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CMS upgrade plan for high-luminosity era & outlook on heavy-quark production in nuclear collisions

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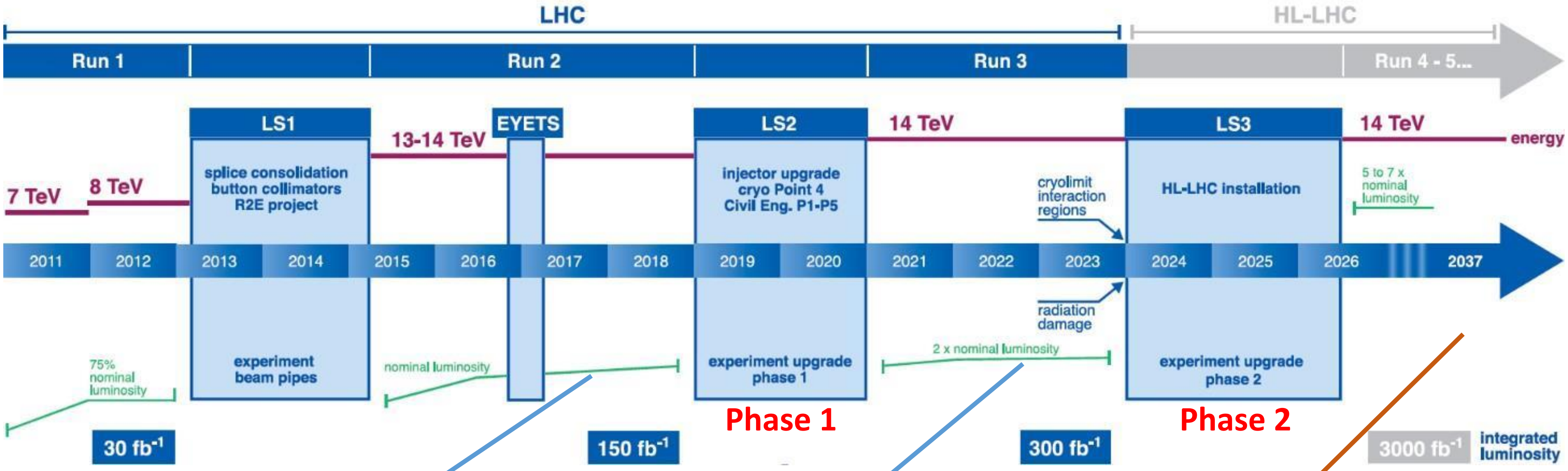
CENuM
Center for
Extreme
Nuclear Matters

Path to high-luminosity (HL) LHC

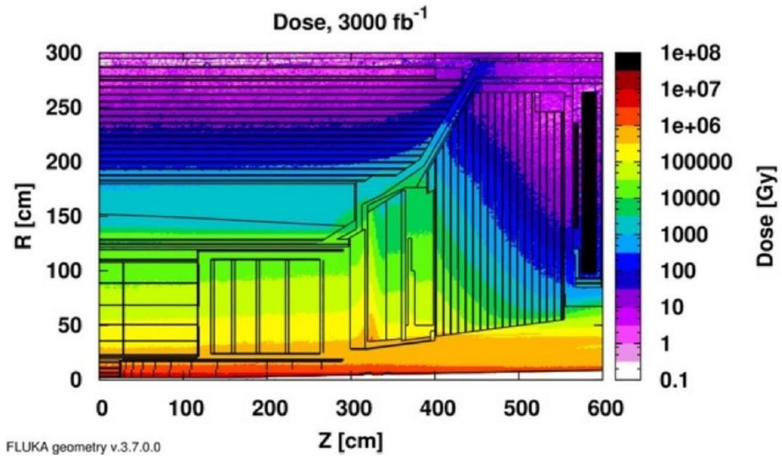


Phase 1

Phase 2

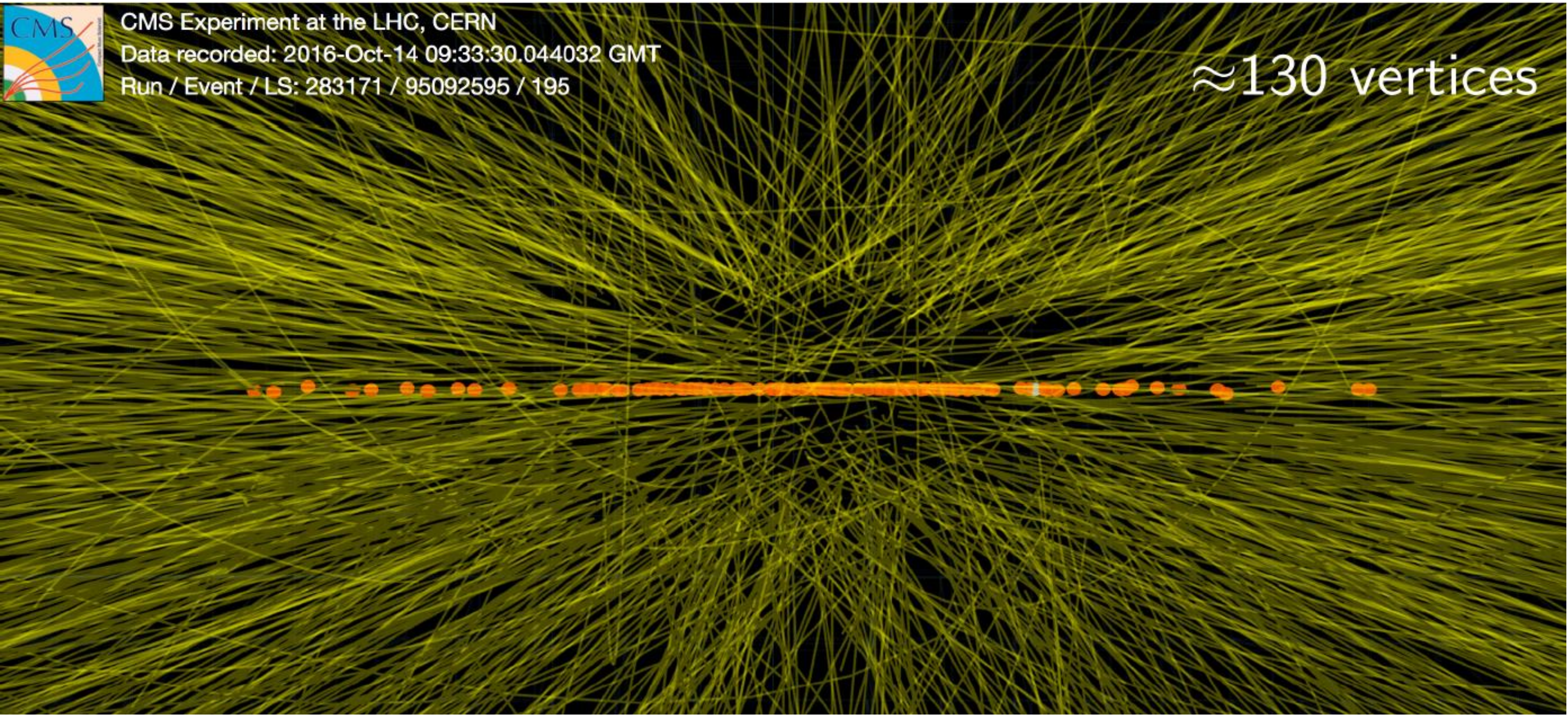
RUN2:
Design $\mathcal{L}_{pp} = 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
for 150 fb^{-1}

RUN3
Design $\mathcal{L}_{pp} = 2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
for 300 fb^{-1}



HL-LHC
Nominal scenario $\mathcal{L}_{pp} = 5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
for 3000 fb^{-1} (Pileup $\langle\mu\rangle \approx 140$)
Ultimate scenario $\mathcal{L}_{pp} = 7.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
for 4000 fb^{-1} (Pileup $\langle\mu\rangle \approx 200$)

LHC pp event with ∼130 vertices

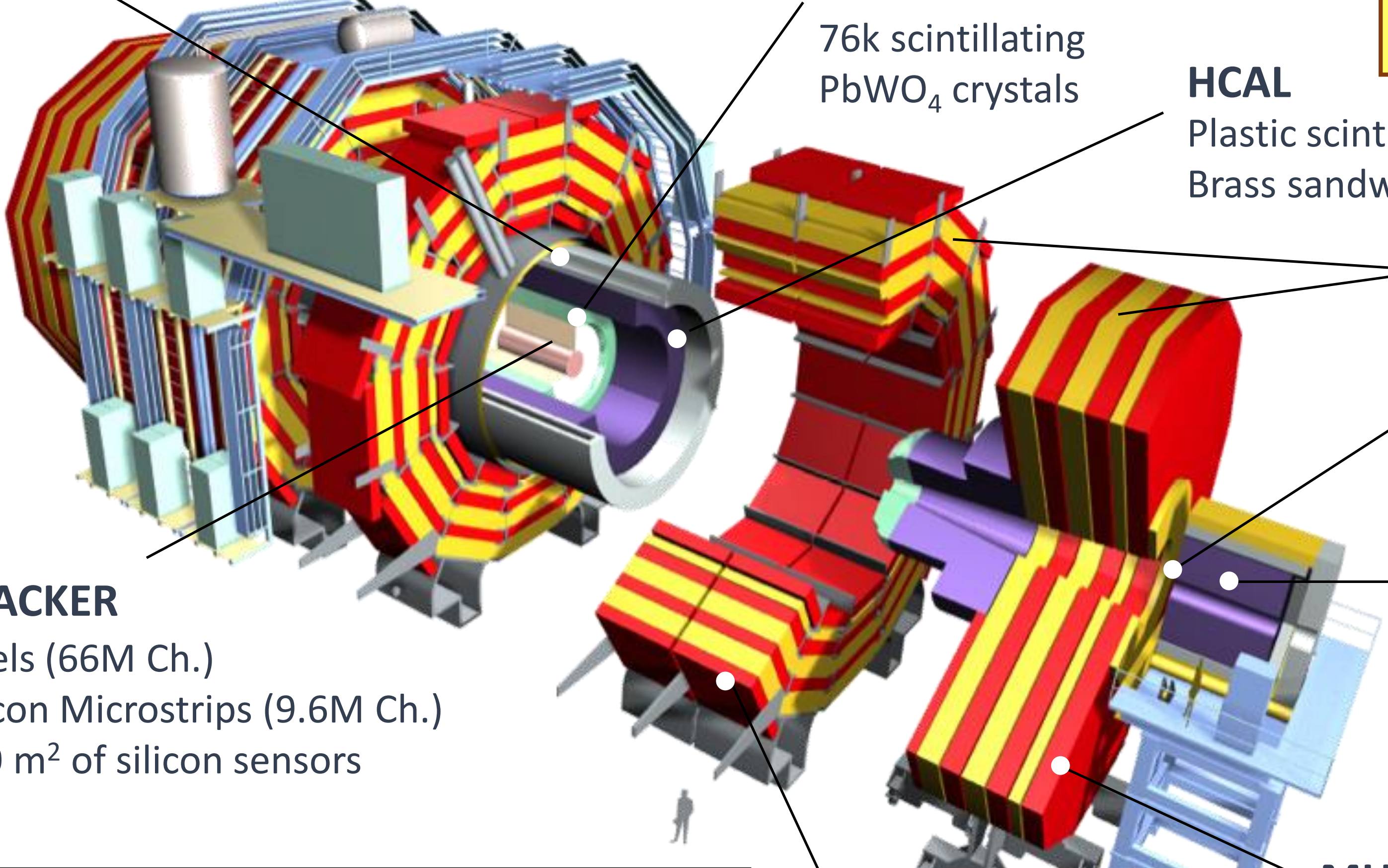


Real-life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches

Current CMS detector

Design to cope with
$\mathcal{L}_{pp} = (1\sim2) \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Weight: 12,500 tons
Diameter: 15 m
Length: 22 m



Superconducting Coil (3.8 T)

CALORIMETERS

ECAL
76k scintillating
$PbWO_4$ crystals

HCAL
Plastic scintillator/
Brass sandwich

Steel YOKE

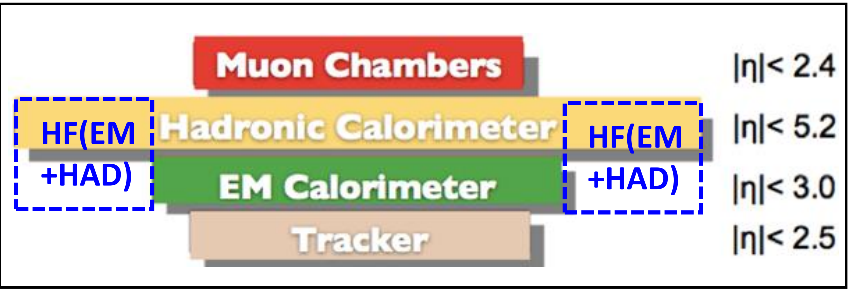
BSC
MB trigger

HF
MB trigger
Centrality in HI

TRACKER
Pixels (66M Ch.)
Silicon Microstrips (9.6M Ch.)
220 m^2 of silicon sensors

MUON BARREL
Drift Tube Chambers
Resistive Plate Chambers

MUON ENDCAPS
Cathode Strip Chambers
Resistive Plate Chambers



CMS Phase-2 upgrade

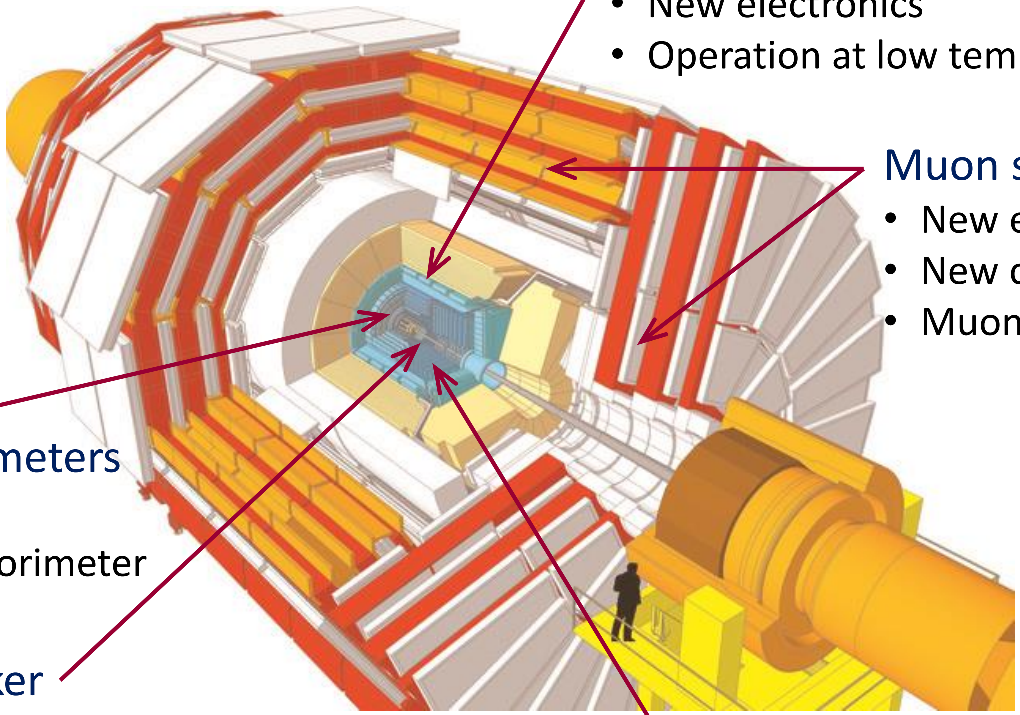
- Purpose
  - To take about 5 × LHC design luminosity
    ⇒ Detectors have to be operated in very high radiation rate
    ⇒ High pileup: 140∼200 events per beam crossing (25 ns)
  - Target for $\int \mathcal{L}_{pp} dt$: 3,000 fb^{-1} (baseline) ∼ 4,000 fb^{-1} (ultimate)
- Detector upgrade
  - Radiation hardness
  - Mitigation of physics impact caused by high pileup
- Physics goals/opportunities
  - Precision Higgs measurements
  - Higgs self coupling
  - Precision electroweak measurements
  - Extension of BSM searches to smaller production cross sections
  - Precision measurements of rare B decays
  - *Heavy-Ion Physics*

