Future Plan from CMS

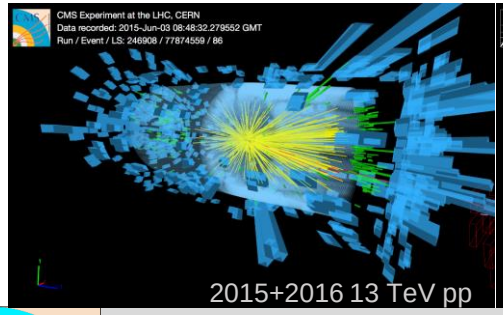
Yen-Jie Lee

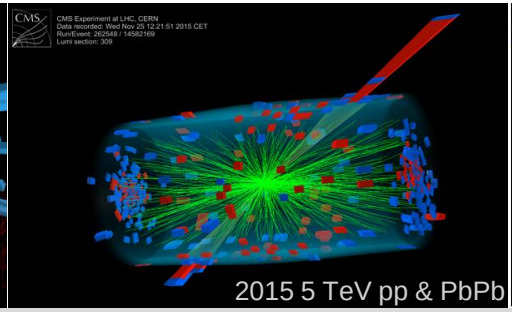
For the CMS collaboration

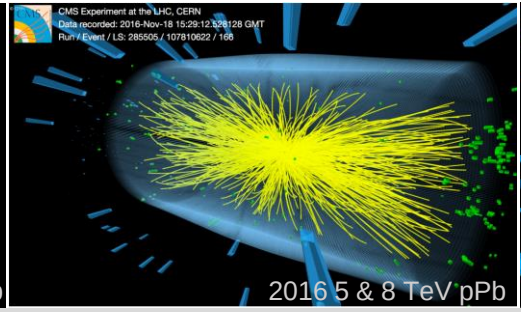
Town meeting: Relativistic Heavy ion physics 2018

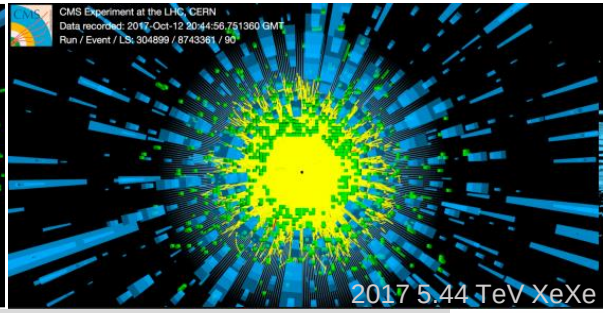
CERN, Geneva, Switzerland

24 October, 2018

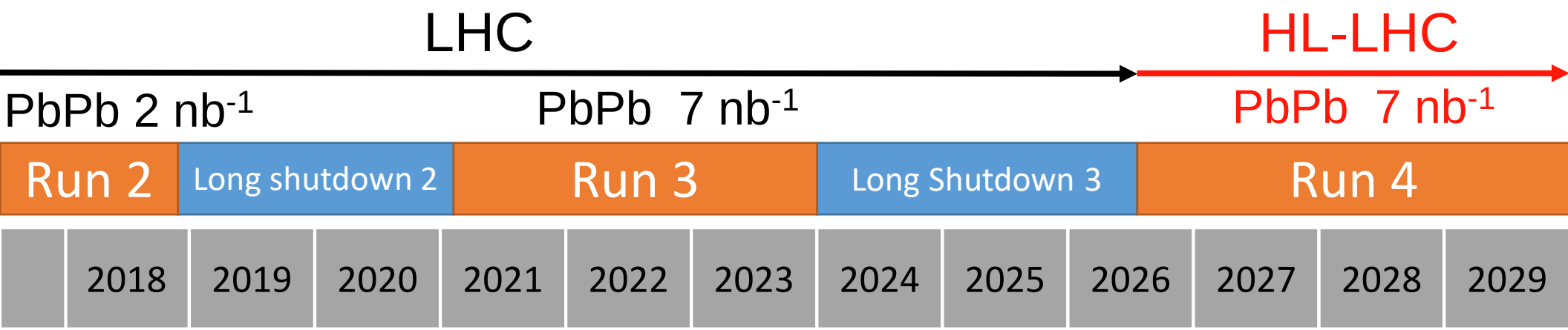








LHC Timeline and CMS Upgrade

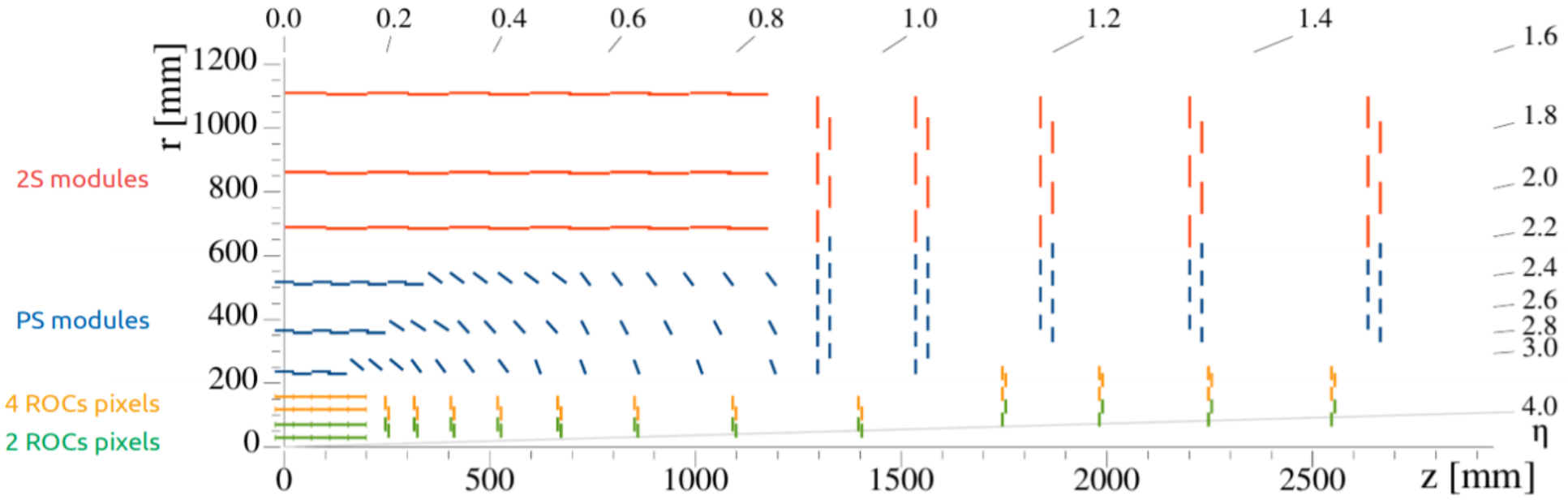


- 2016: Major upgrade of L1 trigger
- 2017: 4-Layer Pixel Detector
- 2018 Performance:
  - pp L1 100kHz
  - PbPb L1 **30kHz** (3x of 2015)
  - DAQ: 6 GB/s
    - Up to **6.5 kHz** MinBias events to tape (20x of 2015)

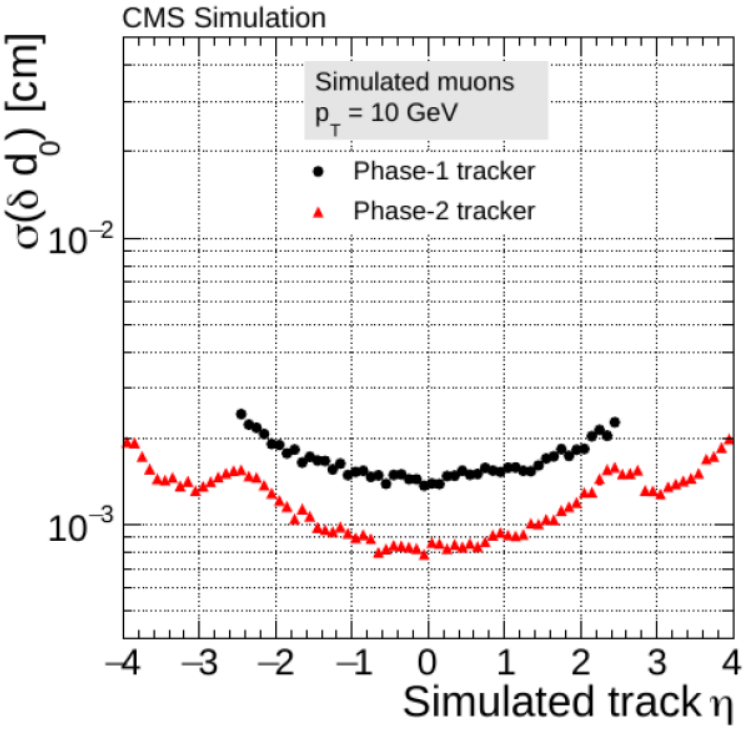
2024-26

- Tracker **|η|<4**
- Muon ID up to **|η|<3**
- High Granularity Calo **1.6<|η|<3.0**
- MIP timing detector
  - 4D vertexing
  - Possible p/K/π PID
- pp L1: 750 kHz
- DAQ: 60 GB/s

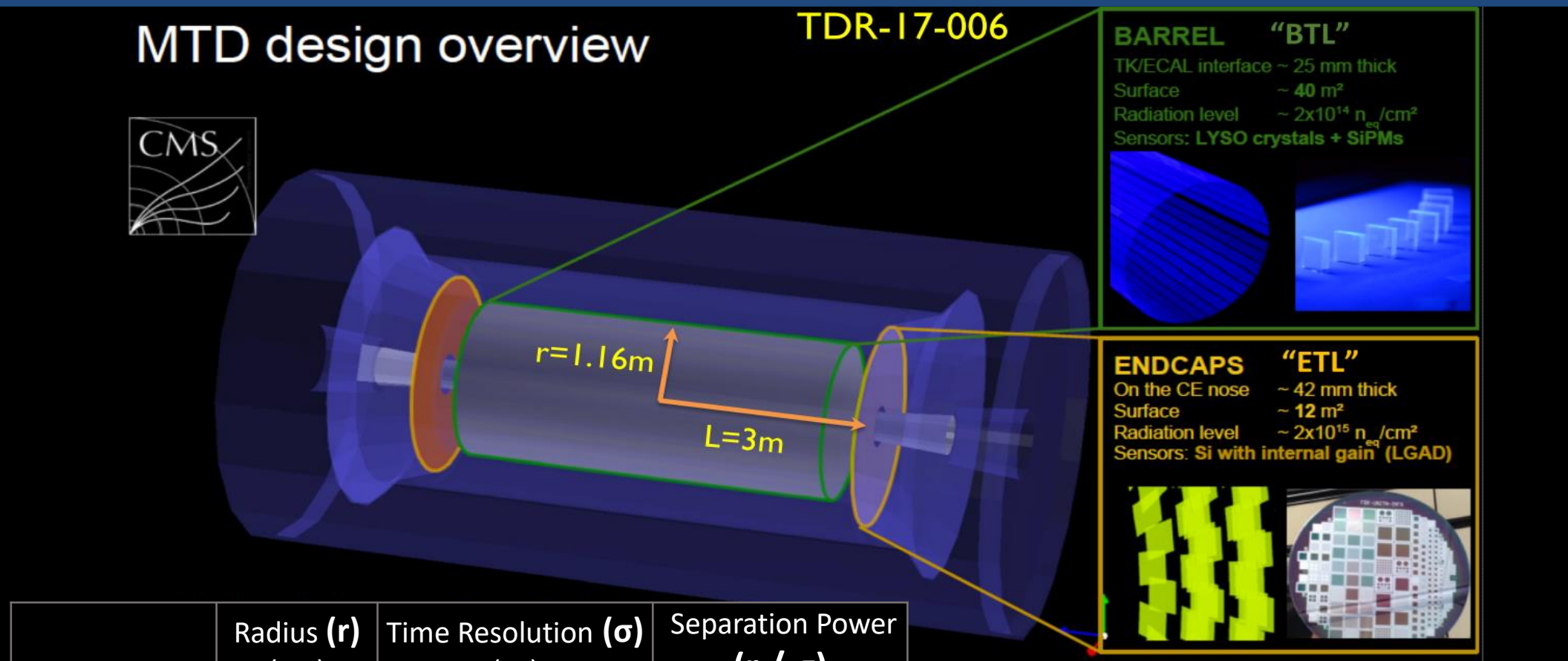
Phase 2 CMS Tracking System



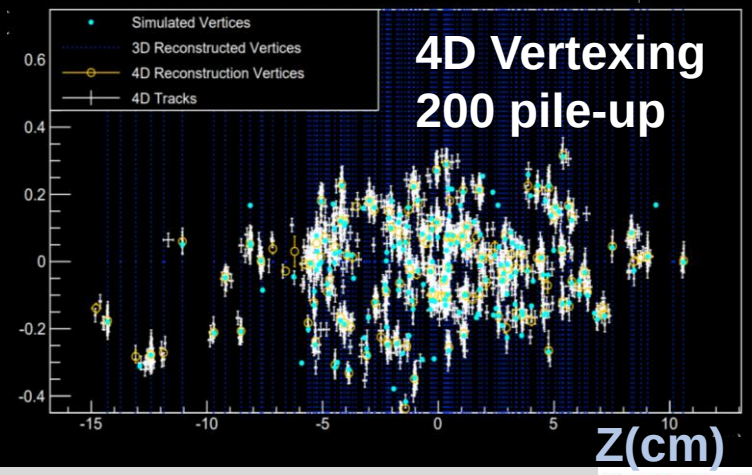
- Installation before Run 4
- Charged particle reconstruction up to **|η|<4**
- At <Pile-Up>=200 (heavy-ion like):
  - Efficiency > 90%, fake rate < 3%
- Significantly better p_T and d_0 resolution
  - Improvement on heavy flavor meson and b/c-jet tagging



Time of Flight with MIP Timing Detector



	Radius **(r)** (cm)	Time Resolution **(σ)** (ps)	Separation Power **(r / σ)**
STAR	220	80	2.75
ALICE	370	80	4.63
CMS-MTD	116	30	3.87



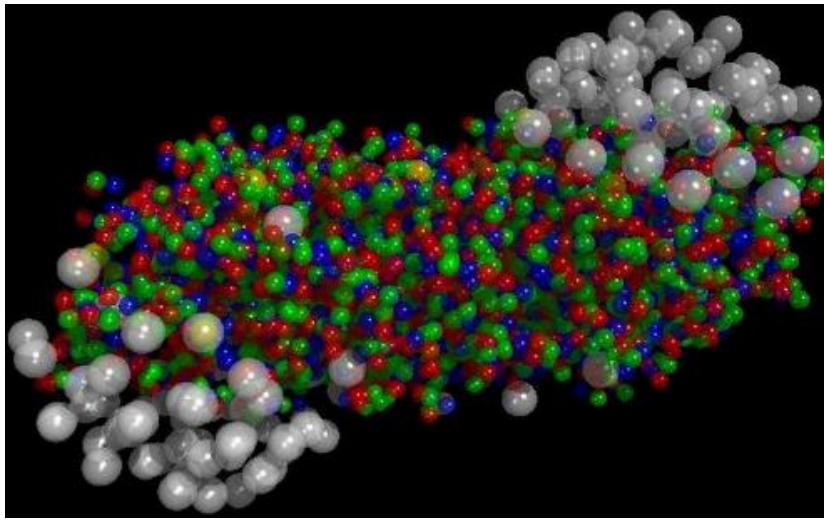
- 4D vertexing (x,y,**z**,**T**) in high PU pp collisions
- Possible p/K/π separation with $0.7<p_T<3$ GeV

Label

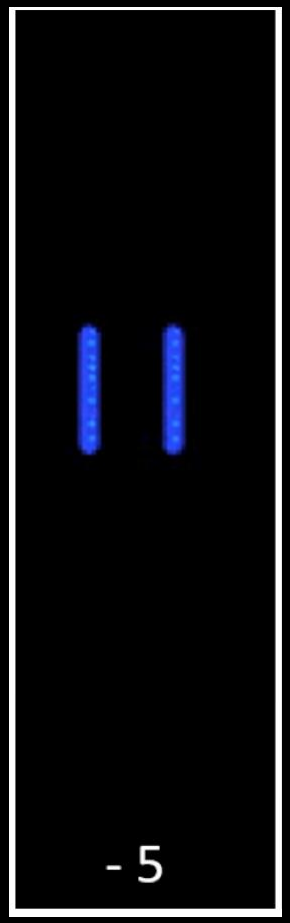
HL-LHC 10/nb of triggered PbPb sample and 0.2 /nb of MB PbPb data
2/pb of pPb data

Present Data CMS data taken up to 2017 (e.g. 0.5/nb of PbPb sample)

QCD Phase Diagram



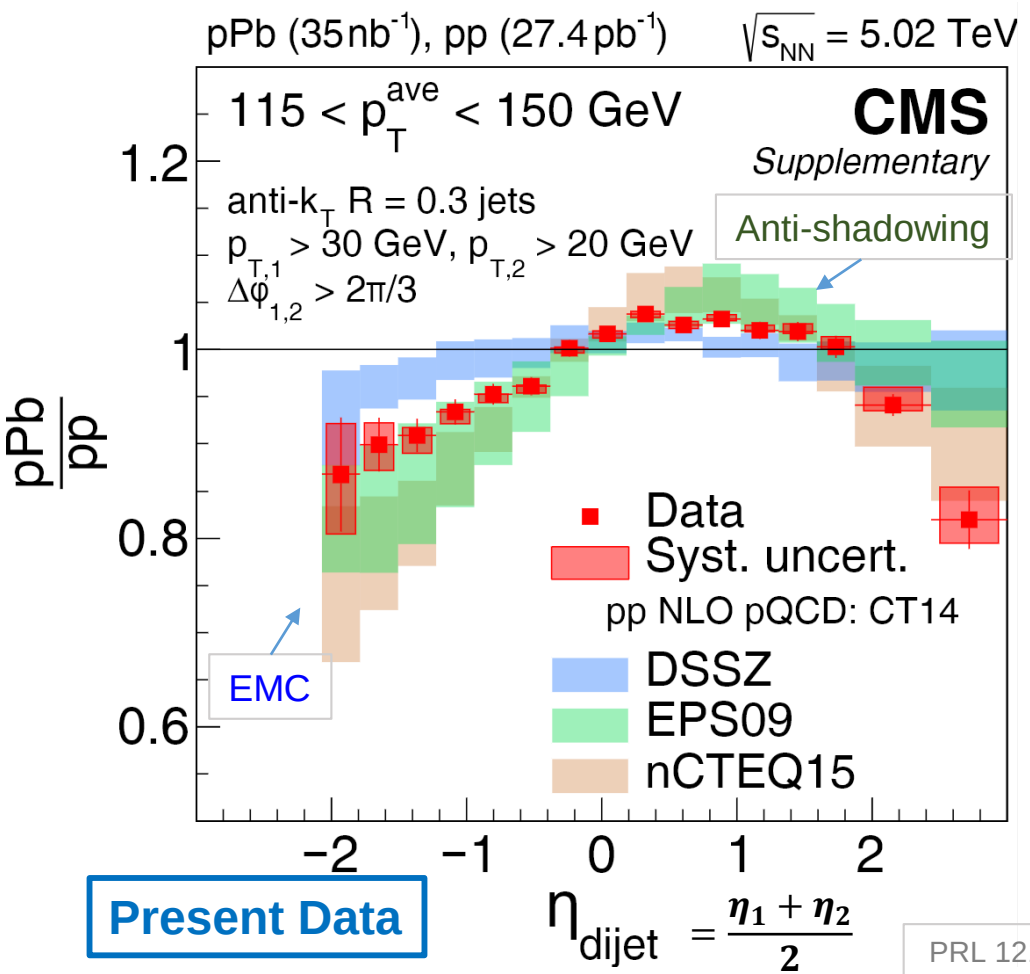
Relativistic Heavy Ion Collisions



Two discs of almost real quarks and gluons

Modification of PDF in Pb

Dijet average η in pPb

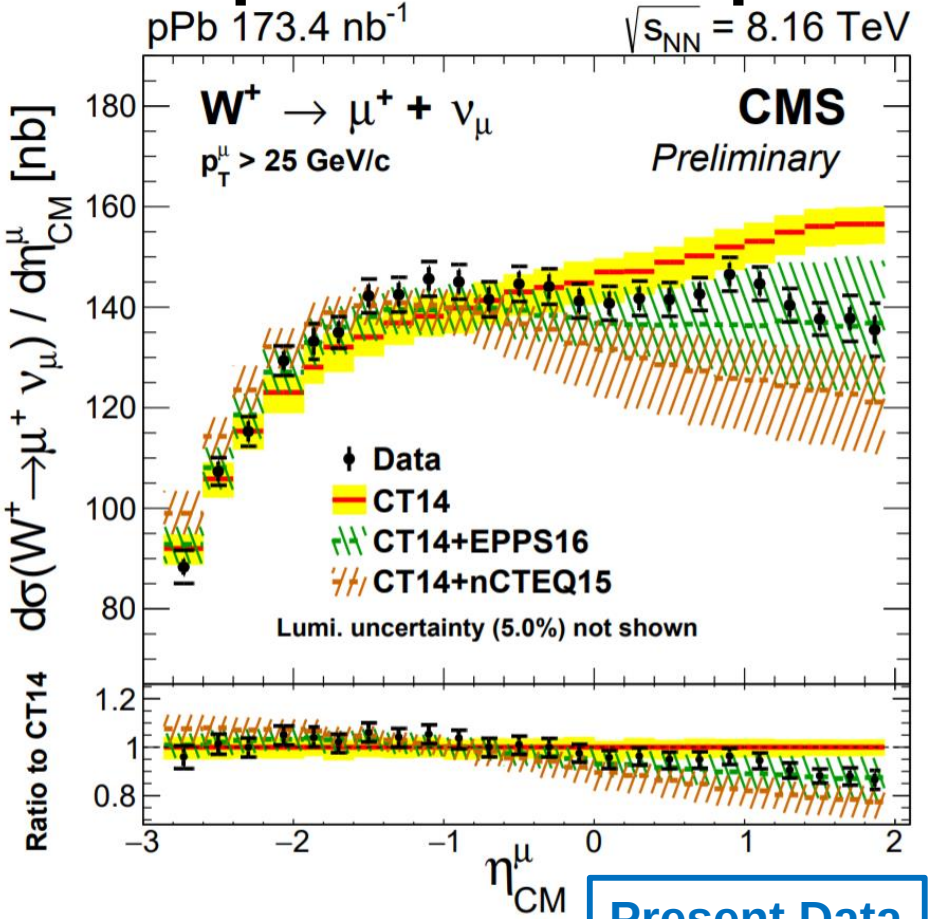


Present Data

PRL 121 (2018) 062002

- Evidence of gluon **anti-shadowing** and modification in the EMC region $x > 0.3$

