"Future direction of Jet Physics"

Gunther Roland

INT Program 17-1b
May 2017

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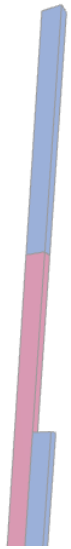
The Direction

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE



There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

c.f. 2014 Hot QCD White Paper (arXiv:1502.02730)

Future directions of Jet Physics

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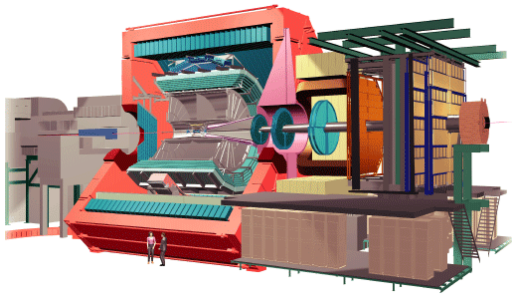
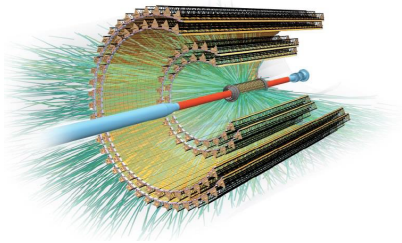
EXPERIMENTS OF
THE FUTURE

LHC Phase-1 Upgrades

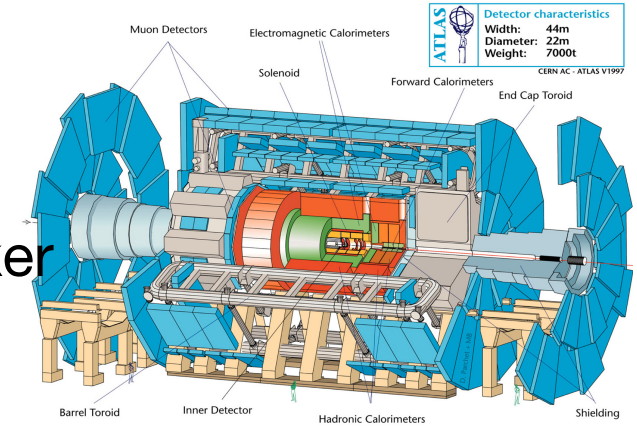
ALICE





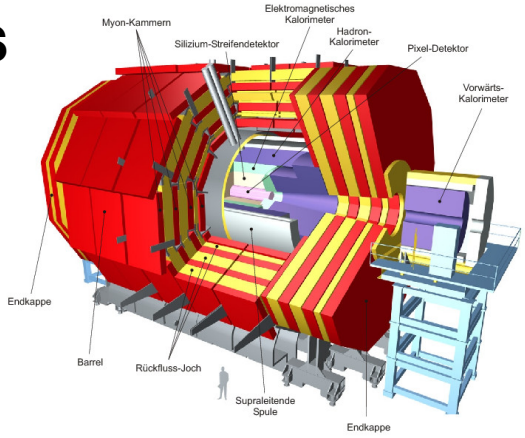
Expanded calorimetry
Continuos readout TPC
MAPS-based inner tracker
Improved data acquisition rate (full PbPb lumi)

ATLAS



Improved trigger system
New/extended inner tracker

CMS



Improved trigger system
New/extended inner tracker

n.b. more extensive phase-II upgrades for ATLAS/CMS for LHC Run IV, 2026-2030

Future LHC Jet Capabilities

- 2015 HI run brought ~ 0.5/nb PbPb, 30/pb pp @ 5 TeV
  - max PbPb collision rate > 15kHz
  - pp stat ~ 1.5xPbPb in 1/5 of data taking time
- In Run 3, 4 expect ~1.5-3/nb per run per experiment; 10-20/nb total
  - ATLAS, CMS should be able to take pp reference in 1/6 of PbPb running time; ALICE?

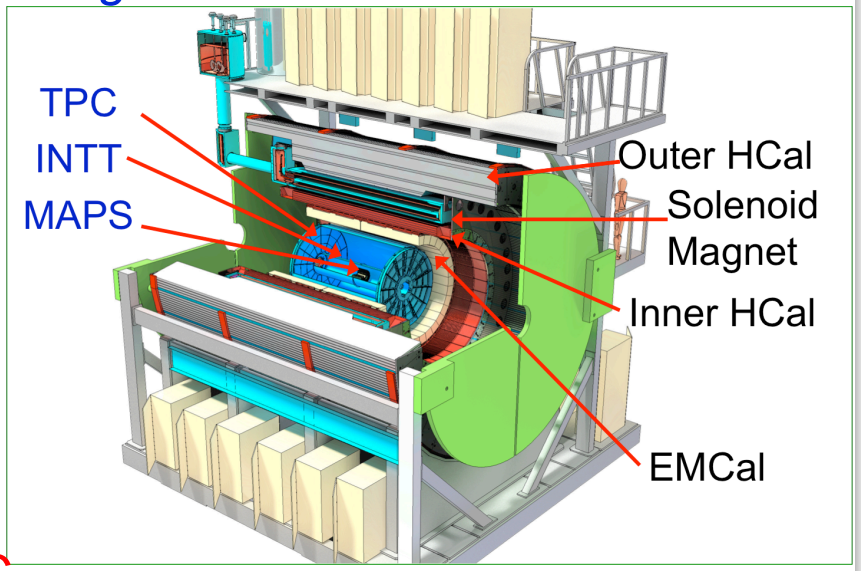
	2010–2011 2.76 TeV 160 μb^{-1}	HL-LHC 5.5 TeV 10 nb^{-1}
Jet p_T reach (GeV/c)	~ 300	~ 1000
Dijet ($p_{T,1} > 120$ GeV/c)	50k	~ 10M
b-jet ($p_T > 120$ GeV/c)	~ 500	~ 140k
Isolated γ ($p_T^{\gamma} > 60$ GeV/c)	~ 1.5k	~ 300k
Isolated γ ($p_T^{\gamma} > 120$ GeV/c)	–	~ 10k
W ($p_T^{W} > 50$ GeV/c)	~ 350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

- In addition: larger acceptance, better tracking efficiency, better vertex resolution, “infinite” DAQ/Trigger for Run 4

…meanwhile at RHIC

Also On The First Day

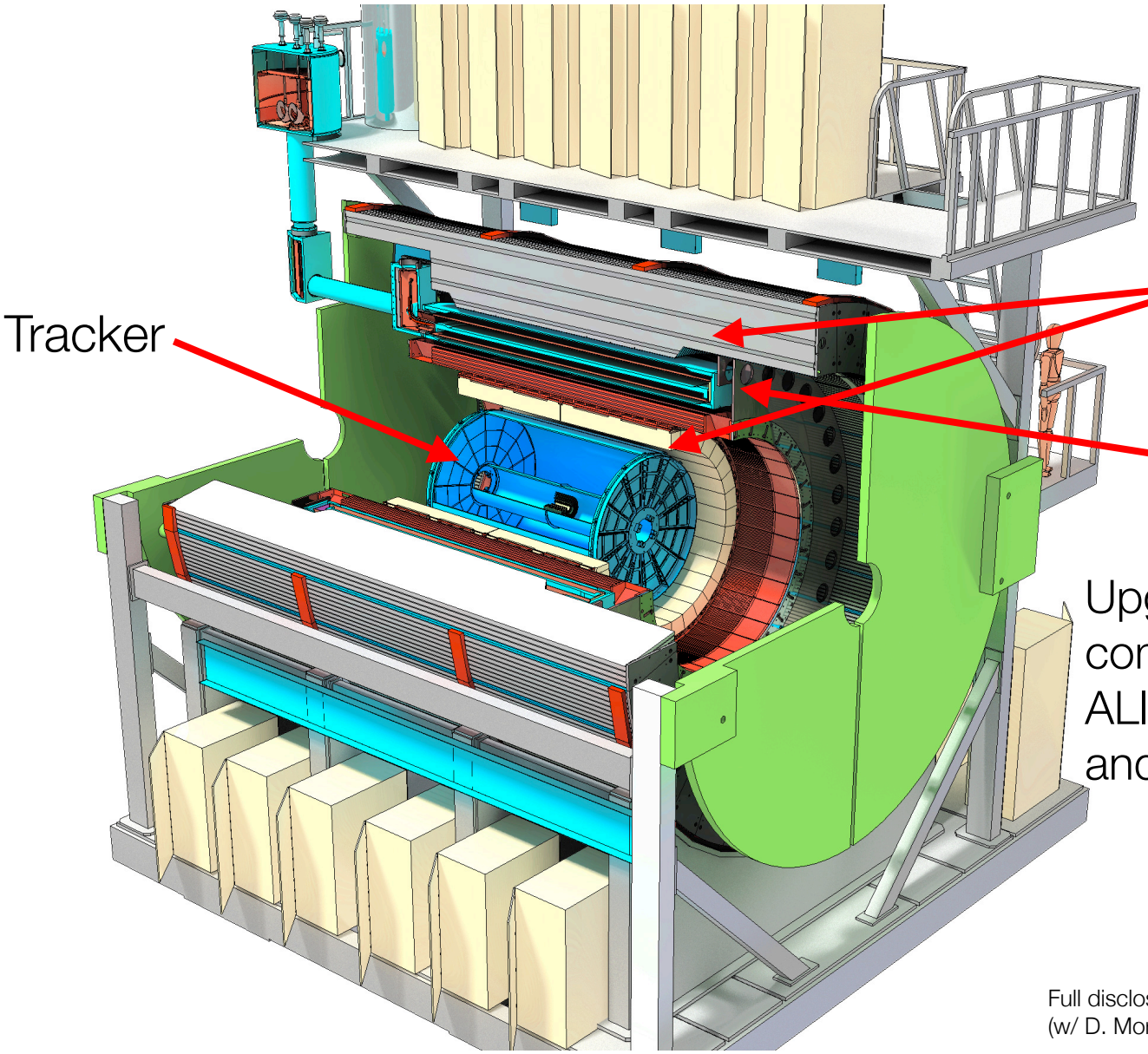
- Dr. T. Hallman stated U.S. DOE Nuclear Physics "*is committed to building* sPHENIX"
- sPHENIX provides full jet and HF capability in order to:
  - Probe the sQGP with the highest resolution possible at RHIC
  - Perform vital comparisons to same probes at LHC



M. Connors: Design, status and schedule of the sPHENIX experiment at RHIC

Bill Zajc on last day of QM'17

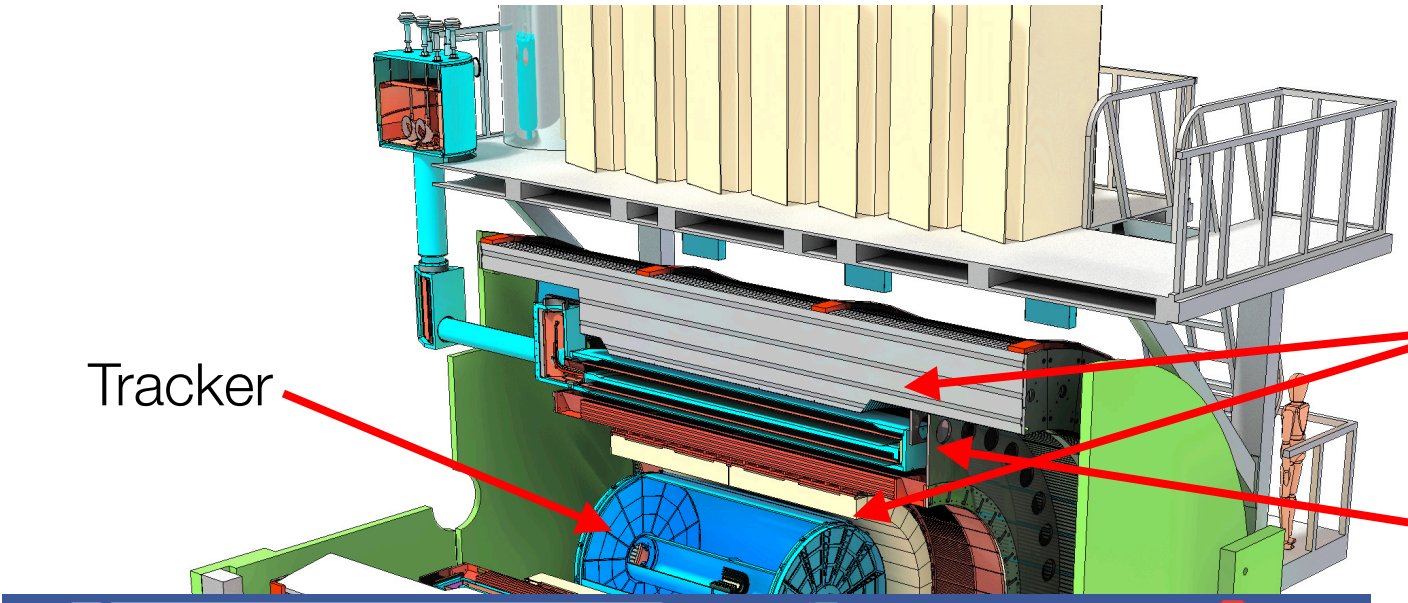
“State-of-the-Art Jet Detector at RHIC”

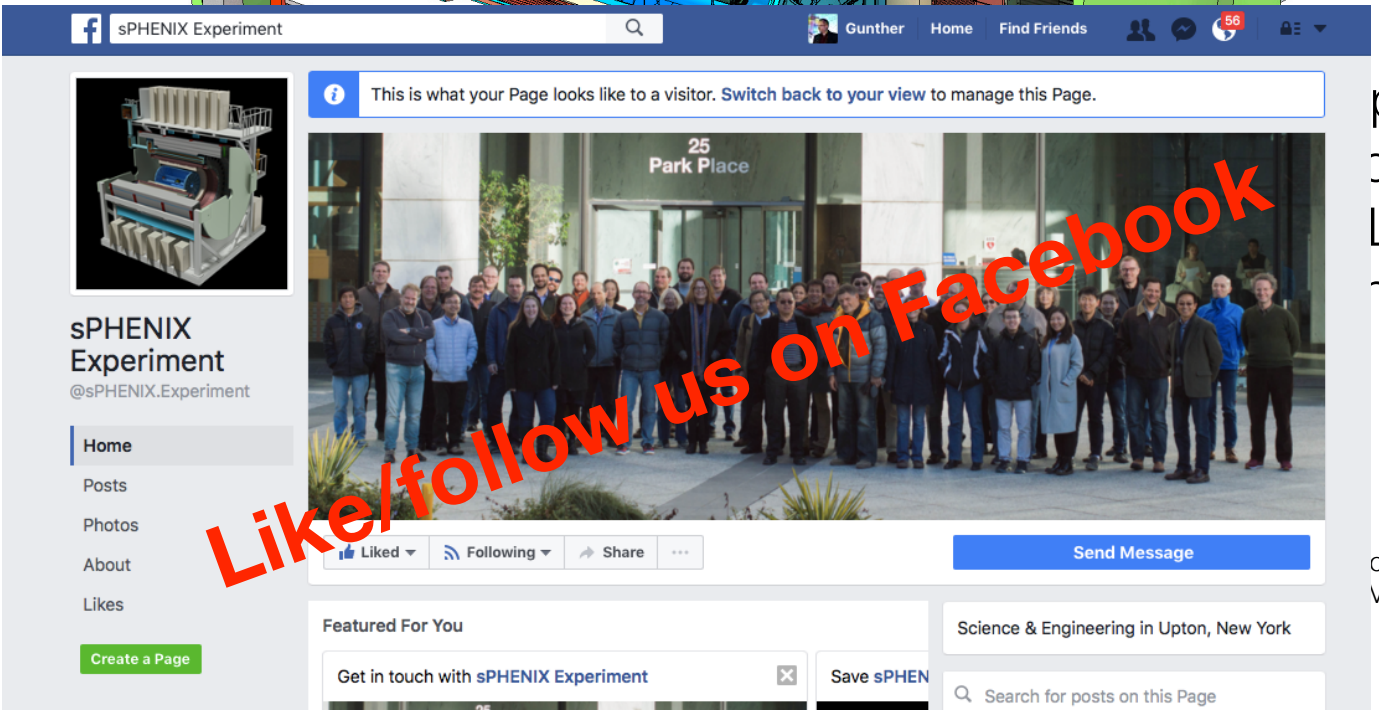


Upgrade of PHENIX that combines concepts from ALICE phase-1 upgrade and ATLAS/CMS