CMS Phase-2 upgrade (Overview)

(CMS-TDR-15-002)

Trigger/HLT/DAQ

- Track information in hardware event selection
- 750 kHz L1 hardware event selection rate
- 7.5 kHz HLT rate



Barrel EM calorimeter

- New electronics
- Operation at low temperature $\approx 10^{\circ}$C

Muon systems

- New electronics for DT & CSC
- New chambers in $1.6 < |\eta| < 2.4$
- Muon tagging in $2.4 < |\eta| < 3$

New endcap calorimeters

- Radiation tolerant
- High granularity calorimeter

New tracker

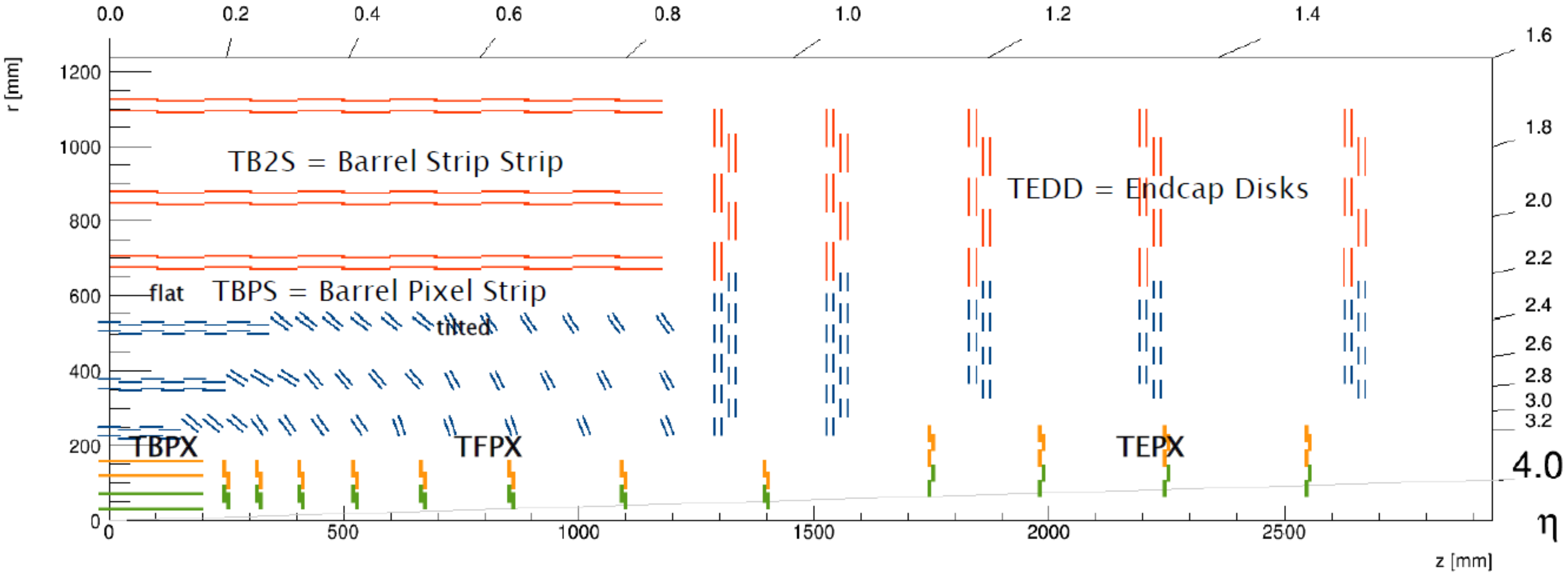
- Radiation tolerant
- Low material budget
- Tracks in hardware trigger
- Extended pixel coverage to $|\eta| \approx 4$

MTD: MIP Timing Detector

- 4D vertexing in high PU pp events
- Possible $p/K/\pi$ separation in $0.7 < p_T < 3$ GeV

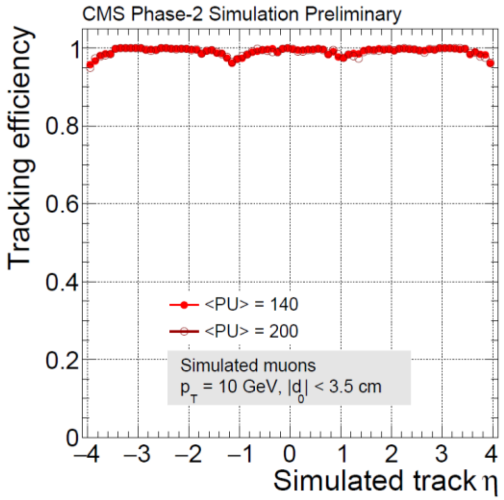
Tracker upgrades

(CMS-TDR-17-001)

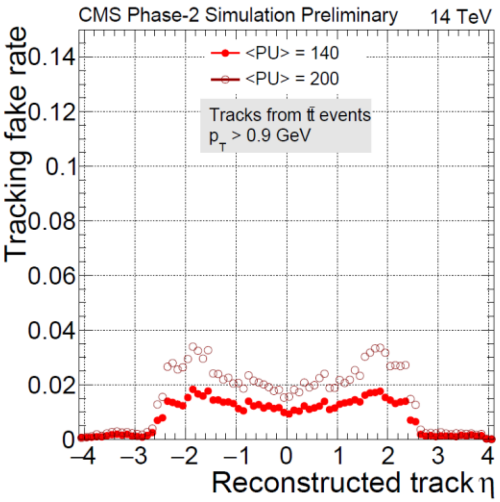


- Tracking detector upgrade to cope with increased amount of radiation and high occupancy
  - Inner tracker (TBPX+TFPX+TEPX): ~2×10^9 pixels for 4.9 m^2
  - Outer tracker: 170M macro pixels (25 m^2) and 42M strips (192 m^2)
- Rapidity coverage of inner tracker extends to $|\eta| = 4$
- Addition of L1 hardware for track trigger capabilities up to $|\eta| = 2.4$
- Large reduction of the material budget

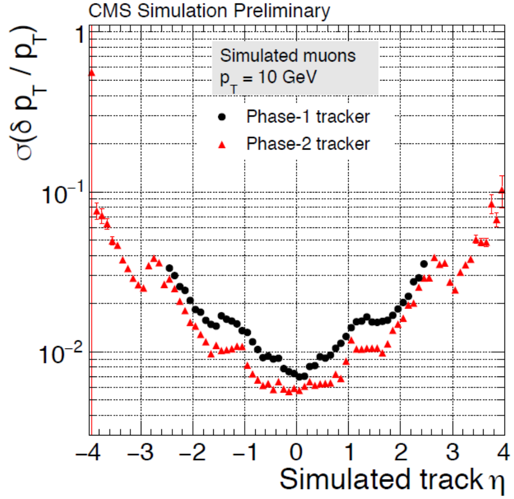
Expected tracker performance (CMS-TDR-17-001)



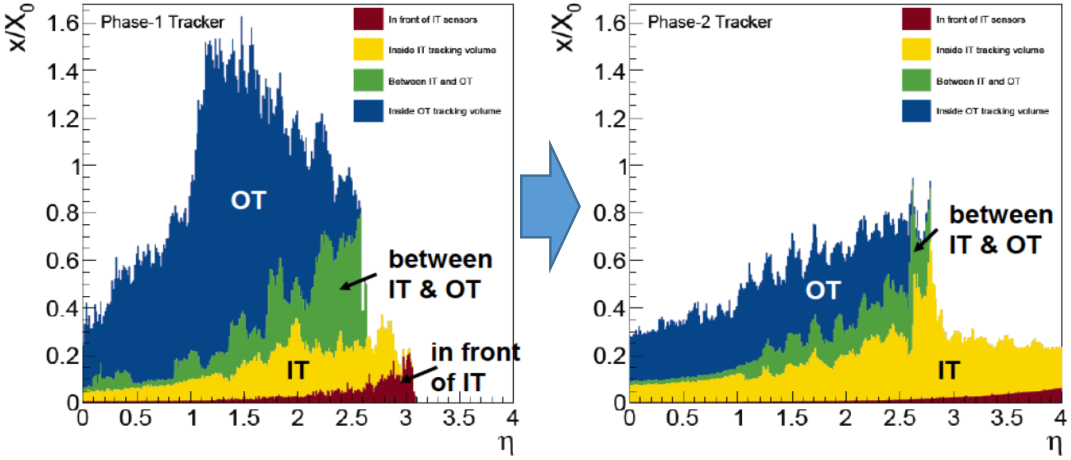
↑ High efficiency across geometrical coverage



↑ Manageable increase of fake rate with pileup



↑ Improved momentum resolution compared to the phase-1 system



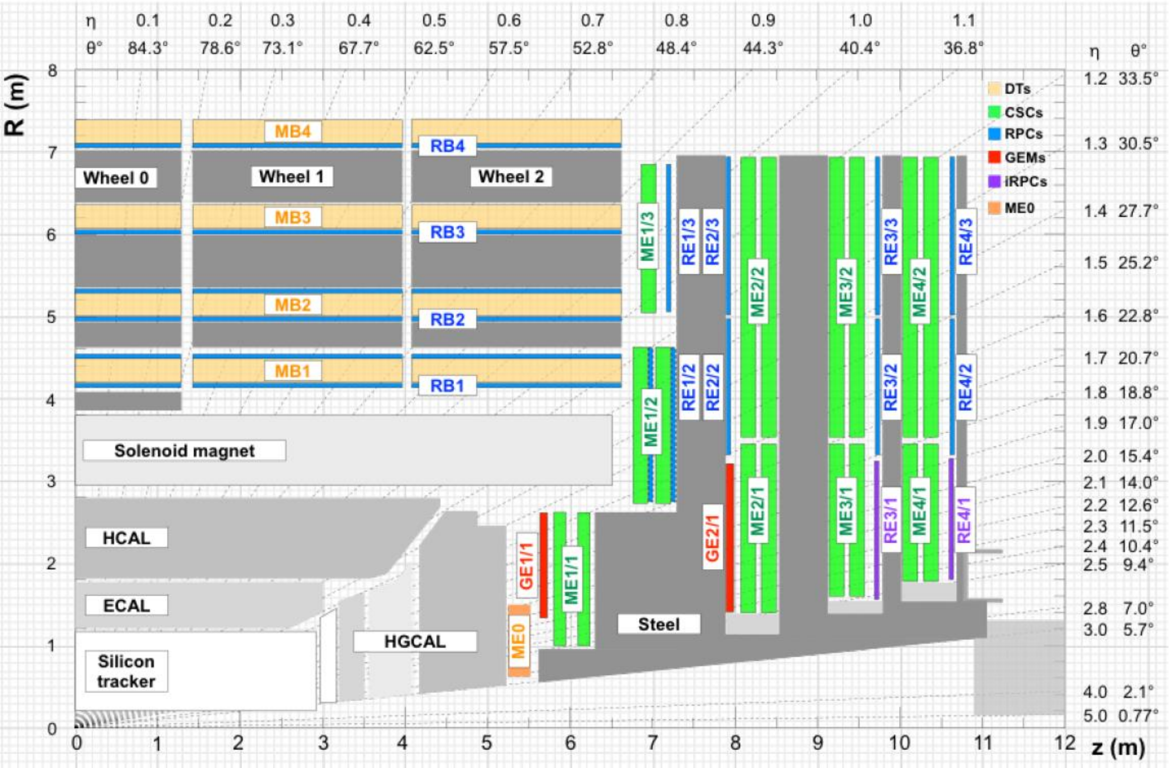
↑ Substantial reduction of the material budget

- Impacts on HI physics
  - Dimuon mass resolution for B_S improves by ~30%.
  - Rel. statistical uncertainty, due to a better S/N ratio, improves by ~10% for $\Upsilon(3S)$ and ~ 30% for $\Upsilon(1S)$.