W^+ production in pPb



Present Data

CMS-PAS-HIN-17-007

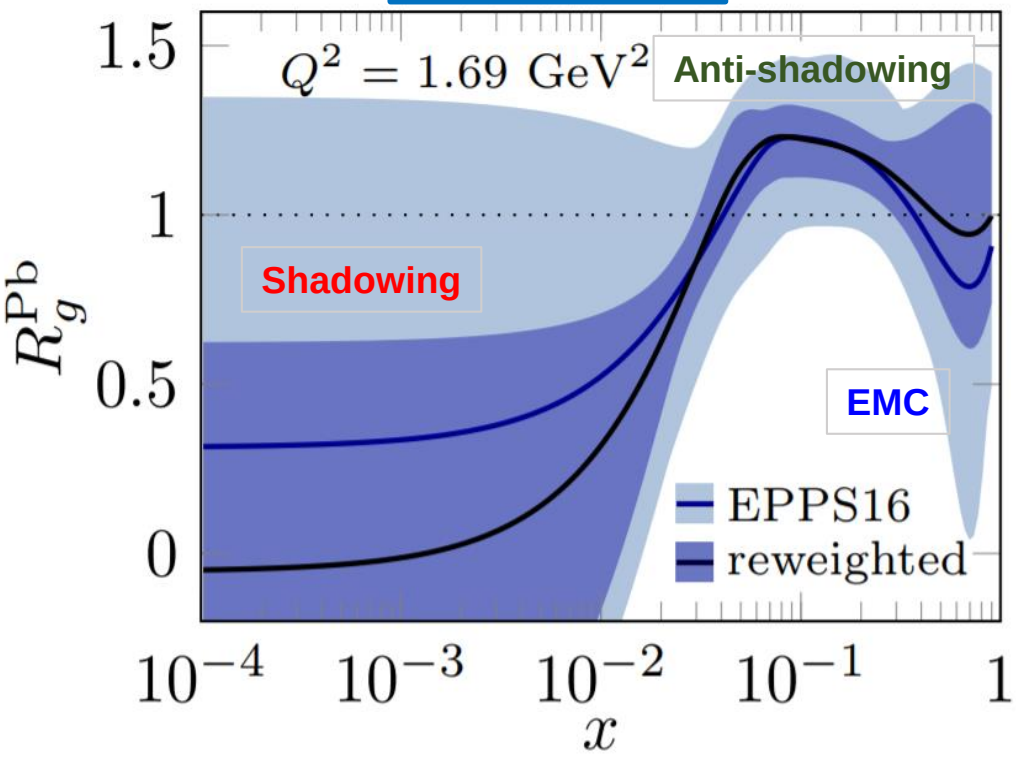
- Constrain quark PDF in Pb

Present W and dijet data are consistent with **EPS09** and **EPPS16**
Not compatible with **DSSZ**, **nCTEQ15** and **CT14** (nucleon)

Modification of PDF in Pb

Gluon nPDF from pPb dijet

Present Data

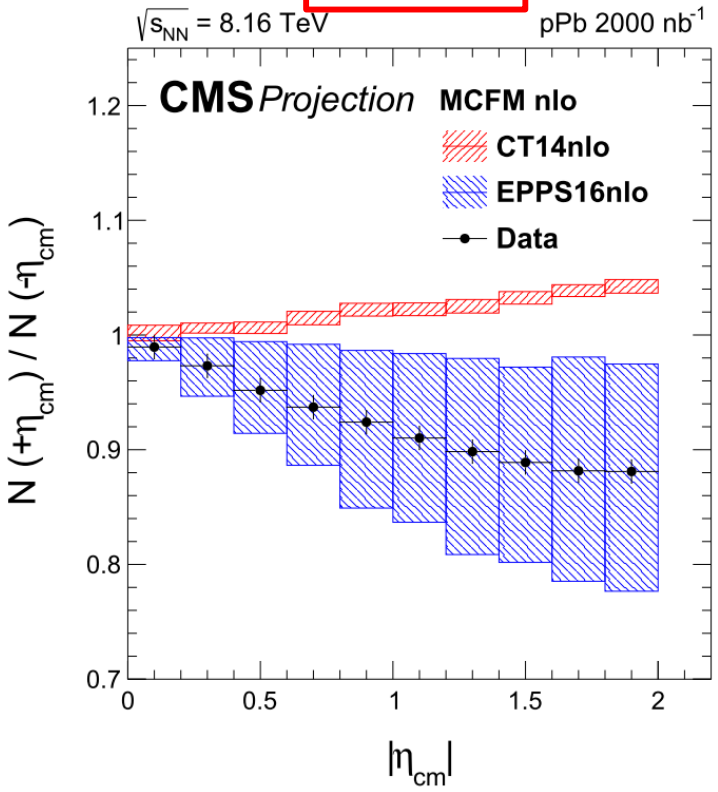


Petja Paakkinen HP'18

- Strong constraint on gluon PDF
- Half the **anti-shadowing region** uncertainty
- Prefer a deep shadowing and a EMC slope

W^+ production in pPb

HL-LHC



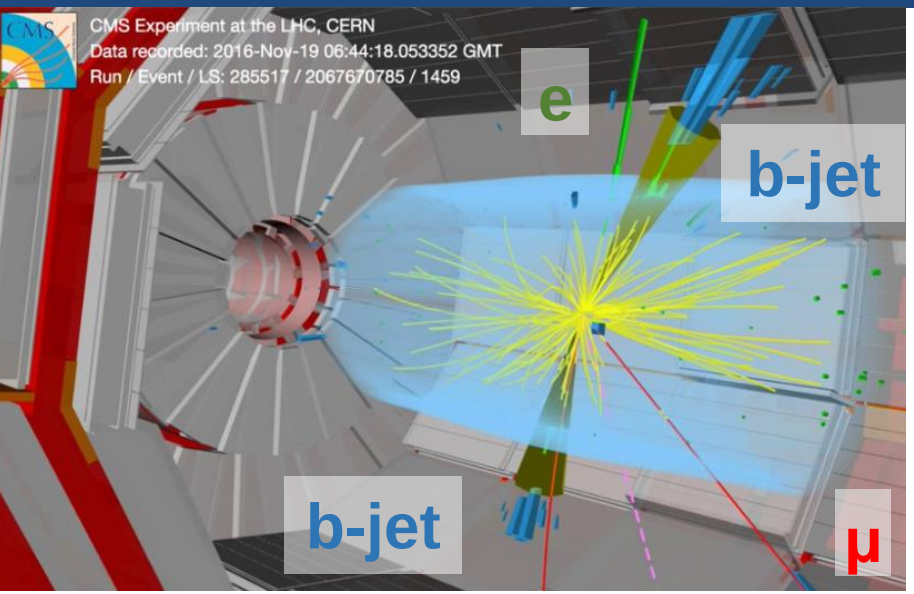
CMS-PAS-FTR-17-002

- Constrain quark PDF in Pb

Significantly more precise boson and (b-)dijet data in pPb at 8 TeV could provide stringent constraints on nuclear PDF

PRL 121 (2018) 062002

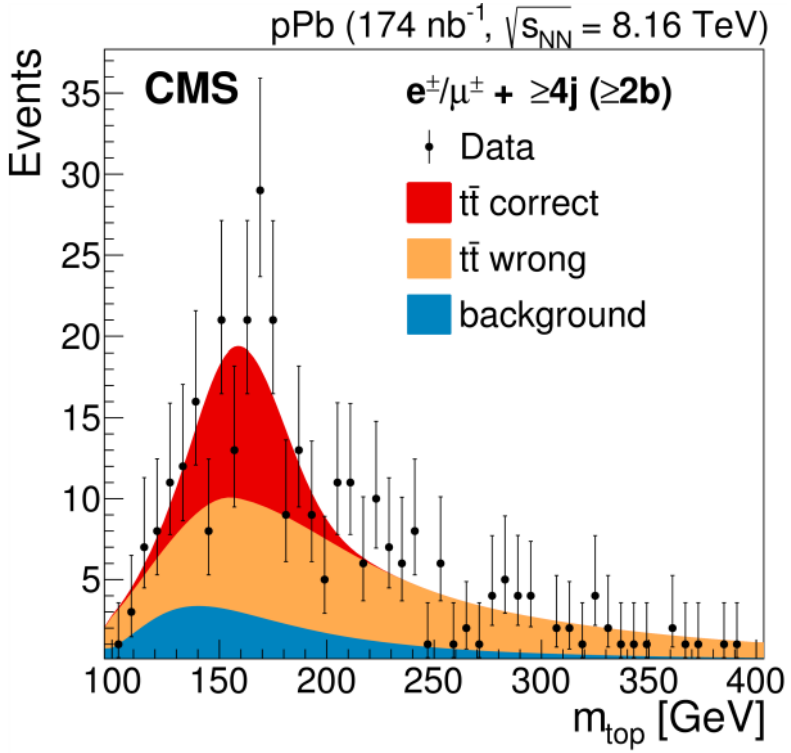
Observation of Top Production in pPb



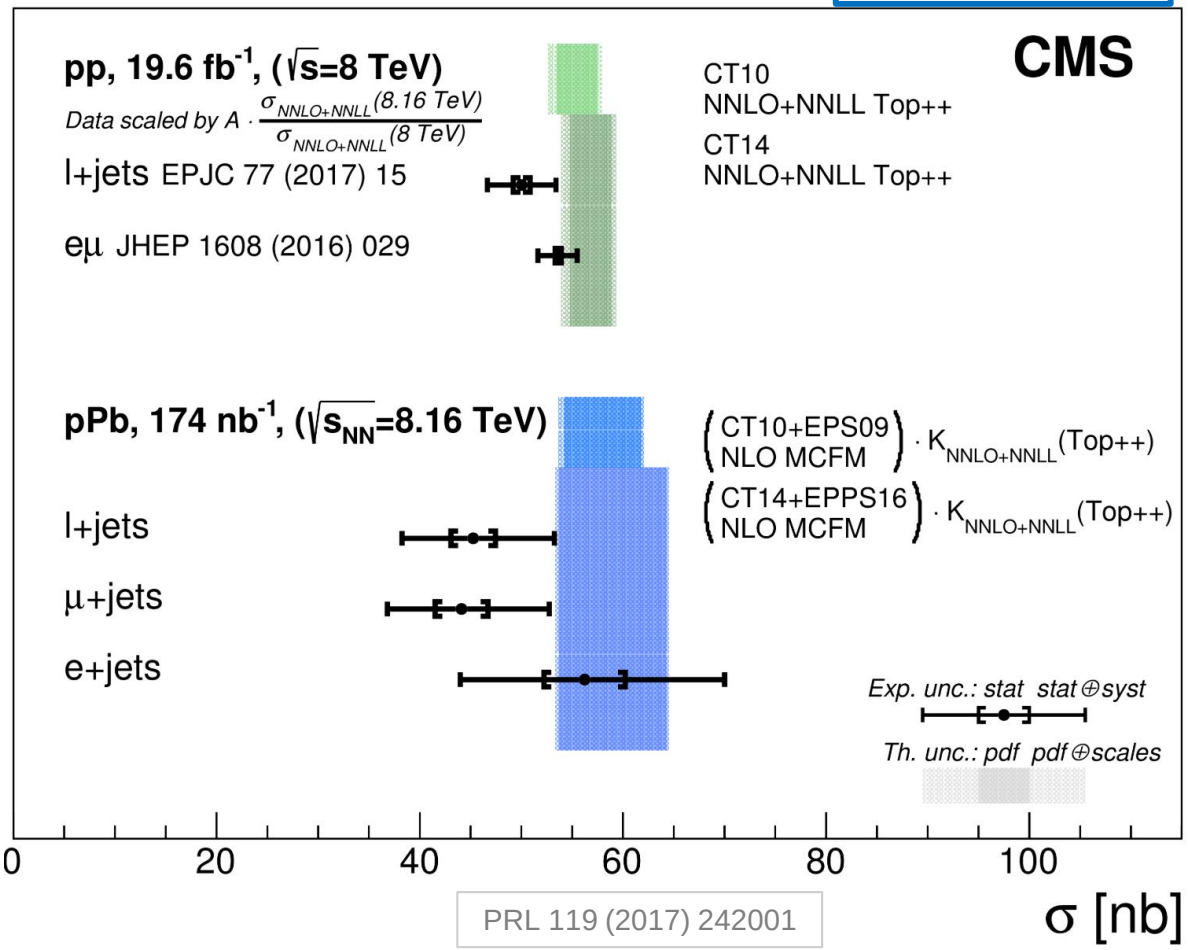
Top pair cross-section in **pPb** at 8.16 TeV

Compatible with pQCD calculations with nPDF

New constraint on gluon PDF at large x



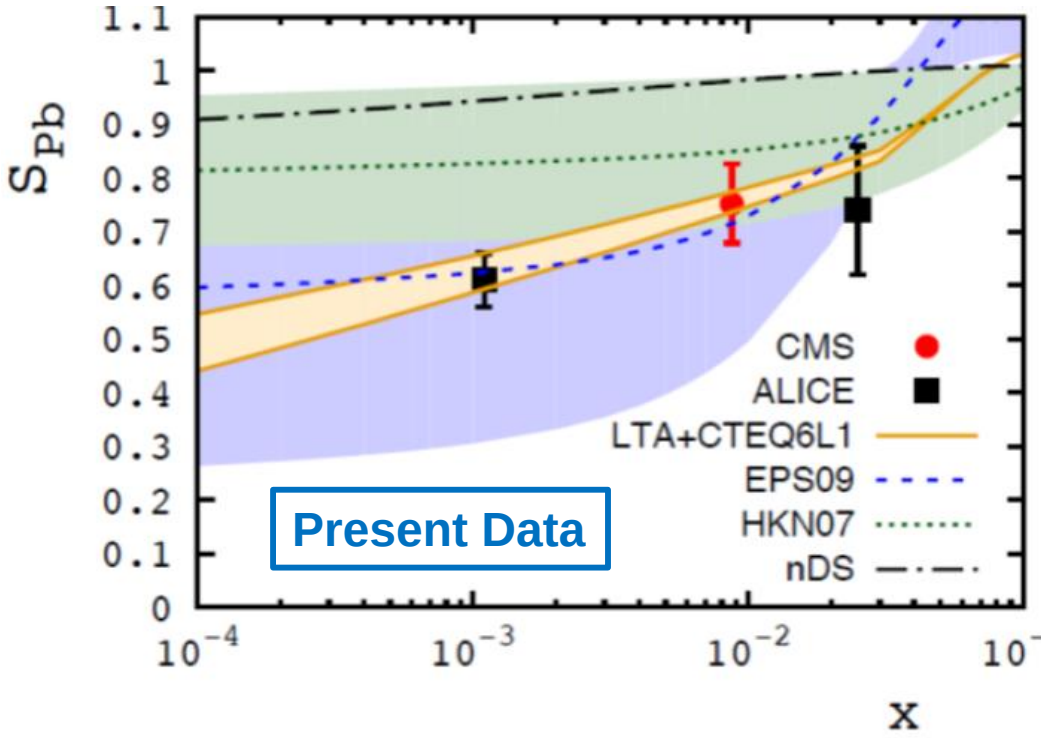
Present Data



PRL 119 (2017) 242001

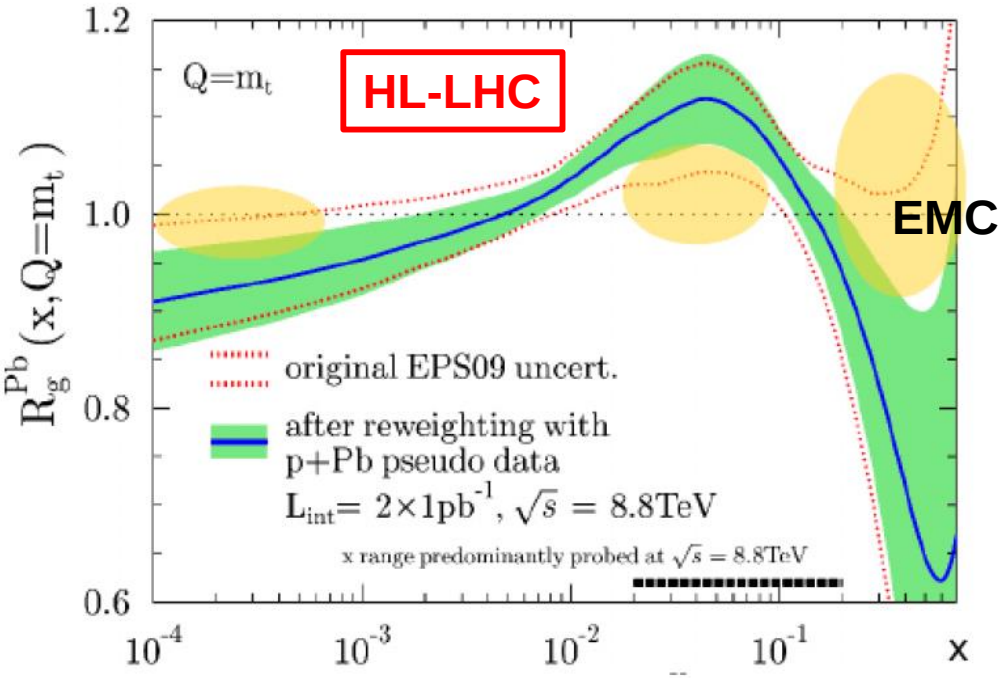
Constraint from PbPb UPC and Top in pPb

J/ψ in PbPb Ultra-Peripheral Collisions



- 2 pb^{-1} pPb data provide larger kinematics range
- Dijet and vector meson in UPC

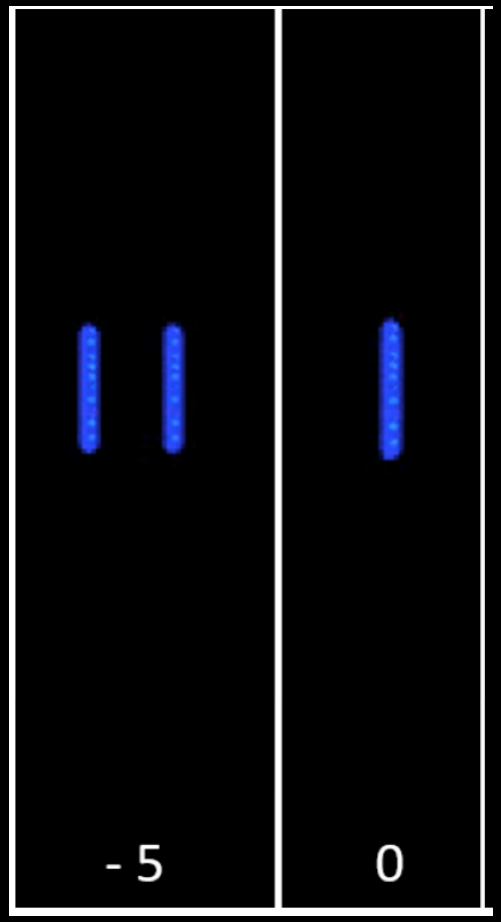
Constraining Power from Top in pPb



- Constraint on the gluon PDF (especially the **EMC region**)
- Complementary to dijets in pPb

Relativistic Heavy Ion Collisions

Collision! Highest energy density state. Huge amount of soft (low momentum transfer) scatterings.



Two discs of almost real quarks and gluons

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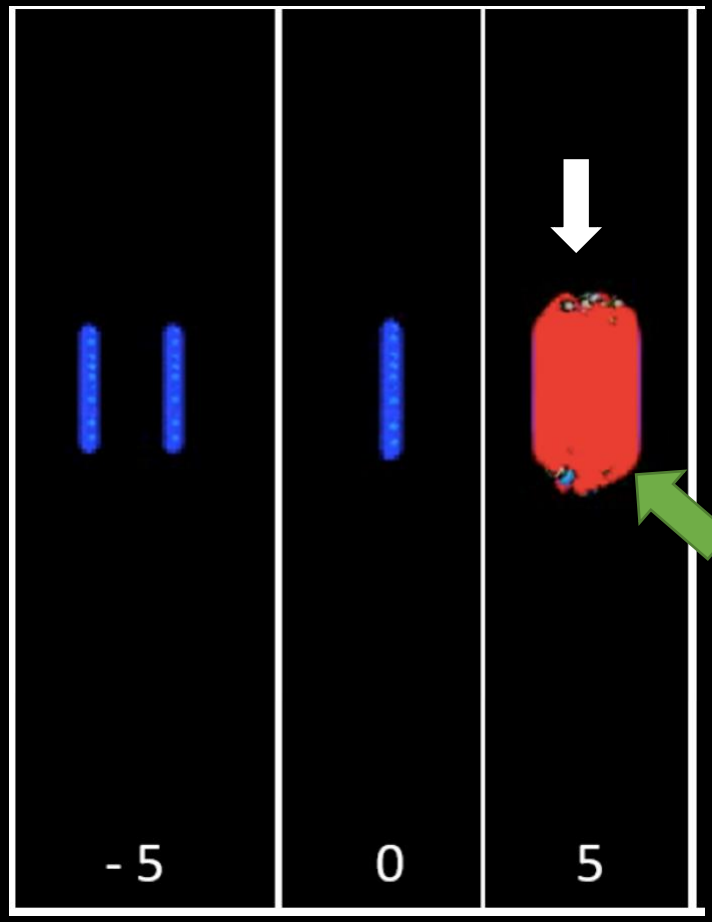


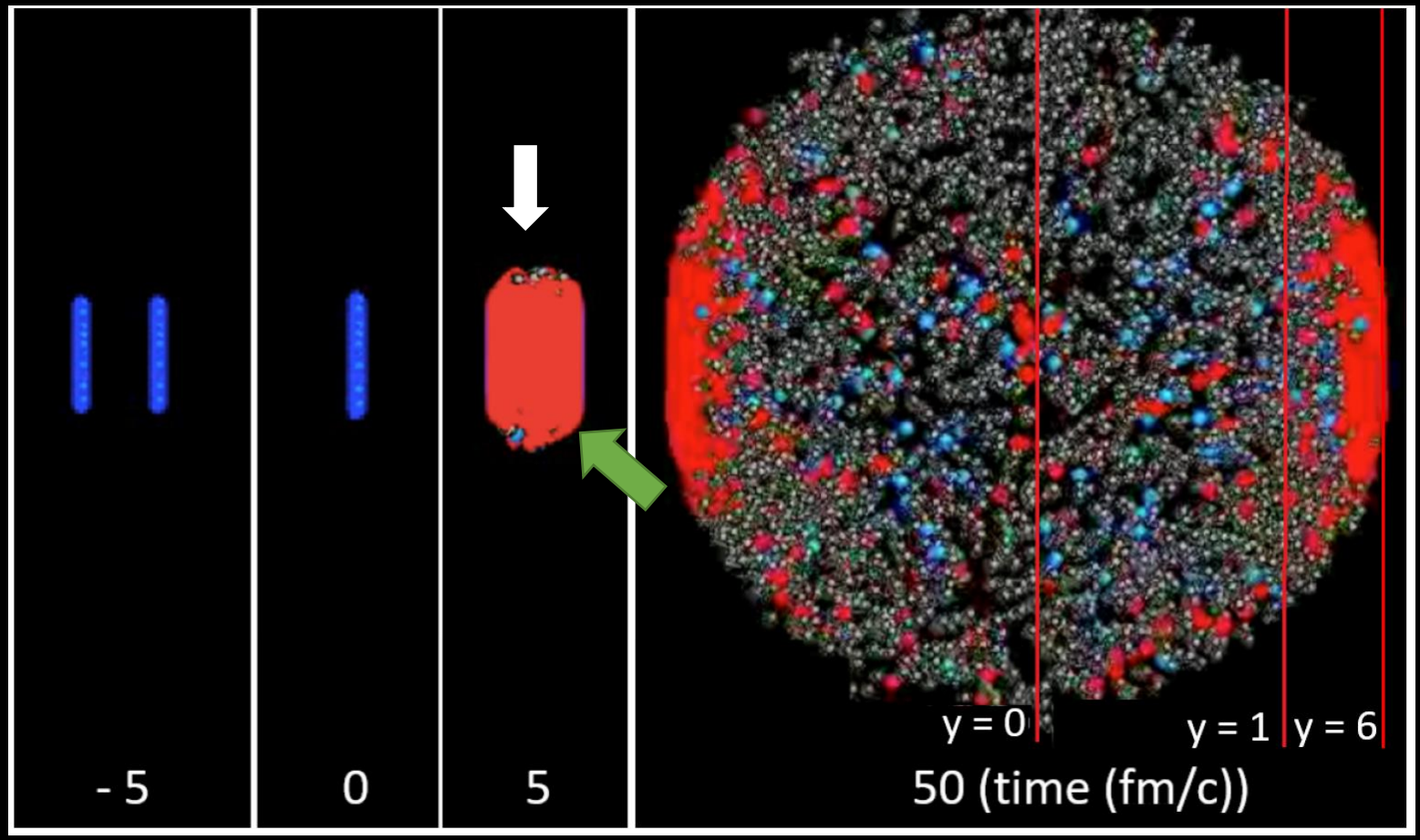
Two discs of almost real quarks and gluons

Midrapidity: thermalized QGP with very small baryon doping (μ_B)
Forward: QGP just created

Relativistic Heavy Ion Collisions

Collision! Highest energy density state. Huge amount of soft (low momentum transfer) scatterings.

