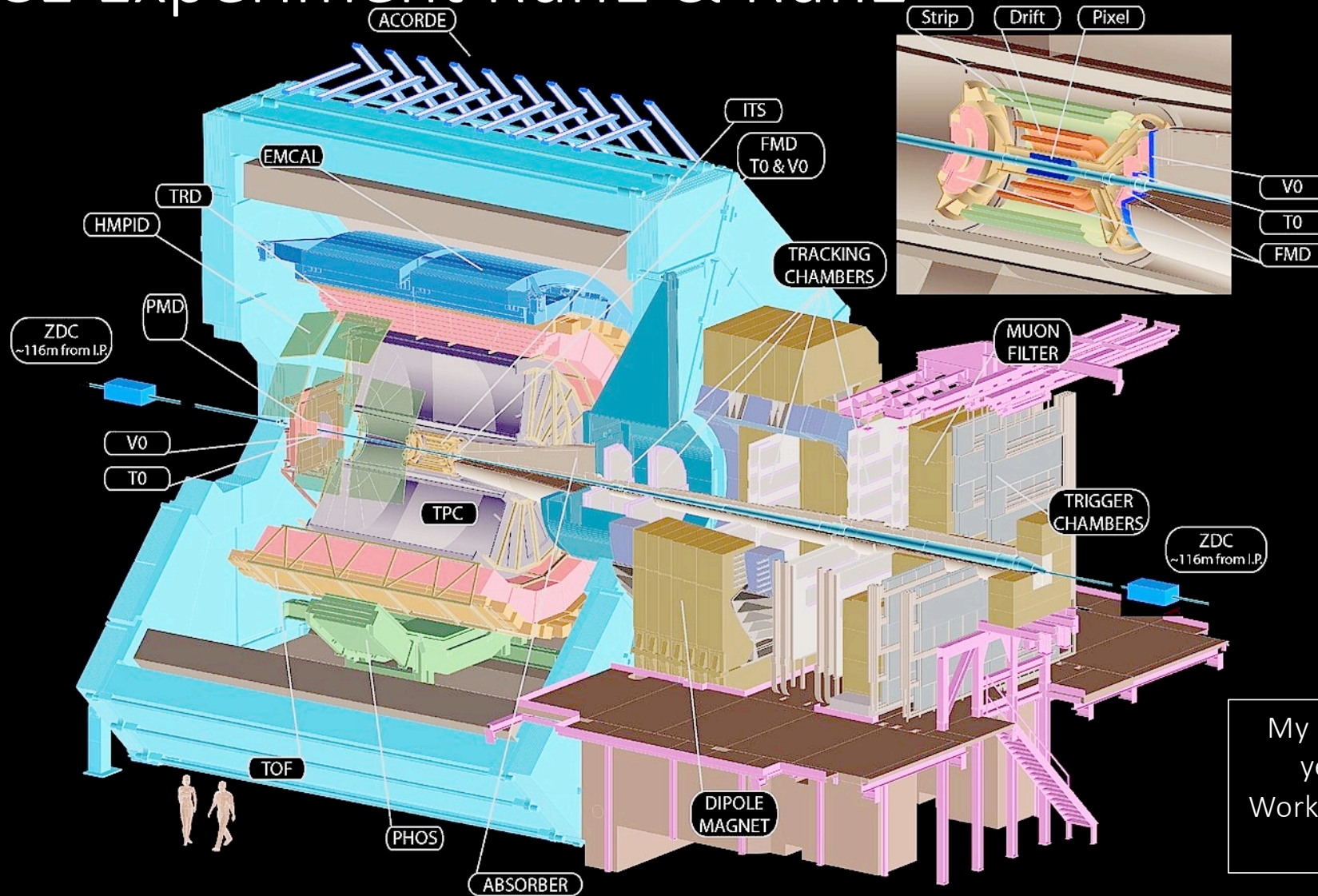
Experimental
published results in
inspirehep:
typ
not typ c and
(t Pb or t Au or t Ne or
t Xe or t Cu or t lead or
t gold)

377 peer-reviewed articles

472 peer-reviewed articles

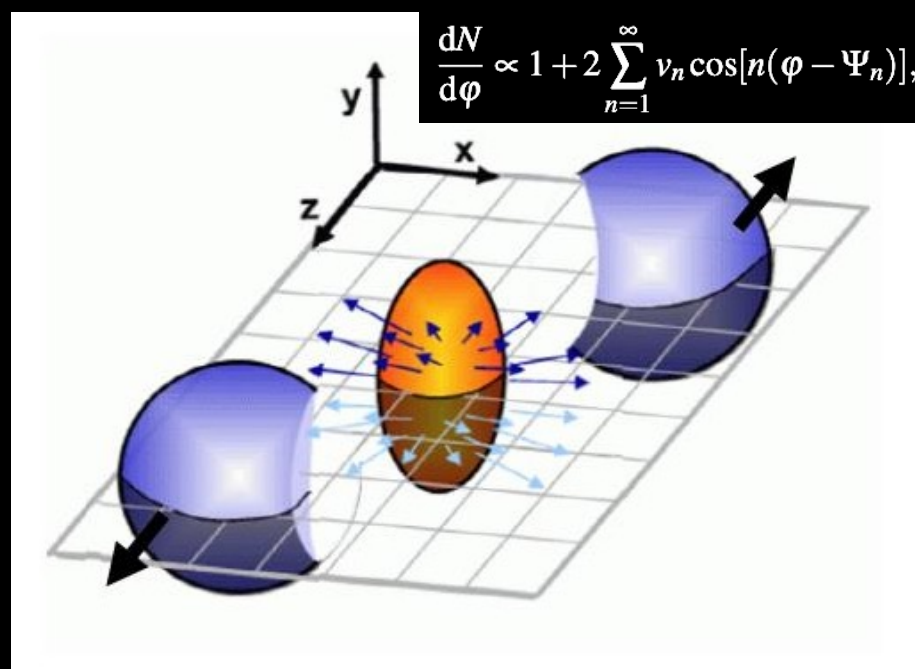
Adding high multiplicity in pp, about 1000 peer-reviewed articles
from large experimental collaborations at RHIC and LHC

ALICE Experiment Run1 & Run2

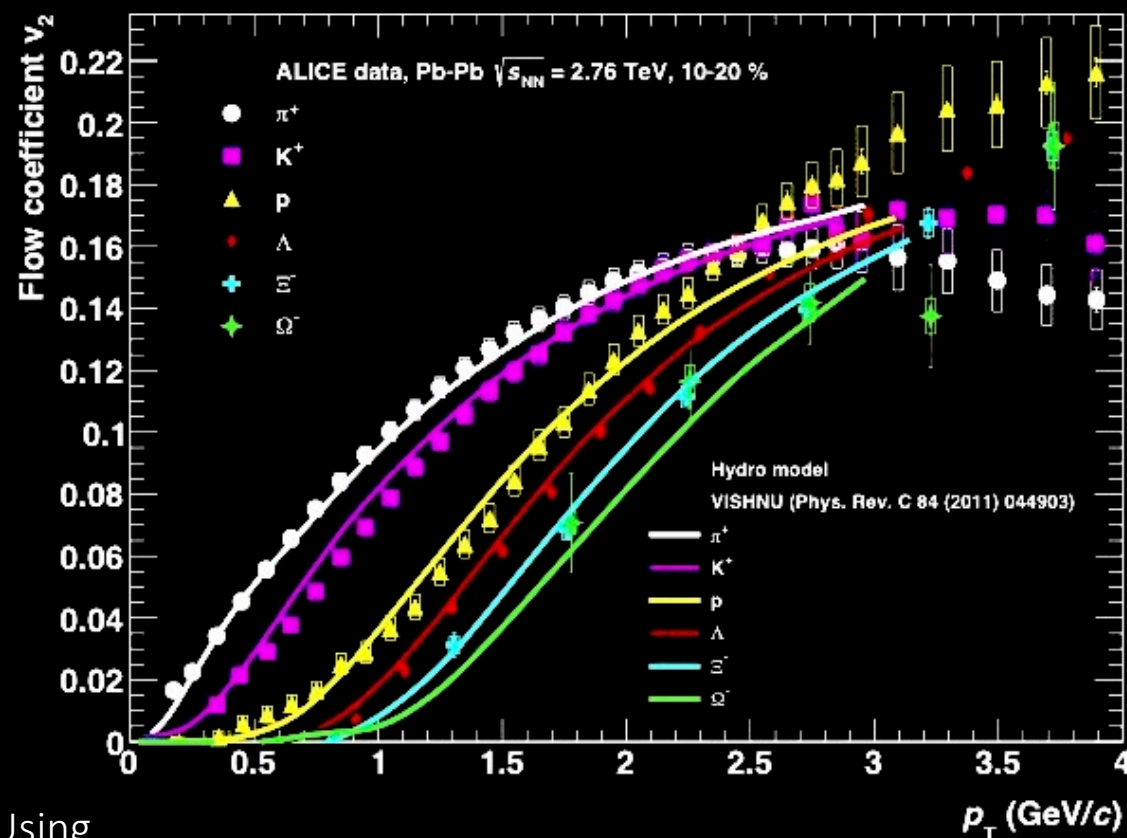


My experiment for 26
years. 1998-2024
Working mainly on heavy
flavour probe.

v_2 azimuthal asymmetry and viscous hydrodynamics



Successful global fit of soft hadron production data! Using viscous hydrodynamics with QCD based equations of state. shear-viscosity, initial time, temperature, EoS are the main parameters of these models



F Gross et al. Eur. Phys. J. C83 (2023) 1125
C Shen et al Phys. Rev. C 84 (2011) 044903

Statistical Hadronization Model

Few parameters in the model :

