Future Jet Measurements

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Jets now and then…

- The LHC Run I data on Jets taught us a lot
  - First direct observation of parton energy loss via dijet momentum balance
  - “lost energy” recovered in low pT particles at large angles
  - Rather moderate modification of fragmentation functions and jet shapes
  - Possibility to tag parton flavor: Z/Gamma jet balance, bJet tagging
  - Hadron RAA out to few 100 GeV
  - Jets are by now a well established tool to study the medium

- However: Current observables have rather little distinguishing power for different models of parton energy loss
  - Very active field of research
  - Big progress in the theory community
  - Many new experimental concepts proposed and actively studied

- This begs some questions:
  - How can we improve this situation?
  - Do we have the adequate tools to get the job done?
  - Can we get the data we need?

How can we improve for the future?

- Enhance the power to distinguish between models
  - Increase integrated luminosity – More data!
    - Reduce statistical errors
    - Observables with cleanly defined final states to reduce selection biases and ambiguities
    - Larger dynamic range for measurements
    - Reduce systematic errors by data driven efficiency corrections and calibrations
  - Detector Upgrades – Better precision!
    - How can we make the detectors better to improve our measurement precision
    - Improved trigger selectivity
    - Higher efficiency and/or acceptance for rare probes
    - Better precision for physics object reconstruction
    - Better control over underlying event subtraction

- Consider the long term research program at the LHC (and RHIC)
  - Is the currently scheduled program sufficient to answer all our questions?
    - Enough total integrated PbPb luminosity
      - pp and pPb reference statistics
      - Do we need to extend it the program?
    - Identify detector limitations to the current experimental program
      - Eliminate by upgrading the detectors

The Time to Act is now!

- CMS/ATLAS Upgrades for Phase 2 (starting 2026!) starting to take shape
  - We may be able to influence the design still
    - What detector improvements would enhance the physics performance for HI?
    - DAQ? HLT? Calorimeters?
  - For eventual CMSHI contributions discussions with funding agencies need to start soon

- On many CERN long term planning bodies questions are raised about “what about Heavy Ions”
  - E.g. CERN computing planning
  - Currently no good answers
  - The Lack of planning is becoming apparent and “crazy” ideas are put forth to fill the void:
    - E.g. Dave Carlton (ATLAS spokesperson) is proposing a very long HI run in 2023 (cooldown before LS3) to deliver any requested integrated lumi to the HI community and then turn off HI for good.
  - If people start to assume there will be no Ion running after Run IV it may become very difficult to put ion running back in the schedule

- In 2016 and 2018 we have little resources to spare
  - Simulations to study future/upgrade scenarios need a significant workforce to make sense
  - Very difficult to allocate in years with an Ion run plus many major conferences
- In 2017 we have a window of opportunity - No Ion run
  - Start thinking now!
  - Prepare a concrete physics plan backed by simulation
  - Write a citable document containing nice figures useful for presentations, seminars, discussions with funding agencies and the LHCC

- Meeting at MIT in October to continue the brainstorming
  - https://indico.cern.ch/event/558954/

