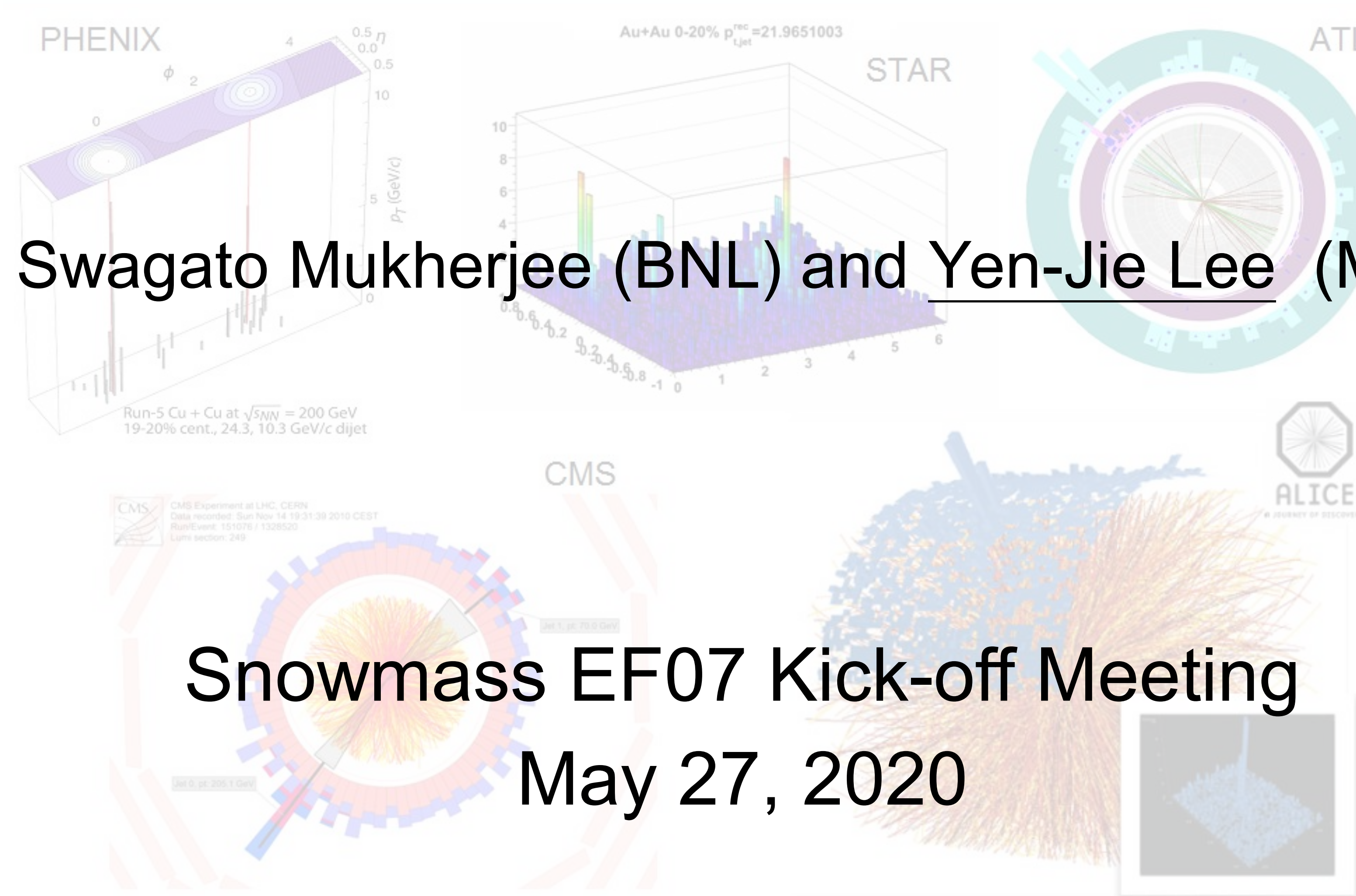
EF07: Heavy Ions



Swagato Mukherjee (BNL) and Yen-Jie Lee (MIT)

Snowmass EF07 Kick-off Meeting

May 27, 2020

MIT group's work was supported by US DOE-NP and DOE Early Career Program

Snowmass Process

- The Snowmass Process is organized by the Division of Particles and Fields (DPF) of the American Physical Society. Snowmass is an opportunity for the entire HEP community to come together to identify and document a vision for the future of particle physics in the U.S. and its international partners.

- We aim for everyone's voice to be heard. Your contributions and participation are critical for the success of Snowmass and they will naturally occur as part of one or more working groups directed by the conveners. There will be various Town Hall meetings for us to communicate with you and to receive your feedback.

- We invite inputs from all researchers around the world. Inputs from international participants are essential and strongly encouraged!

https://snowmass21.org/start

Snowmass Process

- The Snowmass process is defined as a science study group

- **The output of this process will be used as input to the P5:** (Particle Physics Project Prioritization Panel) that formulates a 10-year plan (20-year vision) for the U.S. within funding constraints

Snowmass Process

- The last Snowmass study took place in 2013 https://www.slac.stanford.edu/econf/C1307292/

- This is the first time that studies with heavy ion beams is included in the Snowmass process

- The most recent P5 report identified five science drivers https://www.usparticlephysics.org/
  - Use the Higgs boson as a new tool for discovery
  - Pursue the physics associated with neutrino mass
  - Identify the new physics of dark matter
  - Understand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles

Snowmass Process

- Work is categorized in ten frontiers:
  - **Energy Frontier (EF)**
  - Neutrino Physics Frontier
  - Rare Processes and Precision
  - Cosmic Frontier
  - Theory Frontier
  - Accelerator Frontier
  - Instrumentation Frontier
  - Computational Frontier
  - Underground Facilities
  - Community Engagement Frontier

Energy Frontier

- Energy Frontier is split into 10 subgroups, with 3 major categories
    - EW Physics (including EW gauge bosons, Higgs, top)
        - EF01: Higgs Boson properties and couplings
        - EF02: Higgs Boson as a portal to new physics
        - EF03: Heavy flavor and top quark physics
        - EF04: EW precision physics and constraining new physics
    - QCD and strong interactions
        - EF05: Precision QCD
        - EF06: Hadronic structure and forward QCD
        - **EF07: Heavy Ions**
    - BSM Physics
        - EF08: Model-specific explorations
        - EF09: More general explorations
        - EF10: Dark Matter (at colliders)

https://snowmass21.org/energy/start
Conveners of the EF group: Meenakshi Narain, Laura Reina, Alessandro Tricoli

EF07: Heavy Ions and High Density QCD

- Goal: Prospects for heavy-ion physics at future **heavy-ion colliders** and physics at **electron-ion colliders**, with particular emphasis on the impact that this will have on the physics program of the EF.
- Communication
  - Mailing list:
    - SNOWMASS-EF-07-HEAVY-IONS@FNAL.GOV
    - To join: **send an e-mail message to** listserv@fnal.gov with a blank subject line and the following text in the body of your message:
      SUBSCRIBE SNOWMASS-EF-07-HEAVY-IONS Your Name
    - 50 members have joined the list
  - Slack:
    - To join: email rhbob@fnal.gov with subject line "snowmass slack". You will receive an email invitation to slack
    - Channel: **ef07-heavy_ions**

Letter of Interest (April 1 - August 31, 2020)

- The purpose of letters of interest is to allow Snowmass conveners to see what proposals are coming and to encourage the community to begin studying them. Letters of Interest should give brief descriptions of the proposal and cite the relevant papers to study. These letters will help conveners to prepare the Snowmass Planning Meeting that will take place on November 4-6, 2020 at Fermilab.

- The letters should be up to 2 pages not including bibliography and should be uploaded by authors **HERE** between April 1, 2020 and August 31, 2020. An index of submitted letters can be viewed **HERE**. The letters will be stored permanently in the Fermilab archive Doc.db shortly after August 31, 2020.

https://snowmass21.org/loi

Contribute Papers (April 1, 2020 – July 31, 2021)

- Papers submitted to the Snowmass 2021 Proceedings. These papers may include white papers on specific scientific areas, technical articles presenting new results on relevant physics topics, and reasoned expressions of physics priorities, including those related to community involvement.

- Submitted papers will remain part of the permanent record of Snowmass 2021. More ephemeral articles, including the 2-page “Letters of Interest” requested by the DPF, should be presented through a different process, explained here.

https://snowmass21.org/submissions/start

Important Dates

- Kick-off Town Hall meeting on April 18th https://indico.fnal.gov/event/23601/
- Letters of Interest (April 1 - August 31, 2020)
- Contributed Papers (April 1, 2020 – July 31, 2021)
- First community meeting: Nov 4-6, 2020 (Fermilab)
- First draft of Topical Group summaries due March 2021
- Final version of written documents due July 2021 Final meeting: July 11-20, 2021 (UW-Seattle) https://indico.fnal.gov/event/22303/
- Studies must have concluded before this meeting, and the WG reports finalized
- Updated documents (including LoIs) due in November 2021

EF07 Meetings

- We plan to have the biweekly meeting on Wednesday 9:00 – 10:30 AM EDT
  - Kickoff meeting on 5/27 (Today)
  - Indico page: https://indico.fnal.gov/category/1141/

- The first joint EF05, EF06, EF07 meeting on June 1st :
  https://indico.fnal.gov/event/43488/

- EF07 Workshop at MIT / RIKEN in 2021

HEP@EIC

- Will be single joint effort among EF04, EF05, EF06 & EF07
  - Coordinated with the EIC user group
  - There will be a single workshop, jointly among EF04-07 and coordinated with the EIC user group; most likely we will have a CFNS (BNL/SBU) supported Snowmass workshop in early 2021
  - The outcome of this Snowmass workshop will be a single combined Snowmass proceeding addressing HEP@EIC

LHC Timeline and RHIC (STAR/sPHENIX)

LHC — pO, OO, pPb — **HL-LHC**

PbPb 1.8 nb^{-1} | PbPb 7 nb^{-1} | PbPb 7 nb^{-1}

Run 2 | Long shutdown 2 | Run 3 | Long Shutdown 3 | Run 4

Phase 1 Upgrade | Phase 2 Upgrade

Run5

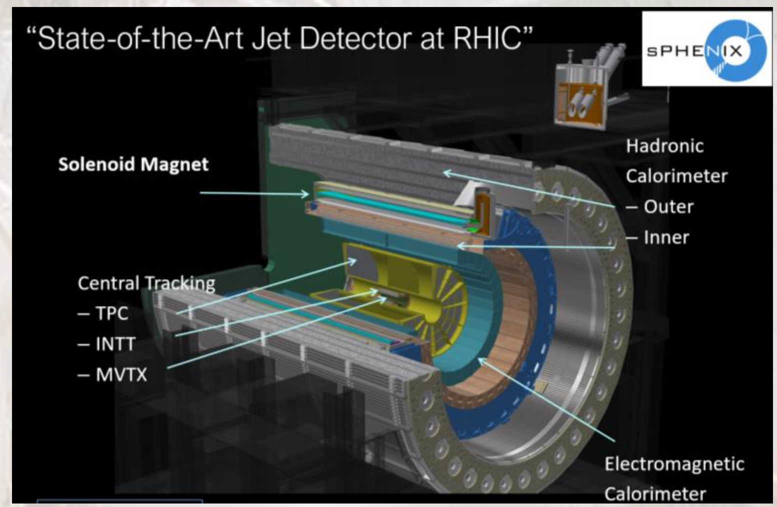
New ALICE detector?

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

sPHENIX construction

STAR Forward Upgrade

sPHENIX Installation commissioning



Jetting through Lower Temperature
Quark Soup from Gold+Gold collisions at 200 GeV
Direct comparison with LHC data!

Run 1 | Run 2 ?

pp, pAu | pp

RHIC — **EIC**

AuAu 120 nb^{-1} | AuAu 80 nb^{-1}

Energy Frontier Probes in Heavy Ion Collisions

- Jet spectra, Jet substructure and top (82%)
  - As chronometer of QGP
  - W mass in boosted top decay
  - Jet substructure as a probe of QGP start and end time
- Heavy flavors production (59%)
  - Charm diffusion in AA and search for the effect in pA, pp and eA collisions
  - Hadronization mechanism of charm and beauty
- Search for new physics with heavy ion beam (54%)
- Extremely high multiplicity events: (54%)
  - Emergence of high density QCD phenomena in small systems
  - Search for collective behavior in ee and eA collisions
  - Flow-like signal in pp and pA collisions
- Quarkonia Production: (46%)
- EW bosons: (32%)
  - Nuclear Parton Distribution Functions (from W/Z)
  - Higgs production in heavy ion collisions
- Exotic probes: (27%)
  - Probe X(3872) with QGP
  - Anti-hyper nuclei
- Extreme QED probes: (22%)
  - Light-by-light scattering
  - nPDF from Quarkonia production in UPC

Topics Suggested in the Survey

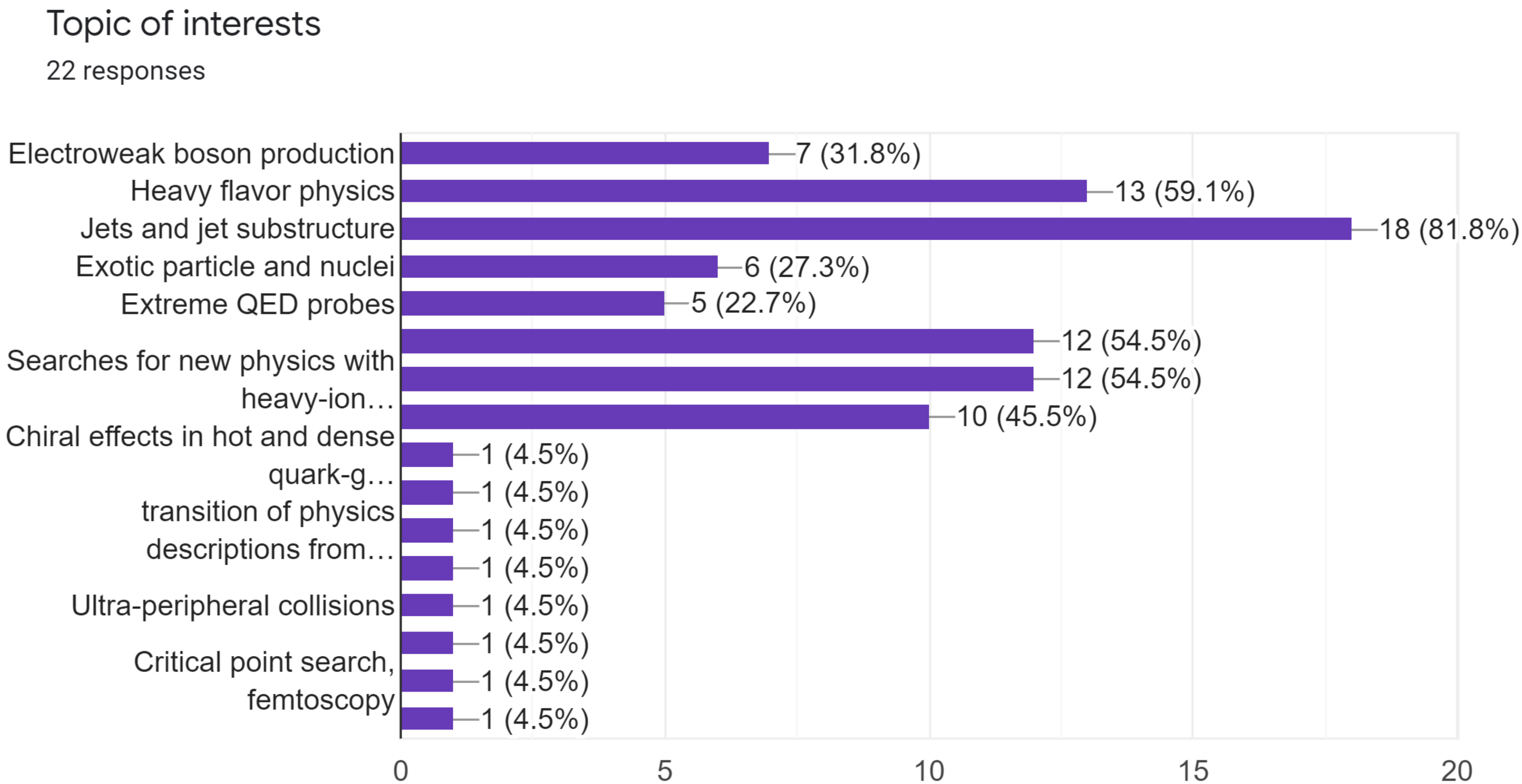
- Chiral effects in hot and dense quark-gluon matter
- Small-x physics in heavy ion and connection to EIC
- UPCs for SM physics
- Top quark production
- QCD Phase Diagram: Current and future direction to explore high temperature and baryon density region

Summary

- Many thanks for joining the meeting and the efforts!
- The next meeting: we will start the discussions and invite people to present their ideas.
- Look forward to see many interesting ideas from the discussions in this forum!

Backup Slides

EF07 Survey Results



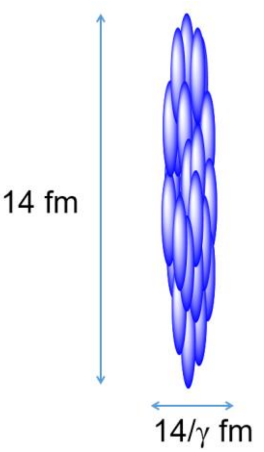
Parton Distribution Function (PDF)

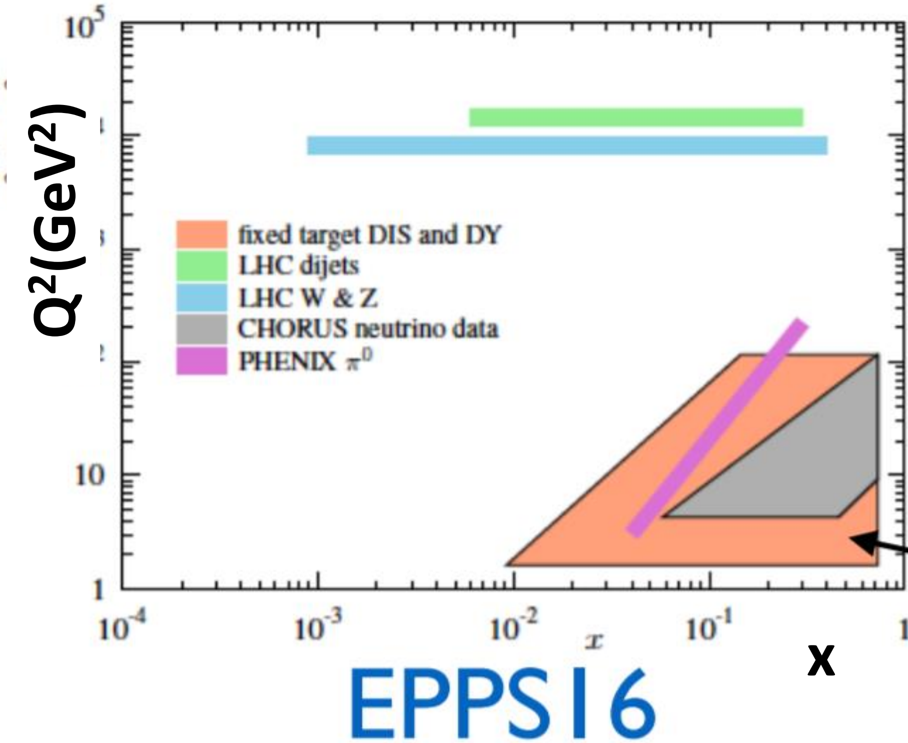
Lead Ion ≠ Superposition of **Neutrons** and **Protons**