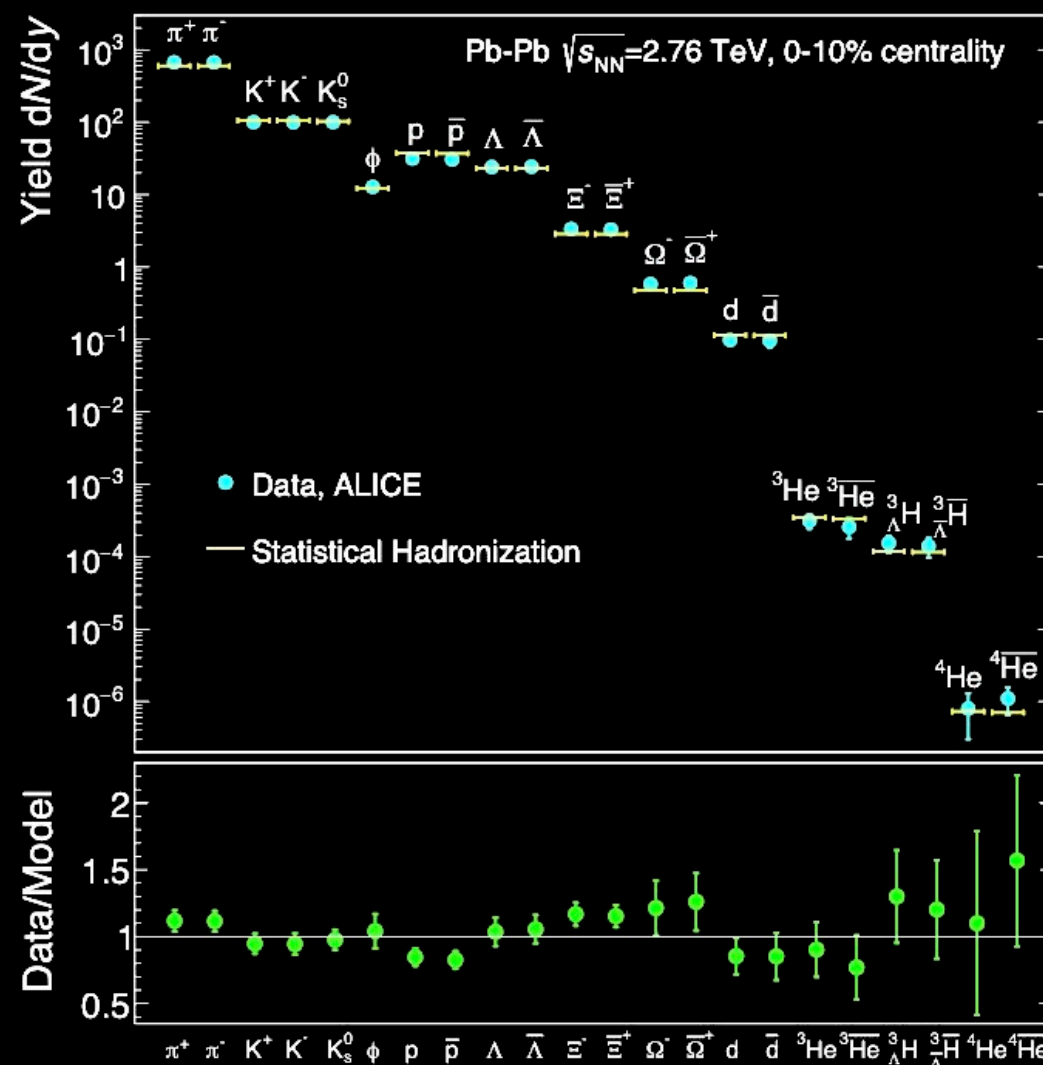
T_{ch}, μ_B and V

$T_{\text{CF}} = 156 \pm 1.5 \text{ MeV}$

Excellent agreement with IQCD
crossover temperature

$\mu_B = 0.7 \pm 3.8 \text{ MeV}$

Even for light (hyper) nuclei



Jet Energy Loss

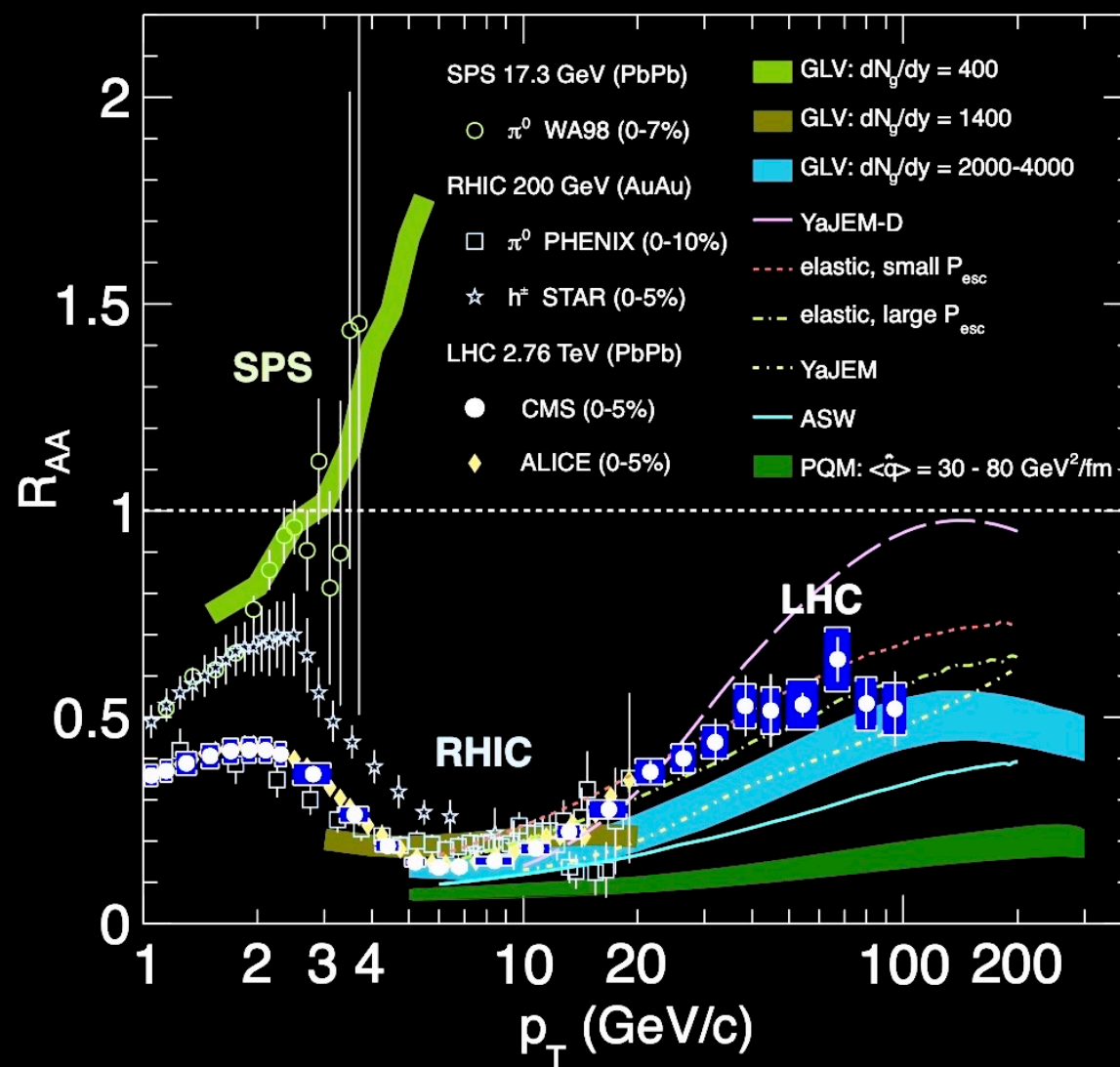
$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}(p_T)/dp_T}{d\sigma_{pp}(p_T)/dp_T},$$

Expected “jet extinction or modification” is observed in central heavy ion collisions → Jet quenching

what factor: jet transport coefficient can be extracted

Different between gluons, light quarks and heavy quarks

Bjorken FERMILAB-PUB-82-059-T. (1983)
CMS EPJC 72 (2021) 1945
JetScape PRC 104 (2021) 024905

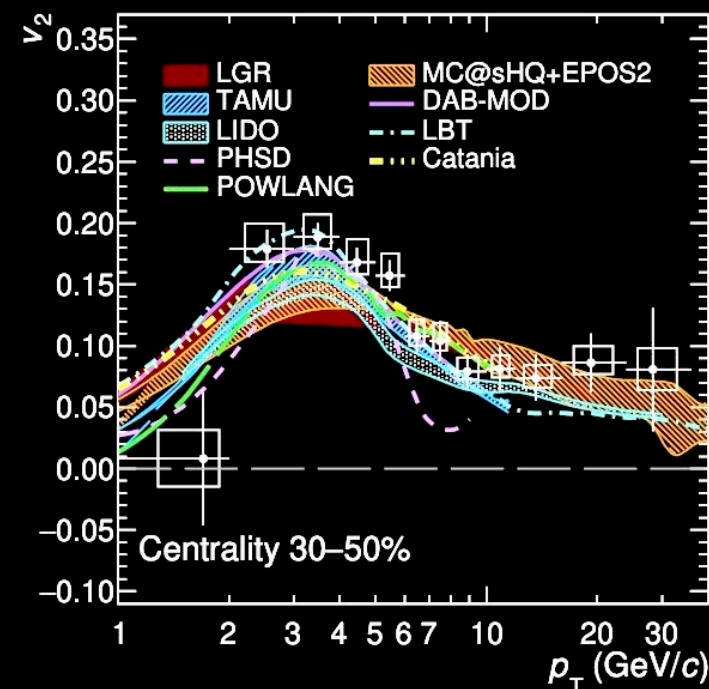
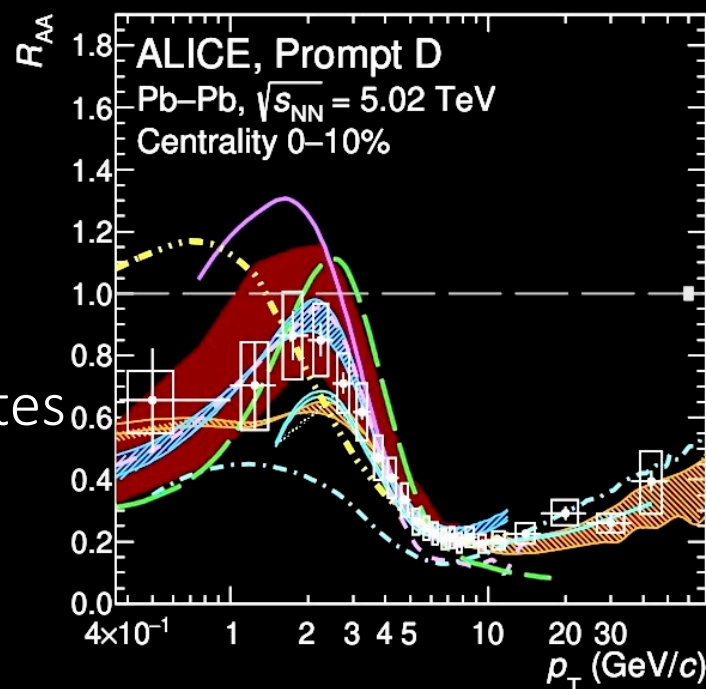


Heavy Flavour in heavy ion collisions

- Heavy quarks ($m > \Lambda_{\text{QCD}}$) : strong coupling < 1
- Heavy Flavours created in the initial state of the collisions
- Initial temperature $T < M_Q \rightarrow$ no thermal production
- Lifetime of the QGP not long enough to heavy quark annihilation
- Co-existing with QGP during all its lifetime : transport and diffusion coefficient
- Heavy quarks can be bound in the QGP
- Q - anti Q bound states (quarkonia) properties sensitive to QGP medium
- Challenging experimental measurement : high vertex precision in high multiplicity environment

Charms interacts with the QGP

- Low p_T : Brownian motion of charm quark. Longer equilibration time than that of QGP formation (M_c/T). Probing equilibration process creating QGP
- High p_T : energy loss by gluon radiation contributes
- Competition between coalescence (needed for v_n) and hadronization.