Full disclosure: GR is sPHENIX co-spokesperson (w/ D. Morrison, BNL) since Jan 2016

“State-of-the-Art Jet Detector at RHIC”





pgrade of PHENIX that
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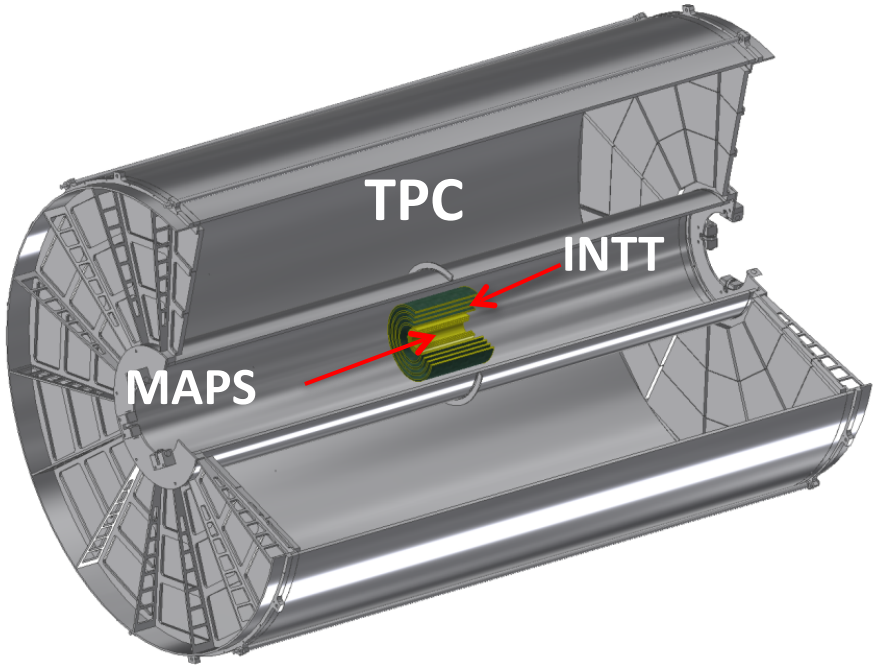
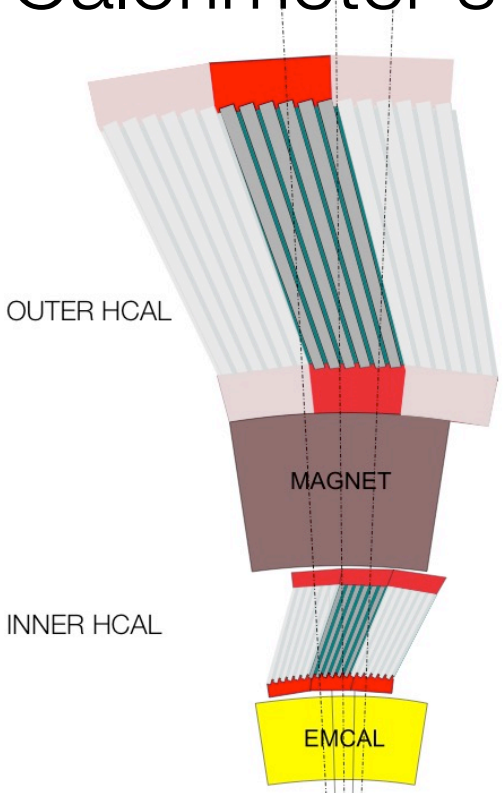
sPHENIX Subdetectors

Tracker



Continuous readout TPC
Si strip intermediate tracker
3-layer MAPS μ vertex

Calorimeter stack

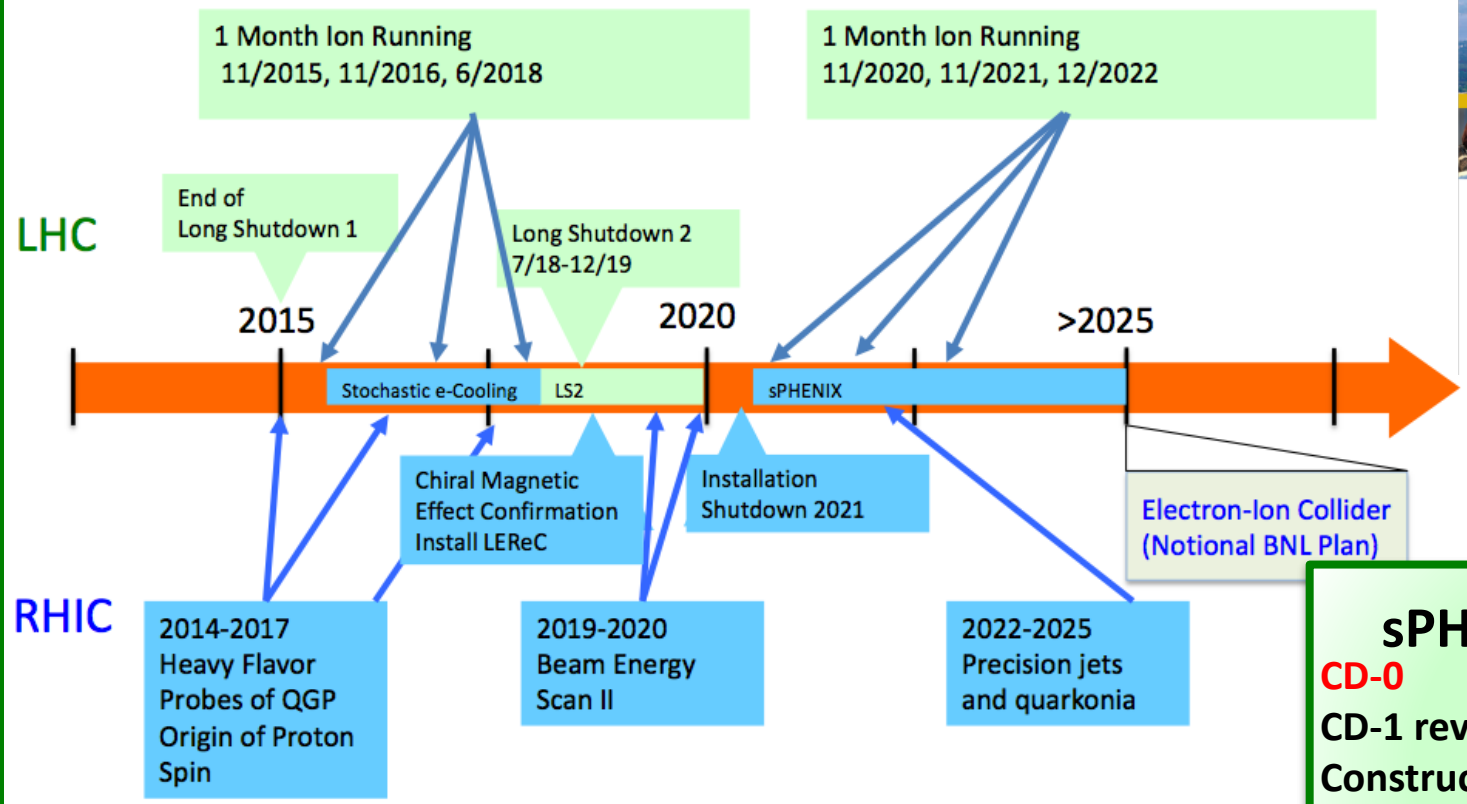


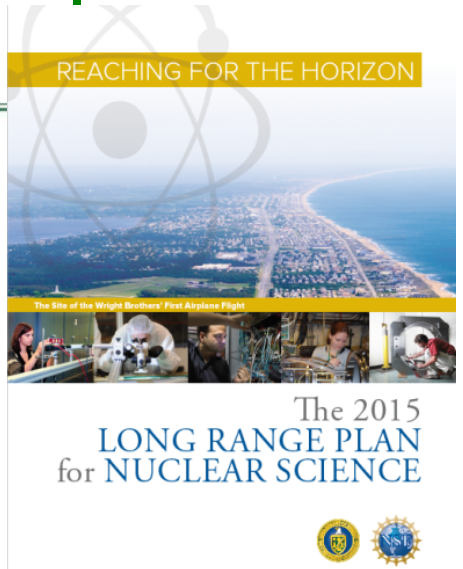
Tungsten/scintillating fiber EMCal
Steel/plastic scintillator HCAL
SiPM readout

15kHz+ readout in Au+Au to match expected collision rate in $|z| < 10$cm

The Next Decade

RHIC / LHC Timeline





sPHENIX Schedule

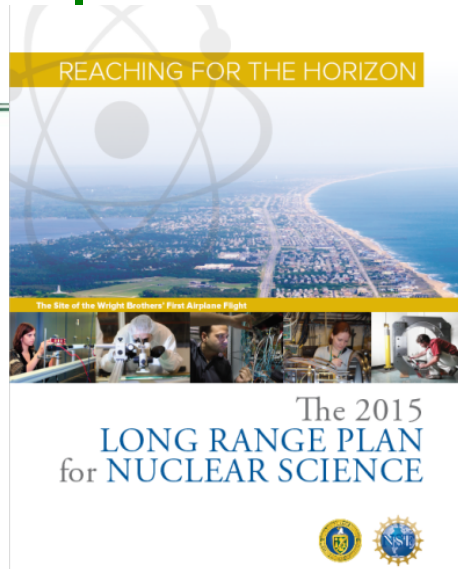
CD-0	Sept 2016
CD-1 review	Nov 2017
Construction Phase	Jul 2018
Installation complete	Apr 2021
Ready for Beam	Jan 2022
Data taking	- 2025+

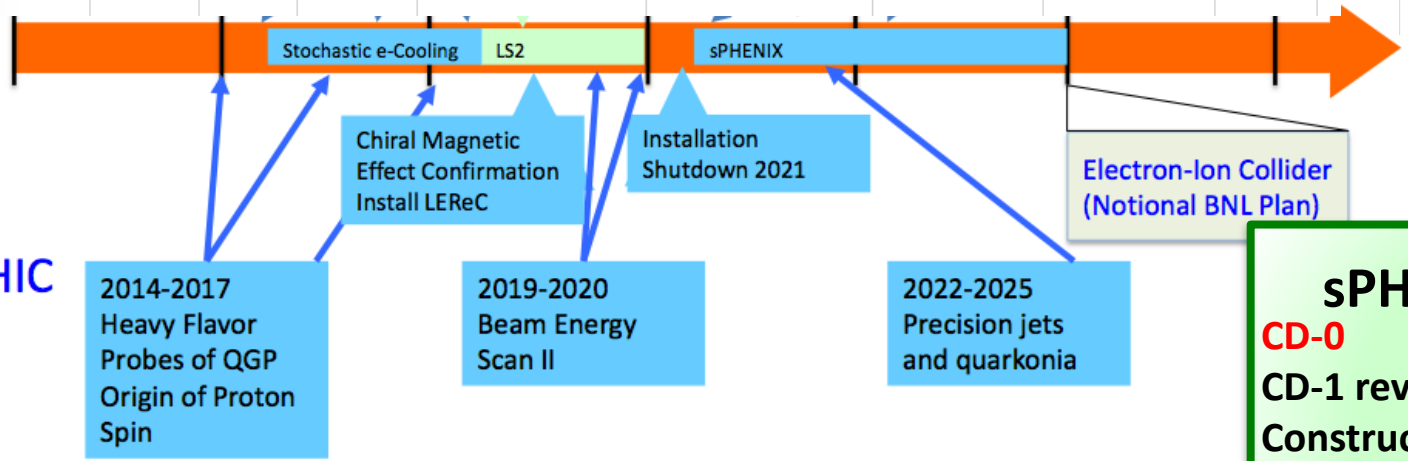
The Next Decade

RHIC / LHC Timeline

Year	Species	Energy	Physics Weeks	Max dNch/deta / second (TPC Charge Issue)	Max Integrated dNch/deta run (Radiation Issue)	Sampled Evts w/ zcut	Sampled Evts w/o zcut	Straight MB
2023	Au+Au	200	23.5	2.8E+07	8.1E+13	9.5E+10	3.5E+11	9.5E+10
2024	p+p	200	11.5	2.2E+07	2.9E+13	2.8E+12	9.5E+12	
	p+Au	200	11.5	2.9E+07	3.7E+13	3.6E+11	2.8E+12	
2025	Au+Au	200	23.5	4.2E+07	1.6E+14	1.7E+11	6.0E+11	9.5E+10
2026	p+p	200	11.5	2.9E+07	3.7E+13	3.6E+11	2.8E+12	
	p+Au	200	11.5	4.2E+07	5.6E+13	1.4E+12	9.5E+12	
2027	Au+Au	200	23.5	4.2E+07	1.6E+14	2.2E+11	7.5E+11	9.5E+10
				Integrated Charge over Run -->	5.6E+14			

Developing 5 year sPHENIX runplan
500b events in $|z_{vtx}| < 10$cm (~100/nb)





