RHIC/LHC Forward Physics and Upgrades

John Lajoie

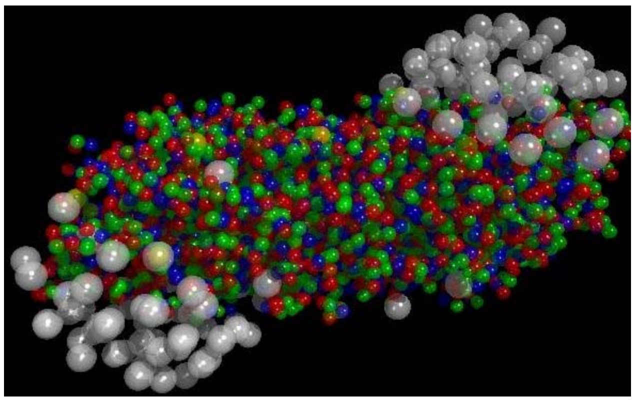
Iowa State University

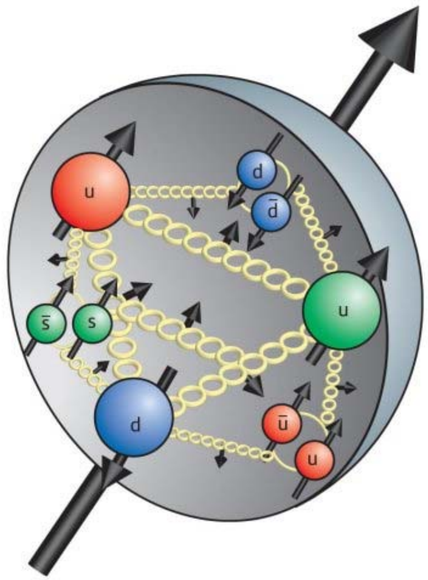
STATE

U.S. DEPARTMENT OF ENERGY
Office of Science

The Big Picture at LHC/RHIC/EIC…

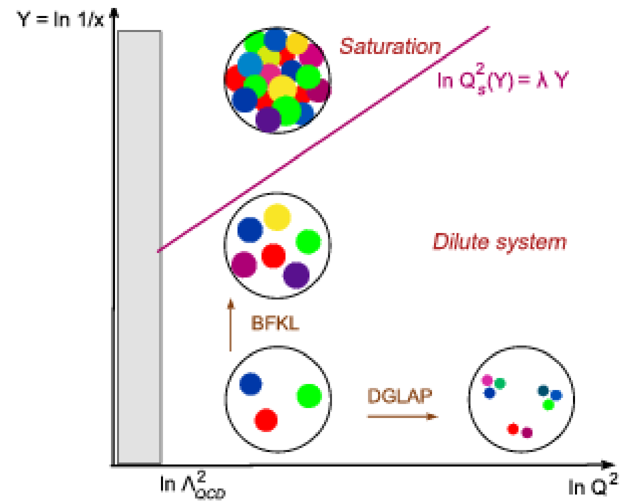
A+A Collisions





$p\uparrow + p\uparrow$ Collisions

p+A Collisions



The Big Picture at LHC/RHIC/EIC…

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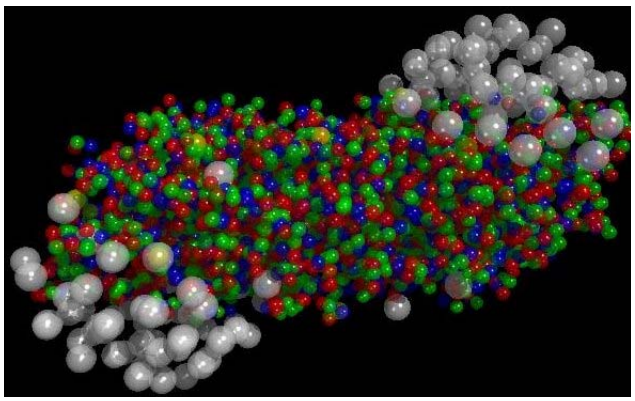