ALICE EPJC 84 (2024) 813
ALICE JHEP 01 (2022) 174
ALICE PLB 813 (2021) 136054

New dynamics for charmonium production at LHC

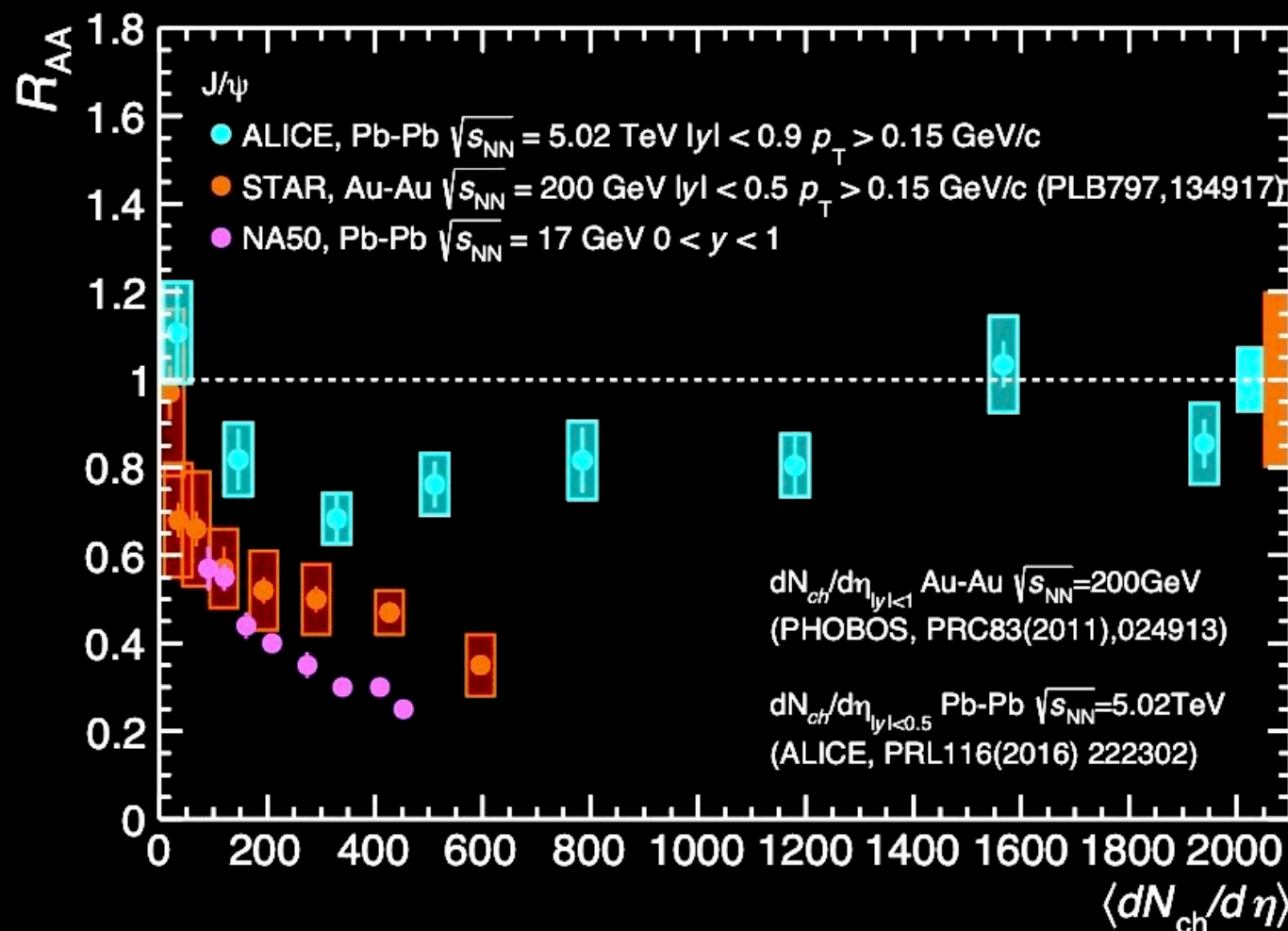
R_{AA} larger than at lower beam energies

Hotter medium at LHC

Colour screening compensated by c-cbar recombination

Recombination is a probe of deconfinement

It is a complex theoretical process from quantum first principles (open quantum systems)



Matsui & Satz PLB 178 (1986) 416
ALICE EPJC 84 (2024) 813
ALICE PLB 849 (2024) 138451

Recombination is dominant at low p_T

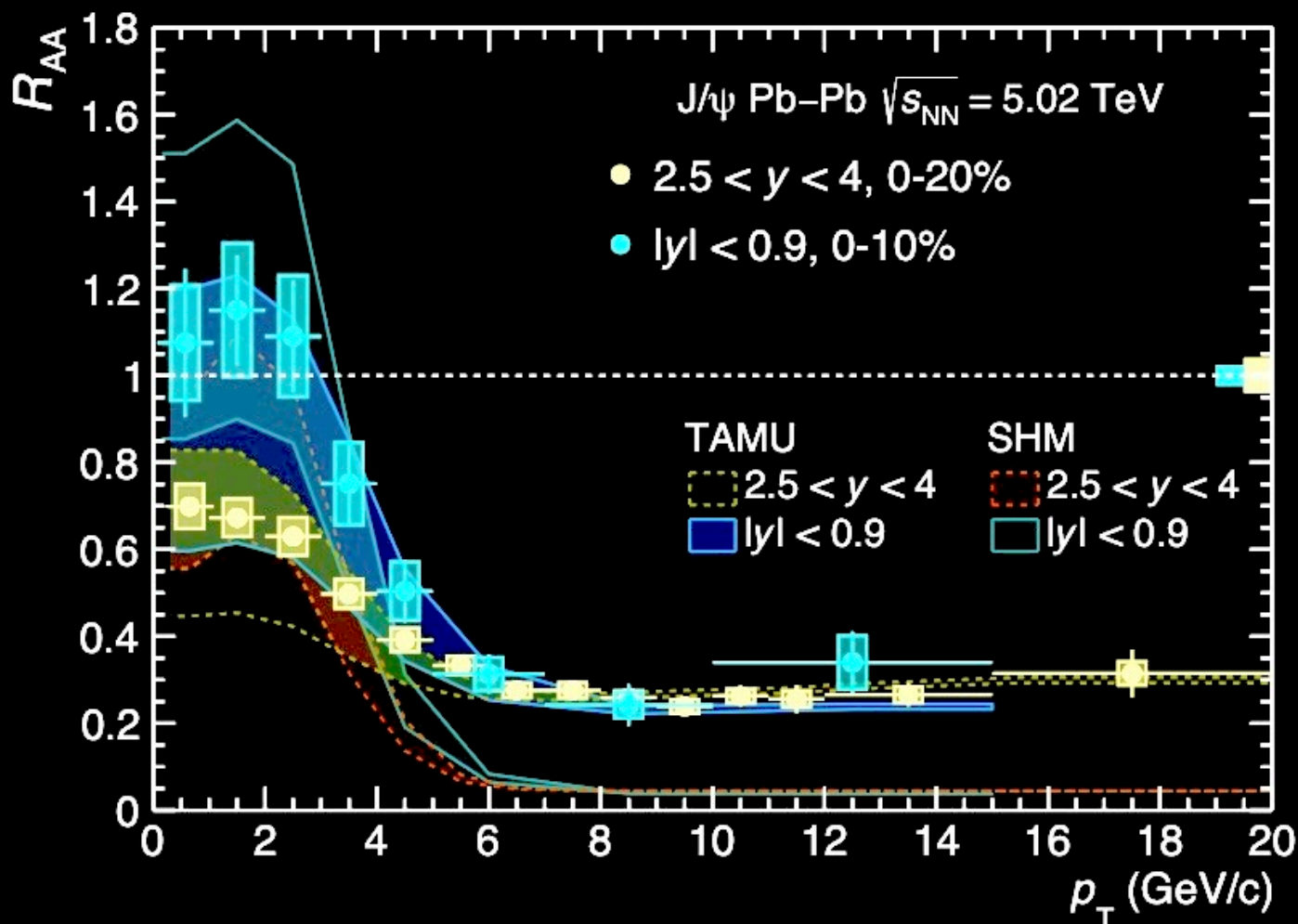
Dominant process at low p_T

Larger at mid-rapidity

Charmonium is suppressed at high p_T

Similar to high p_T hadron suppression

Gluon ($c\bar{c}$) energy loss before charmonium hadronisation



Matsui & Satz PLB 178 (1986) 416
 ALICE EPJC 84 (2024) 813
 ALICE PLB 849 (2024) 138451