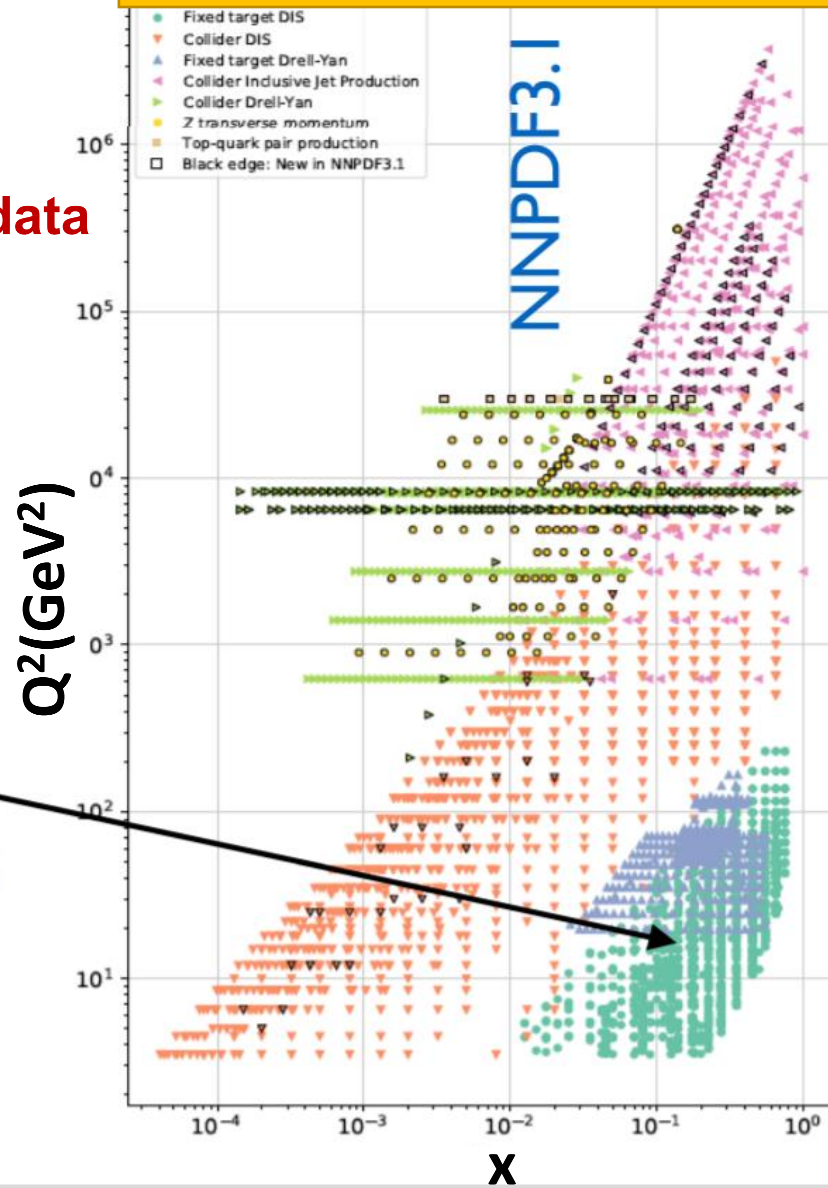
Input Data for Nucleon PDF

Input Data for Ion PDF

45 Pb collider data vs. **1200 proton collider data**

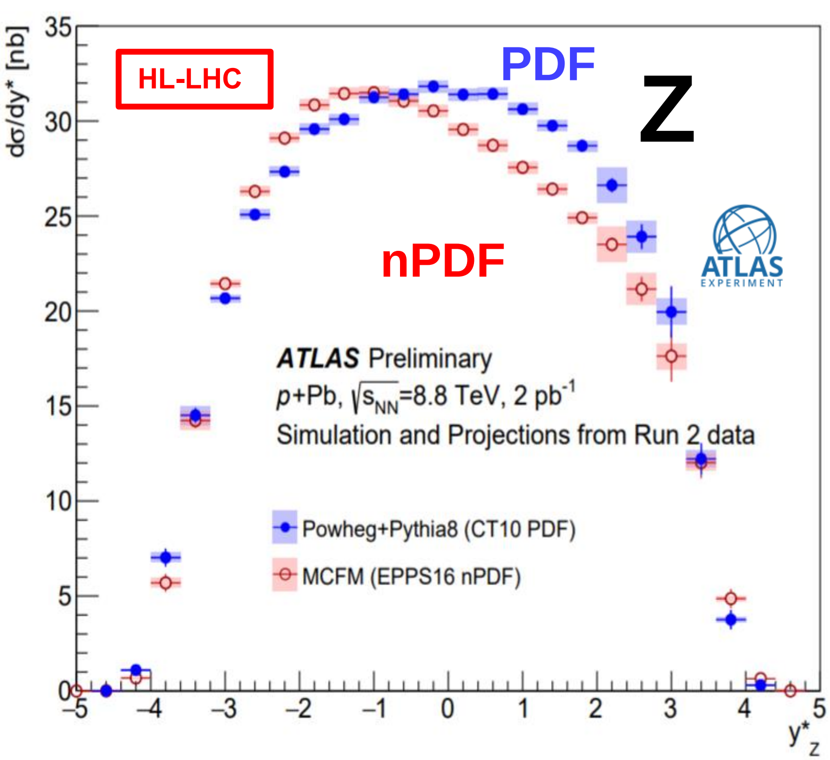


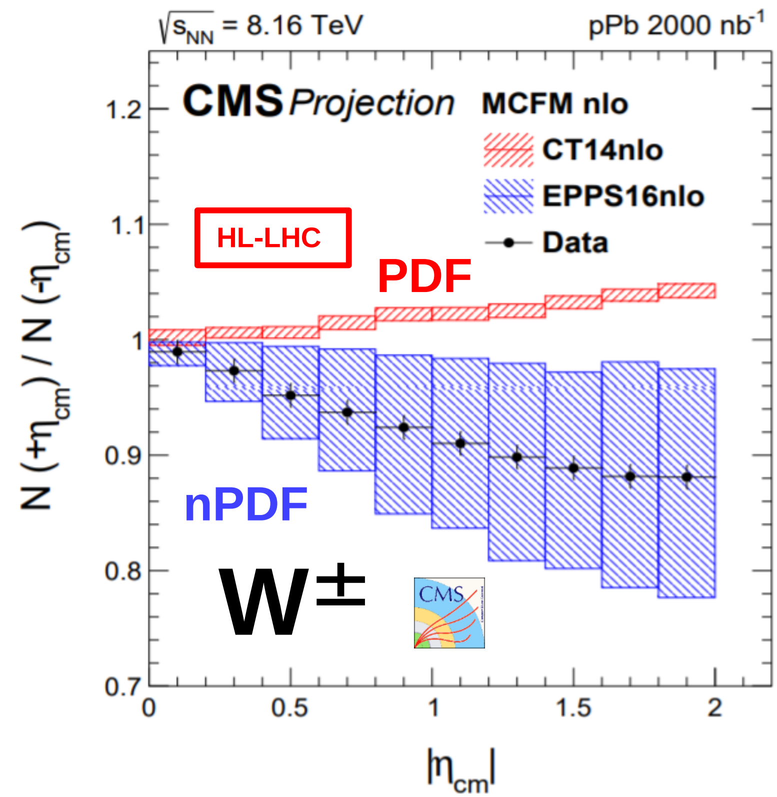


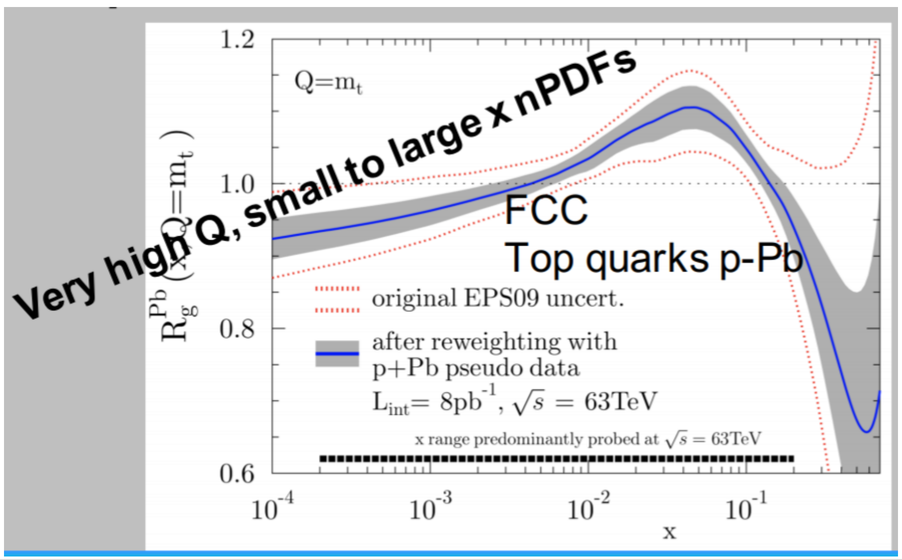


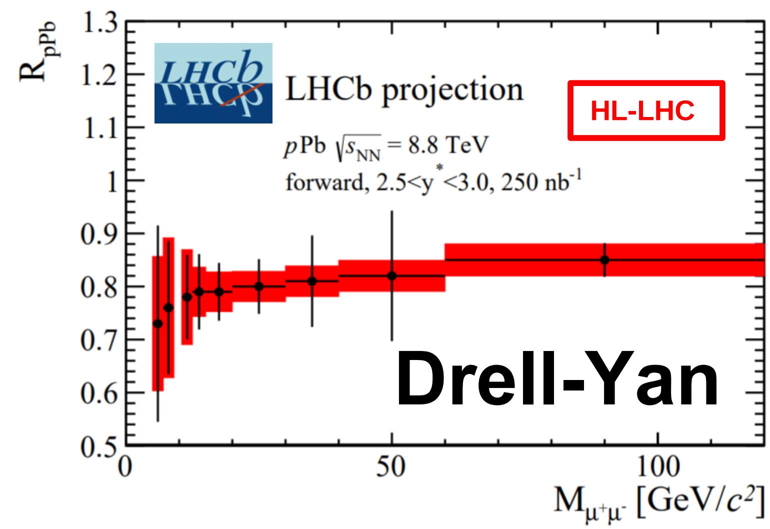
Poor understanding of PDF due to the limited amount of ion data

nPDF Constraint from pPb Collisions



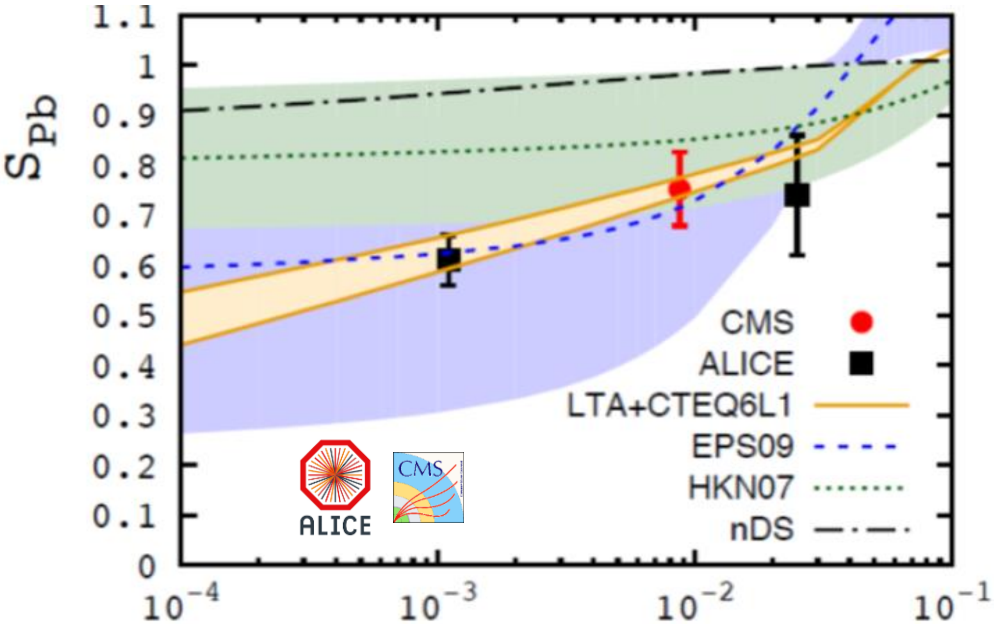


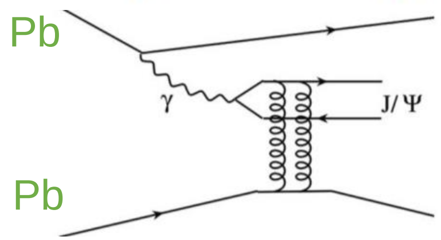




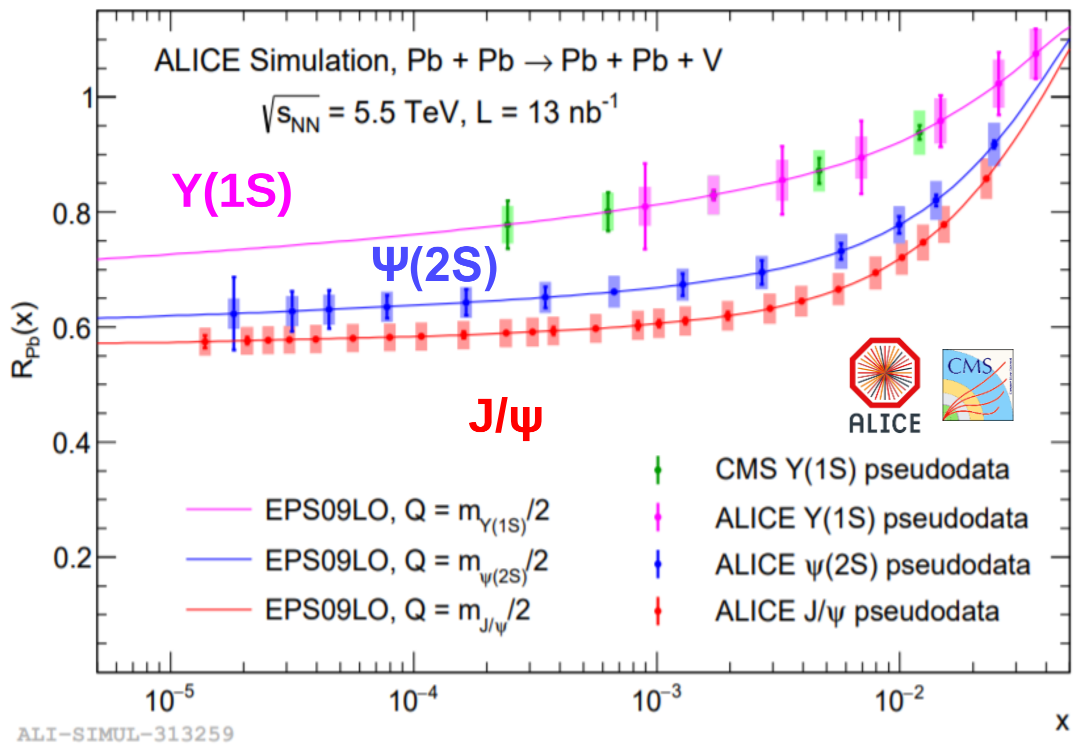
nPDF from Ultra-Peripheral PbPb Collisions

UPC J/ψ in Run 1 + 2015 Data **Present Data**





Performance of UPC Quarkonia **HL-LHC**

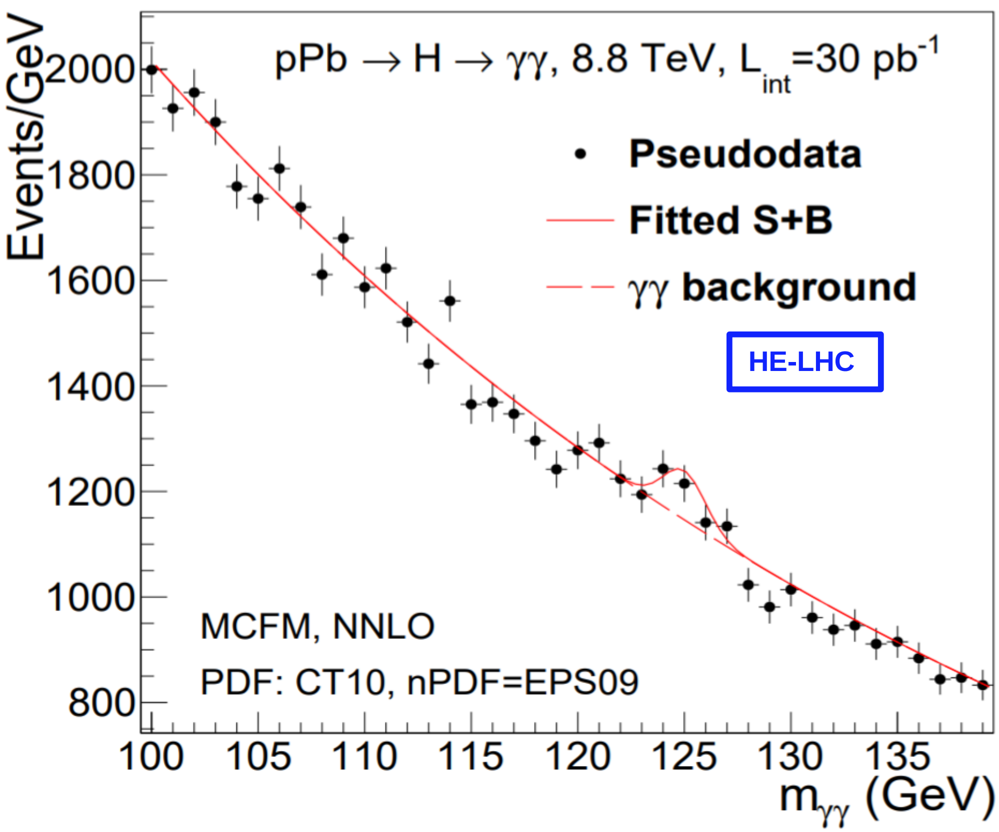


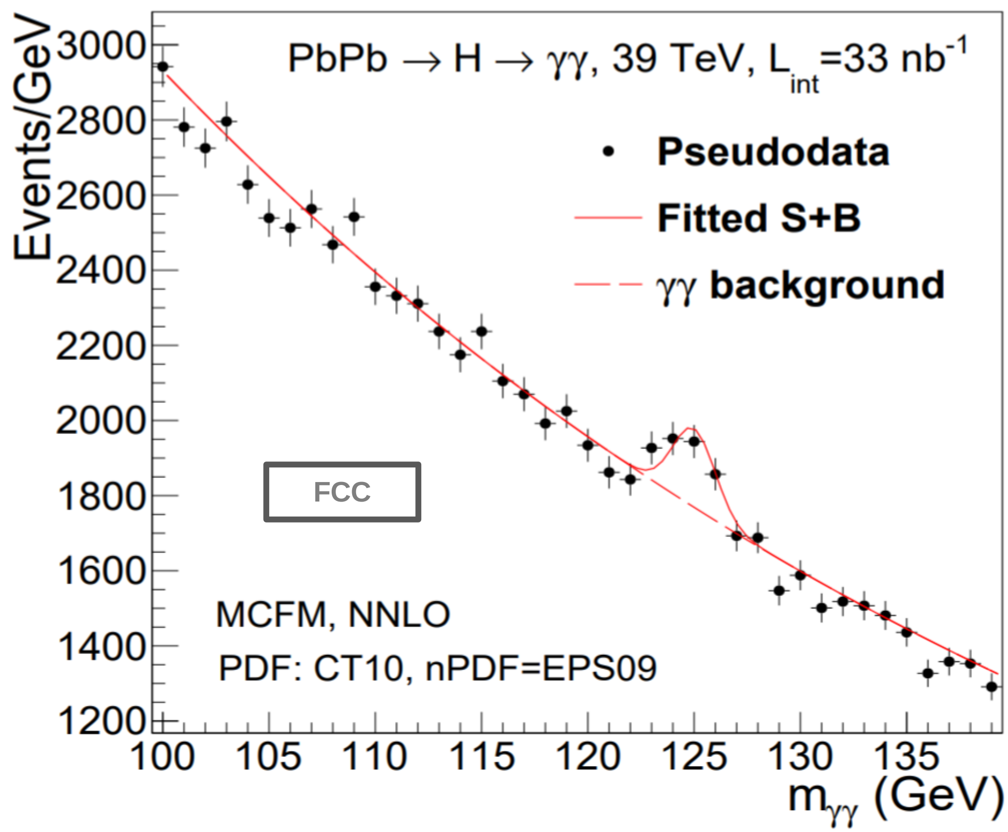
- Ultra-Peripheral PbPb Collisions(UPC): **γ+Pb** collisions!
- HL-LHC data: Precise measurements of Υ(1S), J/ψ and ψ(2S) over a **very wide x range**, test **Q dependence** of nuclear modifications
- Together with (di-)jet data in UPC PbPb and pPb collisions: strong constraint on the gluon nuclear PDF