Muon system upgrades

(Muon system: CMS-TDR-17-003)
(GEM: CMS-TDR-15-001)

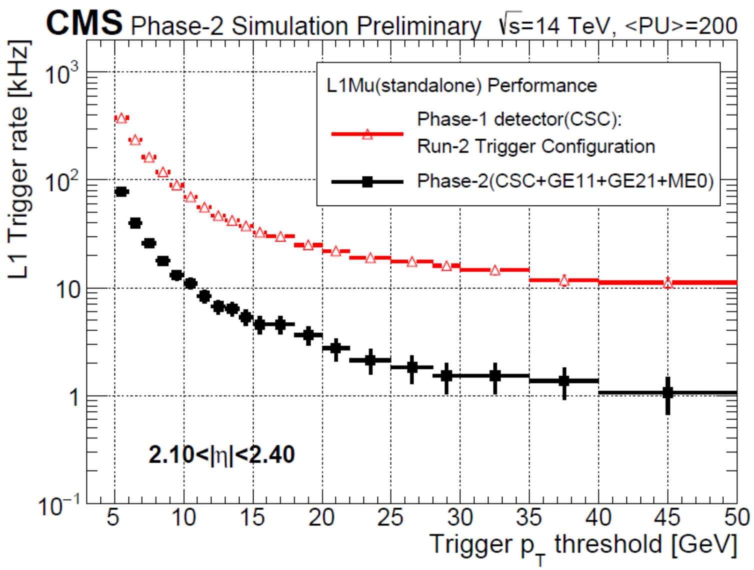
- GE1/1 & GE2/1: Additional GEM based trigger detectors in front of existing muon CSC system
- RE3/1 & RE4/1: Additional RPC's to improve the trigger and reconstruction performance in $1.6 < |\eta| < 2.4$



- ME0: GEM chamber extending the muon system coverage to $|\eta| = 2.8$
- Upgrade of DT and CSC electronics for radiation hardness and better trigger & readout requirements

Expected L1 muon trigger performance

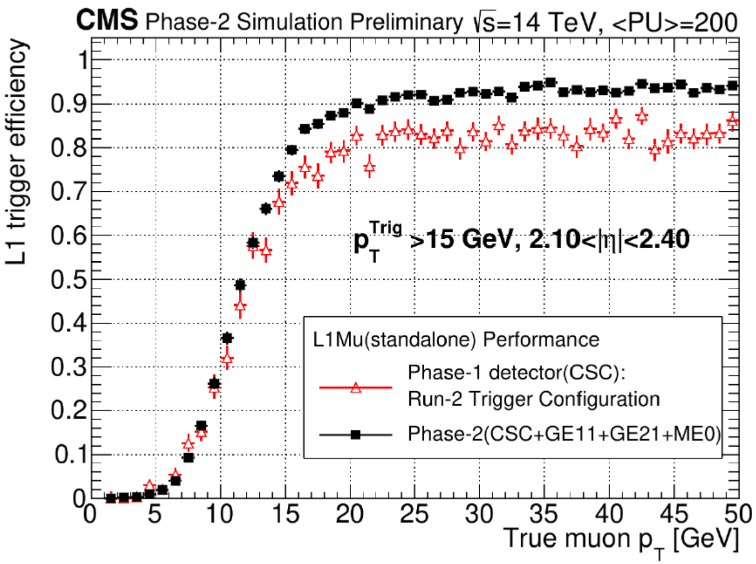
(CMS-TDR-17-004)

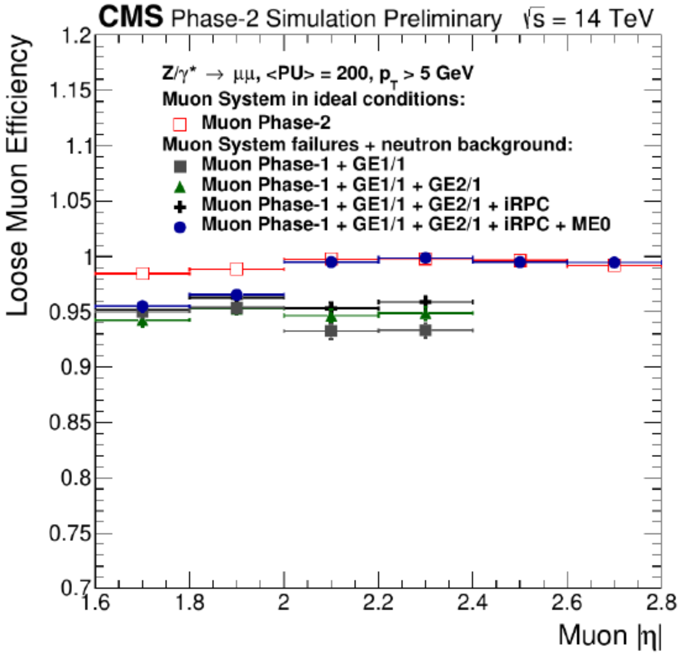


← Drastically reduced L1 trigger rate at a given threshold

↙ Increased L1 trigger efficiency

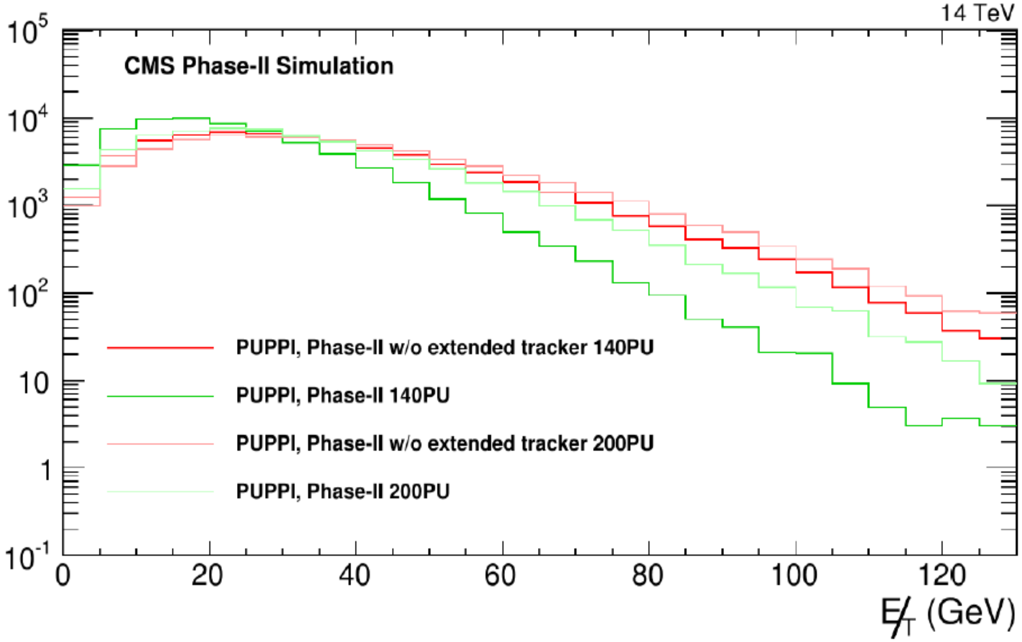
↓ Extended highly efficient offline muon reconstruction and identification up to $|\eta| = 2.8$





Impact of pileup

- Interactions distributed within a spread of 150~200 ps
- Significant on physics reach
  → E.g., missing E_T & jet fake rate largely affected by pileup
- Beam-spot slice in $\mathcal{O}(30)$ ps time bins: effective pileup reduced by factor of 4~5.

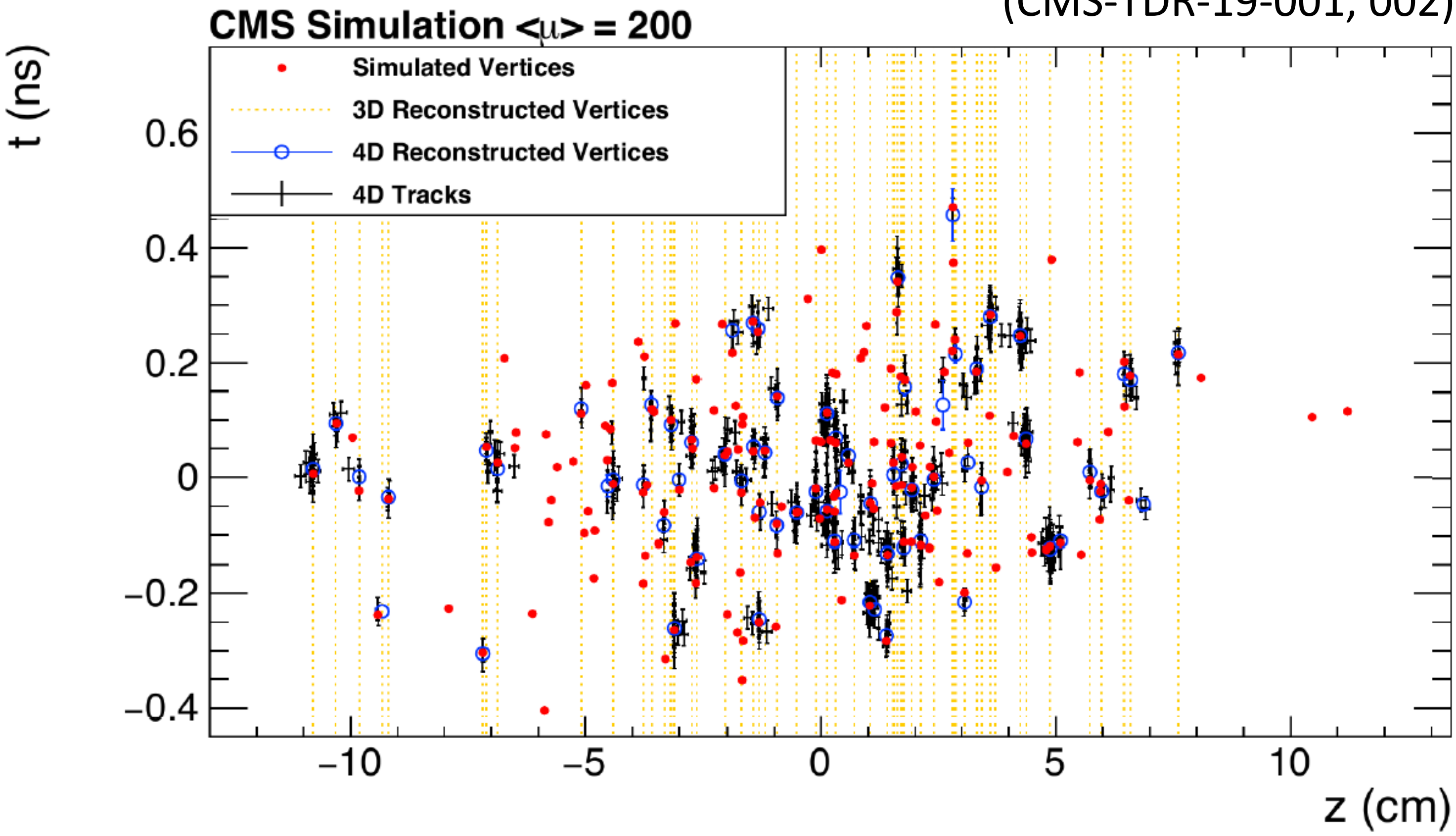


- Calorimeter upgrades: Precision timing of showers (CMS-TDR-17-002, 007)
  - High-energy photons in ECAL
  - All photons and high-energy hadrons in HGC
- MTD: MIP Timing Detector: Precision timing of tracks (CMS-TDR-19-001, 002)
  - A single layer between the tracker and the calorimeters
  - (Barrel) LYSO+SiPM, (Endcap) Si with internal gain (LGAD) for $p > 0.7$ GeV
  - PID: Possible $p/K/\pi$ separation in $0.7 < p_T < 3$ GeV

Pileup impact mitigation: precise timing

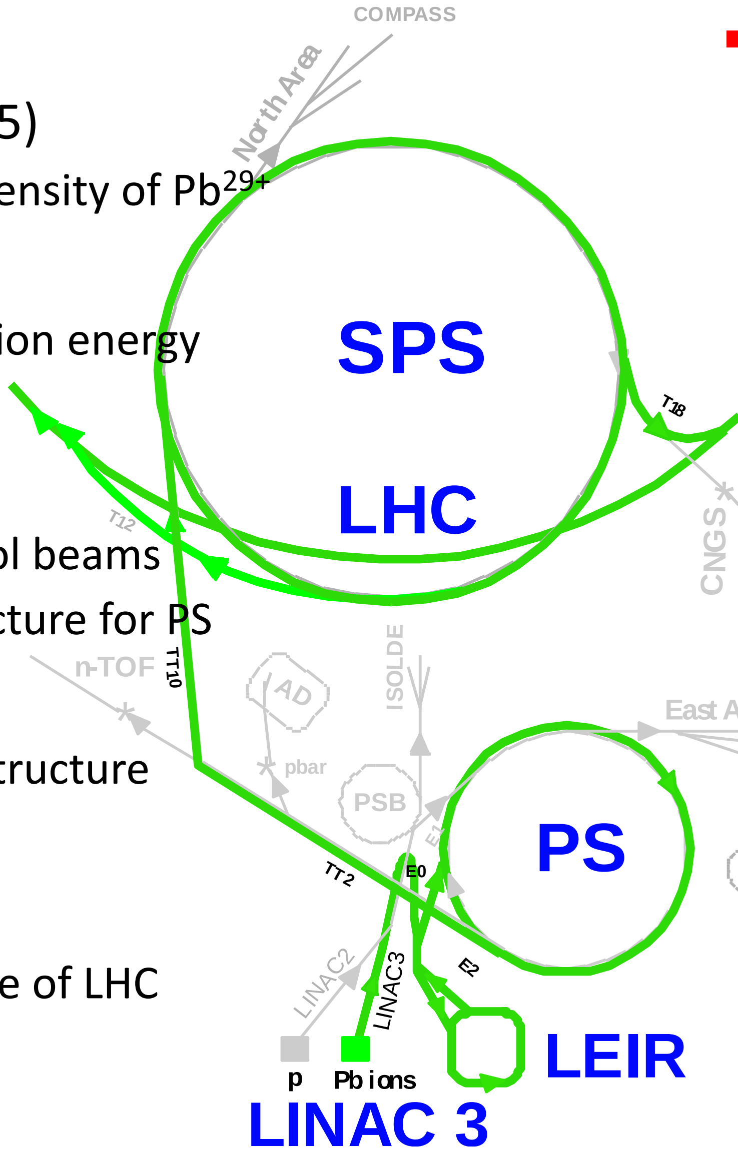
- With sufficient time resolution and coverage for charged particles, traditional three-dimensional vertex fit can be upgraded to a four-dimensional fit

(CMS-TDR-19-001, 002)

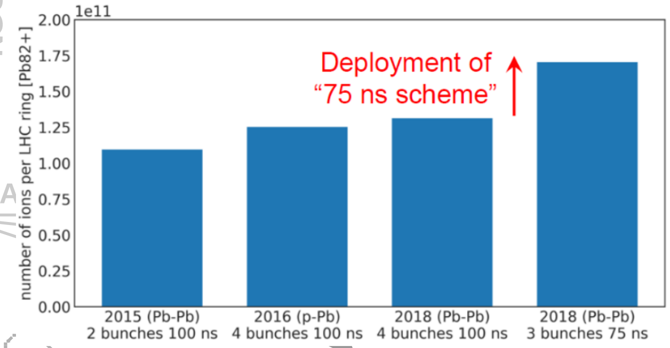


LHC heavy-ion injector chain

- ECR ion source (2005)
  - Highest possible intensity of Pb^{29+}
- RFQ + LINAC 3
  - Adapt to LEIR injection energy
  - Strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool beams
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC



- **Improvement for RUN3**
  - New “75 ns” bunch spacing scheme, introduced in 2018, increases both the number of circulating bunches and bunch intensity



  - Injector upgrades: slip-stacking in SPS

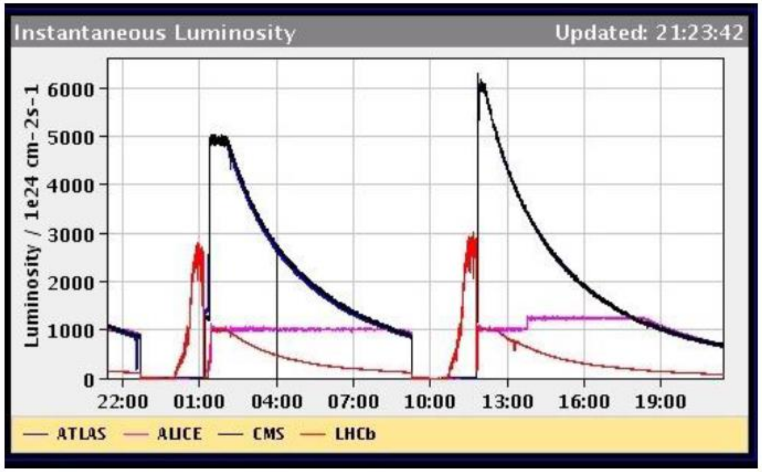
LHC heavy-ion runs (RUN 3+4)

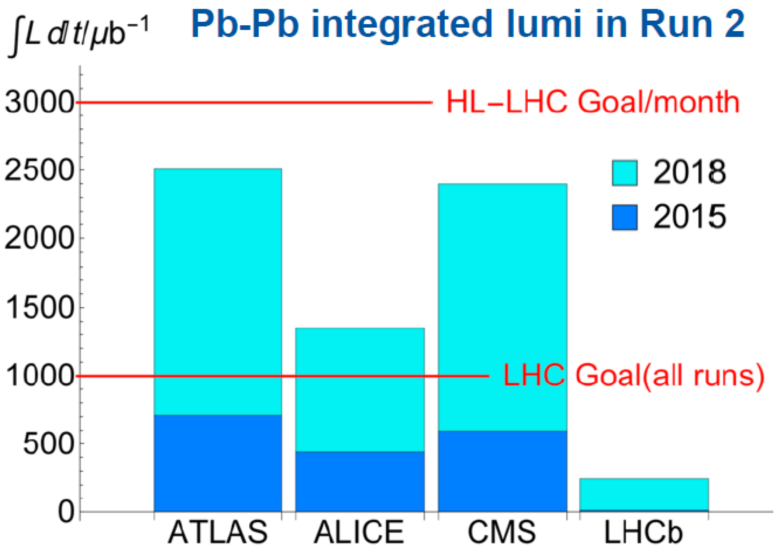
- Current status
  - → HL-LHC instantaneous luminosity (6×10^{27} cm^{-2}s^{-1}), which is 6 times LHC design value, was already demonstrated in 2018.
  - ↘ Integrated PbPb luminosity in 2015 & 2018 runs largely exceeded the "LHC phase-1" goal (1 nb^{-1}).
- Goals *(from the YR, not yet endorsed by LHCC)*
  - PbPb: 13 nb^{-1} at 5.5 TeV
  - pPb: 2 pb^{-1} at 8.8 TeV
  - pp: 200 pb^{-1} at low pile-up ($\mu = 1{\sim}2$)
  - Possibly light-ion runs
- Trigger/DAQ
  - Muons, displaced track triggers, jets, ⋯
  - Strong data reduction needed:

(2018) 50 kHz $\xrightarrow{\text{L1}}$ ~30 kHz $\xrightarrow{\text{HLT}}$ 7 kHz

(Run3+4) Even larger reduction will be needed.

