Highlights from the LHC

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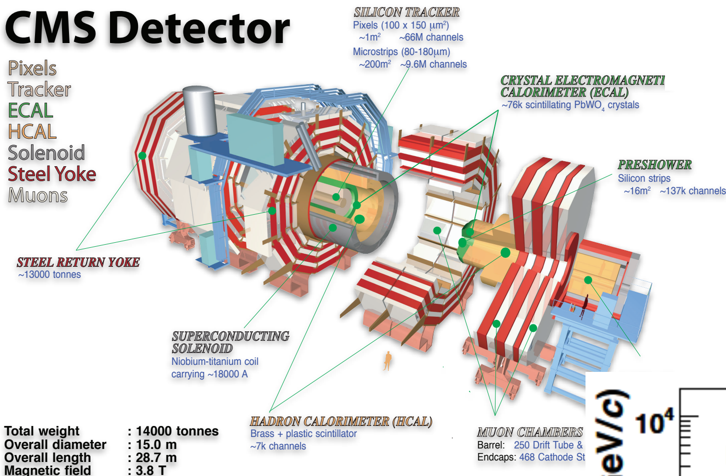
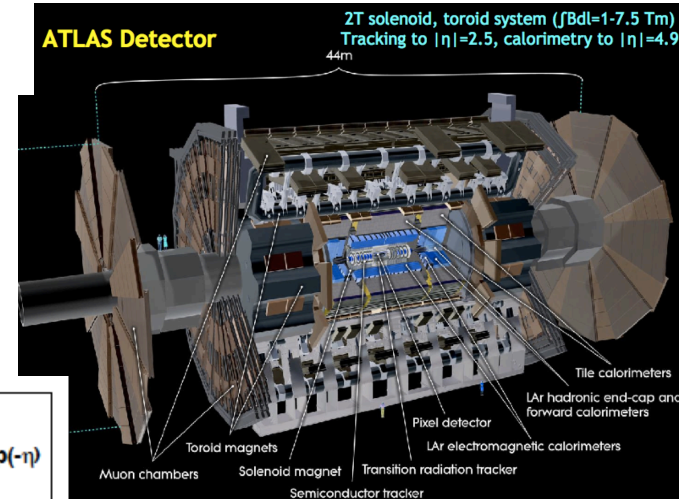
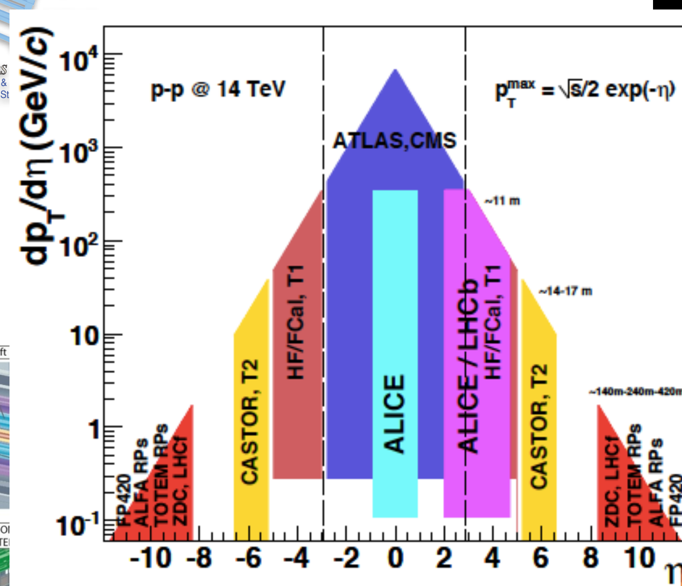
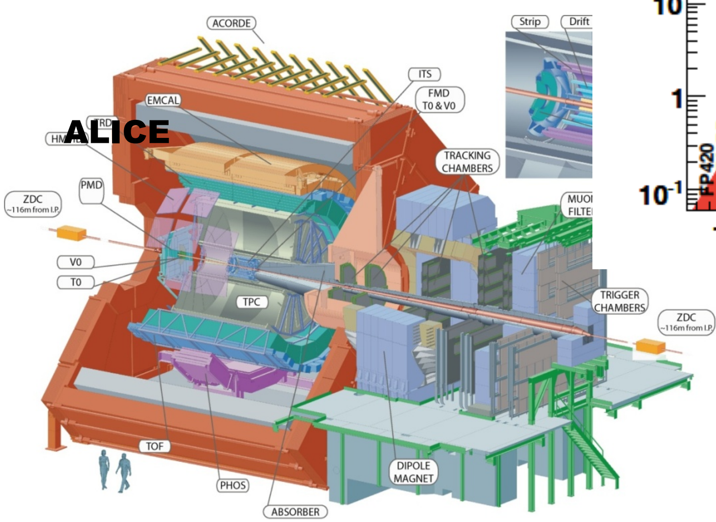
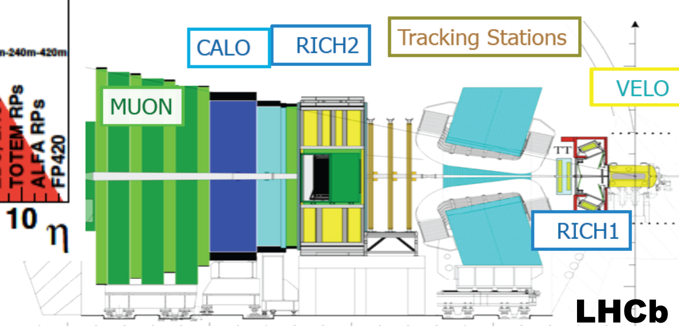
The LHC "players"









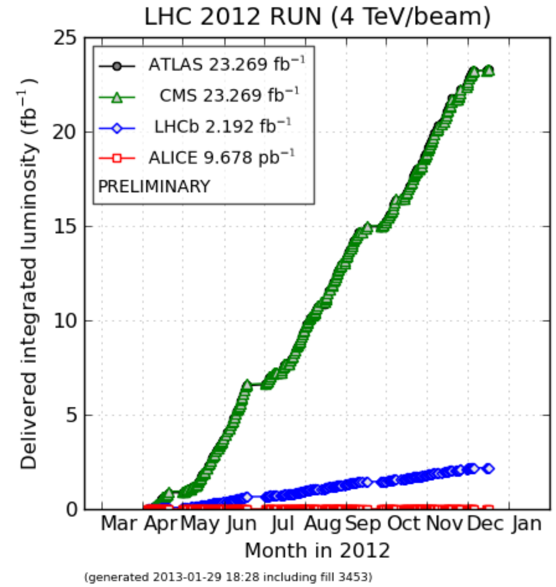


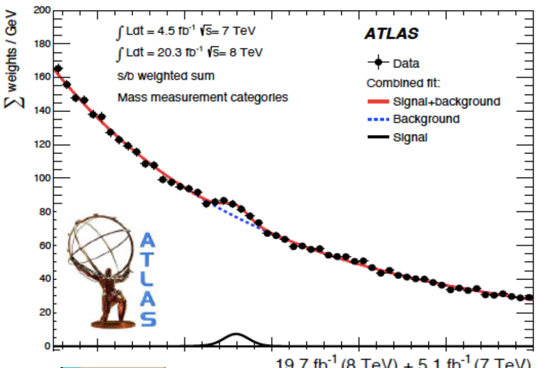
Different rapidities, p_T acceptances, PID & trigger capabilities: a richness in complementarity !

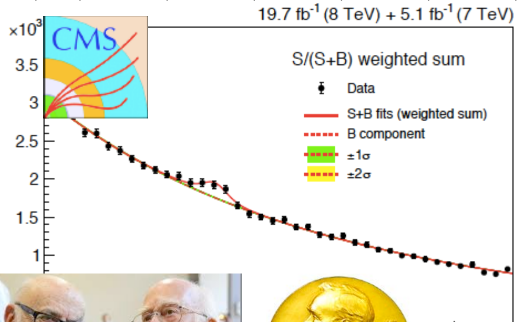
LHC Run-I (2010-1013) … a fantastic start-up

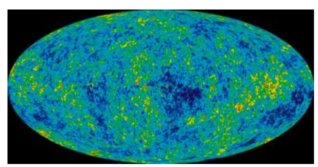
pp data up to 25 fb^{-1}
p-Pb 30 nb^{-1}
Pb-Pb 150 mb^{-1}

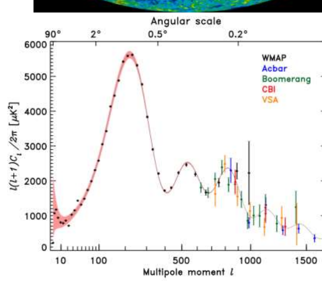
$L_{max} \sim 8 \times 10^{33}\ cm^{-2}\ s^{-1}$