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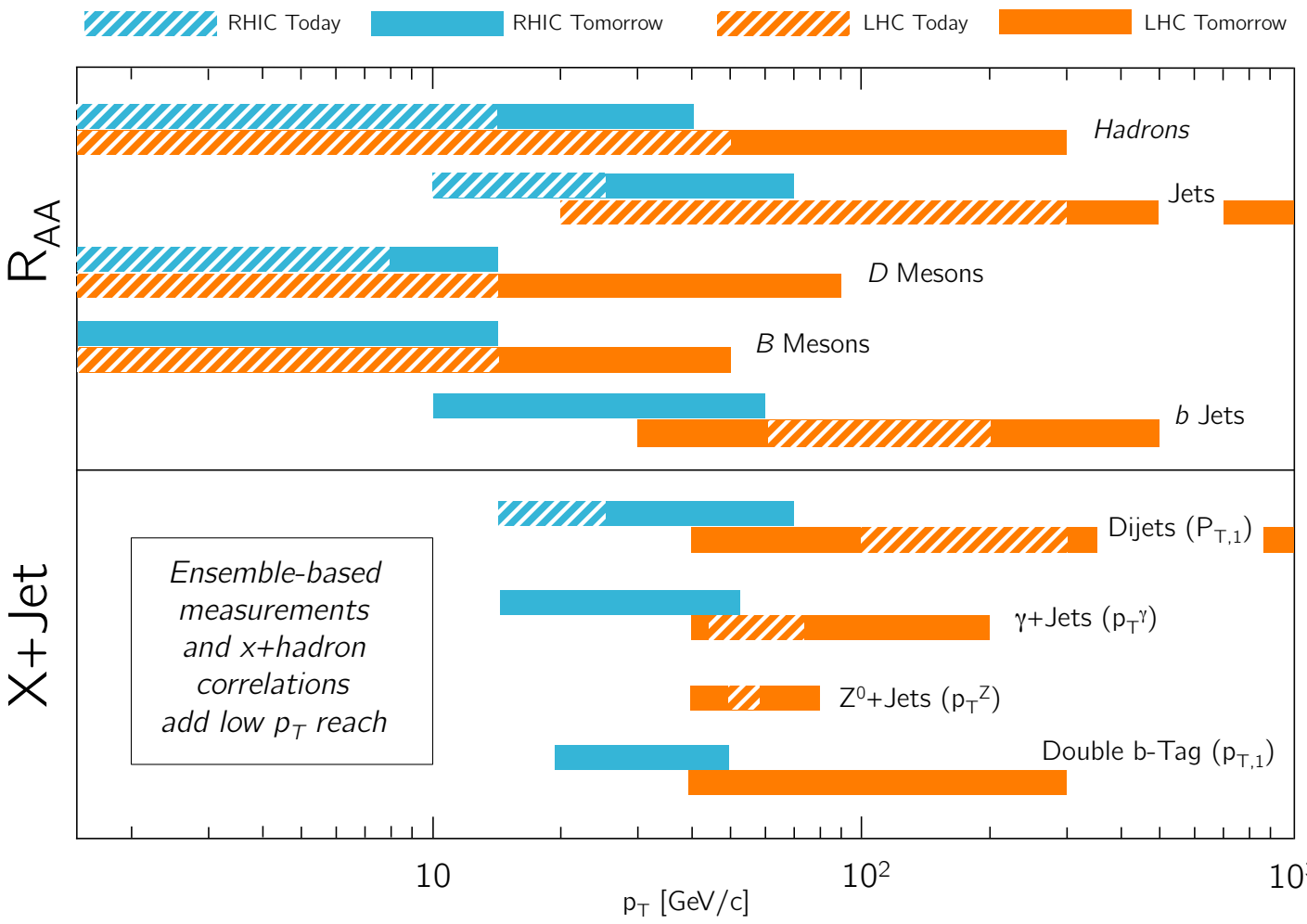
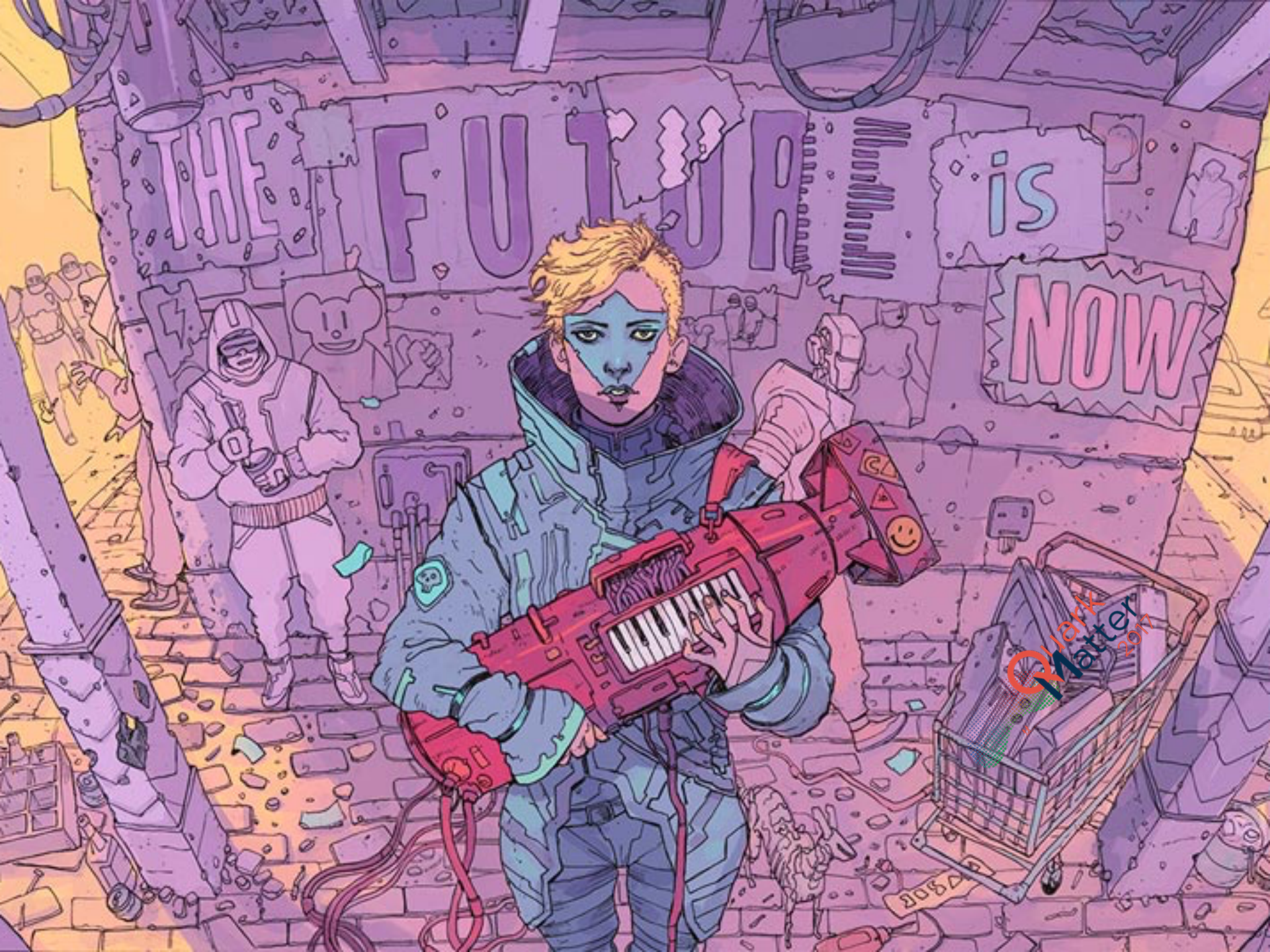
U.S. DEPARTMENT OF ENERGY | Office of Science

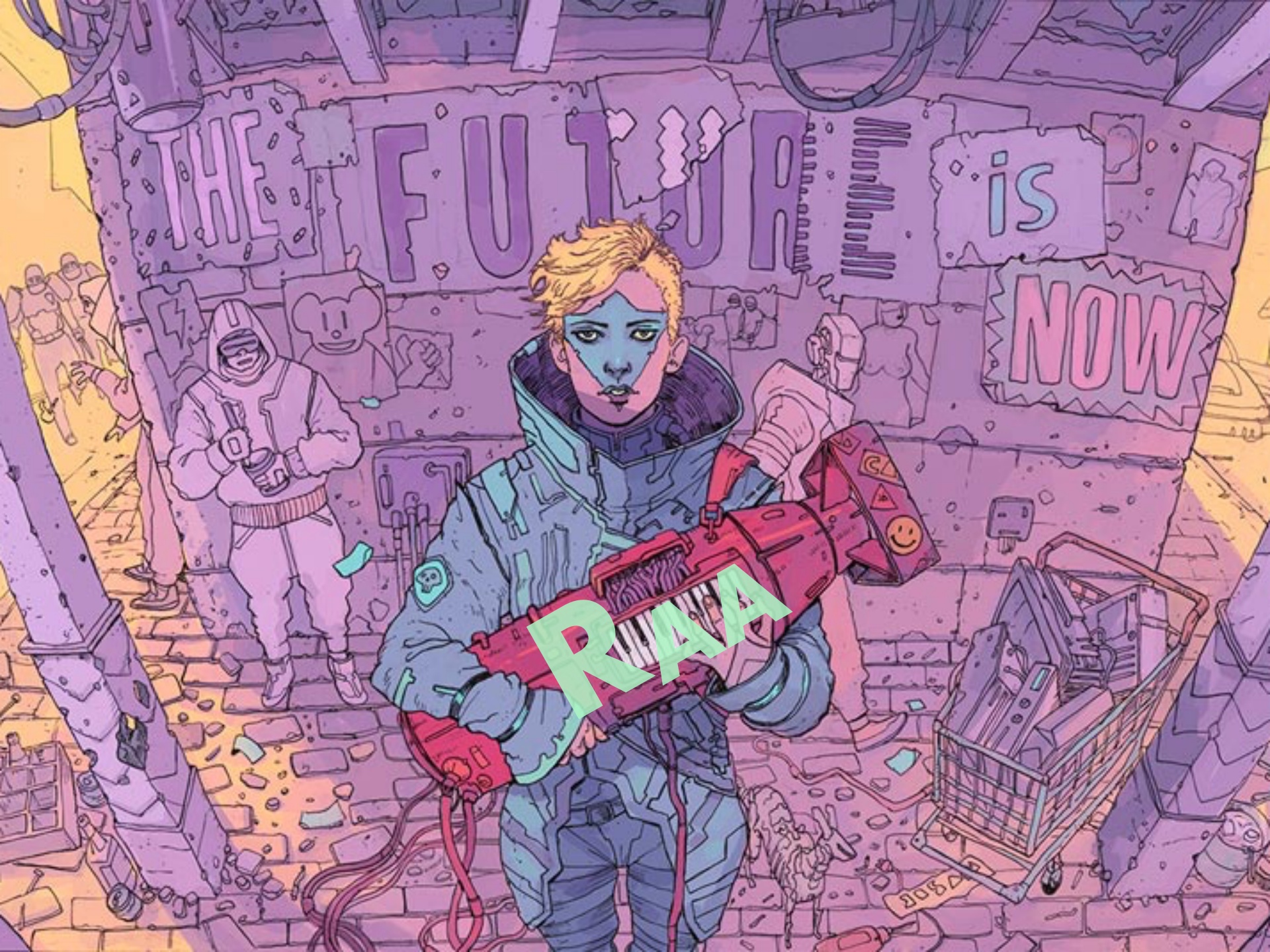
RHIC User Meeting June 9, 2016

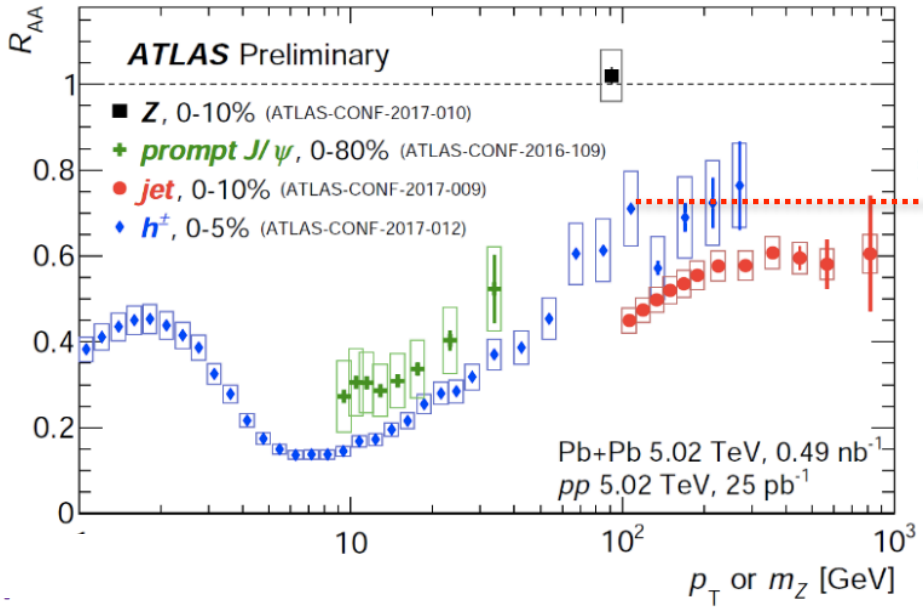
RHIC and LHC complementarity

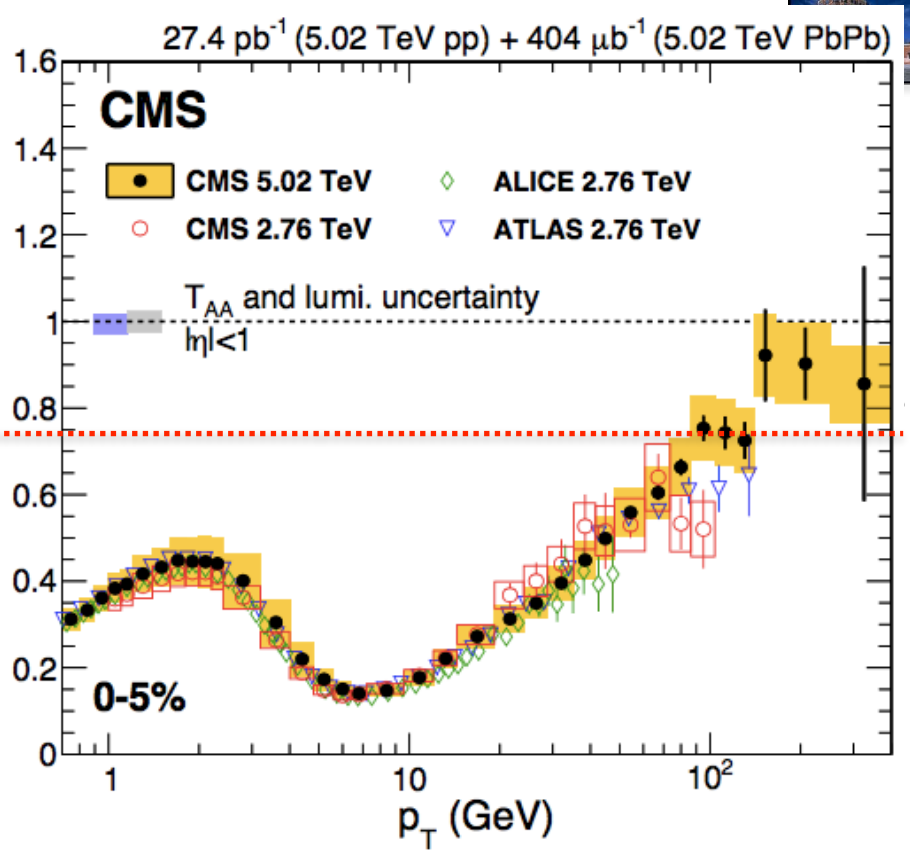


this was based on 100b events for sPHENIX
updated projections for 5 year run plan underway