Pb-Pb luminosity record in 2018

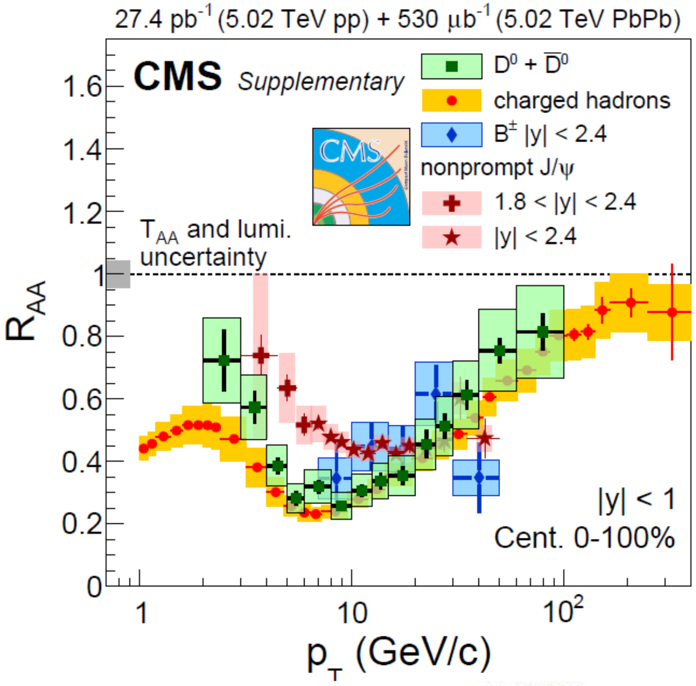


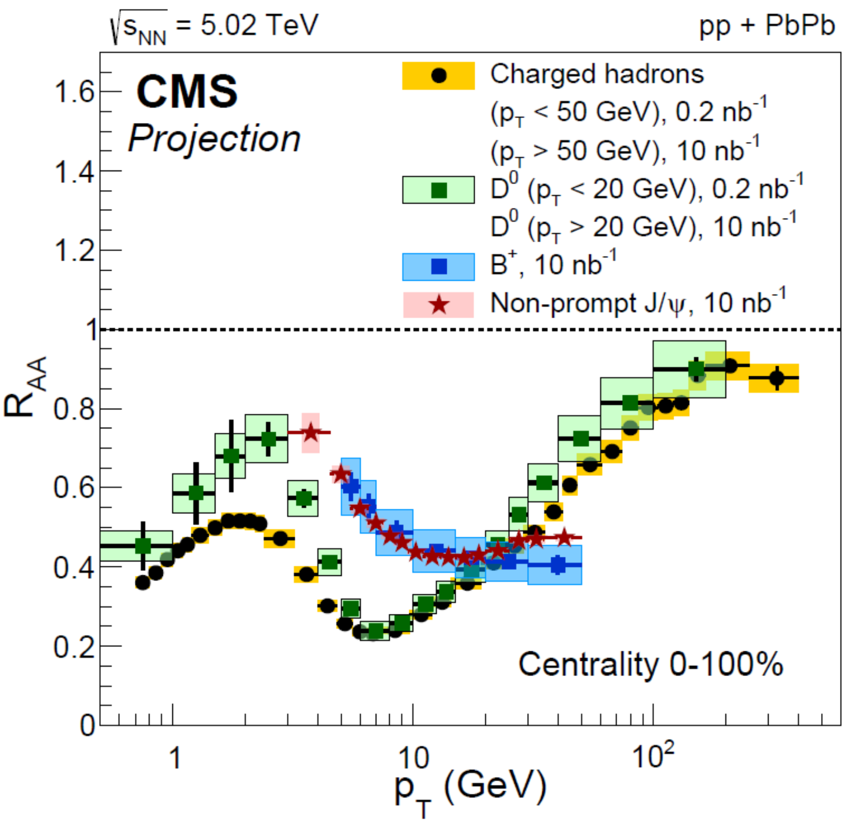


R_{AA} of heavy flavors

(CMS-PAS-FTR-17-002)

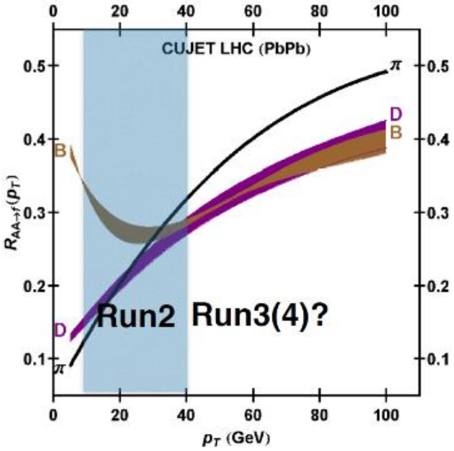
1708.04962





PbPb min. bias trigger: 0.2 nb^{-1}
PbPb high-p_T trigger: 10 nb^{-1}
pp: 650 pb^{-1} with low/limited pileup

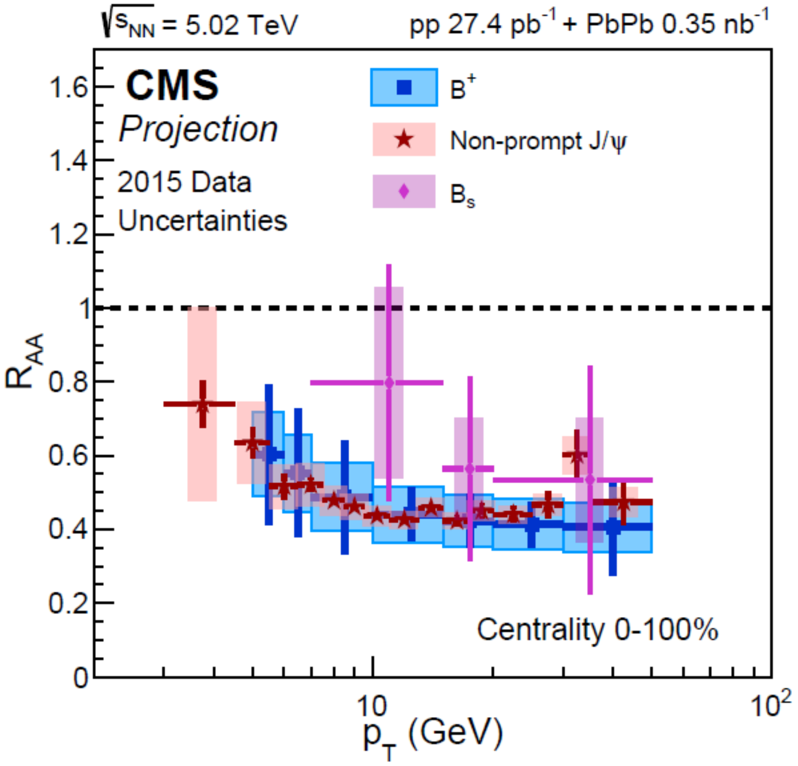
arXiv:1207.6020

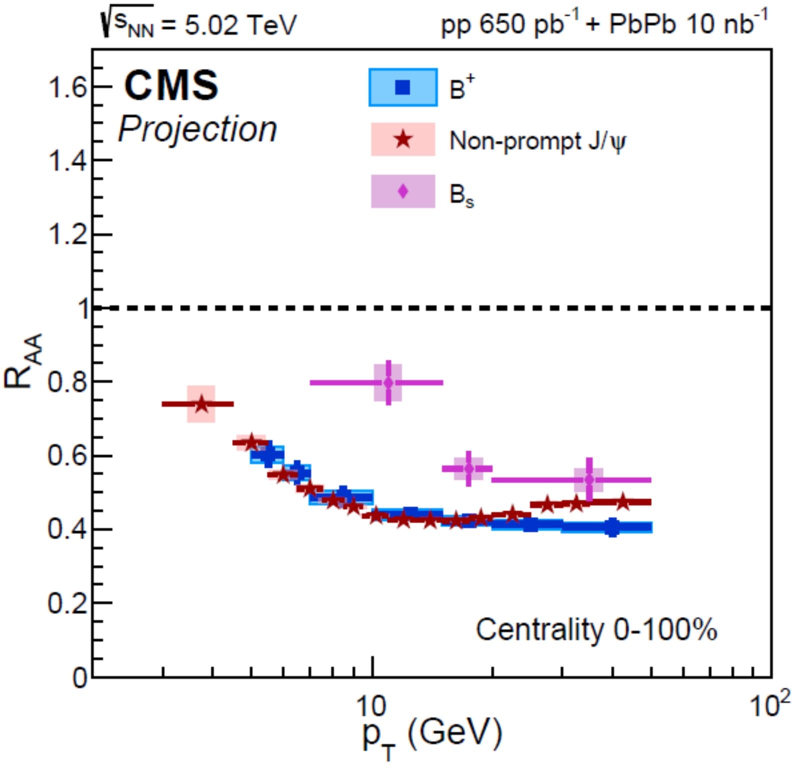


← Flavor dependence of parton energy loss and jet quenching

R_{AA} of B_S

(CMS-PAS-FTR-18-024)





↑ Current uncertainties of R_{AA} from the analysis of 2015 PbPb data (arXiv:1810.03022)

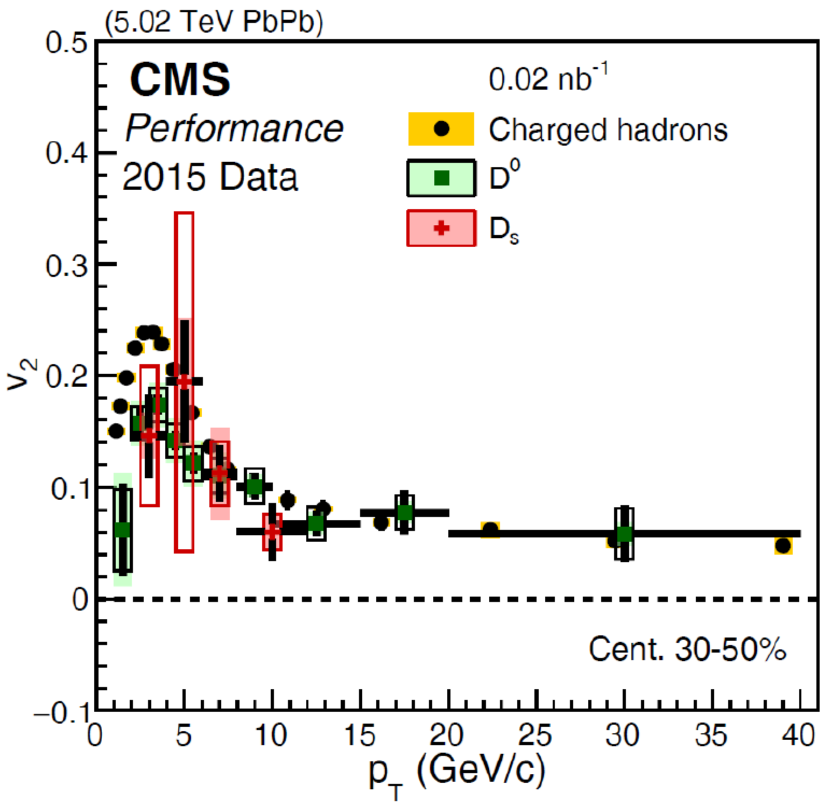
↑ Projection of R_{AA} for 10 nb^{-1}

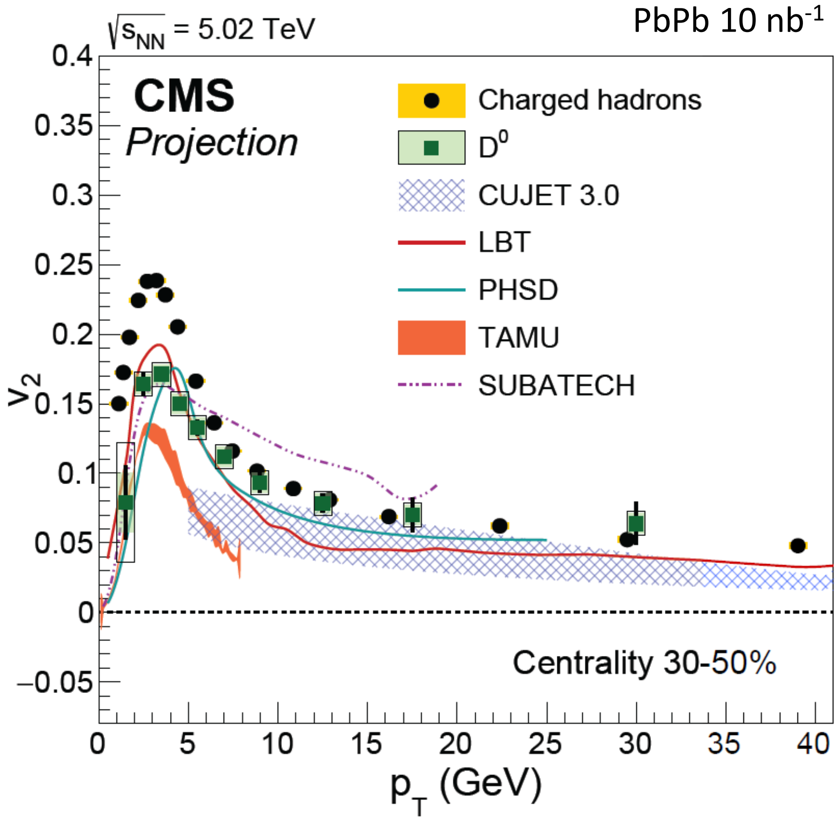
↑ Keep the current uncertainties for B^{+} and non-prompt J/ψ