Charmonium flows

v_2 of Jpsi is large

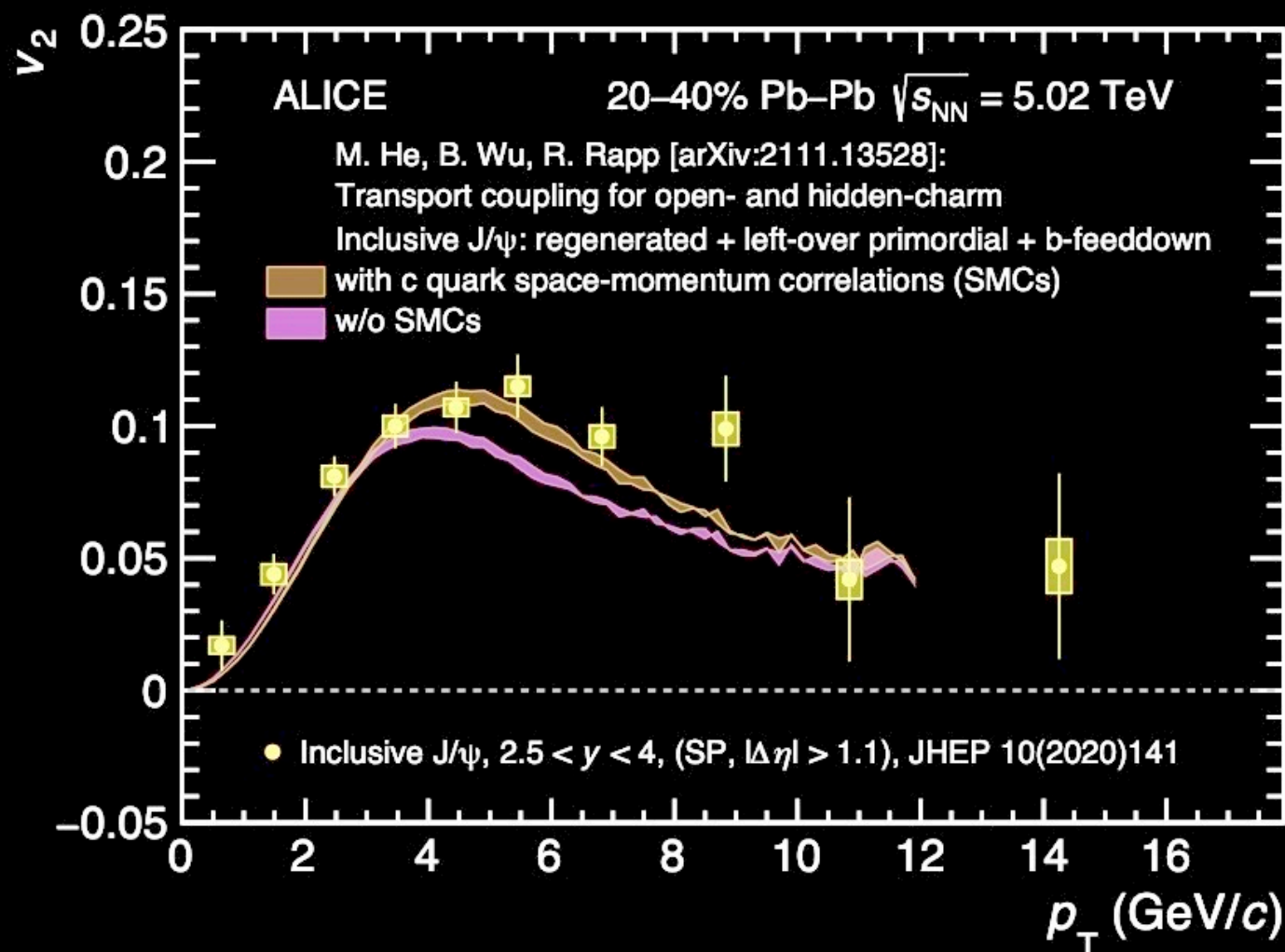
Reaching 0.1 at $p_T=5$ GeV/c

Compatible with recombination mechanism

Recombination would be a late processus

Non-flow effect could contribute to the Jpsi v_2

Matsui & Satz PLB 178 (1986) 416
 ALICE JHEP 10 (2020) 141
 ALICE PRL 119 (2017) 242301
 ALICE, JHEP 02 (2019) 012



Photon-Nucleus Interaction in heavy ion collisions

Weizsäcker-Williams photon distribution (EPA)

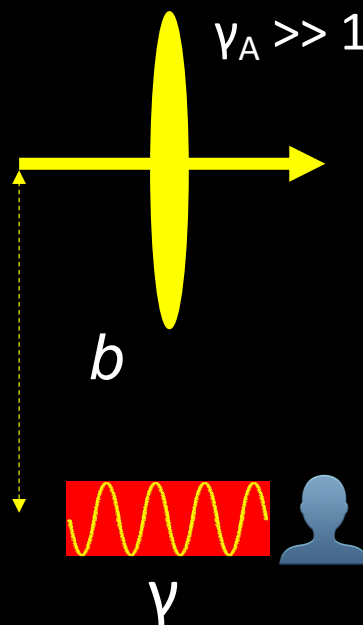
Photon Flux

Modified Bessel
Function order
unity

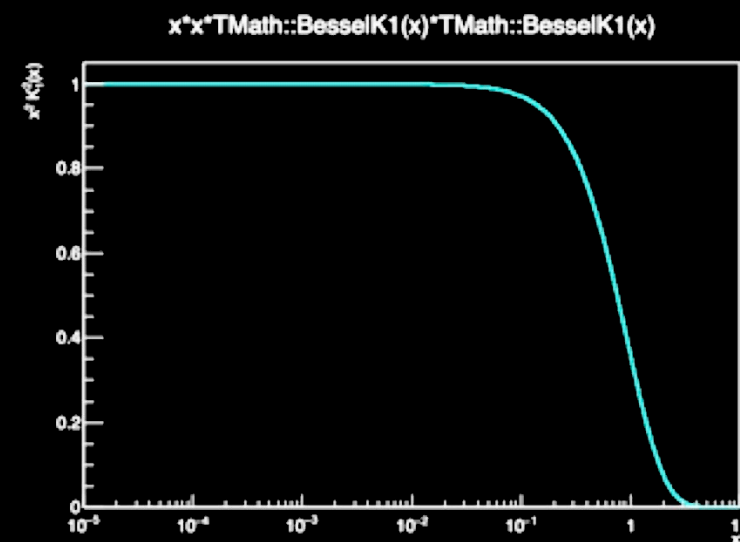
$$N(E_\gamma, b) = \frac{Z^2 \alpha_{QED}}{\pi^2 b^2} x^2 K_1^2(x)$$

Photon flux at $b=14$ fm :
0.025 photons/fm²
 2.6×10^{28} photons/m² !!!

J.D. Jackson Classical Electrodynamics,
section 15.4, 2nd edition Wiley



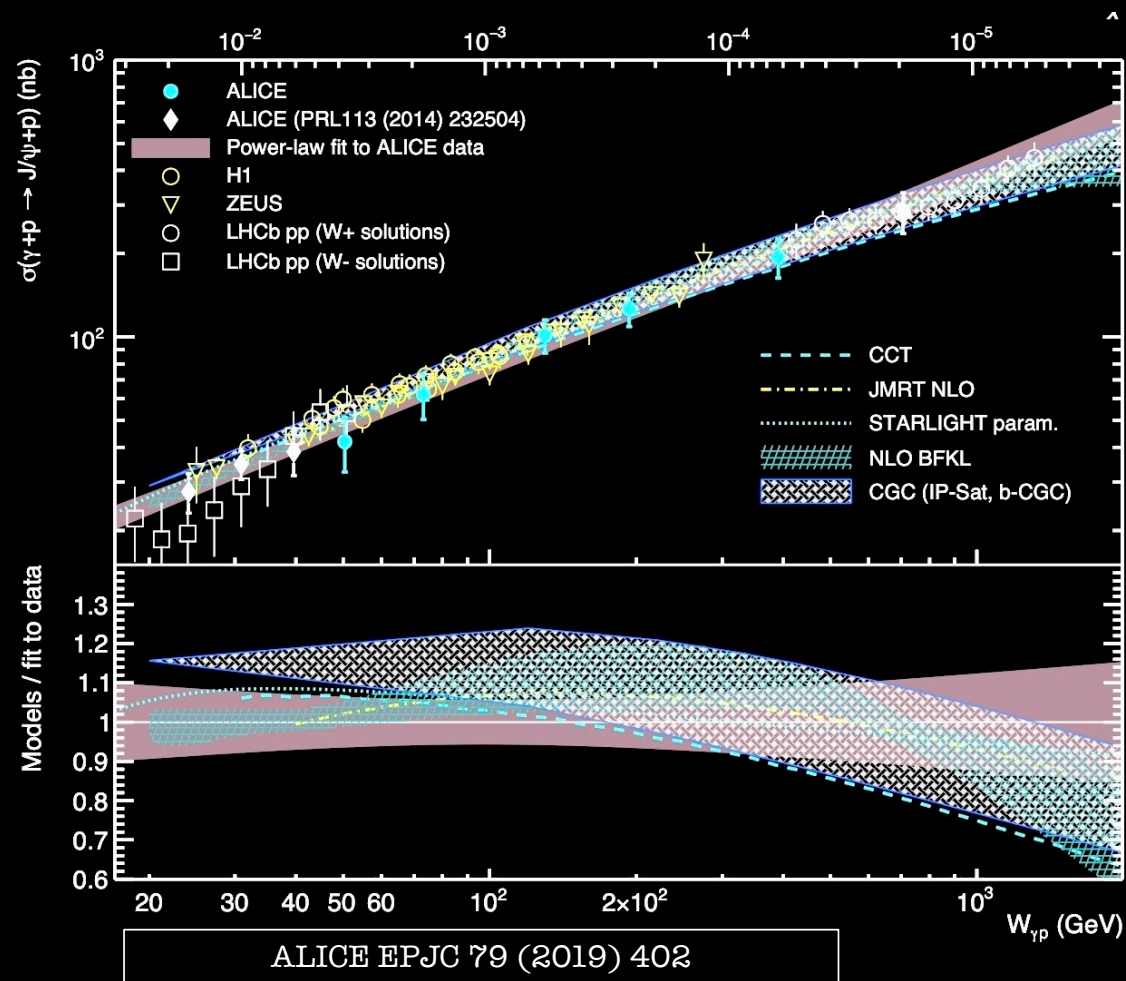
$$x = \frac{E_\gamma b}{\gamma_A}$$



For LHC ($\gamma_A \sim 2700$) and for $b=14$ fm (peripheral collisions), the photon energy distribution reaches 120 GeV ($x \sim 3$)

Exclusive J/ψ photo-production $\gamma p \rightarrow J/\psi p$

- The photon has the same quantum numbers as the J/ψ : $J^{PC} = 1^{--}$
- Non-colour exchange, just photon gets mass
- Two body interaction coherence (within the proton) for Mandelstam variable $t \rightarrow 0$
- In the AA UPC jargon this process is called “incoherent” photo-production, but it is coherent interaction with all the gluon-gluon pairs in the nucleon.