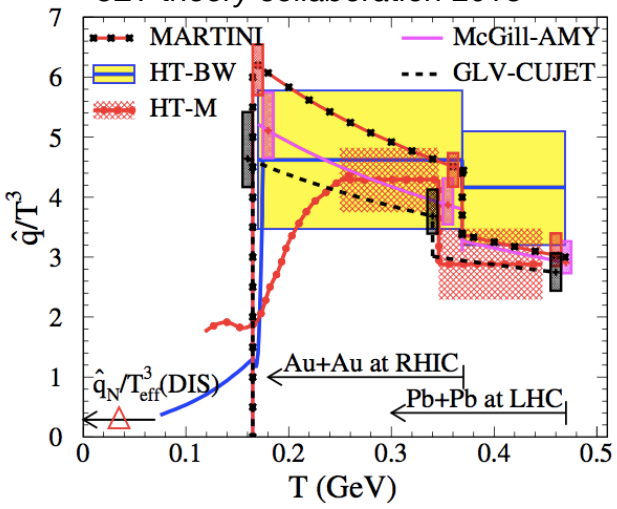

THE FUTUR
is
NOW
Dark Matter
2017


THE FUTUR
is
NOW
RAA



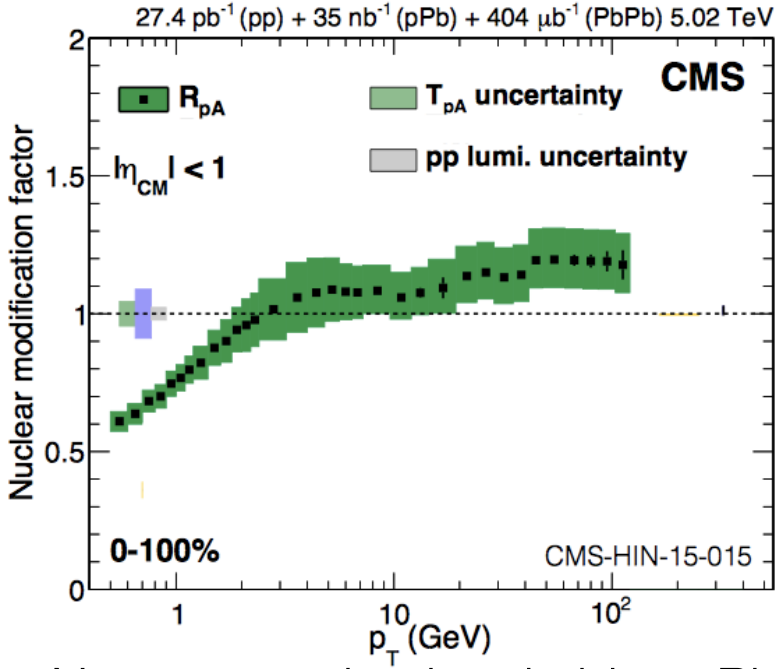


JET theory collaboration 2013

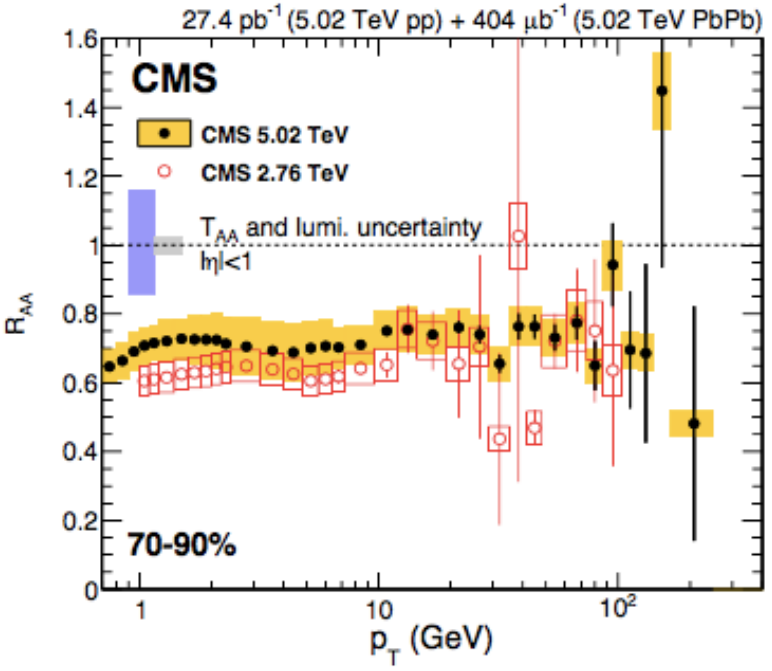


JET or its *Nachfolgeorganisation* needs to follow up with systematic study - what have we learned since 2013?

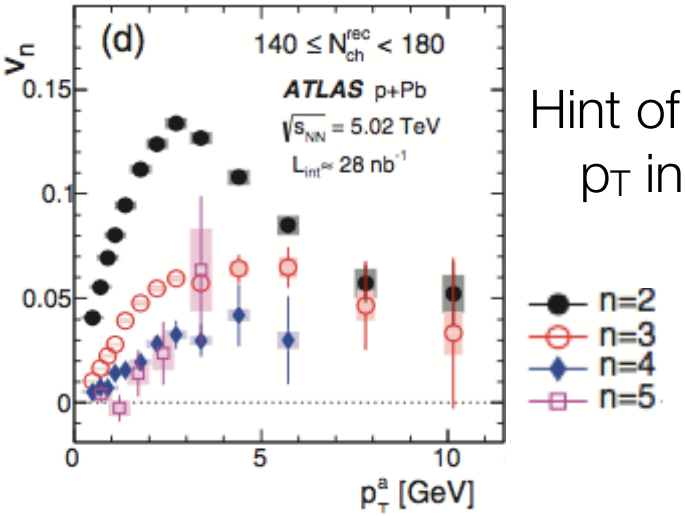
Jet quenching in small systems



No suppression in min bias pPb



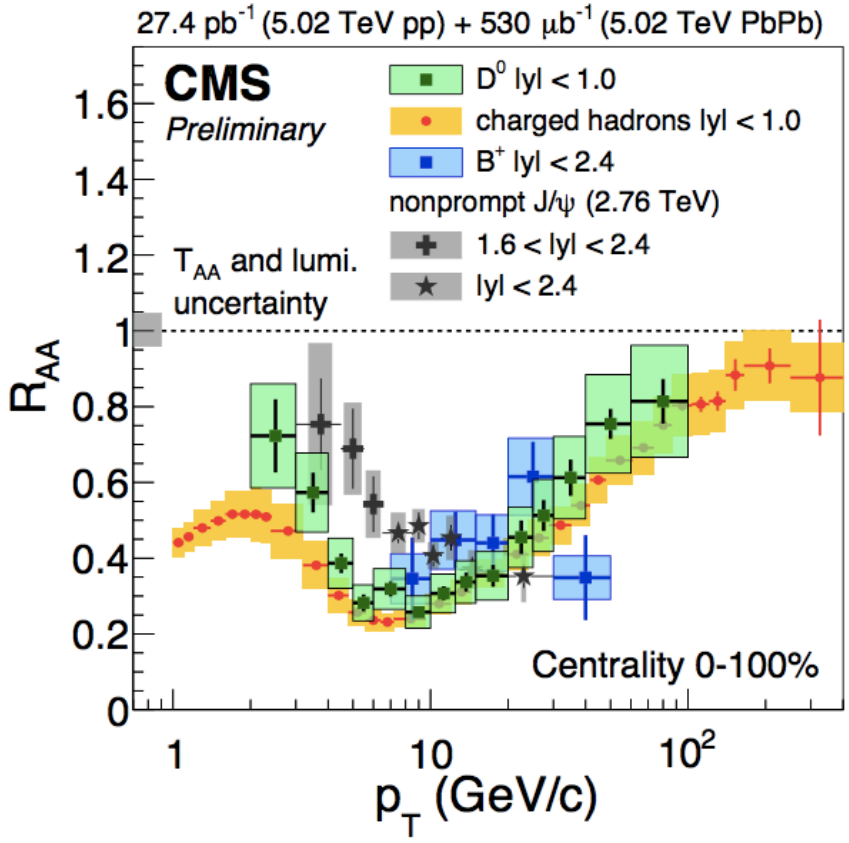
Large suppression in peripheral PbPb



Hint of finite/large v_2, v_3 at high(-ish) p_T in "central" pPb from ATLAS

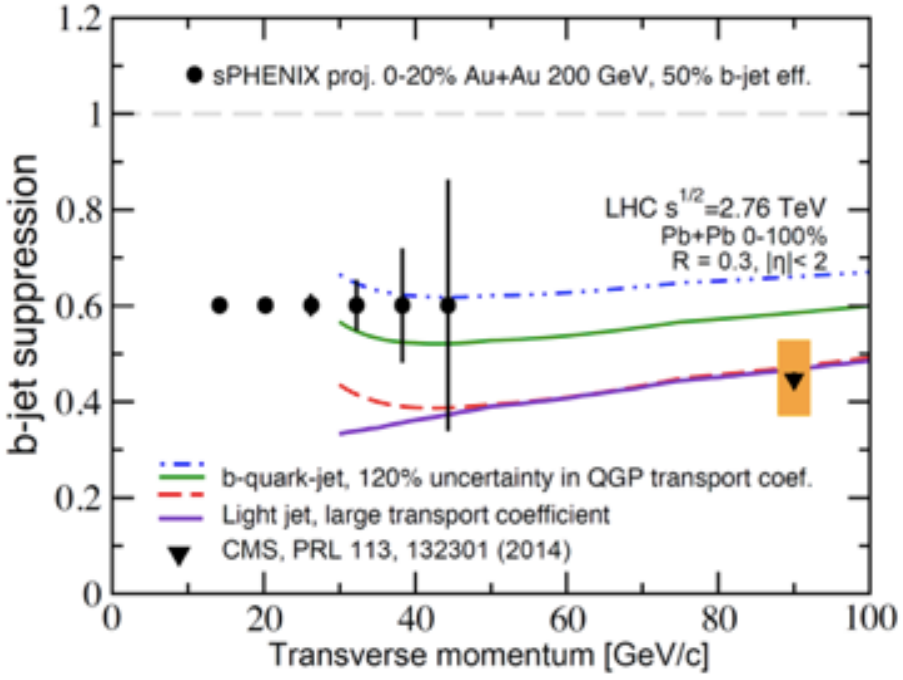
Should be possible to resolve with 2015 PbPb and 2016 8TeV pPb

HF Spectra at LHC

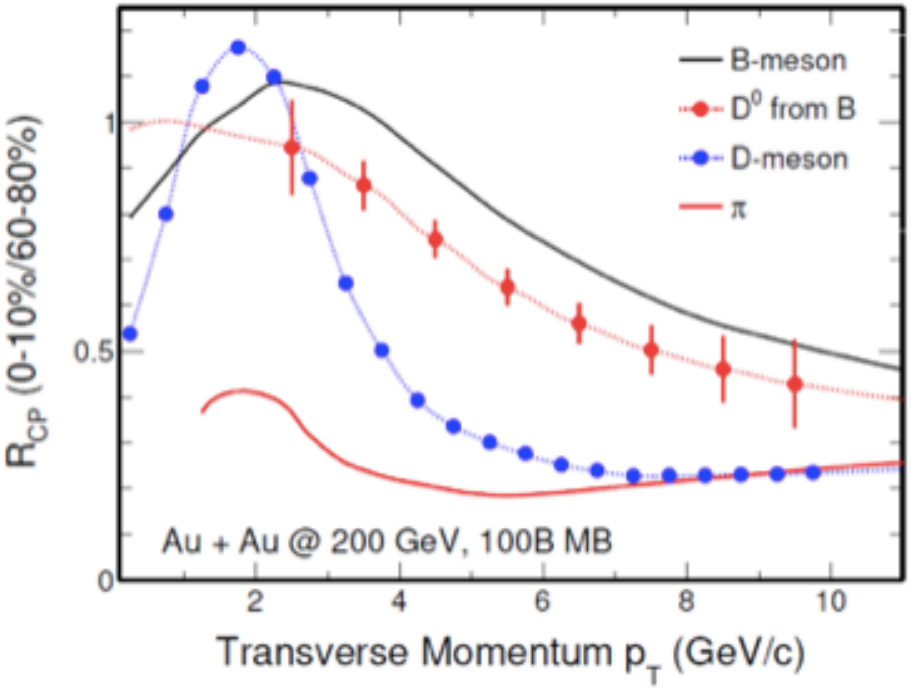


- $B^{+/-}$ Future: 0.5/nb → 10/nb+; 1→3+ experiments; better resolution, efficiency; more decay channels
- Expect errors comparable to $h^{+/-}$ today
- Extension to low p_T (~0 for D^0)

HF Spectra in sPHENIX

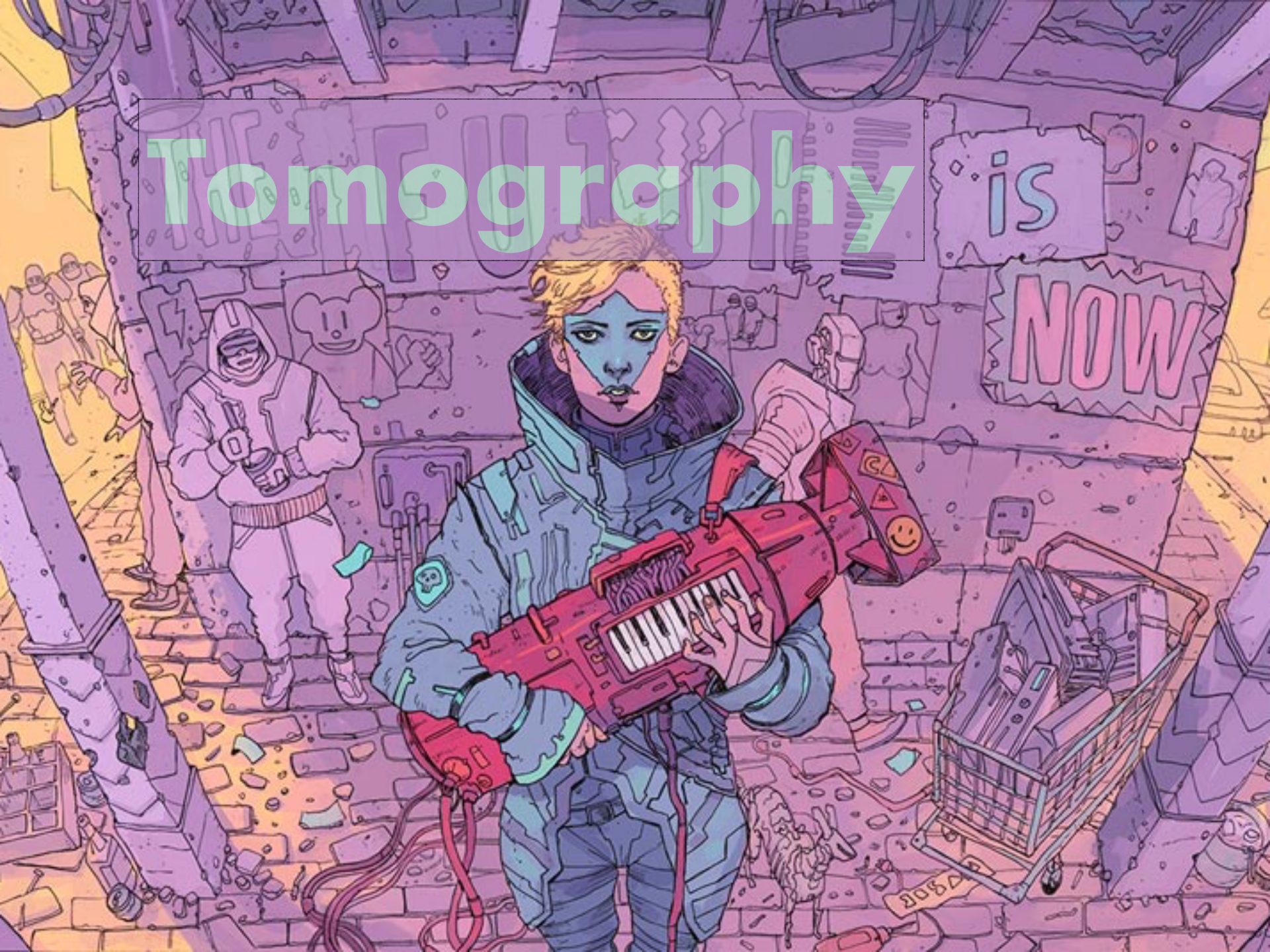


b-tagged jets
(much smaller contribution from gluon splitting than at LHC)



