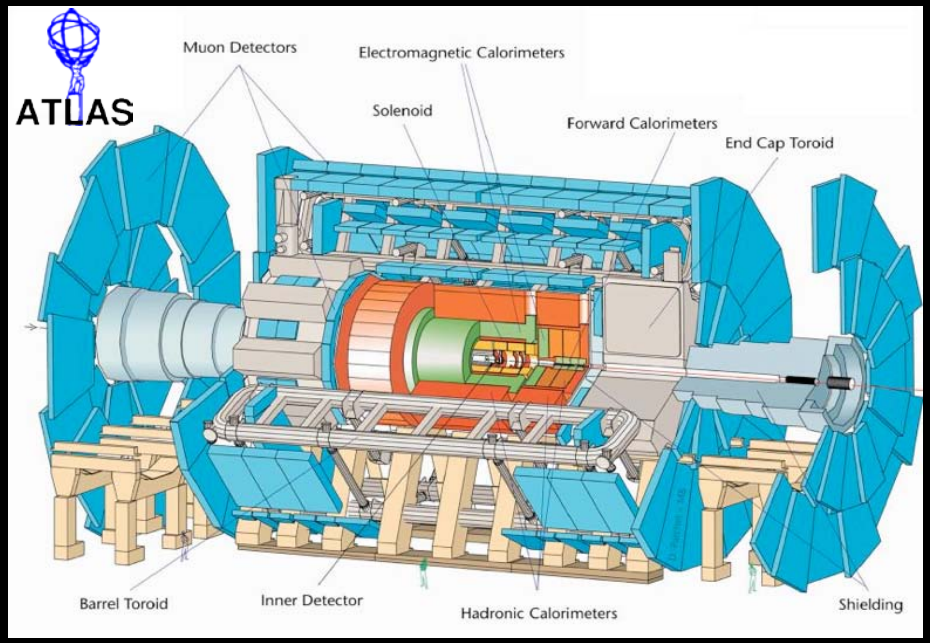
Future of Heavy Ion Physics at the LHC

LHC Heavy Ion Program

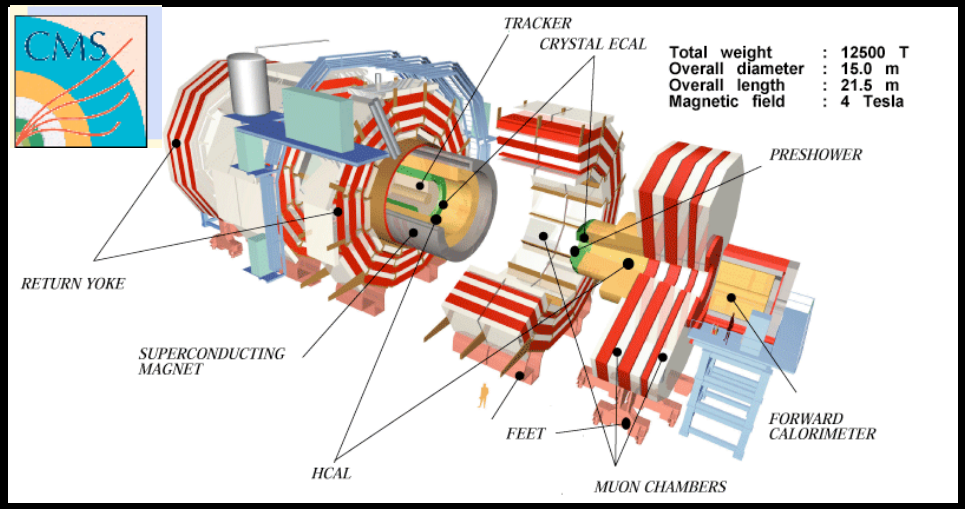


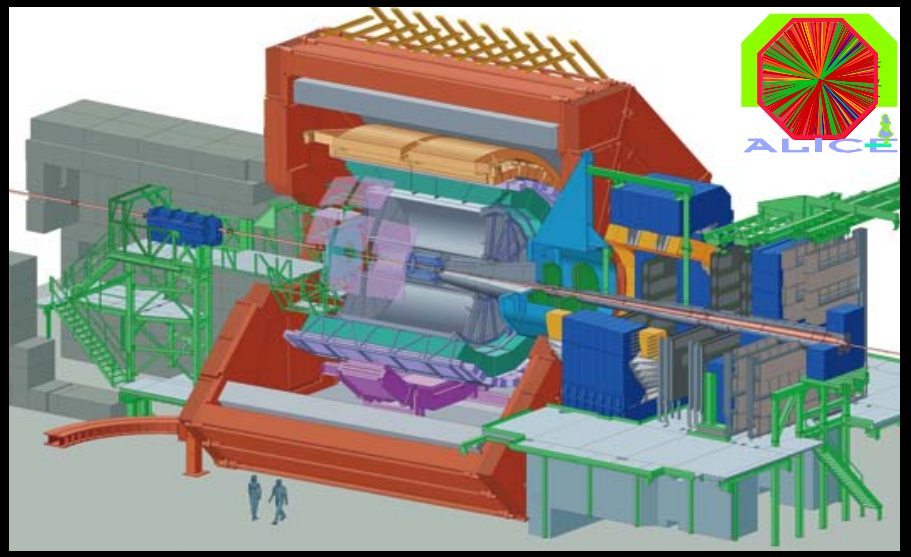
LHC Heavy Ion Data-taking

Design: Pb + Pb at $\sqrt{s_{NN}}$ = 5.5 TeV

(1 month per year)

- LHC Collider Detectors
  - ATLAS
  - CMS
  - ALICE





Heavy Ions at the LHC

- ***Determine Initial Conditions*** – ***What is the extent of shadowing, saturation, CGC?***

  → sets the stage for particle production / dynamics

- ***Expect different timescales, interaction times, higher energy (T) w.r.t RHIC!***

  Does system still equilibrate rapidly?

  Thermal model still apply? → T still ~ T_c (lattice QCD)?

  Does it flow?

  Elliptic Flow change? → v_2 still saturated? More or less v_2? p_T dependence?

  Is the QGP still strongly- (or weakly-) coupled?

  Liquid? More like a gas? → No longer "nearly-perfect" fluid flow? viscosity?

  → Impact on energy loss!!

- ***Understand parton energy loss!*** – ***What are the microscopic processes?***

  → mass and flavor dependence?

  → use high p_T jets & tag heavy quark jets

- ***Understand response of the medium!***

  Strongly interacting quarks and gluons → away-side response?

- ***Color screening of the medium!***

  Deconfinement? (compare LQCD), initial T, other effects → J/ψ & Υ states

"Probable" LHC Near-term Heavy Ion Program

2010 (official)

18 – 31 Oct: Change-over from p + p to Pb + Pb

1 – 28 Nov: $\sqrt{s_{NN}}$ = 2.76 TeV Pb + Pb for physics

2011 (anticipated)

November timeframe: $\sqrt{s_{NN}}$ = 2.76 TeV Pb + Pb for physics

2010 – 2011: increasing L $\rightarrow$ integral luminosity $\int L\ dt \sim 25\ \mu b^{-1}$

2012 (official)

Shutdown for maintenance, installation & repairs

2013

1 month $\sqrt{s_{NN}}$ = 5.5 TeV Pb + Pb for physics

2014

1 month $\sqrt{s_{NN}}$ = 5.5 TeV Pb + Pb for physics to reach $\int L\ dt \sim 1\ nb^{-1}$

2015

1 month* $\sqrt{s_{NN}}$ = 5.5 TeV p + Pb and Pb + p for physics

* Possibly longer than 1 month due to proton injector shutdown/upgrade

lighter A + A possible

2010-2011: Early Heavy Ion Running

		Early (2010/11)	Design/ Nominal
$\sqrt{s}$ per nucleon pair	TeV	2.76	5.5
Initial Luminosity (L_0) – to increase with time (2010 → 2011, 2013, 2014)	$cm^{-2}s^{-1}$	1.25×10^{25}	10^{27}
Number of bunches		62	592
Bunch spacing	ns	1350	99.8
β^*	m	2	0.5
Pb ions/bunch		7×10^7	7×10^7
Transverse norm. emittance	μm	1.5	1.5
Luminosity half life (1,2,3 expts.)	h	τ_{IBS}=7-30	8, 4.5, 3

Initial interaction rate: 100 Hz (10 Hz central collisions b = 0 – 5 fm)
~10^8 interaction/10^6s (~1 month)
In two years: 2 x10^7 central collisions, integrated luminosity 25 μb^{-1}

Prospects (ala ALICE) for "First Physics"

- **First physics** is NOW – pp important reference data for heavy-ions
  Examples:
  - multiplicity distribution, baryon transport
  - identified particle spectra
  - measurement of charm cross section major input to pp QCD physics

- **First 10^5 PbPb events:** global event properties
  - multiplicity, rapidity density, charged particle spectra
  - elliptic flow
- **First 10^6 PbPb events:** source characteristics and spacetime evolution
  - identified particle spectra, resonances
  - differential flow analysis
  - particle correlations, interferometry
- **First 10^7 PbPb events:** high-p_T and heavy flavors
  - suppression, "jet" quenching, heavy flavor energy loss
  - charmonium production
- Eventual goals - bulk properties of medium & parton energy loss mechanisms
  - energy density, temperature, pressure
  - heat capacity/entropy, viscosity, sound velocity, opacity
  - susceptibilities, order of phase transition

Soft Physics at LHC

Event Characterization (baseline, shadowing, CGC, ….)

- Multiplicity, centrality, transverse momentum and pseudo-rapidity distributions

Bulk Properties of the Medium (T, μ, …)

- Particle ratios, hadronic resonances

Chiral Symmetry Restoration

- Short-lived resonances & medium-modified masses

Collision Dynamics (space-time evolution, transport properties)

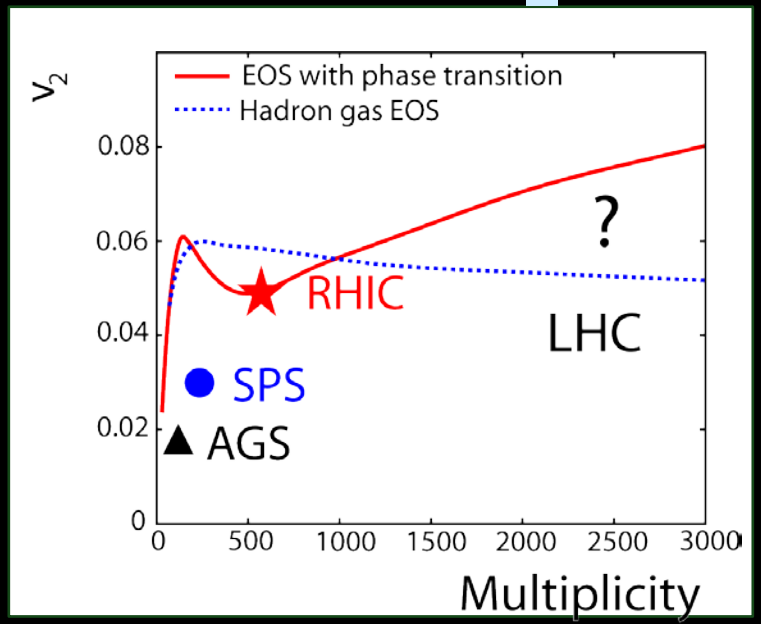
- Momentum correlations (3D HBT – one of first measurements)
- Collective Flow (radial, anisotropic)
- Baryon number transport