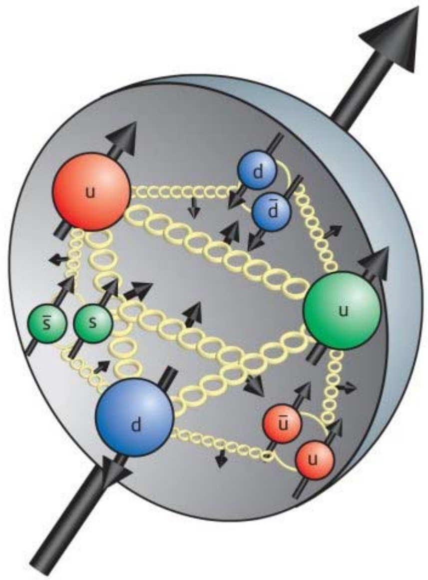

$p\uparrow + p\uparrow$ Collisions

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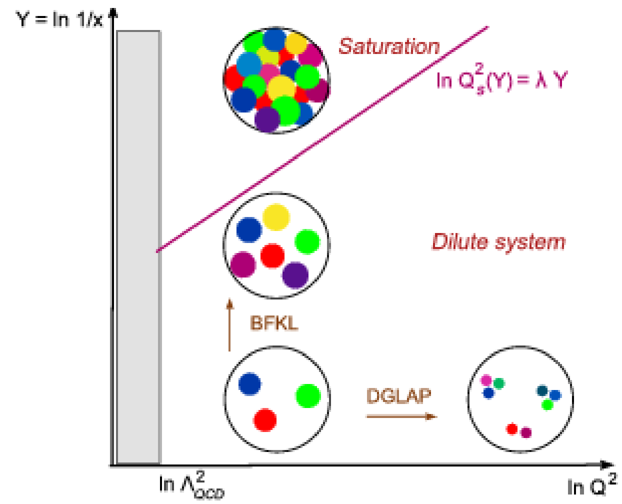
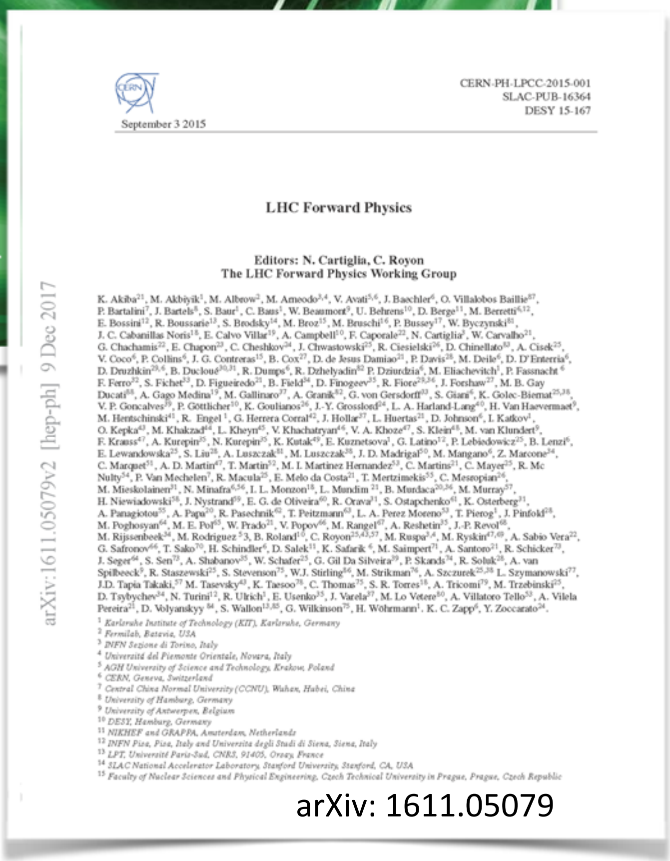


How do collective, many-body phenomena arise from first-principles QCD?