⁂ *Central values are taken from TAMU.*

v_2 of D^0

(CMS-PAS-FTR-17-002)

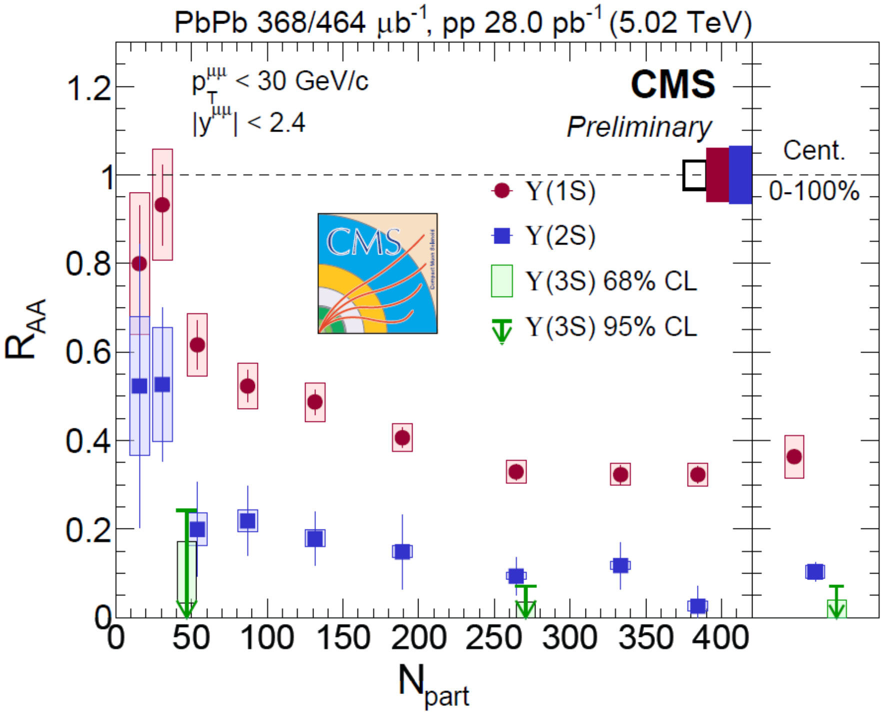




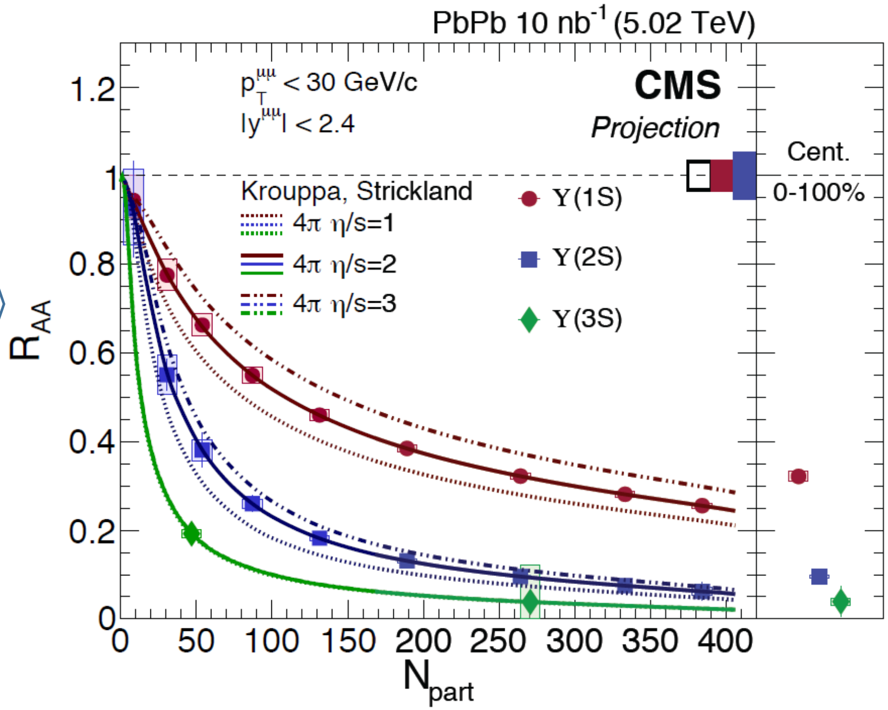
- Powerful constraint on the *c* quark diffusion coefficient and pathlength dependence of the parton energy loss

R_{AA} of Υ states

(PLB790, 270 (2019))



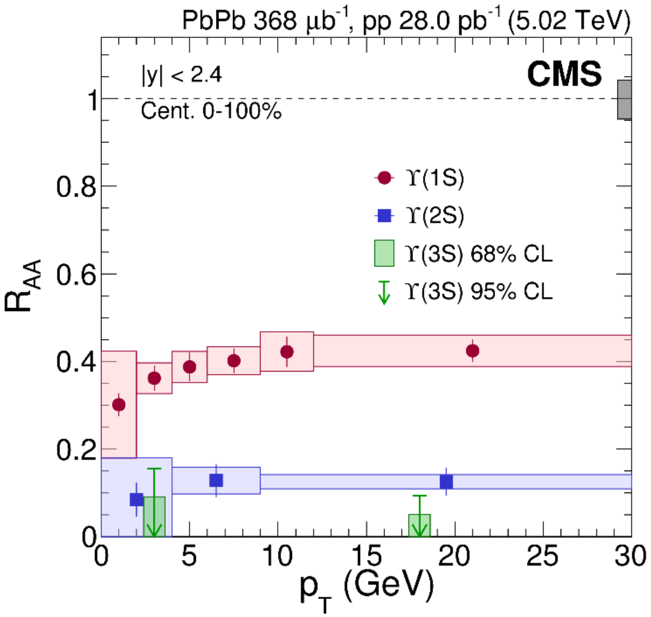
(CMS-PAS-FTR-17-002)



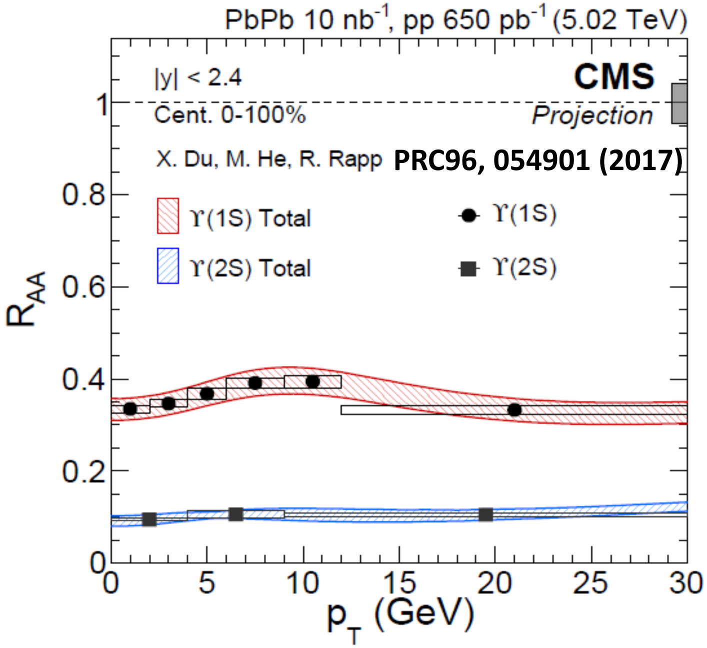
- Expect that $\Upsilon(3S)$ suppression measurement, not just upper limit, is possible!

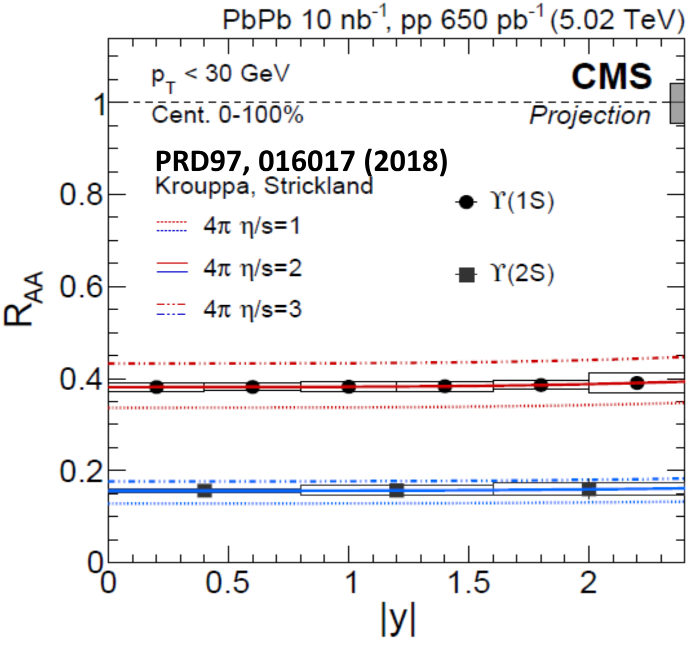
R_{AA} of Υ states

→ Current status of Υ states (PLB790, 270 (2019))



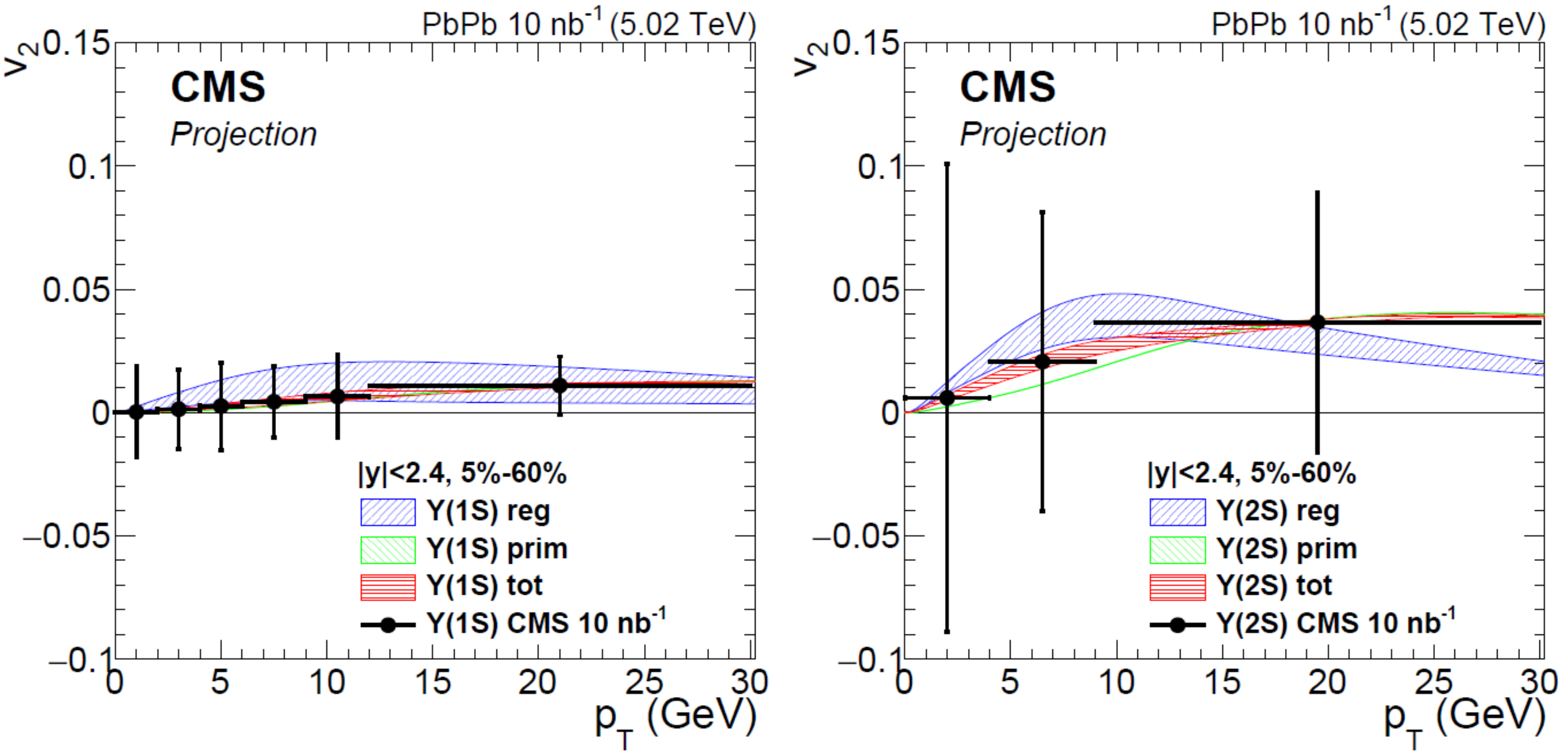
↓ Expected sensitivity guided by hydro-dynamics model, assuming the reduction of total systematic uncertainties by 1/3 (CMS-PAS-FTR-18-024)





v_2 of Υ states

(CMS-PAS-FTR-18-024)

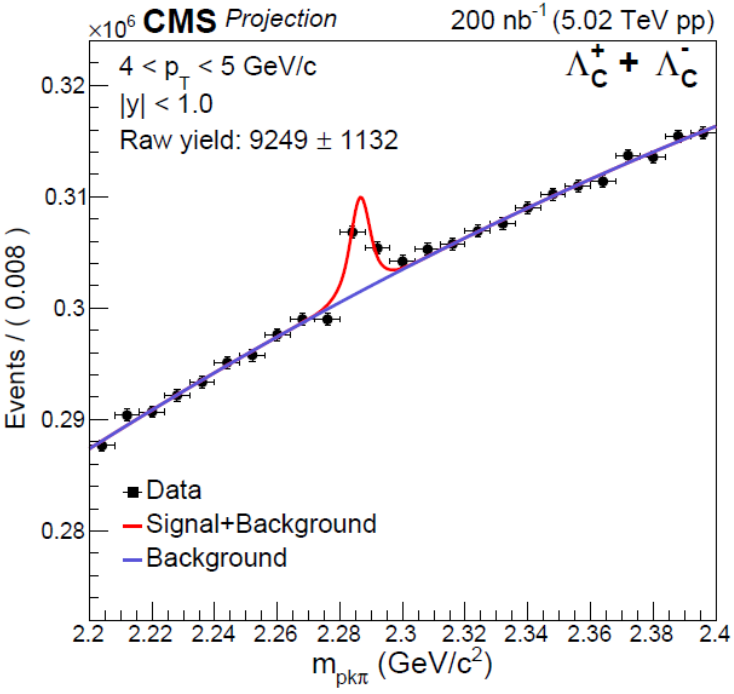


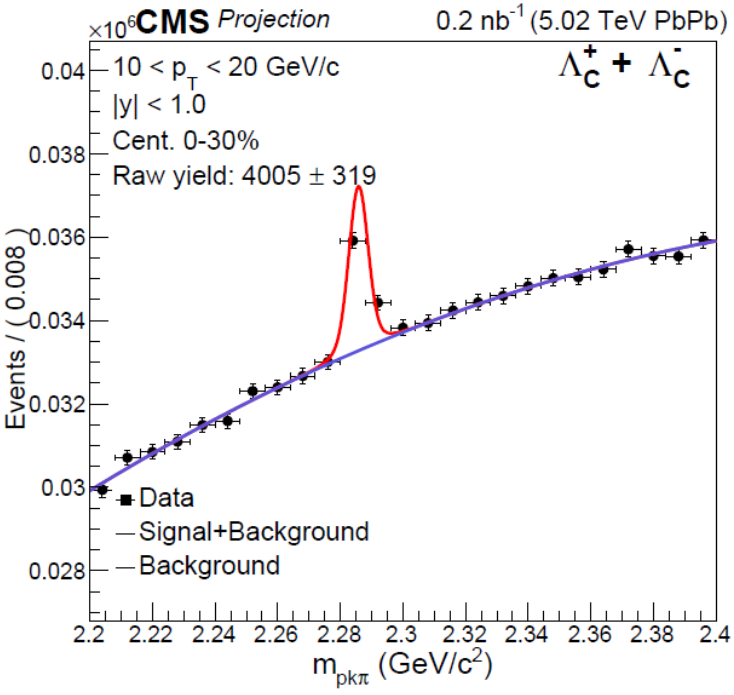
- Expected statistical precisions are shown.
- Statistics are too low to make any conclusive statement, assuming the model predictions in PRC96, 054901 (2017) are correct.