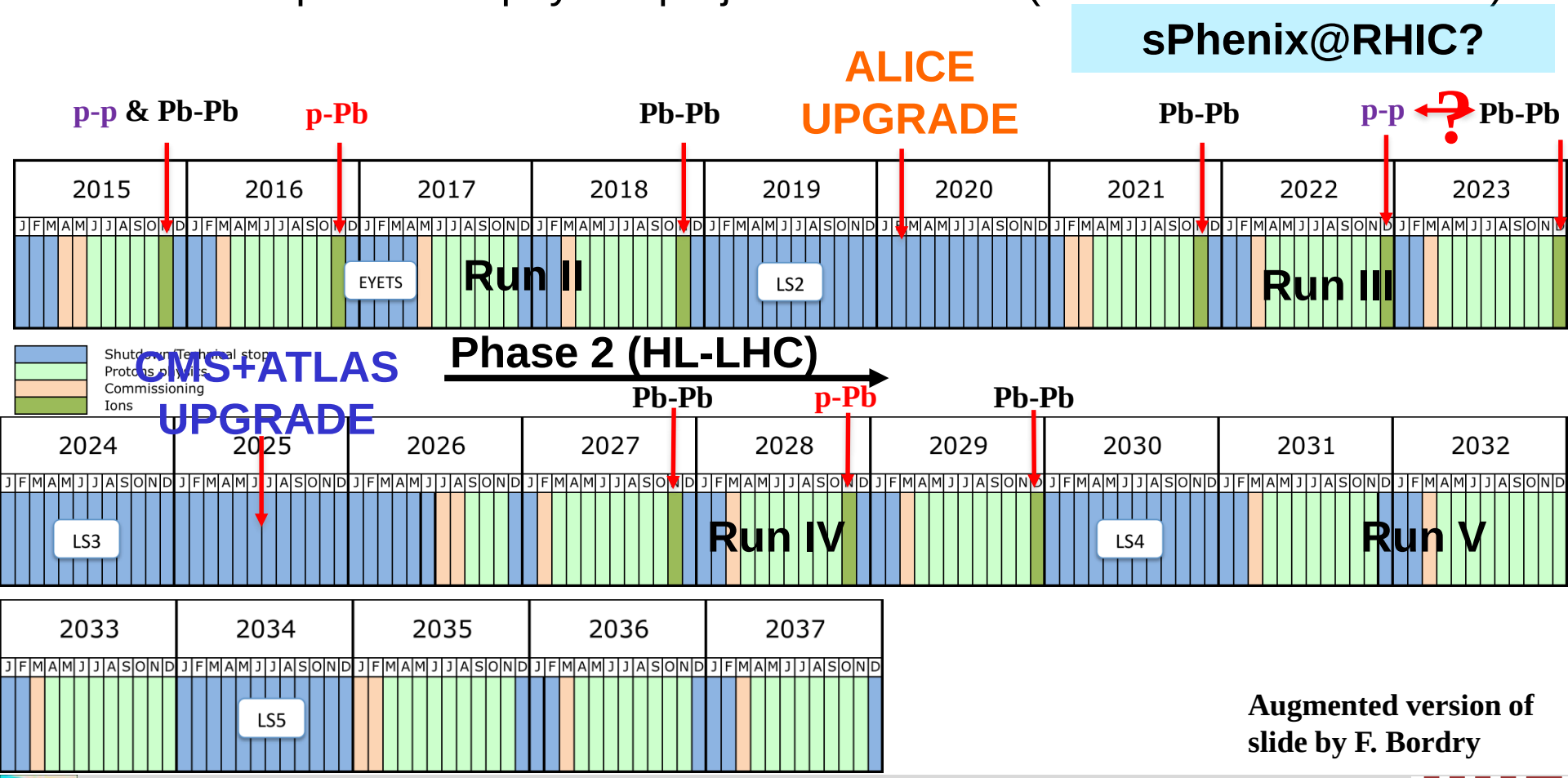
Future? What Future?

12 ~one Month heavy ion runs scheduled, 4 done already

Physics program defined, ~10/nb PbPb requested

Mostly driven by ALICE LoI (low pT heavy flavor)

CMS+ATLAS presented physics projections as well (CMS-PAS-FTR-13-025)



Augmented version of slide by F. Bordry

PbPb performance projection beyond LS2

(Ideal parameters to meet ALICE request)

J.M. Jowett, LHC Performance Workshop, Chamonix, 28/1/2016

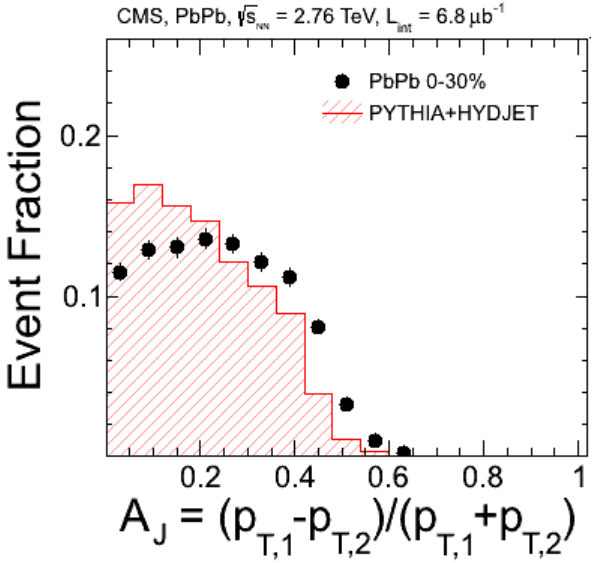
Table 4: Time-averaged (during intervals of fully successful operation) and integrated luminosities over a run in each luminosity-sharing scenario.