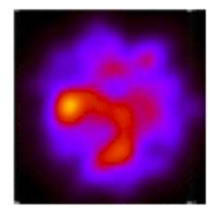


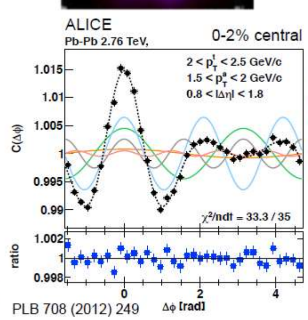




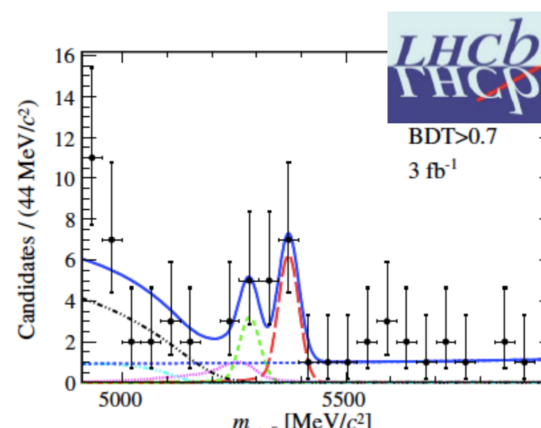








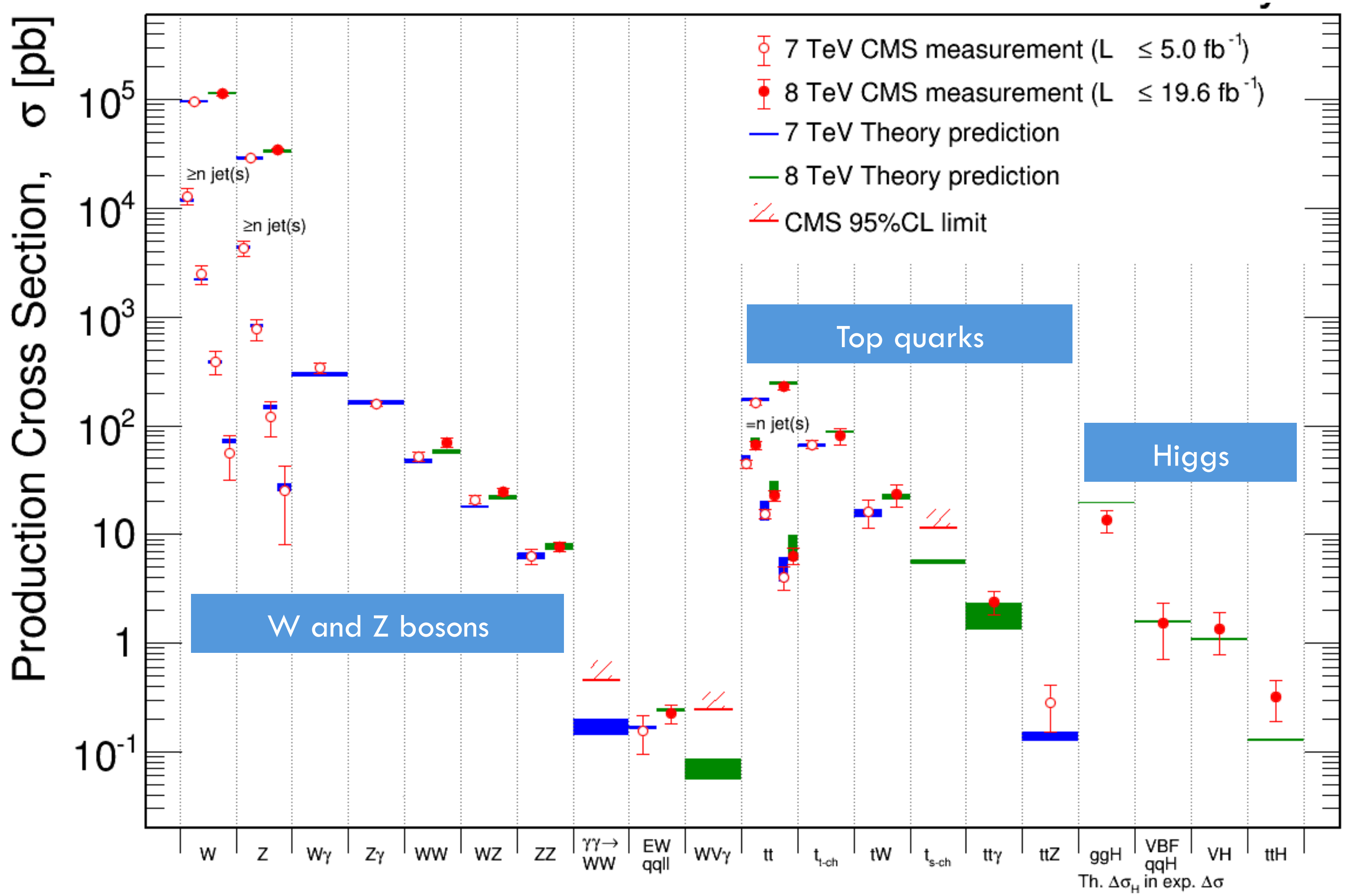
ALICE



Observation of $B_s \rightarrow \mu\mu$ decay

The celebration of the SM

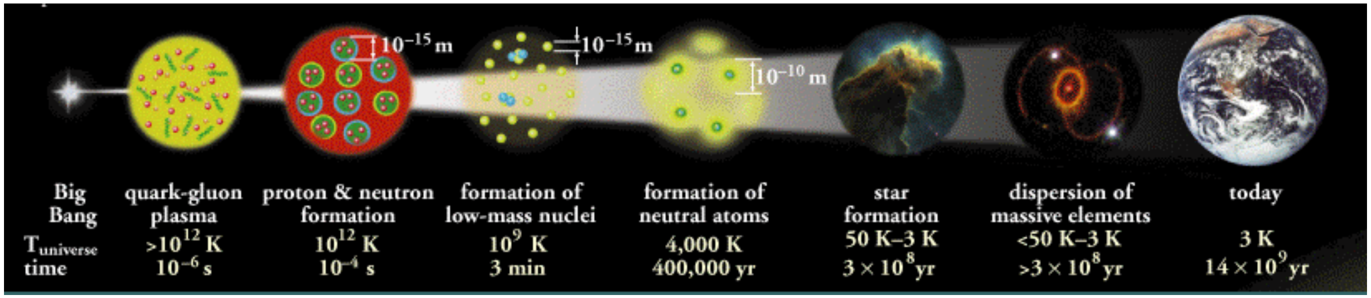
Six orders of magnitude of EWK, top, and Higgs Physics



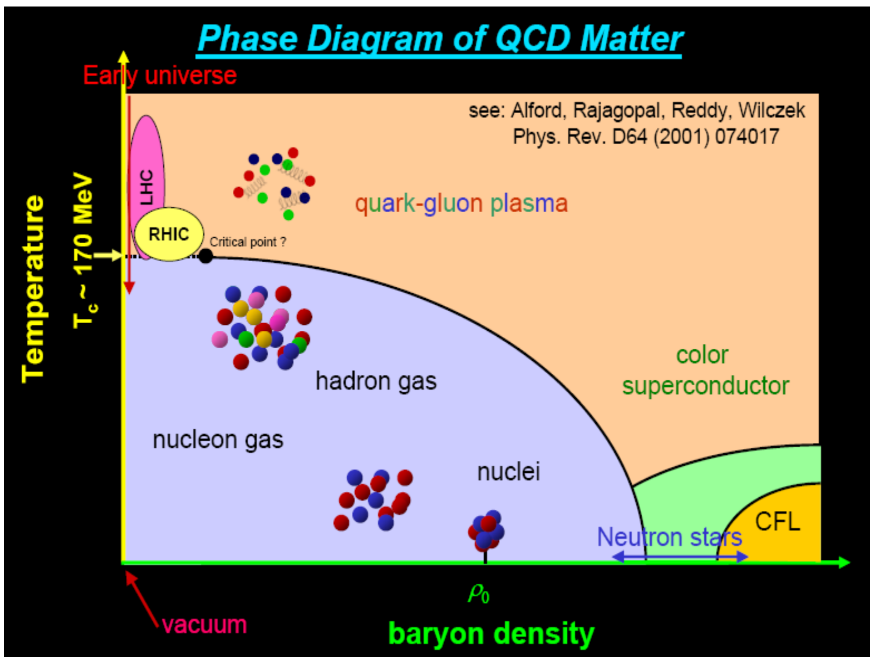
LHC is ready to enter in the precision era from LOG to LIN scale