Hadronization of QGP, different from elementary collisions like e^+e^- or pp collisions



Two discs of almost real quarks and gluons

Midrapidity: thermalized QGP with very small baryon doping (μ_B)
Forward: QGP just created

Based on particle correlation analyses, QGP is found to be consistent with
"Near Perfect Liquid"

Open Questions for Large System

- Why does the system hydrodynamize so fast? How does the strongly interacting medium emerge from an asymptotic free theory?
- What is the role of the pre-hydrodynamization phase? How big is the initial magnetic field? When is QGP formed?
- How does the QGP hadronize?
- What are the precise properties and inner workings of the QGP?

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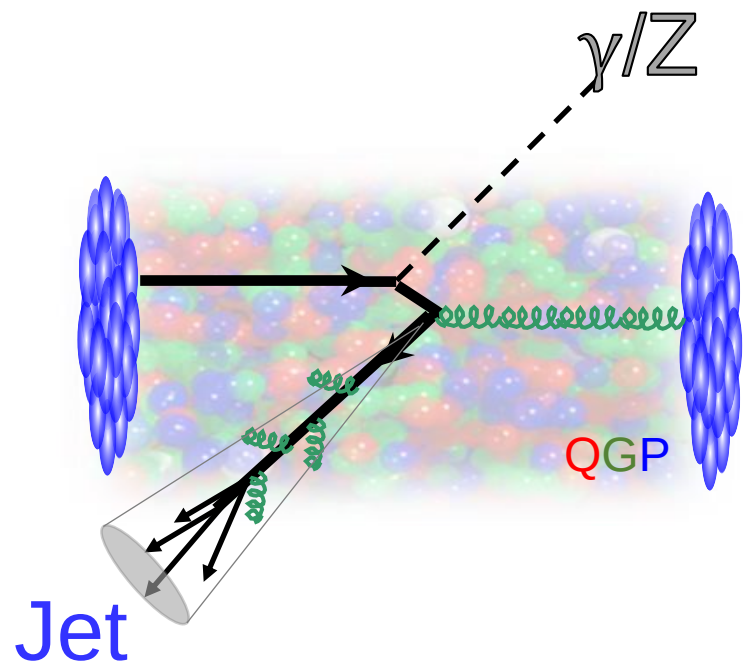
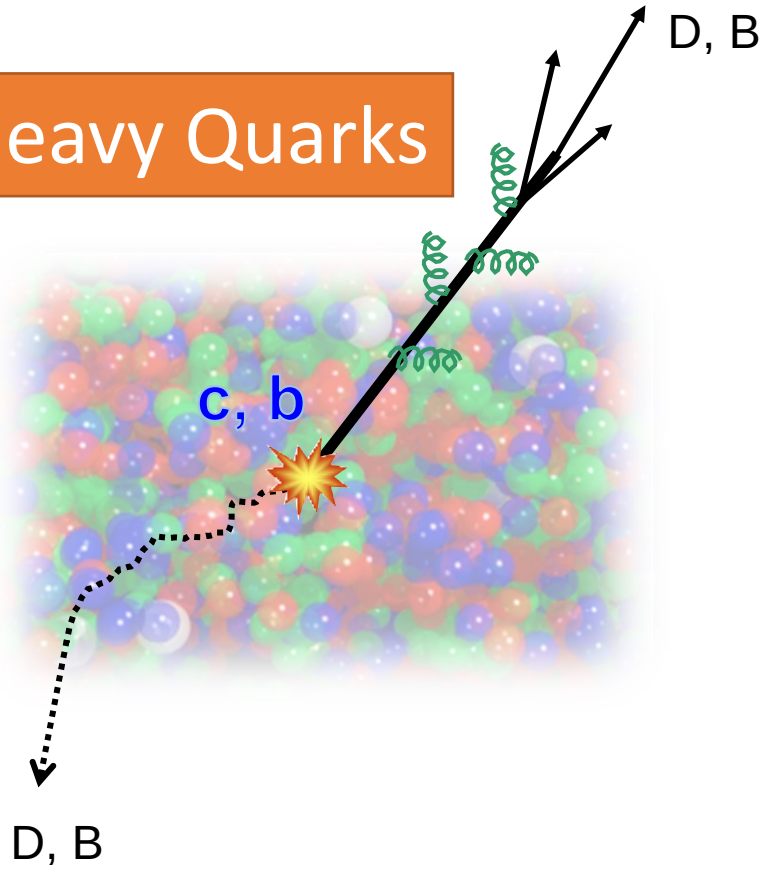
Hard Probes

Electroweak Bosons

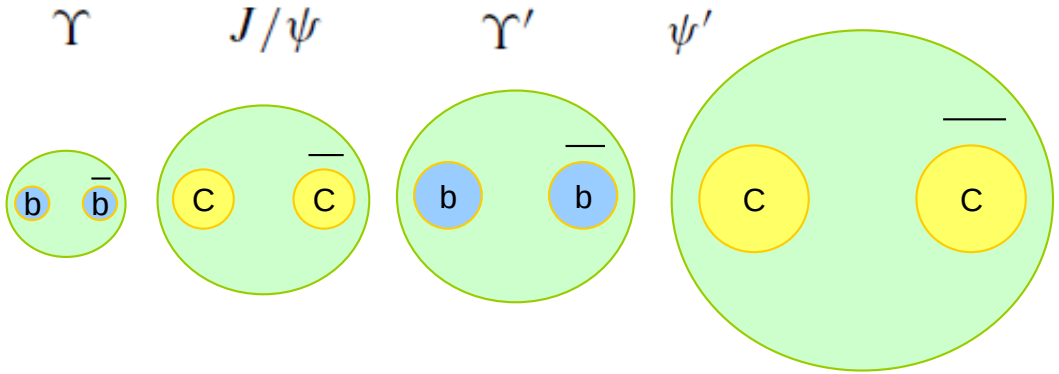


Jets

Heavy Quarks

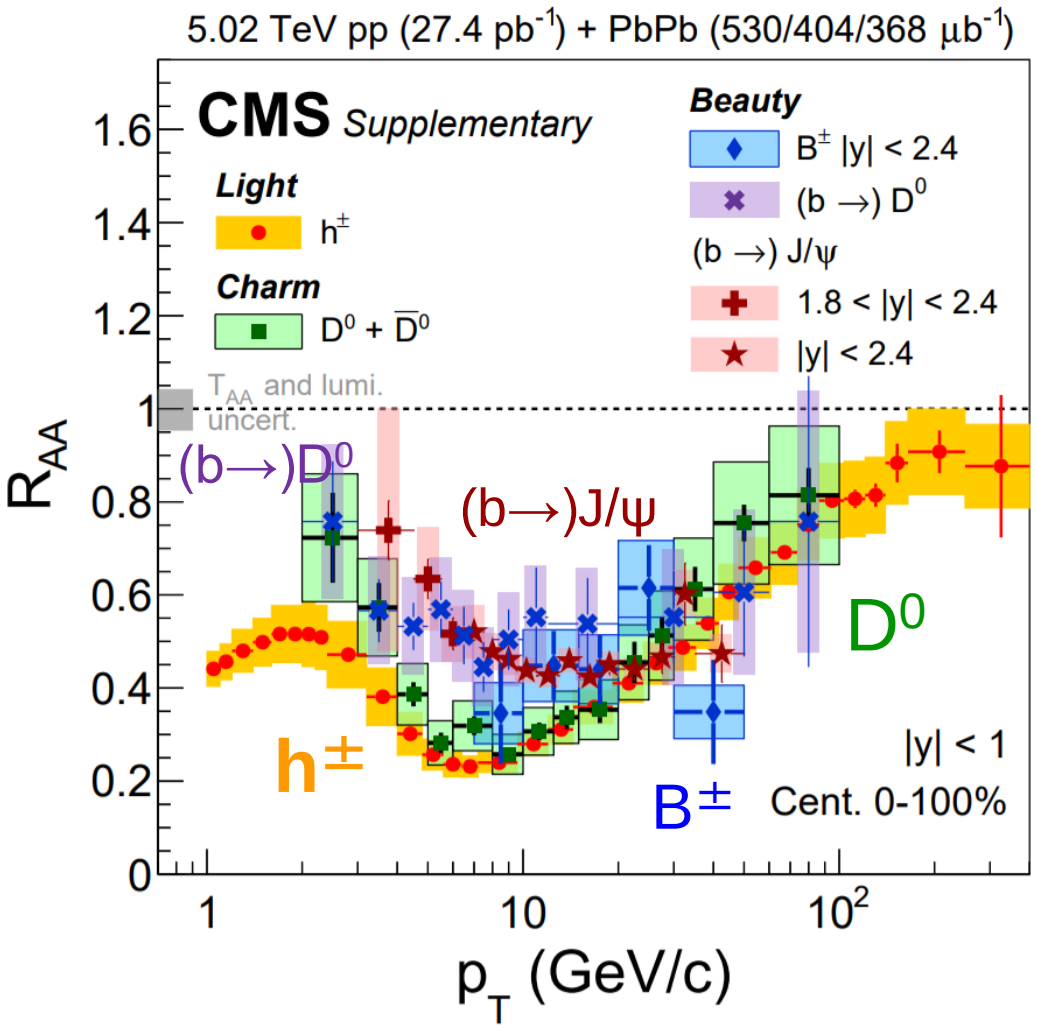


Quarkonia

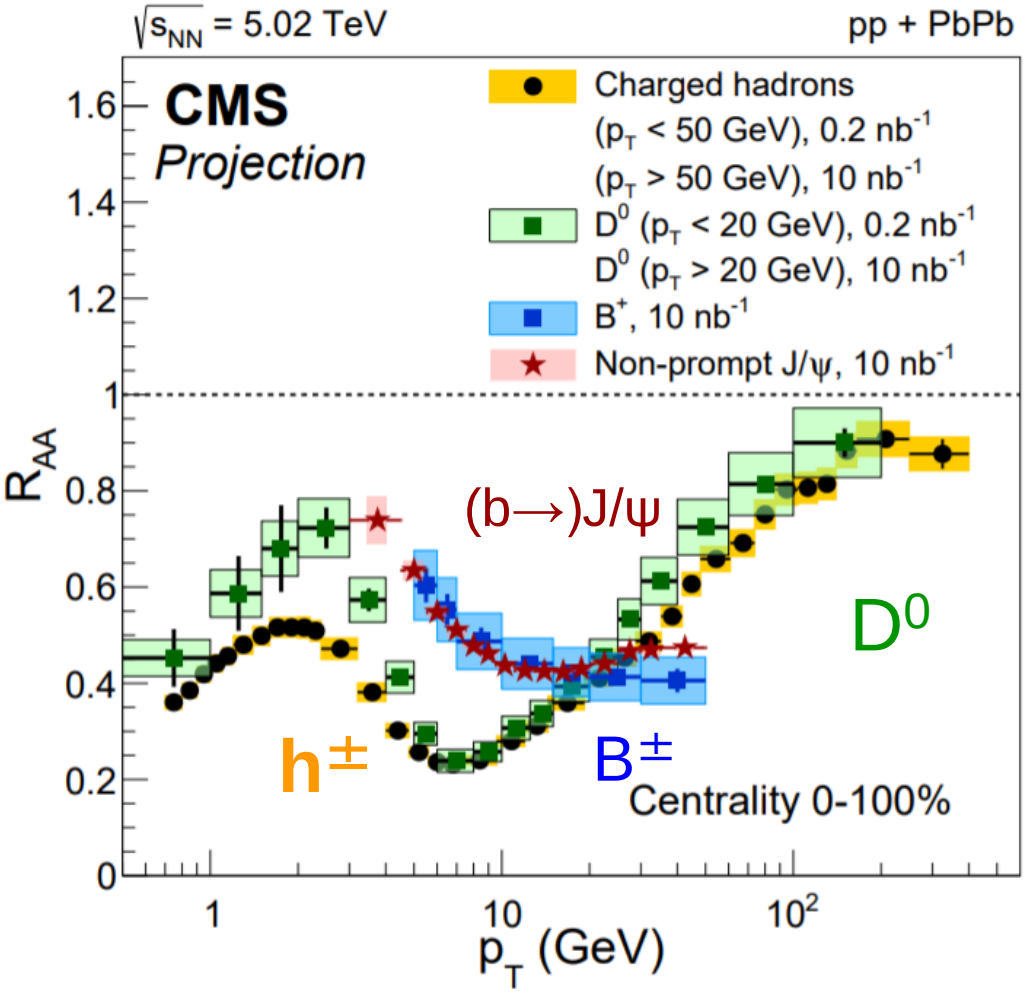


Flavor Dependence of Jet Quenching

Present Data



HL-LHC

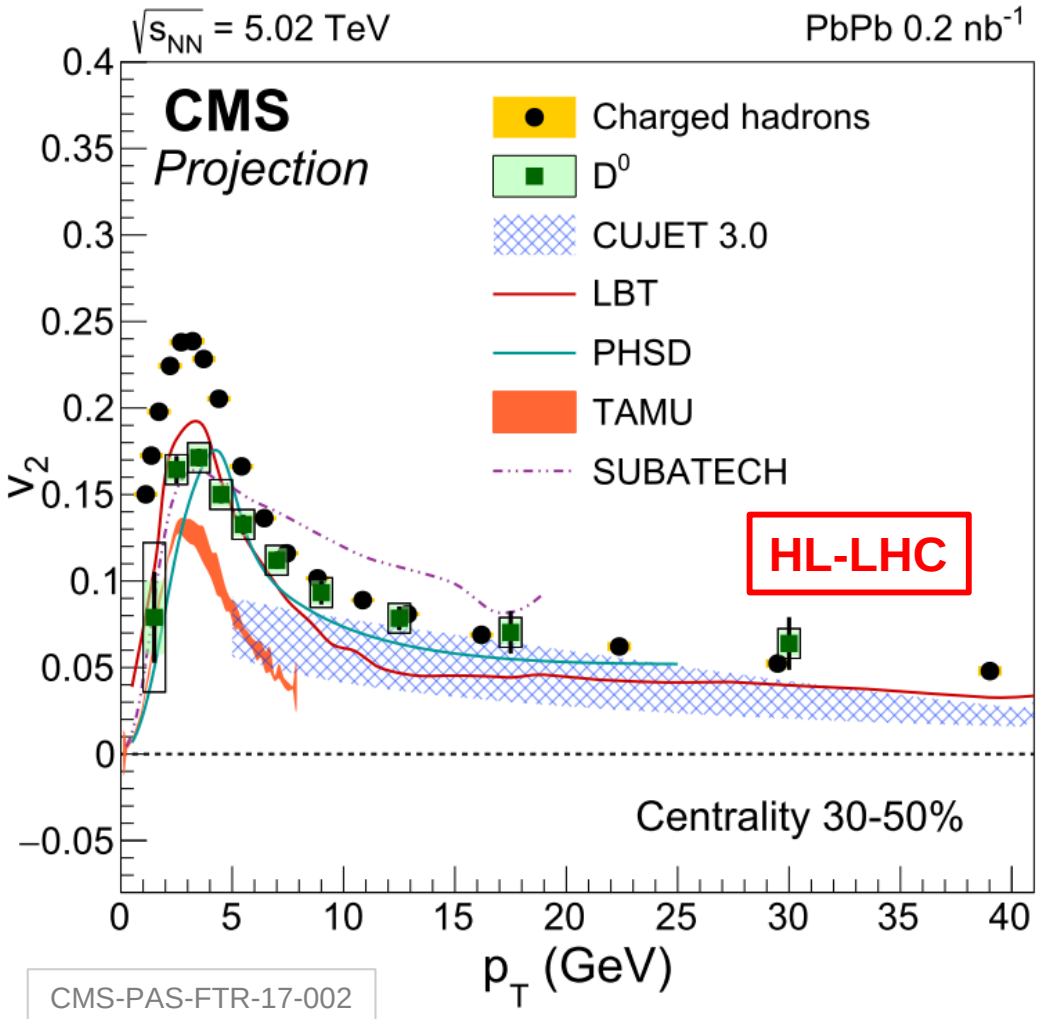


CMS-PAS-FTR-17-002

- HL-LHC data allow unprecedented accuracy of meson R_{AA} measurements down to very low p_T.