Plans for Forward Physics


CERN-PH-LPCC-2015-001
SLAC-PUB-16364
DESY 15-167

September 3 2015

arXiv:1611.05079v2 [hep-ph] 9 Dec 2017

LHC Forward Physics

Editors: N. Cartiglia, C. Royon
The LHC Forward Physics Working Group

arXiv: 1611.05079

- **Total Elastic/Inelastic Cross Section**
- **Diffraction**
- **Coherent Central Production**
- **Cosmic Rays**
- **nPDF's and nFF's**
- **Ultraperipheral Collisions**
- **A+A Collisions**
- **Polarized Measurements (RHIC)**

Plans for Forward Physics

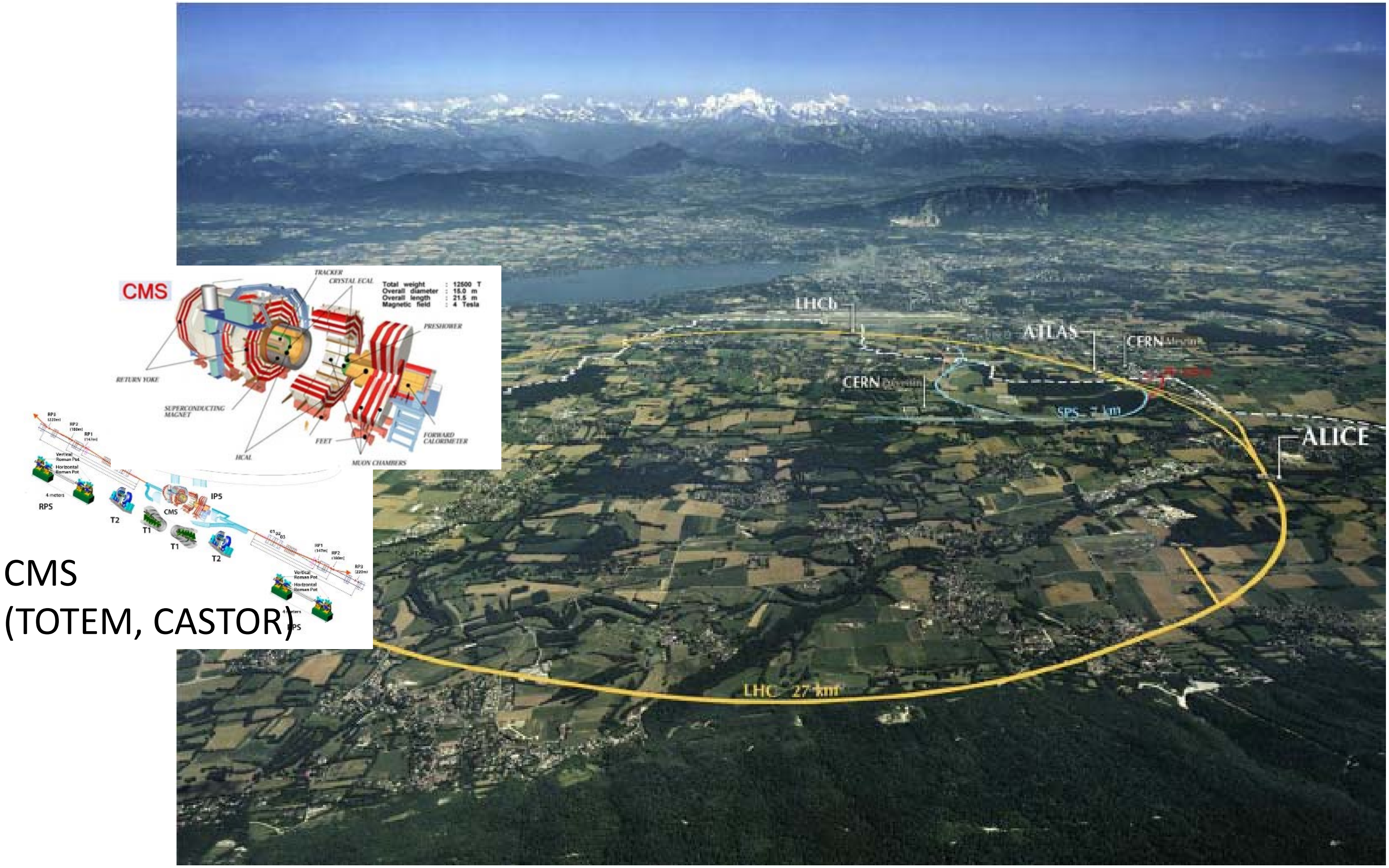
- Total Elastic/Inelastic Cross Section
- Diffraction
- Coherent Central Production
- Cosmic Rays
- nPDF's and nFF's
- Ultraperipheral Collisions
- A+A Collisions
- Polarized Measurements (RHIC)