Higgs Production in Heavy Ion Collisions

τ ~ 50fm/c > lifetime of QGP

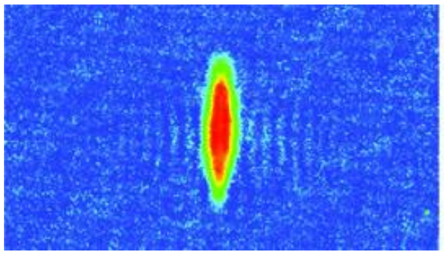
arXiv:1701.08047

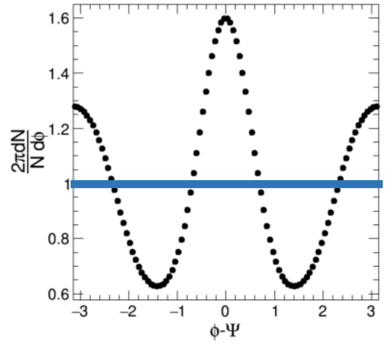


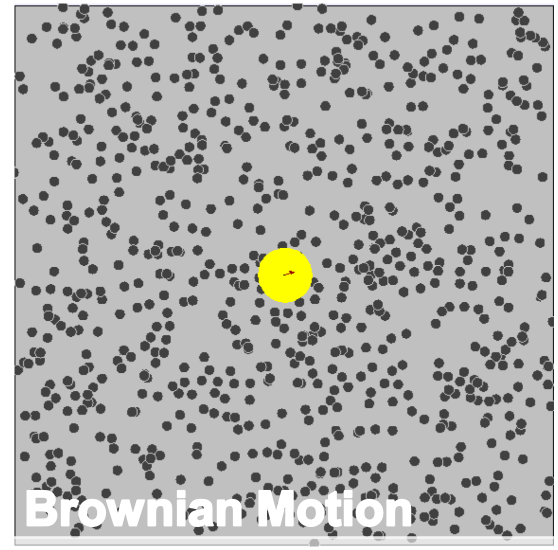


Cross-section of Higgs increase by a factor of 20 in PbPb collisions from 5.5 TeV to 39 TeV

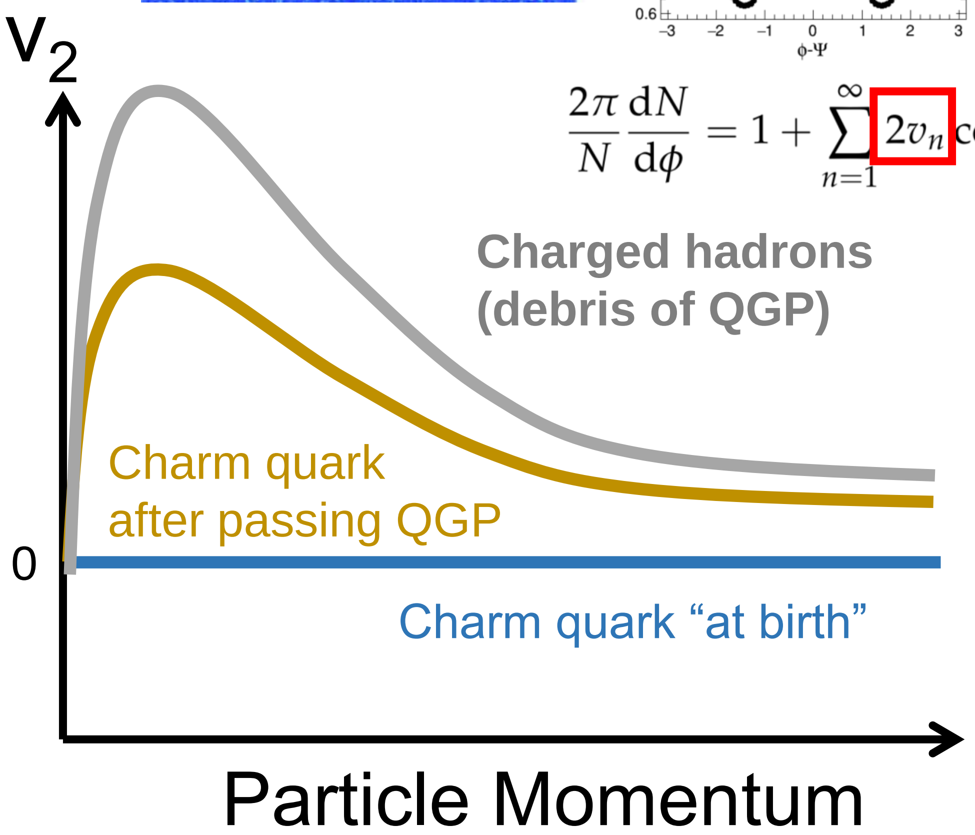
Heavy Quark (Charm and Beauty) Diffusion

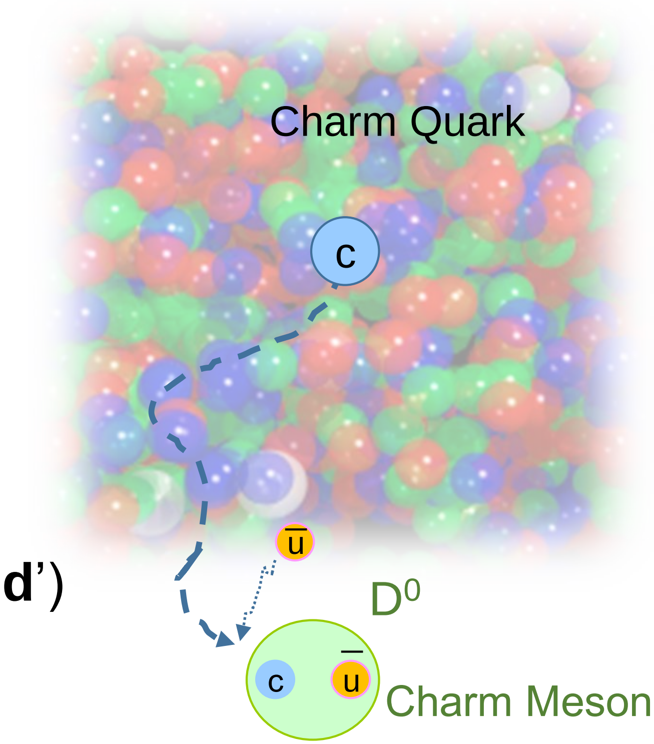






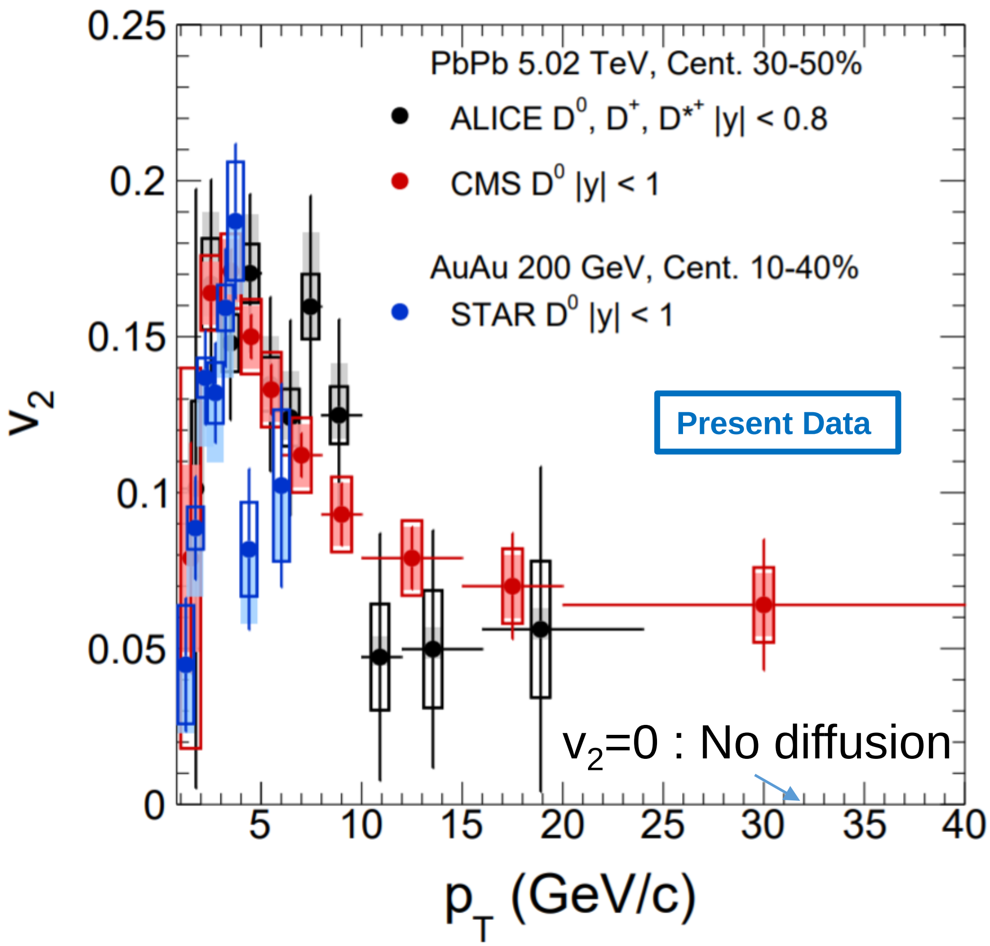
$$\frac{2\pi}{N}\frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$

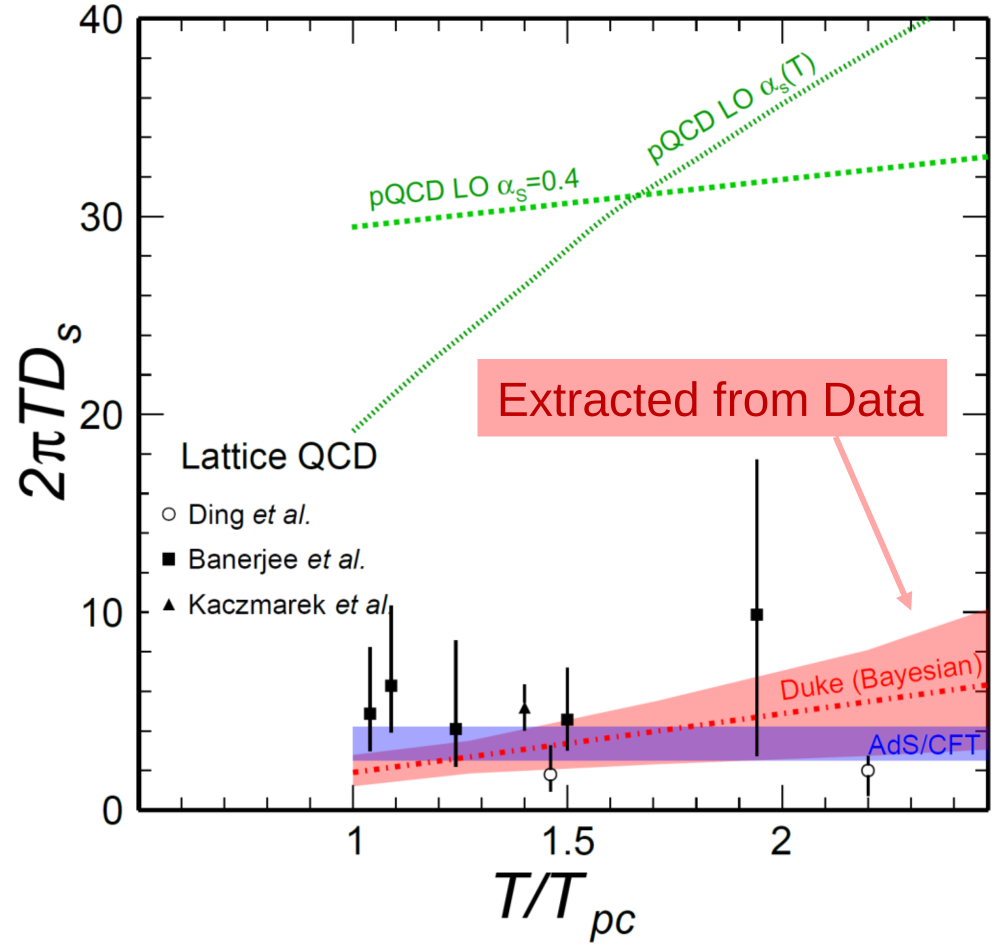




Since the **QGP is expanding radially**, QCD force (like '**wind**') increases the azimuthal anisotropy (v_2) of the charm quarks in the QGP bath!!

Charm Meson Diffusion Signal





Observation of charm meson elliptic flow (v_2)

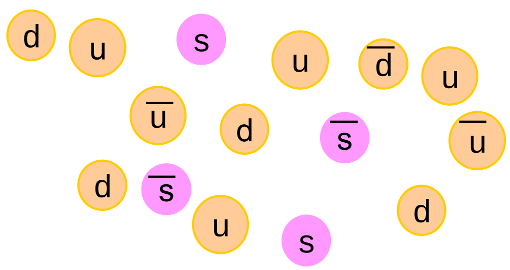
Charm quarks moving toward thermalization

Heavy quark diffusion coefficient D_s is extracted from LHC data using a Bayesian analysis, comparable with **LQCD** and **AdS/CFT** calculations

Duke Group PRC 97 014907 (2018)

Hadronization of Heavy Quarks in QGP

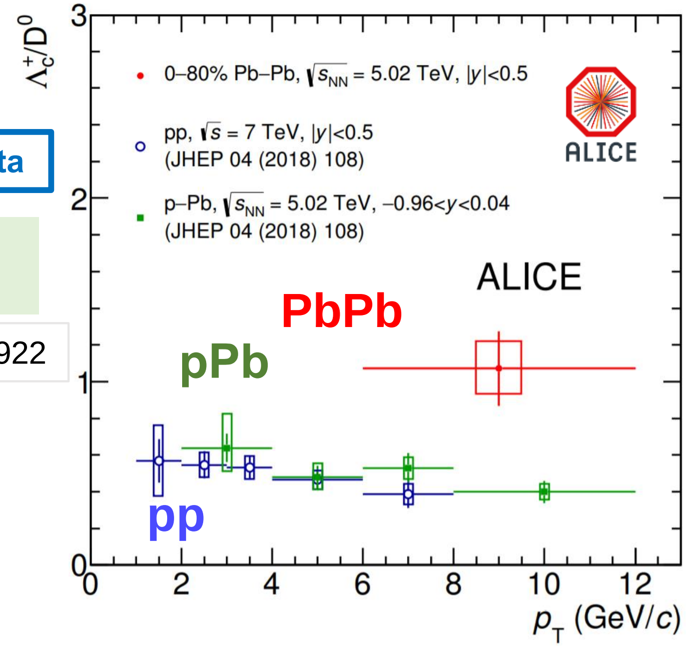
Strange quark content is enhanced in QGP (Due to the high temperature)



Present Data

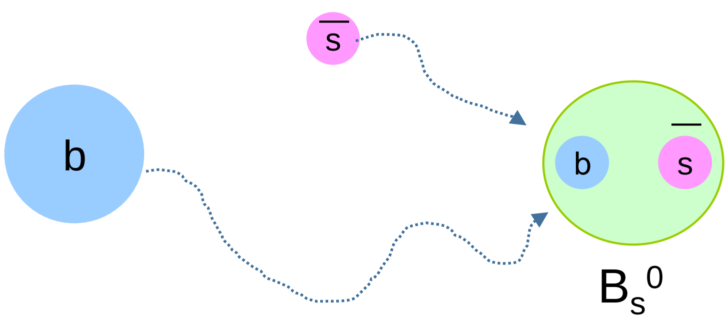
Λ_c/D

arXiv:1809.10922



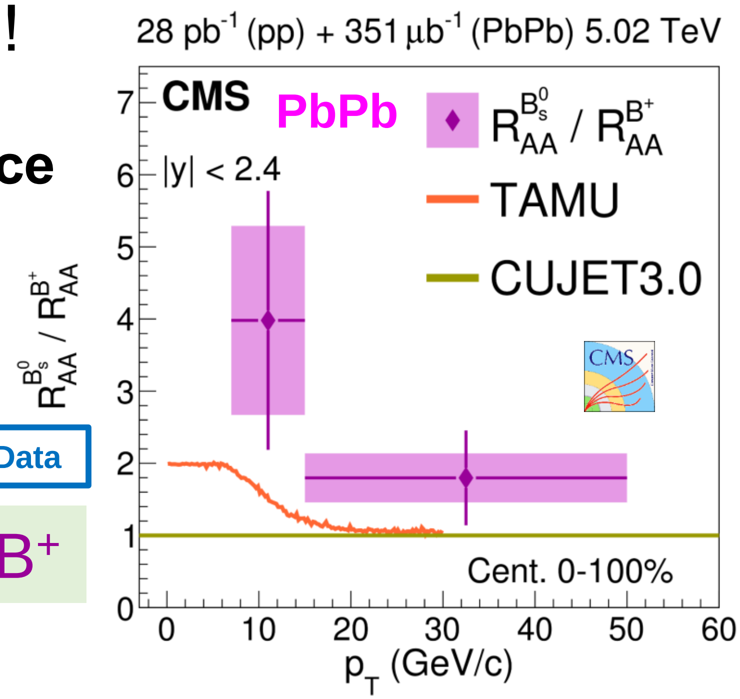
Idea: Probe the partonic QGP by heavy quarks!