"The" Phase Diagram

NATURE



EXPERIMENT

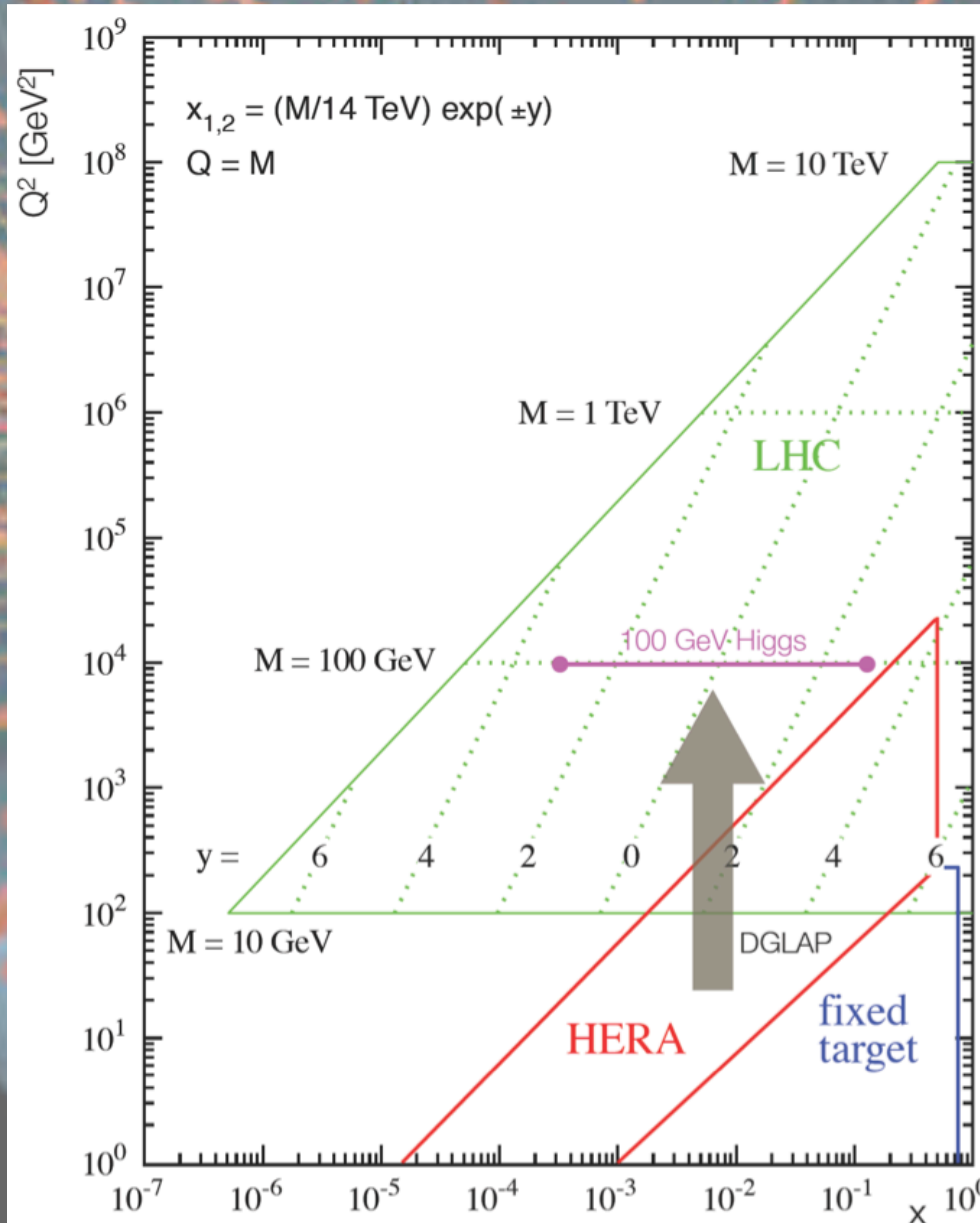


Temperature at deconfinement $= 1.9\times10^{12}$ K

QCD studied in a new kinematic range never reached before

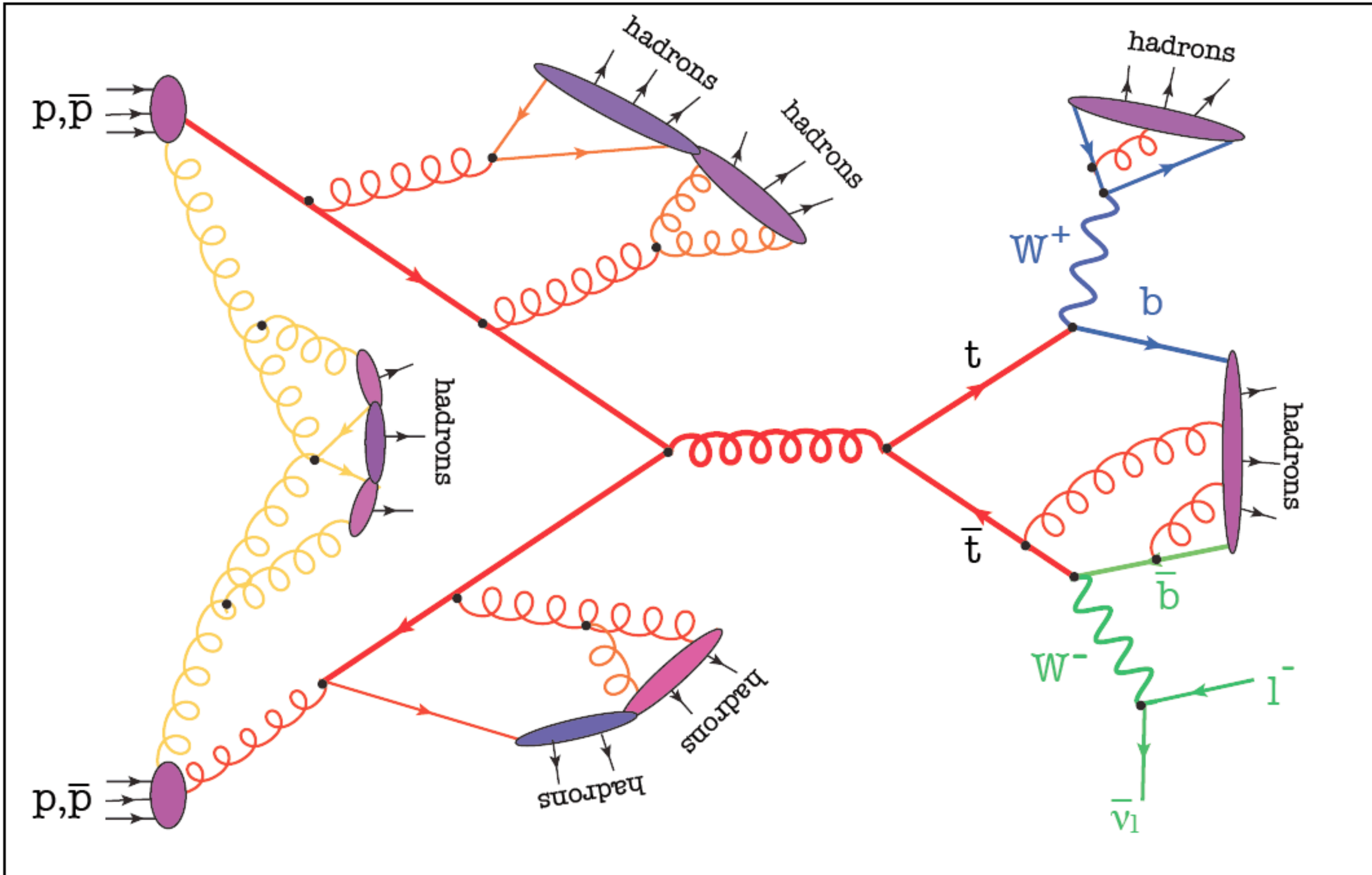
Understanding and modeling the QCD interactions in a variety of initial/ final states

Phase Space



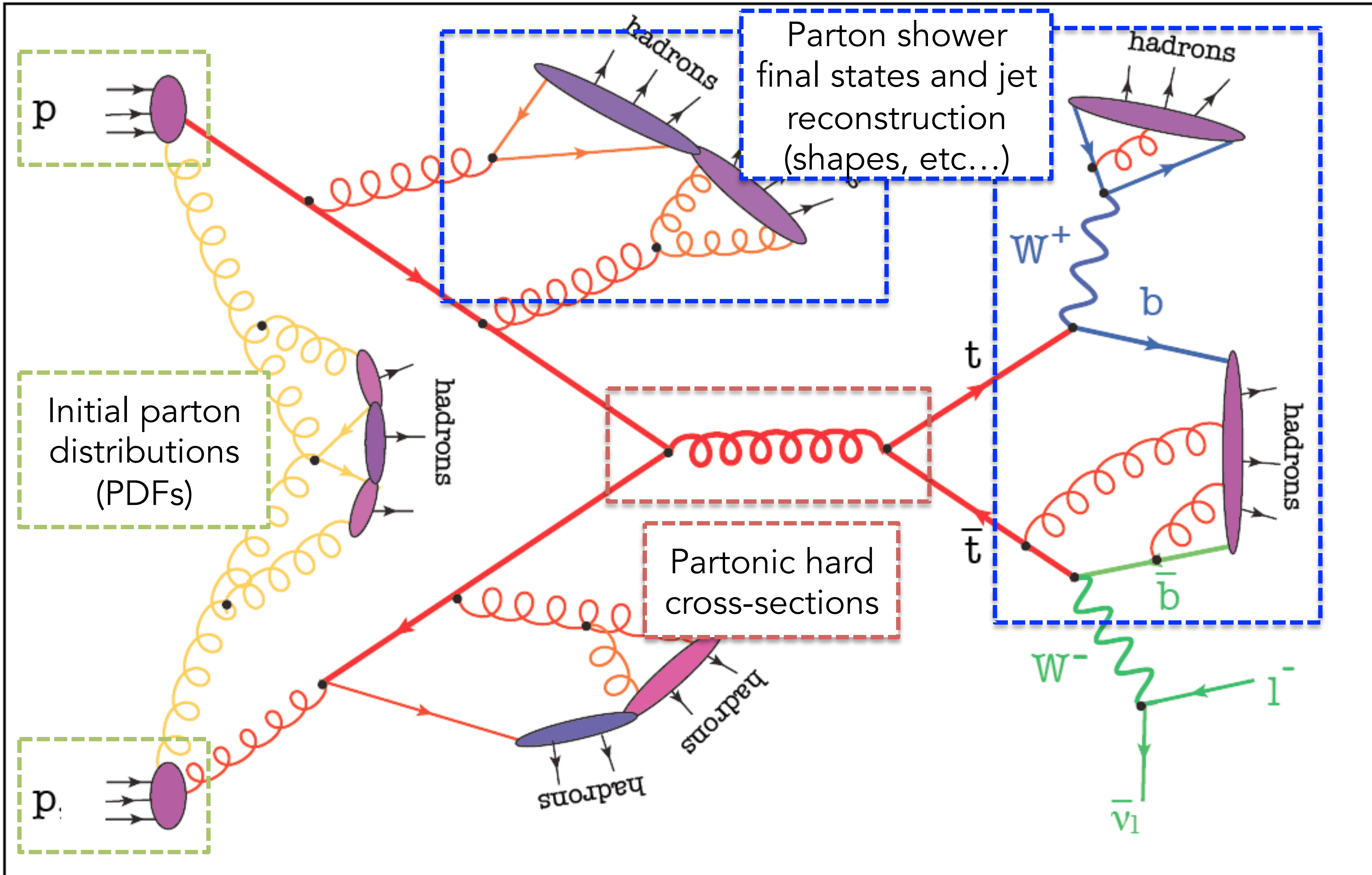
$x_{1,2}$ = (M/14 TeV) exp(±y)
Q = M
M = 10 TeV
M = 1 TeV
LHC
M = 100 GeV
100 GeV Higgs
y = 6 4 2 0 2 4 6
M = 10 GeV
DGLAP
HERA
fixed target
Q^2 [GeV^2]
x

QCD at the LHC



Drawing by K. Hamilton

QCD at the LHC



Drawing by K. Hamilton

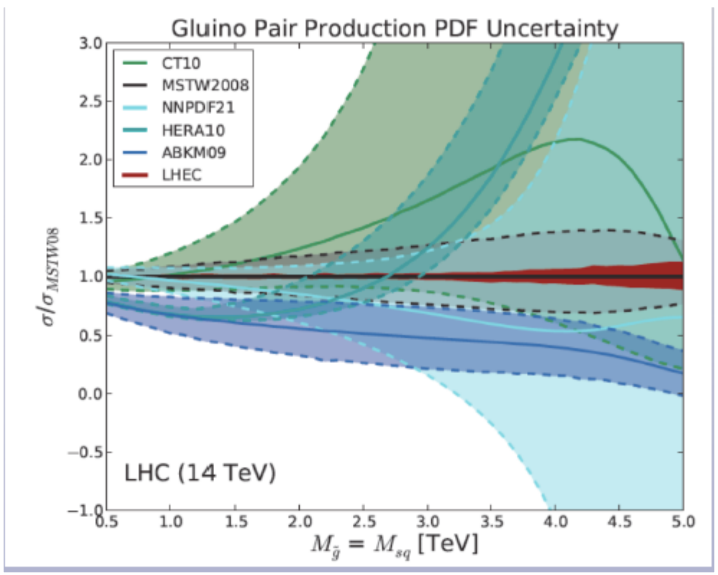
PDFs and LHC interplay

Knowledge of the PDFs is one of the fundamental limits for Higgs boson characterization in terms of couplings …

Production		Decay	
gg→H	14.7	H→bb	3.3
VBF	2.9	H→ττ	5.7
WH	3.9	H→γγ	5.0
ZH	5.1	H→WW	4.3
ttH	14.4	H→ZZ	4.3

■ scale ■ PDF+αs

Systematic error (%) – Campbell ICHEP 2012



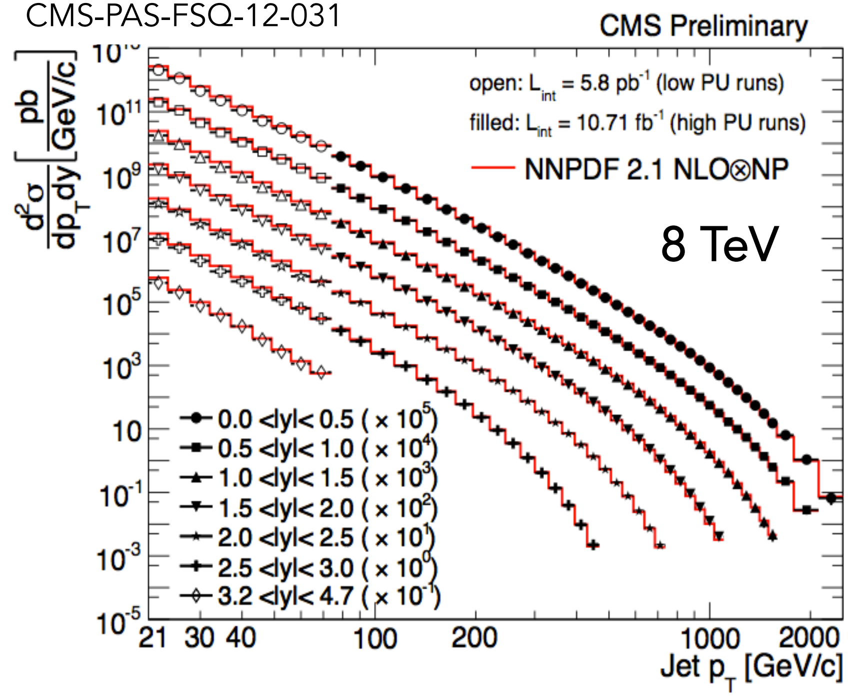
… and is essential to evaluate the rich capabilities in the search for new particles

PDFs uncertainties are a crucial factor in the accuracy of theoretical predictions and parameter determination

Exploit the power of precise data to reduce PDF uncertainties and discriminate among PDF sets

Inclusive jet production

CMS-PAS-SMP-12-012
CMS-PAS-FSQ-12-031



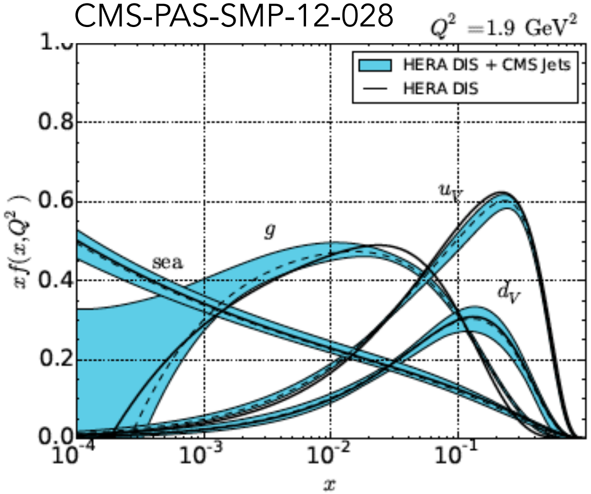
LHC data span 13 order of magnitude!