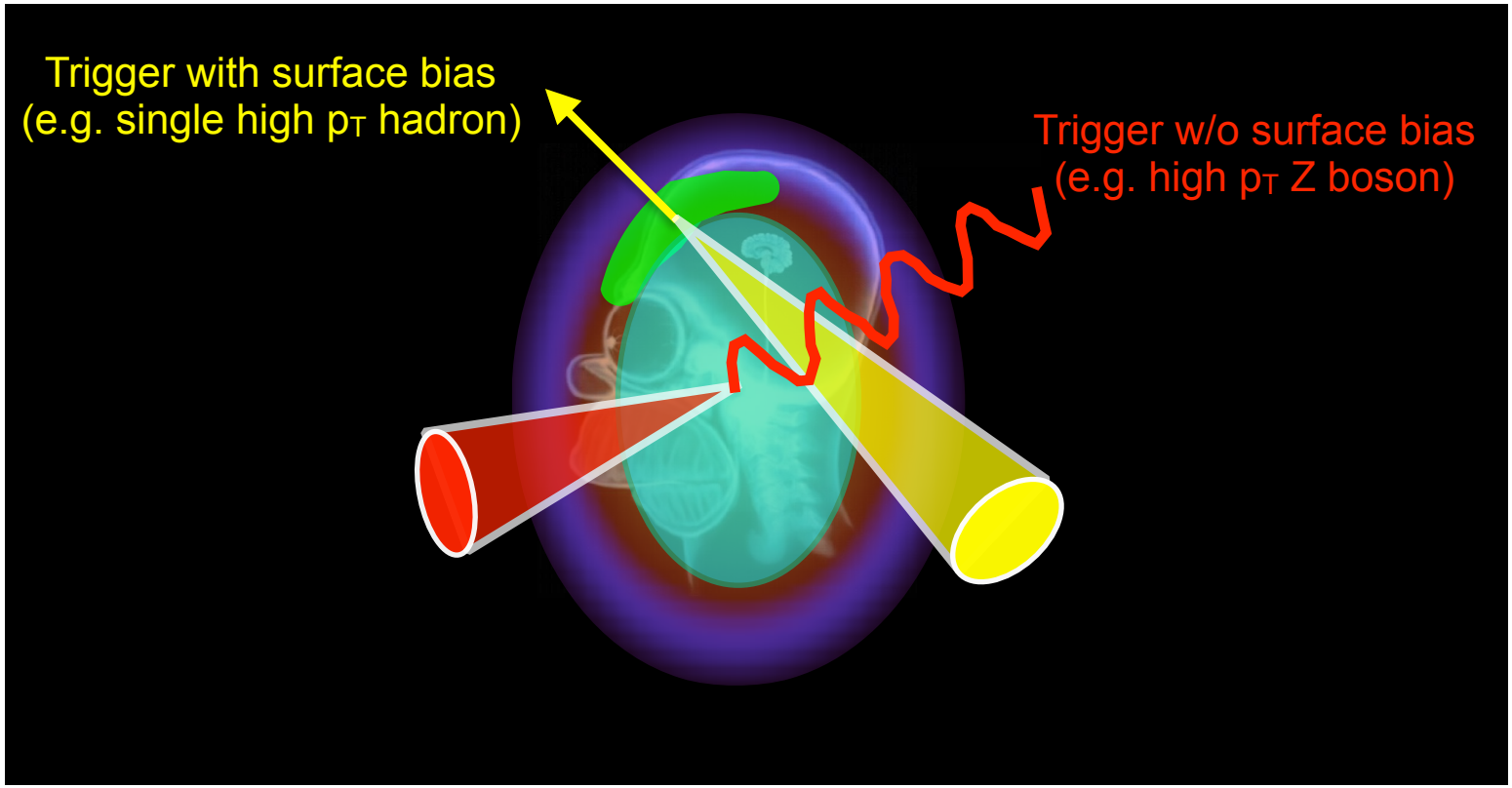
Displaced D^0 mesons as handle B meson suppression

Connect with and extend LHC b measurements


Tomography
is
NOW

QGP Tomography

TOMOGRAPHY
: a method of producing a three-dimensional image of the internal structures of a solid object by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures

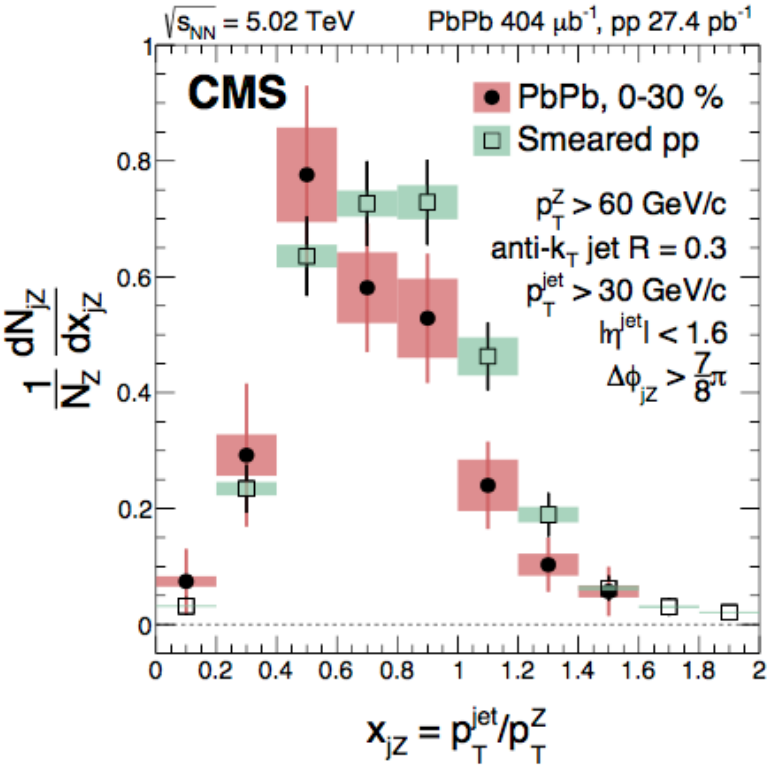


Use p_T, centrality, pathlength, $\sqrt{s}$ dependence, trigger biases, flavor tags,… to isolate different processes in time, coordinate and momentum space

Jet+X correlations

Z+jet

CMS 2017

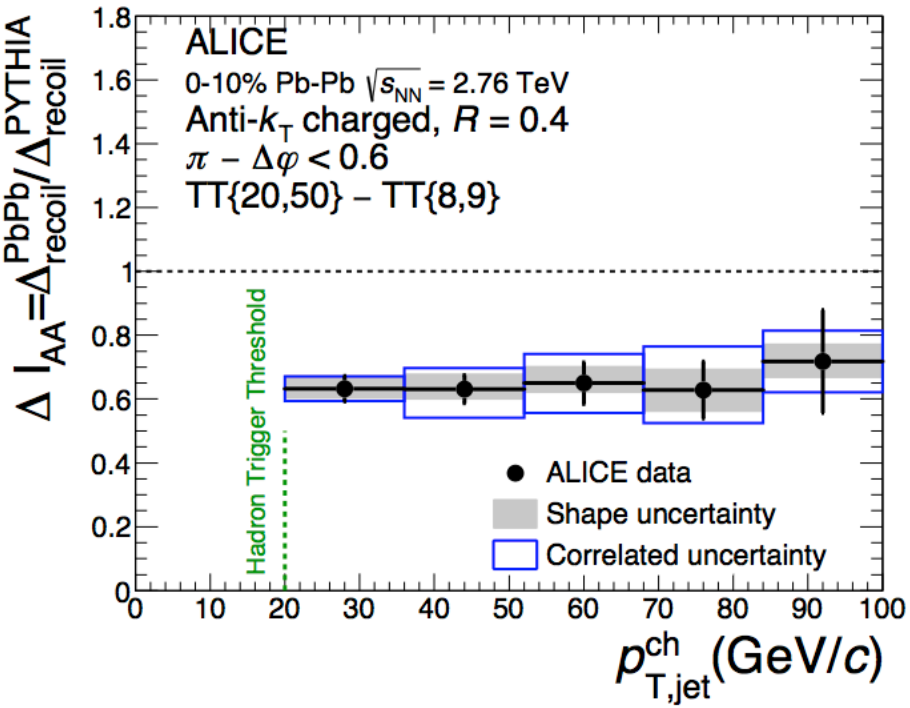


Shift of final state jet momentum relative to initial parton (Z) momentum

(no geometry bias)

jet-hadron

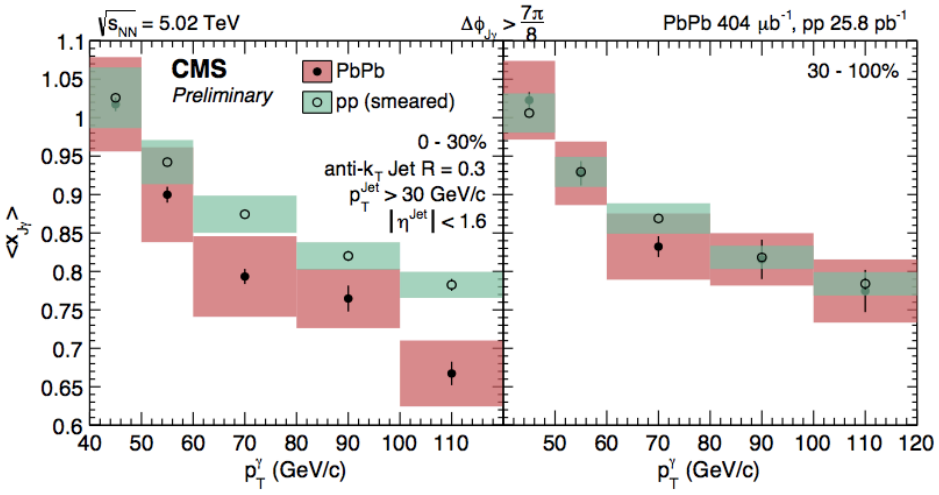
ALICE 2016



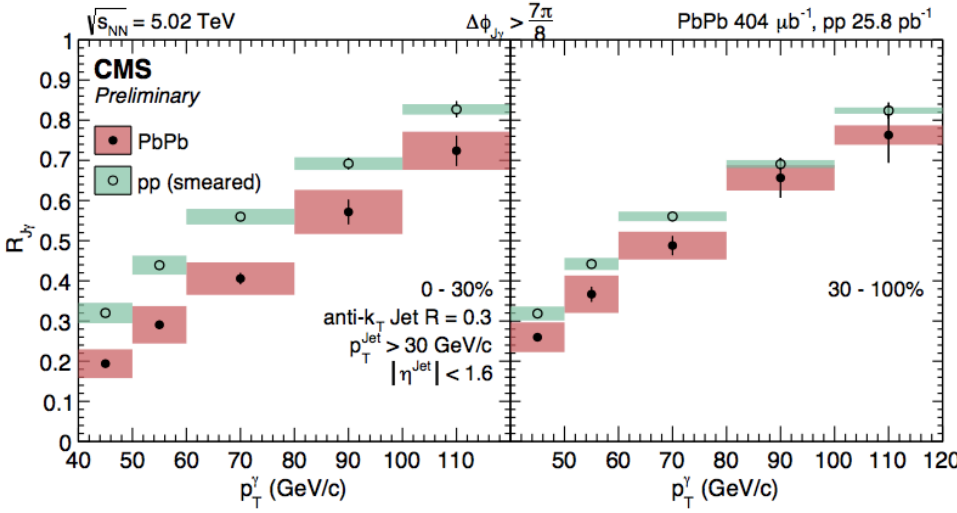
Change in yield of jets recoiling against high p_T hadrons at given p_T

(geometry bias)

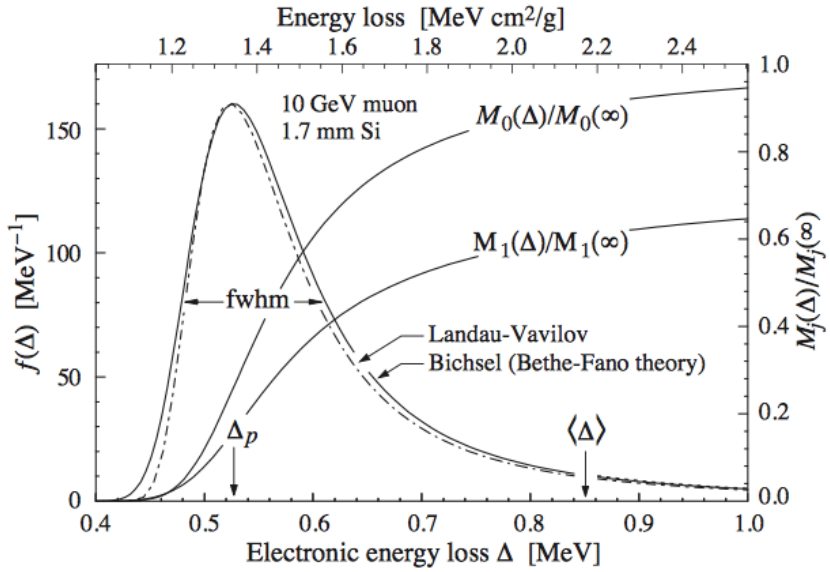
Energy loss distribution



$\langle x_{jg} \rangle$: average energy loss

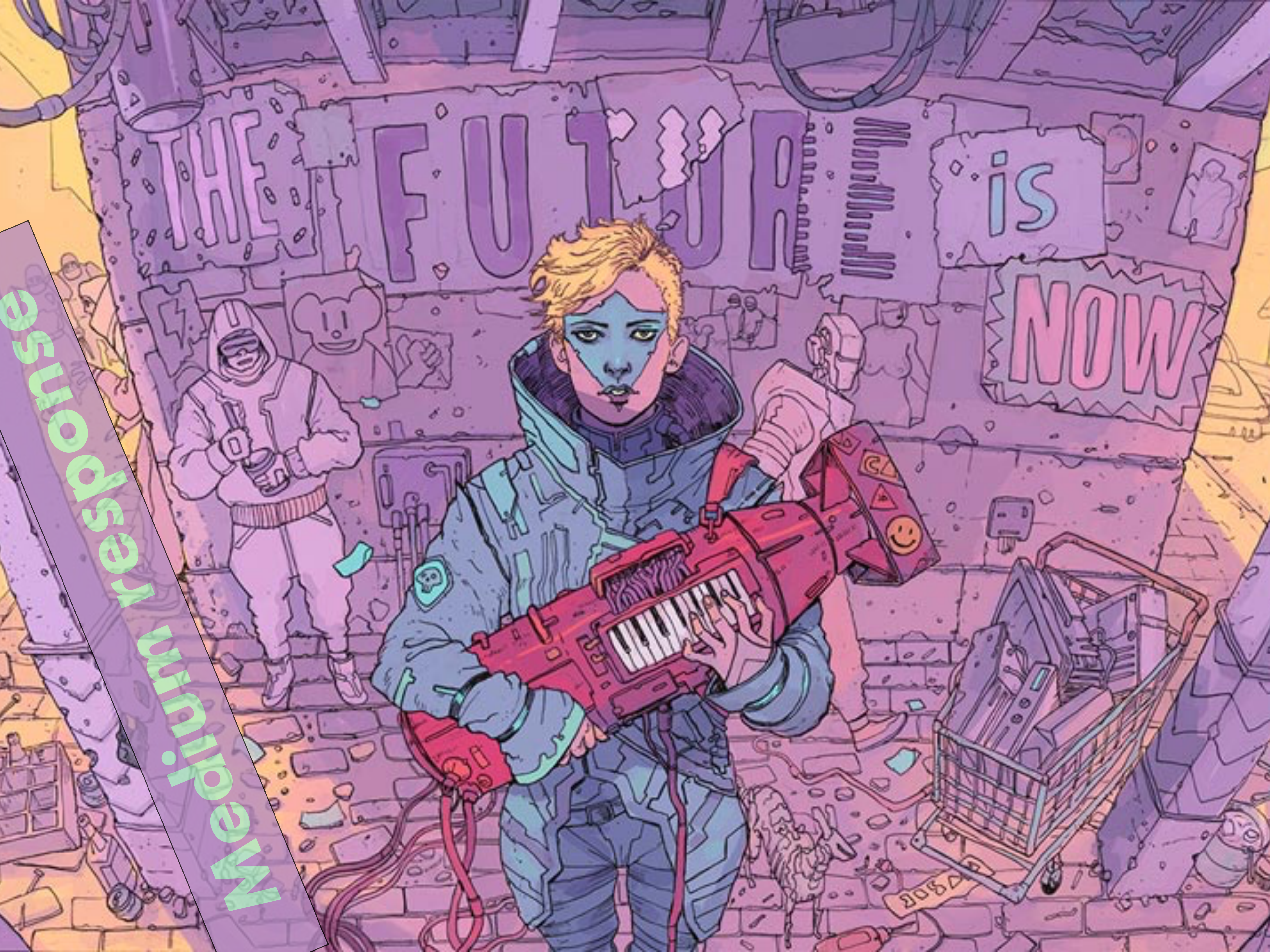


R_{jg}: tail of energy loss distribution



What is the energy loss distribution for partons in QGP?