“Hydrodynamization Process” of Charm Quark

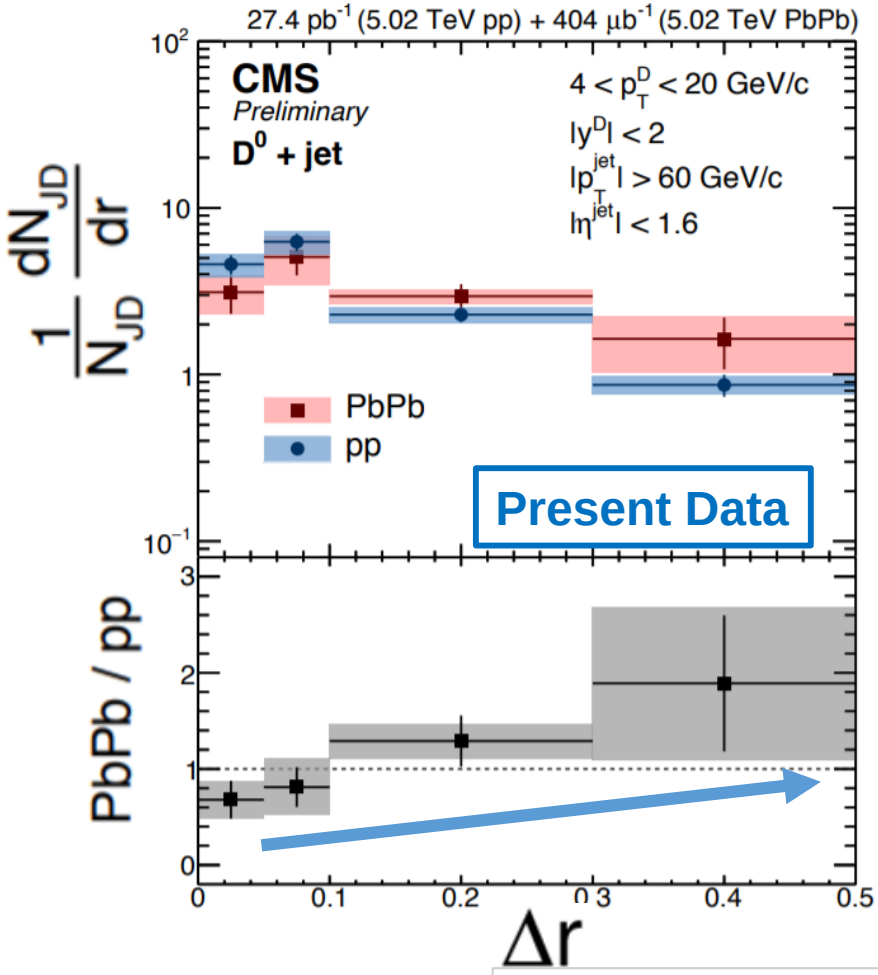
Hadron v_2 measurement in PbPb



CMS-PAS-FTR-17-002

- Unprecedented accuracy of meson v_n measurements from very low p_T to high p_T

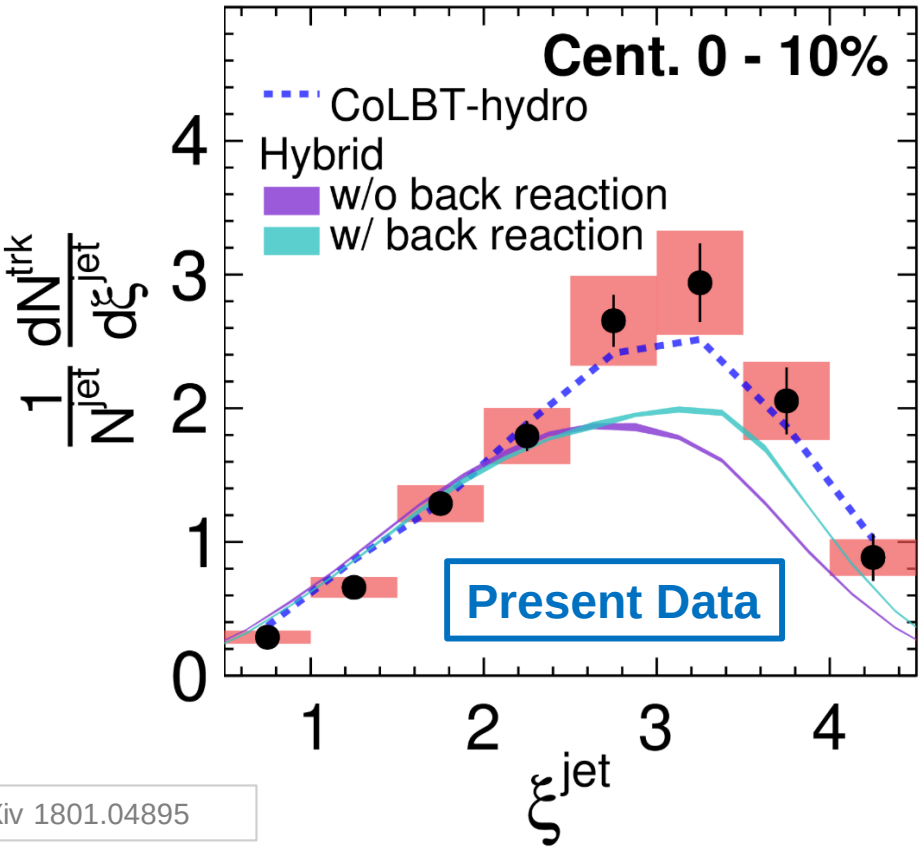
D^0 angular distribution in Jets



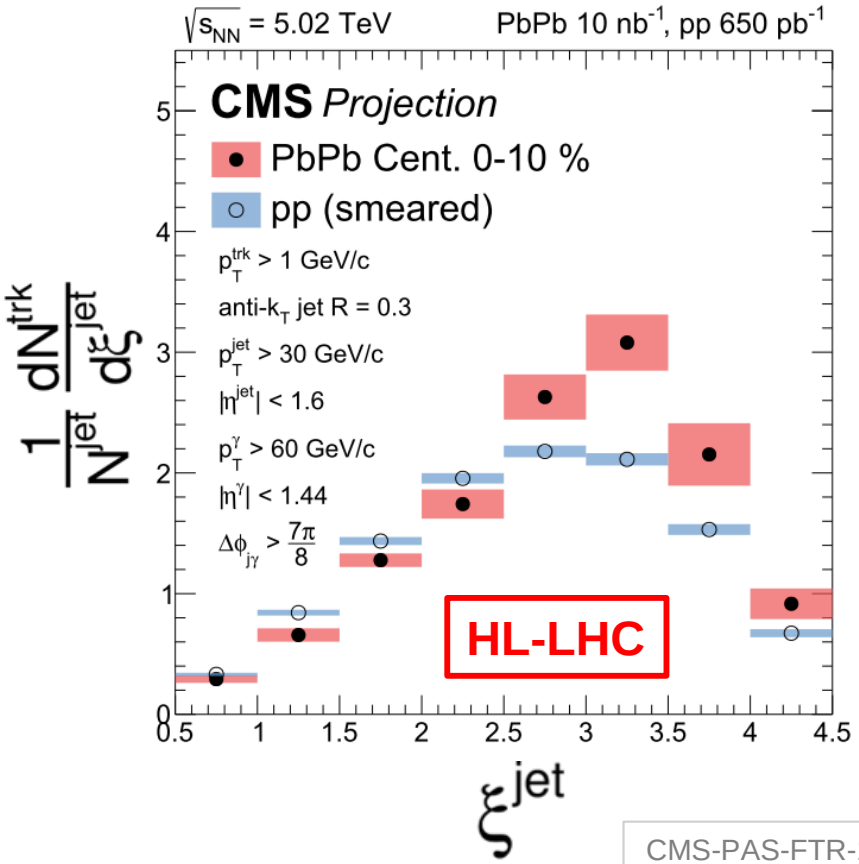
D⁰ in Jet CMS-PAS-HIN-18-012

- Hint of larger distance between D^0 and the jet axis in **PbPb** than **pp**
- Connection to charm diffusion in QGP?
- HL-LHC: allow jet p_T differential measurements

Photon-tagged Jet Substructure



arXiv 1801.04895

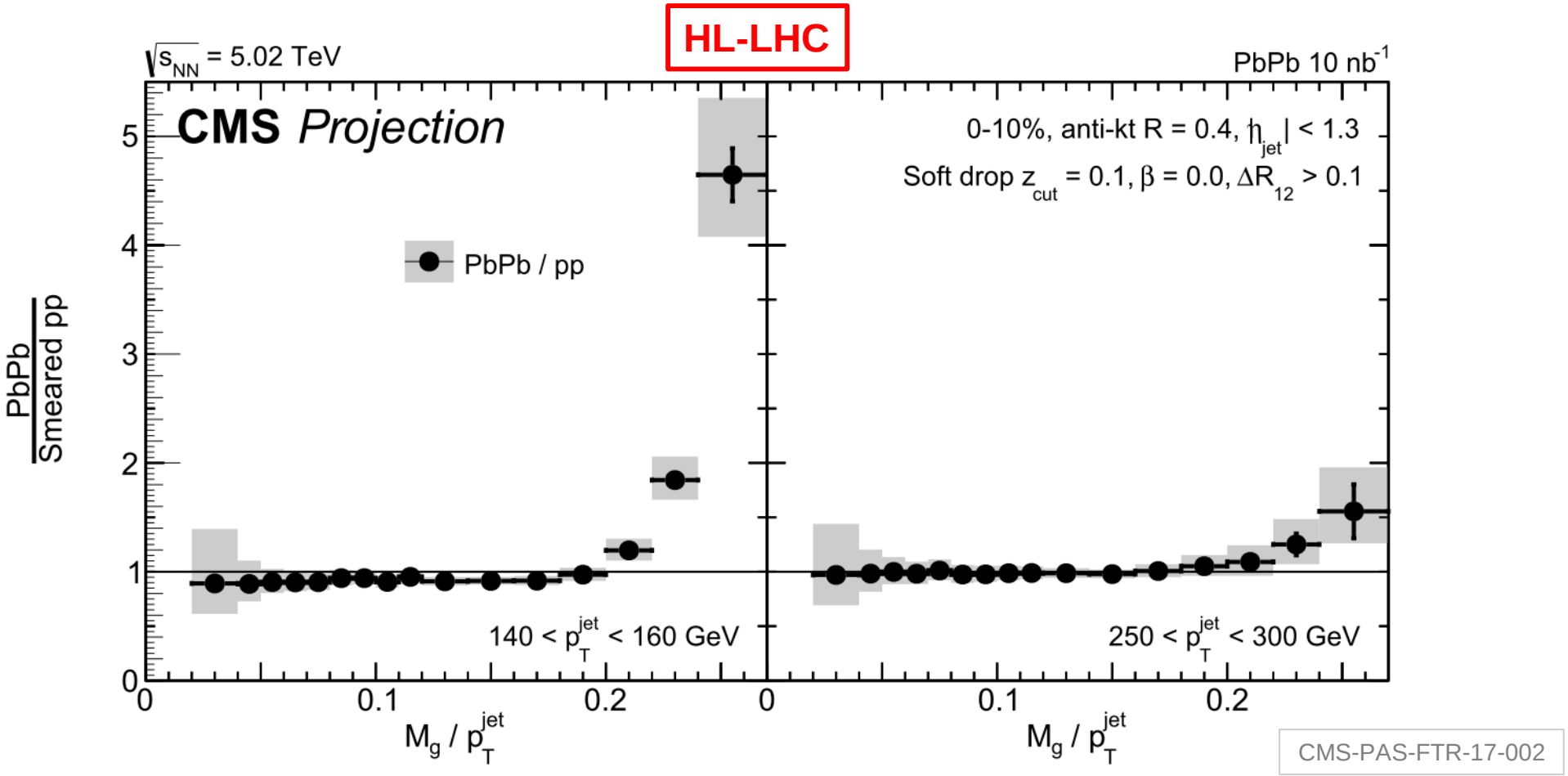


CMS-PAS-FTR-17-002

- "Thermalization of jets" from photon-tagged away-side partons
- Phase 2 upgrade: "Particle flow" jets and isolated photons up to |η|<3
- The role of medium response to hard probes: Jet Chemistry
- Possible data-driven extraction of gluon and quark jet substructure by comparing Photon-Jet and Z-Jet (and dijet): Jet Topic

PRL 120 (2018) no.24, 241602

Groomed Jet Mass



- High statistics jet sample delivered in HL-LHC:
  - Opening a new era of jet quenching studies with jet substructure
- Use of grooming techniques enable us to study **"Parton Shower Shape Dependence of Jet Quenching"**
- **Stress test on the jet quenching models**

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  Find a way to "turn off" temporarily the interaction with QGP

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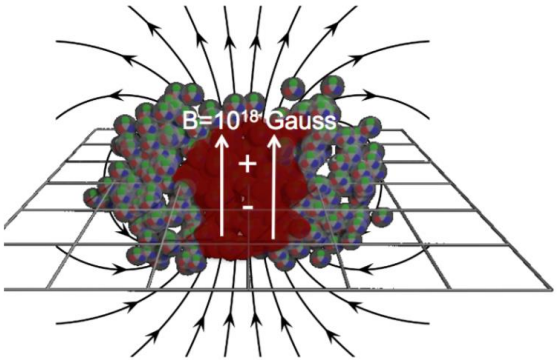
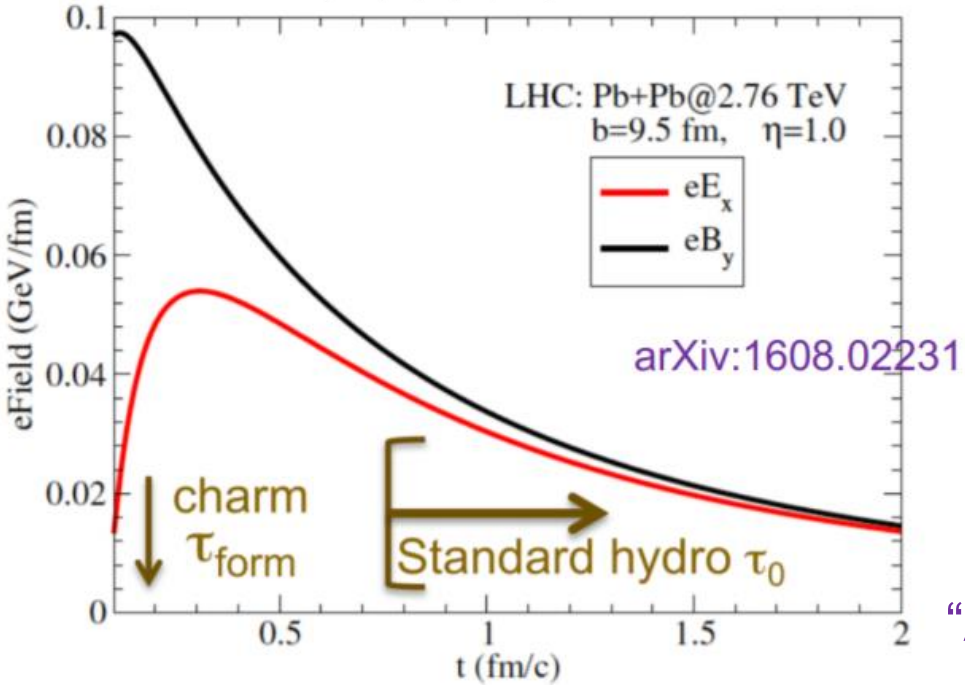
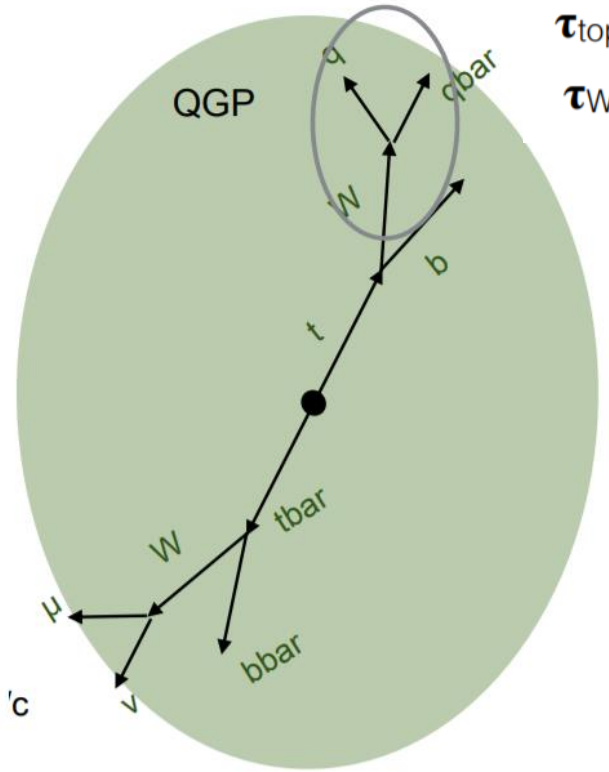
Early Phase of Collisions with Heavy Flavor and Top





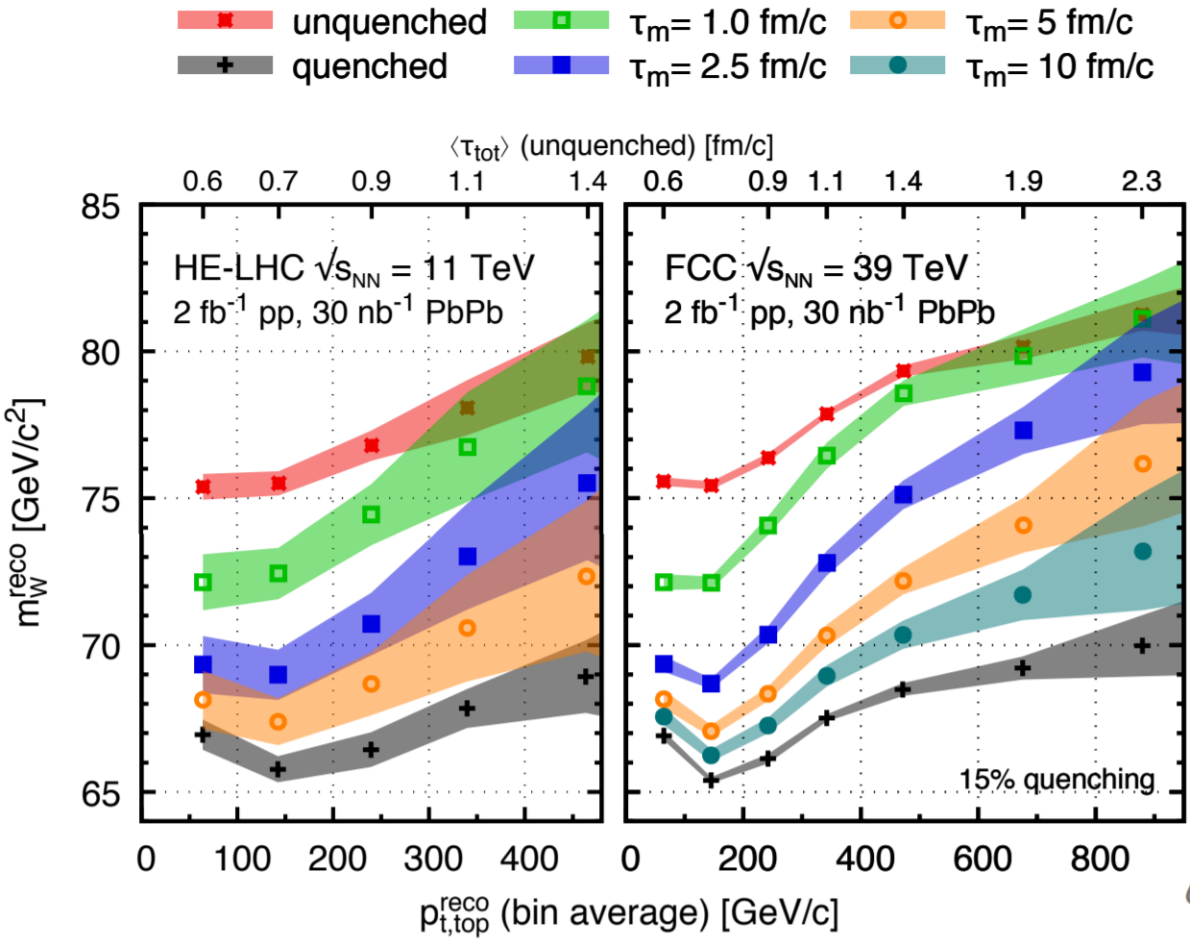


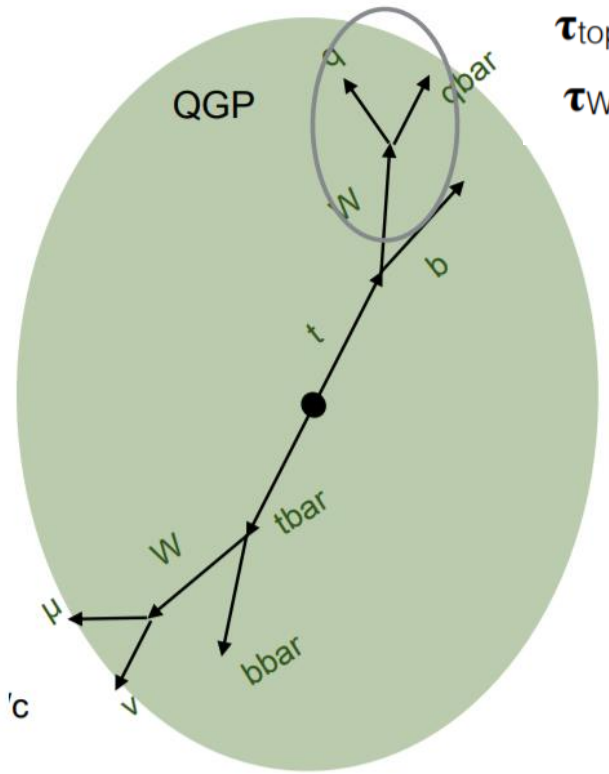
τ_m : quenching end time

"A Yoctosecond Chronometer." (Gavin Salam)

- Heavy Quarks:
  - More sensitive (than light flavor) to early magnetic fields and vorticity
  - Ex: High precision v_1 could be performed by CMS with HL-LHC data
- Negligible interaction between top / W and QGP: "Tune off" quenching at early time

Modification of W mass in Top event





τ_{top}=0.15 fm/c

τ_W=0.10 fm/c

τ_m : quenching end time

"A Yoctosecond Chronometer." (Gavin Salam)

- Longer total delay time of the W (τ_{tot}) leads to smaller modification of (hadronic decay) W mass in heavy ion collisions
- Probe the "start" and "end" time of the QGP!!
- **CMS will allow the first measurement of this probe at HL-LHC**

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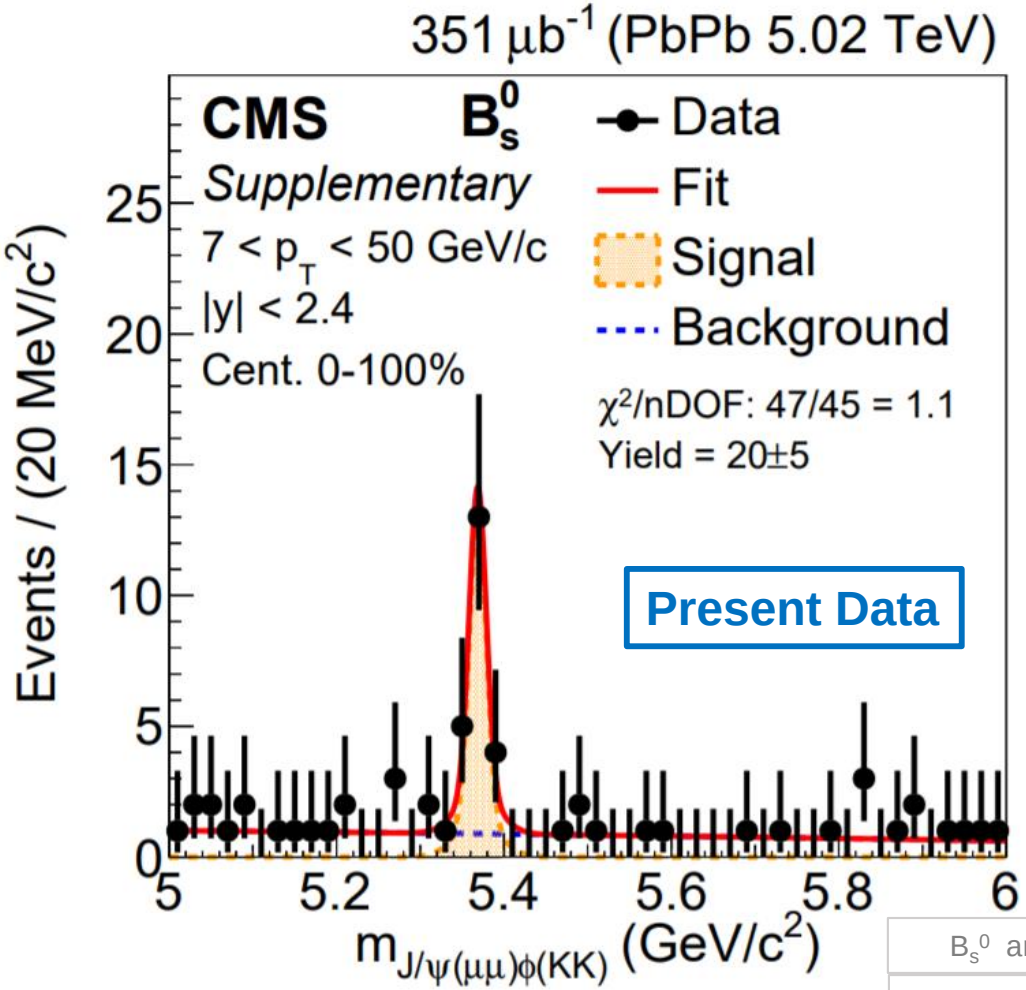
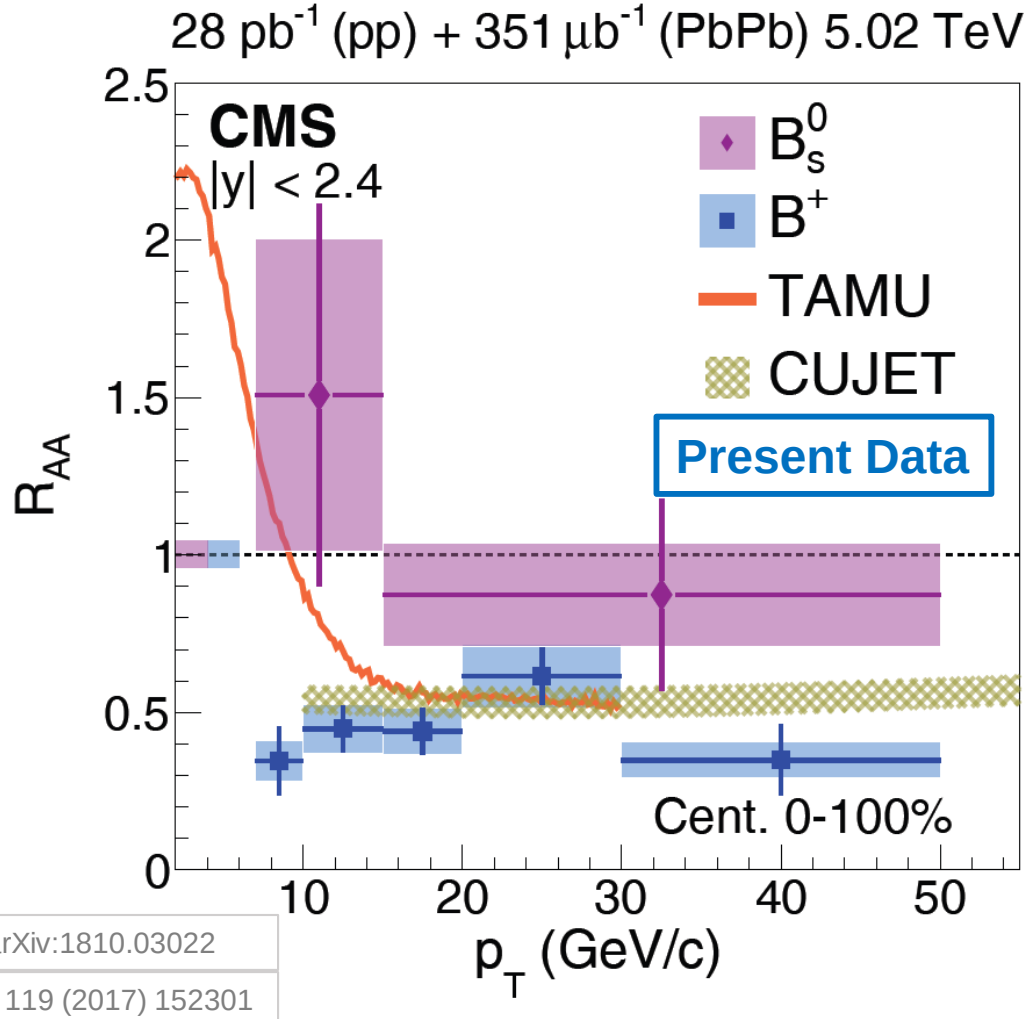
  Study the hadronization of hard scattered partons and heavy quarks production

- What are the precise properties and inner workings of the QGP?