Ex: D_s , B_s and Λ_c could be **enhanced via coalescence**



Present Data

B_s/B^+

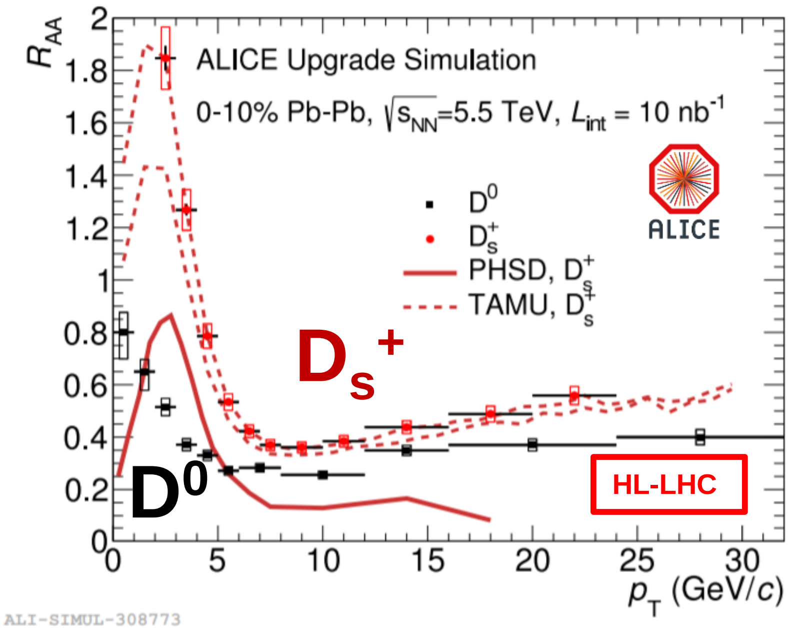


B_s^0 arXiv:1810.03022

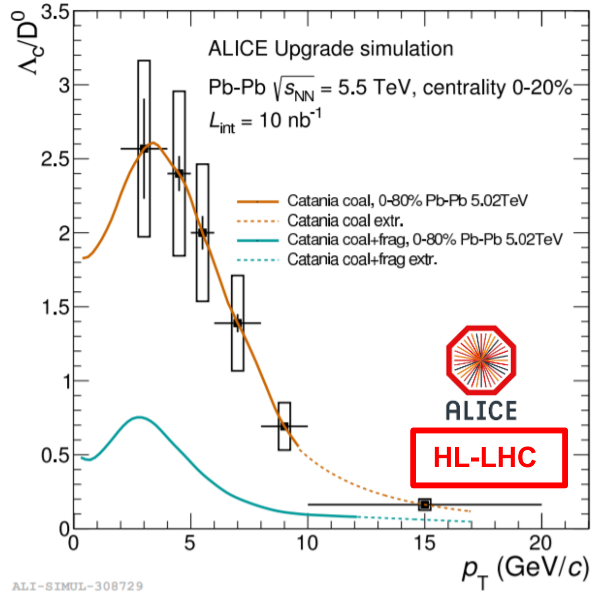
$B^\pm$ PRL 119 (2017) 152301

Heavy Quark Hadronization

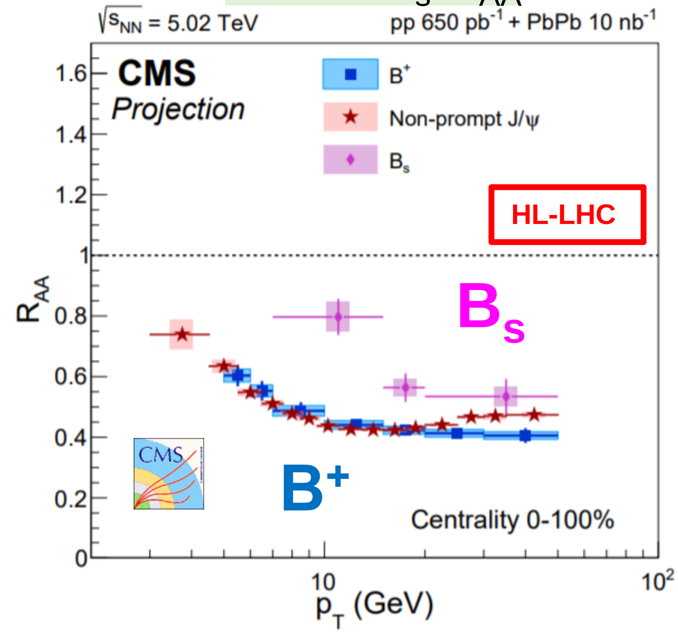
D_s R_{AA}



Λ_c/D



B^+ and B_s R_{AA}

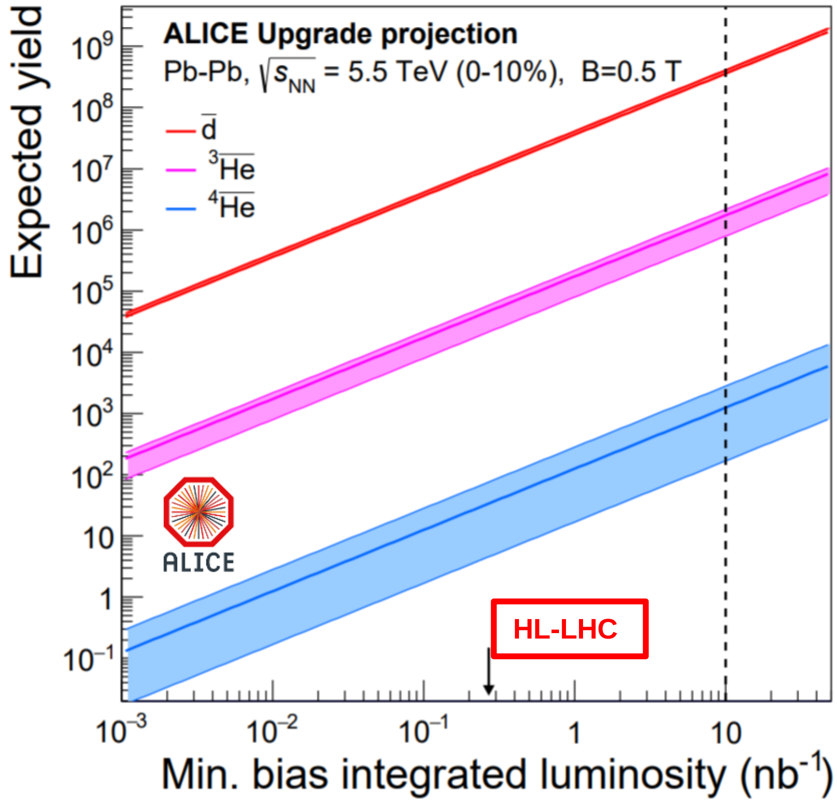


$$R_{AA} \rightarrow \frac{PbPb}{pp}$$

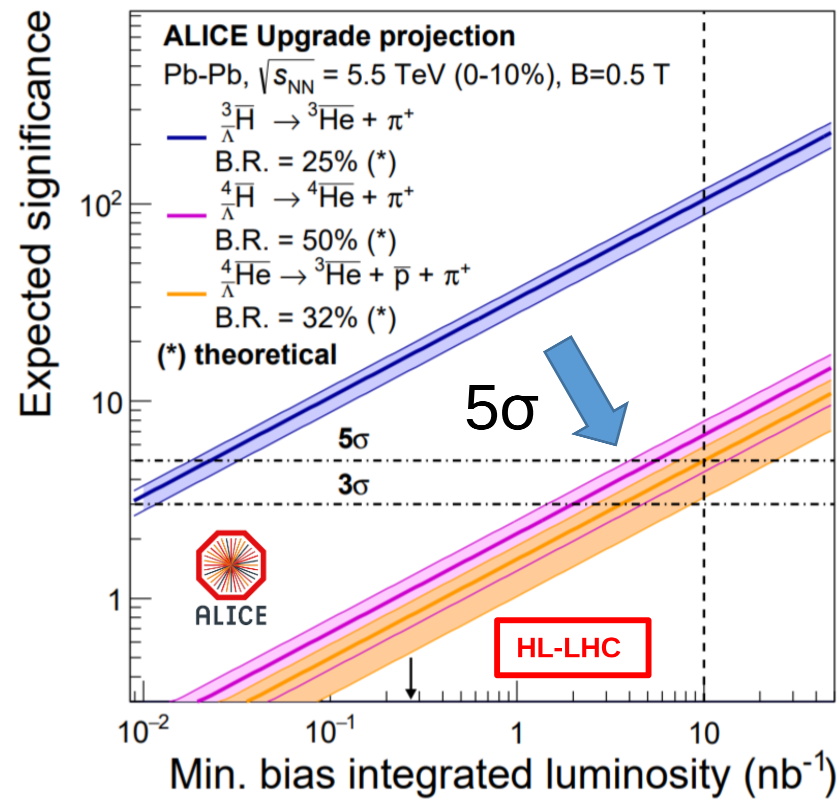
- Charm quark number is **conserved** in strong interaction
  - Hadronization chemistry: crucial for the interpretation of the heavy flavor hadron spectra ("keep track of all the c quarks")
- Run 3+4 data will allow the first comprehensive survey of this effect
  - D_s, B_s and Λ_c spectra from low to high p_T in pp and PbPb
  - Provide the necessary statistical accuracy to see the emergence of the effect at low p_T

(Anti-)(hyper-)nuclei Production

- **Precision test of coalescence / thermal production models**
  Sensitive to size ratio of the object and the source
- **Search** for rarely produced **anti-** and hyper-matter: Insights on the **strength of the hyperon-nucleon interaction**, relevant for nuclear physics and neutron stars. HL-LHC: first observation for anti-hyper-nuclei with A = 4
- **Constrain** models with pp measurements:
  Estimates of **astrophysical background** for dark matter searches



ALI-SIMUL-312336



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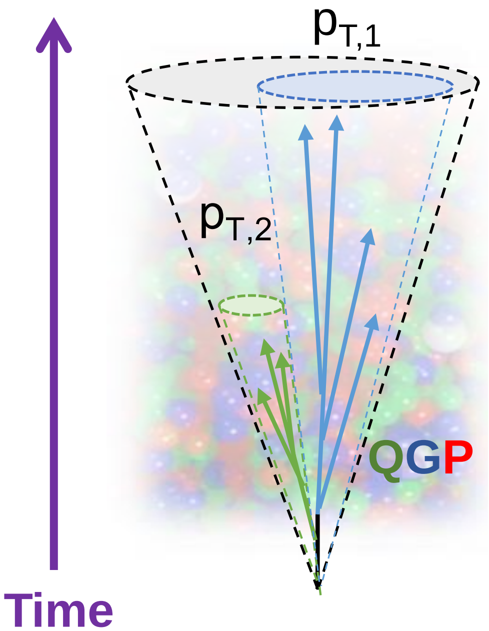
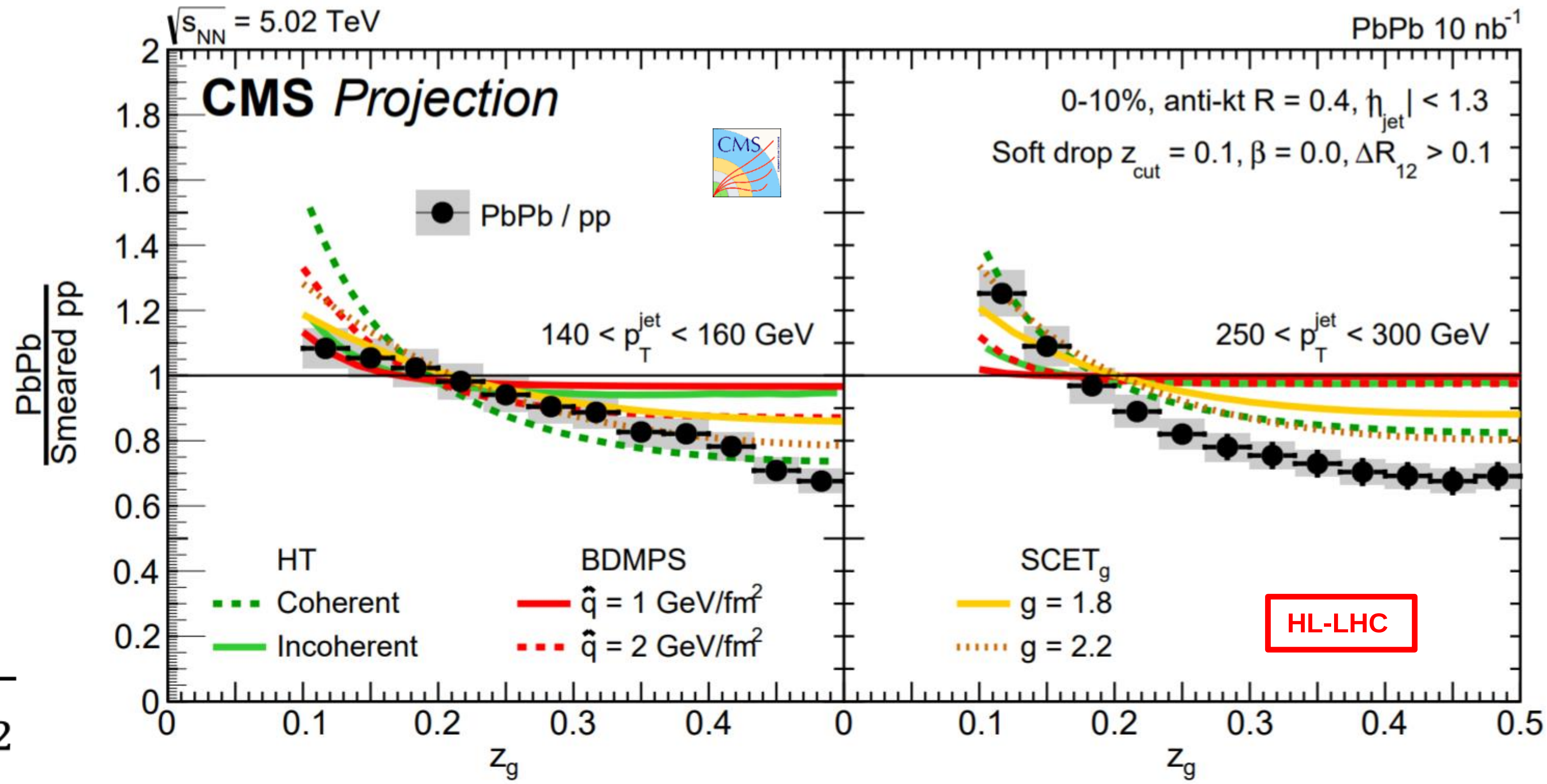
Subjet Momentum Sharing



$$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$



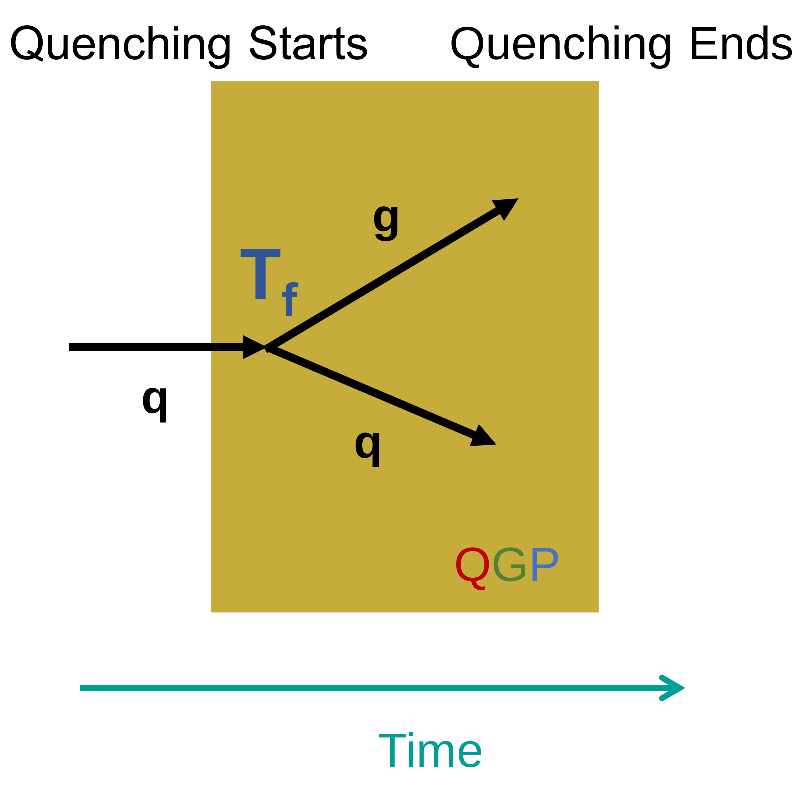
- Parton energy loss in QGP: **space-time evolution of the parton shower matters** since QGP is cooling down vs. time
- New era of jet substructure fluctuation studies: **constraints on the QGP scattering power with a completely orthogonal observable** (vs. jet or hadron spectra)
- Grooming techniques enable us to classify jets and to study **"Parton Shower Shape Dependence of Jet Quenching"**

Probing the QGP Evolution

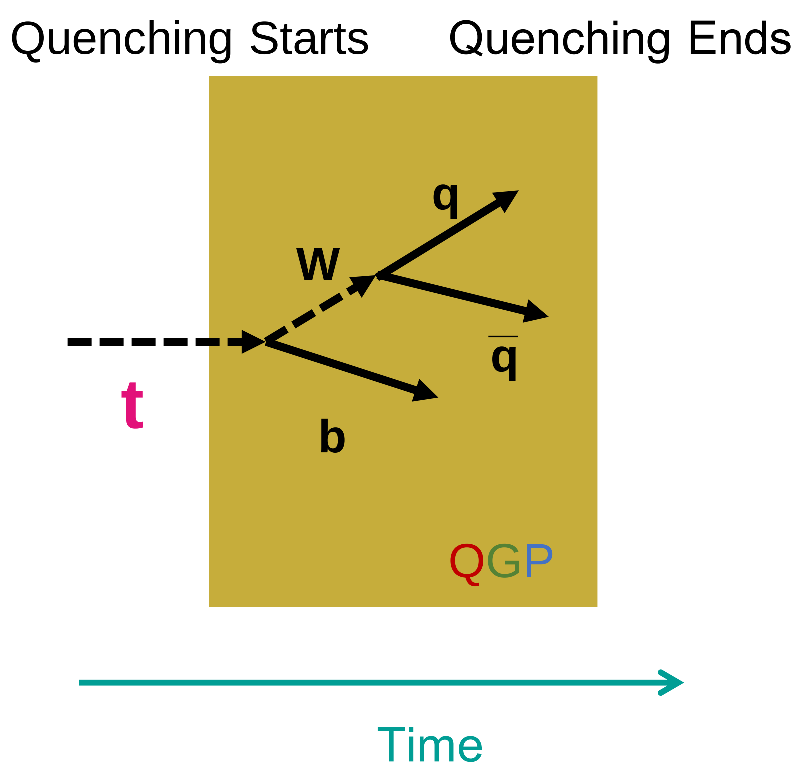
EMMI taskforce 2019

PRL 120.232301 (2018)

Formation Time (T_f) Tagging



Boosted Top

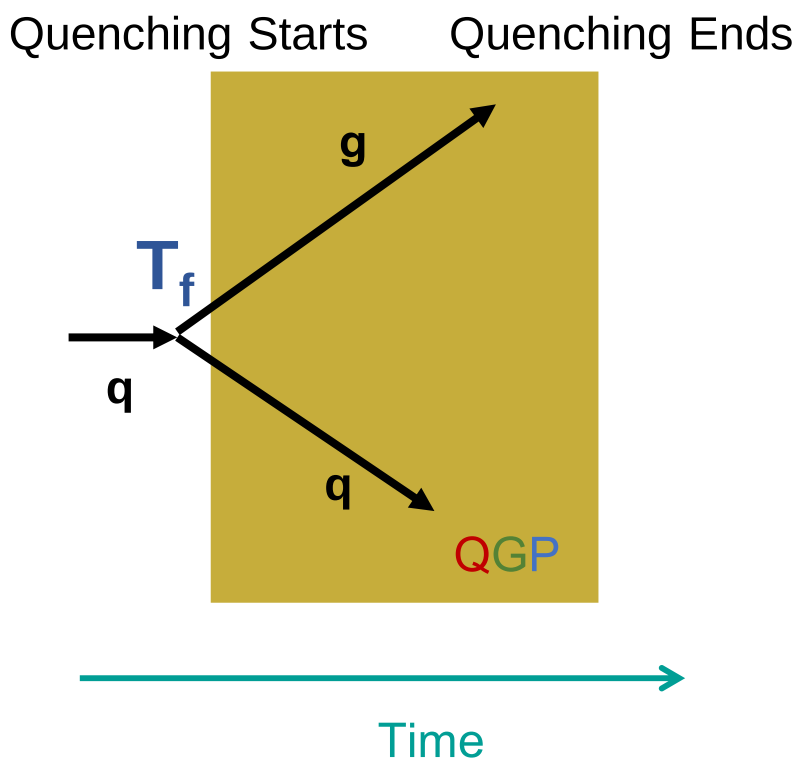


Probing the QGP Evolution

EMMI taskforce 2019

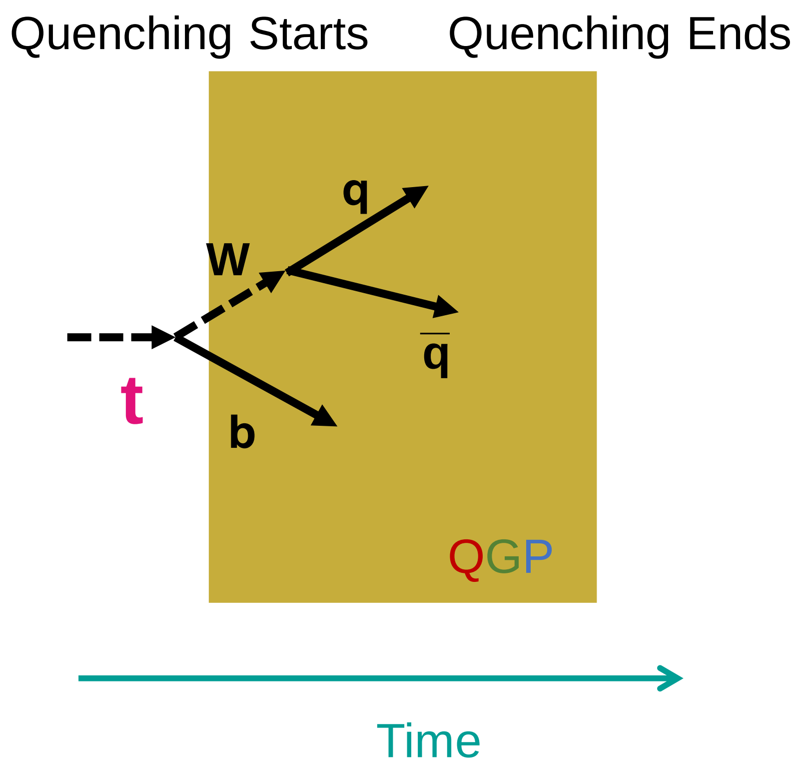
PRL 120.232301 (2018)