Λ_c^+

Projected data with minimum bias trigger based on 2015 data analysis

- 5~6 times more statistics & extension to lower p_T region down to 4 GeV/c compares to CMS-PAS-HIN-18-019
- More bins with better precision





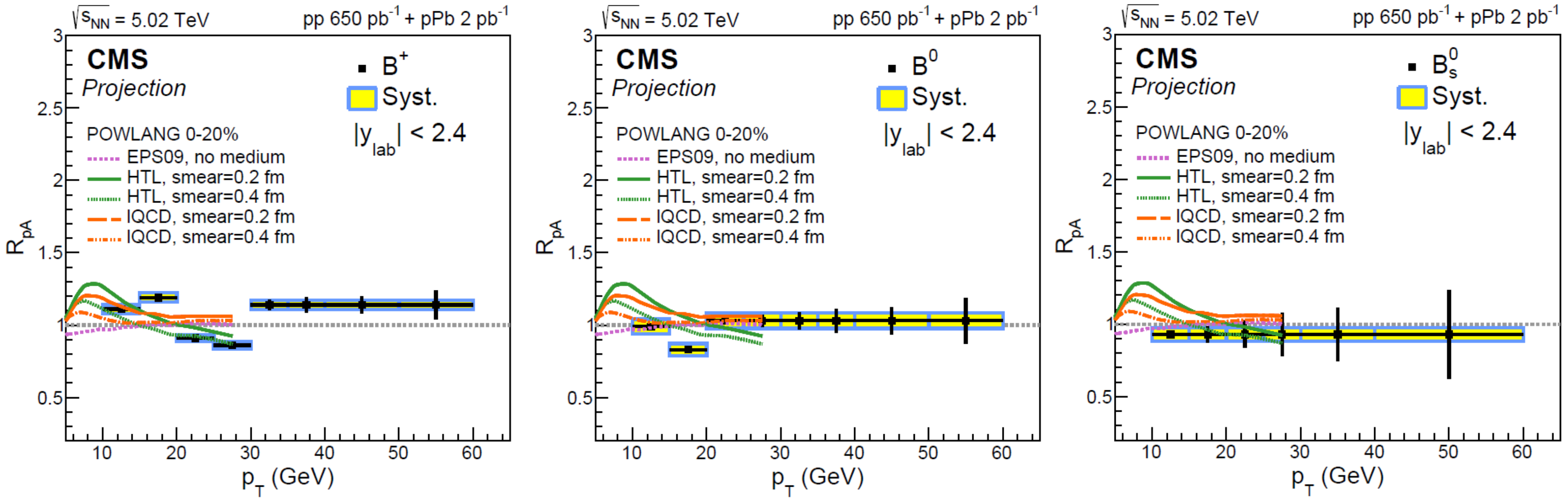
(CMS-PAS-FTR-18-024)

- Important for heavy-quark transport and fragmentation via coalescence.

R_{pA} for B^+, B^0 and B_S

Projected data for 2 pb^{-1} pPb data

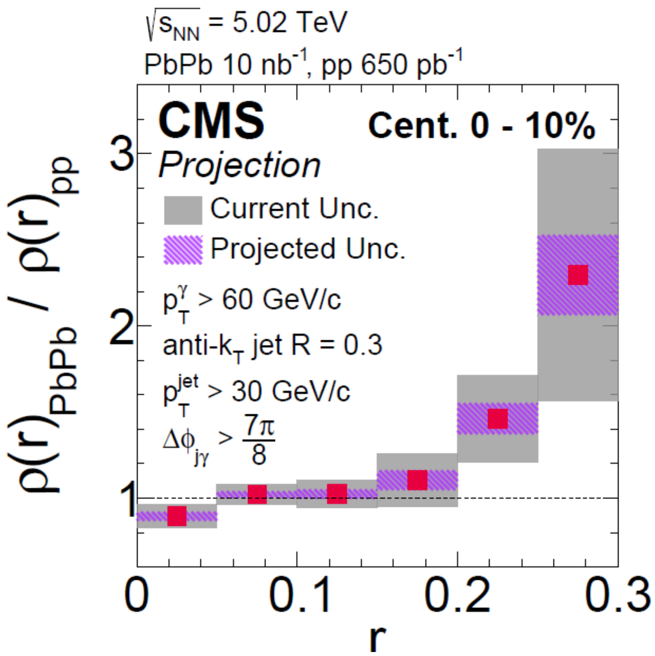
(CMS-PAS-FTR-18-024)



- Data points are from POWLANG model with different assumptions on transport coefficients and smearing of initial condition. [A. Beraudo et al., JHEP03, 123 (2016)]
- It is desired to extend the coverage to $p_T < 10$ GeV/c.
  - Possible with non-prompt D measurement in the future

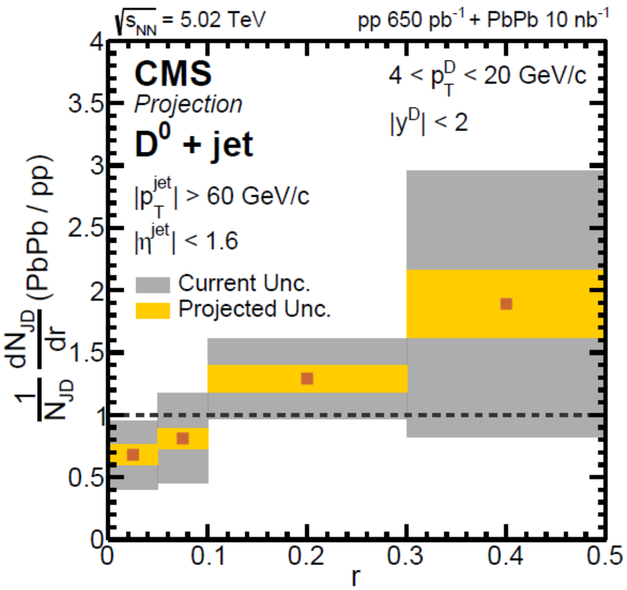
Jet quenching in pp & PbPb

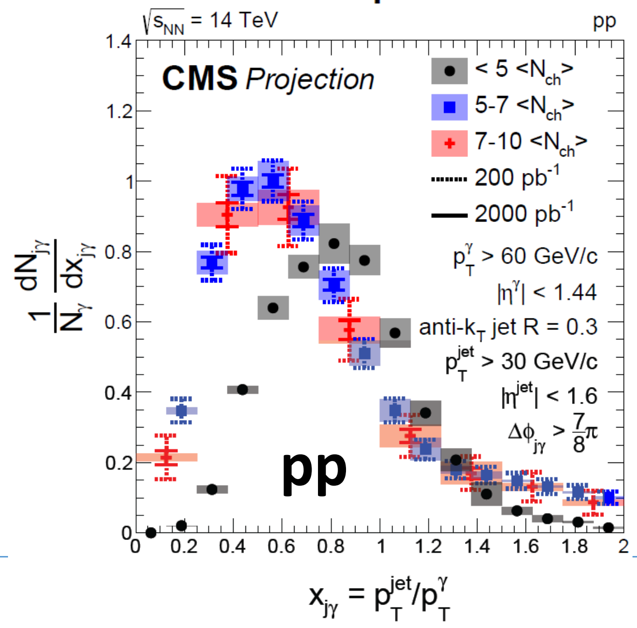
(CMS-PAS-FTR-18-025)



← Ratio of particle densities in γ-tagged jets in PbPb & pp

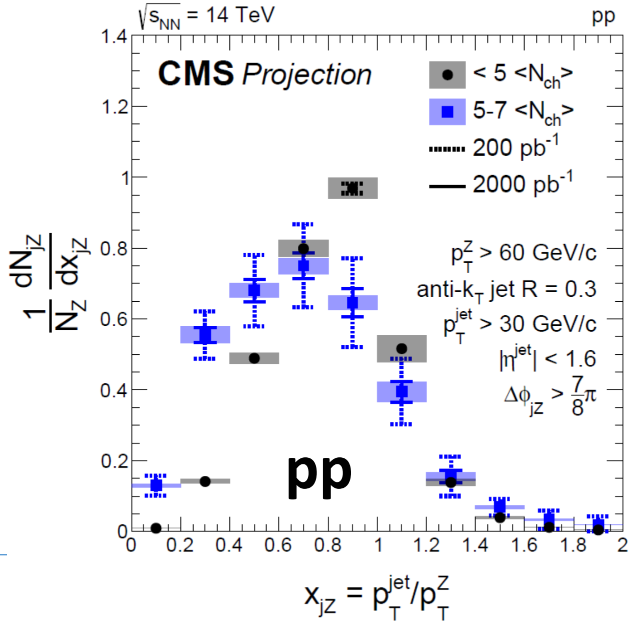
→ Ratio of D^0 distributions in jets in PbPb & pp





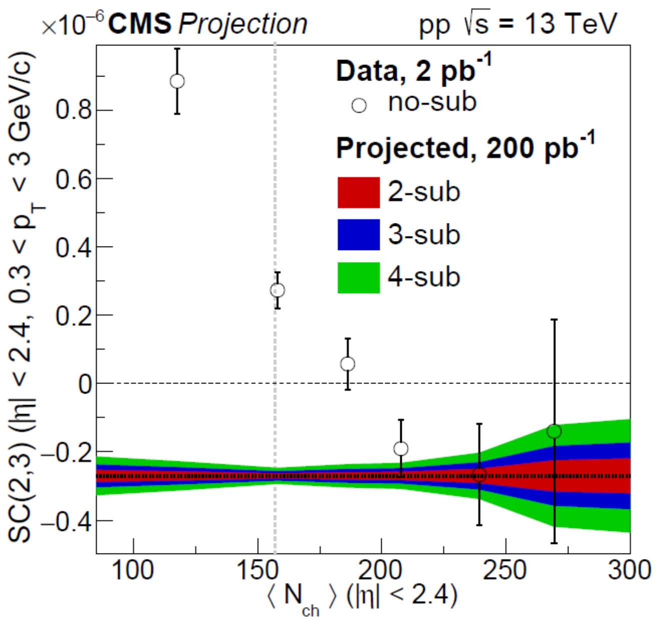
← p_T imbalance distribution in γ- jet events in pp

→ p_T imbalance distribution in Z- jet events in pp



Flow in small systems

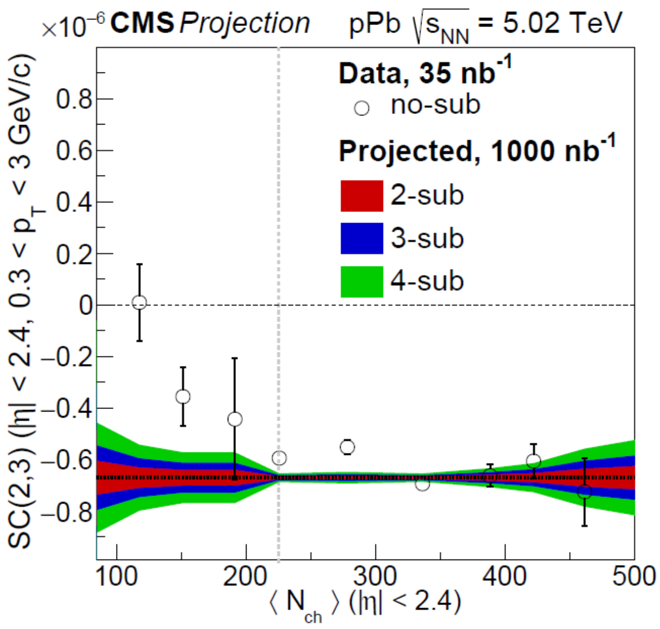
(CMS-PAS-FTR-18-026)