Hadronization of Beauty Quarks in QGP





B_s^0 arXiv:1810.03022

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

$$B_s^0 \rightarrow J/\psi\,\phi \rightarrow \mu^+\mu^-K^+K^-$$

- Evidence of B_s^0 production in PbPb
- Indication of **B_s^0** enhancement in PbPb
- Consistent with expectation from beauty+strange coalescence model

- HL-LHC: Precision measurement of D_s , B_s , Λ_c and Λ_b
- **Crucial for using heavy flavor meson spectra for QGP Ds and $\hat{q}$ extraction**

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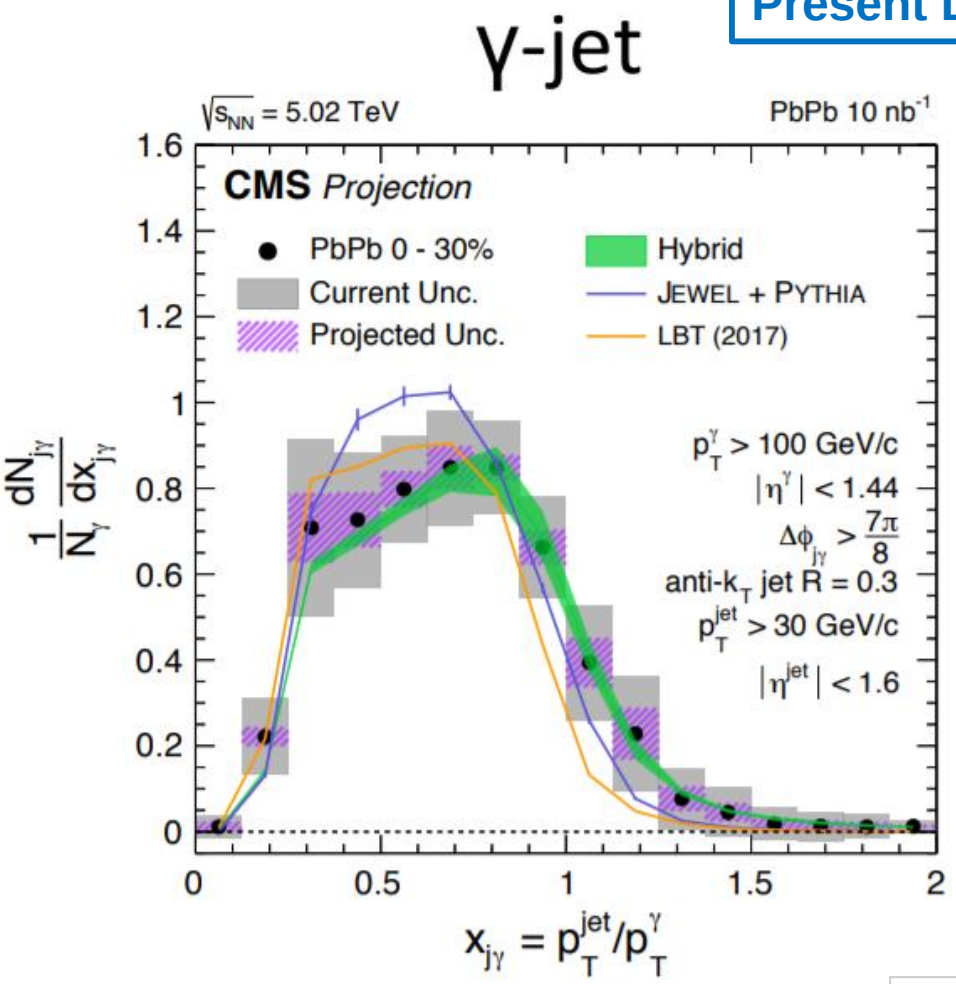
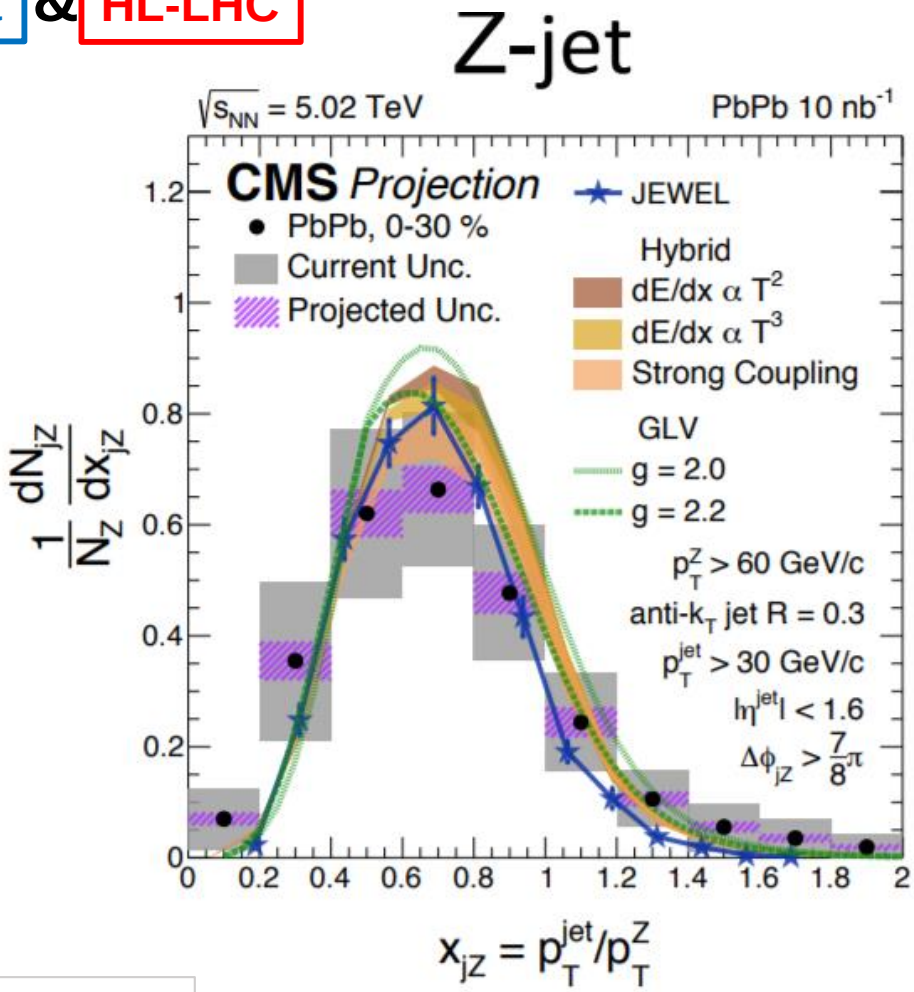
  Go beyond perfect fluid: search for the microscopic length scale for QGP. Extract medium properties with soft and hard probes

Jet Quenching Observables

Present Data & **HL-LHC**

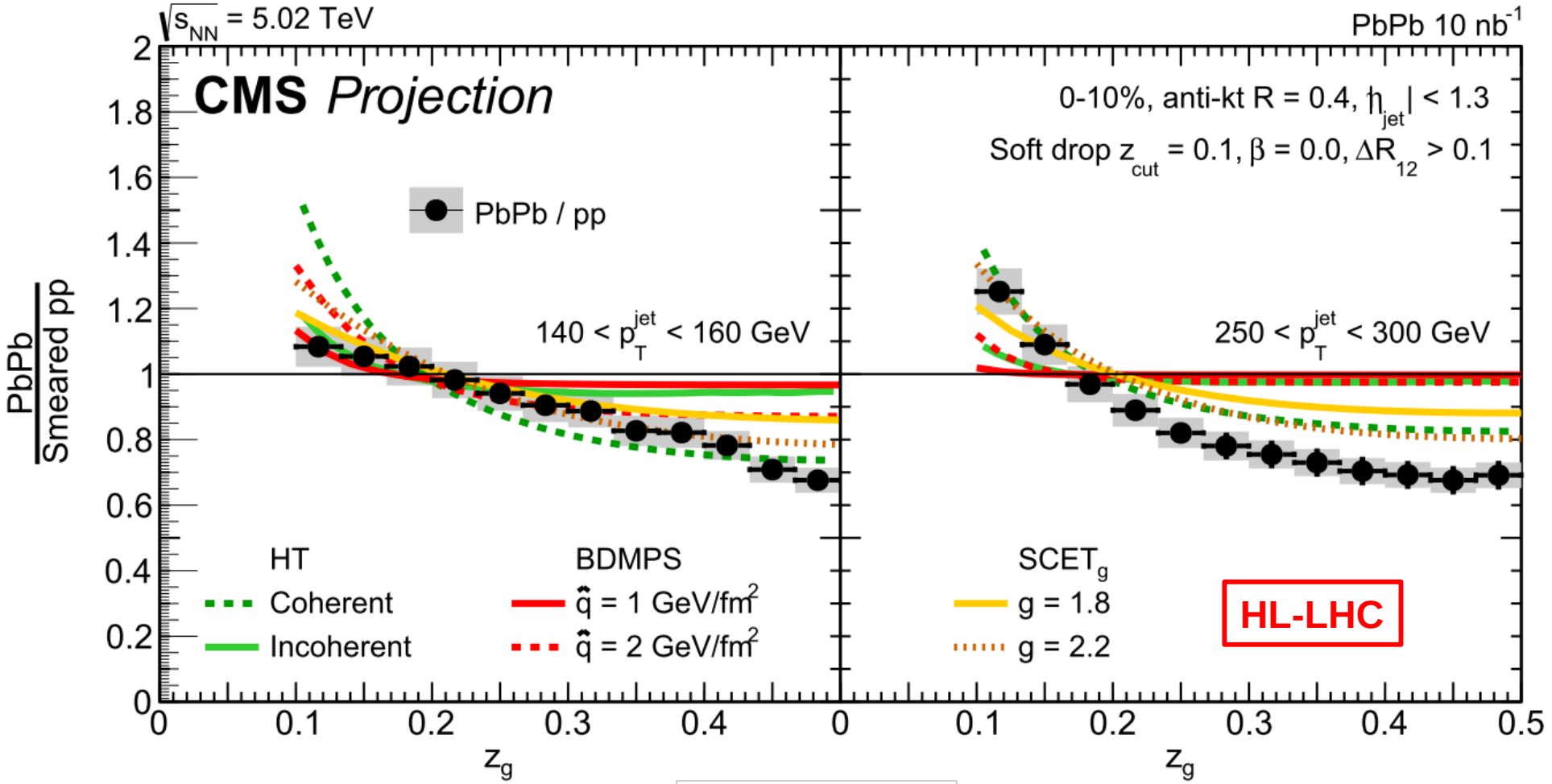




CMS-PAS-FTR-17-002

- HL-LHC data allow significant higher statistical accuracy of the boson-tagged jets measurements
- **Boson-Jet** angular correlation: Probe the inner structure of the QGP

Medium Property from Jet Substructure

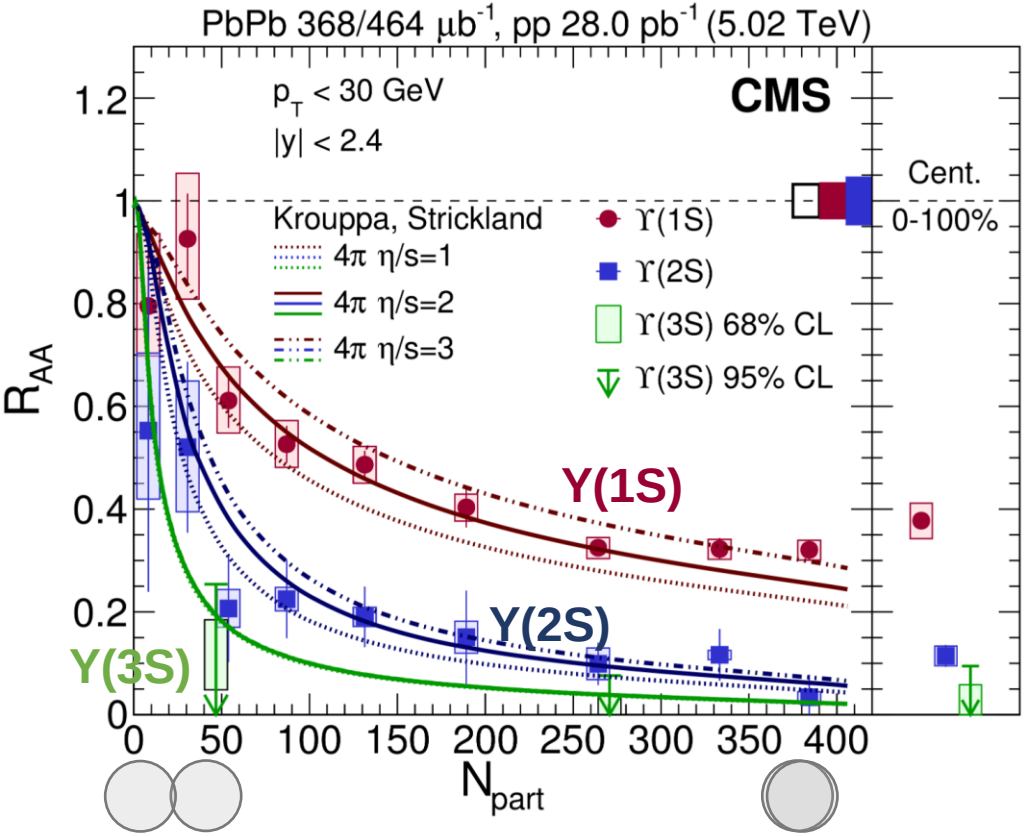


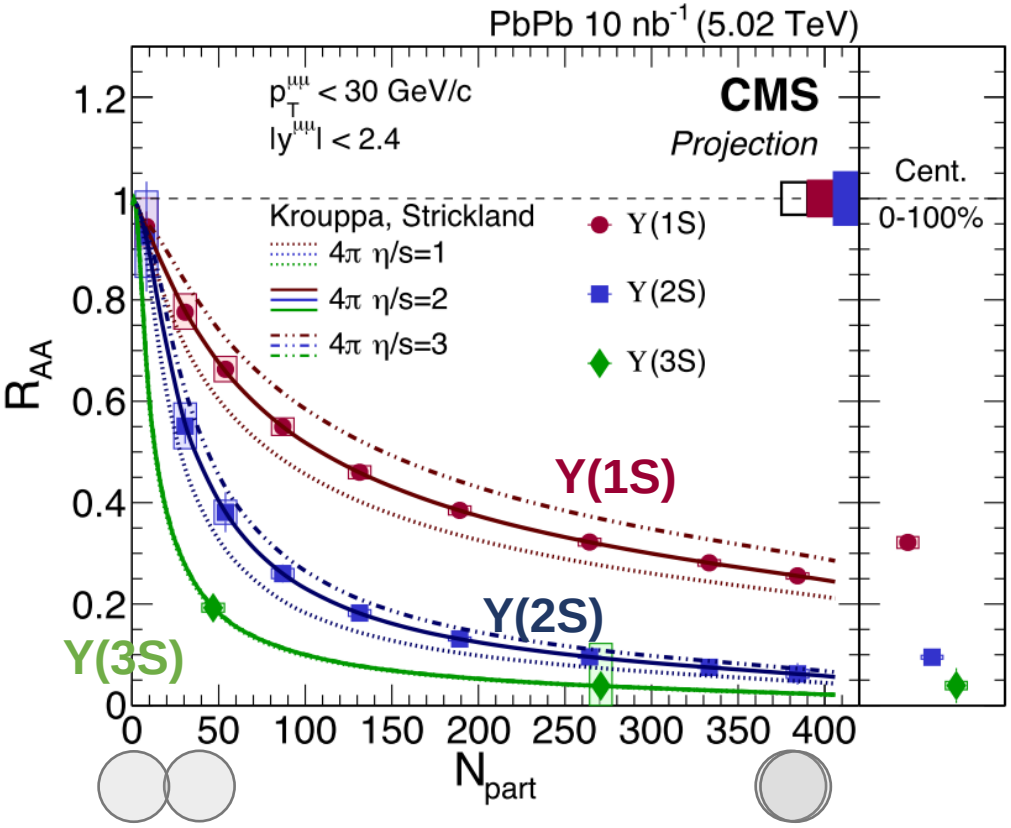
CMS-PAS-FTR-17-002

- Constraints on the QGP scattering power with a completely orthogonal observable
- To be compared with the extraction from jet and hadron spectra

Inclusive Upsilon Sequential Suppression

Present Data PbPb at 5 TeV → **HL-LHC**





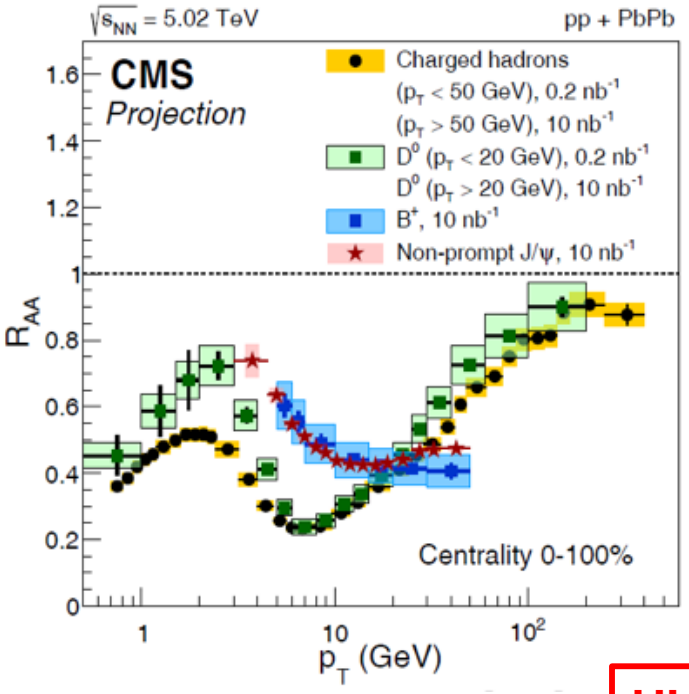
- No sign of **Y(3S)** in the high statistics data
- Consistent with models **with Y(1S) melting** and (with or without) Y regeneration
- Extracted initial medium temperature **550 - 800 MeV** based on models PLB 770 (2017) 357

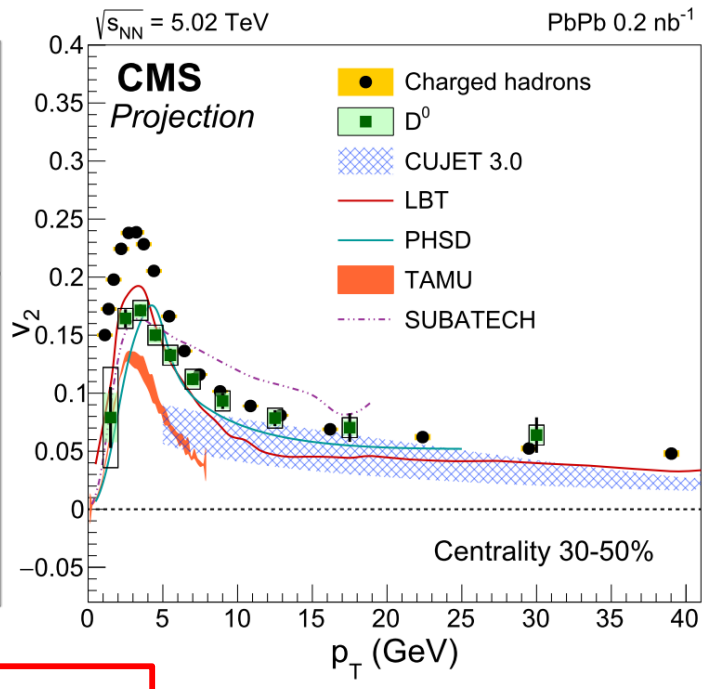
- Better mass resolution in Phase 2
- Measurement of Y(3S) suppression
- Relevance of Y regeneration
- Extraction of initial temperature and η/s from quarkonia CMS-PAS-FTR-17-002