The bulk of the physics portion of this talk…

Forward Facilities/Upgrades at the LHC

see talk by Martin Rybar (Thursday)

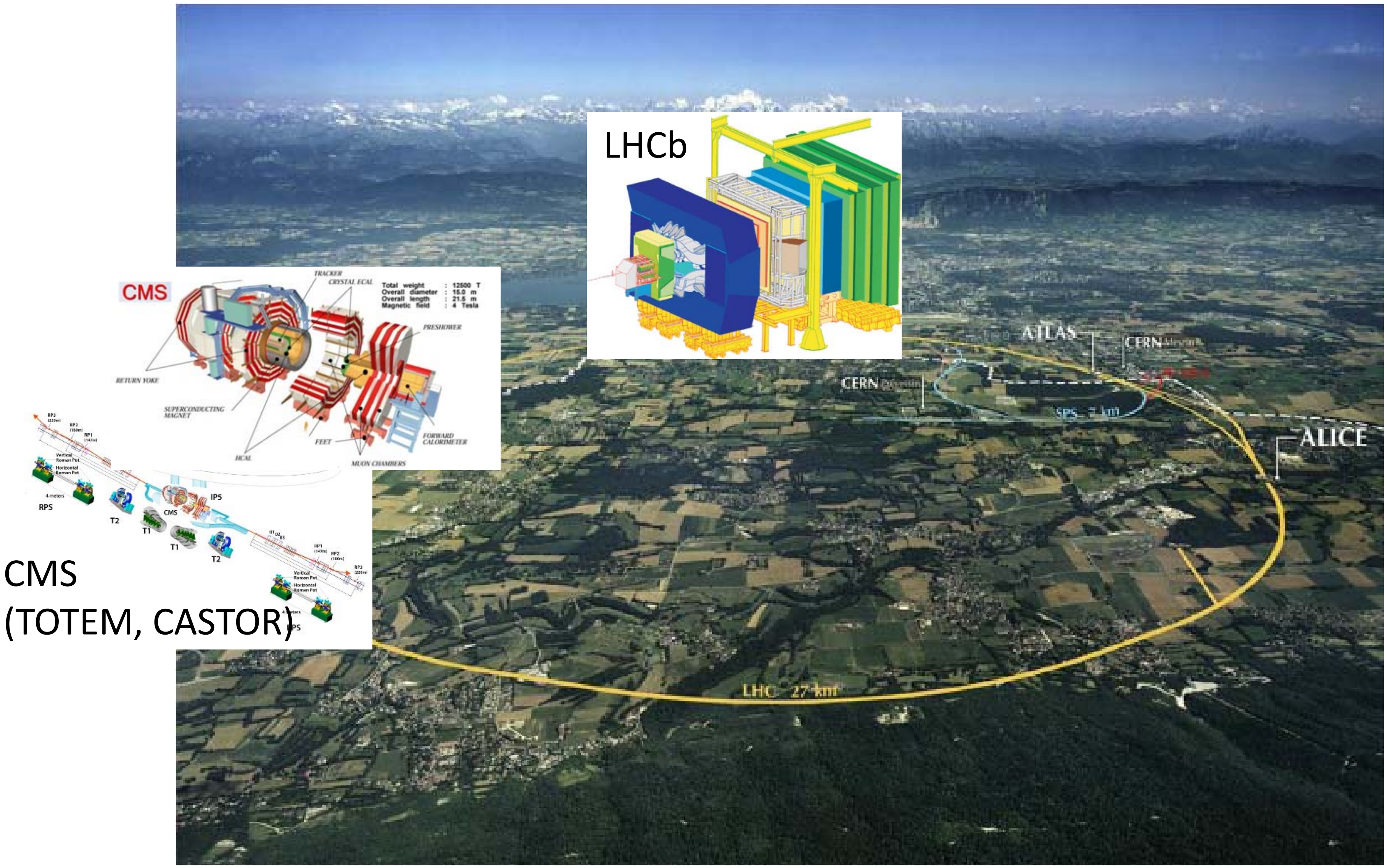
Forward Facilities/Upgrades at the LHC



CMS
(TOTEM, CASTOR)

see talk by Martin Rybar (Thursday)