Formation Time (T_f) Tagging



Short formation time

Boosted Top



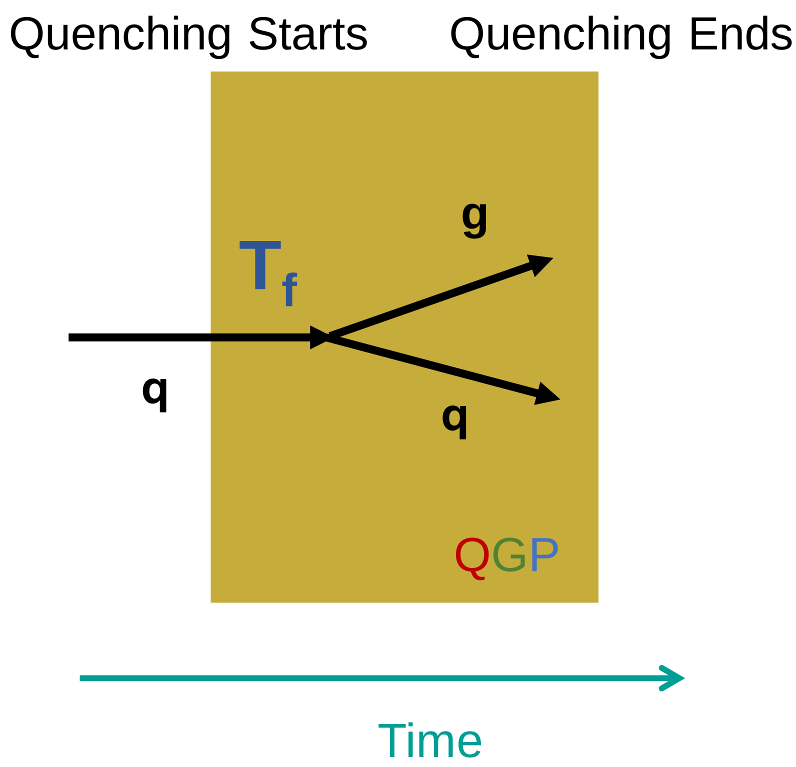
Low p_T top

Probing the QGP Evolution

EMMI taskforce 2019

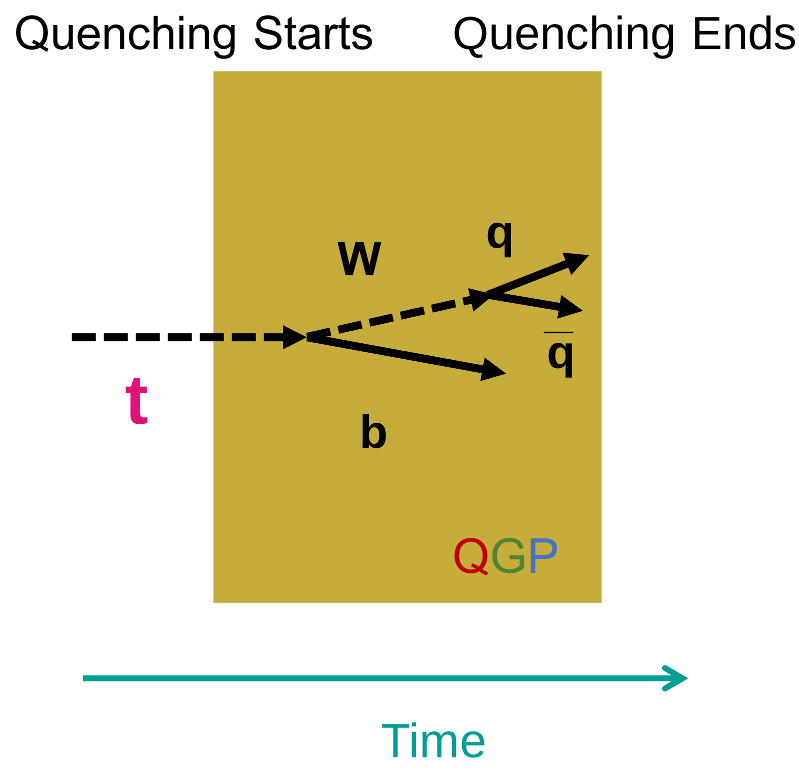
PRL 120.232301 (2018)

Formation Time (T_f) Tagging



Long formation time

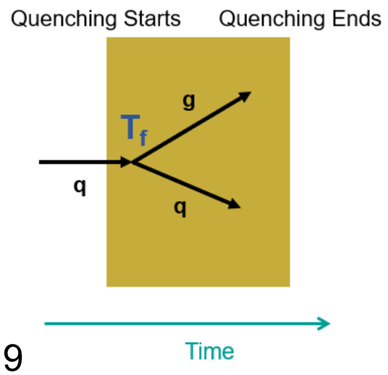
Boosted Top



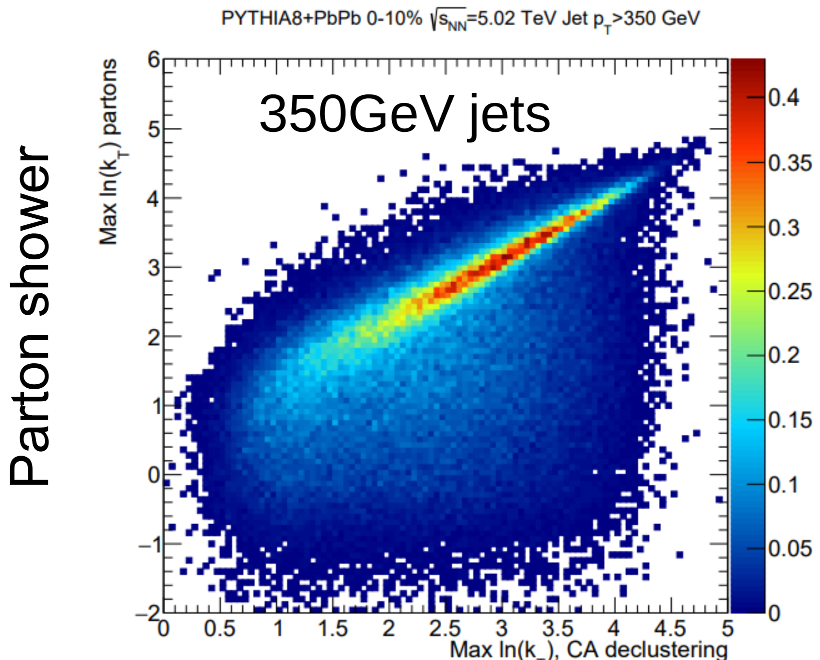
High p_T top

Time Dependent Evolution of QGP

Formation Time (T_f) Tagging



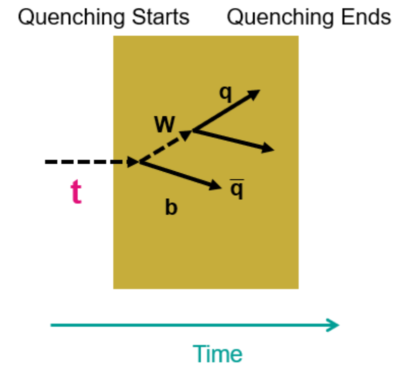
EMMI taskforce 2019



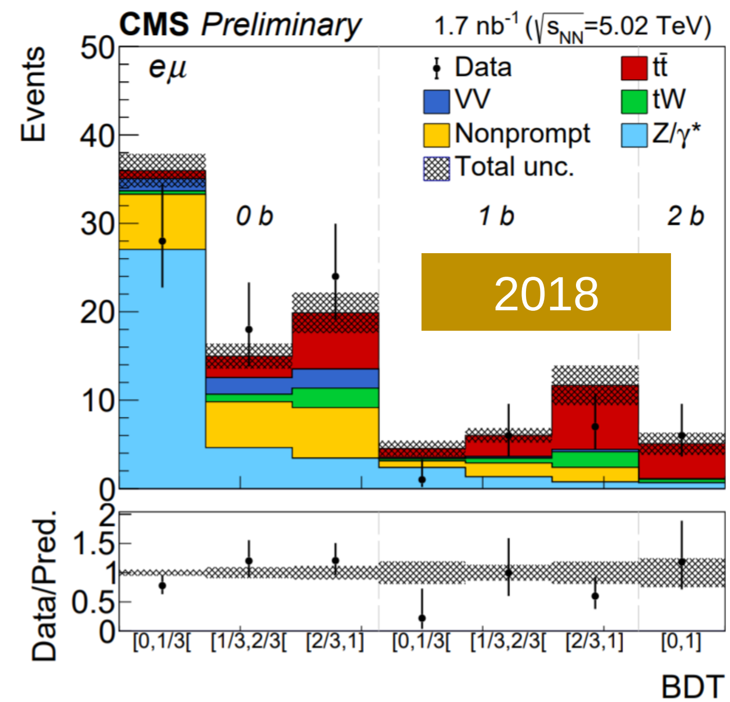
Hadron level (C-A declustering)

Modification of jet structure and correlations through interactions with QGP constituents (“Moliere scattering”)

Boosted Top



Present Data

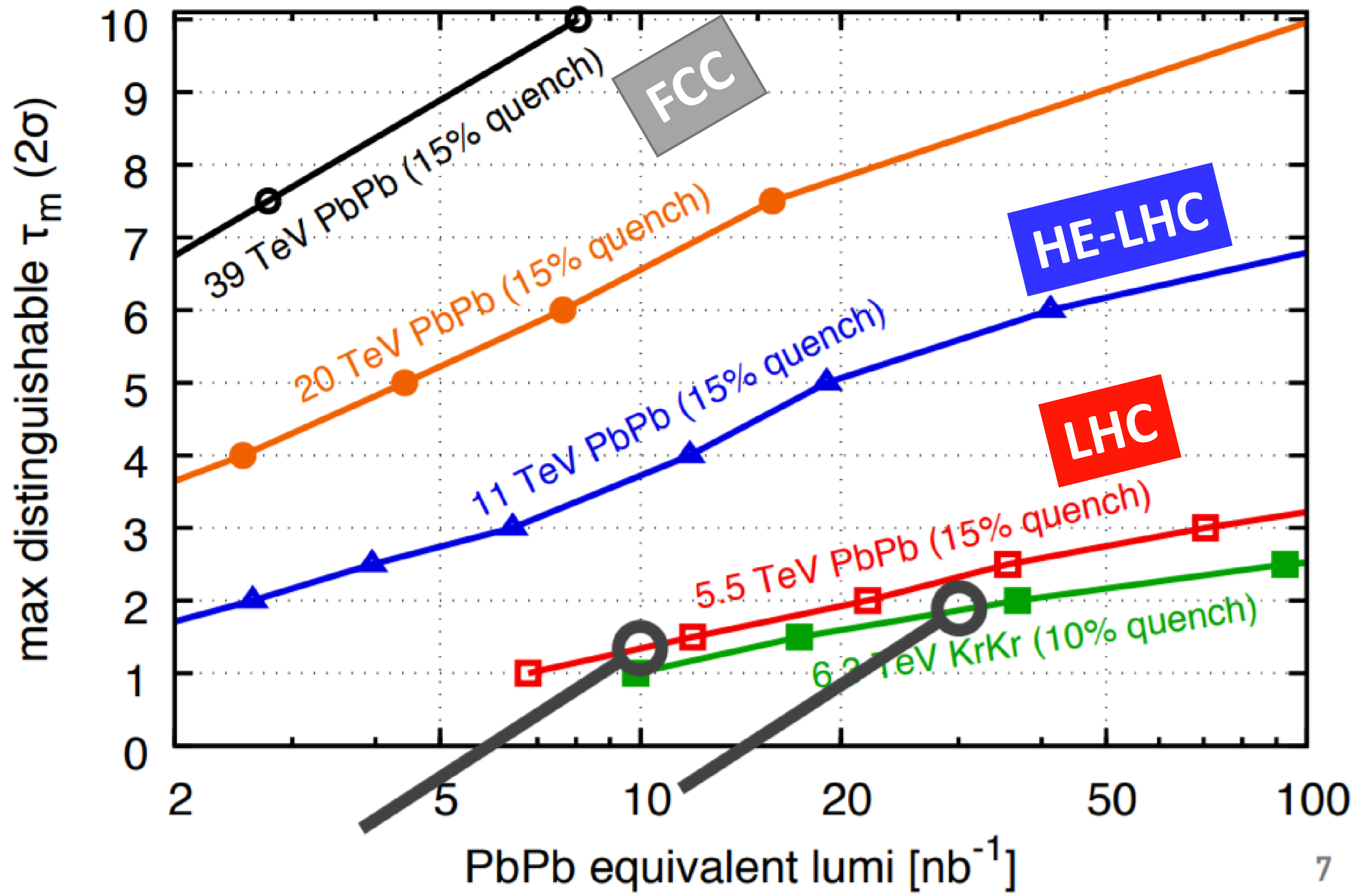


2018 data: 3.8σ

Observation of Top production in Run 3

Sensitivity to the Medium End Time

- Sensitivity to medium end time (τ_m):
  - HL-LHC PbPb Program (10 nb^{-1}): 1.4 fm/c
  - 1 month KrKr (30 nb^{-1}): 1.8 fm/c



Full exploitation of the Top probe only at **FCC energies**

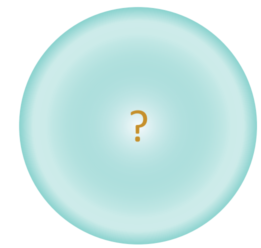
Probe the X(3872) with QGP

X(3872): Observed by BELLE (2003), its internal structure is still under debate

- Also known as $\chi_{c1}(3872)$ on Particle Data Book
- Quantum number determined by CDF and LHCb data: $J^{PC}=1^{++}$
- **Charmonium state**: **abandoned**, predict wrong mass with $J^{PC}=1^{++}$
- Remaining possibilities:
  - D-D̄* hadron molecule: mass X(3872) ≈ D(1875)D̄*(2007), large & extended state
  - **Tetraquark:** a compact four quark state
  - **Hybrid**: mixed molecule-charmonium state

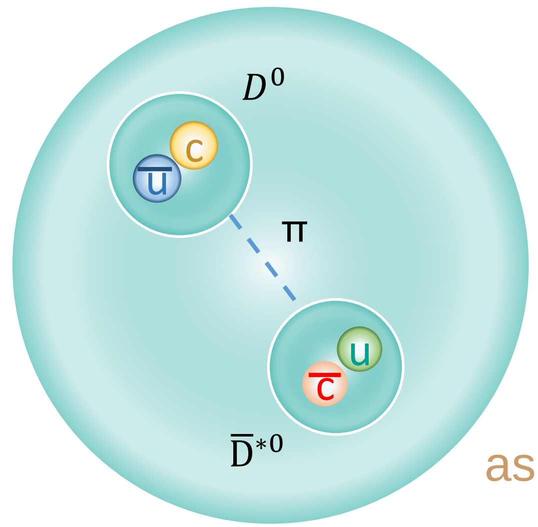
BELLE PRL 91, 262001 (2003)
CDF PRL 98, 132002 (2007)
LHCb PRL 110, 222001 (2013)

Hybrid



EPJA47 (2011) 101

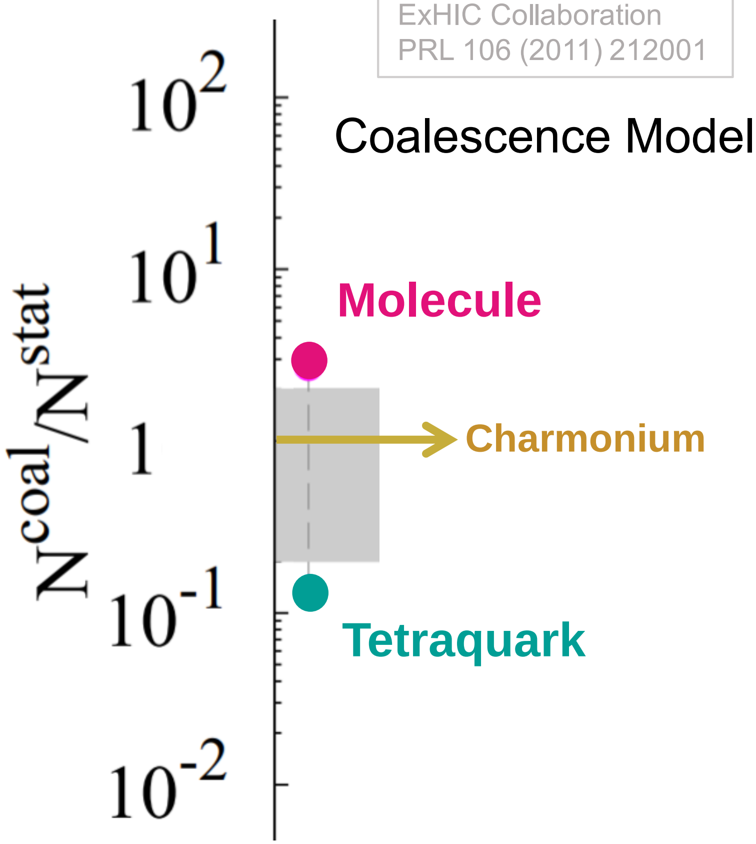
$D^0 - \bar{D}^{*0}$ molecule



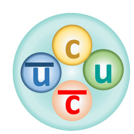
PRD71 (2005) 014028

$r_{molecule}$ as large as 5 fm

ExHIC Collaboration
PRL 106 (2011) 212001



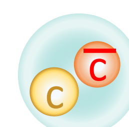
Tetraquark (4q)