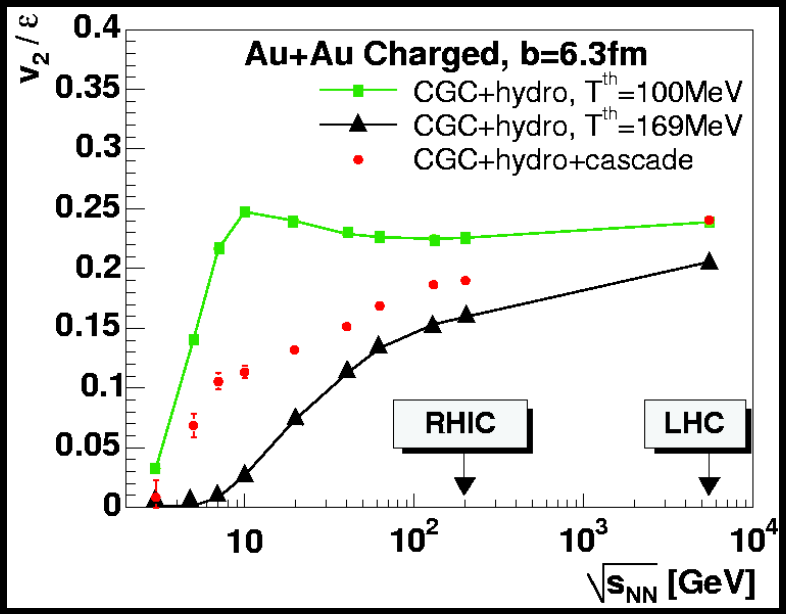
Fluctuations

- Event-by-event – particles, momentum, …

Example – v_2 Predictions for the LHC

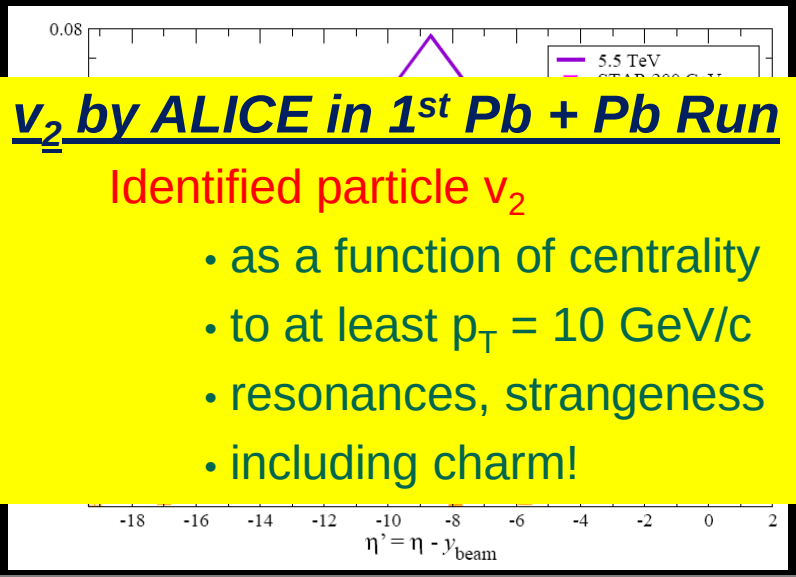
Heinz, Kolb, Sollfrank





Hirano et al , nucl-th/0701075v2

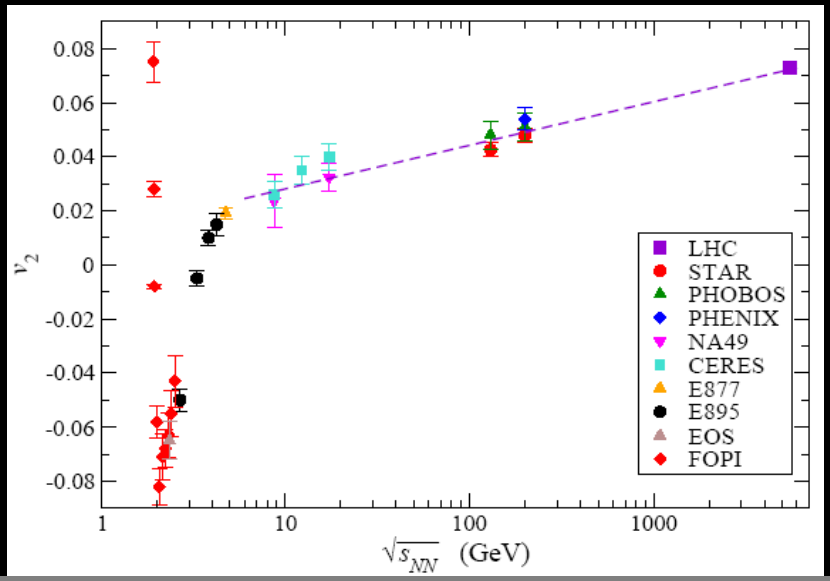
N.Borghini and U.A.Weidemann, J.Phy.G 35 (2008) 023001



v_2 by ALICE in 1st Pb + Pb Run

Identified particle v_2

- as a function of centrality
- to at least p_T = 10 GeV/c
- resonances, strangeness
- including charm!



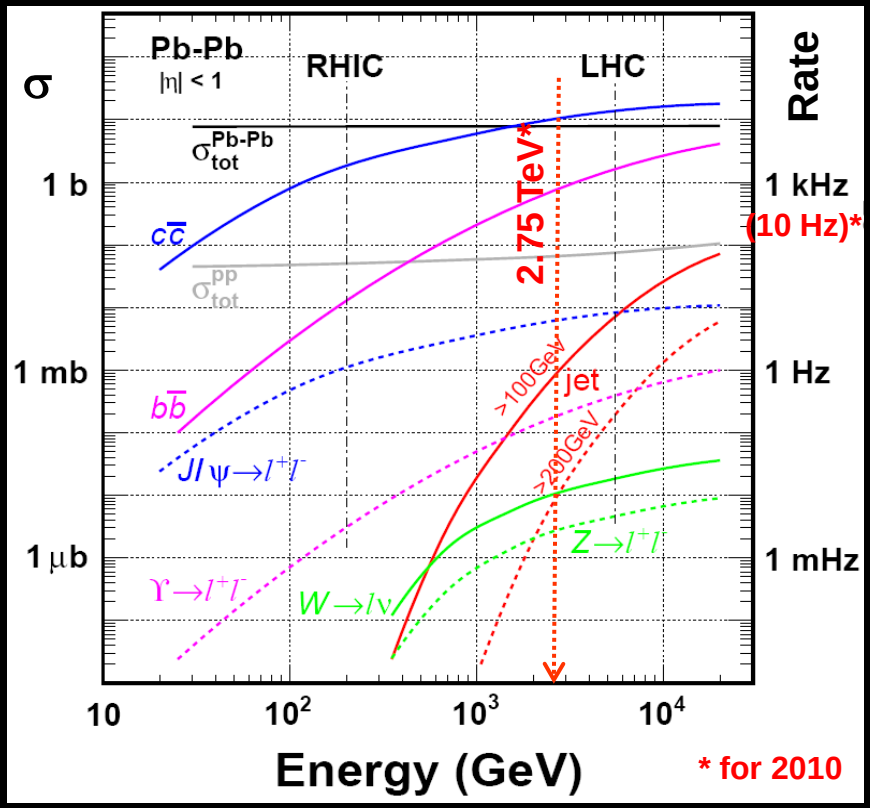
Heavy Flavor at LHC

Significant increase at LHC

- Abundance of heavy flavors
  probe early times, calculable

σ_{cc} (LHC) ~ 10 σ_{cc} (RHIC)

σ_{bb} (LHC) ~ 100 σ_{bb} (RHIC)



Heavy Quarkonia

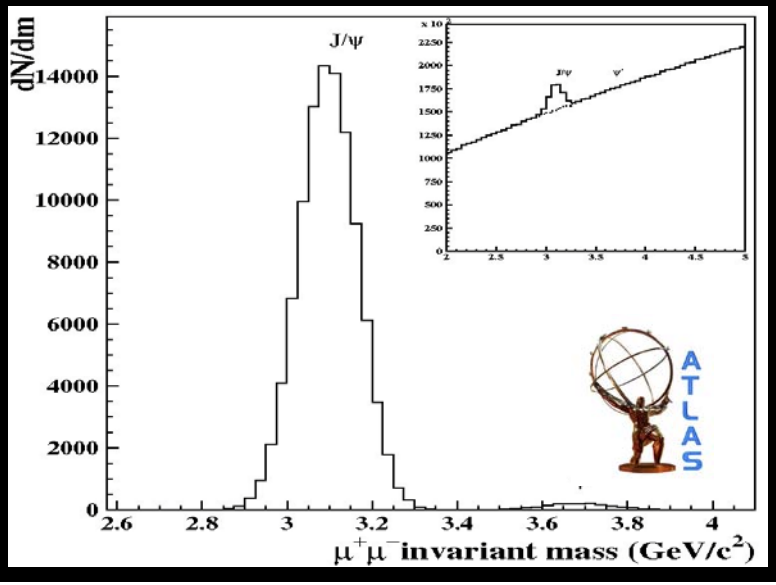
- J/ψ suppression (or enhancement?)
- Υ suppression (statistics limited)

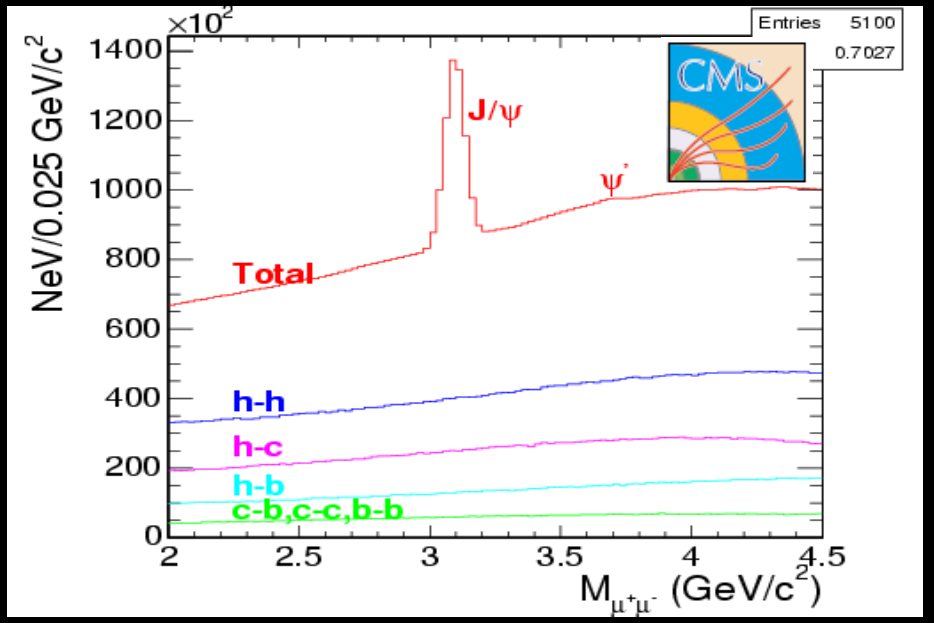
Open Charm & Beauty

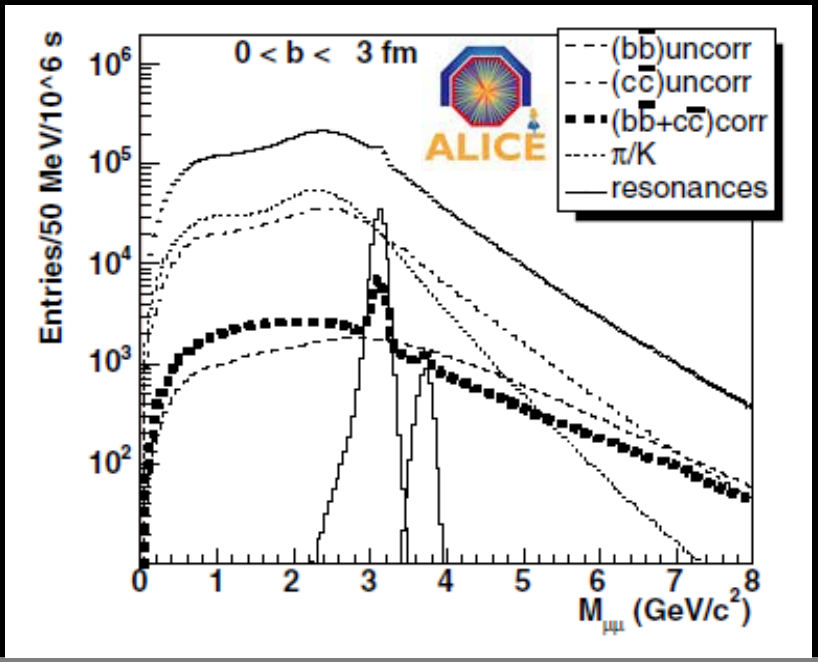
- Open charm and beauty p_T spectra
  Displaced vertices: D- & B-mesons (e.g. $D^0 \to K^- \pi+$, $B \to$ e + hadrons)
- Heavy quark in-medium energy loss → Mass/color charge dependence