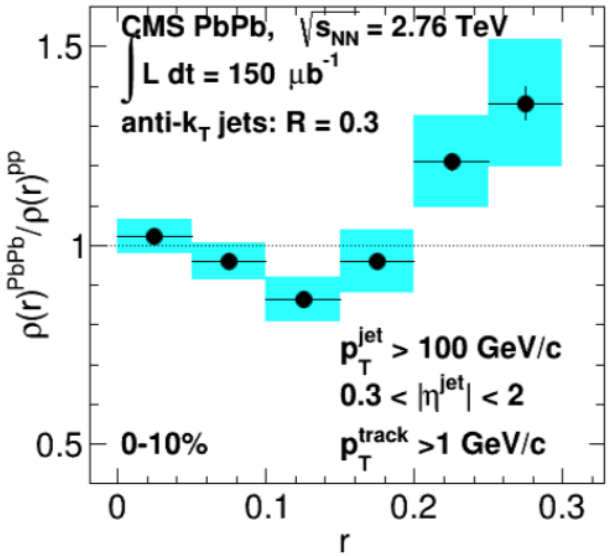
luminosity-sharing scenario β^* /m	ALICE		ATLAS/CMS	
	$\langle L \rangle$ / 10^{27} cm^{-2}s^{-1}	$L_{int,annual}$ / nb^{-1}	$\langle L \rangle$ / 10^{27} cm^{-2}s^{-1}	$L_{int,annual}$ / nb^{-1}
$(\infty, 0.5, \infty)$	4.14	4.29	0	0
$(1.0, 0.5, 1.0)$	3.19	3.30	1.68	1.74
$(0.5, 0.5, 0.5)$	2.80	2.91	2.95	3.06

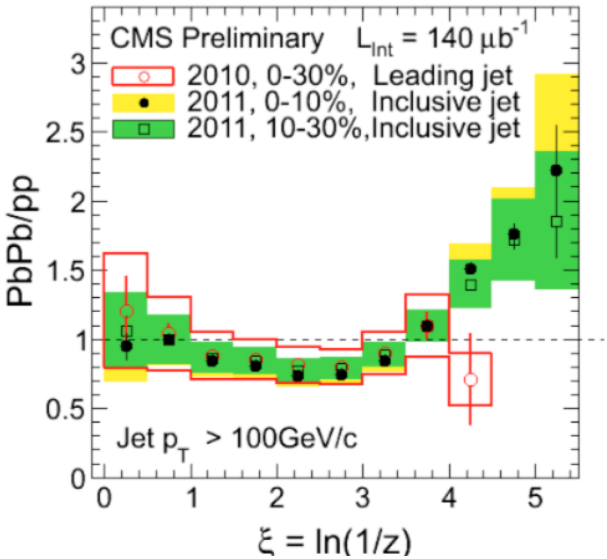
6 Ion periods scheduled for Run III+IV
4 PbPb – 1pPb – 1pp (according to ALICE)
Gives ~12/nb of PbPb

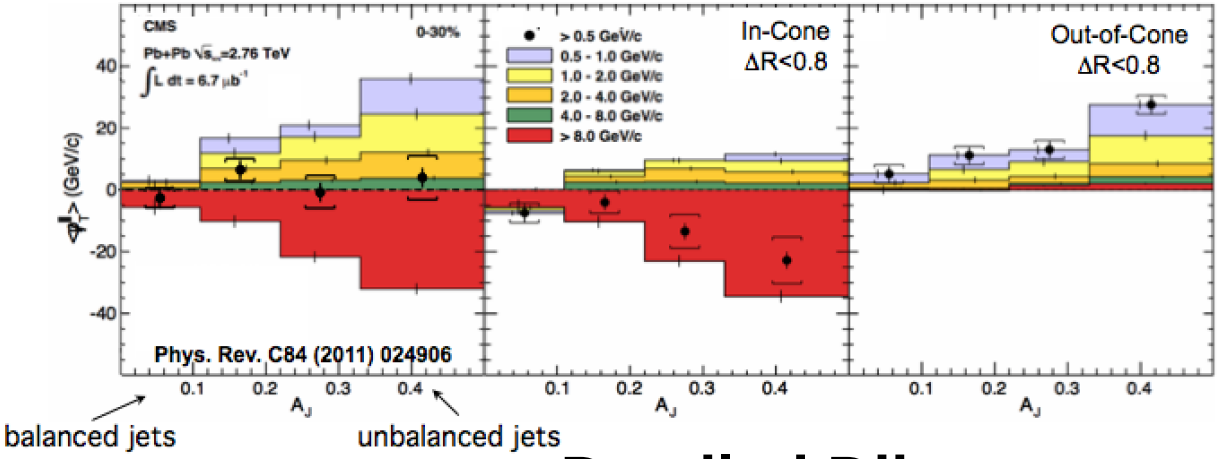
What do we have so far? (Impressionist View)

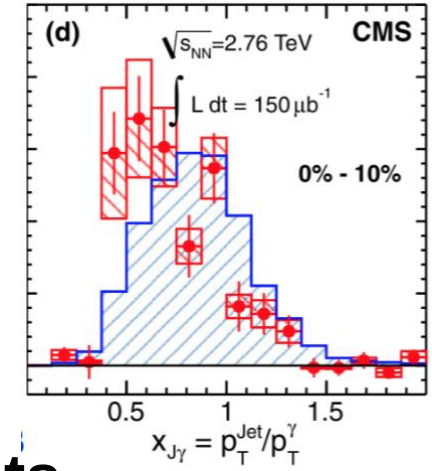
Run I Measurements (0.15/nb)