Unprecedented statistics over a very large p_T range (from 20 GeV to 2 TeV)

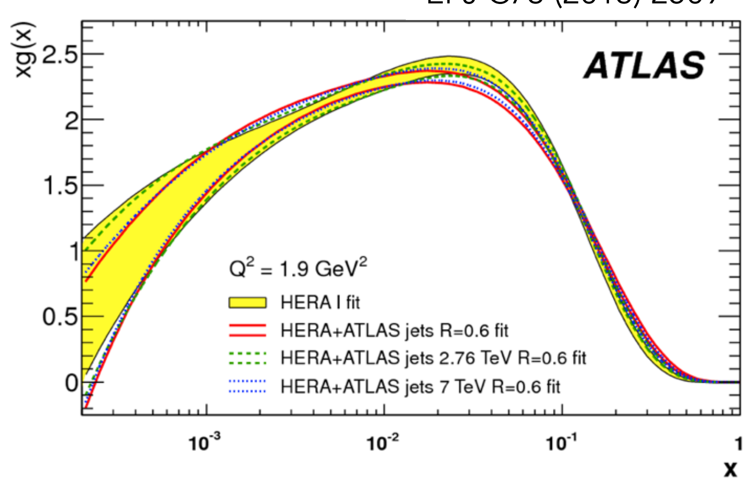
Very good agreement with NLO QCD: jet measurements are used as input to constrain gluon PDFs

ATLAS and CMS started to perform their own PDF fits (HERAfitter)

CMS-PAS-SMP-12-028



EPJ C73 (2013) 2509



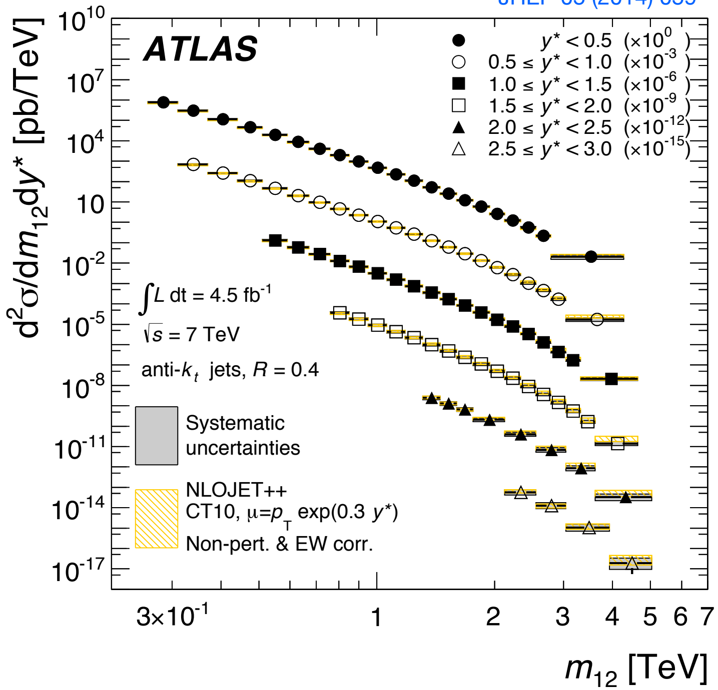
Relevant for consistency checks and for evaluation of systematics

Trend: ATLAS & CMS data prefer a harder gluon spectra in comparison with HERApdf only

Th. Paper: Watt, Motylinski and Thorne ArXiv:1311.5703

Multi-jet production and α_s

JHEP 05 (2014) 059



Distribution sensitive both to jet p_T and angular distributions

The higher the p_T the higher is the x probed

Data used to constrain PDFs of gluons and quarks at high-x where gluons and quarks are mostly unconstrained

Wealth of precise experimental measurements

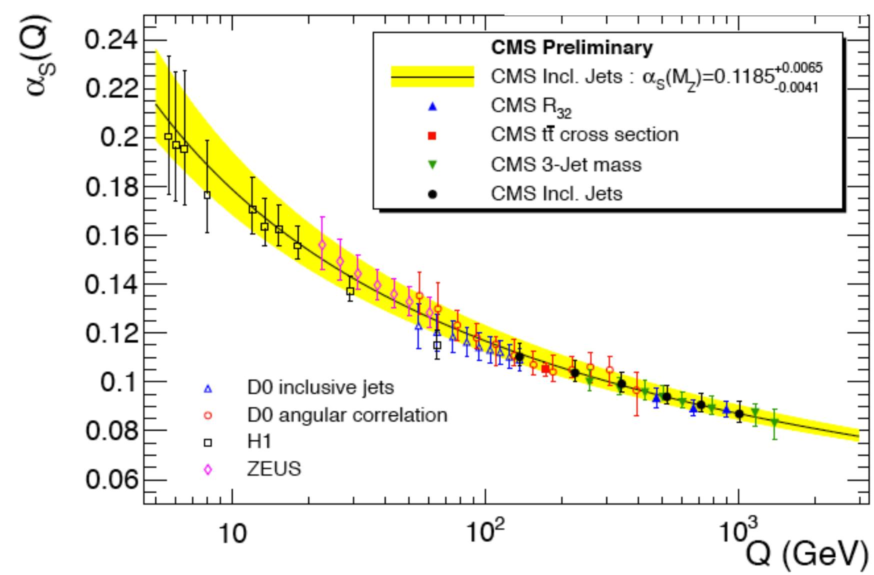
Ratio of 3-jets to 2-jets (classical way to measure α_s since PEP/PETRA/LEP) and 3-jet invariant mass spectrum constrain α_s

Most recent CMS result

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019(\exp) \pm 0.0028(PDF)$$
$$\pm 0.0004(NP) \pm^{0.0055}_{0.0022} (scale)$$

Impressive test of pQCD up to TeV scale

CMS-PAS-SMP-12-028



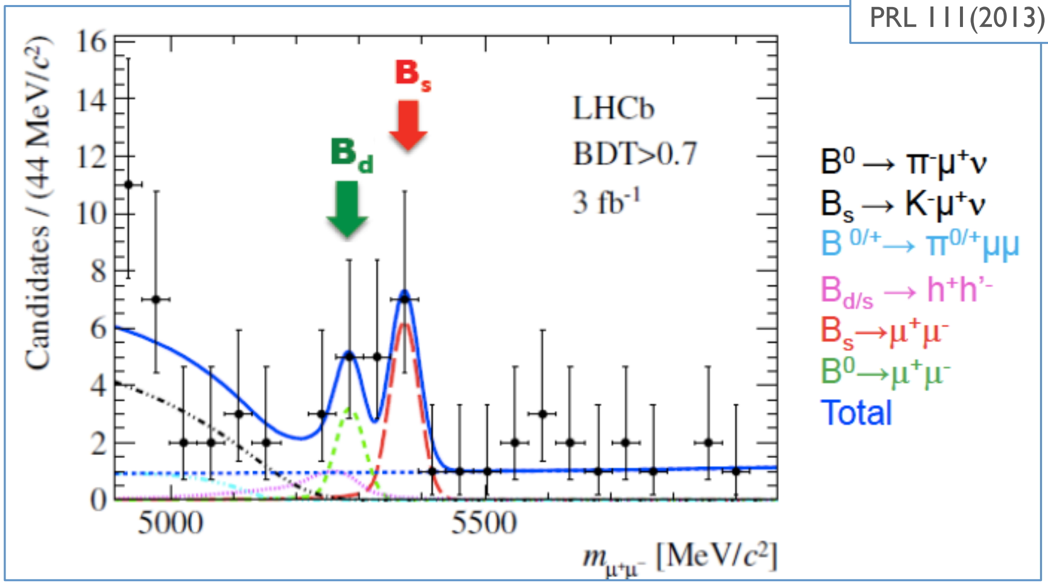
Golden channel for New Physics

Precise predictions in SM:

- $BR(B_s \to \mu\,\mu) = 3.5 \pm 0.2\ 10^{-9}$
- $BR(B_d \to \mu\,\mu) = 1.1 \pm 0.2\ 10^{-10}$

Predicted to be small due to GIM and helicity suppression

PRL 111(2013)101815



$BR(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7)\times 10^{-9}$ Observation!!

$BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4})\times 10^{-10}$ Not statistically significant

In complete agreement with SM

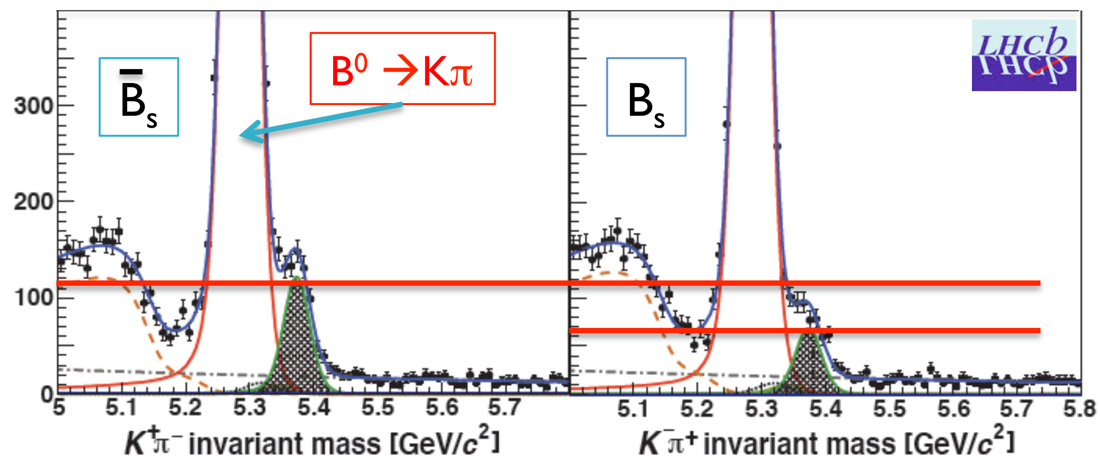
First observation of CPV in B_s decay

First 5σ observation of CP violation in $B_s \rightarrow K\pi$ decays

B_s is the fourth particle known to show CP violation

(after K^0 [1964], B^0 [2000], $B^{\pm}$ [2012])

arXiv:1304.6173

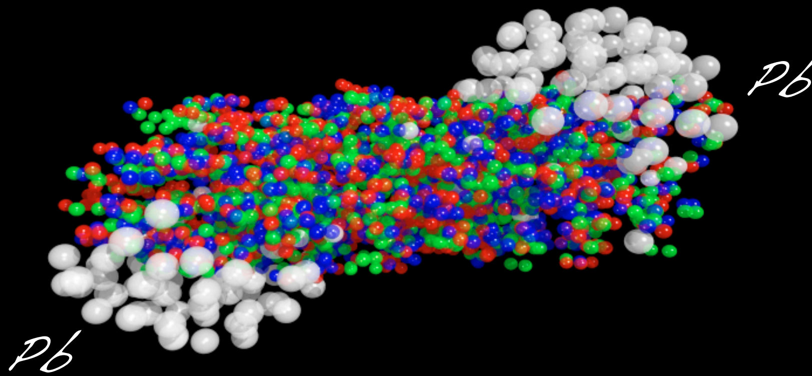


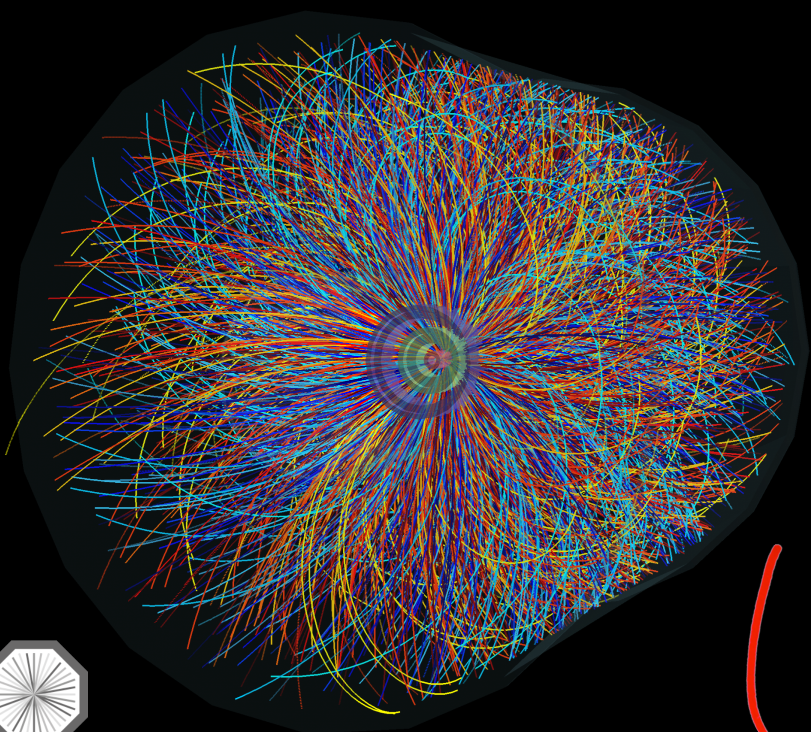
Raw asymmetry

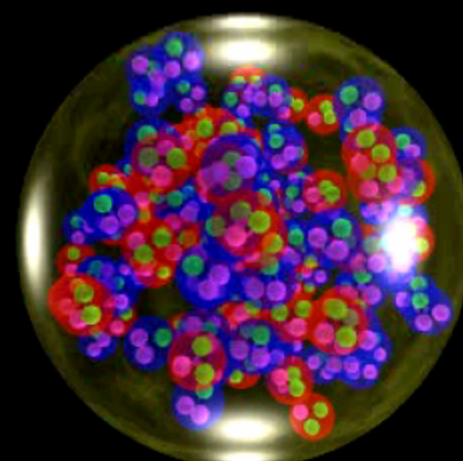
Raw asymmetry is corrected for production and detector asymmetries (small: ~ 1%)

$A_{CP} = 0.27 \pm 0.04 \pm 0.01$ (with 1/fb data sample)

To quench or not to quench



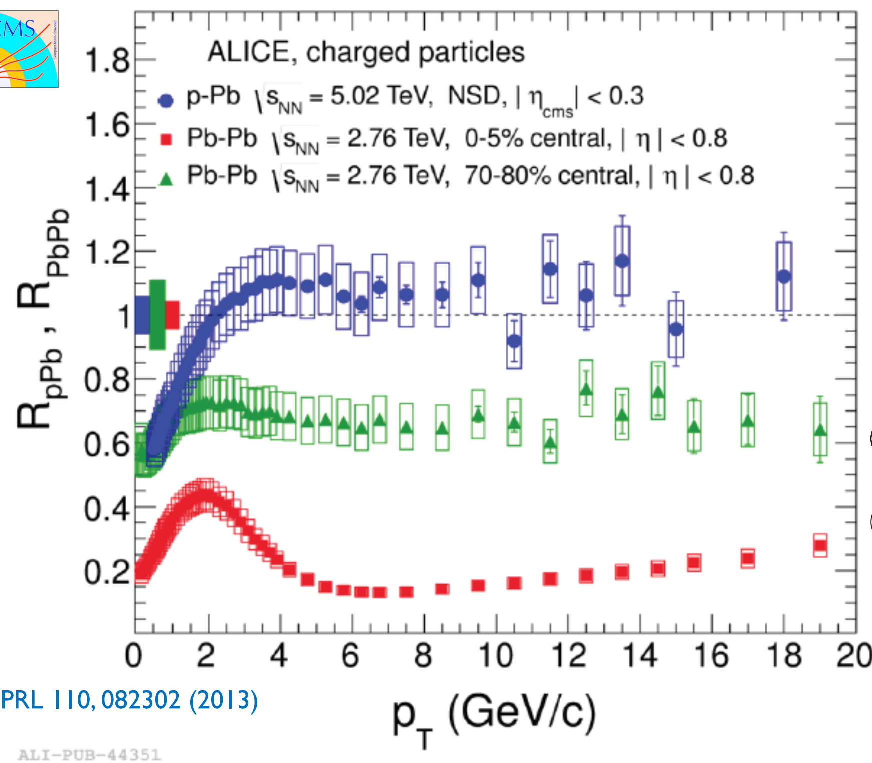




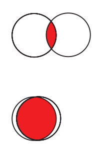
Proton?

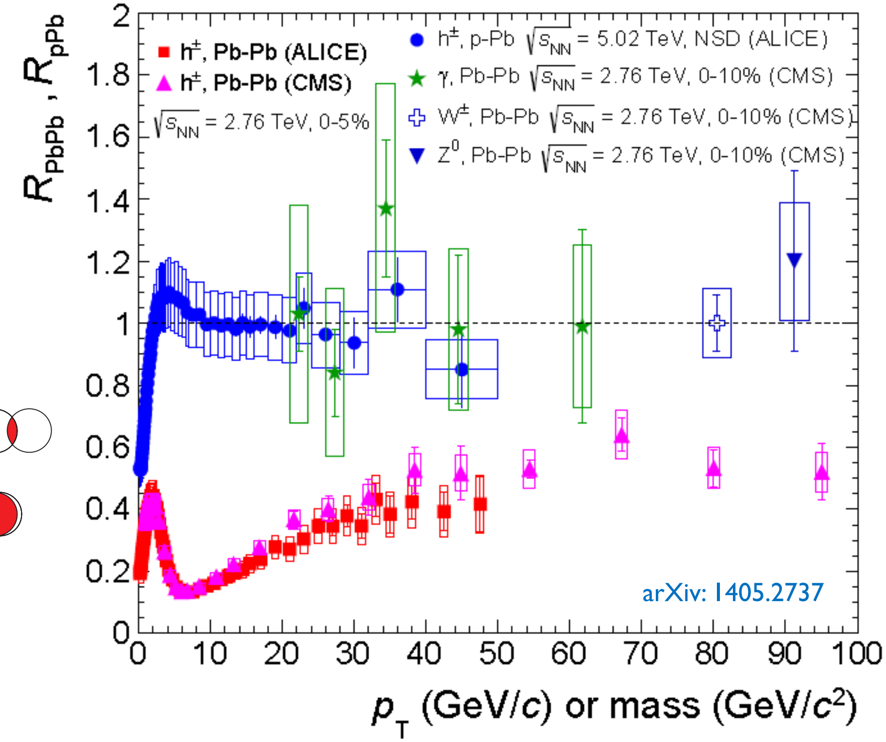
Particles through Pb-Pb and p-Pb

Nuclear Modification Factor: $$R_{AA}(p_T) = \frac{Yield(Pb+Pb)}{Yield(p+p) \times \langle N_{coll} \rangle}$$



PRL 110, 082302 (2013)

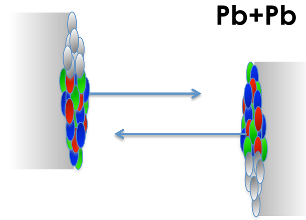


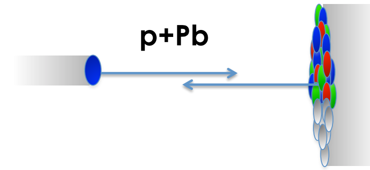


- Strong suppression of charged hadrons in Pb-Pb (wrt pp) up to very high momenta

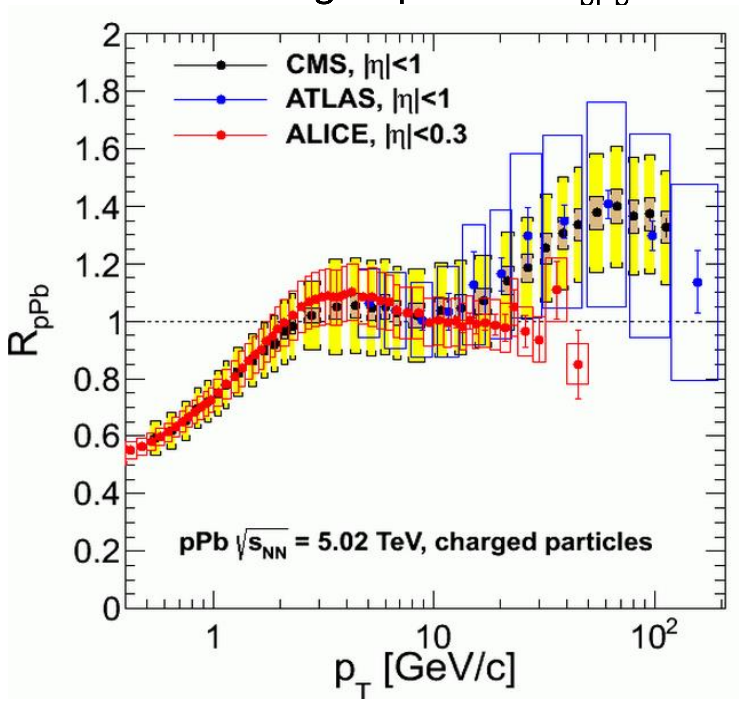
- Direct photons, W and Z are not quenched … reference particles