$J/\psi\ (\Upsilon) \rightarrow \mu^+\mu^-$ at LHC

0.5 nb^{-1} at $\sqrt{s_{NN}}$ = 5.5 TeV





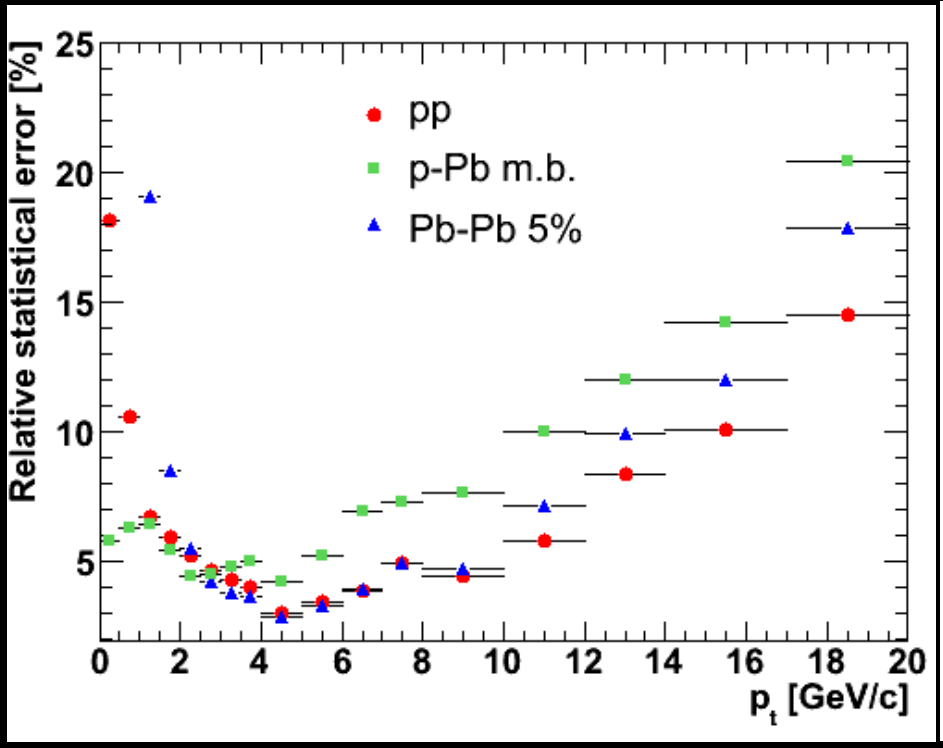


Heavy Quarkonia

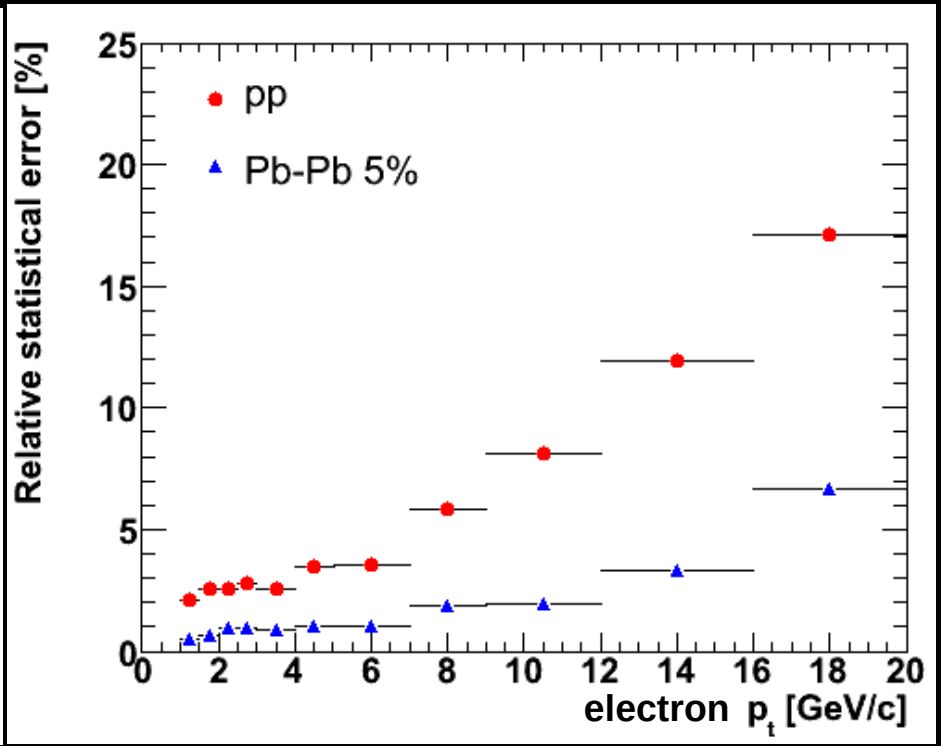
- ~10k J/ψ per experiment
- in several p_T bins up to 10 GeV/c
- in ALICE down to $p_T = 0$
- Several 100 ψ' per experiment, but low S/B & significance
- ~100 Y in ALICE, low background
- ~500 Y in ATLAS/CMS, but low S/B

Heavy Quarks in ALICE - p_t Coverage

$D^0 \rightarrow K\pi$



$B \rightarrow e + X$



Simulation for $\sqrt{s_{NN}}$ = 5.5 TeV
(10^7 central Pb-Pb events, 10^9 pp events)

also for $\sqrt{s_{NN}}$ = 2.75 TeV in 2010 & 2011
Charm p_T spectrum to 15 GeV/c

High p_T Particles and Jet Rates at LHC

Hard probe physics measurements:

- High p_T hadron (PID) suppression (R_{AA})
- Di-hadron $\Delta\phi$ correlations to ~100 GeV/c
- Jet spectra & shapes
- γ, Z, γ-jet (Z-jet) corr's (statistics?)

Hard Probe statistics with 0.5 nb^{-1} in ALICE/ATLAS/CMS:

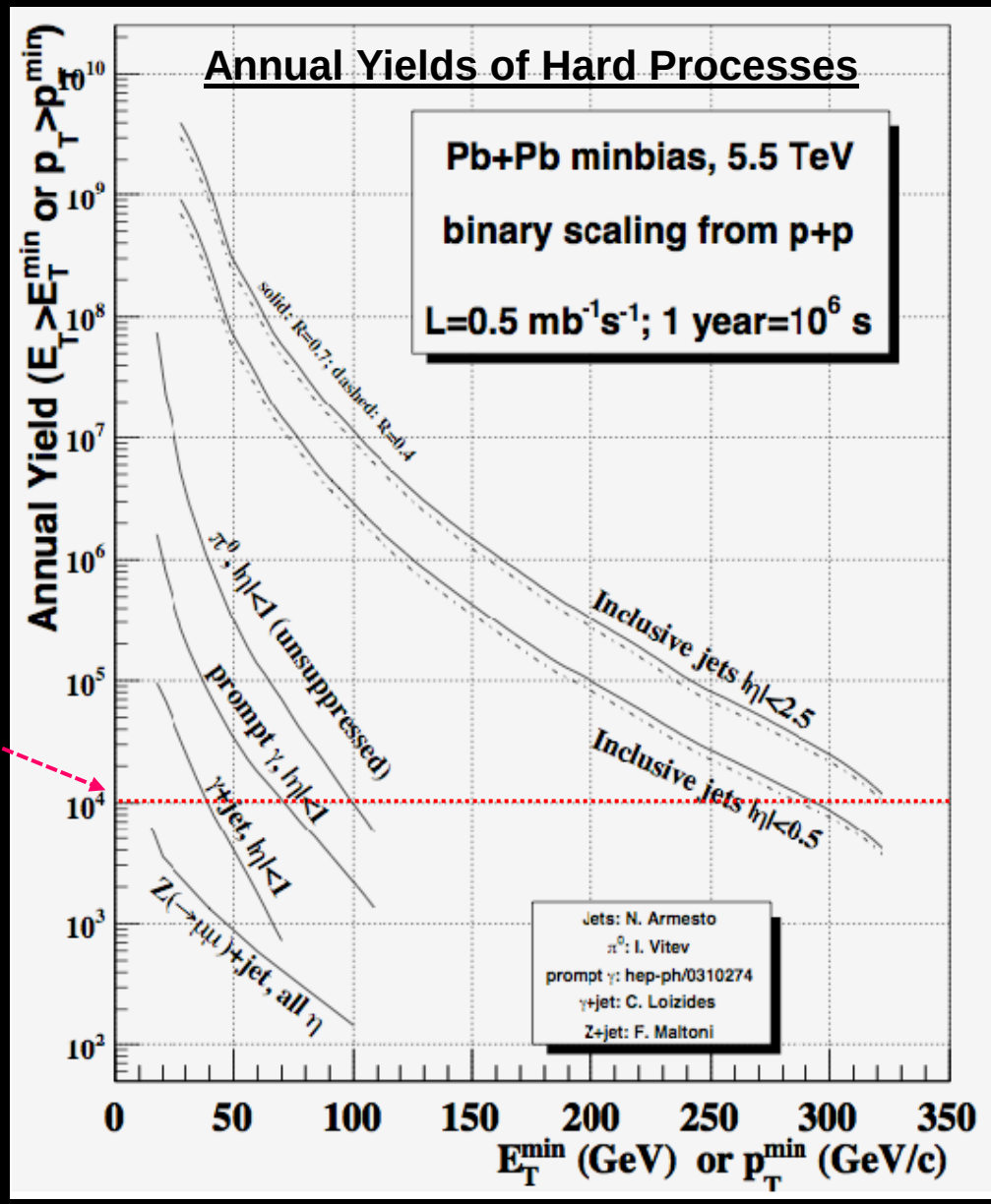
10^4/year

inclusive jets: E_T ~ 200-325 GeV

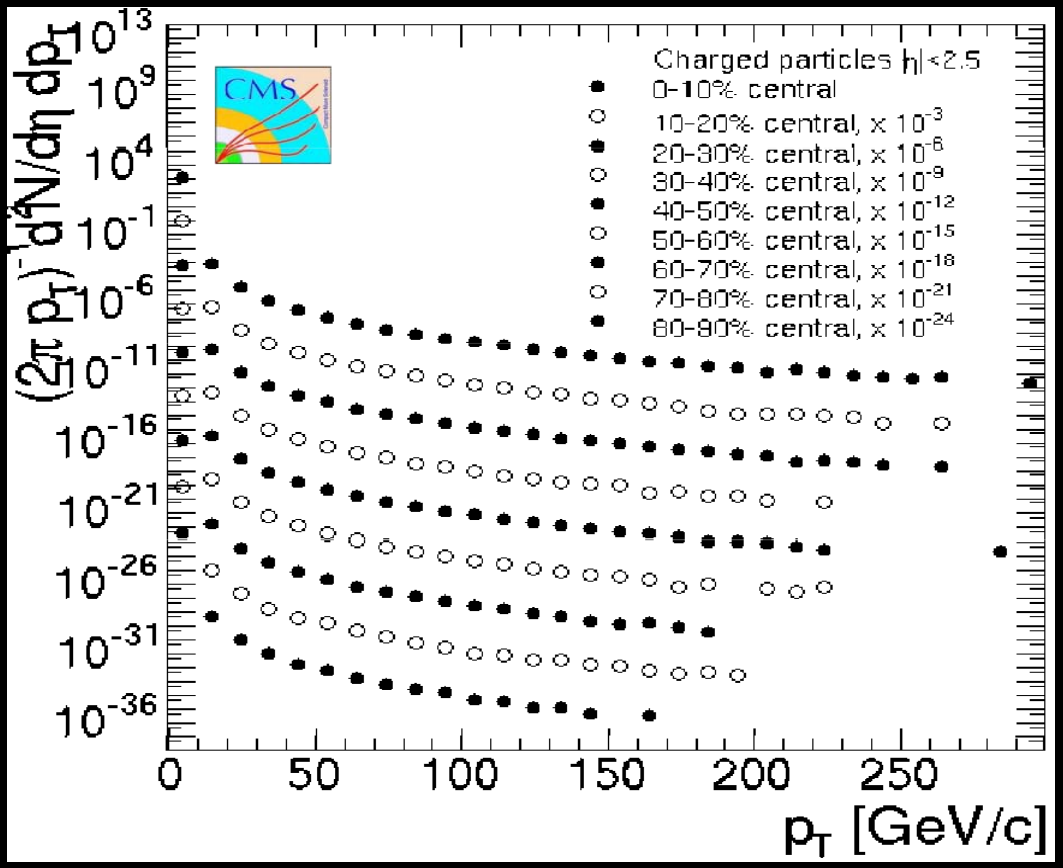
dijets: E_T ~ 170-250 GeV

π^0: p_T ~ 75-150 GeV/c

inclusive γ: p_T ~ 45-100 GeV



Charged Hadrons in CMS – High p_T Trigger



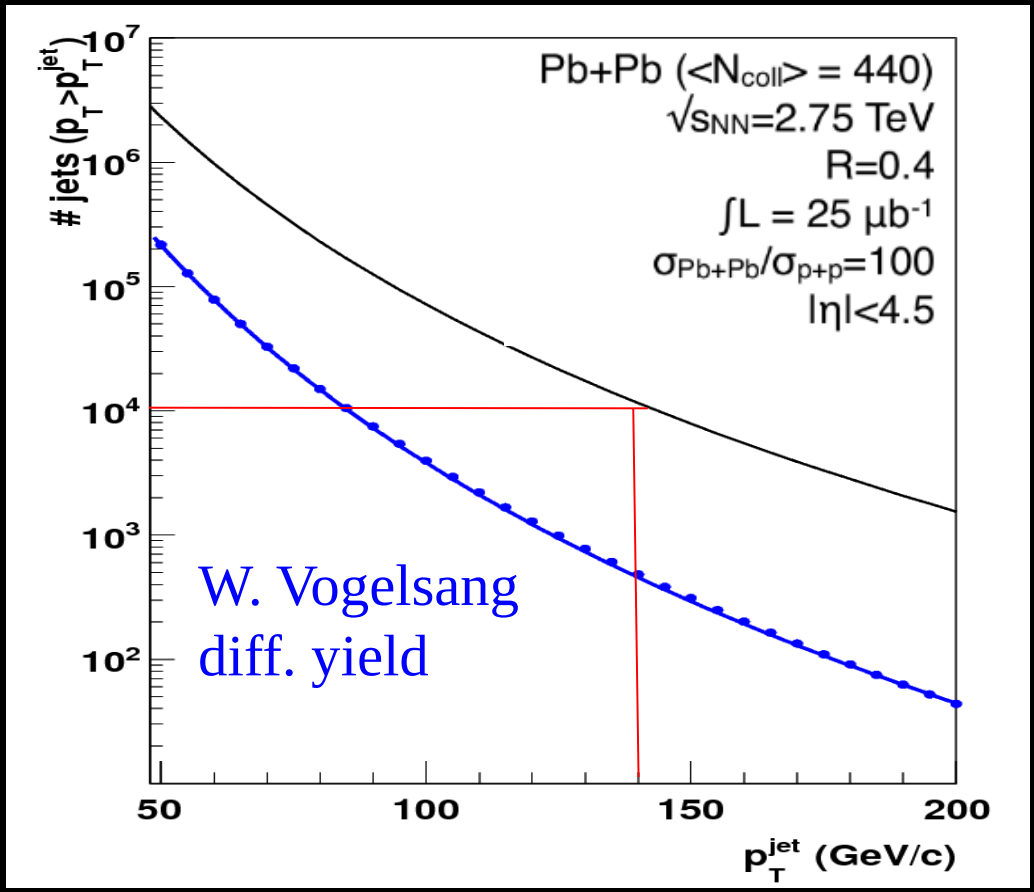
Courtesy B. Wyslouch

ATLAS/CMS spectra p_T reach ~ 300 GeV/c for high luminosity run

~ 60-100 GeV/c for 2010-2011

Jets in Pb + Pb at LHC

25 μb^{-1} + trigger on hard processes



Courtesy P. Steinberg

~ 10k Jets per E_T bin needed for fragmentation studies. E_T reach of exp's:

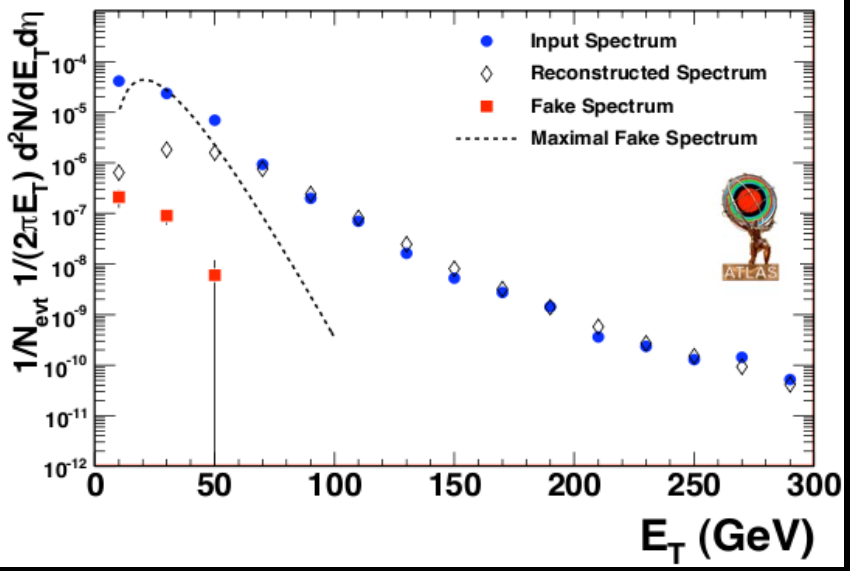
ATLAS/CMS p_T reach ~ 140 GeV/c for 2010-2011

ALICE p_T reach ~ 70 GeV/c for 2010-2011

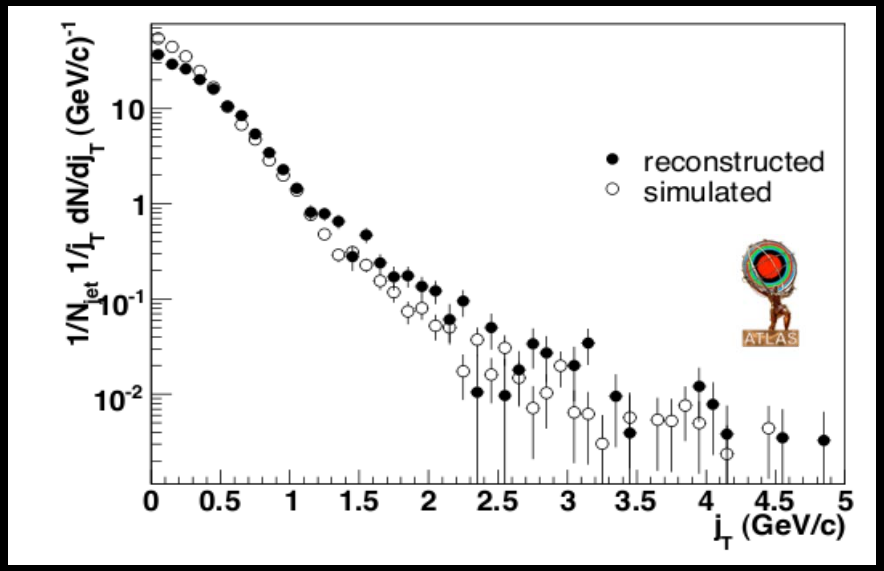
Jet Shapes & Fragmentation in Pb + Pb in ATLAS