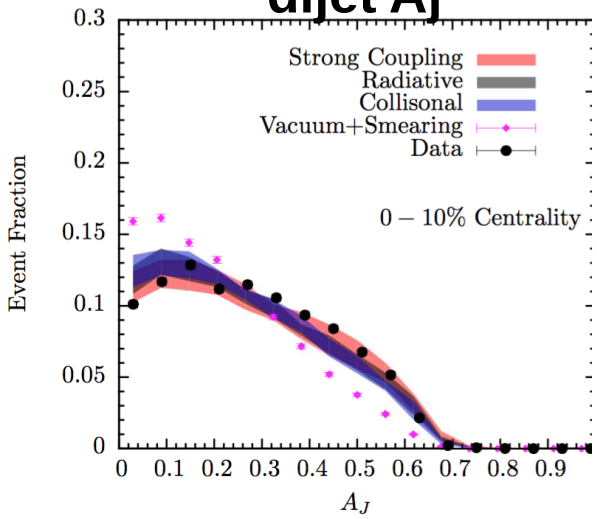




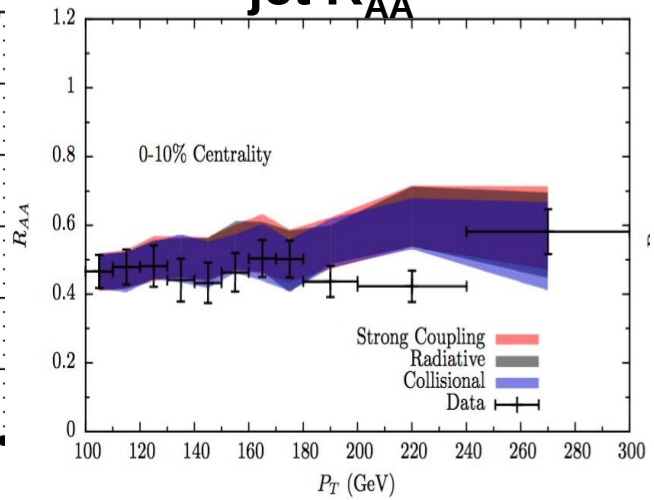
Detailed Dijet measurements
gamma jet proof of principle