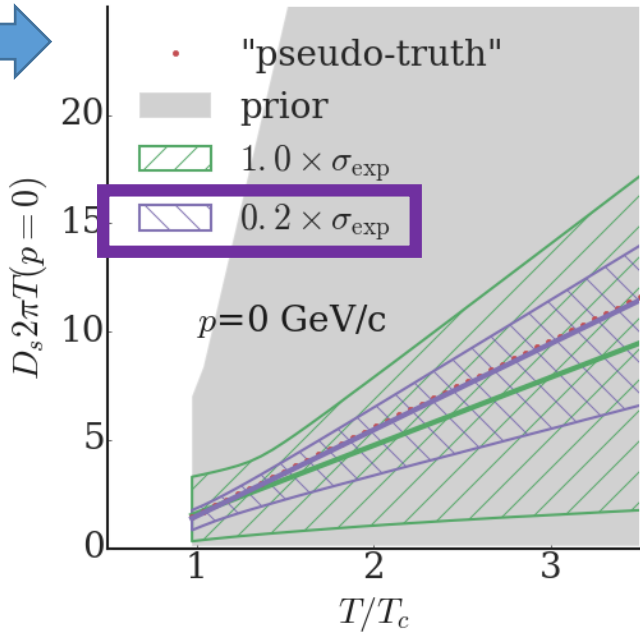
Heavy Flavor Mesons

D^0, B^+, non-prompt J/ψ R_{AA} & v_2

Heavy Quark Diffusion Coefficient **(Ds)**







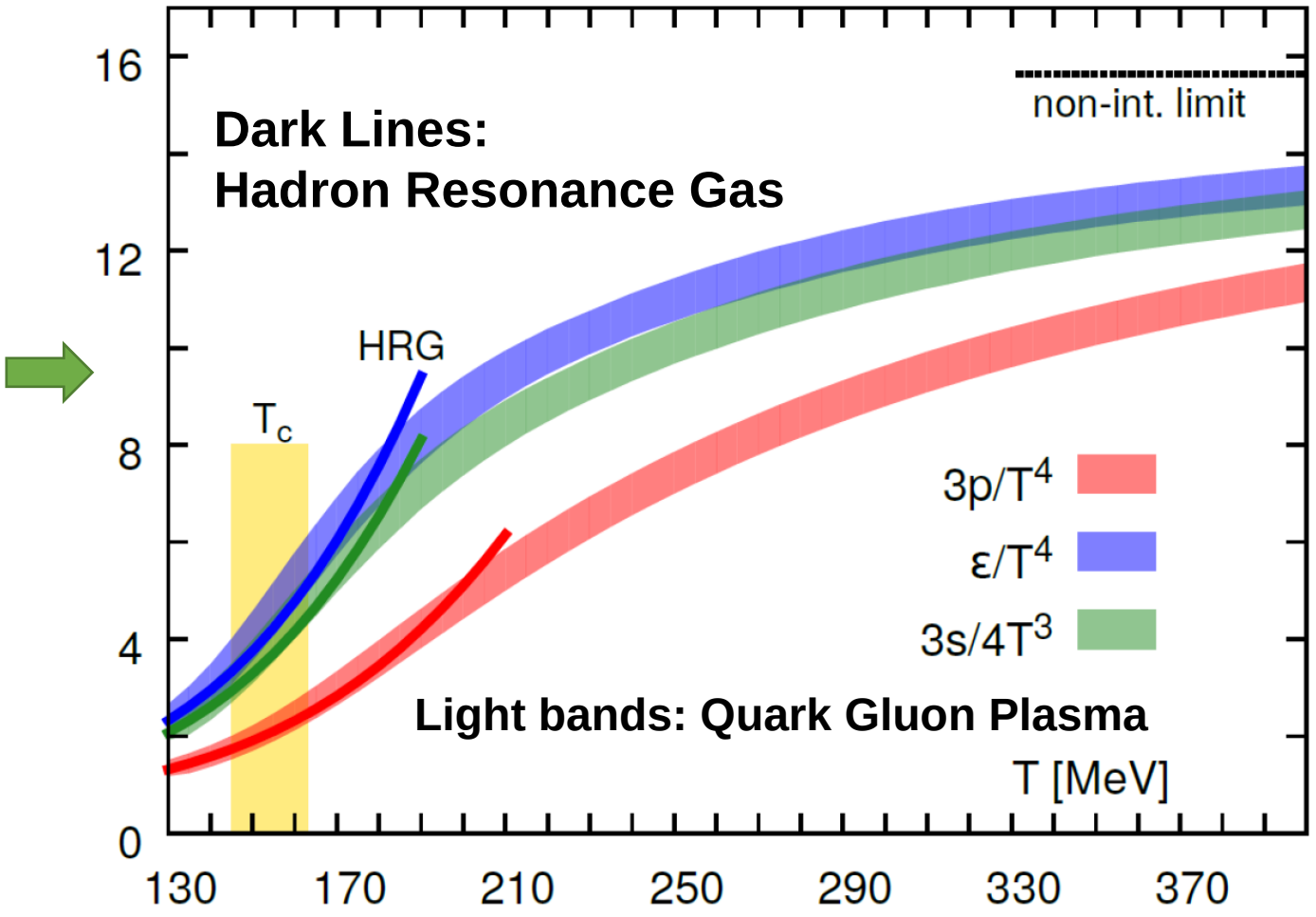
HL-LHC

- HL-LHC data could provide strong constraint on the heavy quark diffusion coefficient **Ds**, characterizing the fundamental QCD force
- Very high precision measurement of heavy flavor meson spectra (from high p_T to p_T~0): **total charm cross-section** which provide strong constraints on the models

QCD Equation of State at μ_B=0

- Could we **"measure" the QCD Equation of State** from data?

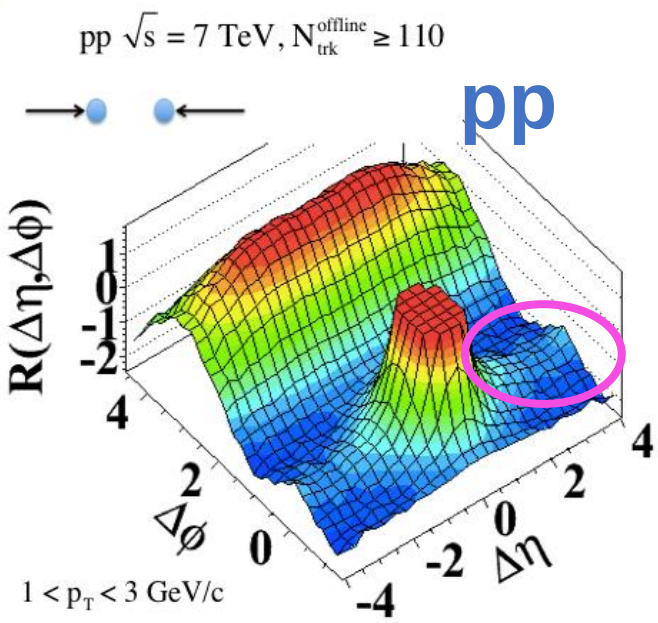
High precision flow and spectra measurements from HL-LHC data

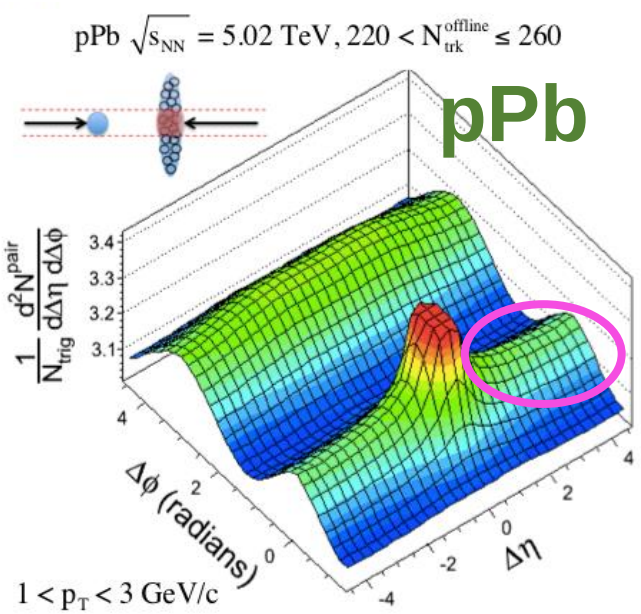


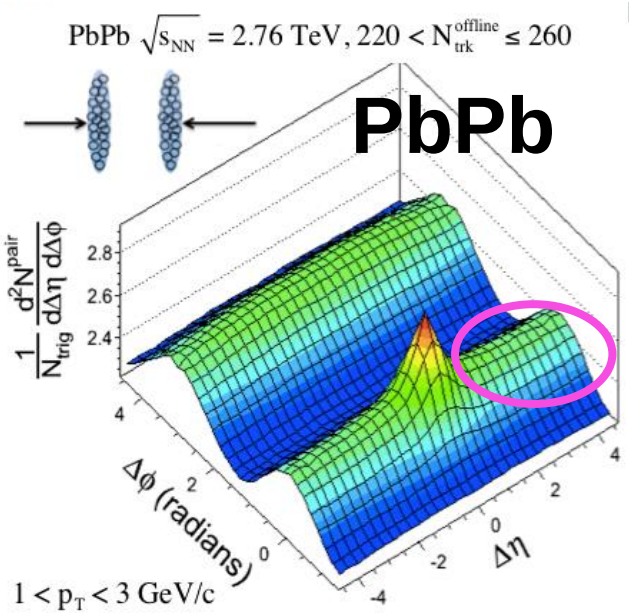
… and many more observables enabled by HL-LHC data

Need to understand the early phase before hydrodynamization and the hadronization of QGP better

“Ridge” signal in pp, pPb and PbPb collisions



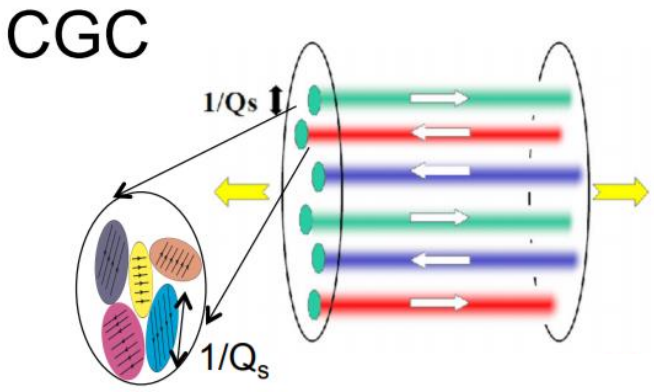


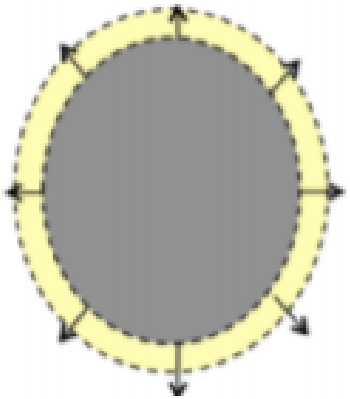


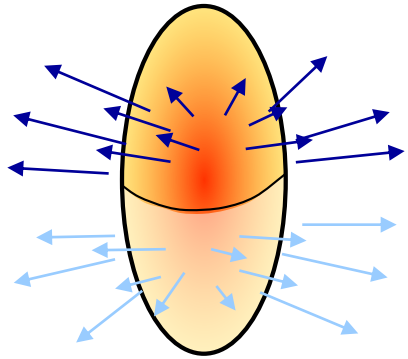
Initial State Correlation

Escape Mechanism

QGP Formation







Open Questions for Small System

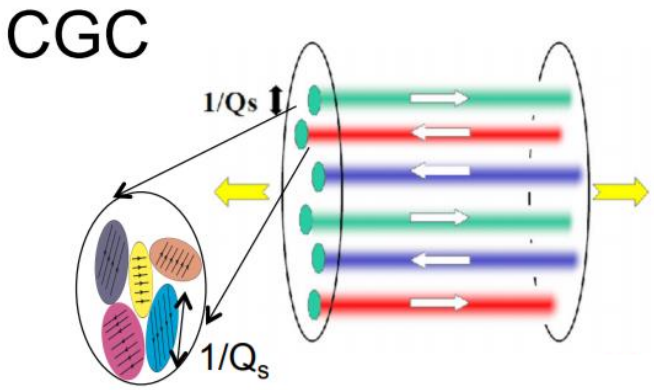
Emergence of hot QCD phenomena in small colliding systems

- "New Physics" in additional to the "Standard Model" of pp and AA Physics?
- Higher luminosity and energy needed for more detailed studies

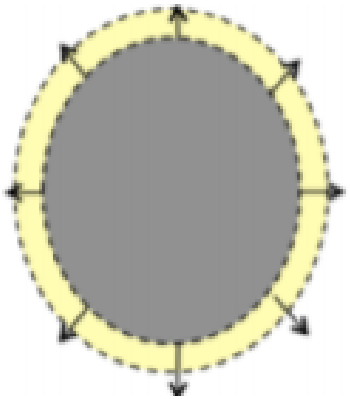
Is there a common paradigm to describe the underlying physics in all colliding systems?

- If yes: QGP production in small system? Smooth transition from pp to AA?
- If no: What are the different mechanisms that come into plays?
- What about an intermediate scenario?

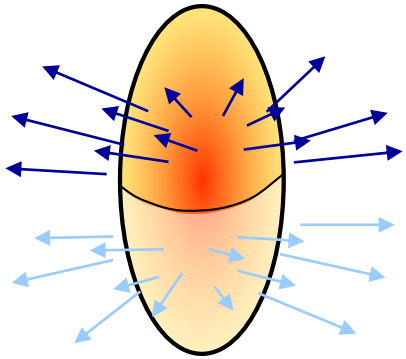
Initial State Correlation



Escape Mechanism



QGP Formation



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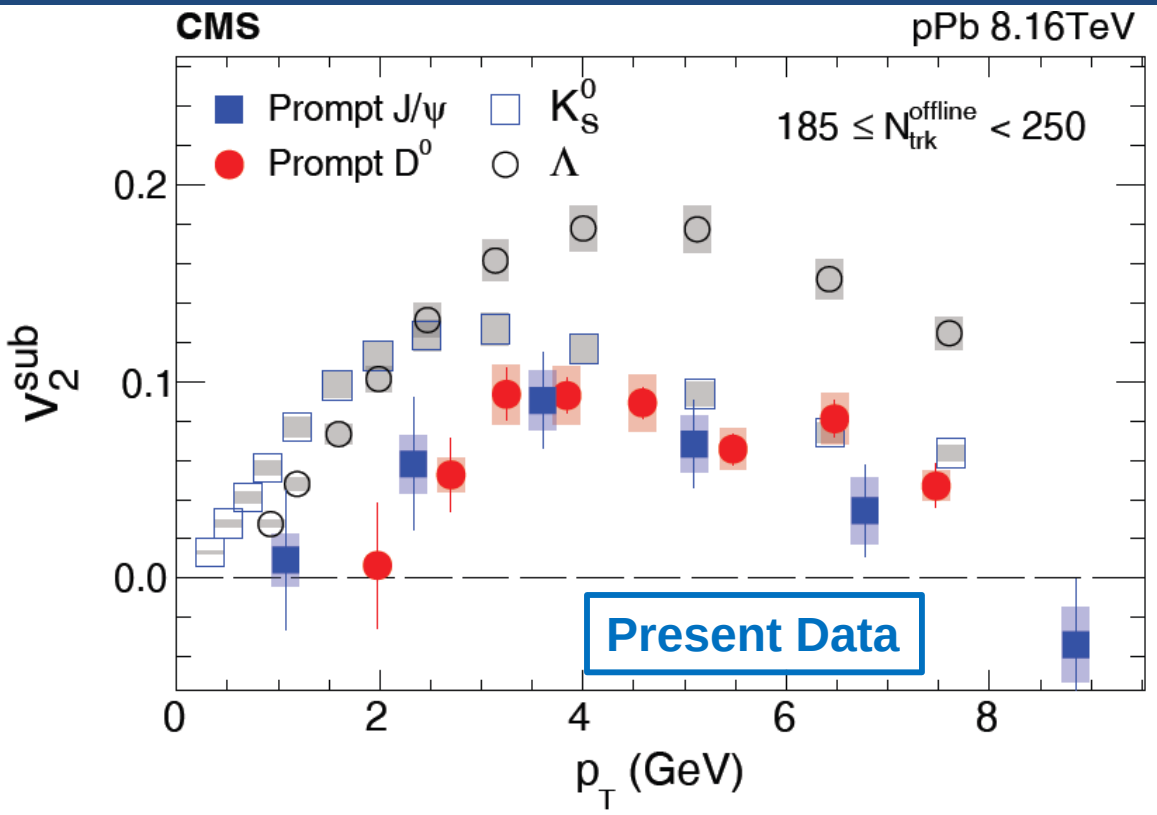
Study of QGP-like signature in small systems

Comparison between pp, pA and AA collisions at similar multiplicity

- 200 pb^{-1} high multiplicity pp program which will produce 25k events with 14-16x <Nch> which is equivalent to 60-65% central PbPb events!
- Possibility to use higher pile-up data with 4D vertexing in CMS

"Qualitatively new aspect of the comparison of pp and PbPb"

“Charm flow” and Jet quenching in small system



- Large v_2 signal from prompt J/ψ: charm flow in high multiplicity pPb?
- Origin of the large v_2 at high p_T (up to ~ 8 GeV): Indication of jet quenching in pPb?
- HL-LHC data with large CMS tracker acceptance could allow new measurements such as v_n fluctuation of hadrons in pPb
- Search for jet quenching effect with boson-jet, dijet and h-jet events

J/ψ pPb arXiv:1810.01473 | D^0 pPb PRL 121 (2018) 082301

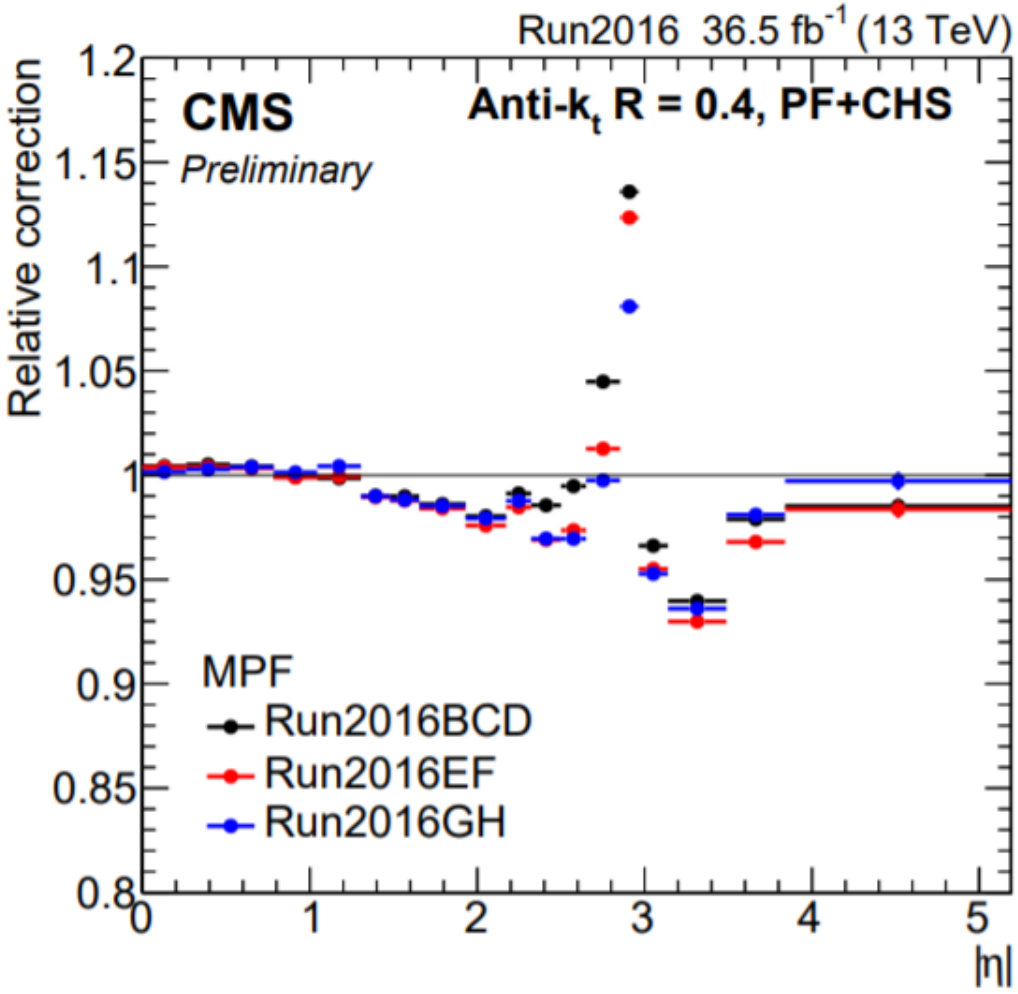
Summary

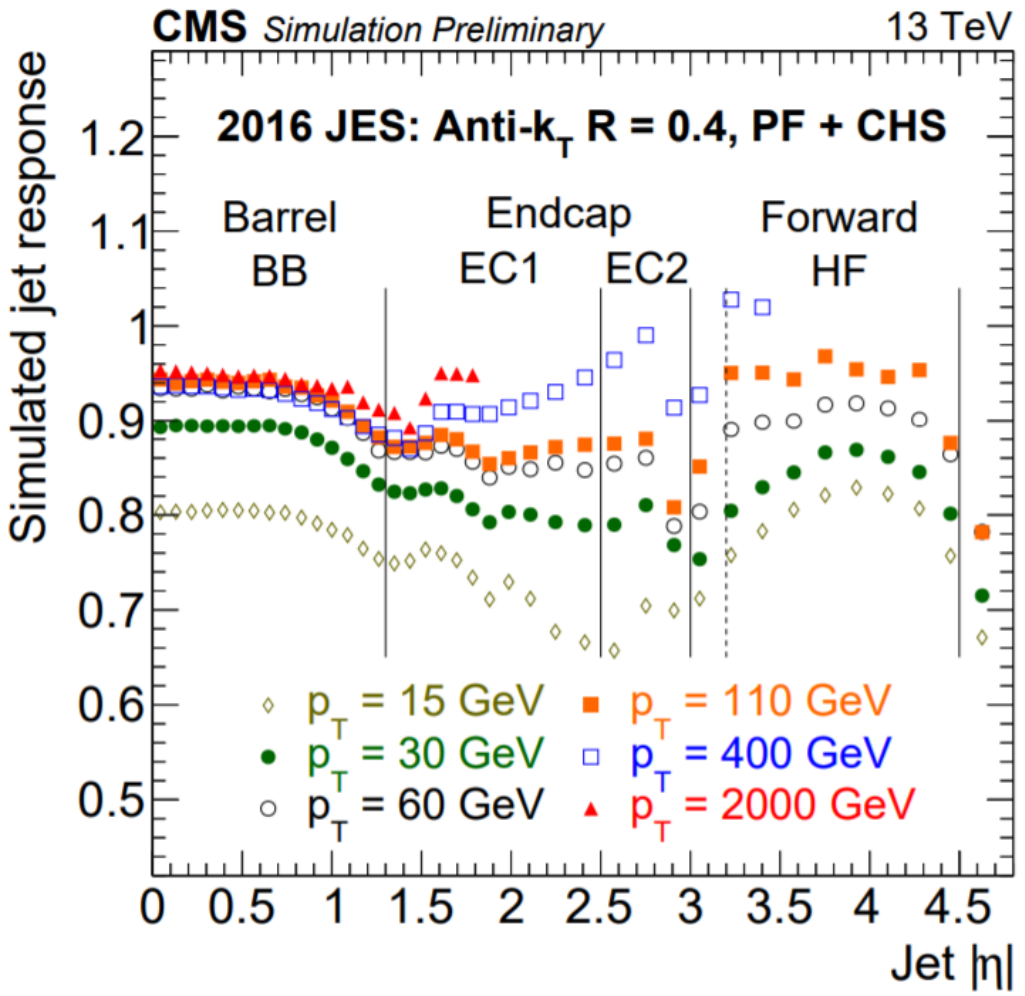
- CMS plan to fully exploit the HL-LHC data
  - Fast trigger and data-acquisition (Now + further upgrade in LS3)
  - Large tracker acceptance up to **|η|<4** (after LS3)
  - Large muon acceptance up to **|η|<3** (after LS3)
  - High Granularity Calorimeter **1.6<|η|<3** (after LS3)
  - 4D vertex reconstruction and possibility of p/K/π PID with MIP timing detector (after LS3)