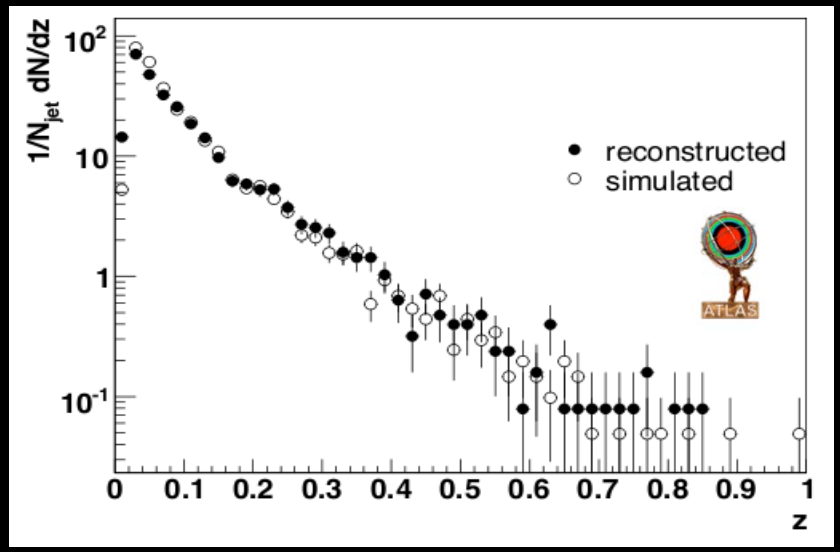
25 μb^{-1} + trigger on hard processes

Inclusive Jet Spectrum

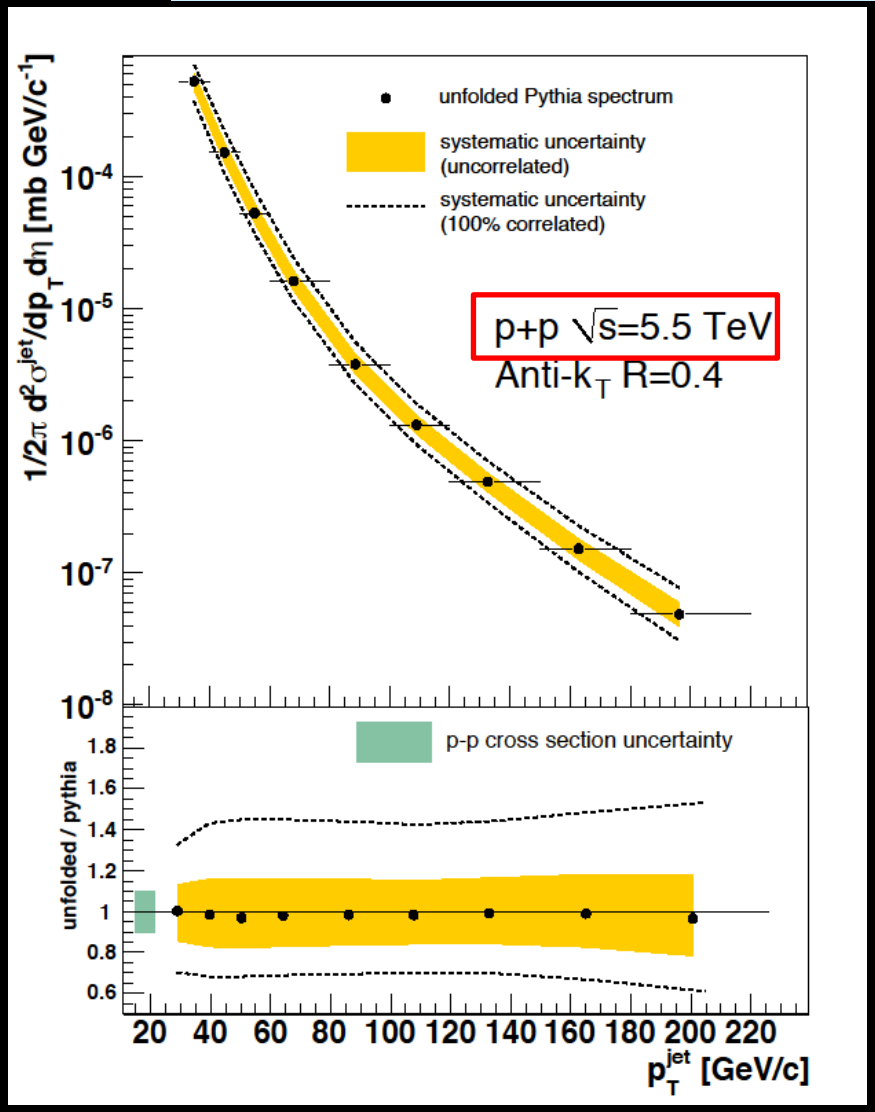


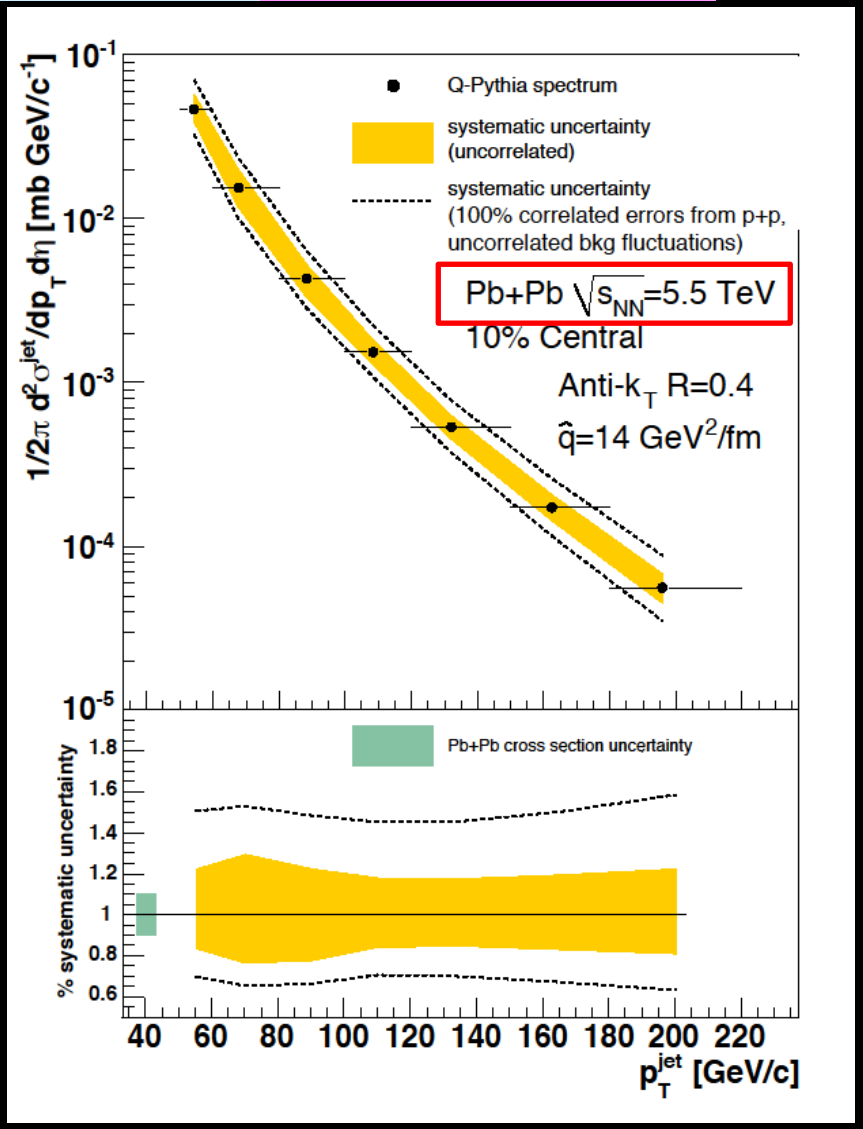
Courtesy P. Steinberg





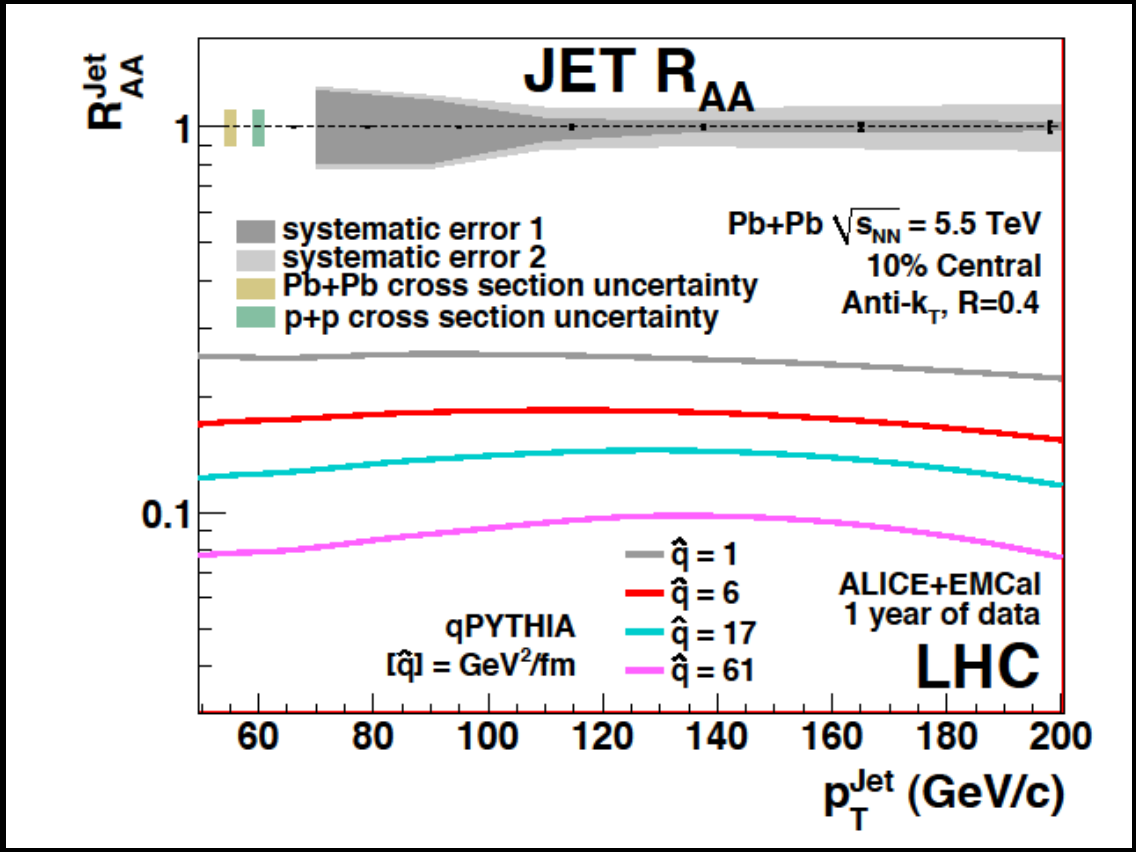
ALICE Inclusive Jet Cross Section Measurement Capabilities with EMCal





Jets in ALICE with EMCal: R_{AA}

Central Pb+Pb $\sqrt{s_{NN}}$=5.5 TeV

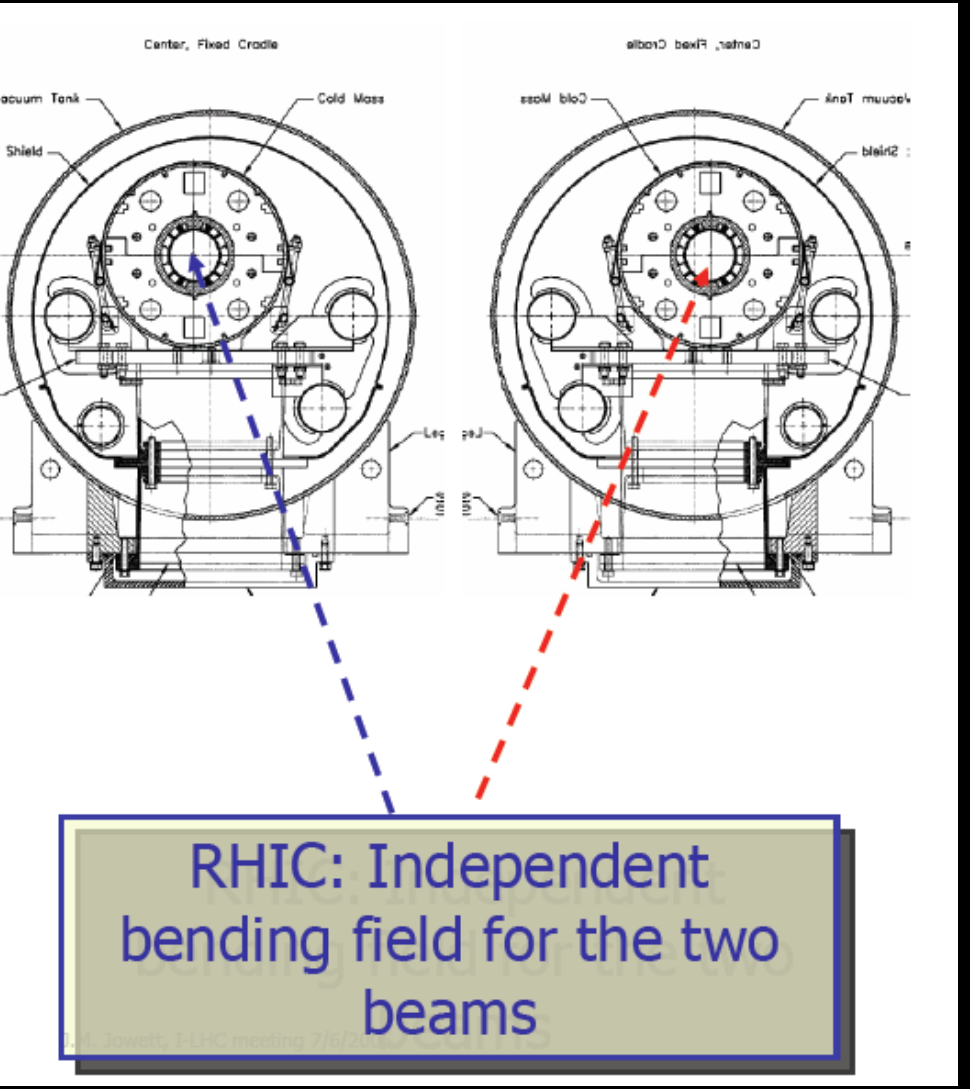


Jet systematic uncertainties small!