Distinguishing between models…

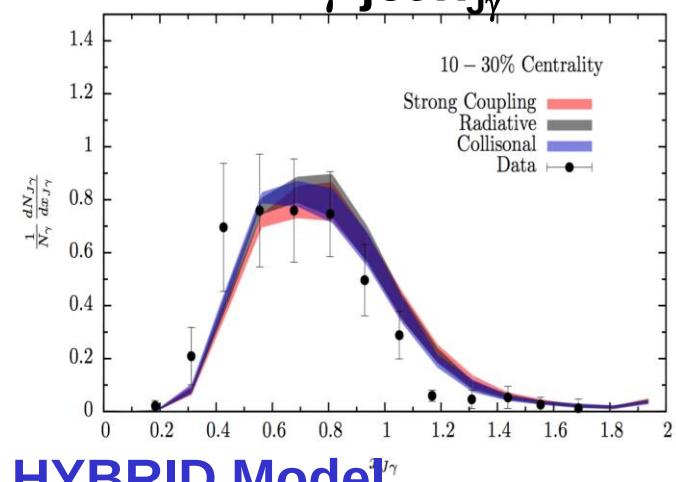
dijet Aj



jet R_{AA}

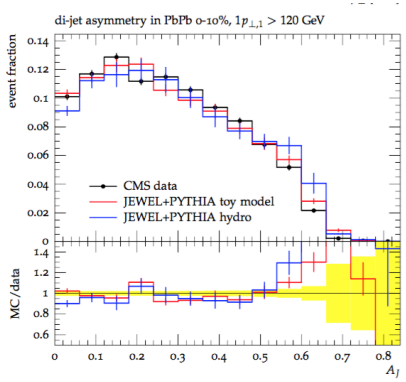


γ-jet $x_{J\gamma}$

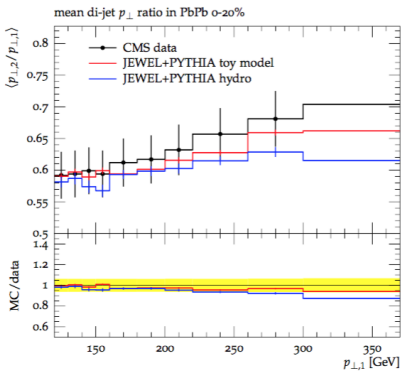


HYBRID Model

dijet Aj

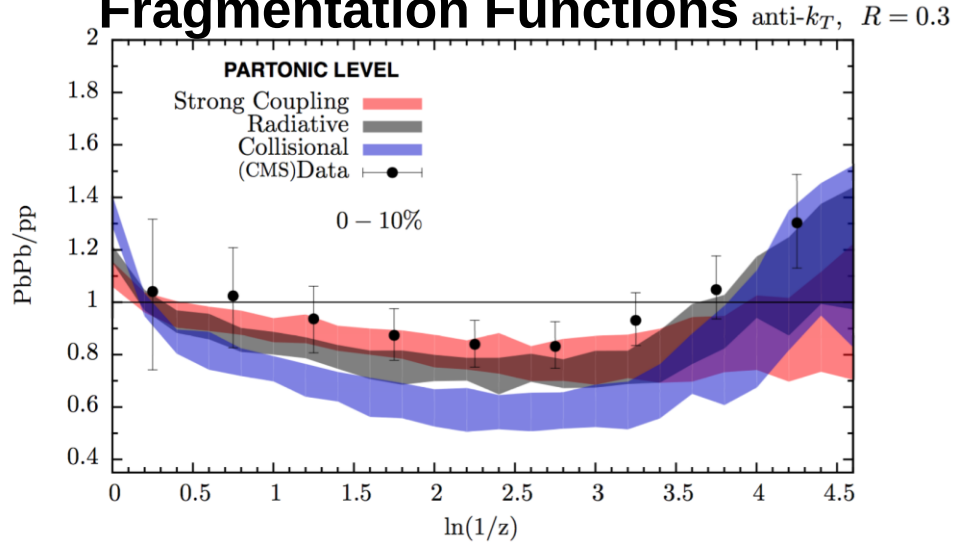


hadron R_{AA}



JEWEL

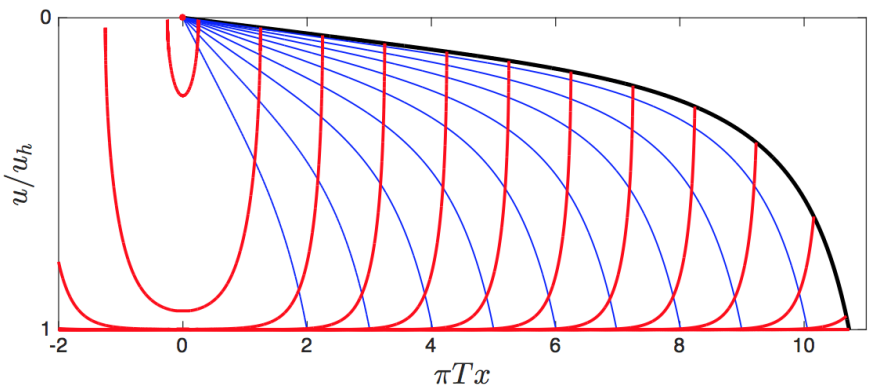
Fragmentation Functions



Very limited discimination power in standard Run I observables

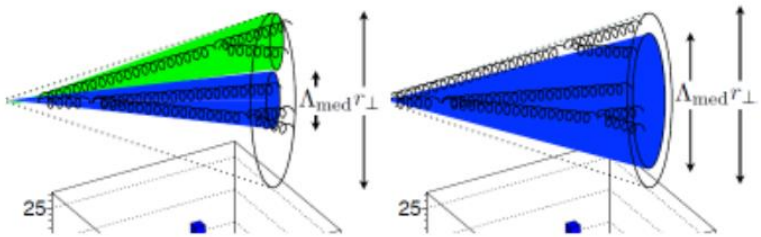
New Observables

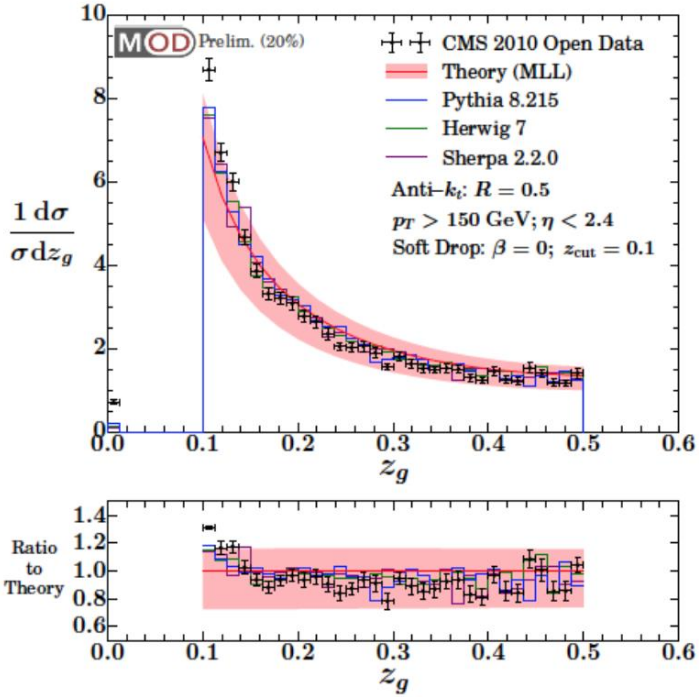
Chesler, Rajagopal, arXiv:1511.07567



Jet energy loss vs Jet opening angle

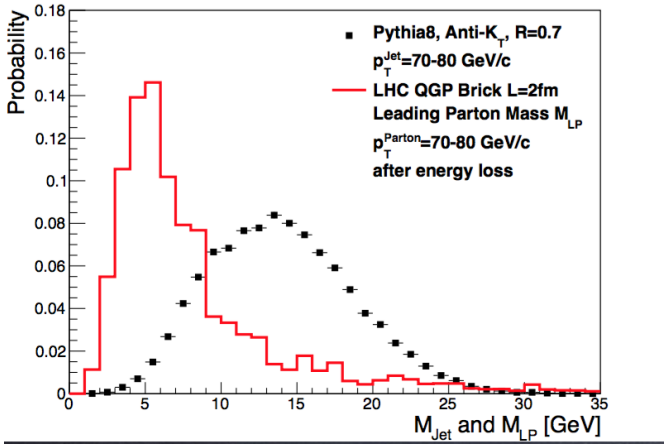
The parton antenna





Splitting functions ala Thaler & Co
Groomed subjet momentum fractions

Jet Mass, A. Majumder QM14



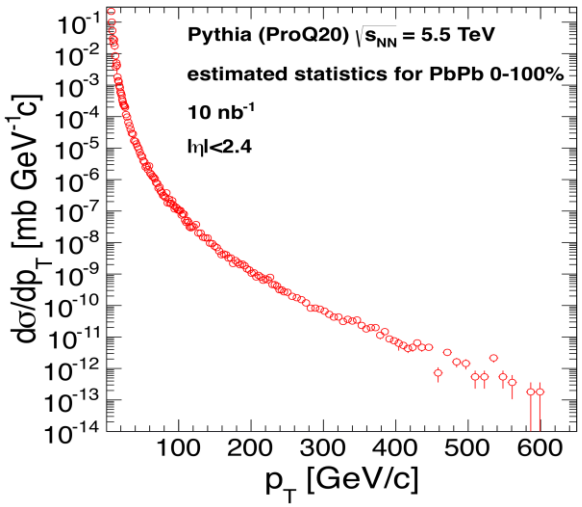
New Techniques