Elementary process

M.G. Ryskin, Z. Phys. C 57 (1993) 89

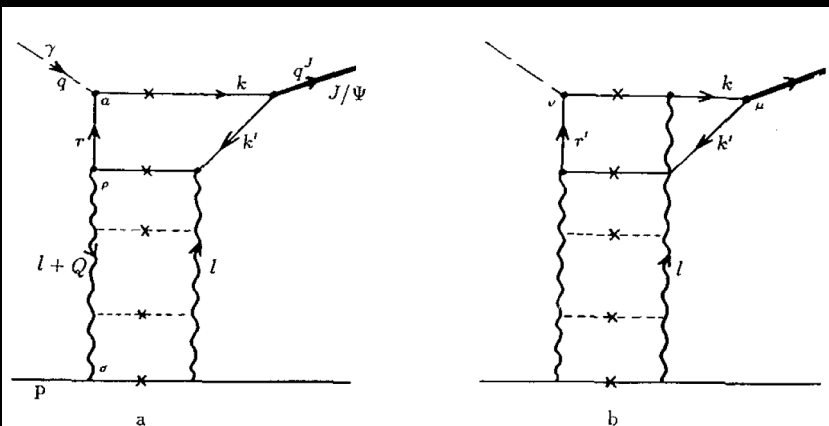


Fig. 1a, b. Feynman diagrams for diffractive J/Ψ production

Photons goes to c-cbar pair

Two gluon colourless interaction

J/ψ is produced

The gluon distribution function $G(x, Q^2)$ is probed at 1st order

$$t = (p_1 - p_3)^2 = (p_\gamma - p_{J/\psi})^2$$

$$t = M_{J/\psi}^2 - 2E_\gamma E_{J/\psi} + 2E_\gamma p_{J/\psi||} \quad (p_T = 0)$$

$$t = M_{J/\psi}^2 - 2E_\gamma M_{J/\psi} e^{(-y_{J/\psi})}$$

$$E_\gamma = \frac{M_{J/\psi}}{2} e^{y_{J/\psi}}$$

($t=0$)

$$t \sim -p_{T,J/\psi}^2$$

$$W_{\gamma p} = \sqrt{2E_\gamma s_{NN}}$$

$$x_g = \frac{M_{J/\psi}}{s_{NN}} e^{-y_{J/\psi}}$$

Diffractive process : t distribution is given by the two-gluon distribution inside the proton, very close to the electromagnetic proton form factor

Photo-production in A-A collisions

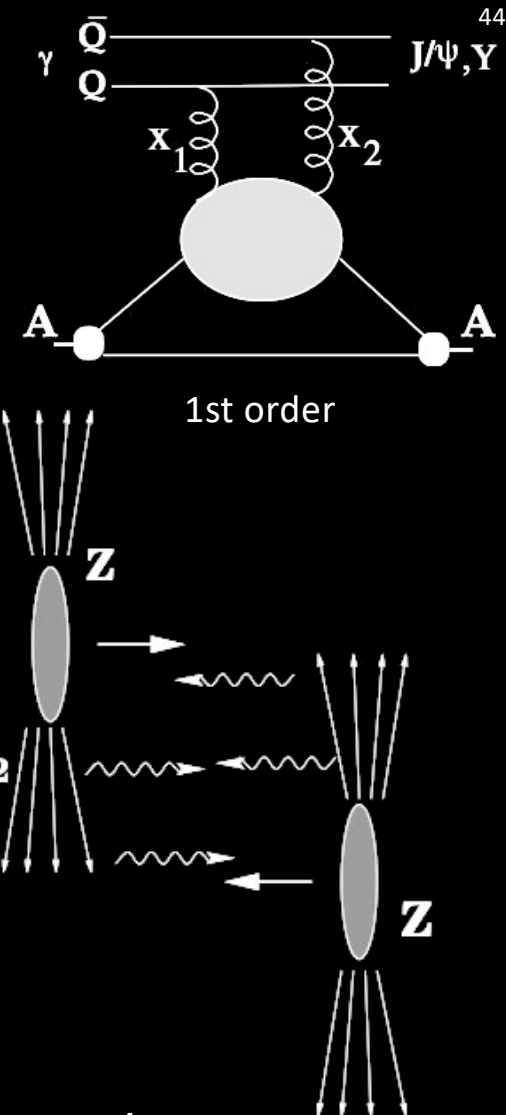
$$\frac{d\sigma_{\gamma A \rightarrow V A}}{dt} = |F(t)|^2 \frac{d\sigma_{\gamma A \rightarrow V A}}{dt} \Big|_{t=0}$$

Nucleus. ("EM") Form Factor

p_T about $1/R_A$, 30 MeV/c

$$A + \gamma \rightarrow J/\psi + A \quad E_\gamma(A + \gamma) = \frac{M_{J/\psi}}{2} e^{-y_{J/\psi}}$$

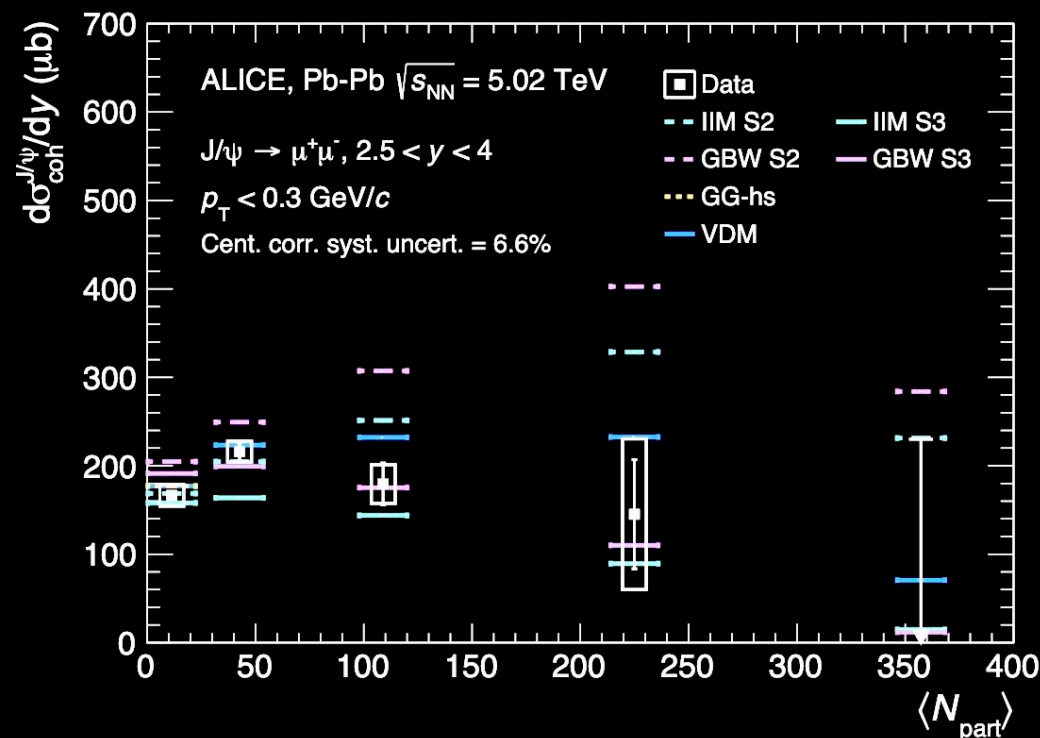
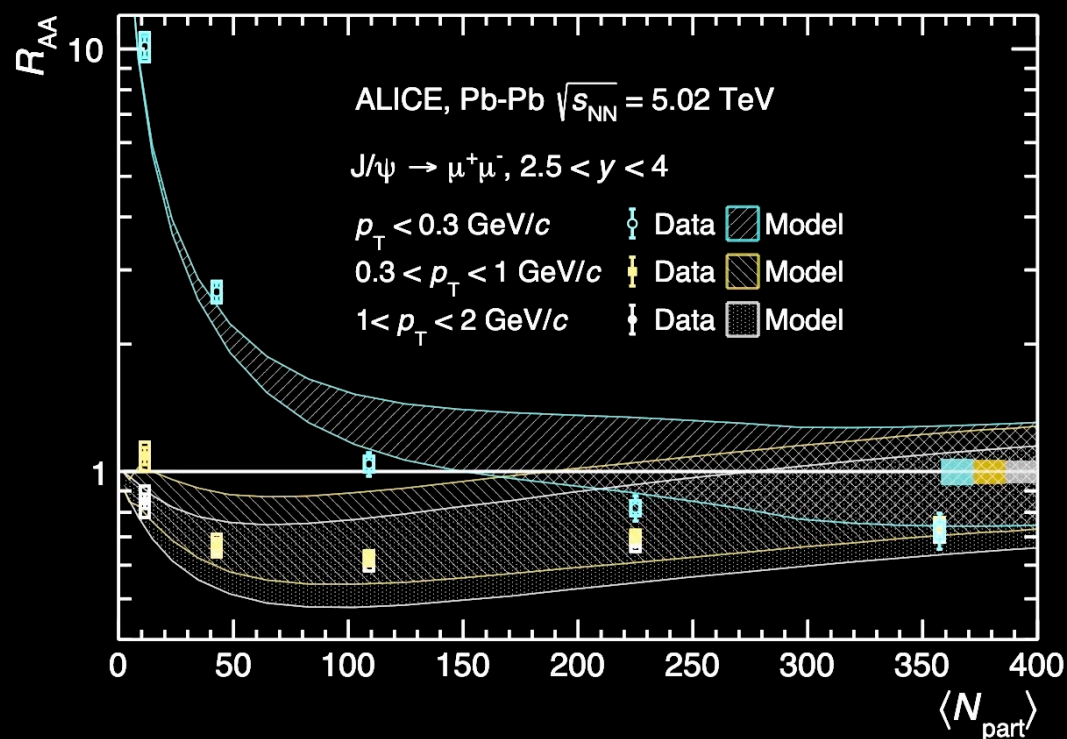
$$\gamma + A \rightarrow J/\psi + A \quad E_\gamma(\gamma + A) = \frac{M_{J/\psi}}{2} e^{+y_{J/\psi}}$$



A.J. Baltz et al. Phys Rep 458 (2008) 171
G. Baur et al., Phys Rep 364 (2002) 359

Expected Quantum Interference of J/ψ

Observed in nuclear AA collisions



Measured in 30-50% centrality class (hint in 10-30%).

Surprising. Models based on photon flux or photon-nucleus interaction region modification agree with data.