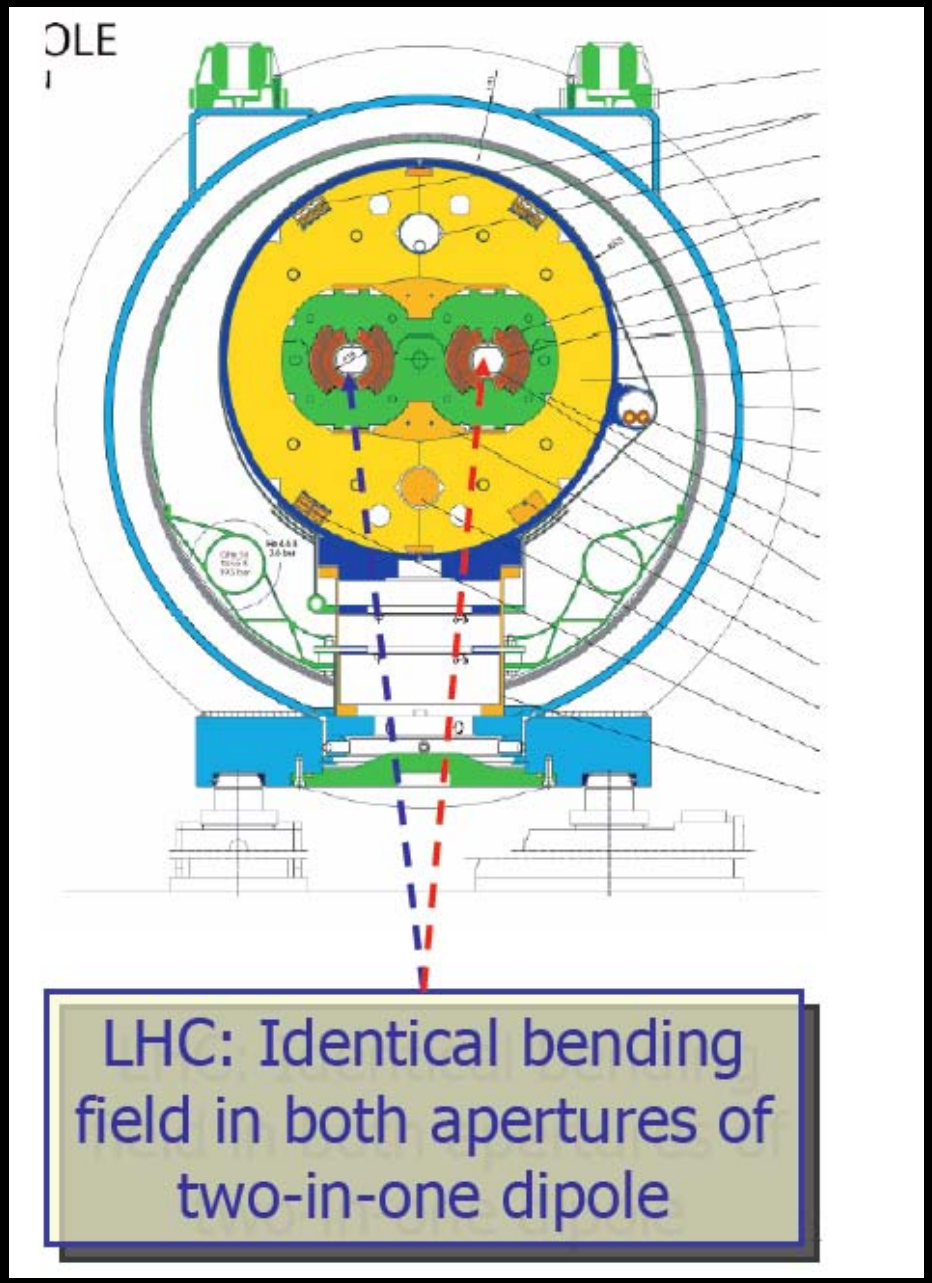
Measurements possible to 200 GeV – statistically and systematically

LHC Design & Machine Upgrade Plans – Impact on Heavy Ion Program

RHIC and LHC Designs – the BIG Difference



RHIC: Independent bending field for the two beams



LHC: Identical bending field in both apertures of two-in-one dipole

Ref: J.M. Jowett, Workshop on pA Collisions at LHC (2005)

Kinematics of Colliding Nuclei in LHC

LHC's two-in-one design requires fixed rigidity of beams:

$$p_{Pb} / Z_{Pb} = p_{proton}$$

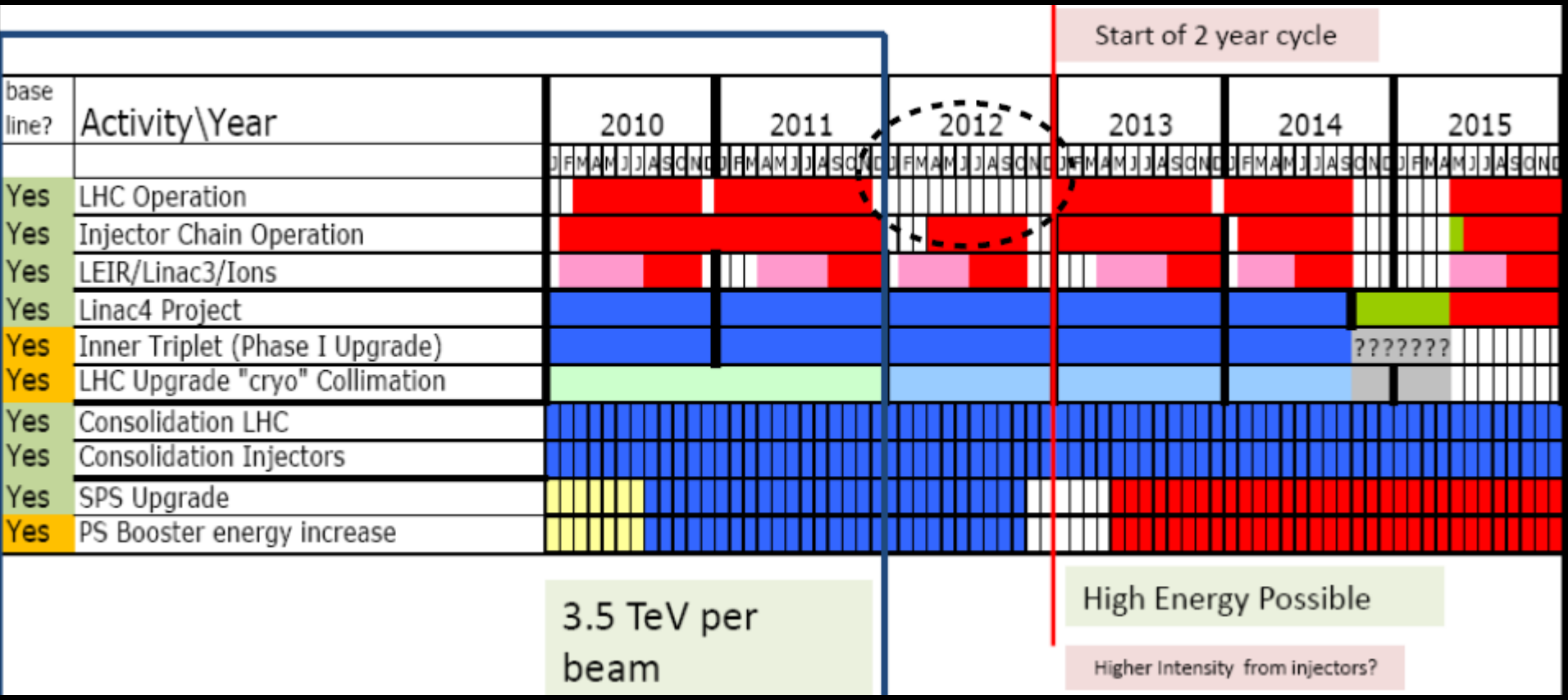
	p-p	Pb-Pb	p-Pb	d-Pb
E / TeV	7	574	(7,574)	(7,574)
E_N / TeV	7	2.76	(7,2.76)	(3.5,2.76)
$\sqrt{s}$ / TeV	14	1148	126.8	126.8
$\sqrt{s_{NN}}$ / TeV	14	5.52	8.79	6.22
y_{CM}	0	0	2.20	2.20
y_{NN}	0	0	-0.46	-0.12

$$\sqrt{s}_{NN} \sim 2\, c\, p_{proton}\, (Z_1\, Z_2 / A_1\, A_2)^{1/2}$$

$$y_{NN} = \tfrac{1}{2} \log (Z_1\, A_2 / A_1\, Z_2)$$

Ref: J.M. Jowett, Workshop on pA Collisions at LHC (2005)

LHC Machine Operation & Upgrade Plans



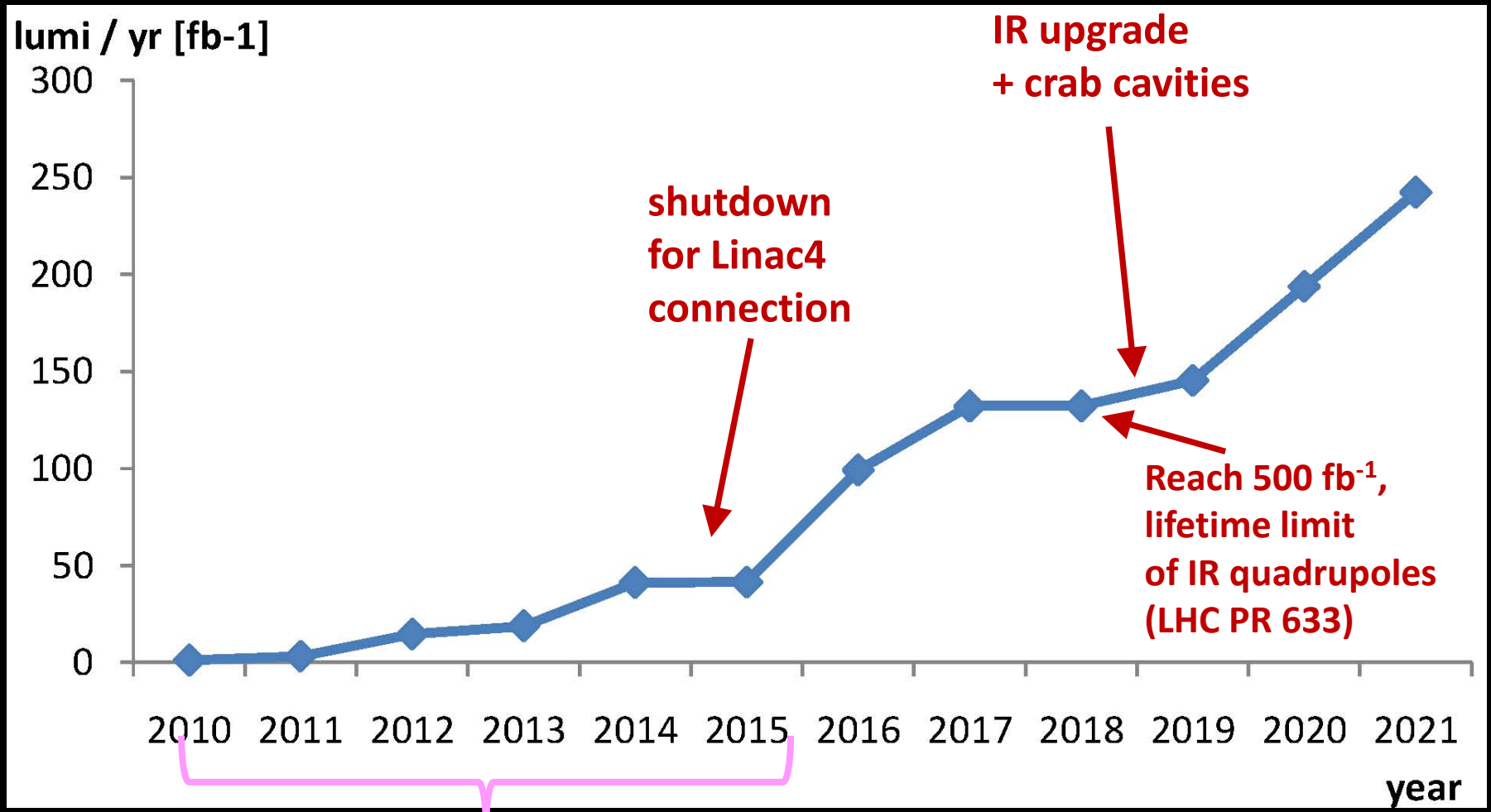
- *Phase 1 –* Linac4 on track, connection to PS ~ 2014/2015