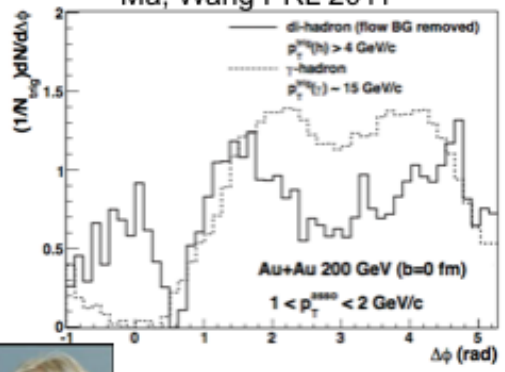
Is there a difference between models/approximations?


THE FUTURE is NOW
Medium response

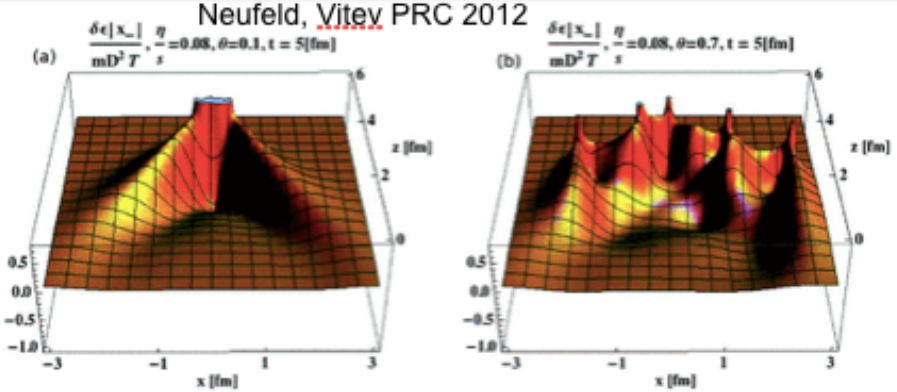
My go-to slide on Medium response (pre-QM'17)

Energy flow and medium response

Ma, Wang PRL 2011



Neufeld, Vitev PRC 2012



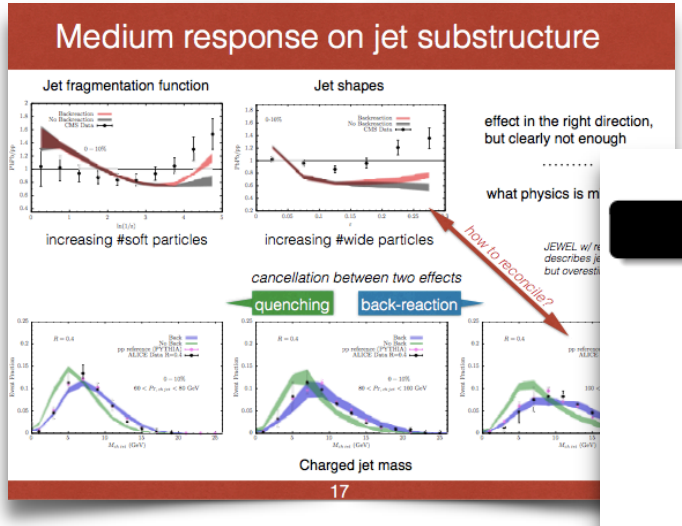
Do we have a medium, if there's no medium response?

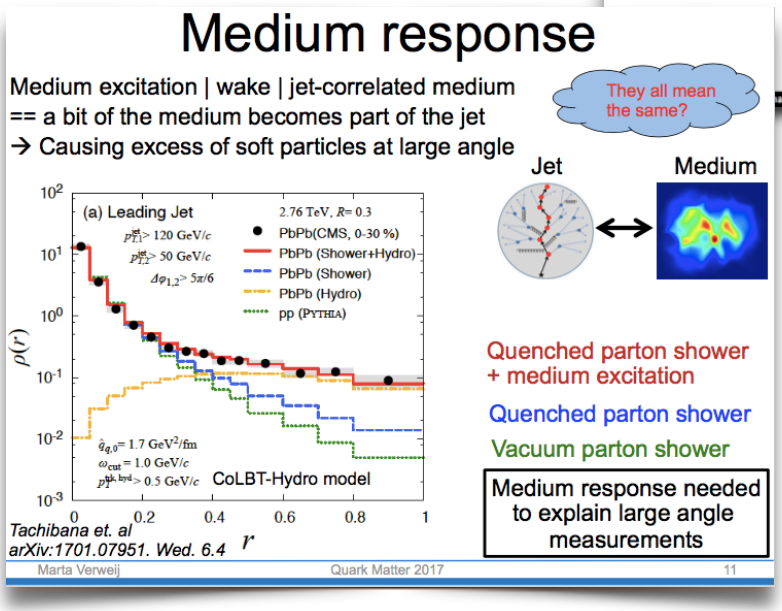
Experimental and theoretical challenges:

- Strength and angular structure of medium response unknown
- Jets are correlated with the complex e-by-e flow fields through quenching
- How to distinguish medium-response from modified jet branching?

Fundamentally simpler for photon-jet events!

Surprising development at QM'17



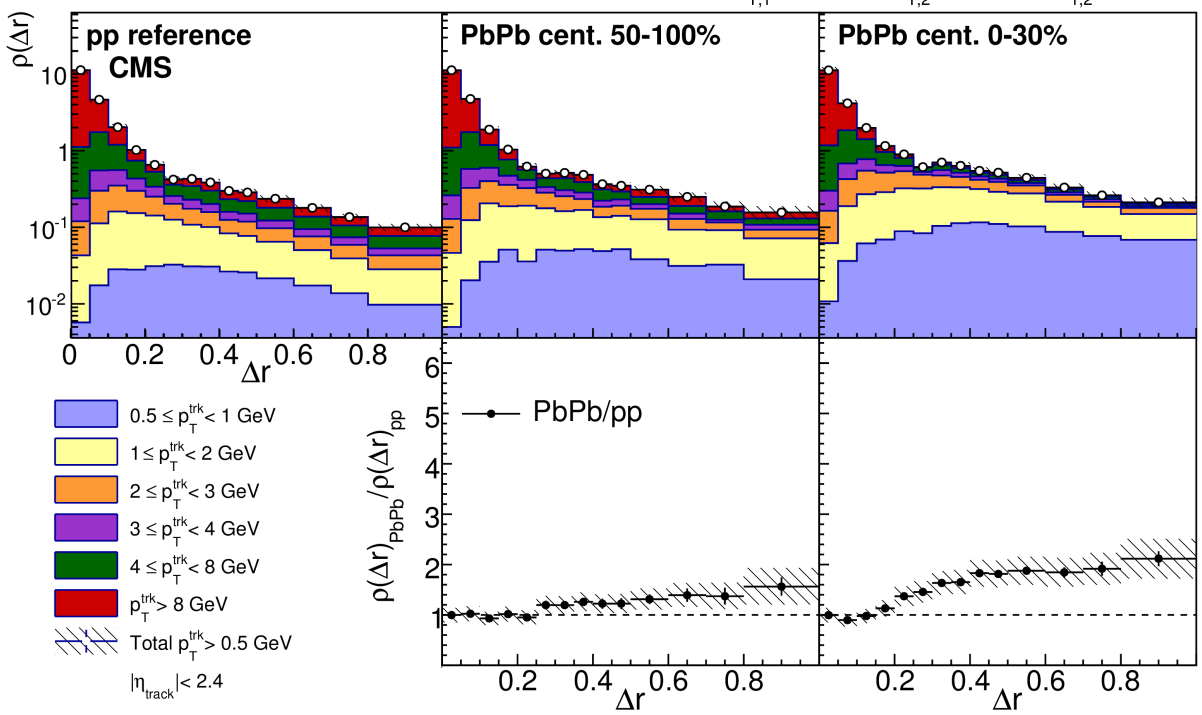


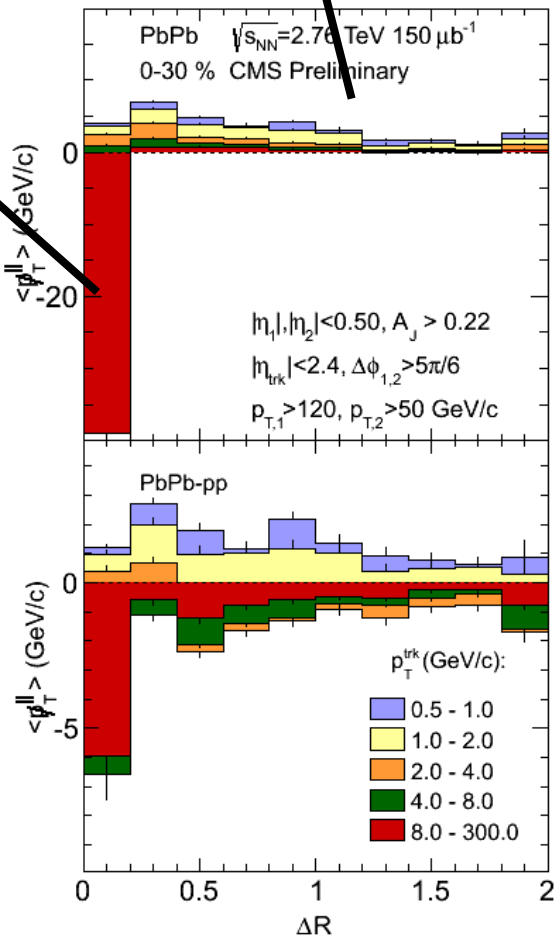
Theorists discover medium response in "old" data

Medium response or modified jets?

In-cone energy difference (leading - subleading jet)

Balanced by low p_T particles at large angles



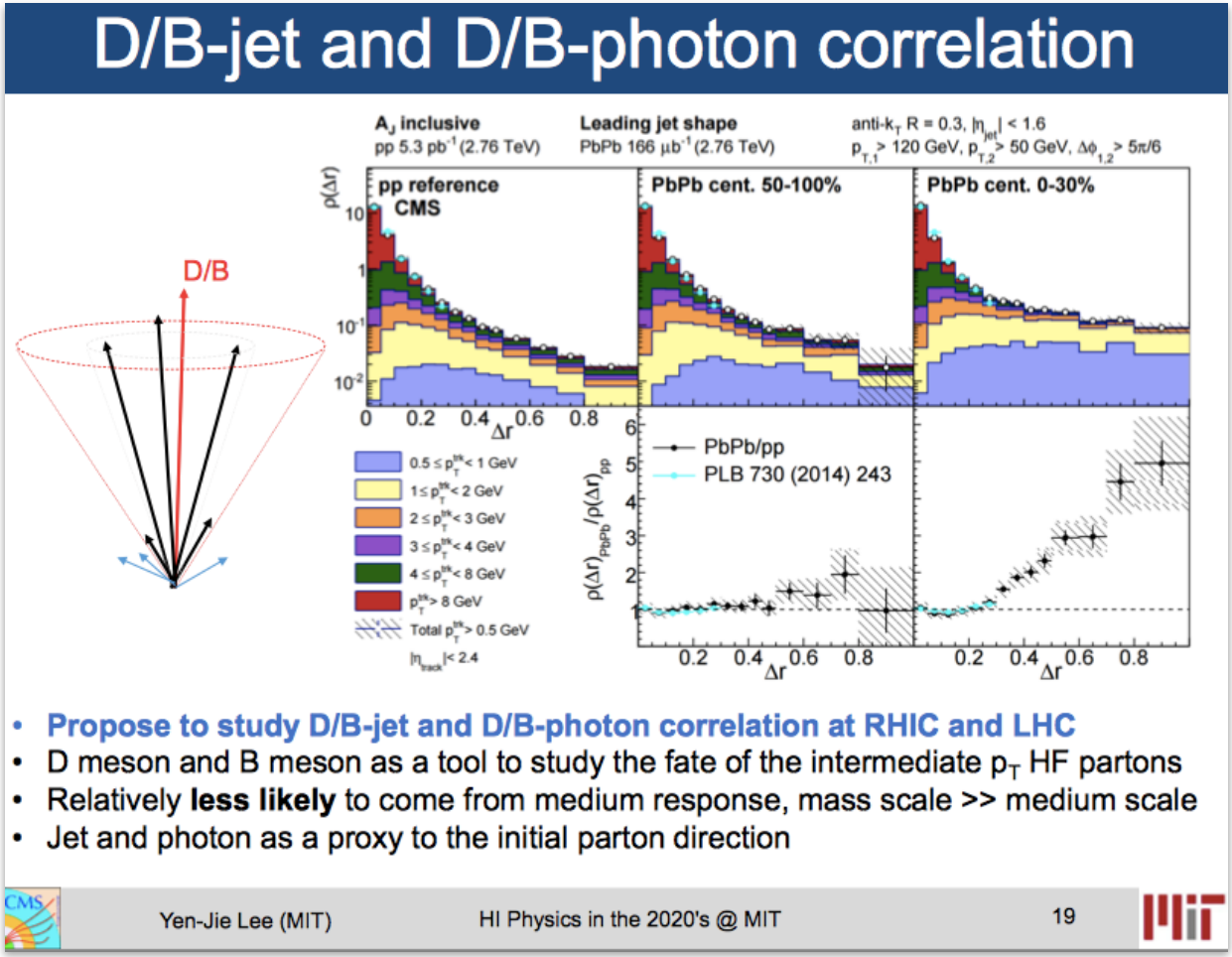


Jet shapes, missing p_T show energy flow out to large angles

Medium response or modified jets?

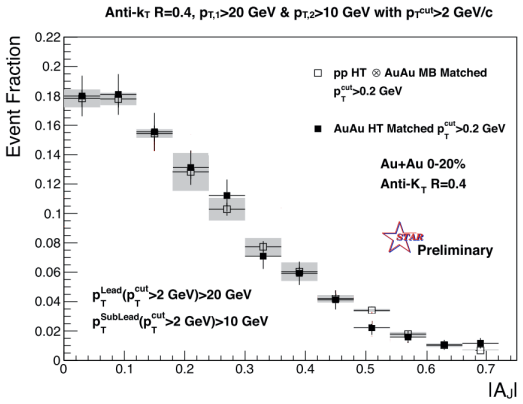
How to distinguish jet-stuff from medium-stuff, if there's no distinct angular structure of medium response?