- CMS HL-LHC data could contribute to
  - Precision measurement of nuclear PDF
  - Understanding the creation and the hadronization of QGP
  - Extraction of QGP properties and QCD EoS from multiple channels
  - Onset of QGP formation in small system
  - Relevance of initial state correlation in small and large systems
  - **… and exciting new discovery!**

- Backup slides

Jet Response in Run 2016





CMS DP2018/028

CMS Request of HL-LHC dataset

- **CMS request**
  - **Pb+Pb:** 13/nb at 5.5 TeV + pp reference
  - **p+Pb:** 2/pb at 8.8 TeV
  - **p+p:** 200/pb at low pile-up μ=1-2
  - Possibility of smaller collision system

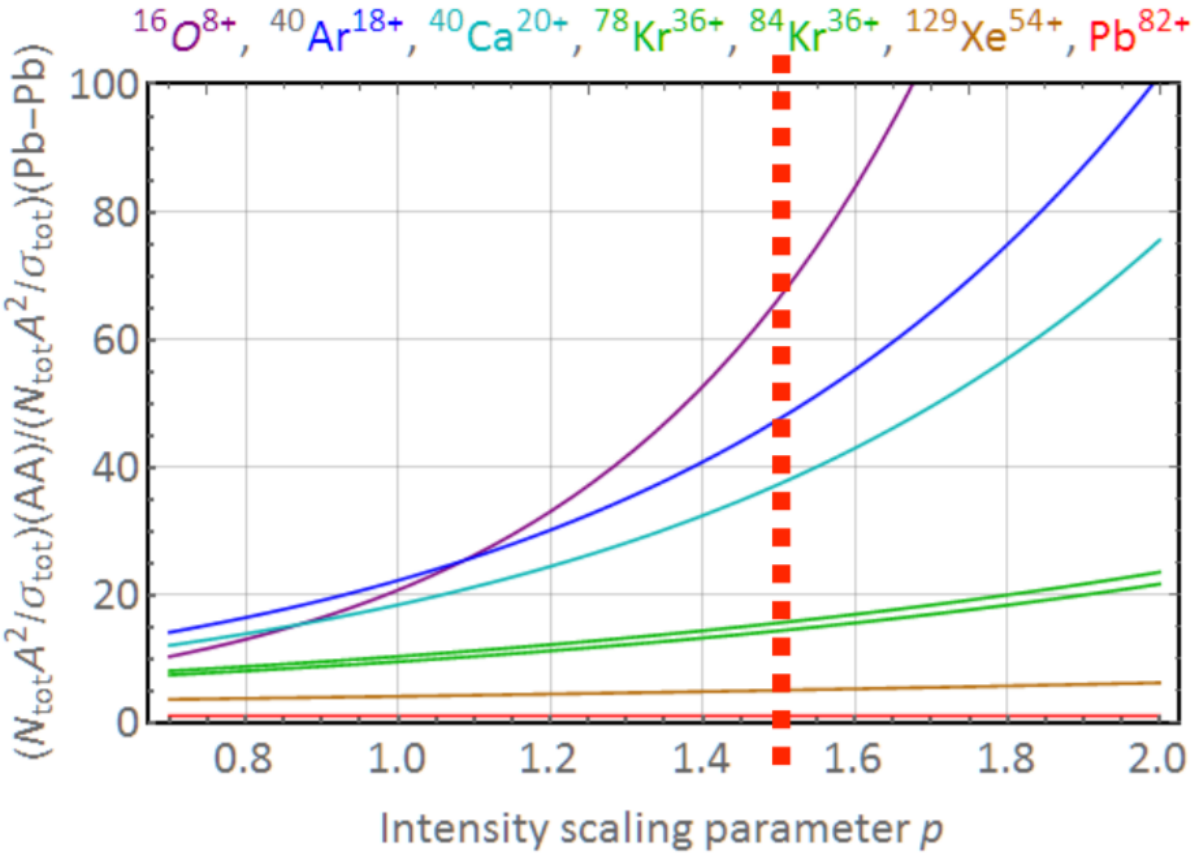
Opportunity with Light Ions

Gains in ULTIMATE integrated nucleon-nucleon luminosity PER FILL wrt Pb-Pb

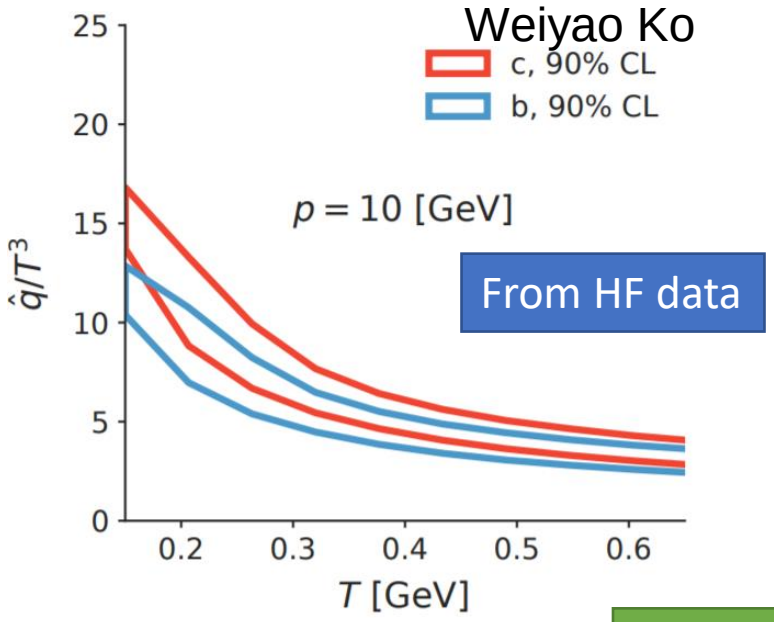
This would be on the assumption that a fill would be kept forever until one beam was exhausted (and other loss mechanisms are neglected). Real gain/fill will be less.

In reality, one also gains from longer luminosity lifetime and less time spent refilling the machine.

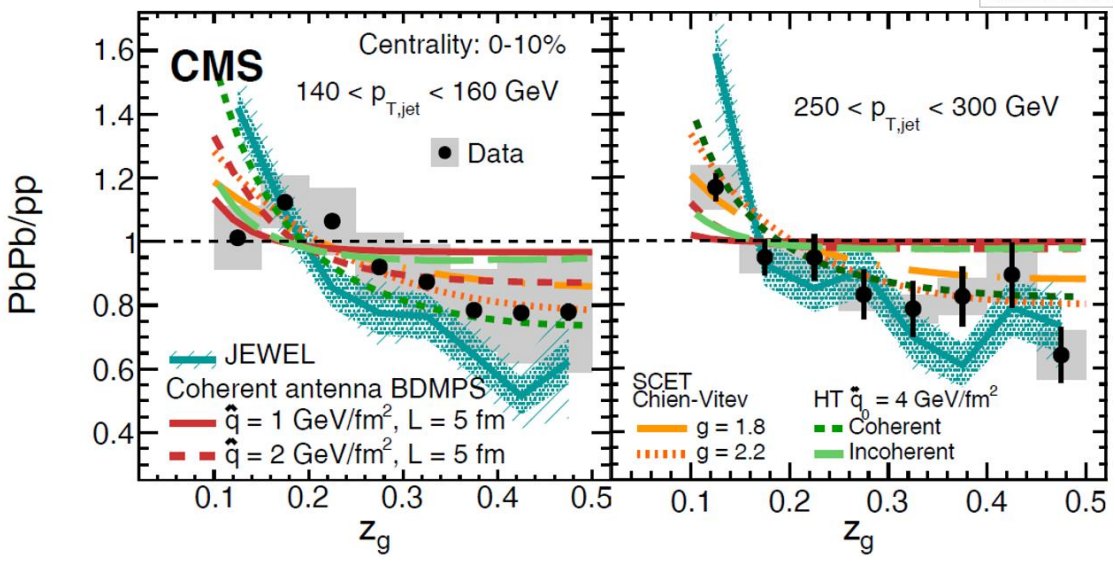
We will try to quantify this better in future.



Extraction of the Medium Scattering Power

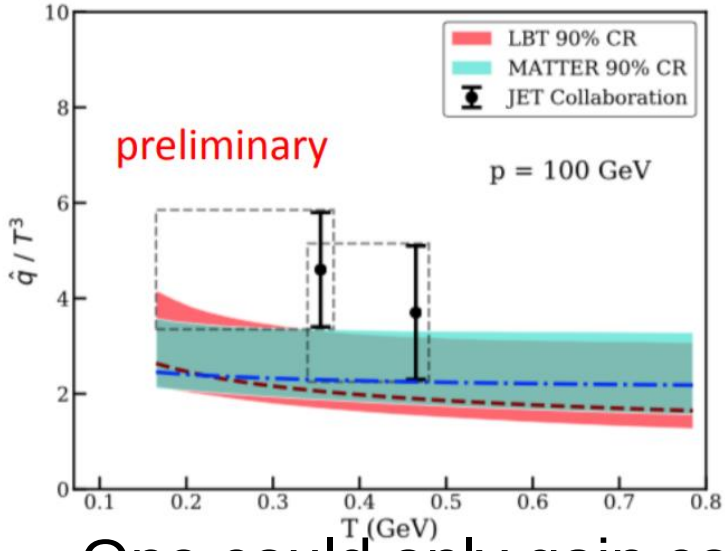


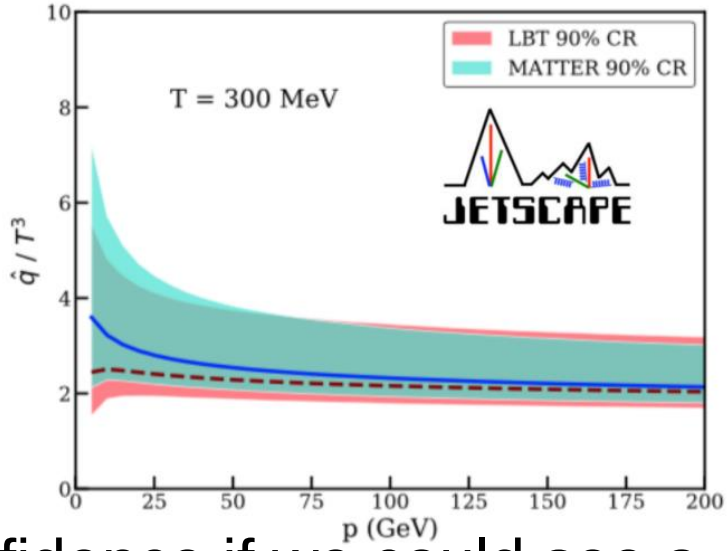
From HF data



From jet substructure data

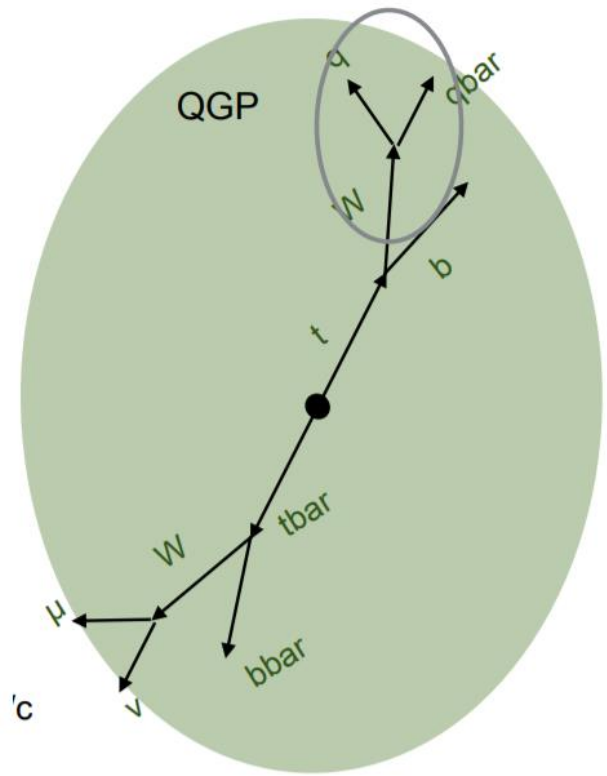
From charged hadron data





One could only gain confidence if we could see a consistent picture from different observables

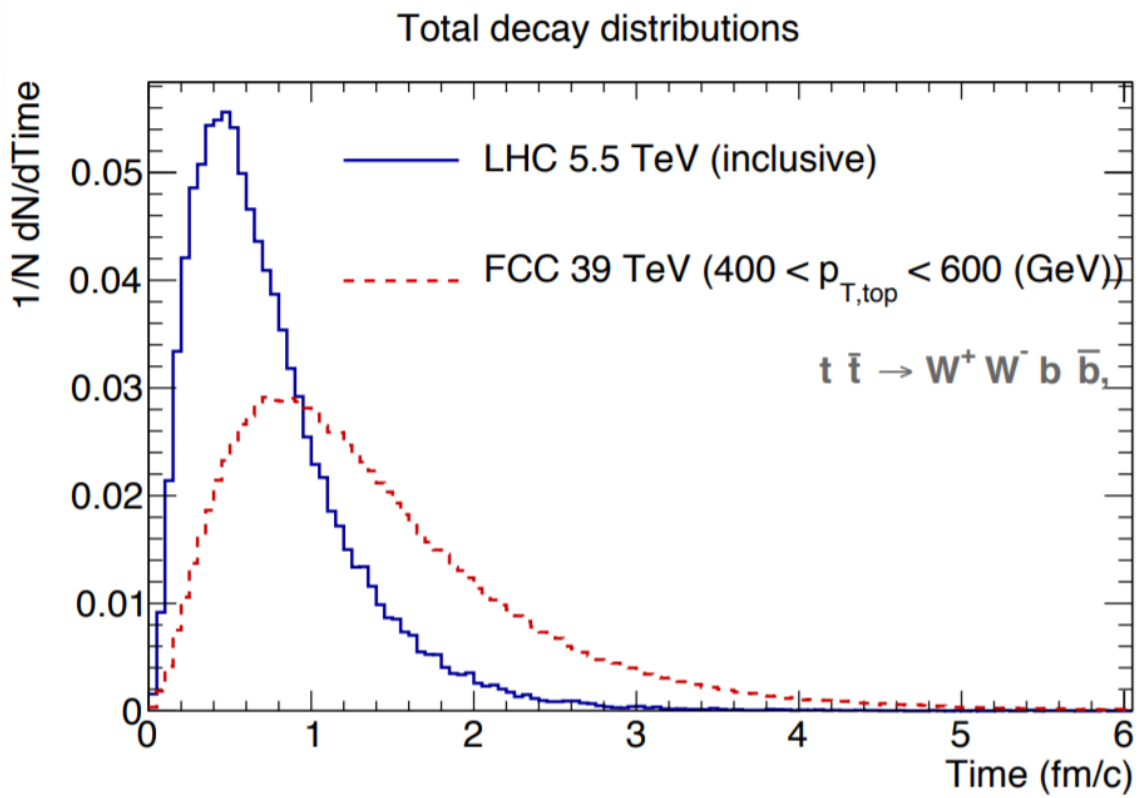
TOP Production



Negligible interaction between Top / W and the QGP

τ_{top}=0.15 fm/c

τ_{W}=0.10 fm/c



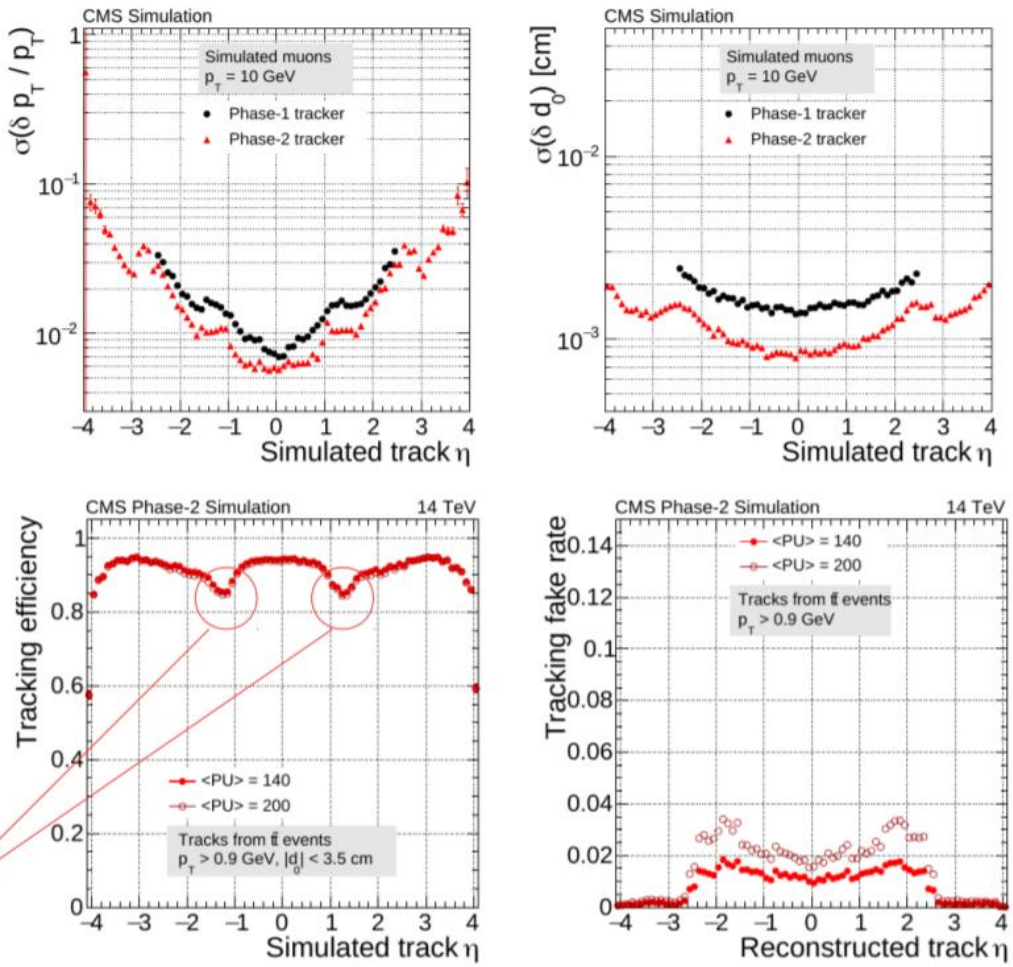
"Turn off the QGP effect" for a period of time!