ALICE PRL 116 (2015) 222301
 ALICE PLB 846 (2023) 137467

UPC versus Peripheral Collisions

UPC	PC
Impact parameter not defined ($2R, \infty$)	Impact parameter range well defined : $\Delta b \sim \pm 1 \text{ fm}$
Reaction plane not defined	Reaction plane can be measured
Hadronic free	Hadronic contamination
Total transverse momentum	Transverse momentum can be decomposed in in-plane and out of plane
No hot matter is formed	Quarkonium can be suppressed by the hot medium
Small interference effect	Larger interference effect

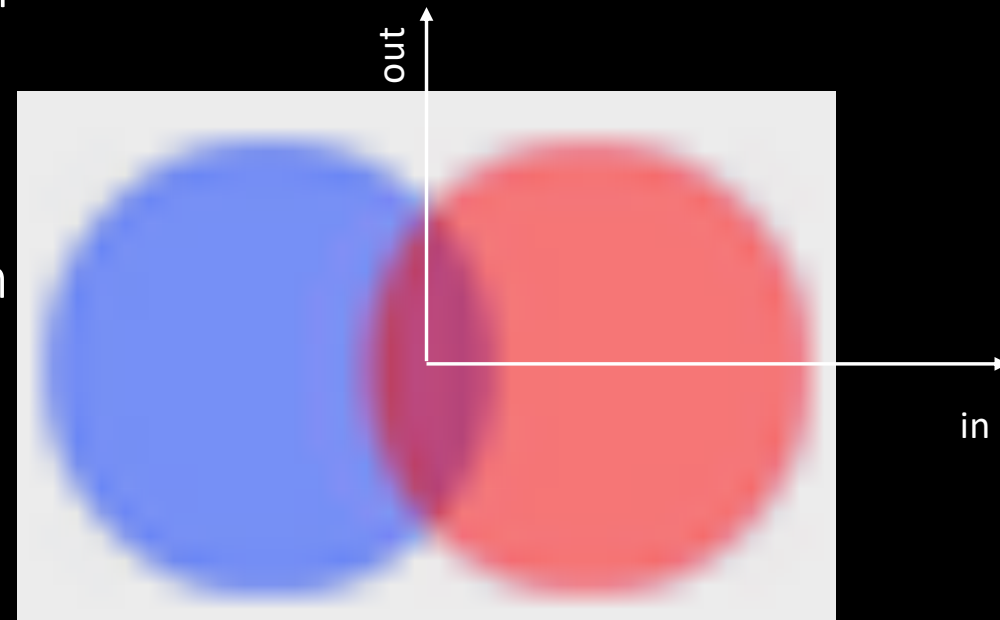
Centrality Selection

Reaction plane determination
Soft hadron correlations
Cumulant technique

t_{in} : p_T square in the direction of b
 t_{out} : p_T square in the transverse plane perpendicular to b

Proposal : Imaging the Heavy Ion Collision

- Study of the $|t_{in}|$ - and $|t_{out}|$ - dependences of coherent J/ψ photo-nuclear production in Pb-Pb collisions
- Utilization of ψ_1 would be excellent for discriminating photon-A and A-photon
- Measurement of “heavy ion collision form factor” in 2D $F(t_{in}, t_{out})$
- Image of the heavy ion collision at first stages
- Observation of the interference effect?
- Role of the overlap region?
- ALICE-ee and LHCb-mumu best performances for this study



Myself, GdR QCD Workshop, IJCLab, October 2023, <https://indico.in2p3.fr/event/30433/>

Prospects with LHCb detector in heavy ion collisions

My personal view

LHCb U1 Detector

σ_{xy} about 10-50 μm

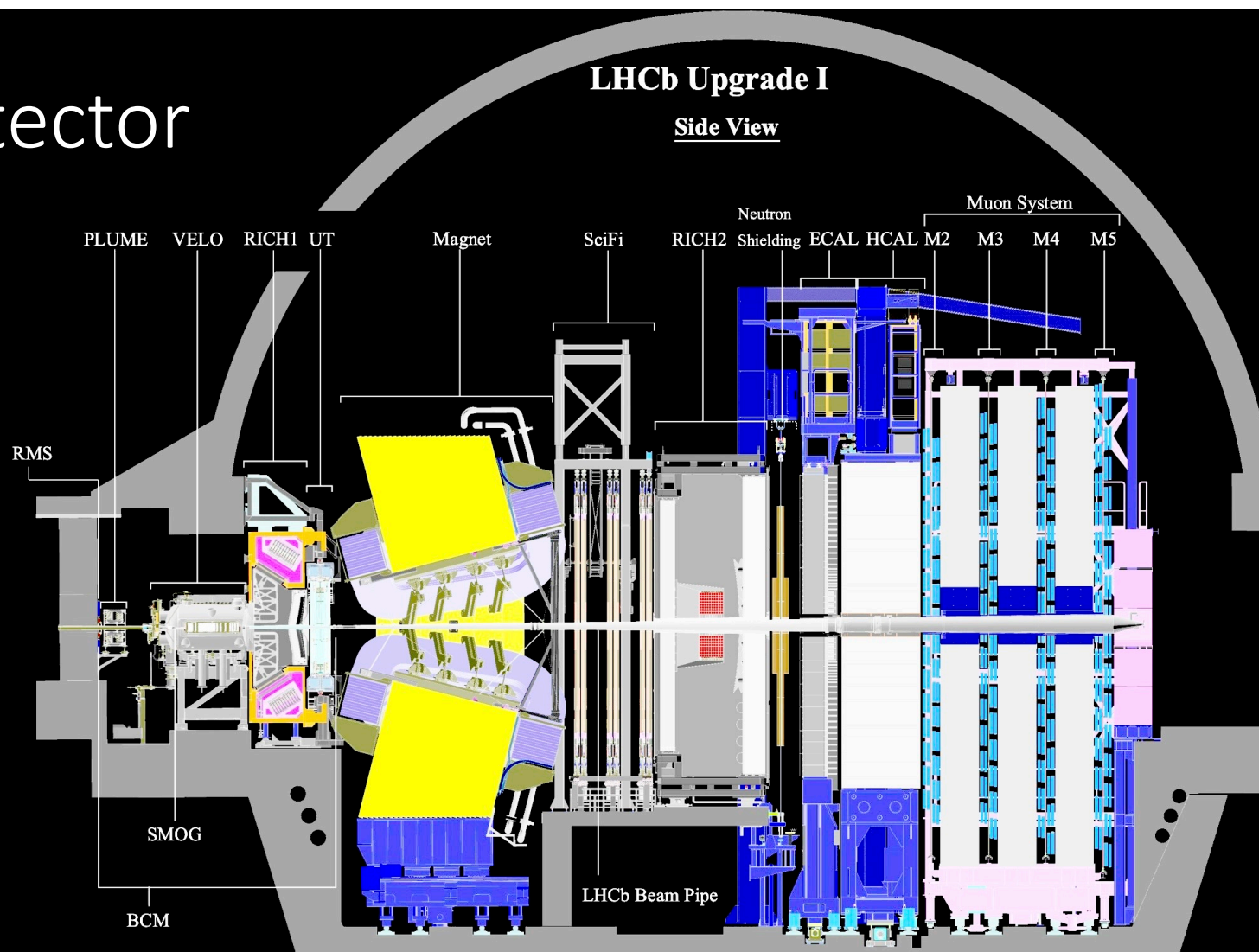
σ_p/p about 0.5 – 1 %

Tracking, calorimetry,
PID (rich), muon

Fixed target with SMOG
gas injection system

Forward coverage
 $2 < \eta < 5$

Saturates in PbPb
below 50-30%
centrality



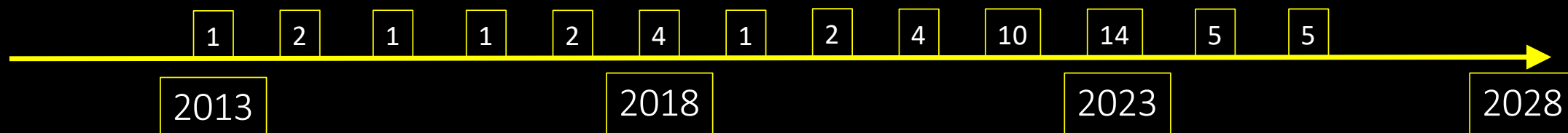
Patrick Robbe private mattermost communication
LHCb-PHO-GEN-2025-001

LHCb in the HI business since pPb@Run1

<https://lbfence.cern.ch/alcm/public/analysis> : Ion & fixed target label

47 (peer-review) articles on arXiv with “Ion & Fixed target” label :

- ✓ 26 in pPb (collider mode)
- ✓ 6 in pp multiplicity dependence (collider mode)
- ✓ 4 in PbPb (collider mode)
- ✓ 4 in pNe (fixed-target mode)
- ✓ 3 in PbPb UPC (collider mode)
- ✓ 2.5 pHe (fixed-target mode)
- ✓ 1 in PbNe (fixed-target mode)
- ✓ 0.5 pAr (fixed target mode)



QCD Matter Open questions

why LHCb with heavy ions

- Longitudinal study of the QGP :
 - Enriching experimental observations at forward rapidities for a full 3+1 hydrodynamical description of the evolution of the system
- Heavy quarks interaction with the QGP :
 - Excellent tracking performances for full and precise measurement of the heavy flavours : hidden and open
 - Lorentz boost allows for measuring heavy-flavour down to $p_T=0$
 - Fixed target collisions at the LHC : Forward experiment for study QGP at RHIC energies from central to backward rapidities
- Emergence of collectiveness :
 - Excellent performances to study with high precision, light systems at maximum integrated luminosity in collider and fixed-target modes

Heavy Flavour studies with LHCb detectors

Collider and fixed-target
modes from pp to PbPb
collisions

Precision measurement of J/psi, upsilons, D^0 ,
resonances. Accessing v1 for the first time.

Study higher resonances (ψ' , χ_c , χ_b , B_c , ...)

Multi-charmed hadrons (Λ_c , Λ_b , ...)

Exotic hadrons (X(2873), ...)

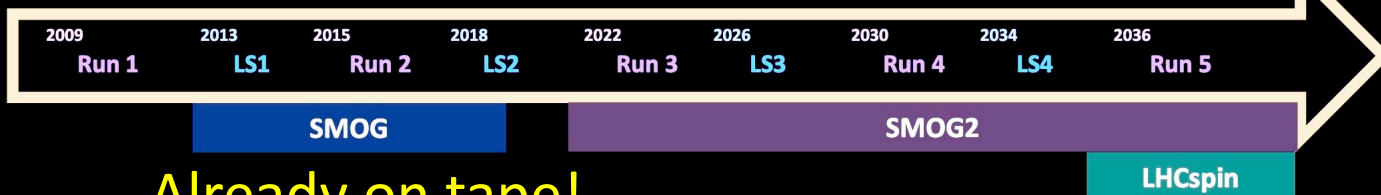
Open charm hadron spectroscopy (down to $p_T=0$)

Hidden/Open normalisation

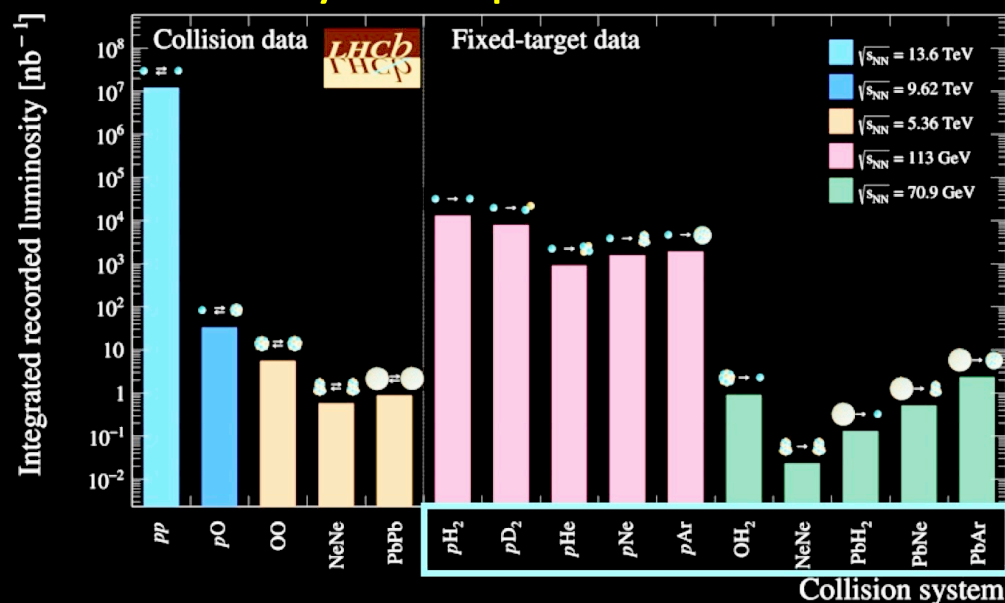
Open – hidden correlations

LHCb-U2 for Run5@LHC should allow for full reconstruction of central
PbPb collisions.