- p-Pb results (consistent with unity up to 50 GeV) confirm that strong suppression in Pb-Pb is due to hot nuclear matter effects

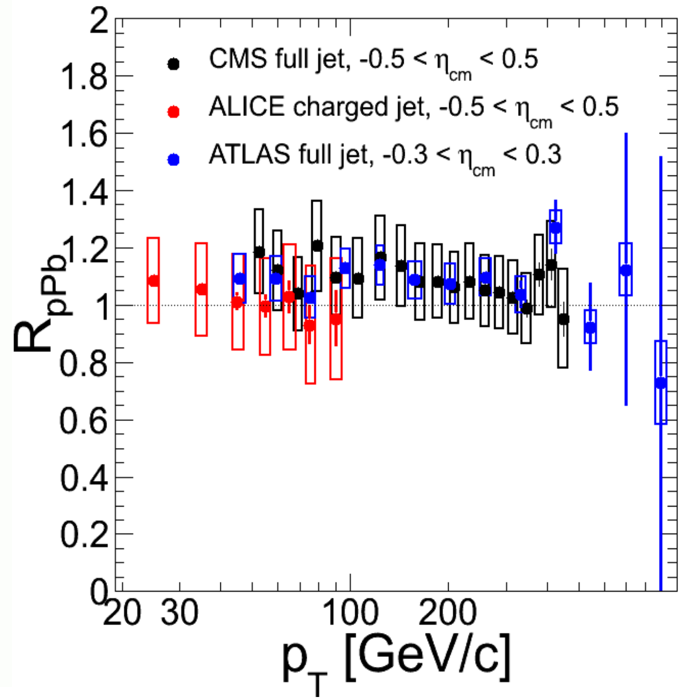
From 

to 

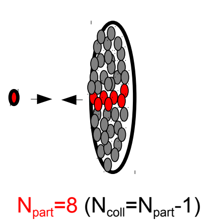
Charged particle R_{pPb}



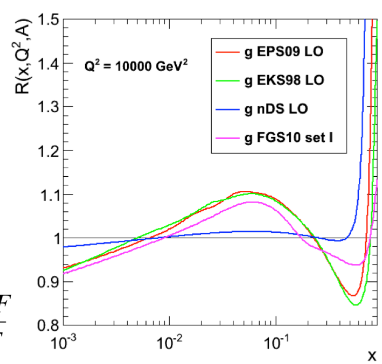
(Charged) Jet R_{pPb}



PDF **nPDF**



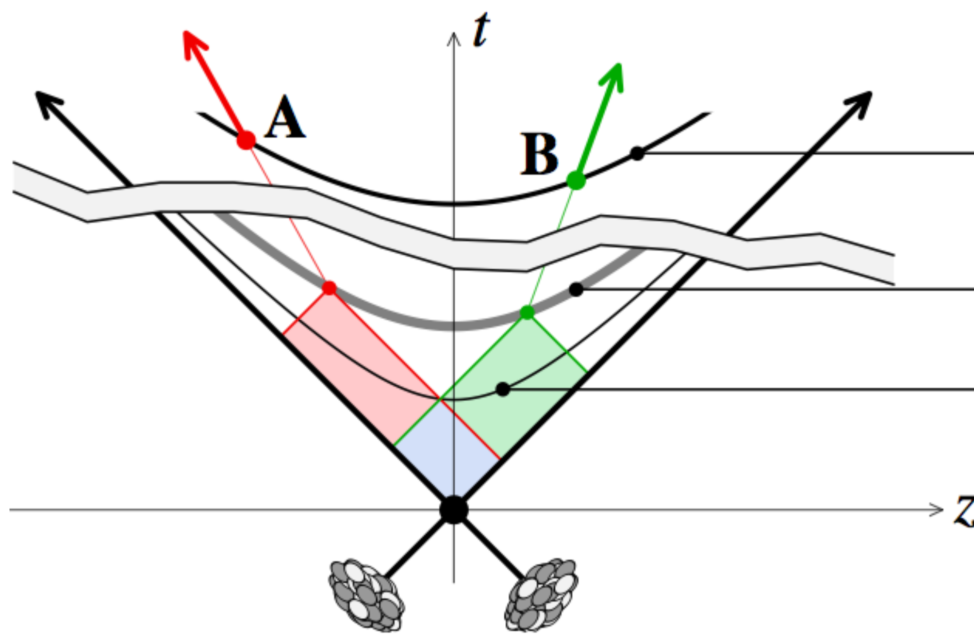
$$R = \frac{nPDF}{PDF}$$



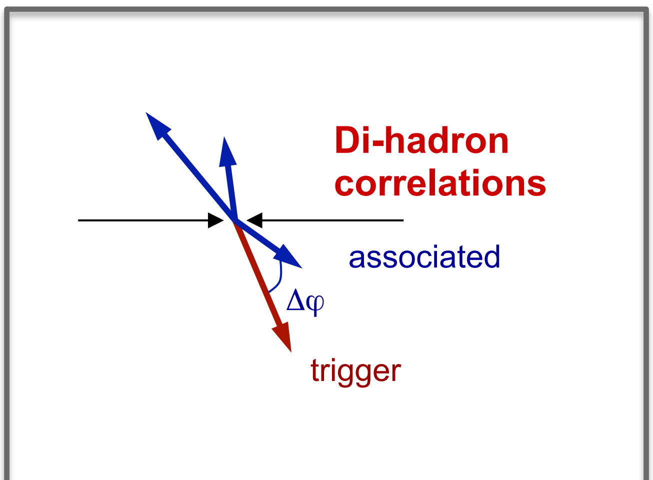
Need to check jet FFs
Normalization problem?
Anti-shadowing?

Is the proton behaving like a proton?

Long range rapidity correlations as a chronometer



(Raju Venugopalan)

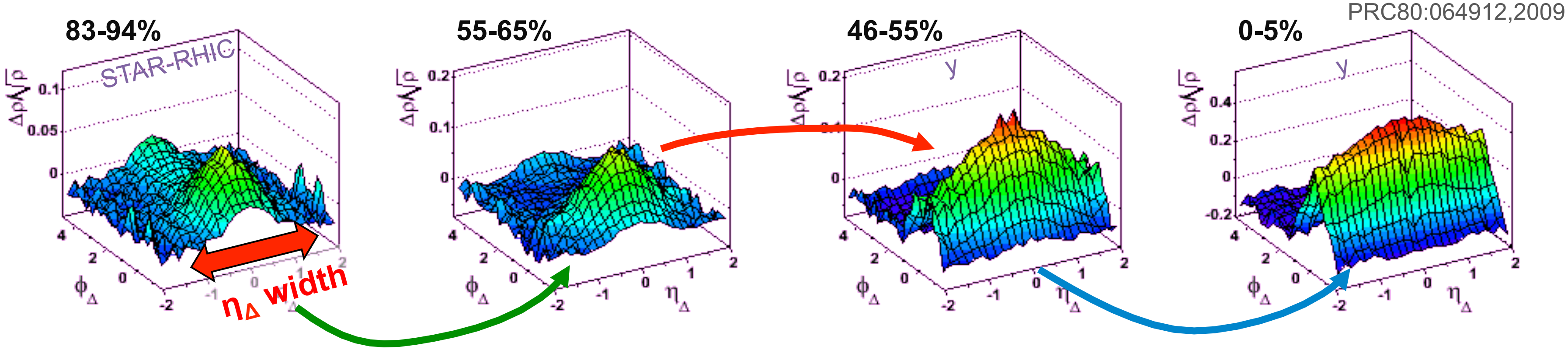


$$\tau \leq \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

Long range correlations sensitive to very early time collision dynamics (fractions of a femtometer ~10^{-24} seconds)

The ridge in A+A collisions

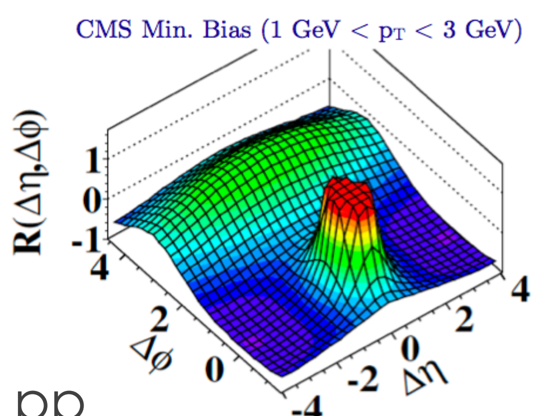
PRC80:064912,2009



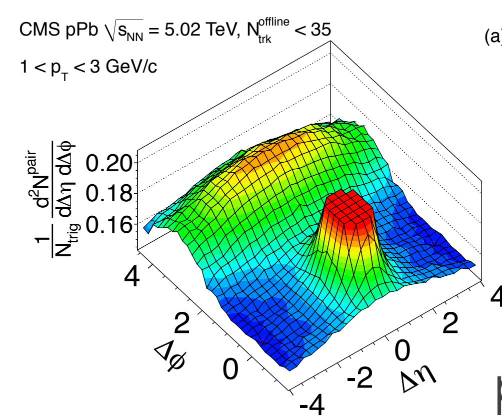
In (central) A+A, the ridge is commonly interpreted as hydrodynamic "hubble" flow of initial "stringy" structures in rapidity

The structures in the $\Delta\,\phi$ direction are decomposed and studied by the v_n Fourier "Flow moments"

Not in pp (low multiplicity) neither in pPb (low multiplicity)