"A Yoctosecond Chronometer." (Gavin Salam)

CMS Tracker Upgrade for the HL-LHC
Expected performances

- Full Monte-Carlo simulation
- Significant improvement expected in p_T and d_0 resolution
- 90% tracking efficiency for tracks from tt events with < 2% fake rate
- Work in progress!
  - Geometry is being optimized
  - Efficiency at $|\eta| \sim 1.2$ is being addressed

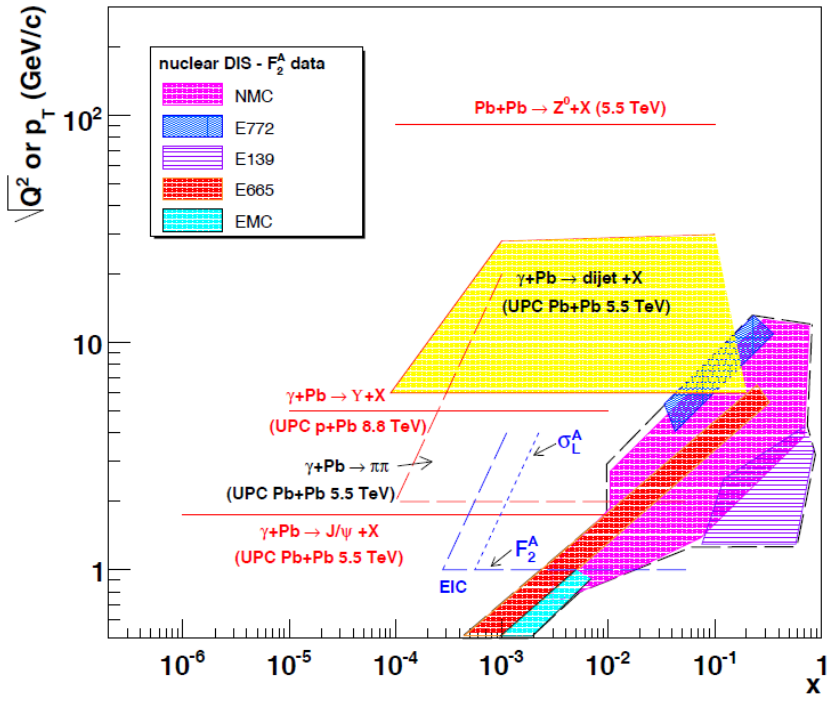
Offline tracking

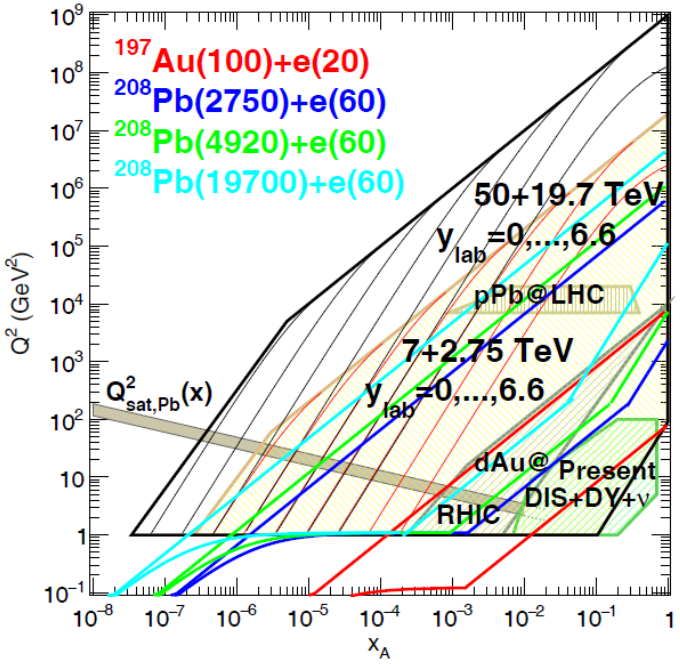


Opportunity at HL-LHC for nPDF

Ultra-peripheral collisions in PbPb and inclusive pPb collisions characterisation of initial wave-functions

- large kinematic range at the LHC for high-energy QCD
- HL-LHC: improve knowledge on nuclear PDFs and on QCD phenomena beyond collinear factorisation ; onset of gluon saturation?





Kinematic planes for UPC LHC kinematics from arXiv:0706.3356; currently used *p*Pb in arXiv:1612.05741 by N. Armesto.

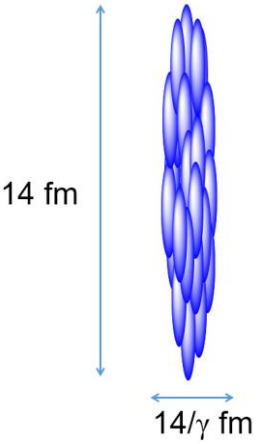
Parton Distribution Function (PDF)

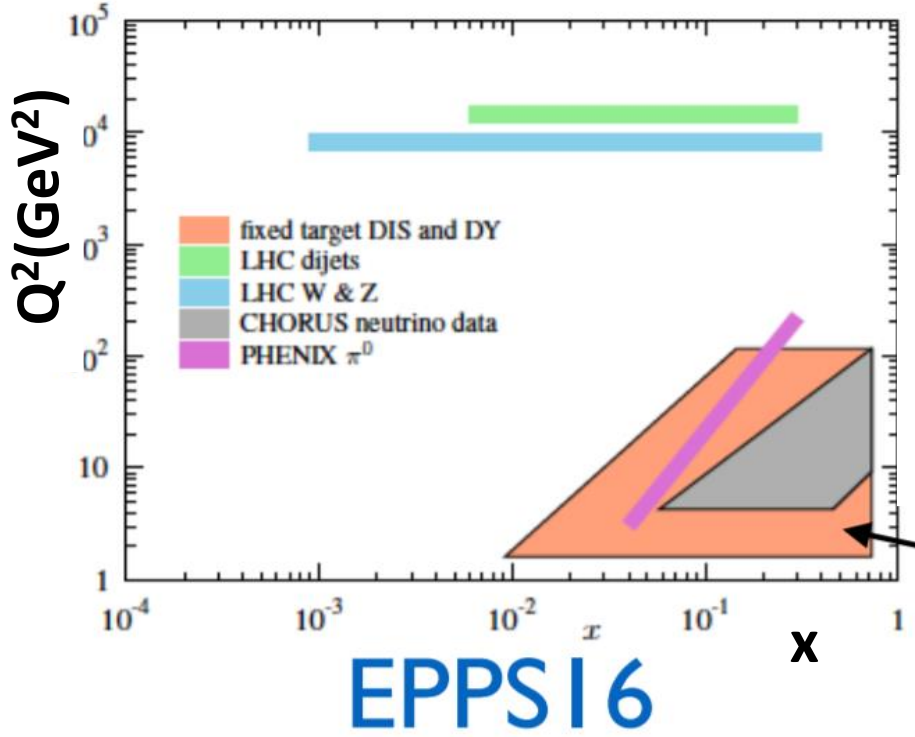
Lead Ion ≠ Superposition of **Neutrons** and **Protons**

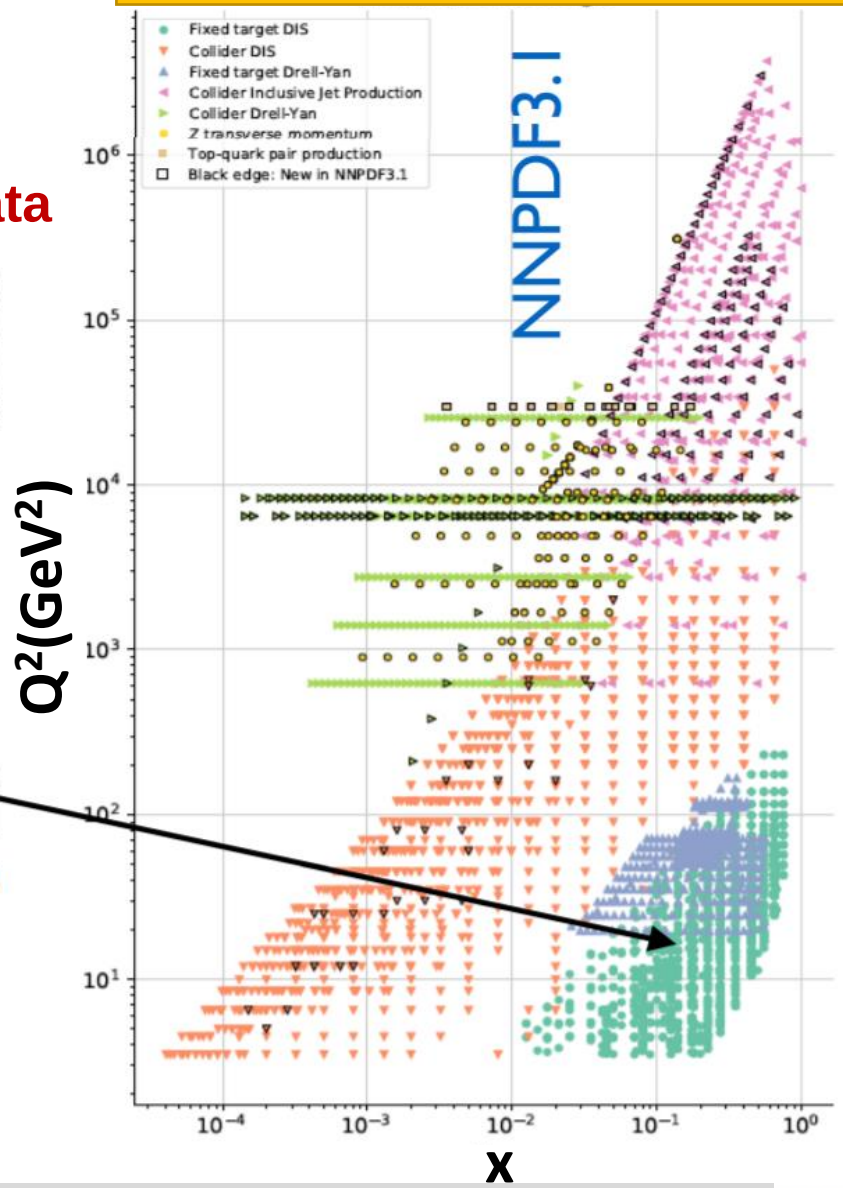
Input Data for Nucleon PDF

Input Data for Ion PDF

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



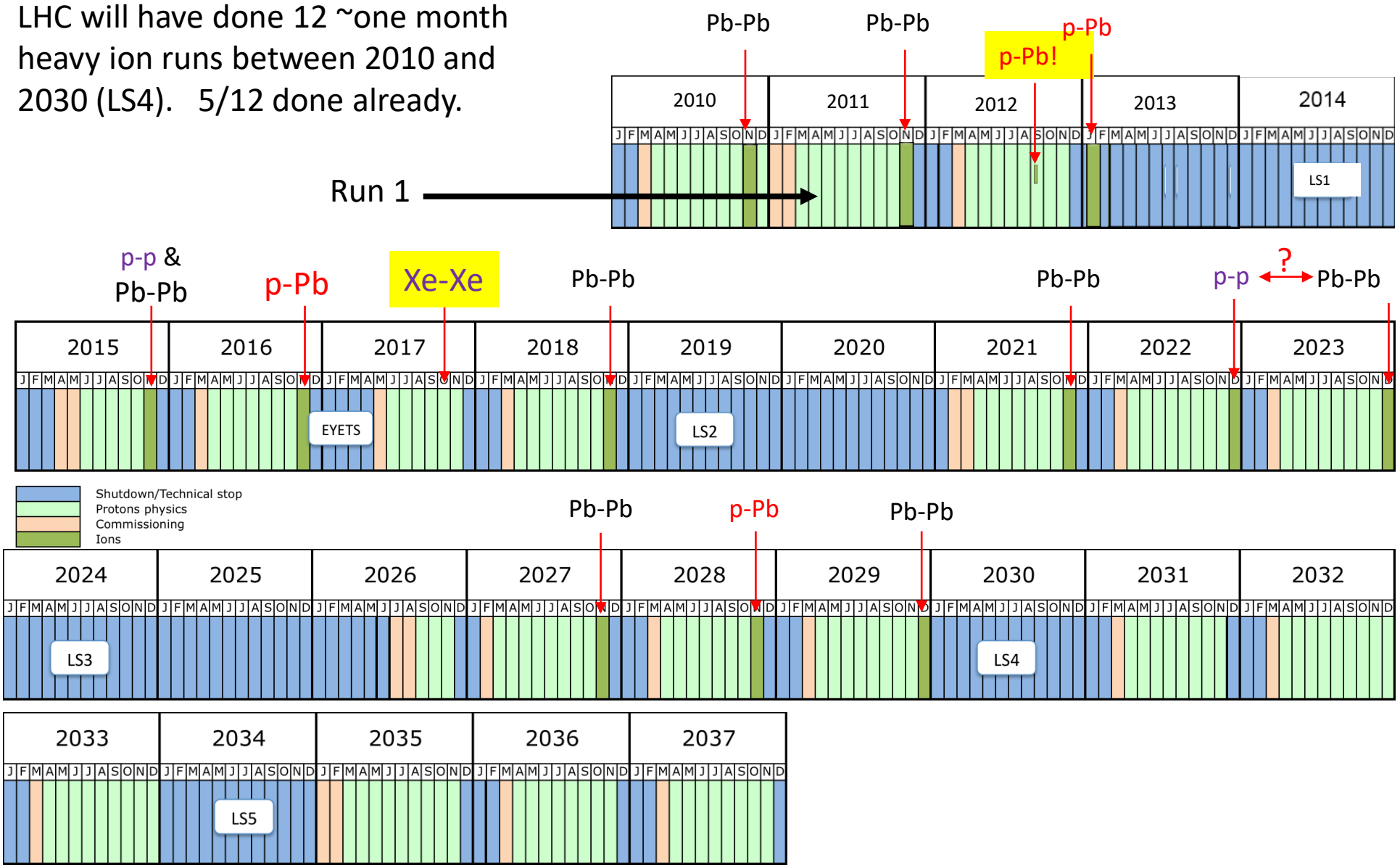




Poor understanding of PDF due to the limited amount of ion data

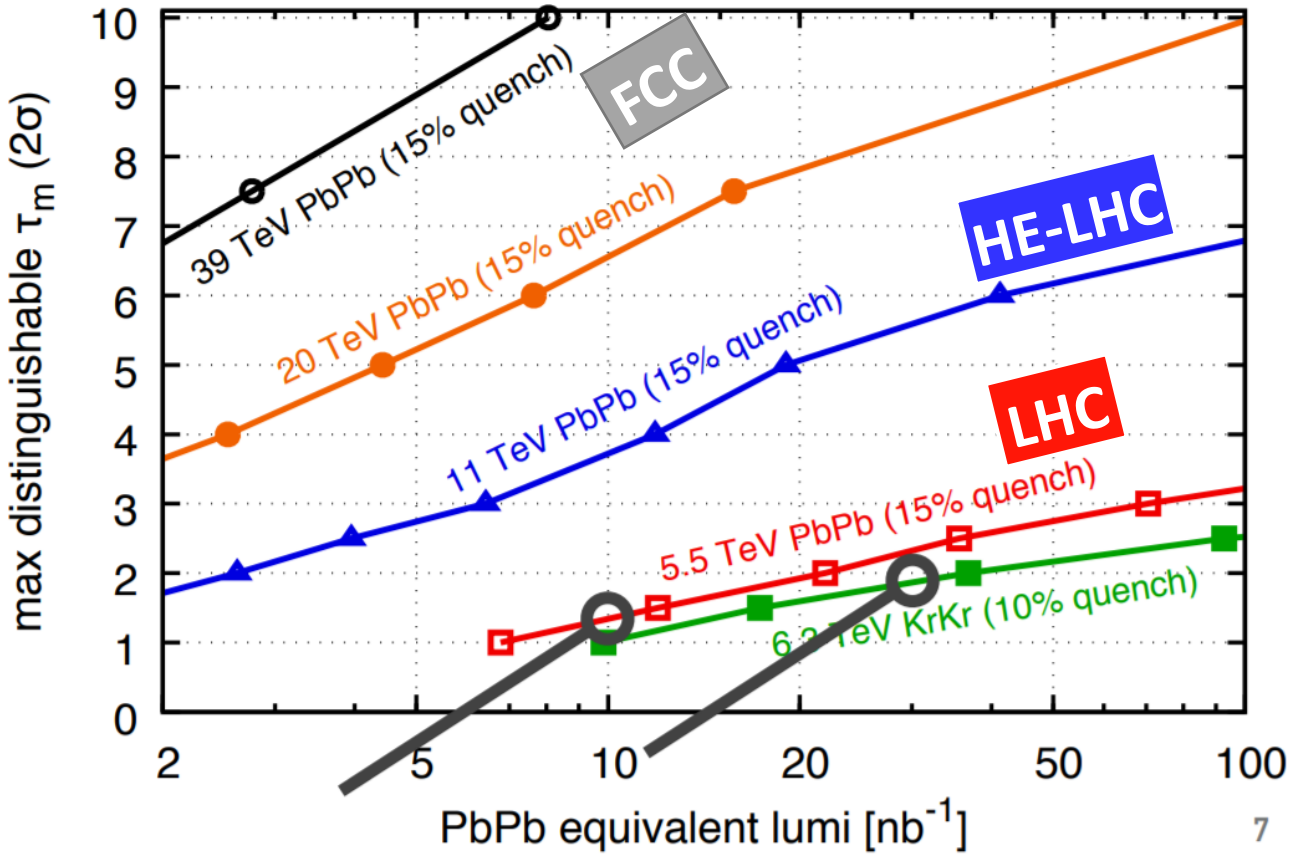
HI Baseline Plan From ALICE 2012 LoI

LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). 5/12 done already.



Sensitivity to the Medium End Time

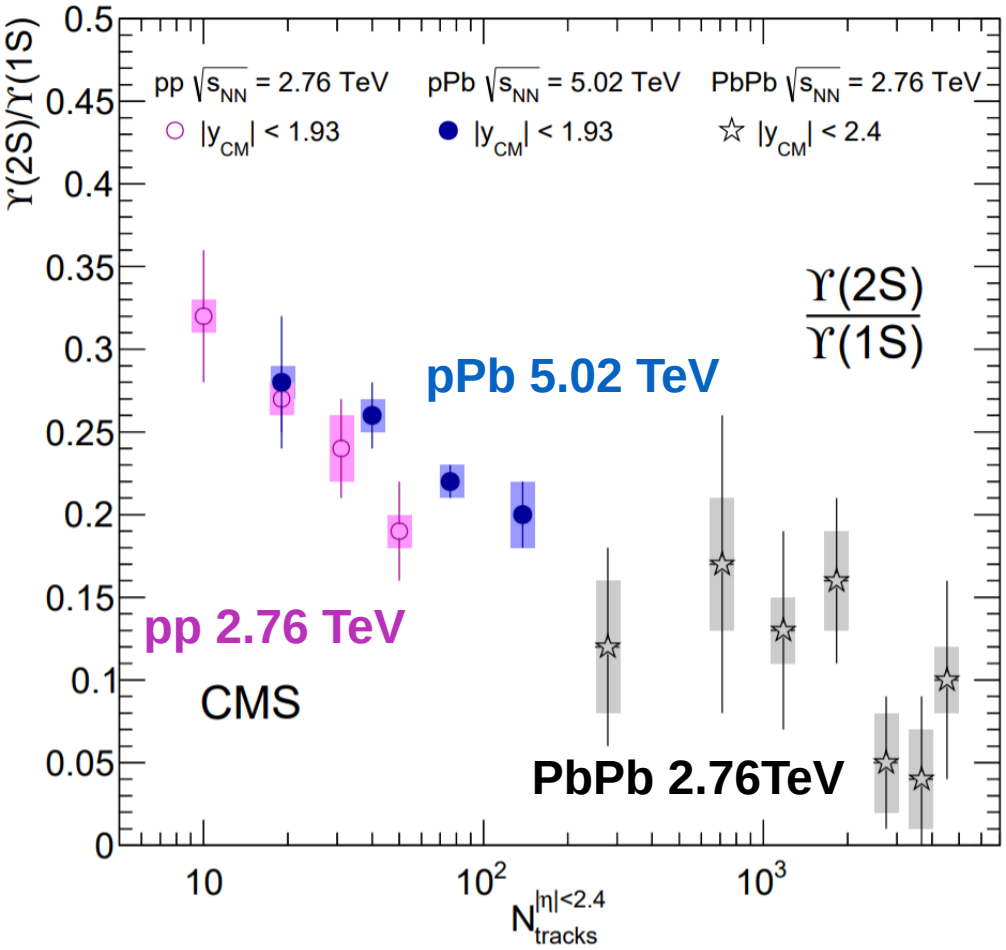
- Sensitivity to medium end time (τ_m):
  - HL-LHC PbPb Program (10 nb^{-1}): 1.4 fm/c
  - 1 month KrKr (30 nb^{-1}): 1.8 fm/c



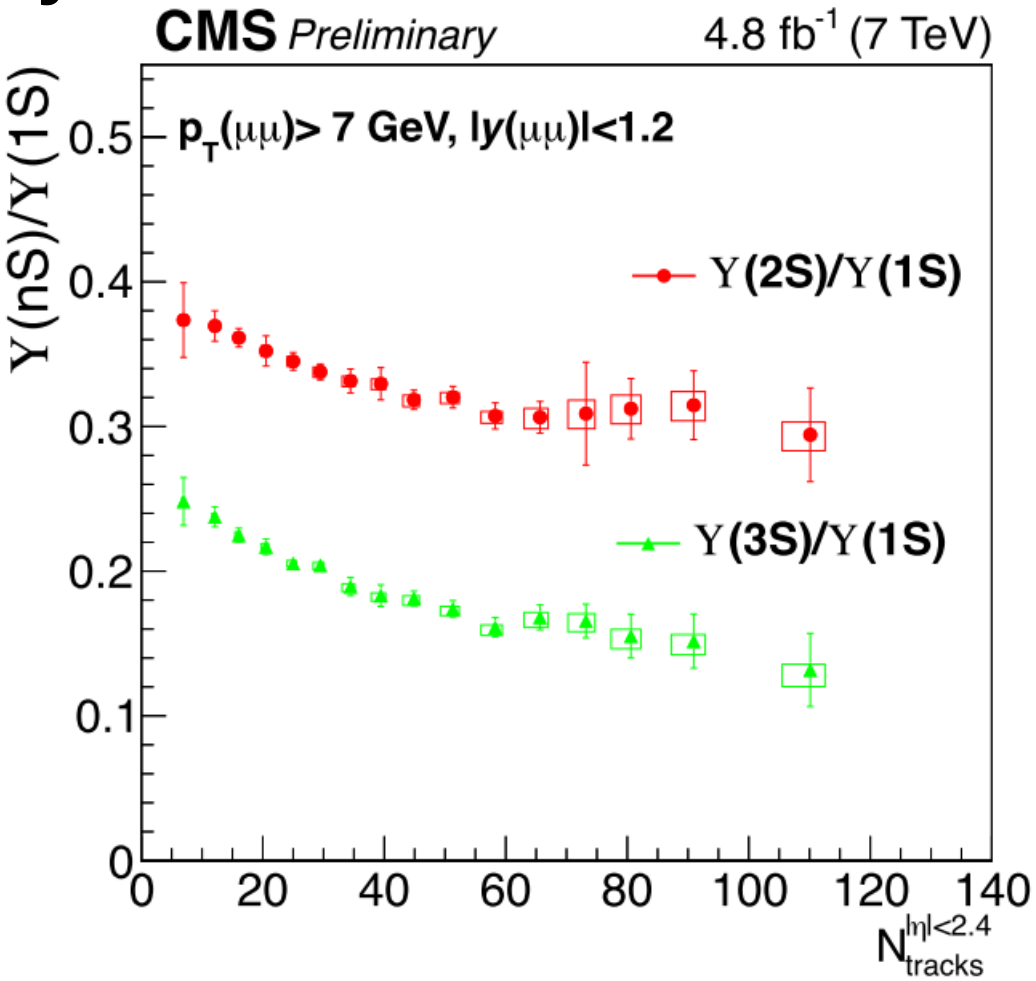
- CMS will allow the first measurement of this probe
- Full exploitation of this probe only at **FCC energies**

Upsilon Sequential Suppression vs. Multiplicity

Y(2S)/Y(1S) ratio vs. multiplicity



pp at 7 TeV



- Origin of the sequential suppression in high multiplicity pp events?

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