Fixed target LHCb : unique at the LHC

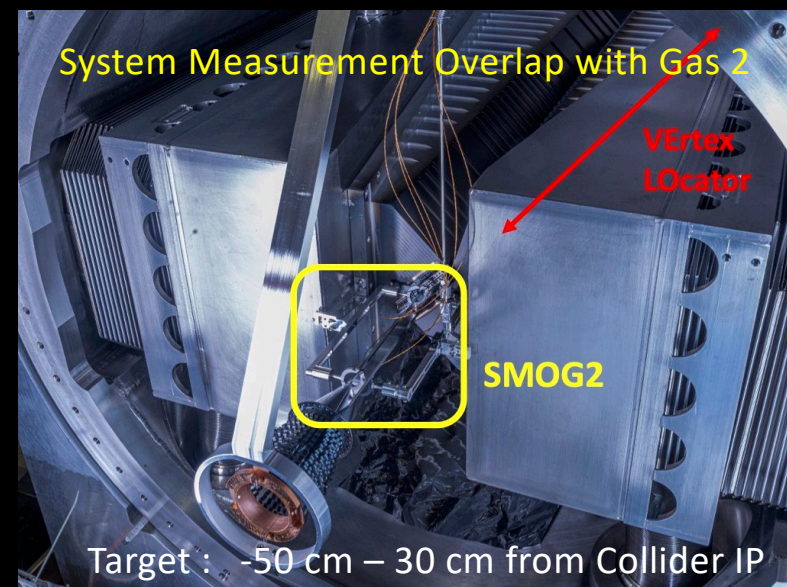


Already on tape!



Physics : Cold nuclear matter, QGP@RHIC energies, central and forward rapidities, PDF, TMD, GPD. Even spin physics if LHCSpin is approved

$pA \ s_{NN}^{1/2} \sim 30 - 115 \text{ GeV}$
 $PbA \ s_{NN}^{1/2} \sim 30 - 72 \text{ GeV}$
 $CaA \ s_{NN}^{1/2} \sim 30 - 81 \text{ GeV}$
 Also OA, ArA, KrA & XeA
 $y_{cm} = 0 \rightarrow y_{lab} = 4.0 - 4.5$
 $-2.5 - 2.0 < y_{cm} < 0$
 Reaching $x_B=1$ for $Q = 10 \text{ GeV}$



Emilie MAURICE private communication

Nuclear (collision) Imaging

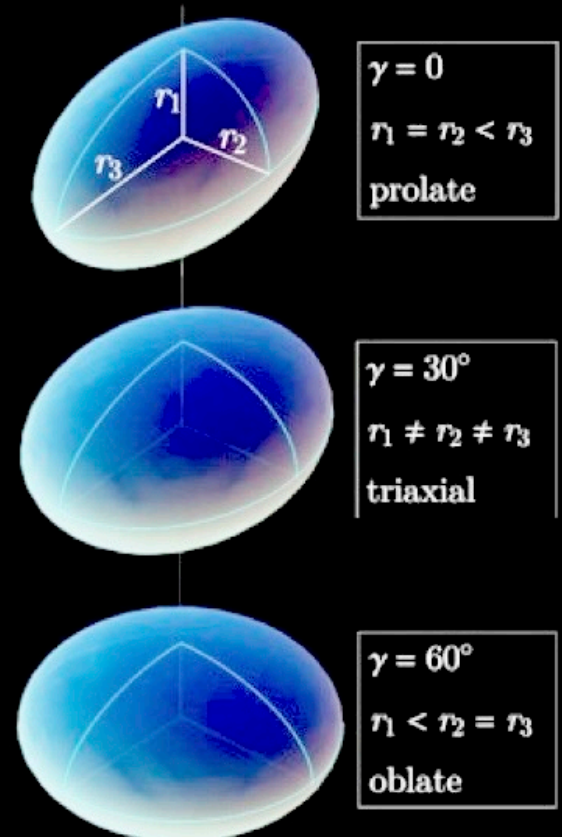
Short times scales at the LHC=> access to instantaneous shape of the nucleus

Fixed-target and collider modes, high integrated luminosity, excellent pT resolution, reaching central AA collisions makes LHCb detector ideal detector for these studies

- Azimuthal coefficients v_n of the QGP expansion, carries memories of the initial shape. Accessing triaxial shapes , alpha cluster, ... Laure MASSACRIER private comm.
- Coherent and incoherent vector meson production in UPC Gonçalves et al., EPJC 78 (2018) 693
- Azimuthal analysis of the coherent vector meson production → 2D imaging of the Heavy ion collision.

Myself, GdR QCD Workshop, IJCLab, October 2023, <https://indico.in2p3.fr/event/30433/>

(a) deformed nucleus ($\beta > 0$)



Bailly et al. PRL 128 (2022) 082301

LHCb Upgrade 2 for RUN5@LHC

Standard Model Benchmarks,
New Physics and CP violation,
new physics in charm, new
physics in rare decays, hadron
spectroscopy, QCD and EW, Dark
sector and Heavy Ions

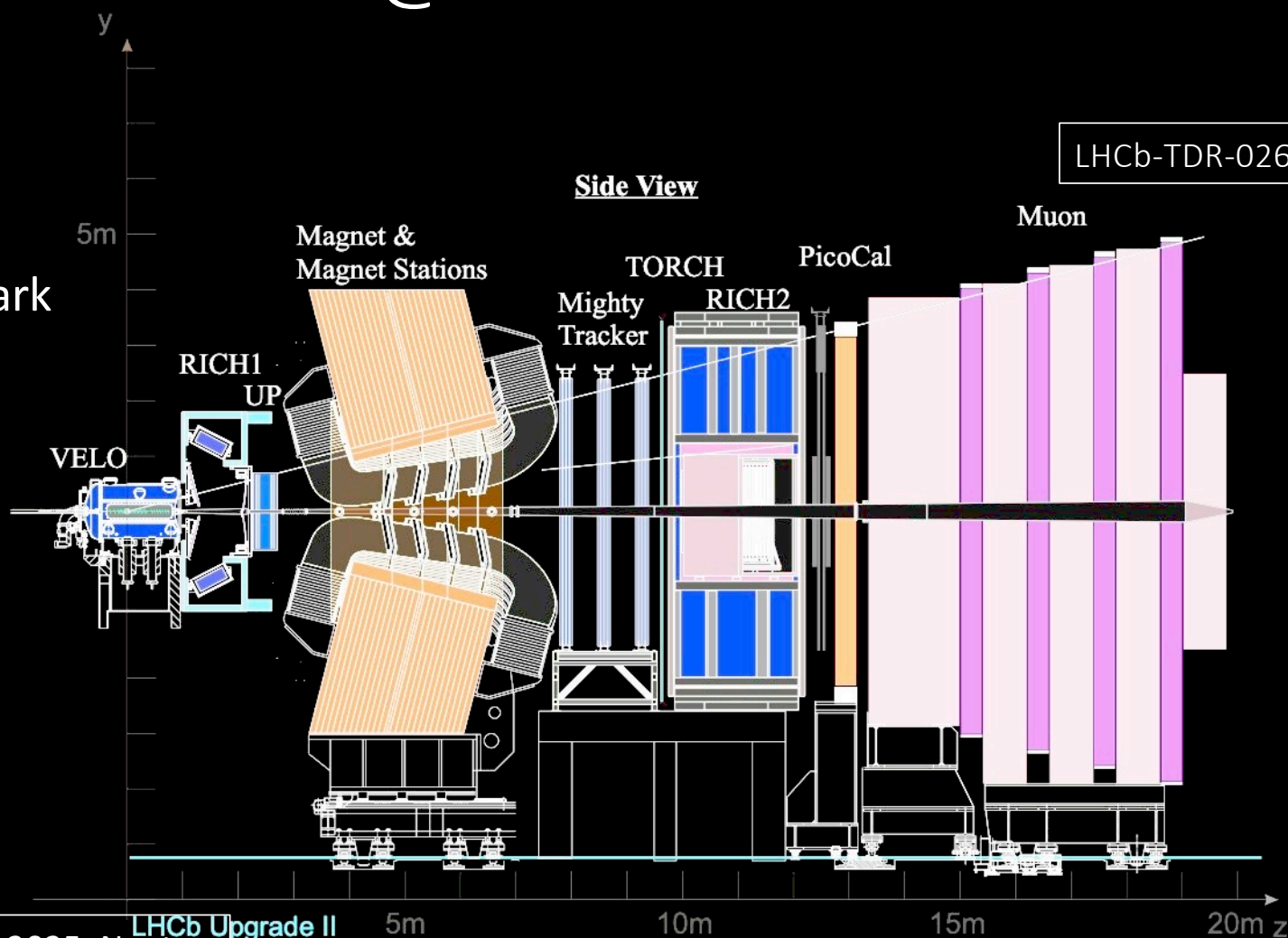
Higher luminosity : 30 pp collisions per
bunch crossing (middle scenario)

Radiation hardness : up to $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$

10-50 ps ToF resolution in VELO, ECAL,
RICH, TORCH

Improved segmentation and tracking
(MAPS sensor)

Real Time Analysis reconstruction (HLT1,
HLT2) : 200 Tbits/s



E. Niel LHCb France Upgrade II workshop 2025, Nantes

Subatech in LHCb-U2

G. Batigne , J.L. Beney, T. Bigourdan, A. Cadiou, D. Charrier, M. Germain ,
G. Grasseau , M. Guilbaud , M. Guillaumet, M. Guittiere , A. Hervo, P. Leray,
S. Martinez, G. Martinez Garcia , P. Pichot, P. Pillot , C. Renard , D. Vintache