- Current industry standard of Jet Finding
  - Anti kT algorithm as implemented in the FastJet package
- Jet substructure measurements need refined techniques
  - UE background subtraction
    - Constituent subtraction
  - Jet Grooming
    - SoftDrop
  - Xcone & Jet Pull
  - …
- Will set the stage for the next round of measurements based on Run II data

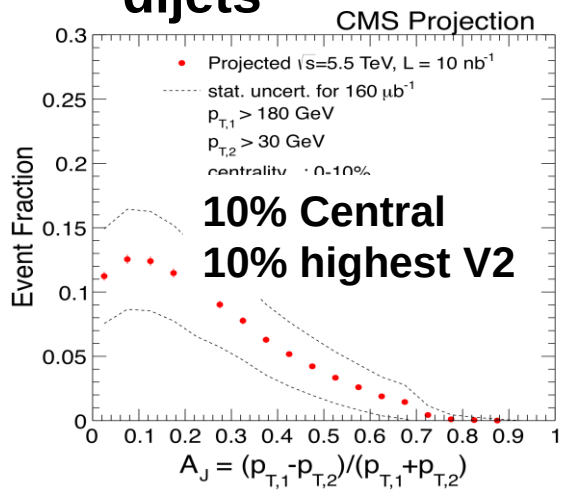
The plan (as of ~2013)

- Run I (0.15/nb)
  - Detailed dijet measurements
  - Gamma jet proof of principle
- Run II (1.5/nb, including 2018)
  - First measurements with parton flavor selected jets
    - γ-jet correlations with good statistics
    - Z-jet proof of principle
    - di-b-jets proof of principle
- HI-HL-LHC Run III+IV (10-15/nb)
  - Detailed measurements with parton flavor selected jets
    - Z-Jet, γ-jet, di-b-jets event plane selected, etc.