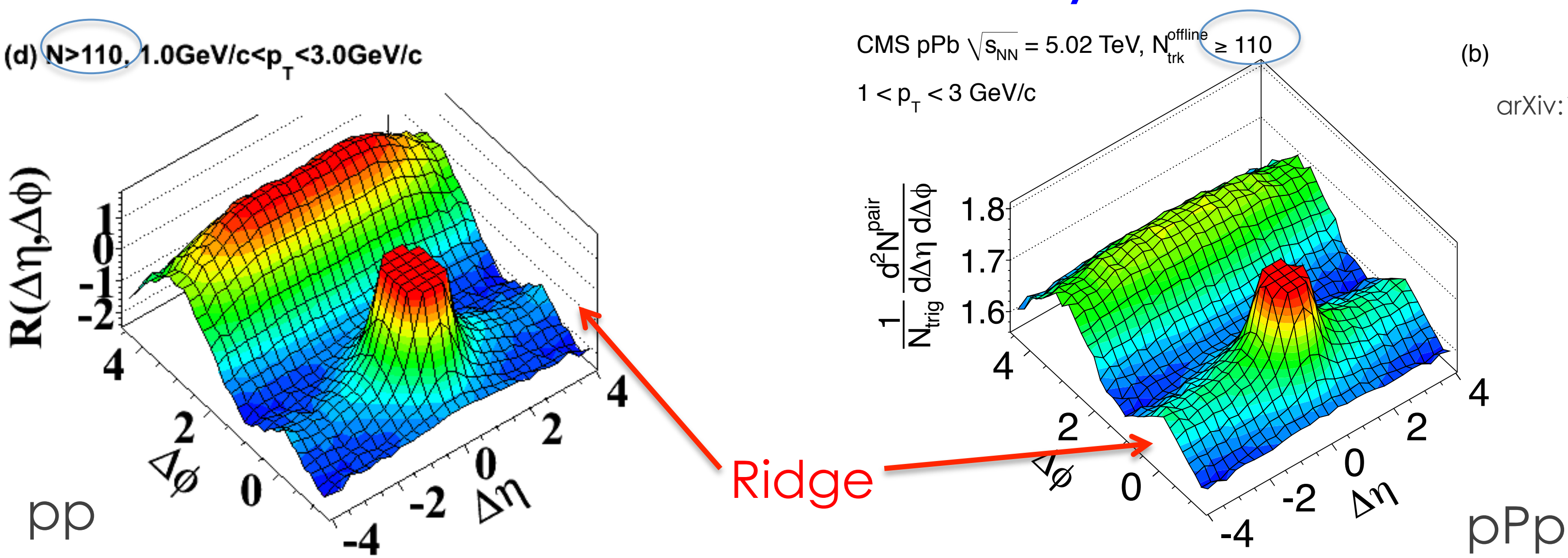


pp

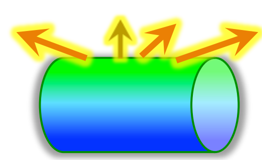


pPb

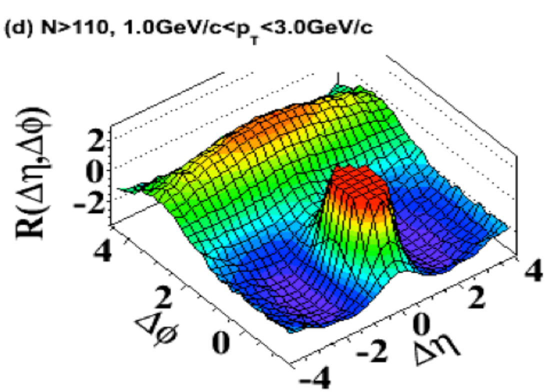
The discovery



arXiv:1210.5482, PLB



Distinct long range correlation in η collimated around $\Delta\Phi \approx 0$

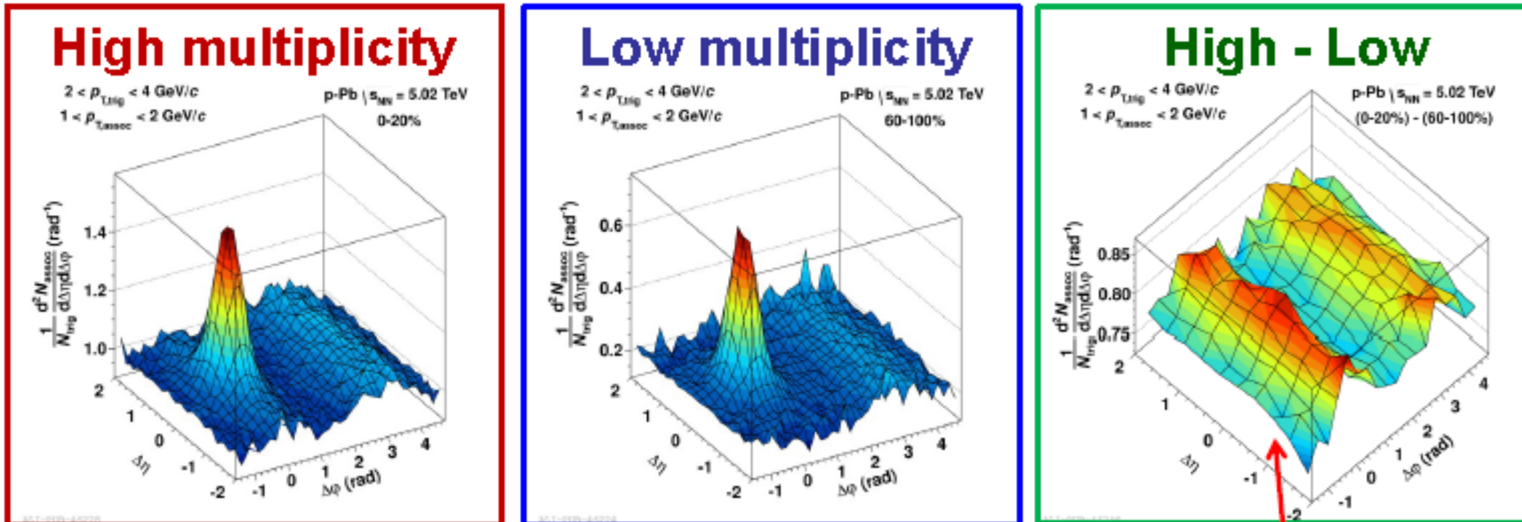


No ridge in MC

Similar for pPb (high mult), pp (high mult) and PbPb (peripheral)

Hydrodynamic flow in pp and pPb collisions?

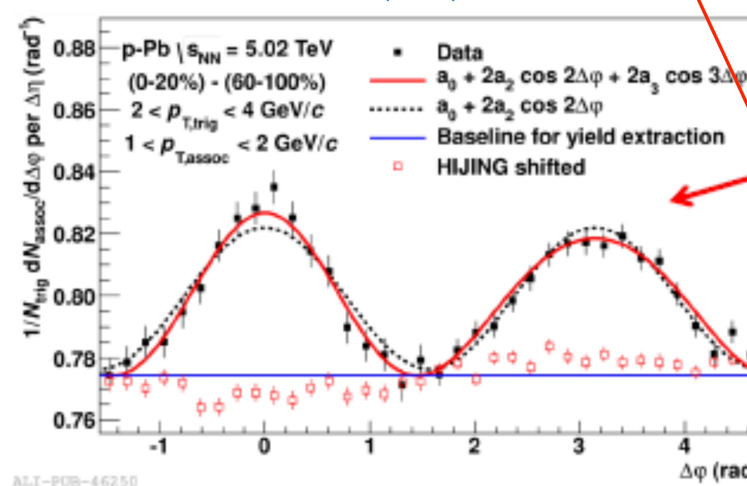
Correlations: double ridge in p-Pb



projected on $\Delta\varphi$

Double ridge described by both Color Glass Condensate (<u>initial state effect</u>) or hydrodynamics (<u>final state effect</u>)

PLB 719, 29 (2013)

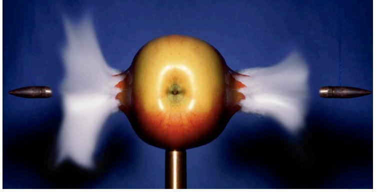


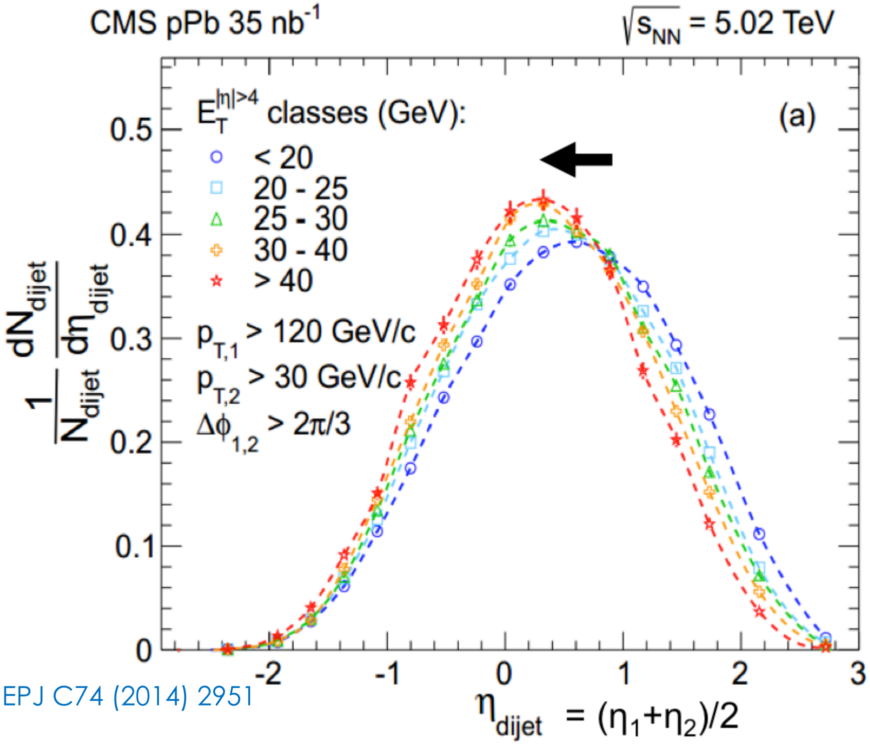
Why sometimes the particles fly in sync?

“The LHC may be uncovering a new deep internal structure of the initial protons … at these higher energies, one is taking a snapshot of the proton with higher spatial and time resolution than ever before”

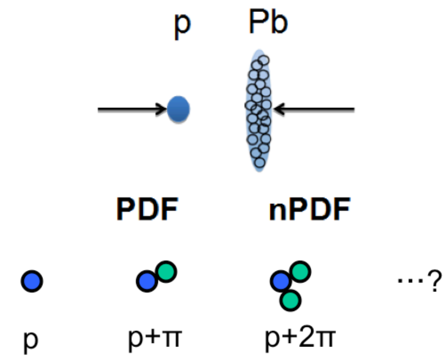
Frank Wilczek

DiJet η distribution in p-Pb





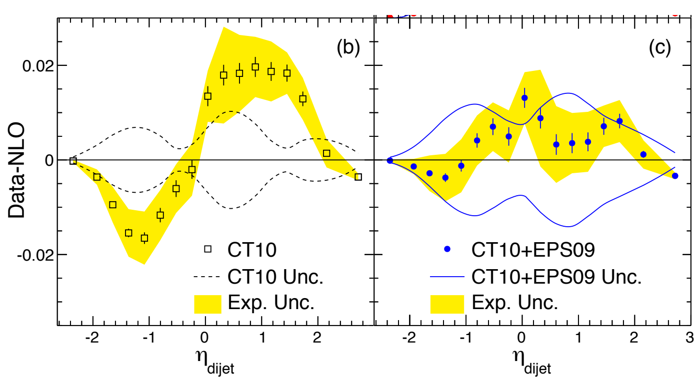
EPJ C74 (2014) 2951



Stringy proton from quantum fluctuations caughter by a nucleus?