YJ Lee: Look for medium response in HF-jet correlations

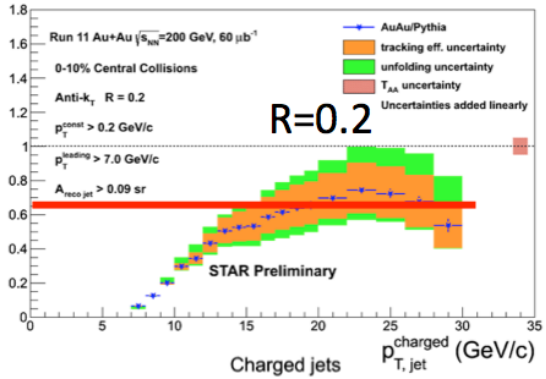


Energy flow differences at RHIC vs LHC

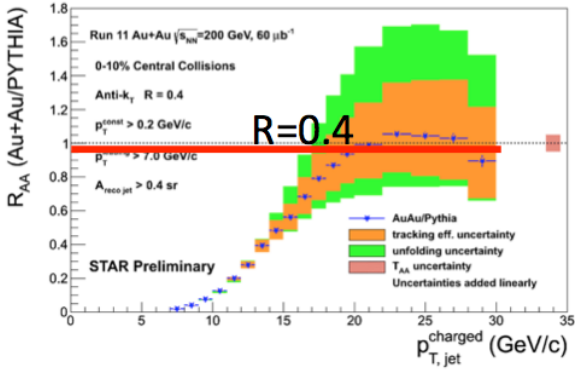
RHIC (STAR)



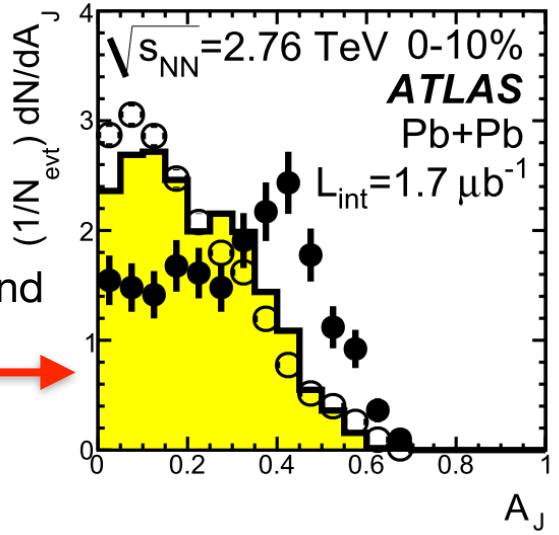
Jets balanced when including $p_T > 0.2$GeV



Strong radius dependence of jet RAA

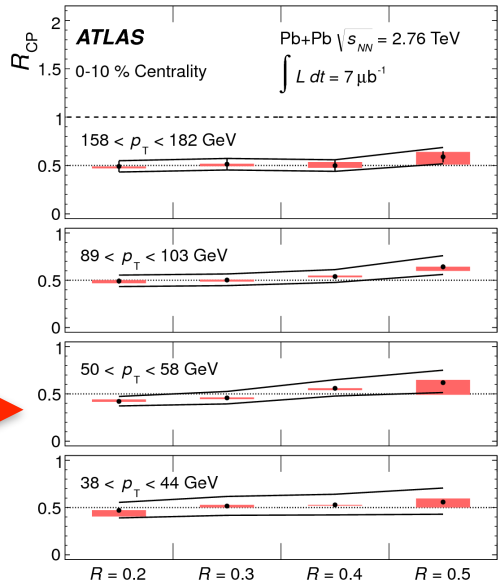


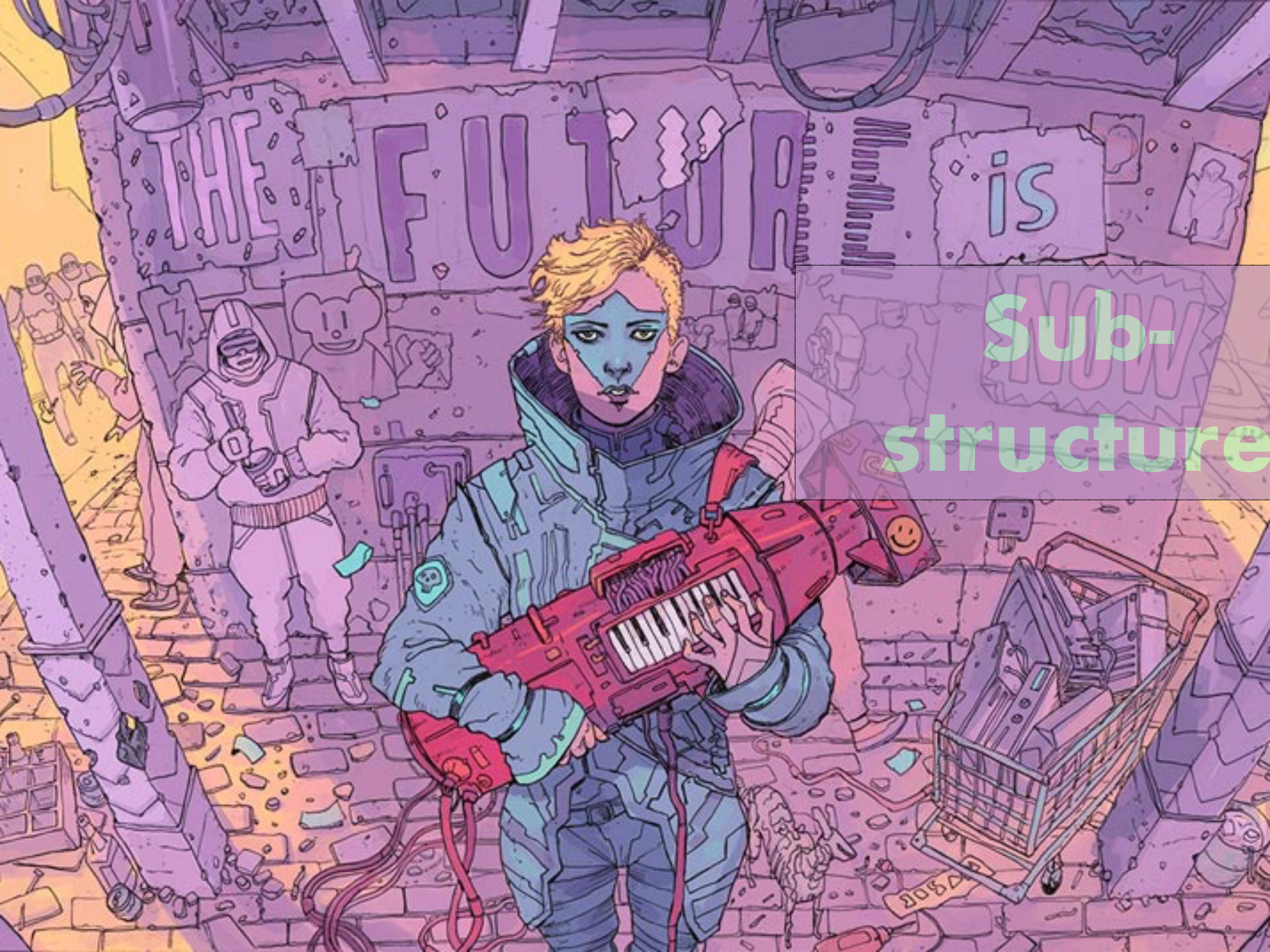
LHC (ALICE, ATLAS, CMS)



Energy balance found outside of jet cone

Weak radius dependence of jet RAA

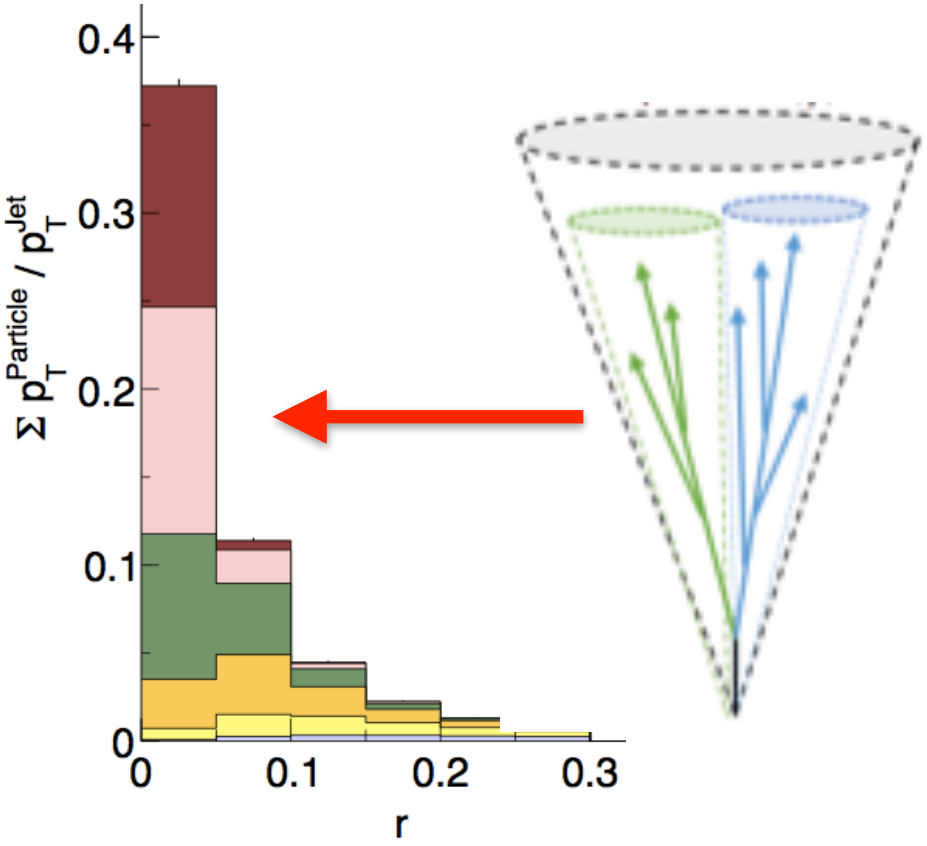



THE FUTUR is
NOW
Sub-
structure

Jets as Multi-Scale Probe

Final state jet

Parton shower



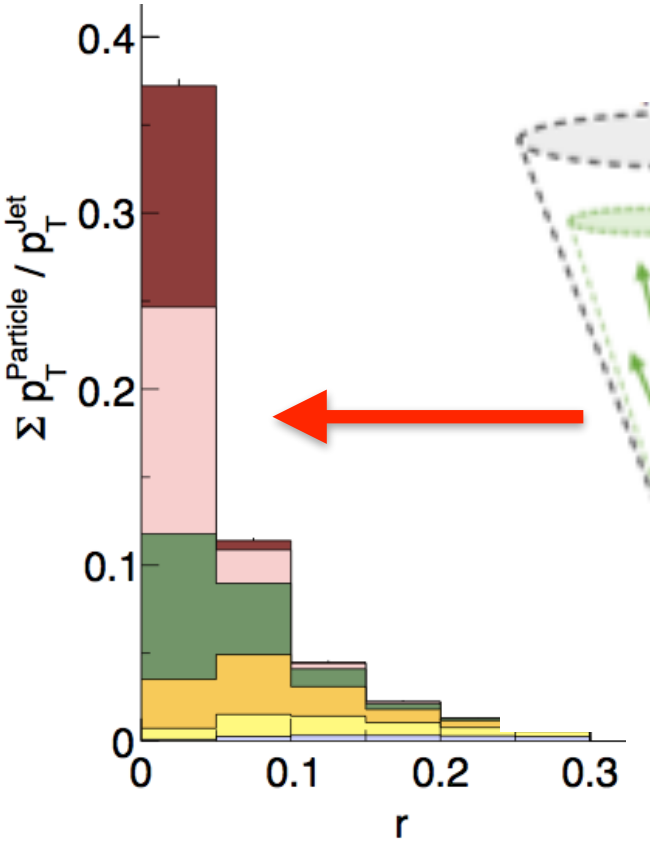
Jets as Multi-Scale Probe

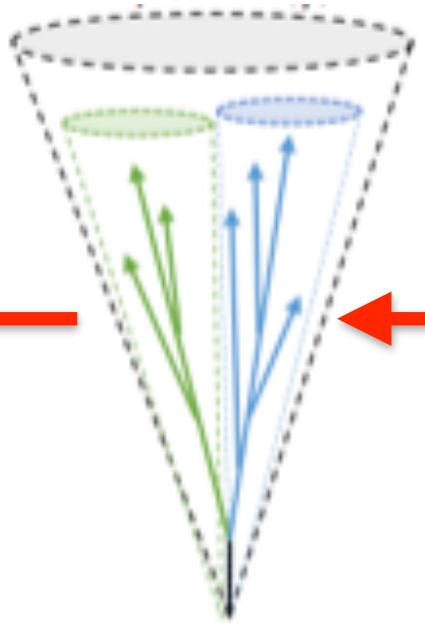
Final state jet

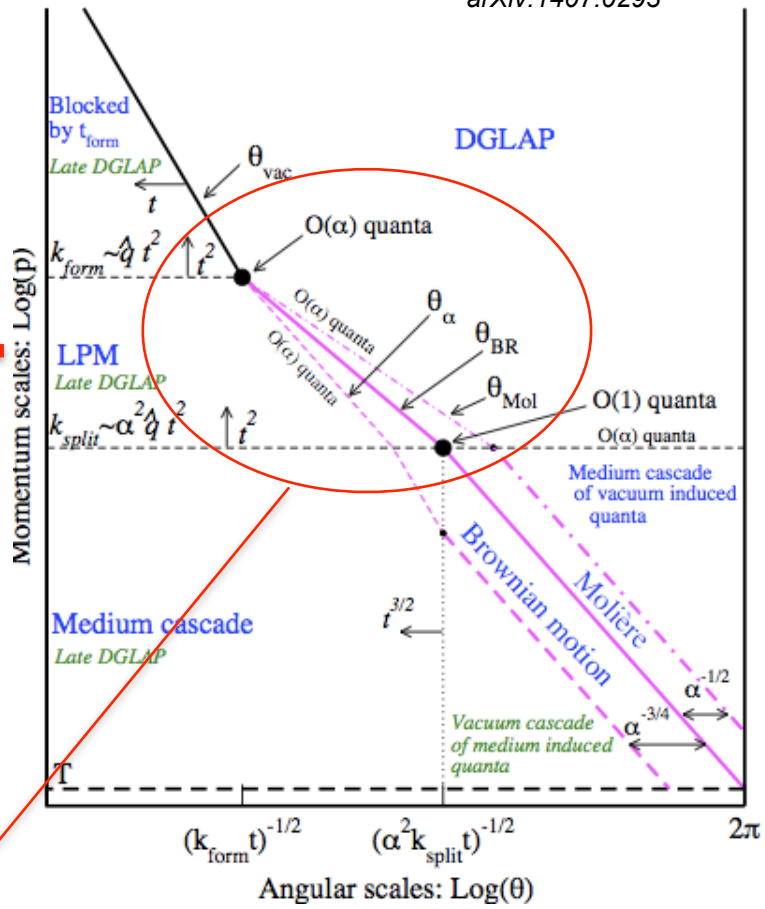
Parton shower

Snapshot of angular and momentum structure of intra-jet parton cascade

Kurkela, Wiedemann, arXiv:1407.0293





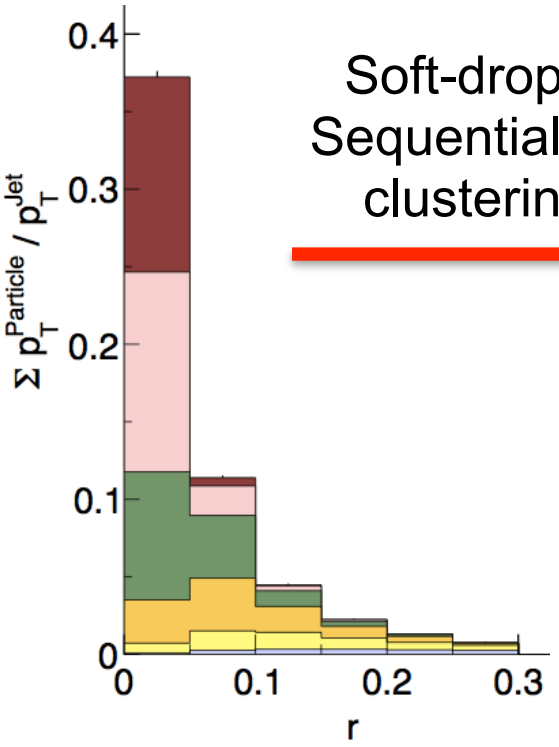


At different scales, evolution is dominated by different mechanisms:

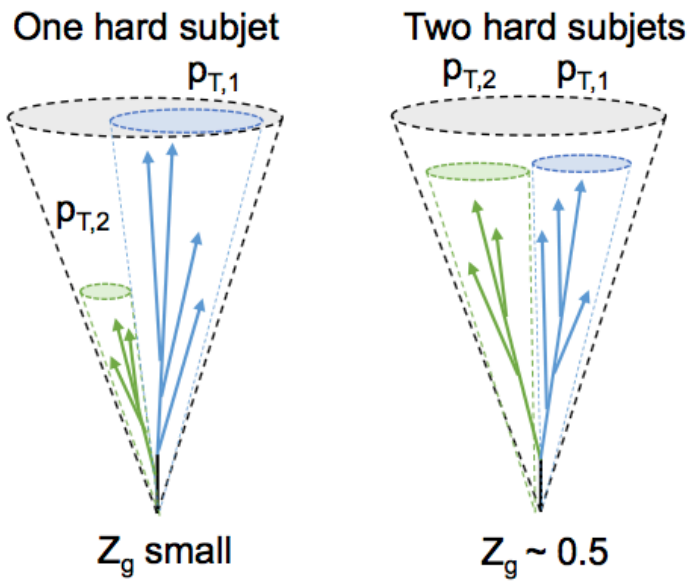
- vacuum evolution
- (jet-constituent)-medium scattering
- in-medium cascade

Detailed understanding of jet modifications on all scales may allow to isolate interactions with "QGP quasiparticles"

New Direction: Jet Substructure



Soft-drop + Sequential re-clustering



from Yen-Jie Lee

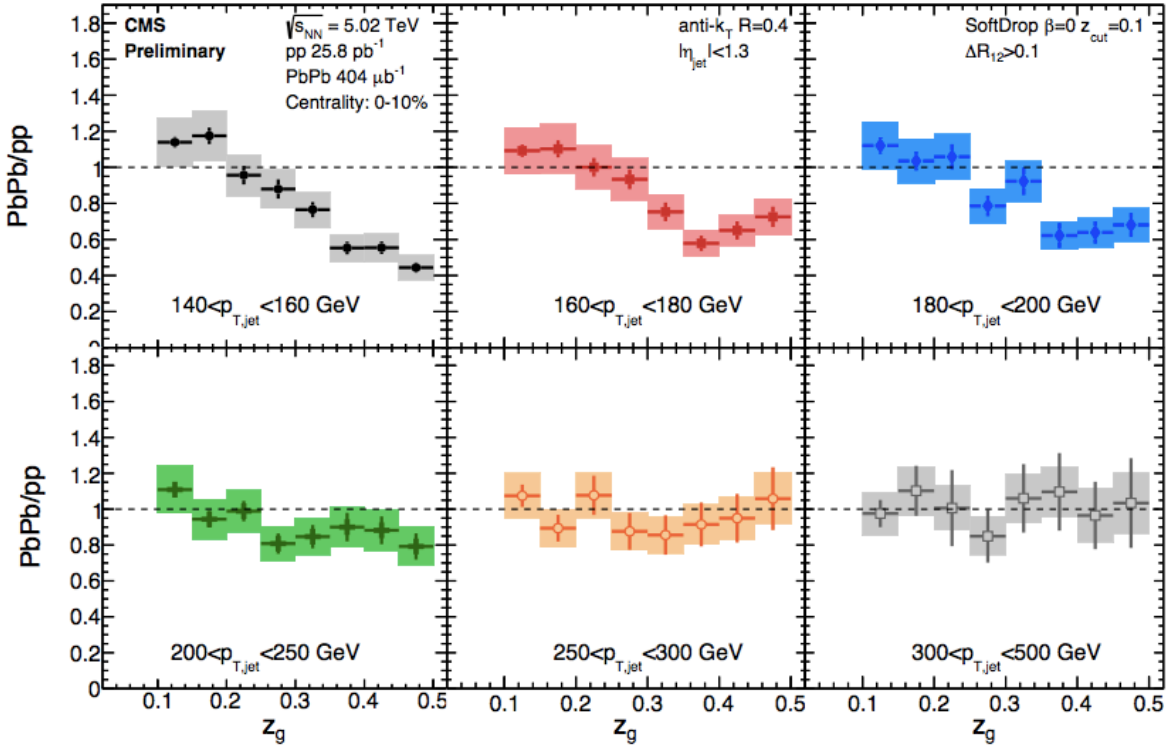
$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

Use clustering + jet grooming techniques to map structure of final state to evolution of parton shower (e.g., “splitting function”)

Does medium resolve early parton shower evolution?

Splitting function in AA

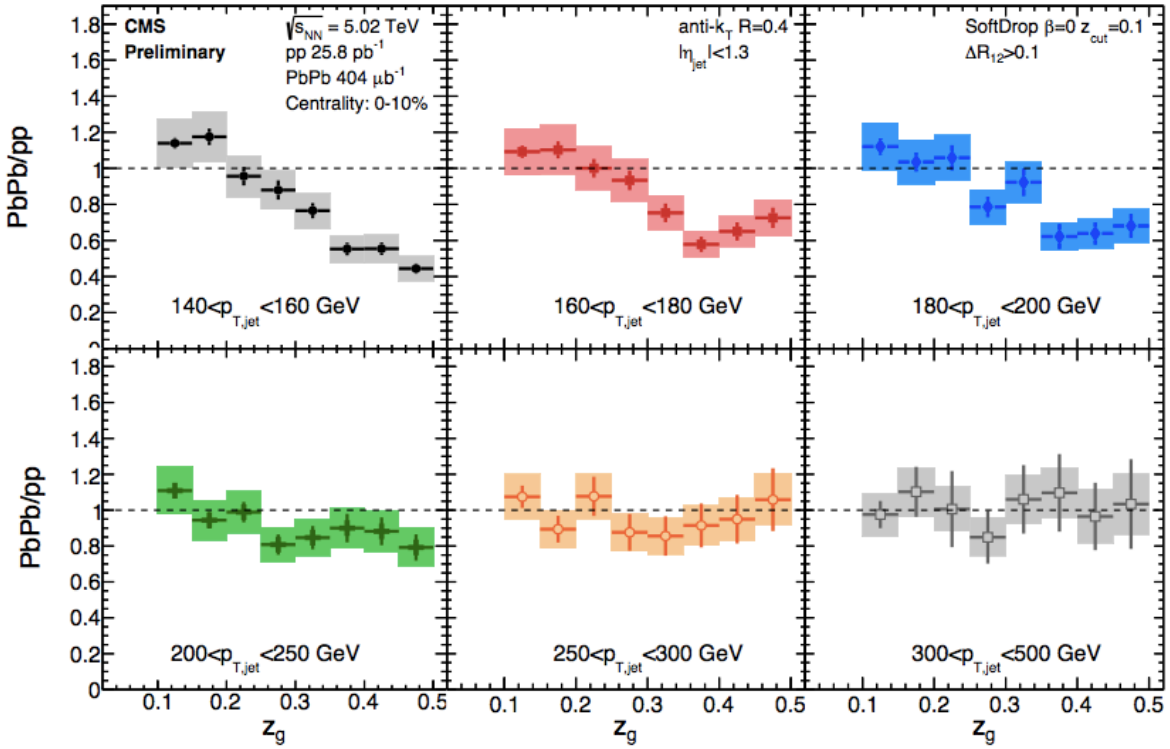
n.b. z_g ratios not corrected; smearing effect on ratio is small
systematic uncertainty includes scale uncertainty for constituent p_T sum

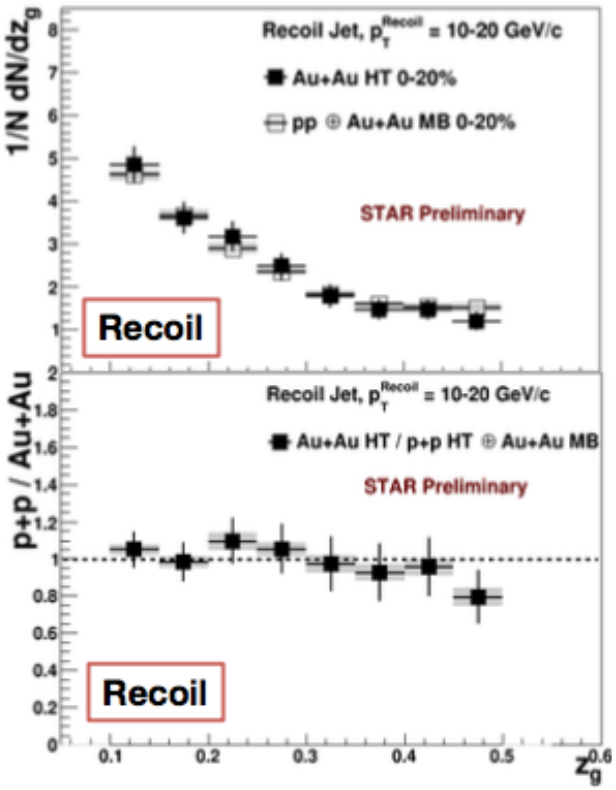


"Splitting function" is modified for "lower" p_T jets at LHC…

QGP resolves earliest hard splitting

Splitting function in AA





"Splitting function" is modified for "lower" p_T jets at LHC…

QGP resolves earliest hard splitting…

…but not for low p_T jets at RHIC

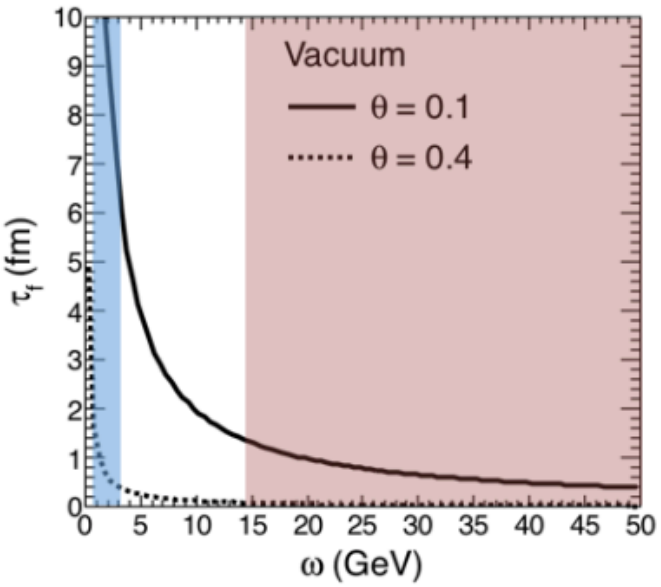
…or not?

Z_g and Formation Time

z_g – RHIC vs LHC

Vacuum formation time of gluons with certain energy

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$



Phase space covered for z_g=0.1

STAR

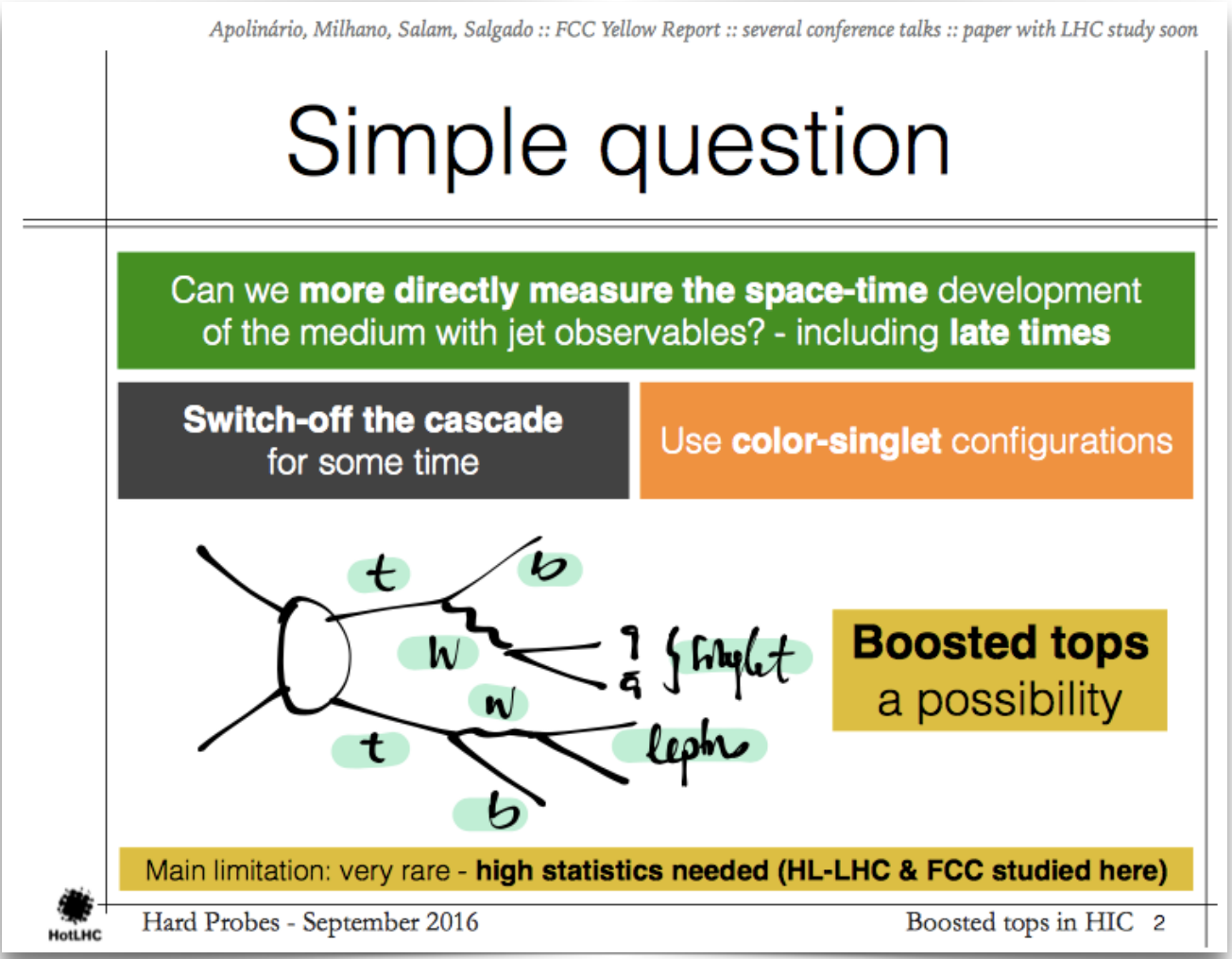
CMS

STAR and CMS are probing very different formation times. No overlap

Marta Verweij Quark Matter 2017 25

Close the gap with lower p_T jets at LHC and higher p_T jets at RHIC (→sPHENIX)

Jet Structure at HL-LHC and FCC



→ see talk by Liliana

Boost (time dilation) allows to control when/ where in plasma top/W decay products appear

Summary

- Goal: QGP microscopy using jets
- Large harvest of new results from Run 2 at LHC and RHIC upgrades
  - Light hadron and HF R_{AA}
  - Jet tomography with h, Z, γ tags
  - Re-interpretation of correlation data as medium response
  - Studies of jet substructure
- Old questions remain; new ones arise
- Expect huge experimental progress at LHC + RHIC in 2020's
  - much more complete control over initial/propagating hard scattered object(s)
- **Critical issue is capability of theory to exploit new experimental information**