  Rough estimate of 200-300 fb^{-1} by 2017

  IR upgrade could be delayed to ~2017

  Parallel effort on LHC crab cavities

LHC Machine Luminosity Upgrade Plans & Longer Term Upgrades



~ forecast from Steve Myers and Roger Bailey

LHC Heavy Ion Luminosity Increase

- **Pb design Luminosity (may be optimistic!)**
  - $L_0 = 10^{27}$ cm^{-2} s^{-1}, $\langle L \rangle \sim 0.3 - 0.5\ L_0$

    "LHC heavy ion year" assume = 10^6 s $\rightarrow \int L_0\, dt \sim 0.5$ nb^{-1}
- **Examples of signals with limited statistics**
  - Υ suppression

    7000 Υ, 1000 Υ'' per Pb + Pb year in ALICE (> 10^5 J/ψ in NA60)
  - γ-jet correlations

    1000 γ-jet events/year with $p_T > 30$ GeV/c

    Fragmentation functions at large z require x 10 more!

  $\rightarrow$ 3-4 years operation at 4-5 x L_0 provides x 10 increase in statistics!
- **Implications for ALICE**
  - Minor detector modifications necessary to benefit from 5 x L_0
  - Limitation is TPC (pile-up, NOT space charge)

    TPC designed for $dN_{ch}/dy = 8000$, expectation is 2000 – 4000

    Rate increase possible (pile-up acceptable for high p_T physics, faster gas if needed)

LHC Detector Upgrade Plans & Heavy Ions

ATLAS Upgrade Plans*

Phase 1 (~ 2015)

Tracker upgrade – Insertable B-Layer

present tracker inner layer reaches rad limit after 1 year of design *L*

insertable inner layer with smaller radius beam pipe

Fast Track Trigger (proposal being developed)

add Level 1.5 tracking hardware trigger for B-tagging

Forward Physics Upgrade (proposal)

far forward – 420 and 220 m distance from IP

using 3D silicon sensors with < 10 ps timing

diffractive production of Higgs

forward physics

Phase 2 (~ 2019 to utilize sLHC L ~ 10^{35} cm^{-2} s^{-1})

Tracker upgrade – replace entire tracking system

very rad hard silicon pixel (3D?) upgrade

Trigger/DAQ upgrade – continuing upgrades to L1 & L2, introduce L1.5 triggers

sLHC goal at L1 – 100KHz rate (~400 interactions per crossing)

* http://www.slac.stanford.edu/exp/atlas/upgrade/

CMS Upgrade Plans

Near Term (2012)

Hadron Calorimeter Upgrades

improve triggers on muons and forward jets

New Beam Pipe and Luminosity Monitors (Diamond)

easier pixel detector installation → B-tagging

Phase 1 (~ 2015)

Tracker upgrade – New Pixel System

low mass, faster readout → reduce deadtime, improve B-tagging

Hadron Barrel and Endcap Calorimeter Upgrade

electronics & trigger upgrades, long segmentation improvement for Higgs ch's

Muon Trigger & ReconstructionUpgrade

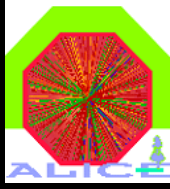
$1.1 < |\eta| < 1.8$, $2.1 < |\eta| < 2.4$

W acceptance and Higgs channels

Phase 2 (~ 2019 to utilize sLHC L ~ 10^{35} cm^{-2} s^{-1})

Replace Tracker, Trigger, Endcap Calorimeter

ALICE Specific Upgrades Now for Heavy Ions

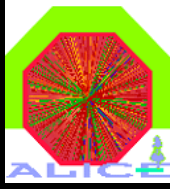


- **ALICE designed primarily for Heavy Ion Physics.**
  - Optimized for Pb + Pb multiplicities / luminosities (10^{27}–10^{28} cm^{-2} s^{-1})
- **ALICE plans only indirectly linked to LHC high luminosity upgrade**
  - Some limitations to maximum Pb + Pb luminosity improved by sLHC luminosity upgrade: improvements in collimation essential.
- **ALICE has evolved considerably from initial Technical Proposal, largely due to new data from RHIC.**
  - Transition Raditaion Detector (TRD) approved much later than other central detectors, expected to be complete by 2011.
  - New EM calorimeter (EMCal), important for jet measurements proposed/approved(LHCC)/funded by US-Italy-France

    40% installed, rest complete by 2011 & next installation period.
  - New Dijet electromagnetic calorimeter (Dcal) for di-jets & π^0-jets proposed/approved/funded by US-Japan-France-Italy-China

    Complete by 2012 shutdown & installation period.

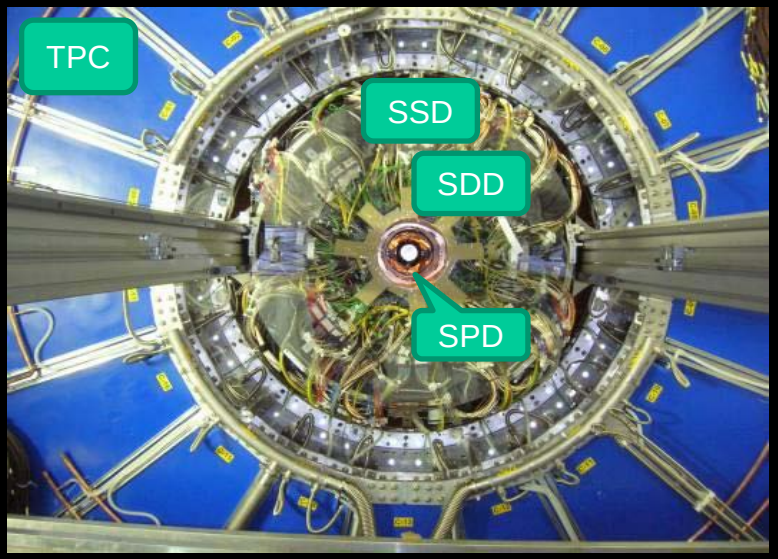
ALICE Upgrade Plans Beyond 2010-11



- **2nd generation vertex detector (smaller beam-pipe)**
  - for improved heavy quark physics

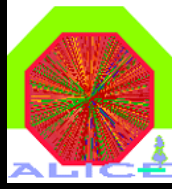
Inner Tracking System Upgrade

- **x2 impact parameter resolution (for p_T < 1 GeV/c)**
  - Increases charm sensitivity x100
  - Access to charmed baryons
    Charm B/M big issue for reco!
  - Allows study of exclusive B decays
  - Allows total B x-section to $p_T \sim 0$
  - Improves flavor tagging



- **Techniques?**
  - Thinnest / smallest beam pipe (a la CDF)
    Reduce R = 2.9 cm to ~1.3 cm
    Reduce thickness from present 800 μm to 400 μm
  - New pixel technology
    thinner (≤ 200 μm + 150 μm)
    higher granularity (≤ 150 μm x 425 μm)

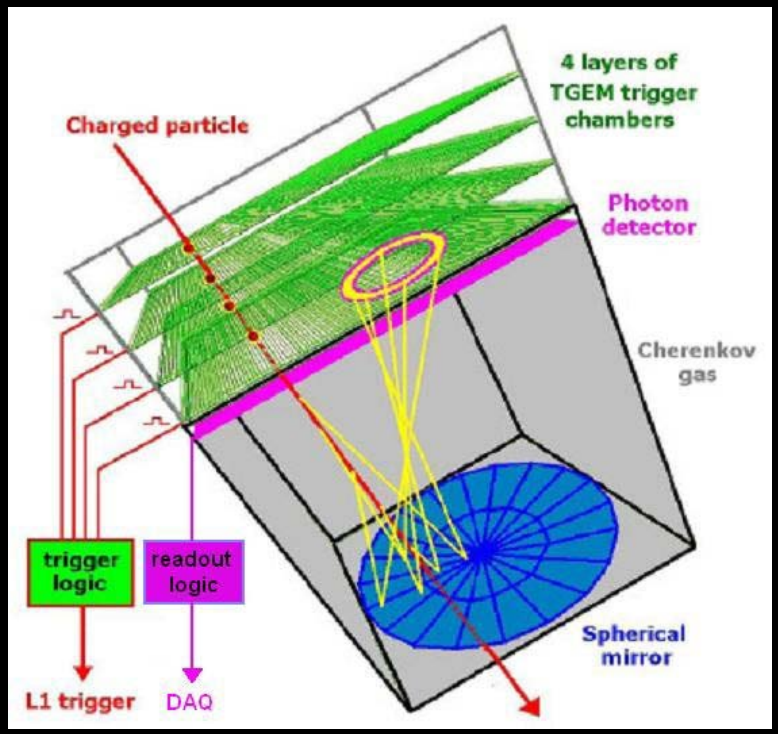
ALICE Upgrade Plans Beyond 2010-11



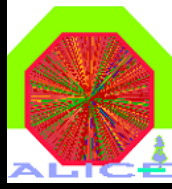
- **2nd generation vertex detector (smaller beam-pipe)**
  - for improved heavy quark physics
- **PID for p_T ~ 5 – 20 GeV/c (based on results from RHIC)**
  - for PID particle & resonance spectra/correlations, flow, recombination,…..