Symmetric cumulant SC(2,3) in

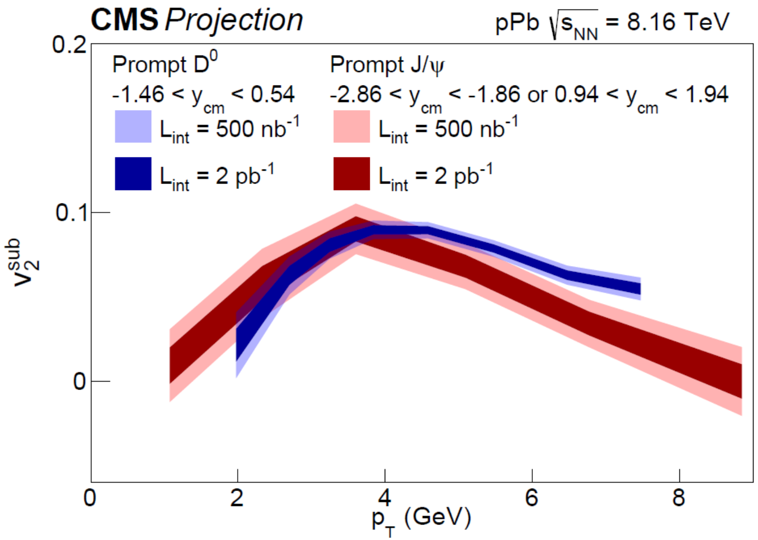
← pp

→ pPb



- Symmetric cumulant: correlation between harmonics based on 4-particle cumulant method

$$SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$

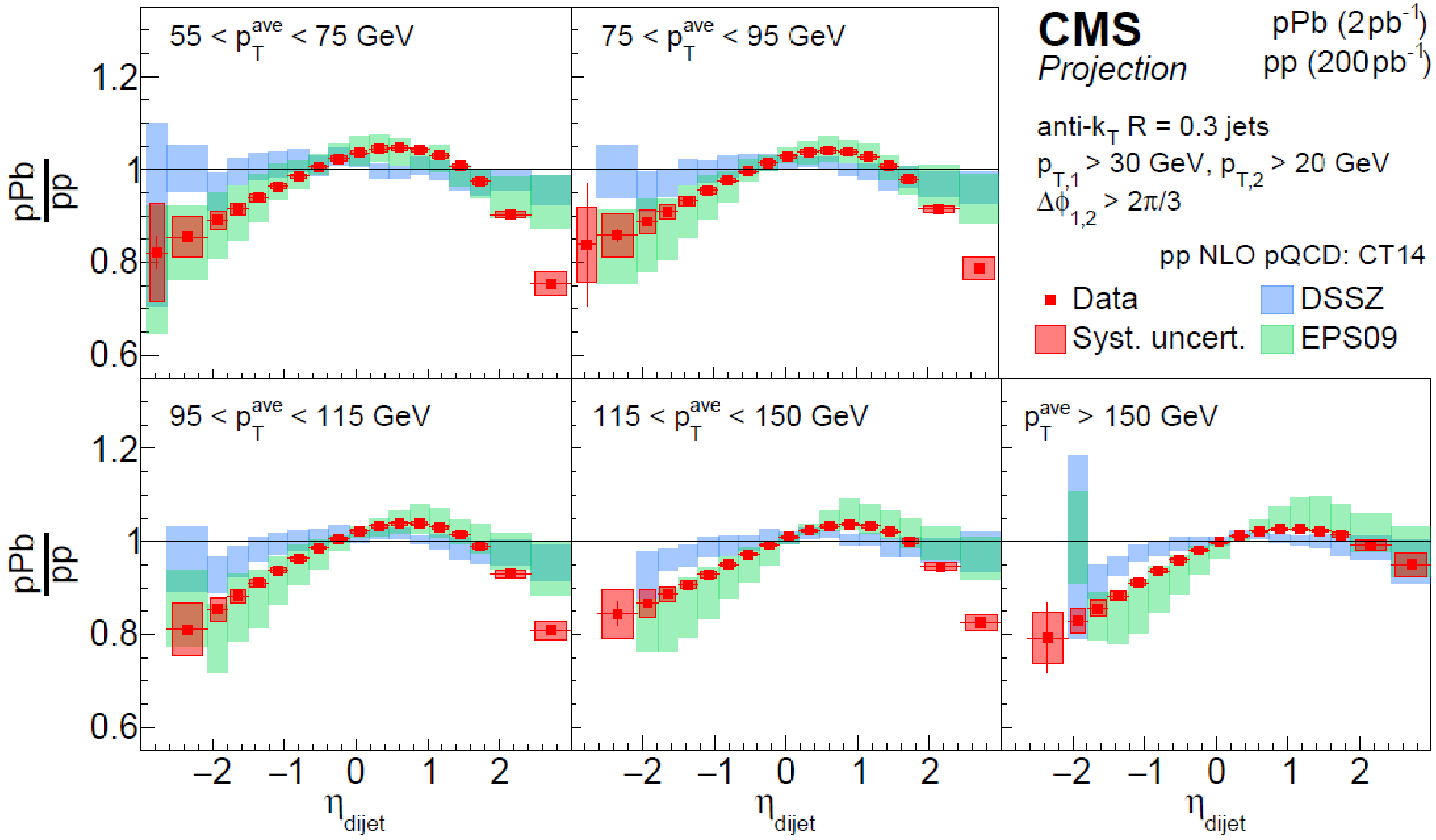


← Projection of v_2 for prompt D^0 and J/ψ

nPDF

Projected dijet pseudorapidity distributions for 2 pb^{-1} pPb events

(CMS-PAS-FTR-18-027)



Summary

- In coming years LHC will increase its luminosity. For pp,
  - Goal is to accumulate the integrated luminosity of $\geq$ 3,000 fb^{-1}
  - Expect 140~200 pileup interactions per beam bunch crossing
- Main challenge in the detector upgrade is mitigation of large number of pileup interactions:
  - Trigger: more bandwidth, new functions (e.g., track trigger)
  - Increased detector granularity and acceptance in η
  - Precise timing measurement
- Prospects for heavy-ion physics
  - PbPb luminosity increase by the injector upgrade
  - Goal: 13 nb^{-1} PbPb, 2 pb^{-1} pPb, 200 pb^{-1} low pile-up pp
  - Expect great improvement on the quality of the various physics data including heavy-flavor production by increasing the statistics and improving the systematic uncertainties.

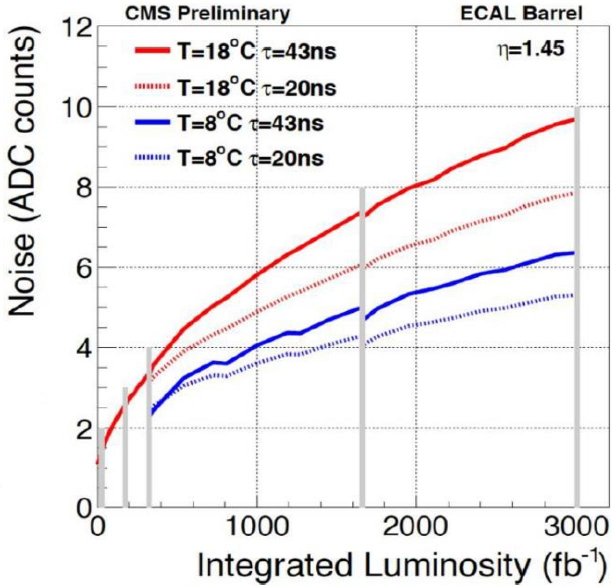
Backups

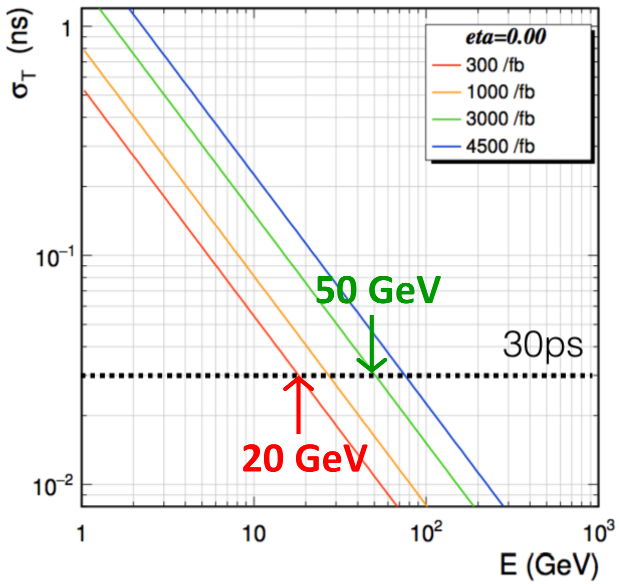
Barrel ECAL upgrades

(CMS-TDR-17-002)

- Keep $PbWO_4$ crystals and APD, but replace electronics for L1 trigger
  - Single crystal readout instead of 5X5 tower at 40 MHz
- Lower operating temperature to mitigate additional noise in APDs due to radiation damage
  - ↓ Timing resolution is limited by the APD dark current rather than crystals
  - ↘ Target resolution of 30 ps is achievable for moderate energy photons

Optimization of the readout shaping time τ

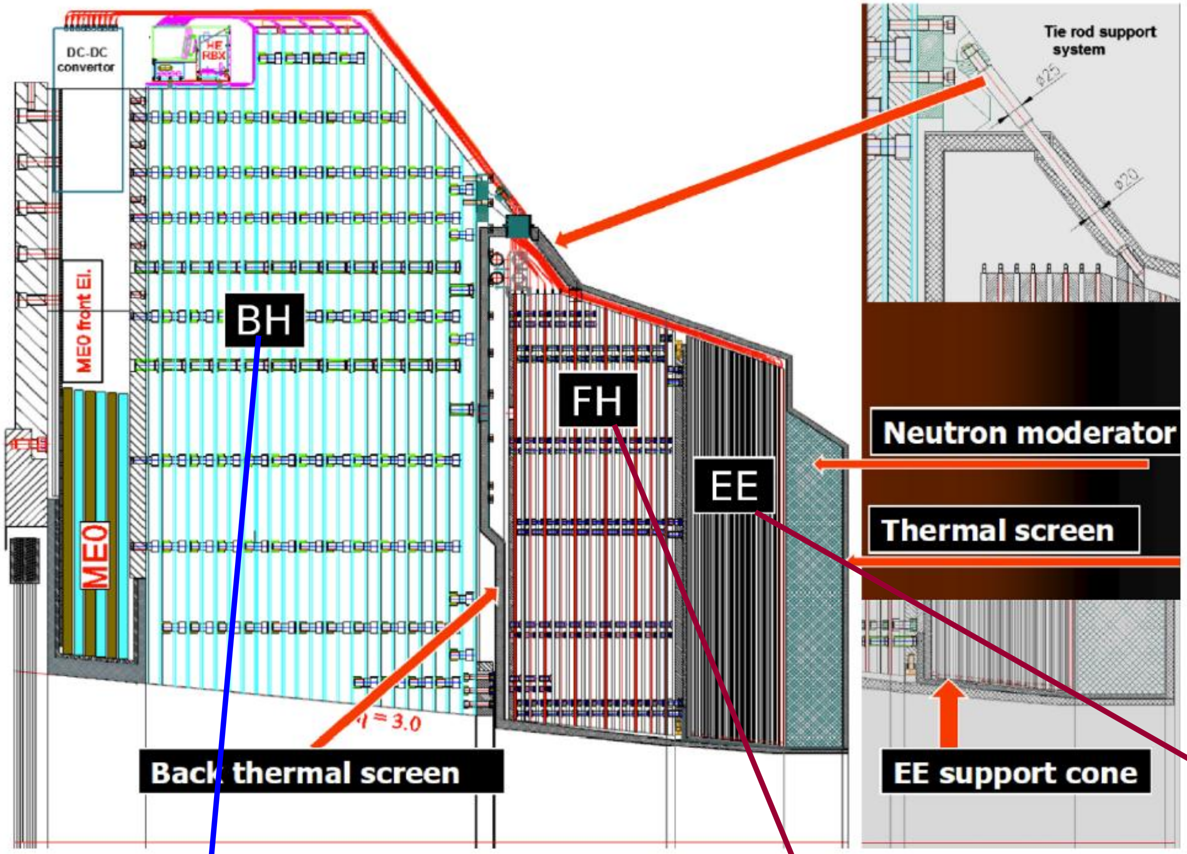




- Significantly reduced shaping time & increase of sampling rate to 160 MHz
  - Precise timing & improved suppression of anomalous signals/out-of-time pileup

New endcap calorimeter

(CMS-TDR-17-007)



- High granularity calorimeter (HGC)
- Hexagonal Si sensors
  - – 0.5 or 1 cm^2 cell size
  - – Total 6M channels
- Excellent longitudinal and transversal segmentation
- Radiation hard

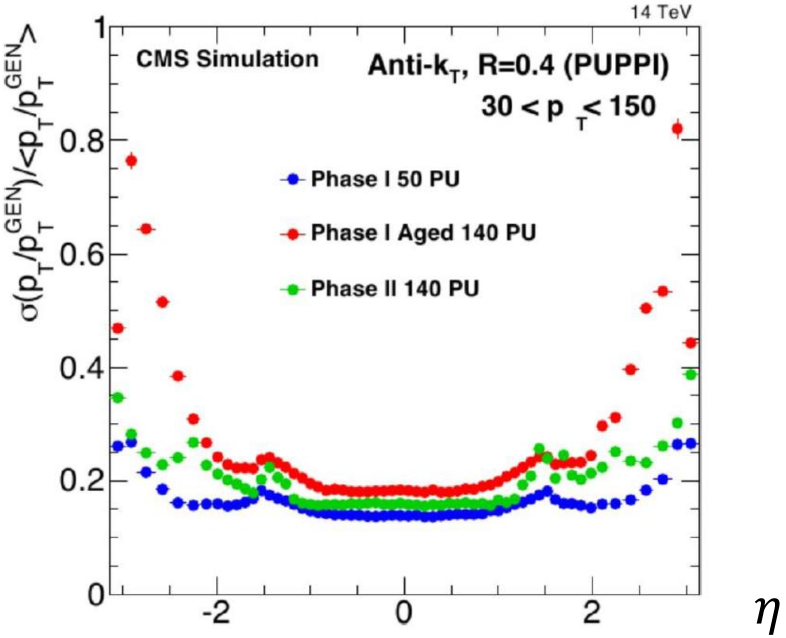
Backing Hadron section (BH):
Brass plates & plastic Scint.
tiles (5 interaction lengths)

Front Hadron section (FH):
12 brass & copper plates
(3.5 interaction lengths)

Endcap EM section (EE):
28 tungsten & copper plates
(25 radiation/1.5 Int. lengths)

Endcap calorimeter performance

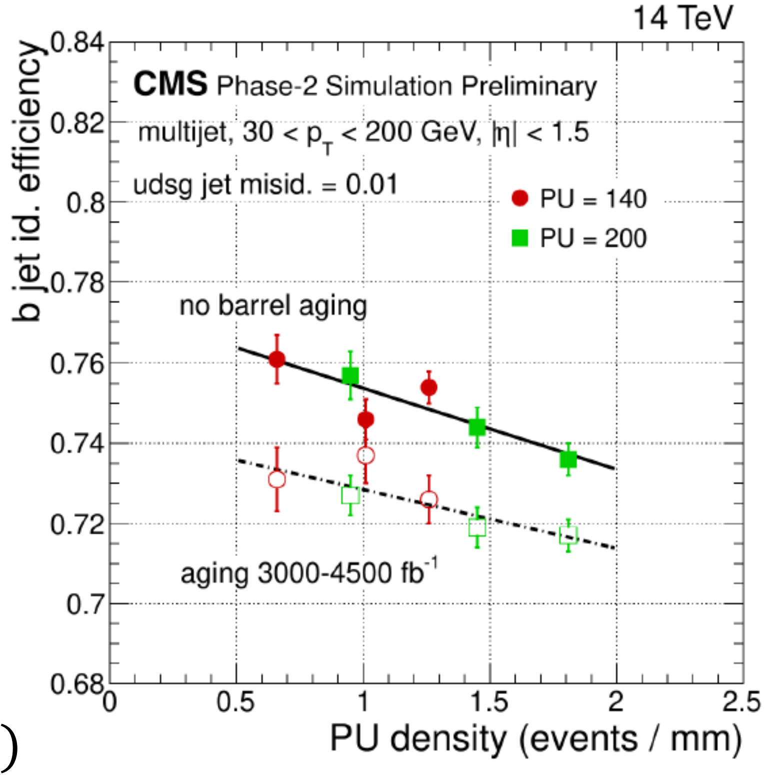
(CMS-TDR-17-007)