PRD 89, 025019 (2014)

- The large modification cannot be explained by nPDF
- Color Fluctuation?
- Proton size fluctuation?
- Energy-momentum conservation?

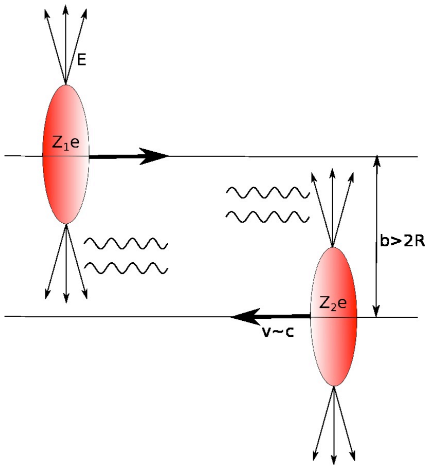


- *Need a mapping of the 3D global structure of the nucleon*
- *Need a better understanding of the dynamics of pA and AA collisions*

Shifted relative to CT10

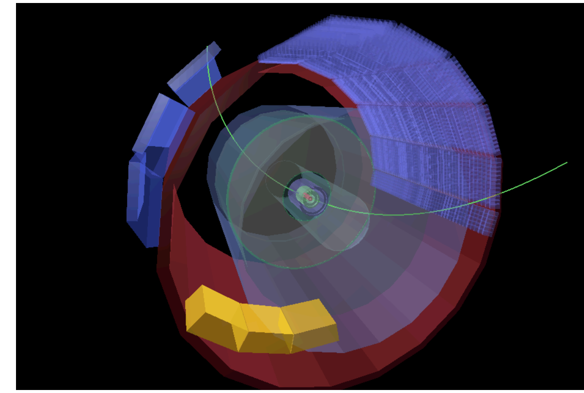
Better for CT10+EPS09 … indication of gluon EMC effect? (includes nuclear gluon shadowing)

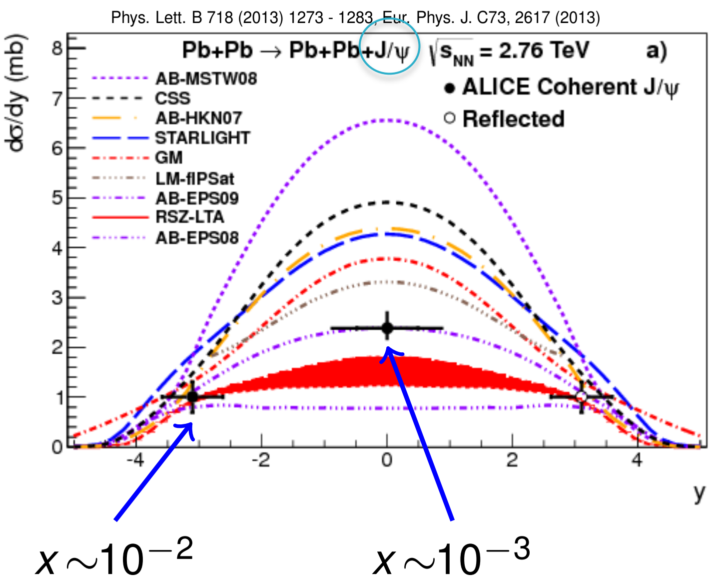
Ultra Peripheral Collisions: clean probes of nPDF

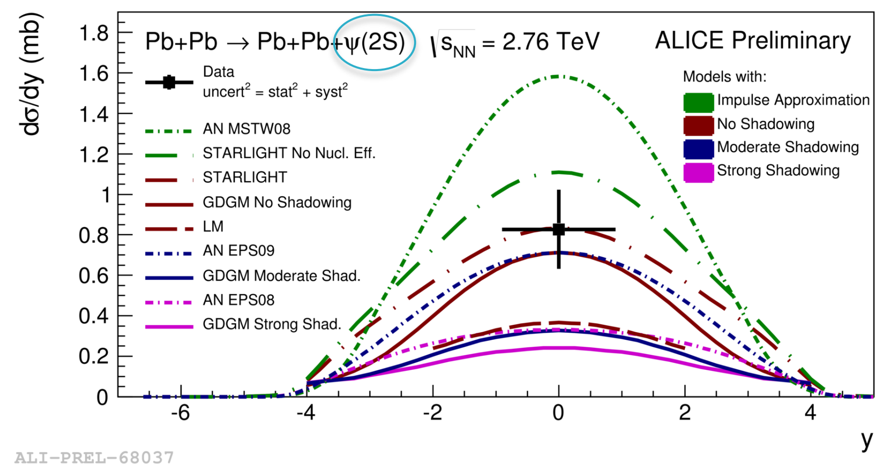


- Hadronic interactions suppressed
- Energy loss free
- Only strong e.m. field as a flux of γ^*
- Field intensity prop to Z^2
- LHC as a photon collider

- To study nPDF, saturation phenomena and nuclear gluon shadowing







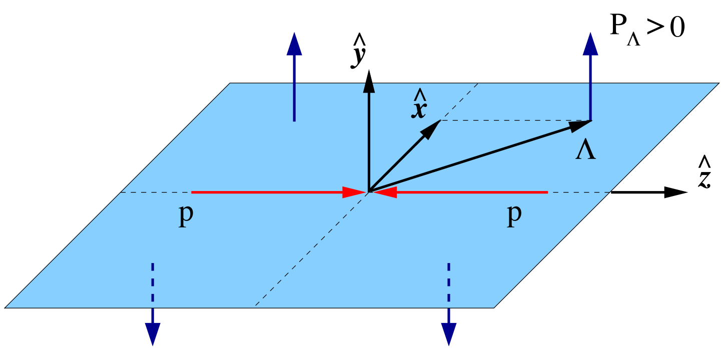
- Nuclear suppression in Pb at small x
- Best agreement with model which incorporates moderate nuclear gluon shadowing and no nuclear effects for gluon PDFs

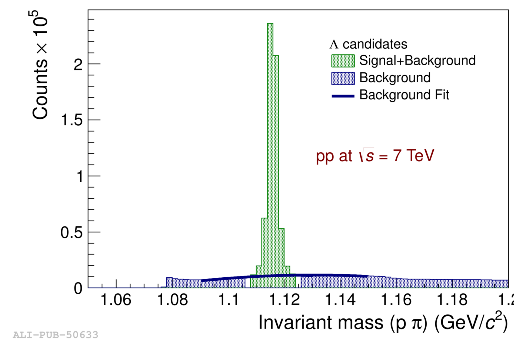
Polarized physics at the LHC

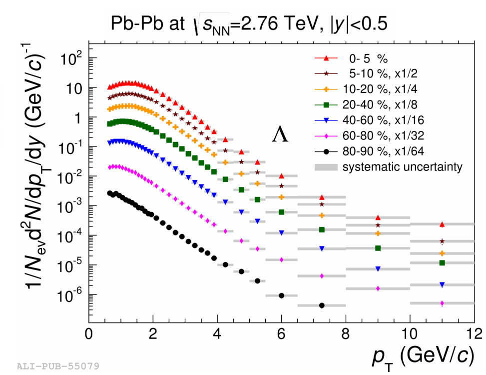
Several theoretical inputs to access to polarized functions by unpolarized pp scattering (M.Anselmino, D.Boer, G.Goldstein, S.Liuti, P.Mulders, R.Tangerman, ...)

Studies of TMDs: $D_{1T}^{\perp}$
Spin Dependence of FF in new regimes
Polarization modification in QGP

$$pp \rightarrow \Lambda^{\uparrow} + X$$
$$pp \rightarrow \Lambda^{\uparrow}(jet) + X$$
$$PbPp \rightarrow \Lambda^{\uparrow} + X$$







Favored by:
Λ reconstruction over a wide p_T range: 0.150 - 16 GeV
Different collision energies: 0.9, 2.76, 5.02, 7, 8, 13 TeV
Different collision systems: pp, pPb, PbPb
Disfavored by:
Gluon dominance contributions
Solenoidal field

Promising results

LHC Run 2 and beyond

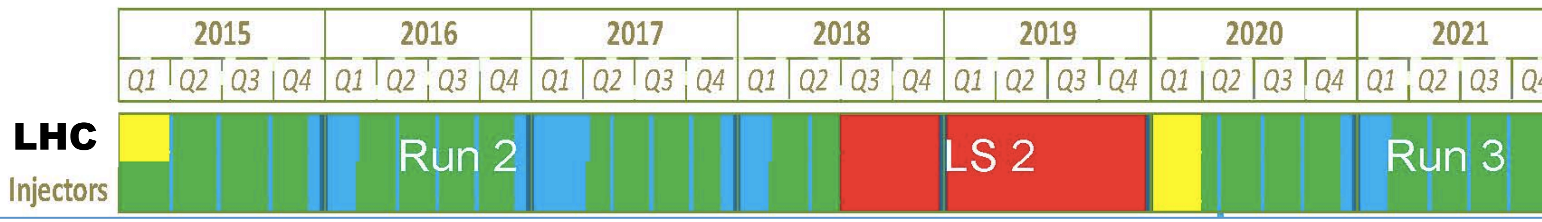
LHC experiments are now completing the refurbishment of detectors started in long shutdown #1. Nearly ready to take data in Run 2

Winter 2016-17: longer end-of-the year shutdown

LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)

LS3 LHC: starting in 2023 => 30 months + 3 BC

injectors: in 2024 => 13 months + 3 BC



Run 2 conditions

- 25 ns beam structure
- planned luminosity (pp collisions)
  - 1.5 10^{34} $cm^{-2}s^{-1}$ ATLAS & CMS (100/fb)
  - ≥ 4 10^{32} $cm^{-2}s^{-1}$ LHCb (7/fb)

LS2

Installing the upgrades:

- ALICE & LHCb
- Phase-1 of ATLAS & CMS

Run 3

- ATLAS & CMS up to 2.2 $10^{34}cm^{-2}s^{-1}$ (500/fb)
- LHCb at 2 10^{33} $cm^{-2}s^{-1}$
- ALICE higher DAQ rate

High Luminosity LHC

In LS3, upgrade of LHC to High Luminosity
Phase-2 upgrades of ATLAS & CMS

In Run 4, and beyond,
Luminosity up to 5 10^{34} $cm^{-2}s^{-1}$
3000/fb integrated up to >2035

ATLAS & CMS : new tracking detectors capable of dealing with high radiation doses and high pile-up (n=140÷200). Extended forward tracking capabilities

R&D for forward calorimetry (CMS)

New track and calorimetry based real-time triggers. Upgraded DAQ systems

ATLAS & CMS upgrades to be installed by 2025

Conclusions

LHC experiments offer an unprecedented opportunity in terms of phase space, statistics and quality of data

Run1 represented only a small "appetizer" of the many potentialities available

Run2 will increase the available statistics by more than a factor 4, not considering the energy effect

Detectors have been upgraded and refurbished during LS1 and are ready for collisions up to 13 TeV

LHC results are guiding the way at the energy frontier.
Exiting prospects in sight also for possible contacts with other physics communities