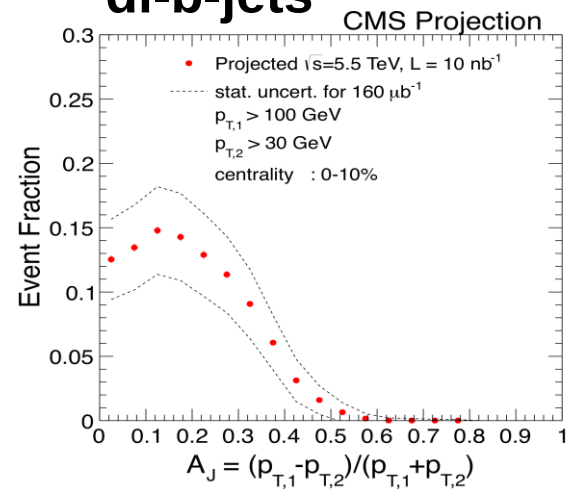
Statistical reach of 10/nb



dijets

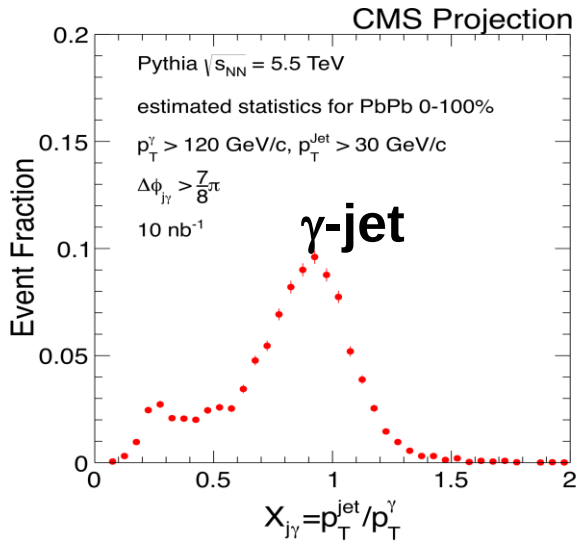


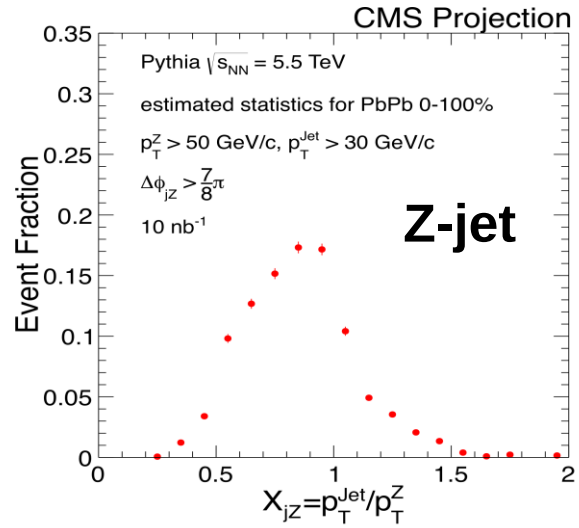
di-b-jets



	2010–2011 2.76 TeV 160 μb^{-1}	HL-LHC 5.5 TeV 10 nb^{-1}
Jet p_T reach (GeV/c)	$\sim$ 300	$\sim$ 1000
Dijet ($p_{T,1}$ > 120 GeV/c)	50k	$\sim$ 10M
b-jet (p_T > 120 GeV/c)	$\sim$ 500	$\sim$ 140k
Isolated γ (p_T^γ > 60 GeV/c)	$\sim$ 1.5k	$\sim$ 300k
Isolated γ (p_T^γ > 120 GeV/c)	–	$\sim$ 10k
W (p_T^W > 50 GeV/c)	$\sim$ 350	$\sim$ 70k
Z (p_T^Z > 50 GeV/c)	$\sim$ 35	$\sim$ 7k

CMS-PAS-FTR-13-025

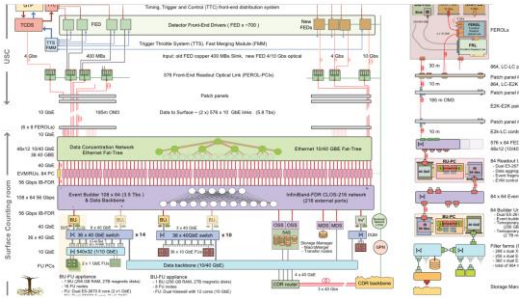


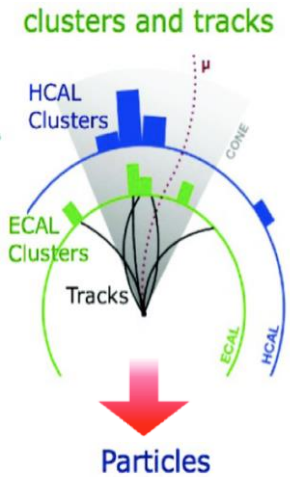


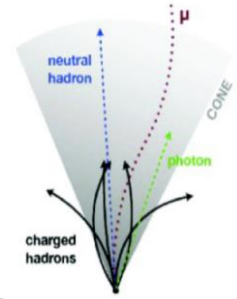
Is this enough?