Very High Momentum PID Upgrade (VHMPID)

- **p_T > 10 GeV/c necessary to study**
  - Flavor-dep jet fragmentation / quenching
  - Gluon vs quark origin of jet
  - p + p flavor-dep multiparticle production
- **Technique**
  - RICH detector with mirrors
    - Gas radiator (C_4F_{10}?)
    - Maximum length ~80 cm
  - Photon detector
    - MWPC with CsI photon converter & pad readout (HMPID technology)
    - Thick GEM (≥ 2 layers) with CsI photo-converter (promising results)
  - Dedicated trigger logic to select high p_T
    - Use TRD detector and/or
      - New trigger detector - 4 GEM layers & algorithm selecting high p_T
    - Use opposite EMCAL detector to trigger on high energy jets



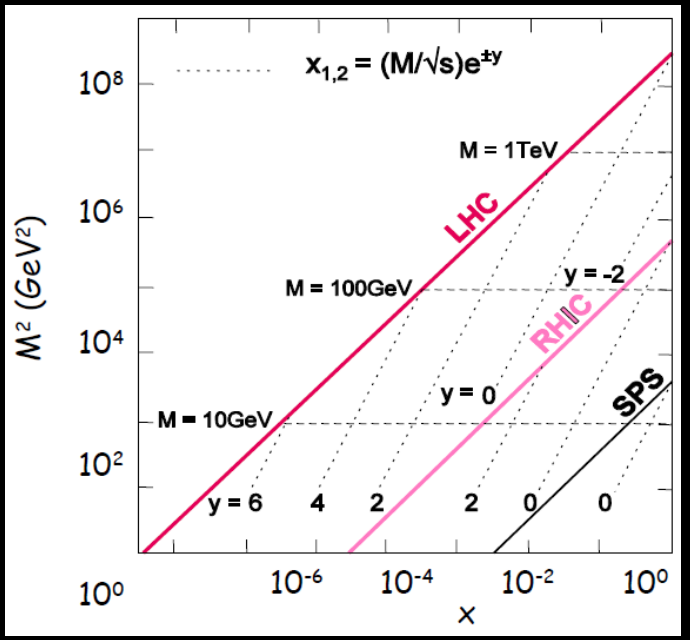
ALICE Upgrade Plans Beyond 2010-11

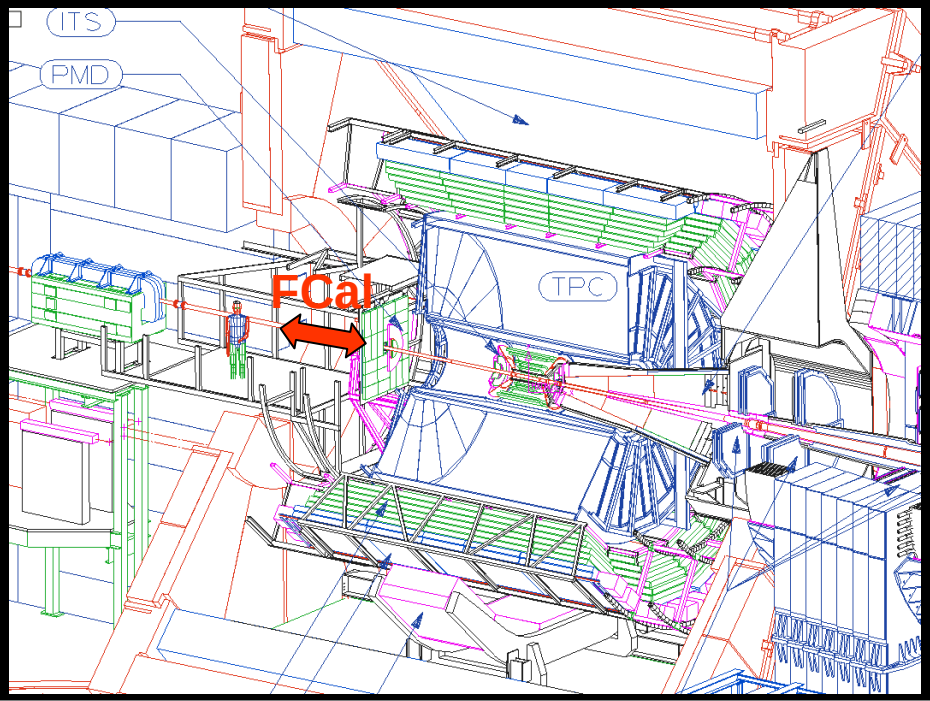


- **2nd generation vertex detector (smaller beam-pipe)**
  - for improved heavy quark physics
- **PID for p_T ~ 5 – 20 GeV/c (based on results from RHIC)**
  - for PID particle & resonance spectra/correlations, flow, recombination,…..
- **New detectors for forward physics (low-x in pA & AA)**
  - Forward calorimeter for π^0

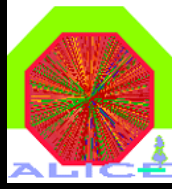
ALICE Forward Physics Upgrade

- **Forward Experimental Study**
  - Strong effects expected at large η
    - gluon shadowing
    - gluon saturation, CGC?
- **At LHC like at RHIC**
  - Small x region – forward at large η
    - Present ALICE accessibility – μ arm
- **Add a Forward Calorimeter**
  - Highly segmented ($\perp$, $\parallel$) EM-Cal
    - 3.6 m from vertex
    - $2.3 < \eta < 4.0$
  - to measure
    - π^0 , $1 < p_T < 50$ GeV/c
    - jets, $20 < E_T < 100$ GeV
- **Extending forward coverage to**
  - $4.5 < |\eta| < 6.5$ region and beyond





ALICE Upgrade Plans Beyond 2010-11



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  - Forward calorimeter for π^0
- **DAQ & HLT Upgrade**
  - more sophisticated & selective triggers
- **Extend EMCal**
  - expand di-jet and gamma-jet Physics reach
- **Improve muon spectrometer – tracking before absorber**
- **Increase rate capability of TPC**
  - (faster gas, increased R/O speed)

A Possible LHC Mid-term Heavy Ion Program

2010 (official) – $\sqrt{s_{NN}}$ = 2.76 TeV Pb + Pb for physics (4 weeks)

2011 (anticipated) – $\sqrt{s_{NN}}$ = 2.76 TeV Pb + Pb for physics (4 weeks)

2012 (official) – Shutdown for maintenance, installation & repairs

2013 – $\sqrt{s_{NN}}$ = 5.5 TeV Pb + Pb for physics

2014 – $\sqrt{s_{NN}}$ = 5.5 TeV Pb + Pb for physics

6 month shutdown - LINAC 4, vertex detector upgrades

2015 – $\sqrt{s_{NN}}$ = 5.5 TeV p + Pb & Pb + p, (lighter A + A, p + p) for physics

2016 – $\sqrt{s_{NN}}$ = 5.5 TeV lighter A + A, p + p for physics

6 month shutdown – IR detector upgrade

2017 – $\sqrt{s_{NN}}$ = 5.5 TeV lighter A + A, p + p for physics

2018 – $\sqrt{s_{NN}}$ = 5.5 TeV *high L* Pb + Pb for hard probe physics

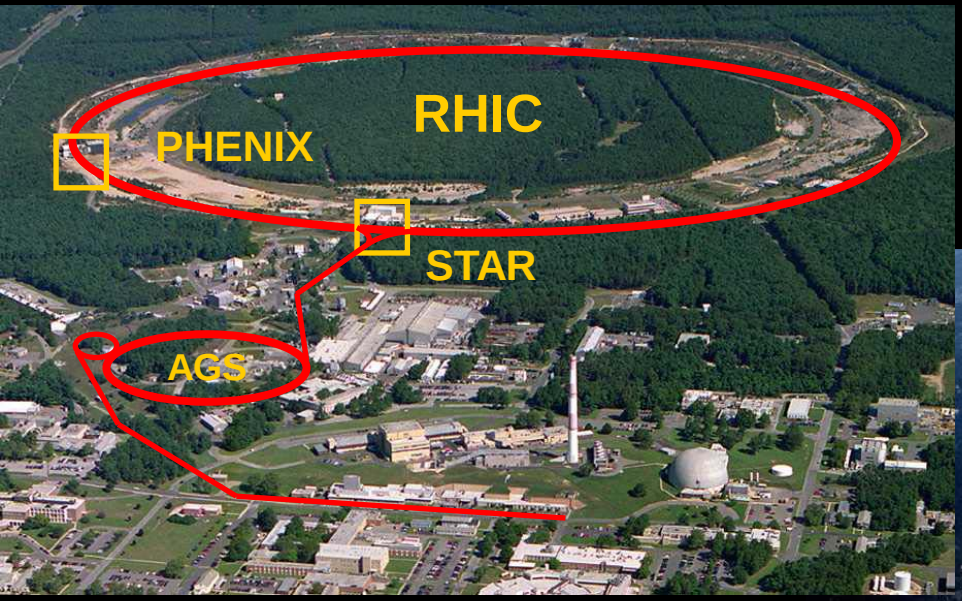
6 month shutdown – IR Quads & detector upgrades

2019 – $\sqrt{s_{NN}}$ = 5.5 TeV *high L* Pb + Pb for hard probe physics

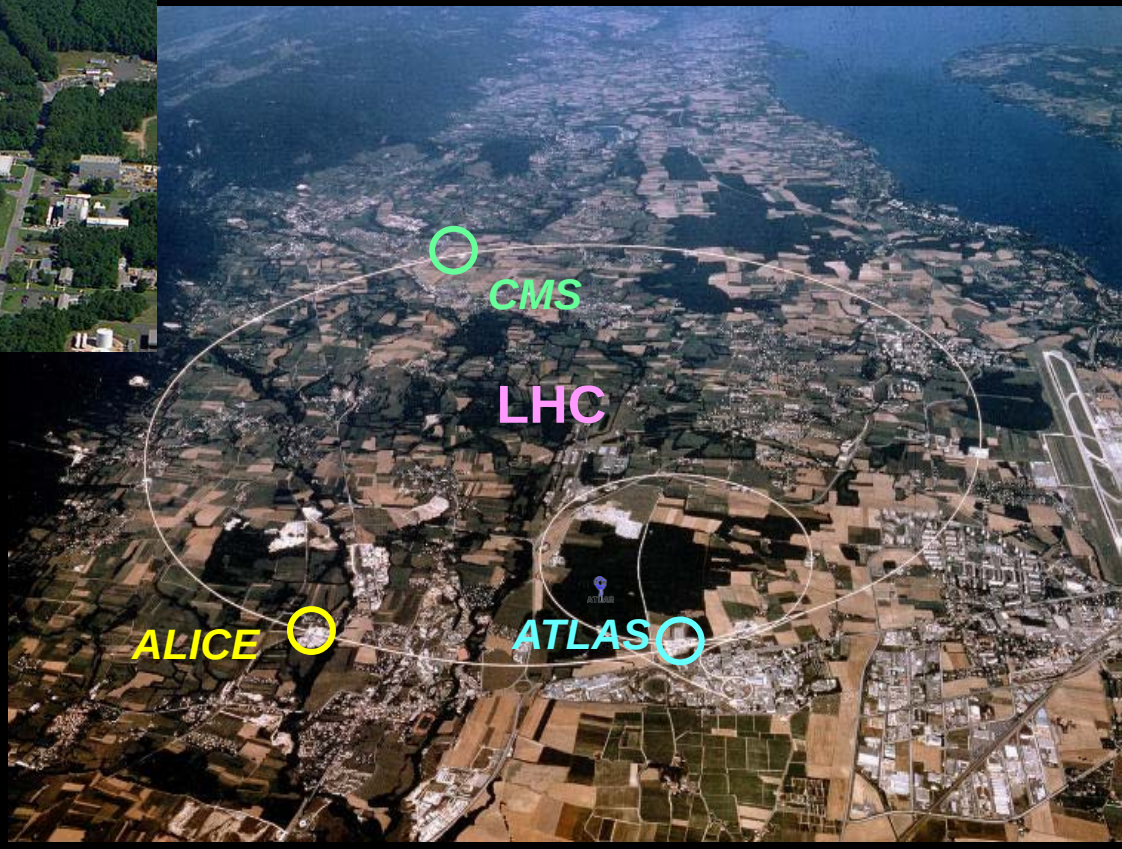
2020 – $\sqrt{s_{NN}}$ = 5.5 TeV *high L* Pb + Pb for hard probe physics

6 month shutdown – …. upgrades

Future Heavy Ion Programs at RHIC and LHC



Cover 3 decades of energy
in center-of-mass



To investigate properties of hot QCD matter at T ~ 150 – 1000 MeV!