$r_{4q} \approx r_{c\bar{c}}$
≈ 0.3 fm

PRD 71 (2005) 014028

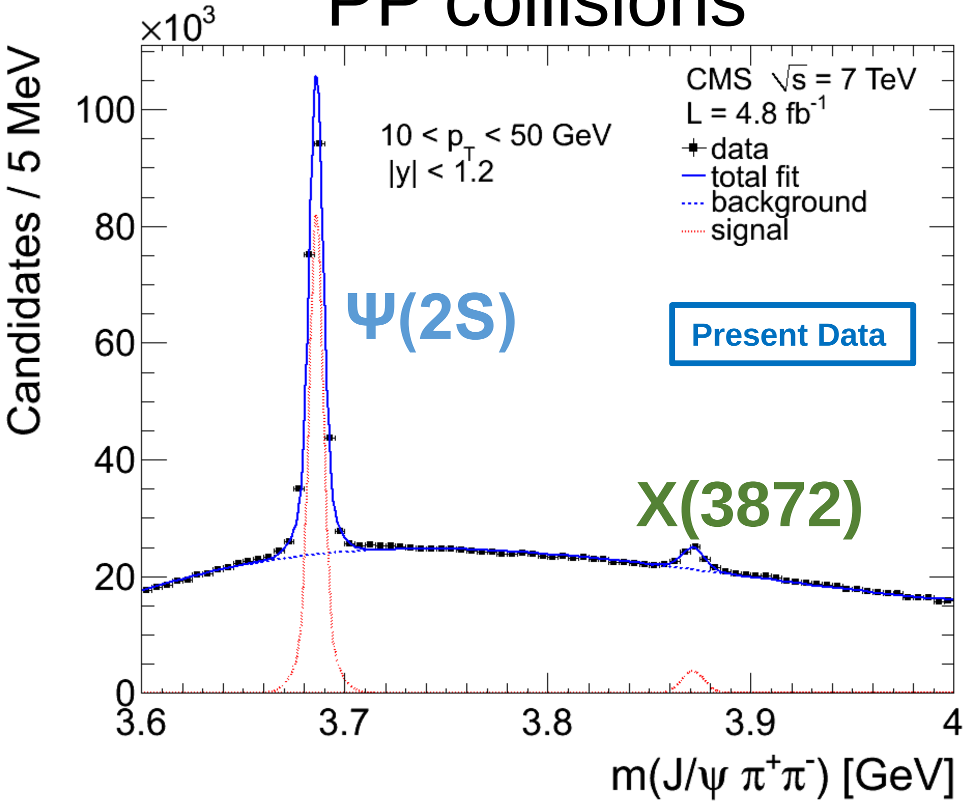
Charmonium



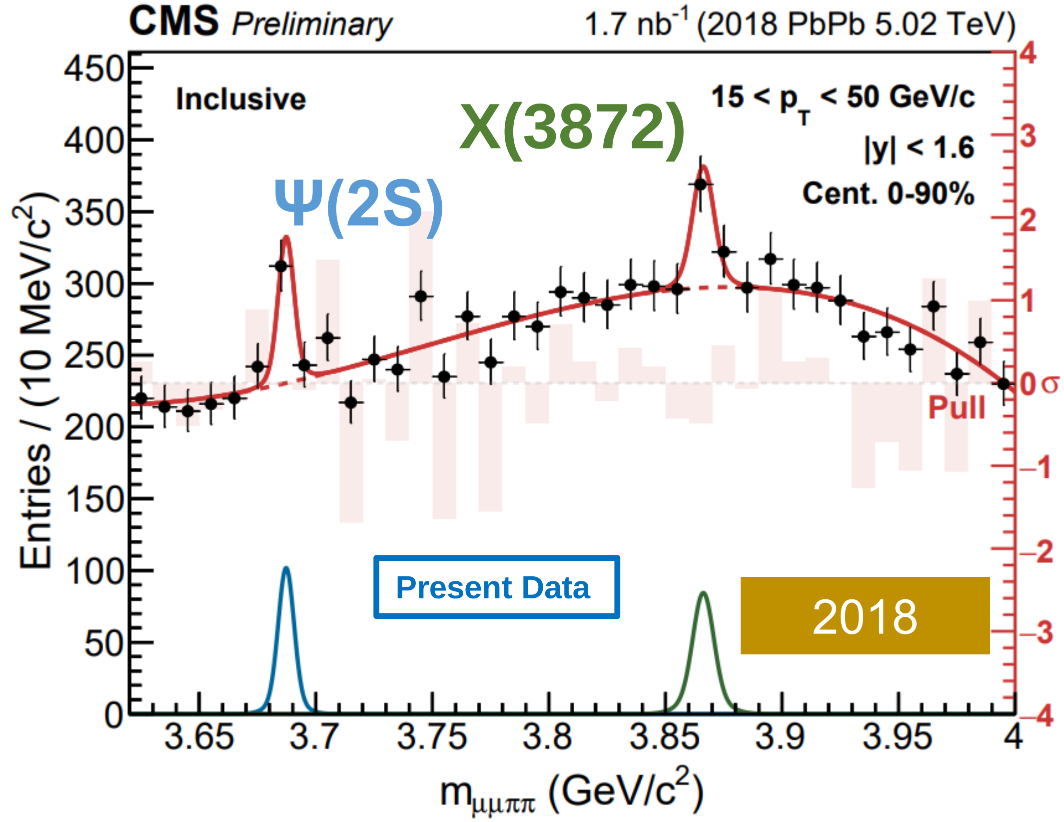
PLB 590 209-215 (2004)

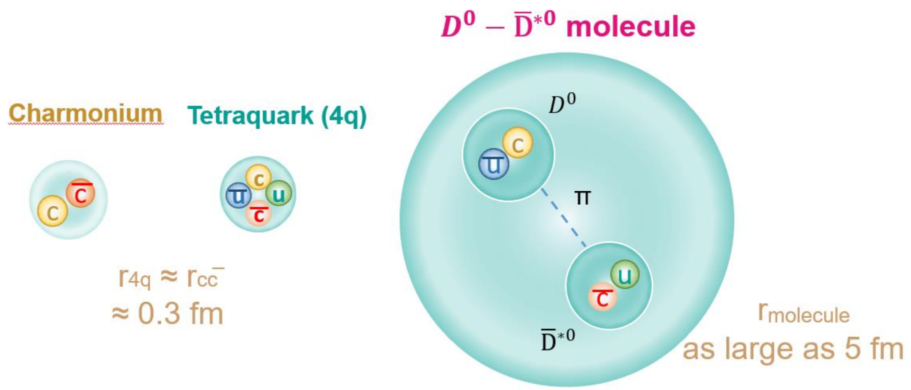
X(3872) Production in PbPb

PP collisions



PbPb collisions





- 2018 data: First evidence of inclusive **X(3872)** production in heavy ion collisions!

(statistical significance ~ **4σ**)

Observation **of X(3872) is expected (>5 σ) in Run3**

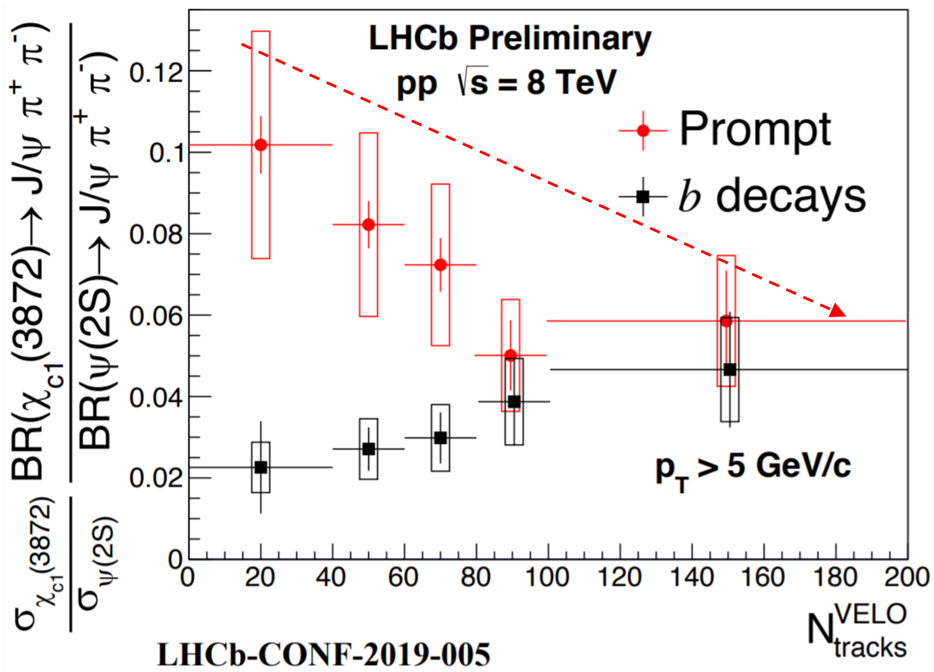
Run3+4: Enables more differential studies (vs. p_T and centrality)

CMS-PAS-HIN-19-005L

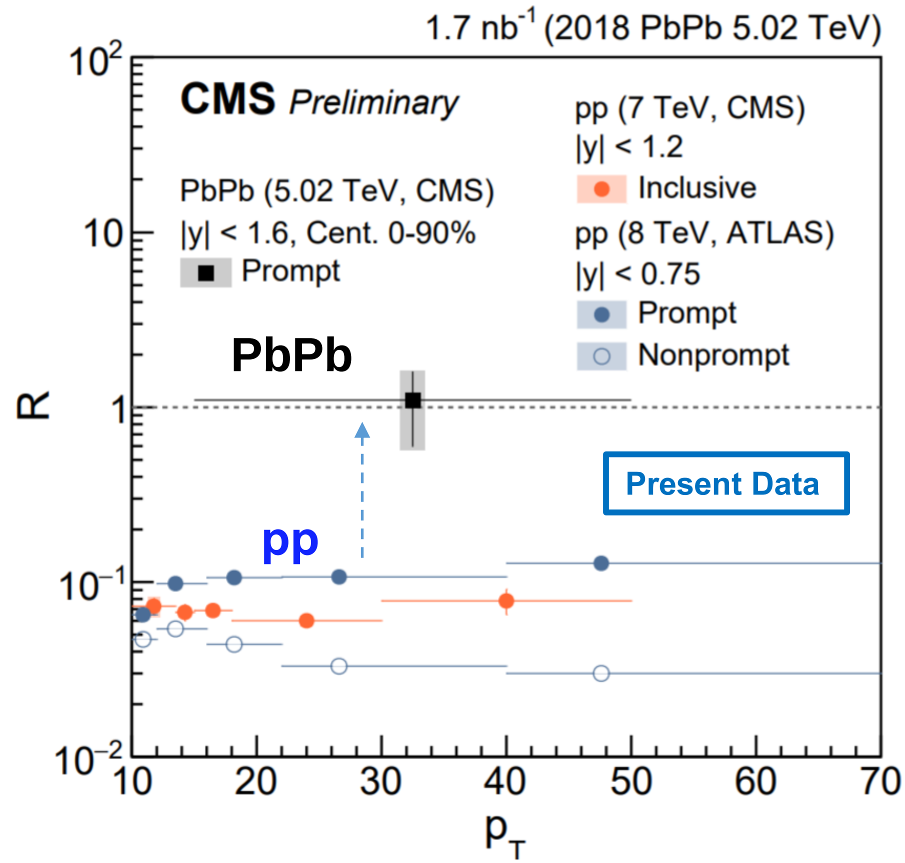
X(3872) Production in pPb and PbPb

pPb collisions

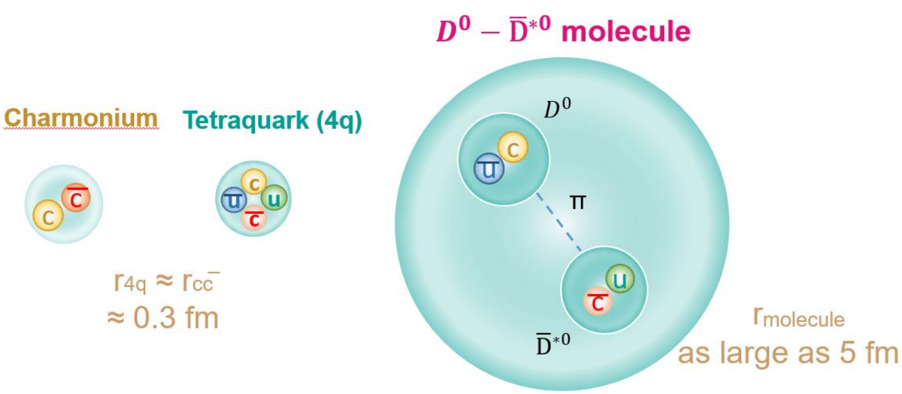
Present Data



PbPb collisions



- $R = N_X / N_{\psi(2S)}$



CMS-PAS-HIN-19-005L

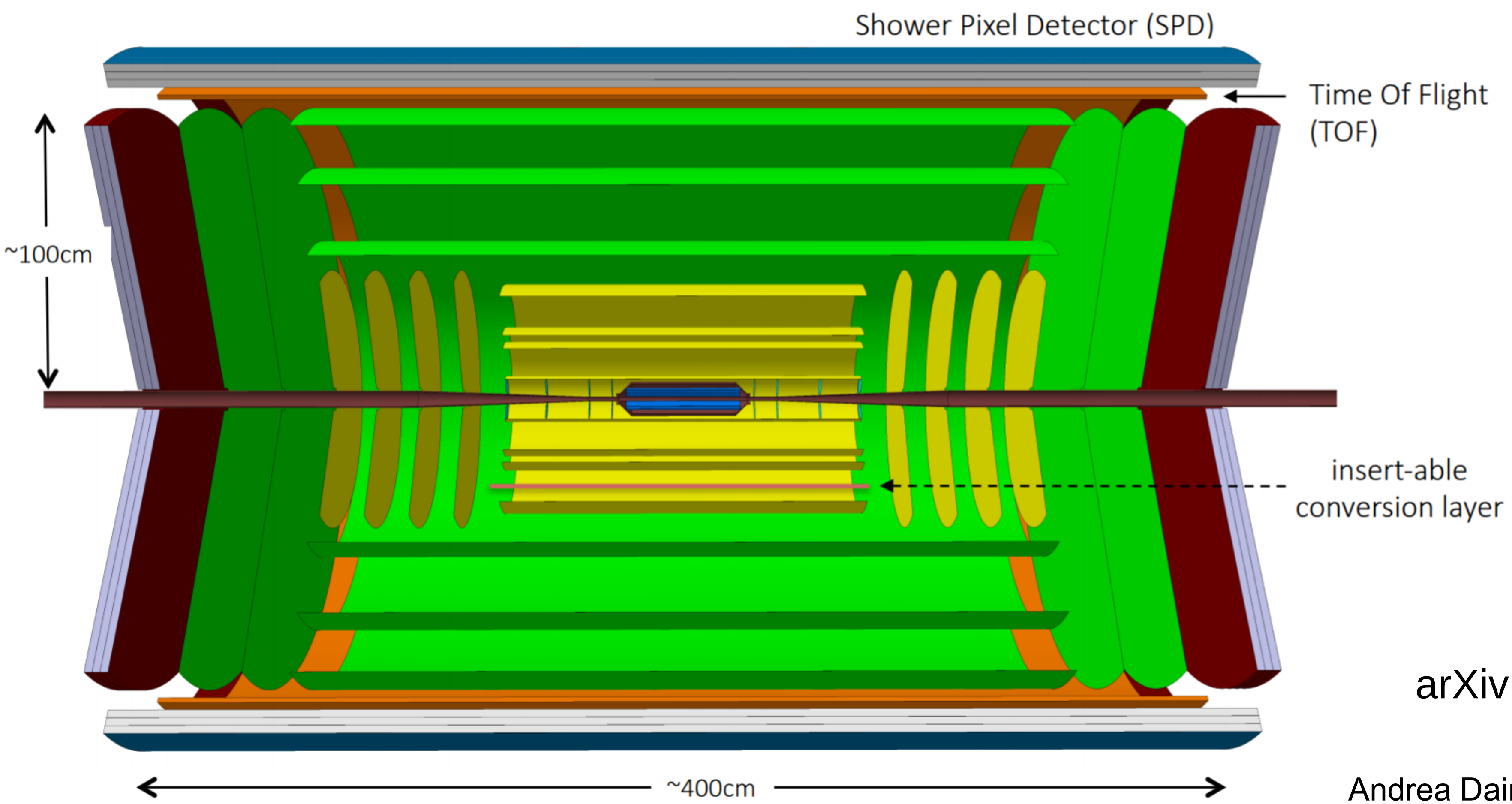
Observation **of X(3872) is expected (>5 σ) in Run3**

Run3+4: Enables more differential studies (vs. p_T and centrality)

”Si-only” HI experiment for LHC Run 5 (>2031?)

Fast, ultra-thin detector with precise tracking and timing:

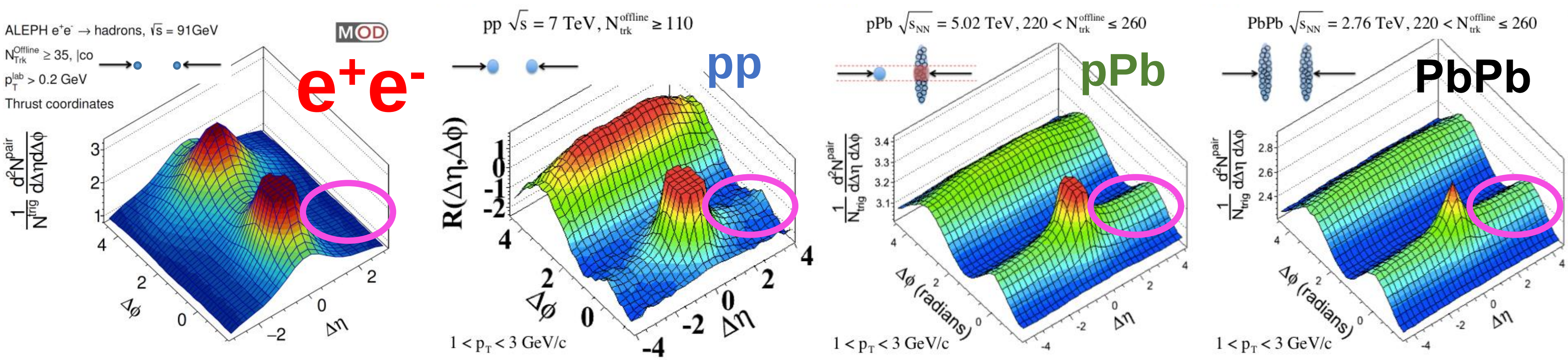
- Exploit higher NN lumi with intermediate-A nuclei
- Ultimate performance for (multi-)HF, thermal radiation and very soft hadrons (<50 MeV)
- Access to exotic mesons such as X(3872) at very low p_T.



arXiv:1902.01211

Andrea Dainese (QM’20)

Hydro Flow Like Signal in Smaller Collisions Systems



- "Ridge" in **PbPb** collisions: Hydrodynamics Flow
- Observed in **high particle multiplicity** **pp** (2010) and **pPb** (2013) collisions!!!
- No sign of jet quenching in **pPb**
- No sign of ridge signal in **e^+e^-** ALEPH archived data

CMS pp ridge
JHEP 1009 (2010) 091
(841+ citations)

CMS pPb ridge
PLB 718 (2013) 795
(612+ citations)

Question: What is the origin of the signal in small system?

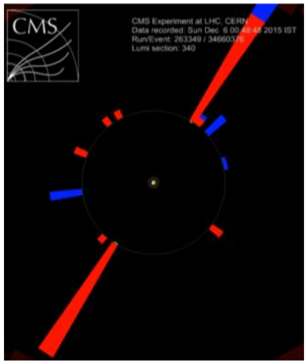
Can we observe other effects like jet quenching in pp, pO, pPb or OO?