⁹¹ *Laboratoire de Physique Subatomique et des Technologies Associees, Nantes, France, associated to*¹³

6 Physicists, 12 Engineers (10 UP and 2 in RTA) signing the LHCb-U2 Project (LHCb-TDR-026)

1. Contribution to Upstream Pixel Tracker LHCb project

- Low material budget, High spatial resolution, BX-tagging time resolution O(ns)
- Integration of a MAPS sensor : RadPix or MightyPix for MT and non-central-UP. COFFEE or SPARC → MANTA for the central-UP part, although is not excluded that RadPix and MightyPix will comply the requirements at the end of the day
- About 15 m² of MAPS sensor coverage (UP & MT) and about 400 cm² for the central UP
- Maximum particle rate 74 MHz/cm² (central-UP) and 17 MHz/cm² (non-central-UP and MP)
- Radiation hardness NIEL : 3.10¹⁴ n_{eq}/cm² (3.10¹⁵ n_{eq}/cm²) and TID : 40 Mrad (240 Mrad)

2. Contributing to Real Time Analysis LHCb project

- From LHC-U2 detector → 200 Tbits/s
- Real-time analysis quality reconstruction & calibration
- Architectures x86 & GPU & ??
- Software Flexible, Maintainable, Without debt of legacy code, Well documented

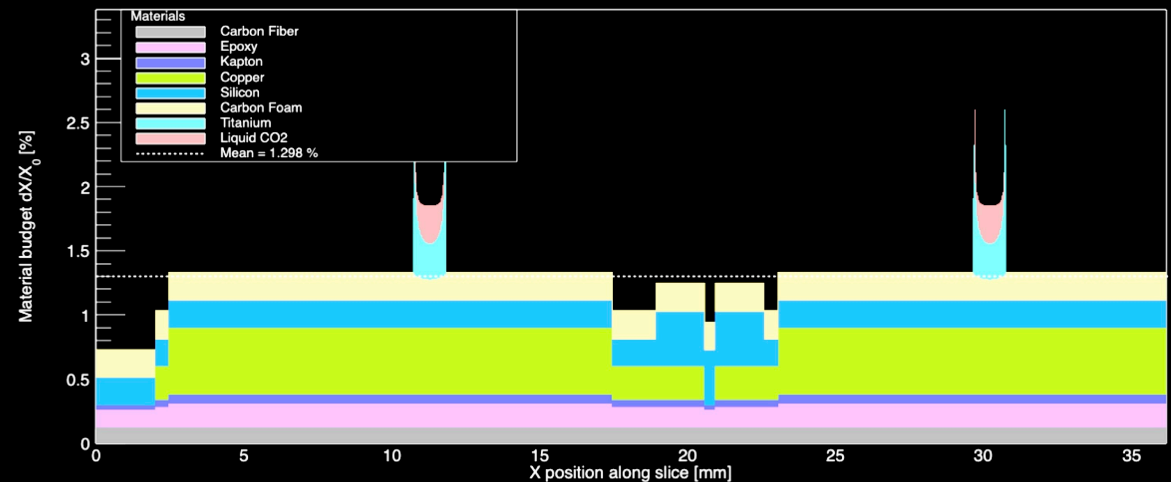
In addition to smaller contributions to PCIe400 R&T project and PicoCal SPIDER ASIC project

E. Niel and D. vom Bruch, LHCb France Upgrade II workshop 2025, Nantes

“LHCb Pixel Tracker” R&T CNRS/IN2P3 project : LLR – Subatech
Closed collaboration with Irfu (CEA Saclay)

- M. Guitti re, LHCb France Upgrade II
workshop 2025, Nantes

A. Cadiou



“RTA pour Upgrade 2 du LHCb” R&T CNRS/IN2P3 project:
CCPM, IJCLab, LAPP, LLR, LPCA, LPNHE, Subatech
Closed collaboration with Irfu (CEA Saclay)

Preparing the Real Time Analysis of the LHCb U2

- Framework Allen to work at 25 TBytes/s (4 TBytes/s today)
 - Creation of AllenCore
 - Library ML/IA : Multi Layer Perceptron, Graph Neural Networks, Transformers, Deep Neural Networks
 - Survey of new architectures
- X86 architecture for HLT2 with ML/IA mixed with classical algorithms
- Including time information in the reconstruction
- **Reconstruction of the most central PbPb collisions :**
 - Tracking with GNN
 - Reconstruction in Fixed-Target and Collider modes
 - Physics selections and luminosity determination

Conclusions

Conclusions

QCD is a major research topic of Nuclear and Particle Physics communities

Many theoretical progresses in the past 20 years, which have not been addressed in this seminar

Discovery of exotic hadrons, jet suppression and the success of hydrodynamical description of the heavy ion collision evolution are major experimental highlights of the field in this century

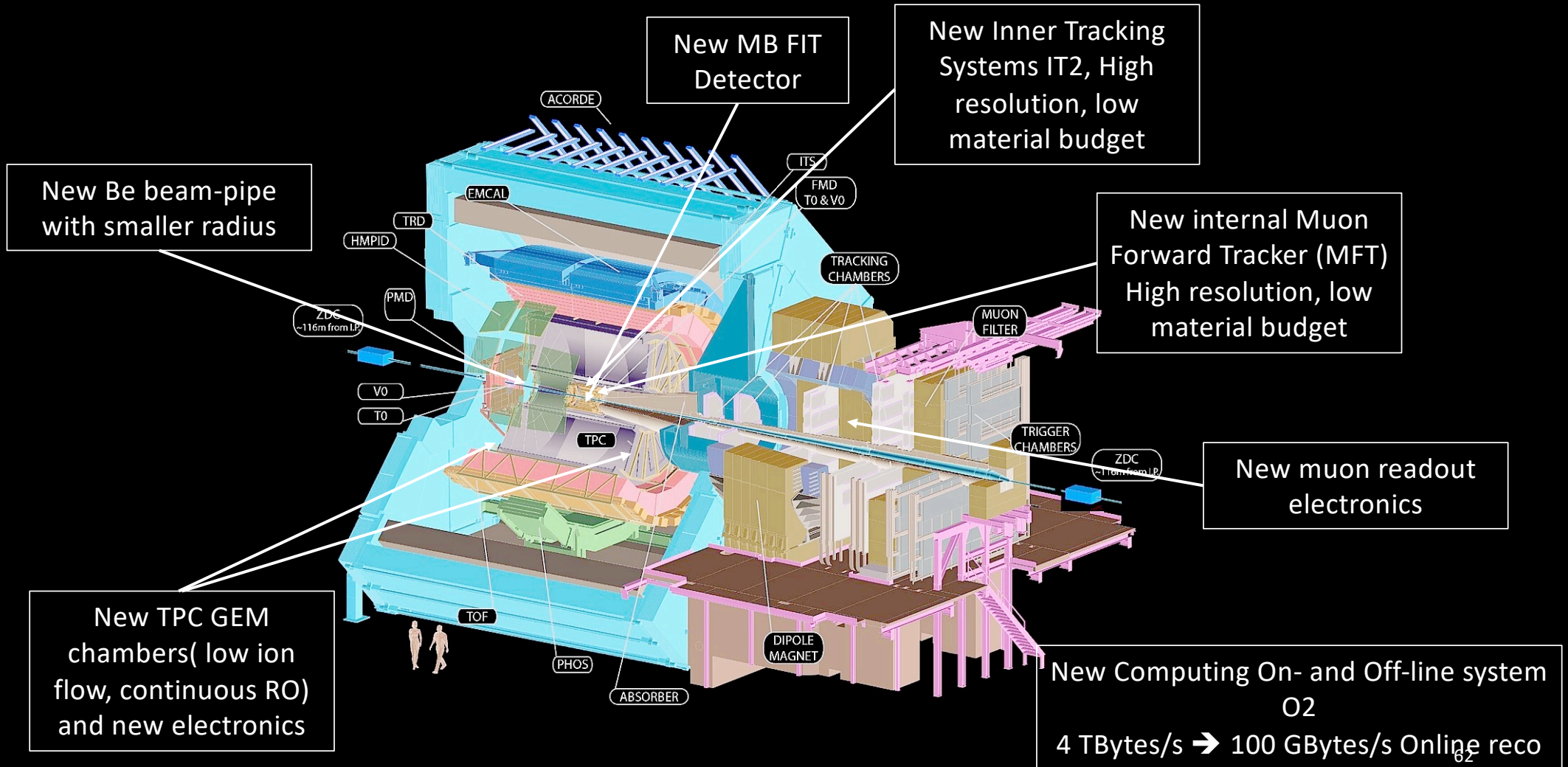
EIC and HL-LHC are the most important experimental efforts for the next 20 years to address the complex subjects of the structure of the proton, the study/discovery of exotics hadrons, and the study of the QCD matter

LHCb collaboration is becoming an eminent actor in the field of heavy ions.

Subatech team plans to contribute to the technical and scientific effort of LHCb-U2 project

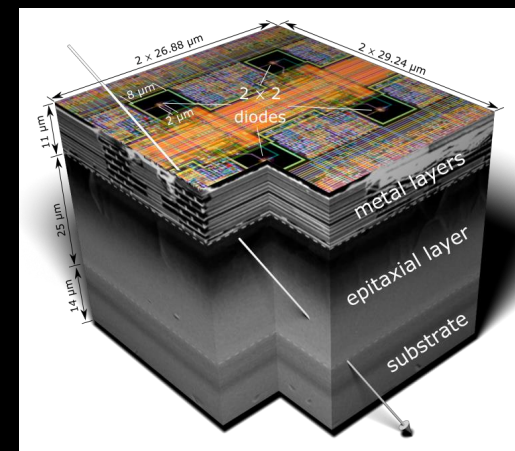
Back-up

ALICE Experiment for Run3



ALICE Detector upgrade main goals for Run3

- High precision and low material budget inner tracking system and muon forward tracker based on ALPIDE MAPS silicon sensor (0.180 μm TowerJazz technology)
- Pushing TPC to its physical limits
- Continuous read-out
- 50 kHz Pb-Pb collisions rate (factor 10-100 more statistics)
- 3.5 TBytes/s
- Online reconstruction (O2 framework)



The ultimate pixel detector for tracking and vertexing in ultra-relativistic nuclear collisions, Magnus MAGER, QM2025, Frankfurt, Germany

Quarkonium Physics : Higher integrated luminosity, Prompt Jpsi, better psi prime significance, Open beauty from non-prompt → Many new results and analysis on going ...