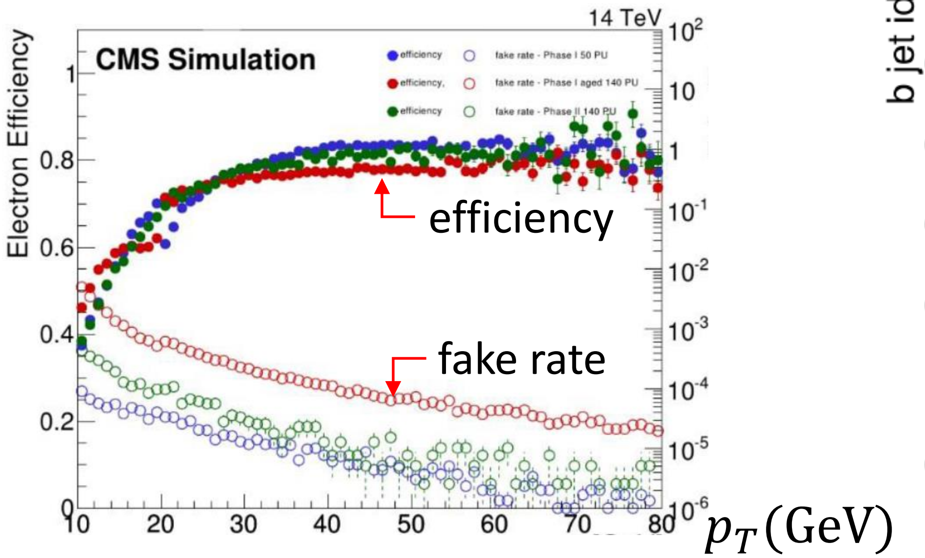


← Jet energy resolution

↙ Electron ID efficiency and fake rate

↓ b-jet tagging efficiency



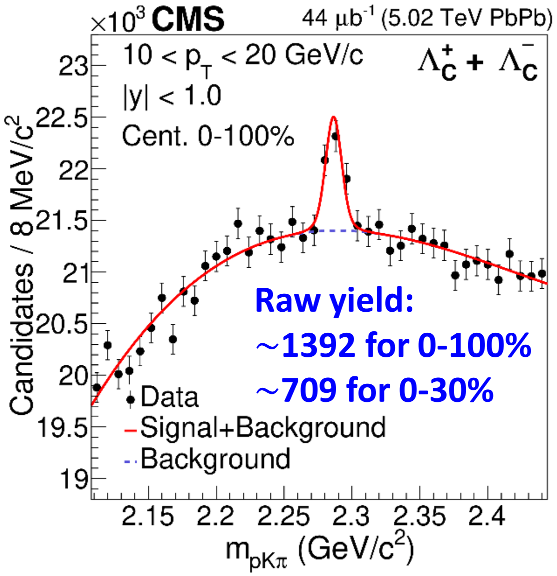


efficiency

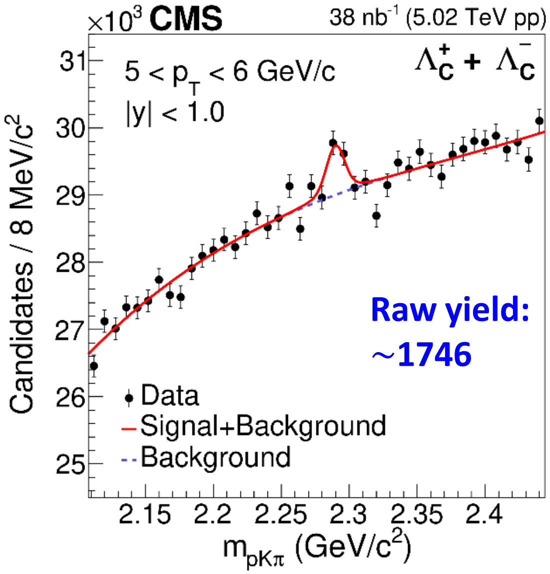
fake rate

Λ_c^+

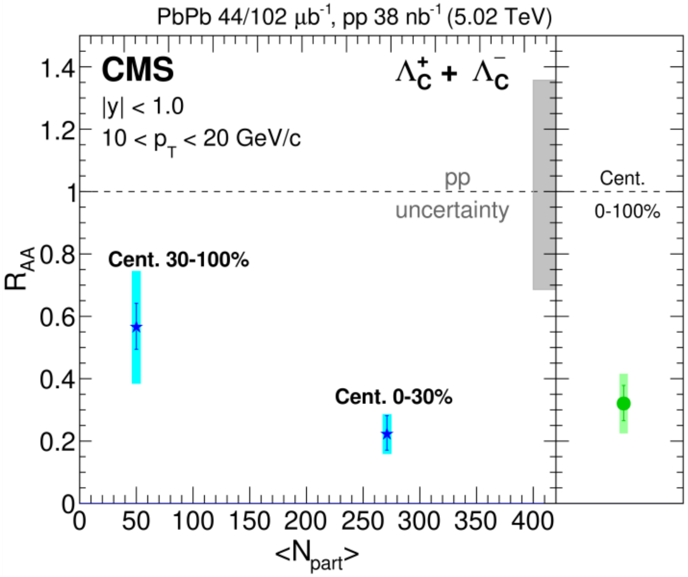
CMS-PAS-HIN-18-009 (Submitted to PLB): 2015 data



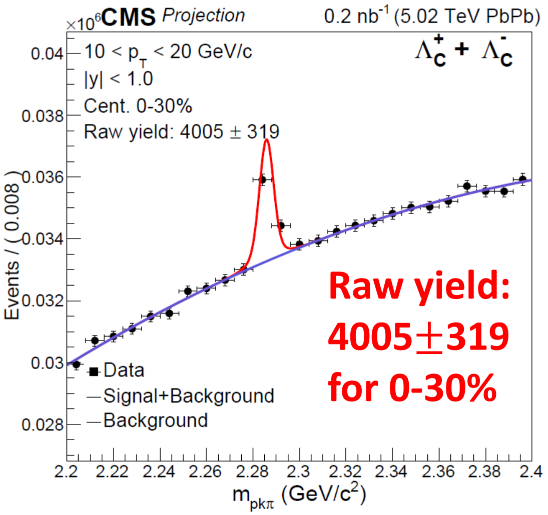
Raw yield:
~1392 for 0-100%
~709 for 0-30%



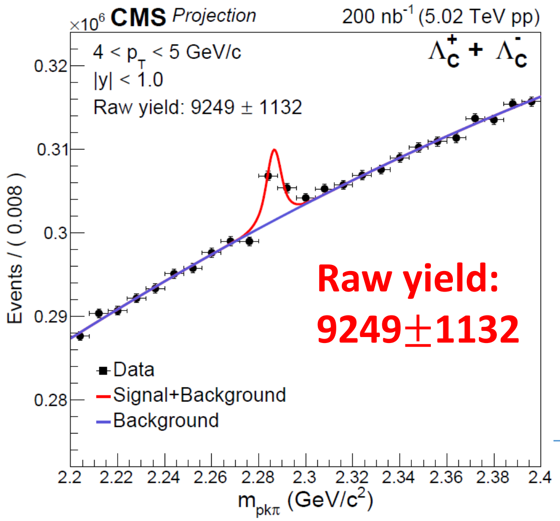
Raw yield:
~1746



Projected data with minimum bias trigger based on 2015 data analysis



Raw yield:
4005±319
for 0-30%



Raw yield:
9249±1132

(CMS-PAS-FTR-18-024)

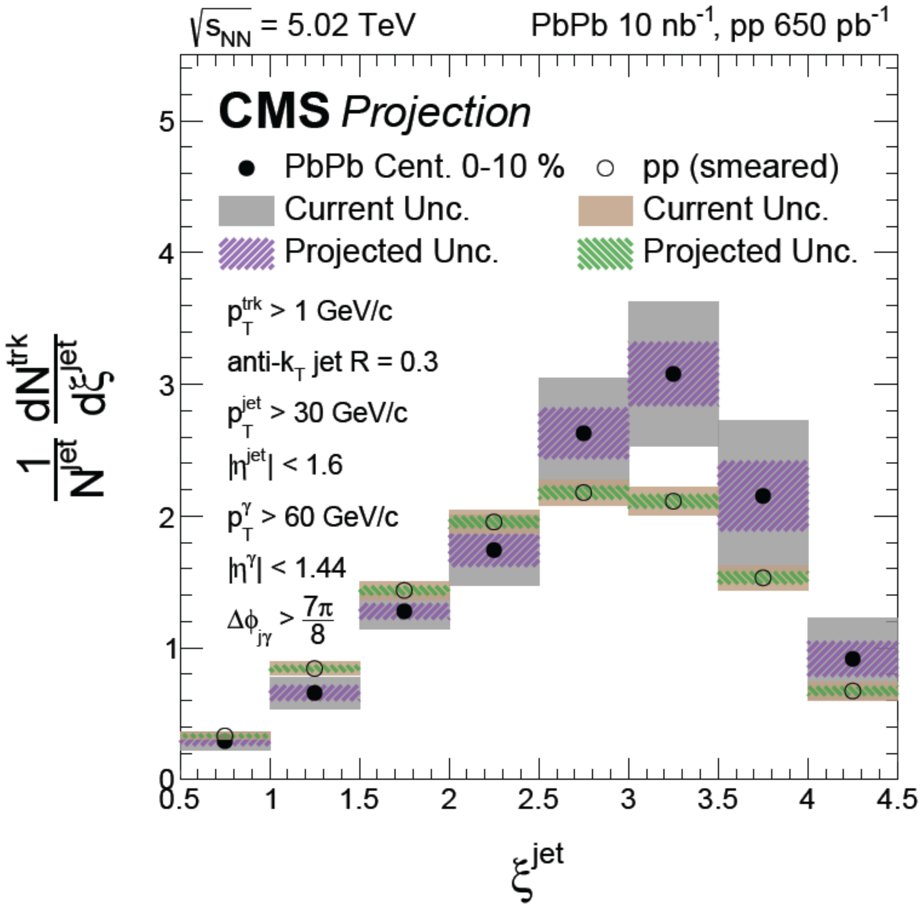
- Important for understanding
  - Heavy-quark transport
  - Heavy-quark fragmentation via coalescence

Photon-tagged fragmentation function

Comparison of uncertainties: 0.4 nb^{-1} (2015) vs. 10 nb^{-1} (HL-LHC)

- Flavor dependence of the modification of the jet fragmentation function using c and b quark initiated jets

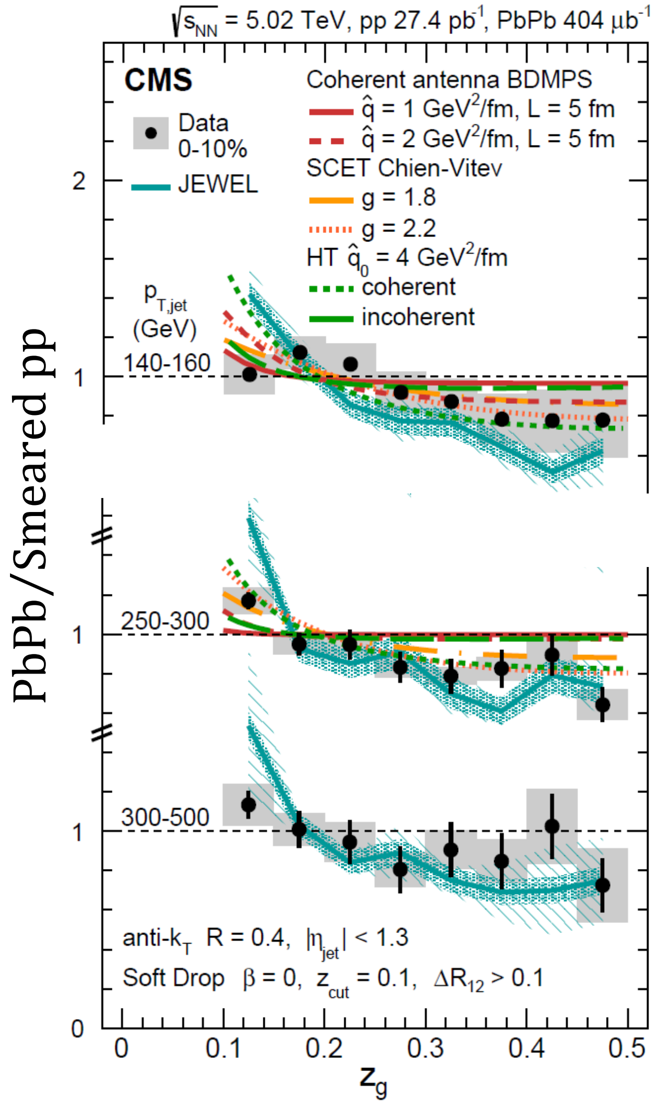
$$\xi^{jet} = \ln\left[\frac{\left||\vec{p}|^{jet}\right|^2}{\vec{p}^{\,jet}\cdot\vec{p}^{\,trk}}\right]$$



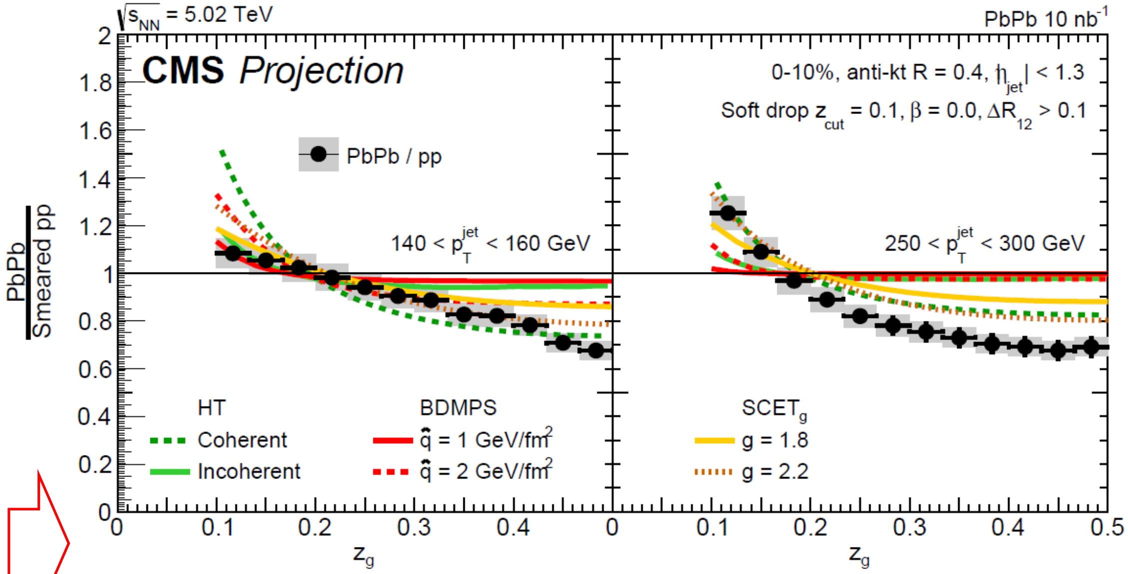
(CMS-PAS-FTR-17-002)

Jet splitting function

PRL120, 142302 (2018)



(CMS-PAS-FTR-17-002)



$$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}}$$

- Groomed jet mass analysis will be also very useful to understand the substructure of jets in the QGP environment. [arXiv:1805.05145]