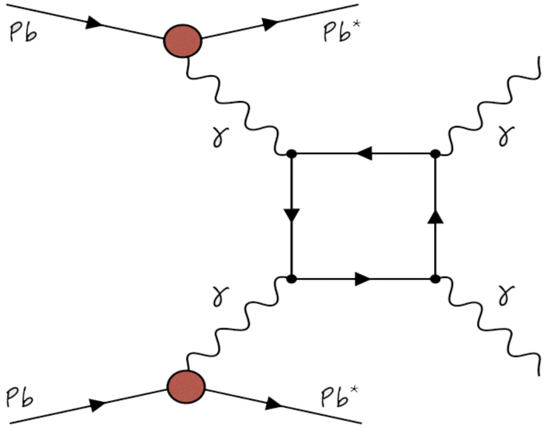
Can we see flow-like signal in EIC?

e^+e^- two particle correlation with ALEPH archived data
PRL 123 (2019) 212002

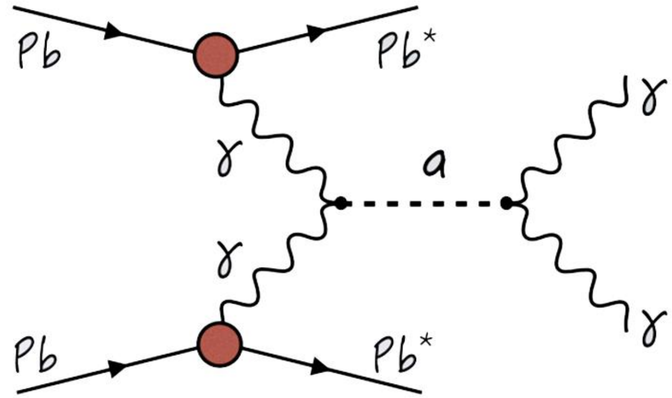
Search for Axion with UPC Event

Observation of **light-by-light scattering**

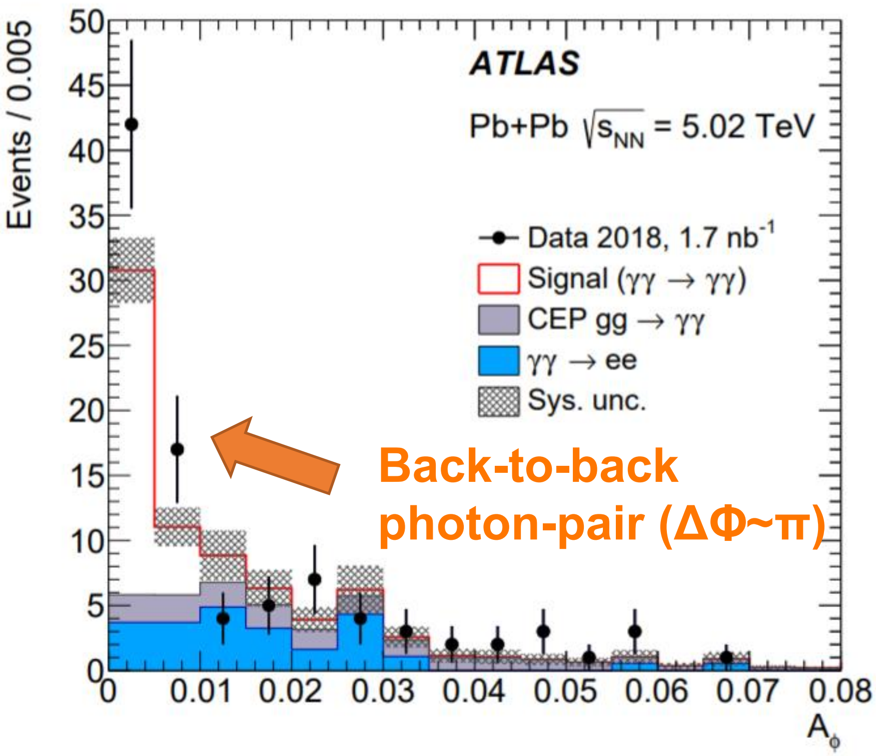




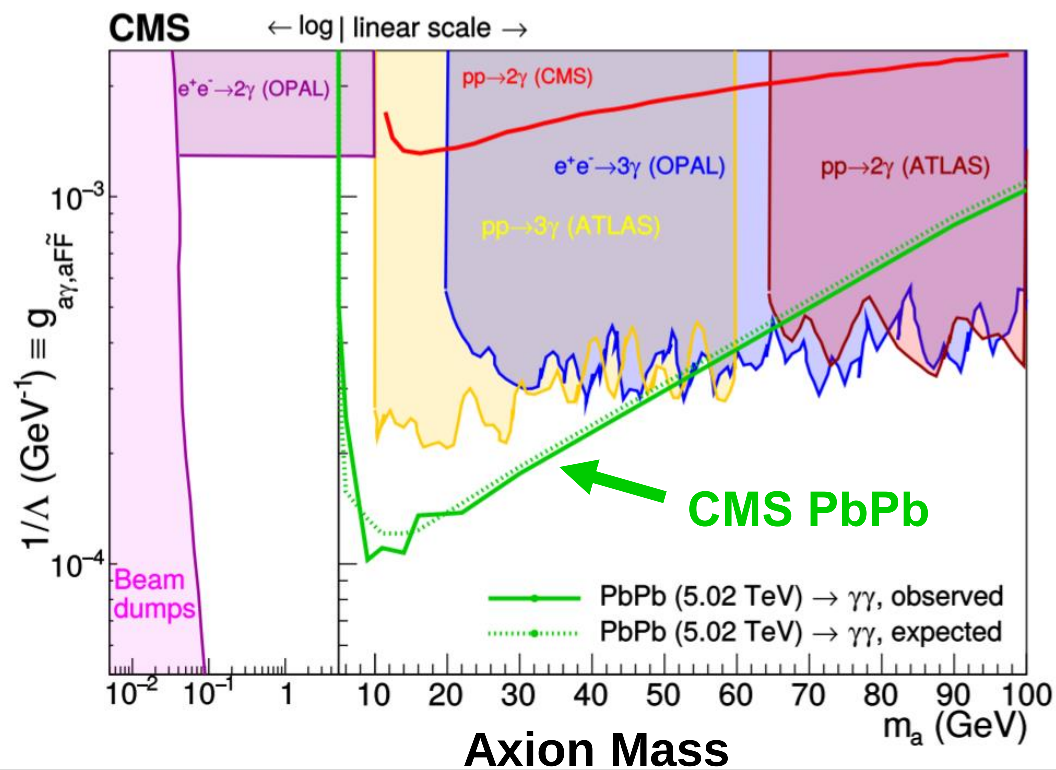
New limit on **axion-like** particle production



Phys. Rev. Lett. 123, 052001 (2019)



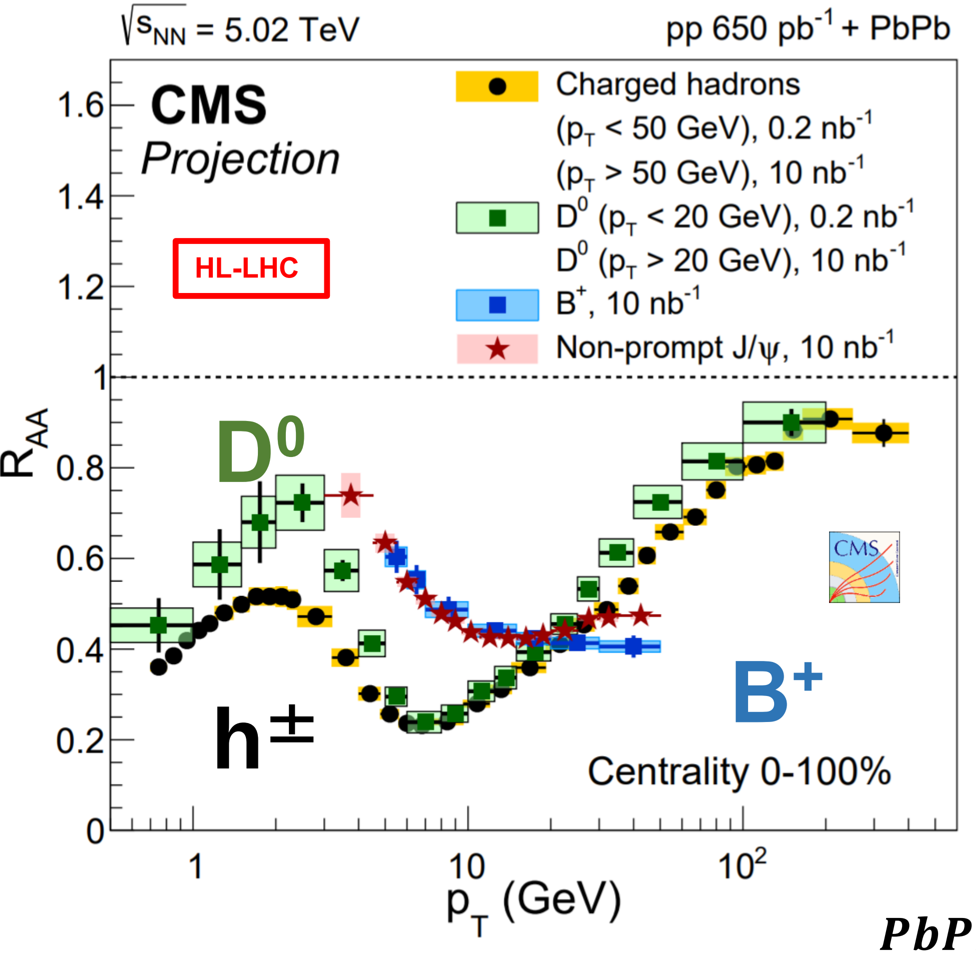
Phys. Lett. B 797 (2019) 134826



- Backup slides

Jet Quenching up to 1 TeV

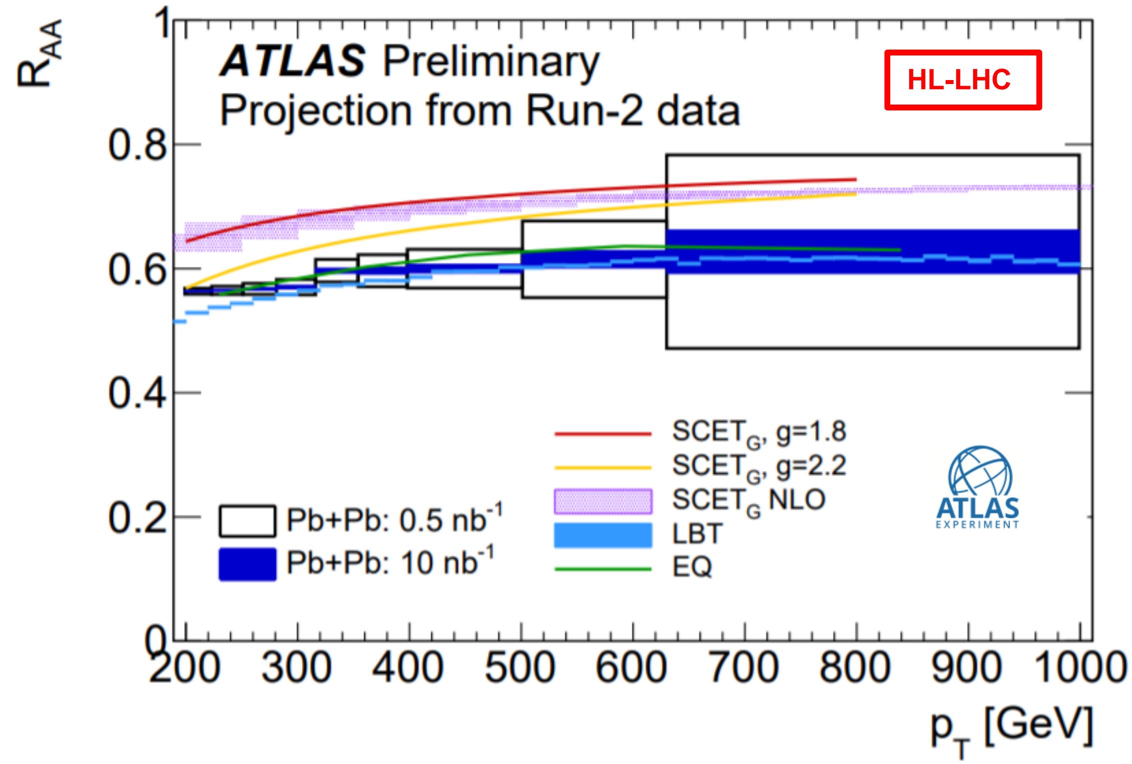
(Heavy Flavor)Hadron R_{AA}



$$R_{AA} \rightarrow \frac{PbPb}{pp}$$

- Precise measurement of light and heavy flavor hadron R_{AA} up to **0.4** to **1 TeV**

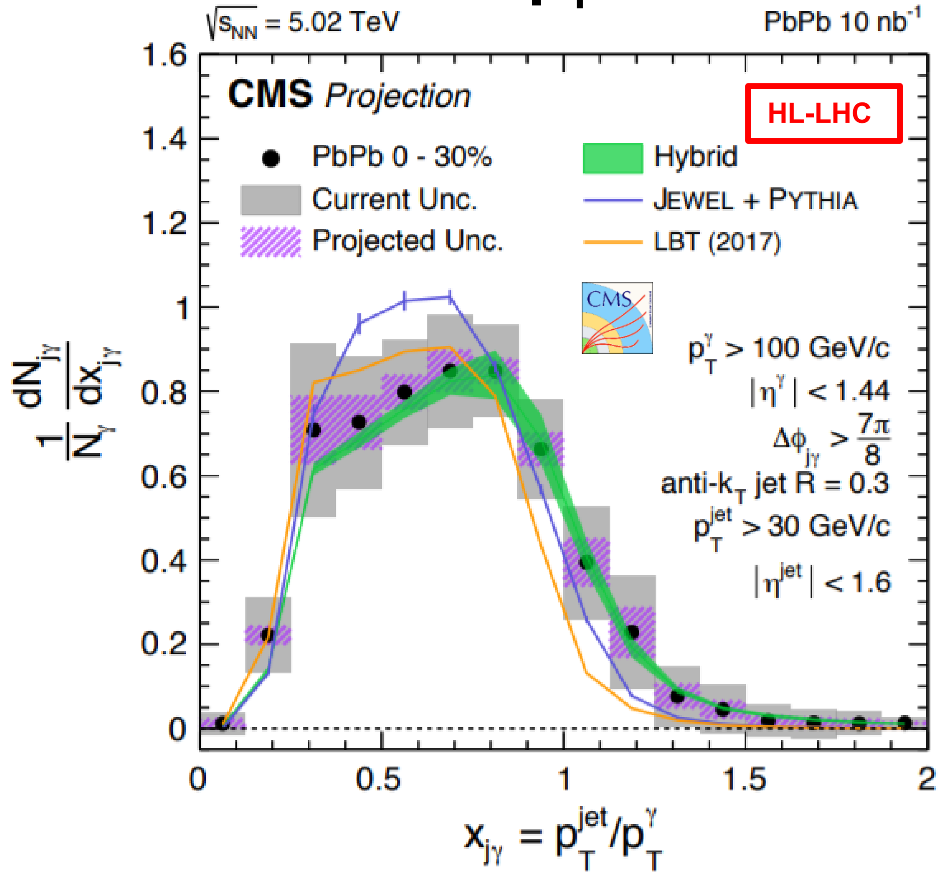
Jet R_{AA}



- High p_T reach of charged hadrons and jet R_{AA} up to **~ 1 TeV**
- The excitement is that the quenched energy will be significant compared to underlying event energy density!

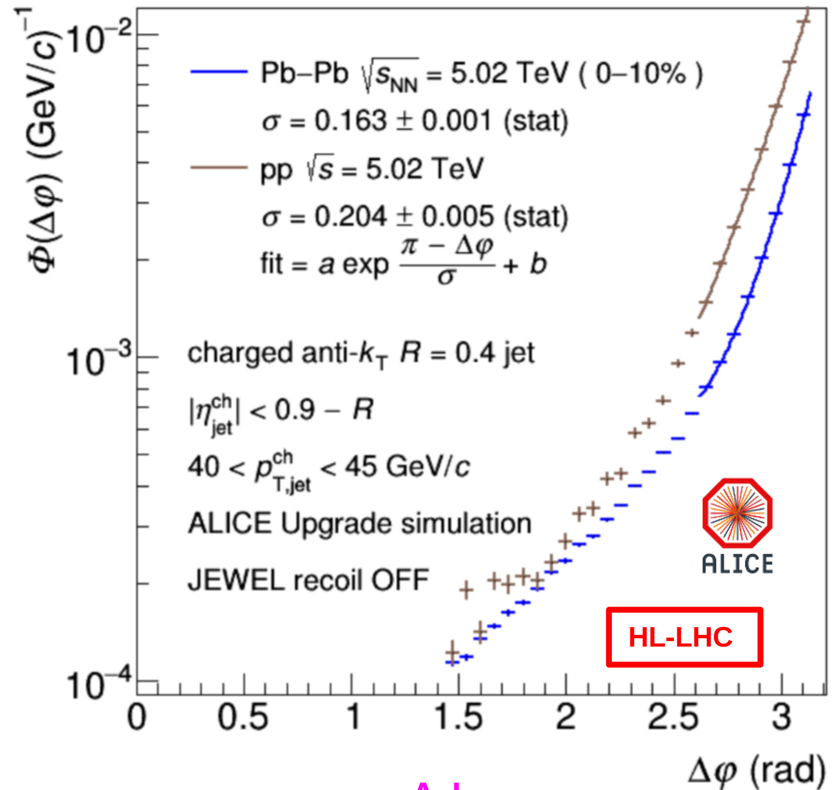
Photon-Jet and Hadron-Jet Correlations

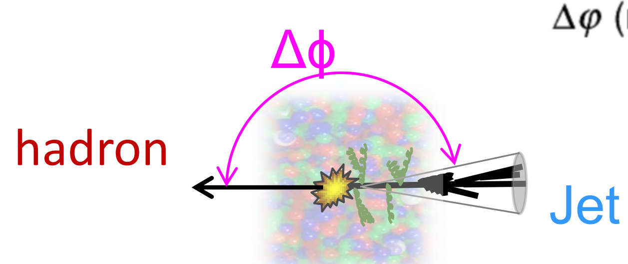
Photon-Jet p_T Ratio



Transverse momentum conservation

Hadron-Jet Correlation

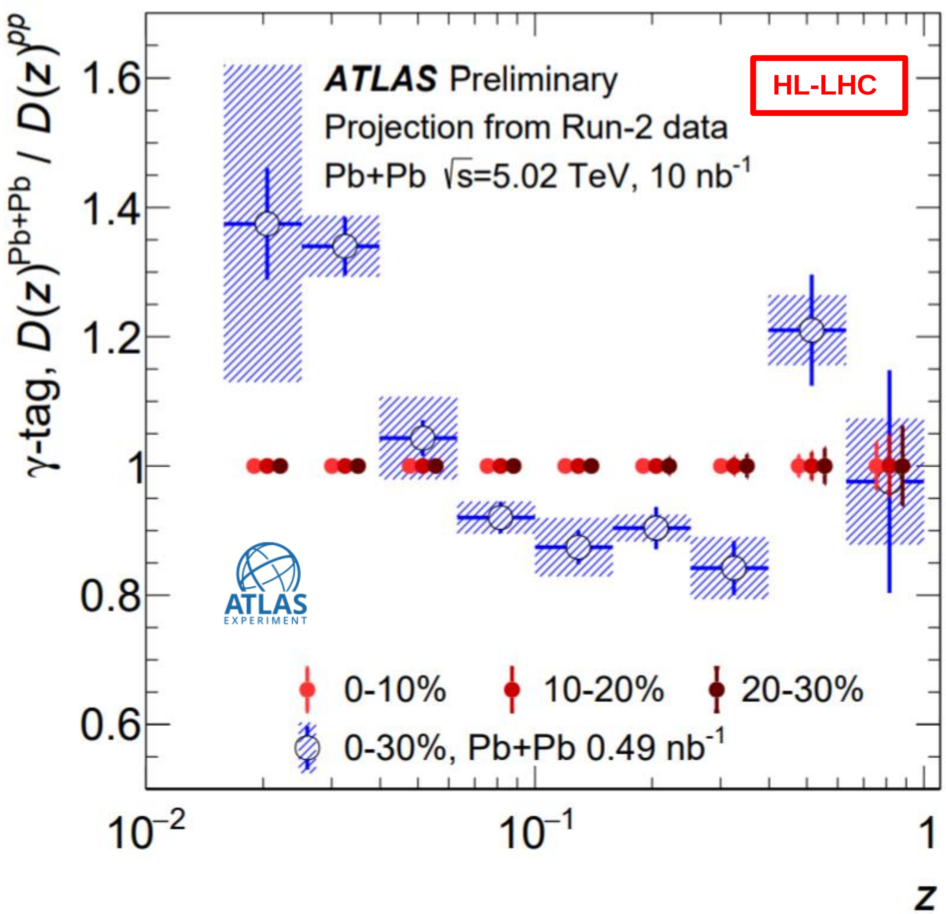




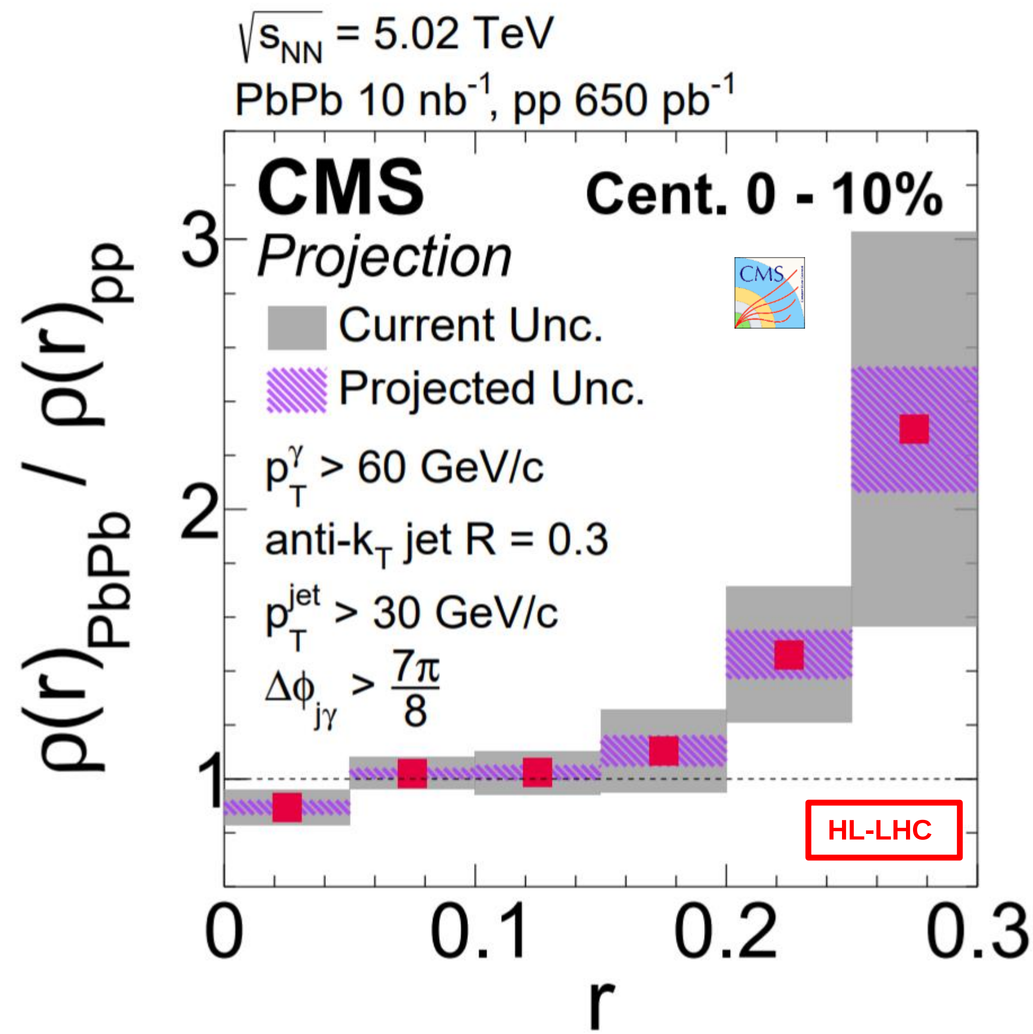
- Quenching reduces boson-jets p_T ratio
- High precision "**absolute energy loss**" measurement at HL-LHC
- Hadron-Jet Angular Correlation: search for **large angle scattering**, study of QGP substructure