Key Phase 2 Detector Upgrades

- "Megaherz" DAQ
  - 1MHz readout rate for 150PU pp events
  - 100kHz readout rate for PbPb no problem
    - Entire event selection can be done based on full event reconstruction in the HLT
- Tracker Upgrade
  - 4 layer Pixel system
    - Higher tracking efficiency
    - Better Particle Flow jet reconstruction
  - New SiStriptracker
    - Fast readout necessary for the MHz DAQ
- High Granularity Calorimetry
  - Better handle on jet constituents
    - Enhanced Particle Flow Object definition
    - Better handle on background subtraction
    - Increased acceptance







Need to reconsider our long term plan

- Current long term plan at LHC defined by ALICE LOI
  - Does not necessarily map well on the goals of ATLAS/CMS and high pT physics exploitation
- Need higher precision measurements
  - Higher integrated luminosity for enhanced physics reach
  - Better references, pp and pPb, nPDFs
  - Upgrade detectors for better performance
  - New classes of observables
    - Borrow ideas from the FCC? Boosted tops?
- Update the current plan with new ideas
  - Prepare a concrete physics plan backed by simulation
  - Write a citable document containing nice figures useful for presentations, seminars, discussions with funding agencies and the LHCC
  - Possible request:
    - Install stochastic cooling for PbPb in the LHC
    - Request 20/nb top up in run 4+5 with consistent (upgraded) detector configurations for ATLAS/CMS
- Shaping the long term future takes time. Need to start now!
- If you have ideas and want to share them: See you at MIT
  - https://indico.cern.ch/event/558954/

Backup

HI @ LHC after LS2: current plans

- Experiments target: integrate >10/nb after LS2 (e.g. ALICE Upgrade
  - ALICE LOI: 13/nb at 50 kHz max
  - pp, p-Pb reference at the same energy as Pb-Pb and with the same (upgraded) detector layout
    - ALICE: 6/pb pp 5.5 TeV (minimum bias)
    - ATLAS/CMS: 300/pb pp 5.5 TeV

- Main observables / objectives (as presented in 2014):
  - Low-pT heavy-flavour and charmonium production + flow (ALICE)
  - Precise multi-differential Y family measurements (ATLAS, CMS, ALICE)
  - Low-mass and low-pT dileptons, ρ, ω, continuum (ALICE)
  - Jets: flavour dependent in-medium fragmentation functions (ALICE, ATLAS, CMS)
  - differential jet, b-jet, di-jet, γ/Z0-jet measurements at high pT (mainly ATLAS, CMS)

Is this enough?

- Need higher precision measurements to distinguish between models
  - Smaller statistical errors (obviously)
  - Higher pt reach for low cross section probes
  - Infrared/Collinear safe measurements?
  - Smaller systematic errors, <10%
    - Higher integrated lumi for data driven calibrations
    - Exact selection of physics channels
    - Better experimental techniques
      - Better algorithms
      - Better detectors

HI running in the Future

- What do we have to improve to continue to learn about the medium properties?
  - Shooting a projectile through a piece of matter is still one of the most efficient ways to learn about its microscopic structure/properties
  - The only analogous way to probe a strongly interacting medium created in heavy ion collisions are fast partons created in hard scatterings during the interation of the nuclei
  - Jets resulting from fragmenting partons are by now a well established tool to study the medium

- Can we make a Physics Case for HI beyond run 4 or 10/nb?
  - Some ideas: borrow FCC use case
    - Parton decay chains in the medium to explicitly probe different timescales
    - ttbar and similar channels

- What should we request from the LHC?
  - Sharpen baseline request for run 3+4
    - Which species to run when
    - Light Ions?
  - Longer term:
    - Implement stochastic cooling and top up int lumi by10-20/nb in run 5?

- Why should CMS take HI data?
  - What is our “entry ticket” to HL-LHC
    - Need a contribution to CMS like the HLT project (~5 Million $US) in the past
    - CMS upgrade coordinators are starting to push us

- How can we make CMS a better HI detector?
  - For the high luminosity LHC (HL-LHC) after LS3 the experiments will essentially be completely new detectors!
  - We may be able to influence the design still
    - What detector improvements would enhance the physics performance for HI?
      - DAQ? HLT? Calorimeters?
    - HI contribution to CMS to guarantee our participation in CMS