Photon-Tagged Jet Structure

Modification of Jet Fragmentation Function

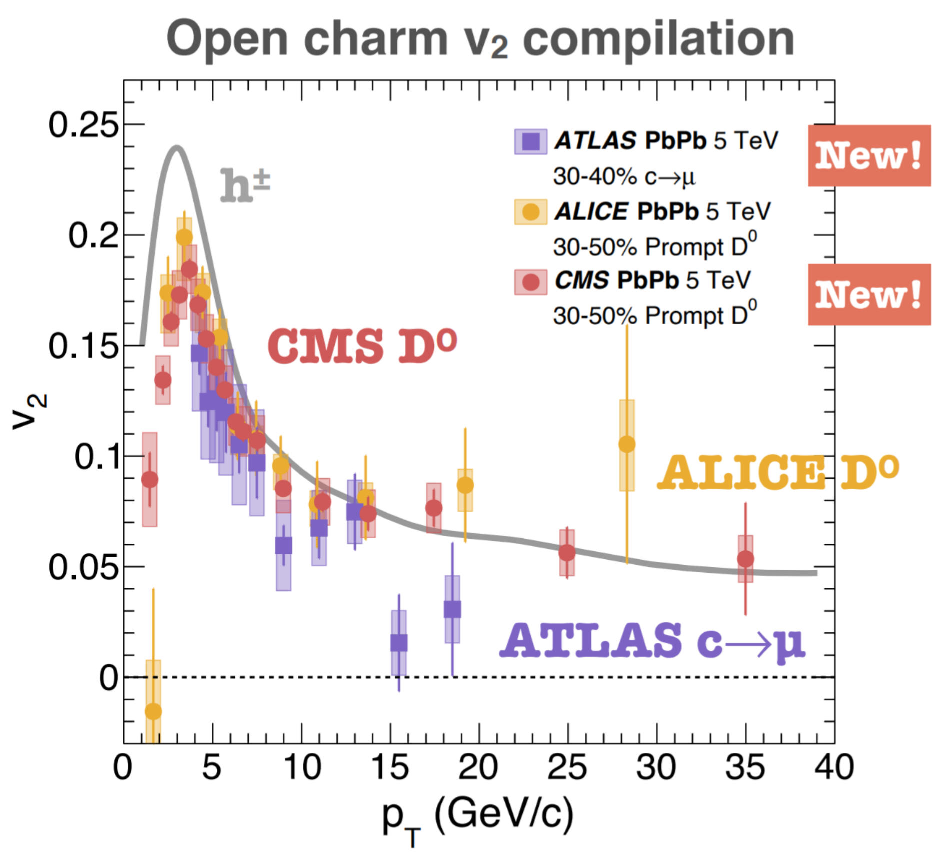


Modification of Jet Shape



- High precision measurement of photon-tagged jet substructure
- Study of medium response and "jet thermalization"

Open heavy flavor v2 preliminary results (QM'19)



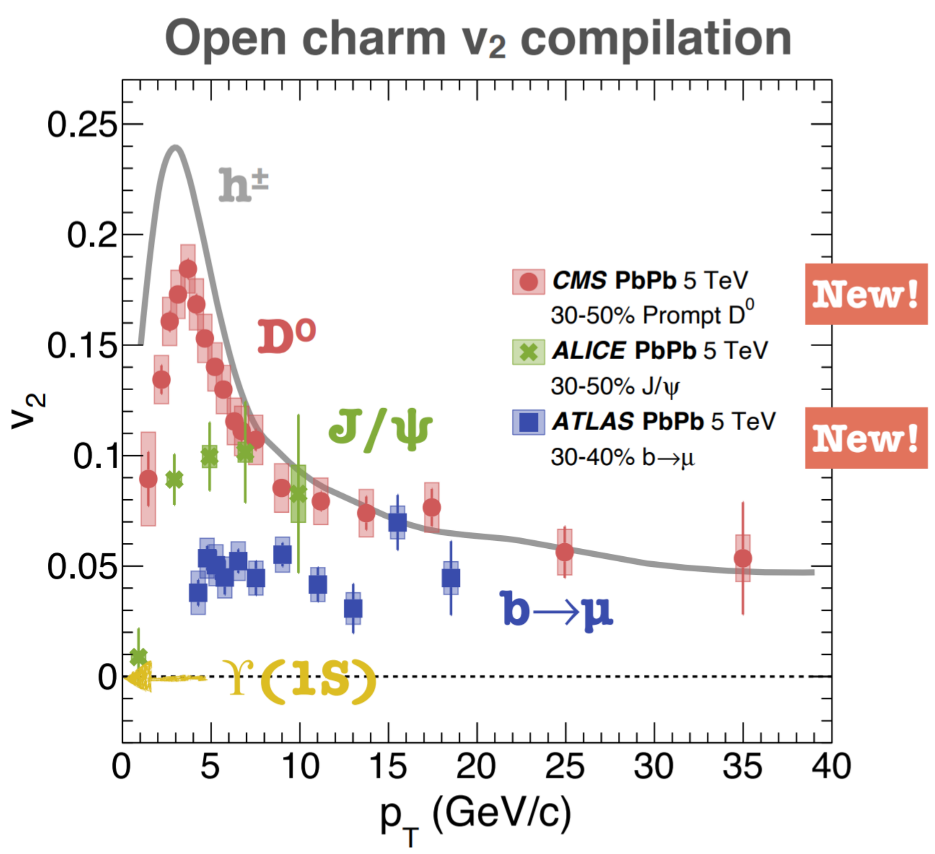
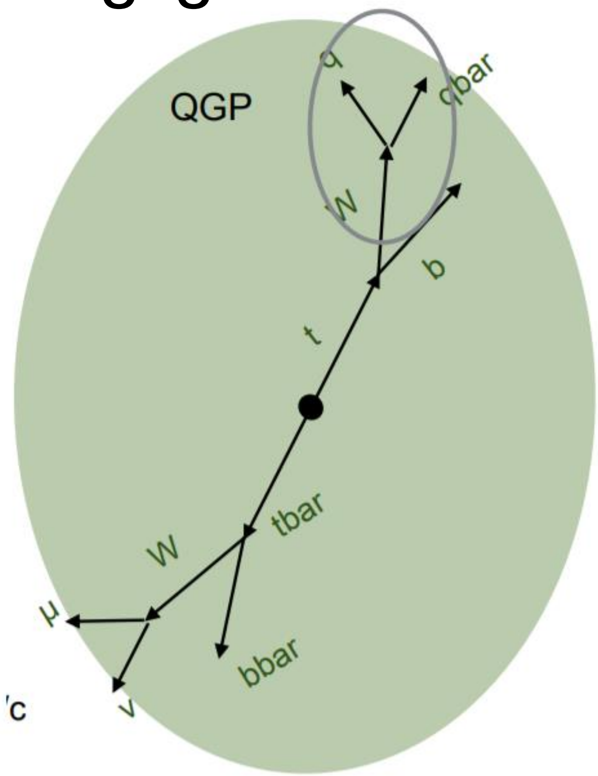


Figure from Jing Wang

Modification of W mass in Top event

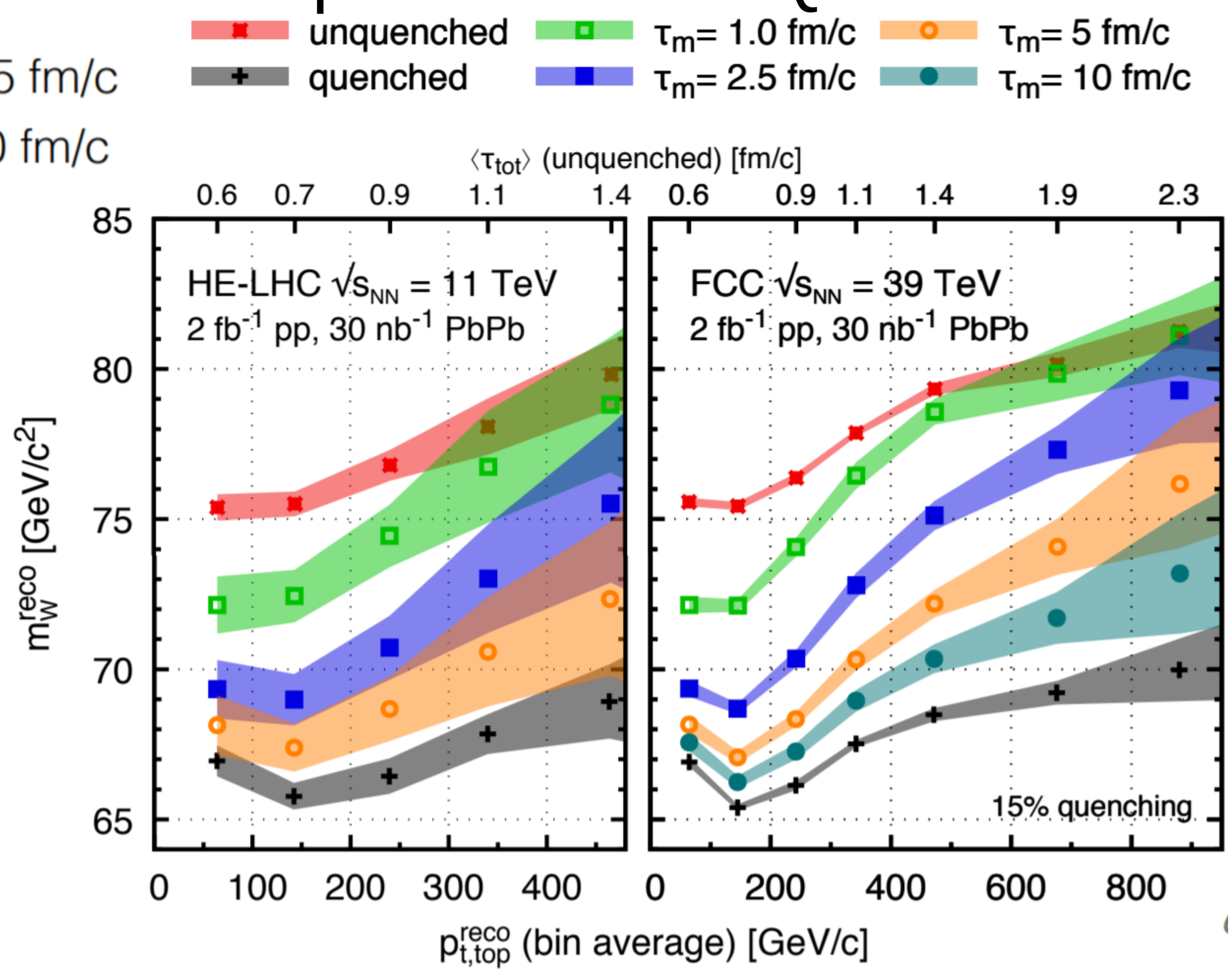
Negligible interaction between Top / W and the QGP



τ_{top}=0.15 fm/c

τ_W=0.10 fm/c

τ_m : quenching end time

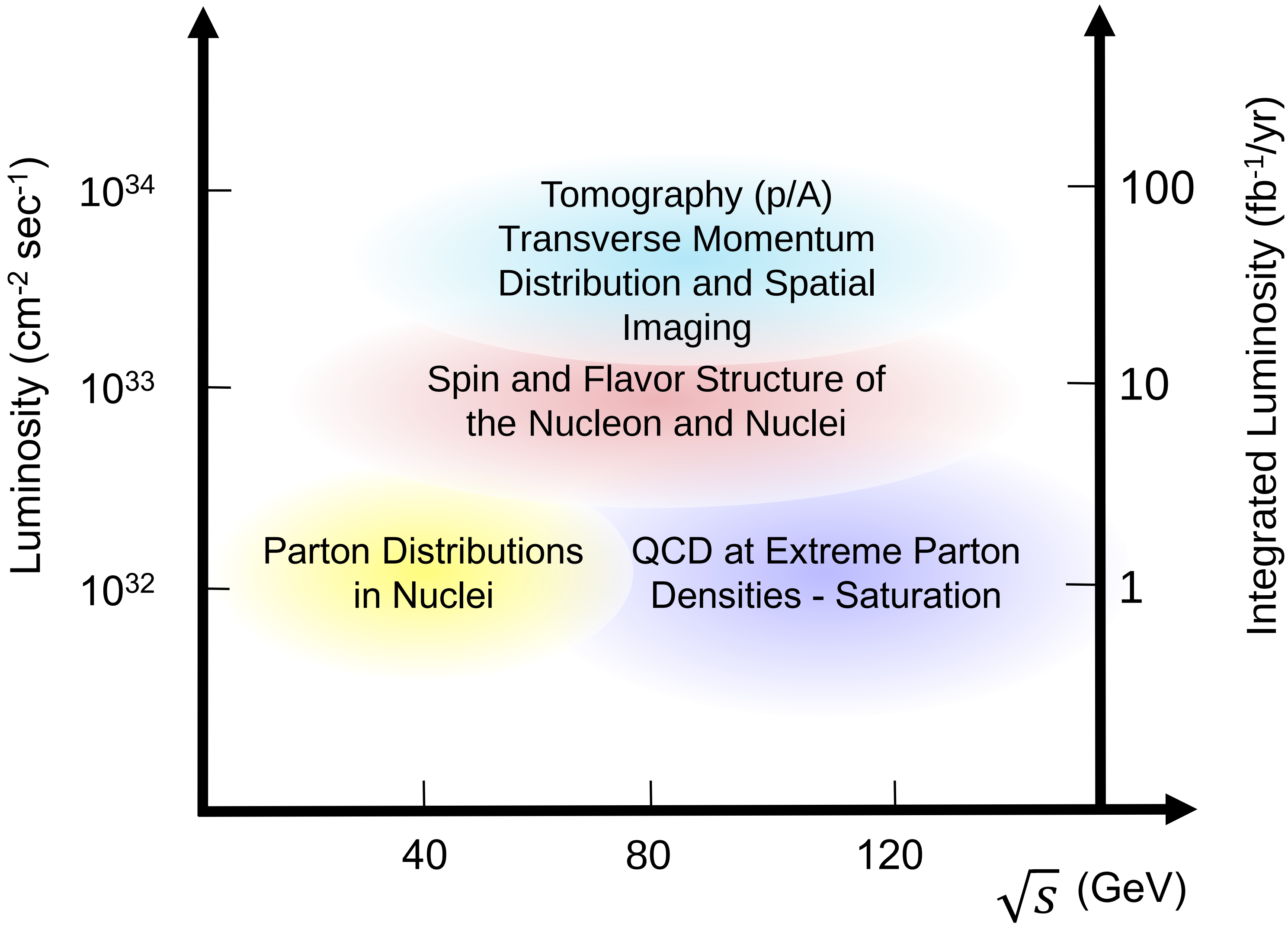


- Longer total delay time of the W (τ_{tot}) leads to smaller modification of W mass in heavy ion collisions
- Probe the "start" and "end" time of the QGP!!

"A Yoctosecond Chronometer." (Gavin Salam)

The EIC Physics Pillars

- EIC: Study structure and dynamics of matter at **high luminosity, high energy** with **polarized beams** and wide **range of nuclei**



EIC CD0 and Site Selection

- Announcement by the Department of Energy on January 9, 2020

https://www.energy.gov/articles/us-department-energy-selects-brookhaven-national-laboratory-host-major-new-nuclear-physics

Department of Energy

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

WASHINGTON, D.C. – Today, the U.S. Department of Energy (DOE) announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility. The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between \$1.6 and \$2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the “strong force” that binds the atomic nucleus together.

The EIC’s high luminosity and highly polarized beams will push the frontiers of particle accelerator science and technology and provide unprecedented insights into the building blocks and forces that hold atomic nuclei together. Design and construction of an EIC was recommended by the National Research Council of the National Academies of Science, noting that such a facility “would maintain U.S. leadership in nuclear physics” and “help to maintain scientific leadership more broadly.” Plans for an EIC were also endorsed by the federal Nuclear Science Advisory Committee.

Secretary Brouillette approved Critical Decision-0, “Approve Mission Need,” for the EIC on December 19, 2019. “The Department is excited to be moving forward with an Electron Ion Collider at Brookhaven National Laboratory,” stated **Office of Science Director Dr. Chris Fall**. “However, participation from many parts of the DOE laboratory complex will be essential if the EIC is to be a success.”
Thomas Jefferson National Accelerator Facility in Newport News, VA will be a major partner in realizing the EIC, and several other DOE laboratories are expected to contribute to EIC construction and to the groundbreaking nuclear physics research program that will be accomplished there.

Engagement in SnowMass2021 process

EIC program provides excellent opportunities for HEP community such as QCD and electro-weak physics in addition to novel instrumentation applications.

The EIC User group is committed through the EICUG Steering Committee to engage in the process of formulating Letters of Interest for various working groups including EF04, EF05, EG06 and EF07, besides Instrumentation Working Groups. Several informal discussions took place between the EICUG Steering Committee and several co-conveners.

The EICUG Steering Committee is committed to help this process to ensure that EIC-related submissions are consistent with the overall EIC planning of a new collider facility in the US at Brookhaven National Laboratory in cooperation with the DOE Office of Nuclear Physics.