Forward Facilities/Upgrades at the LHC



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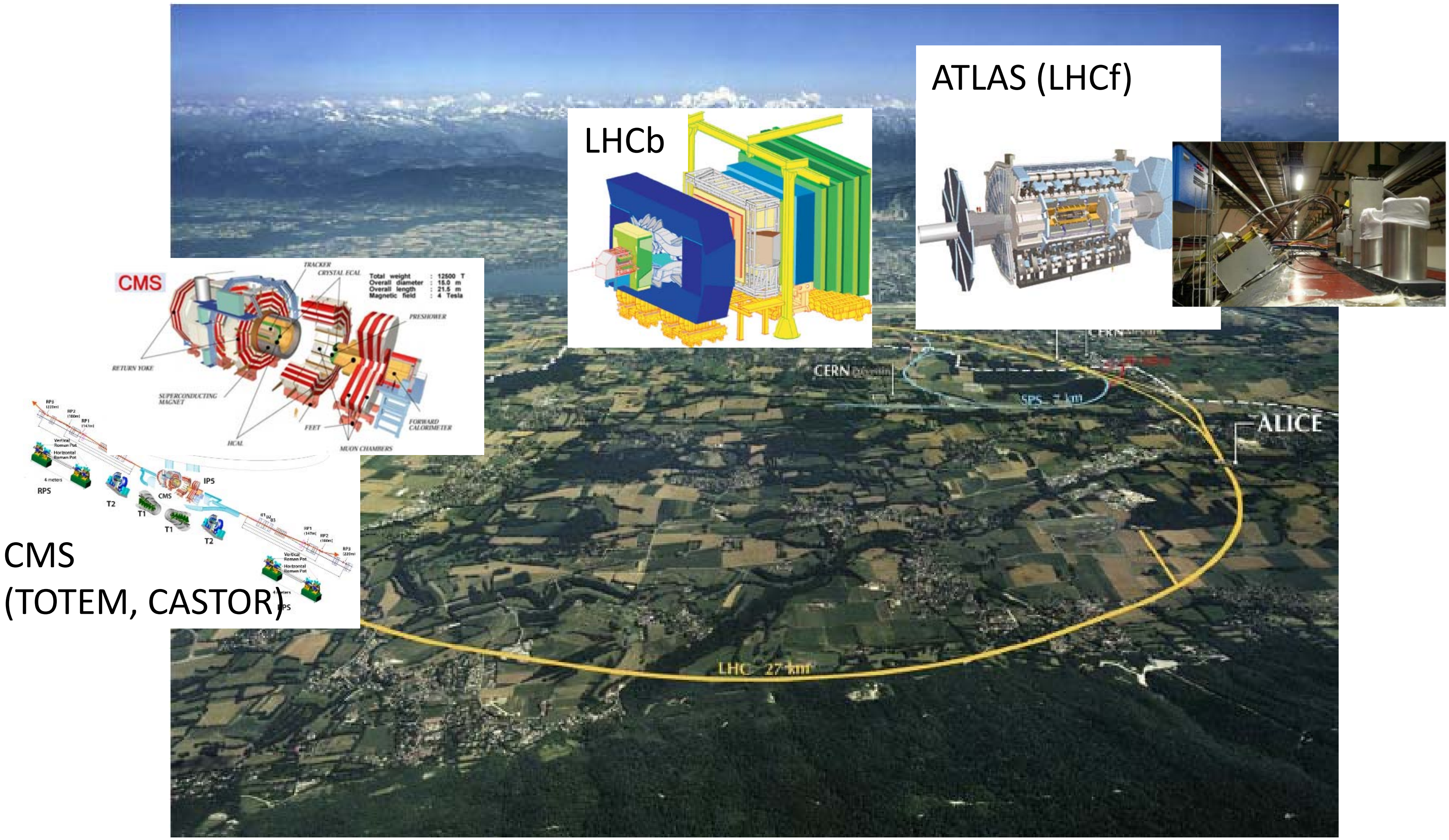

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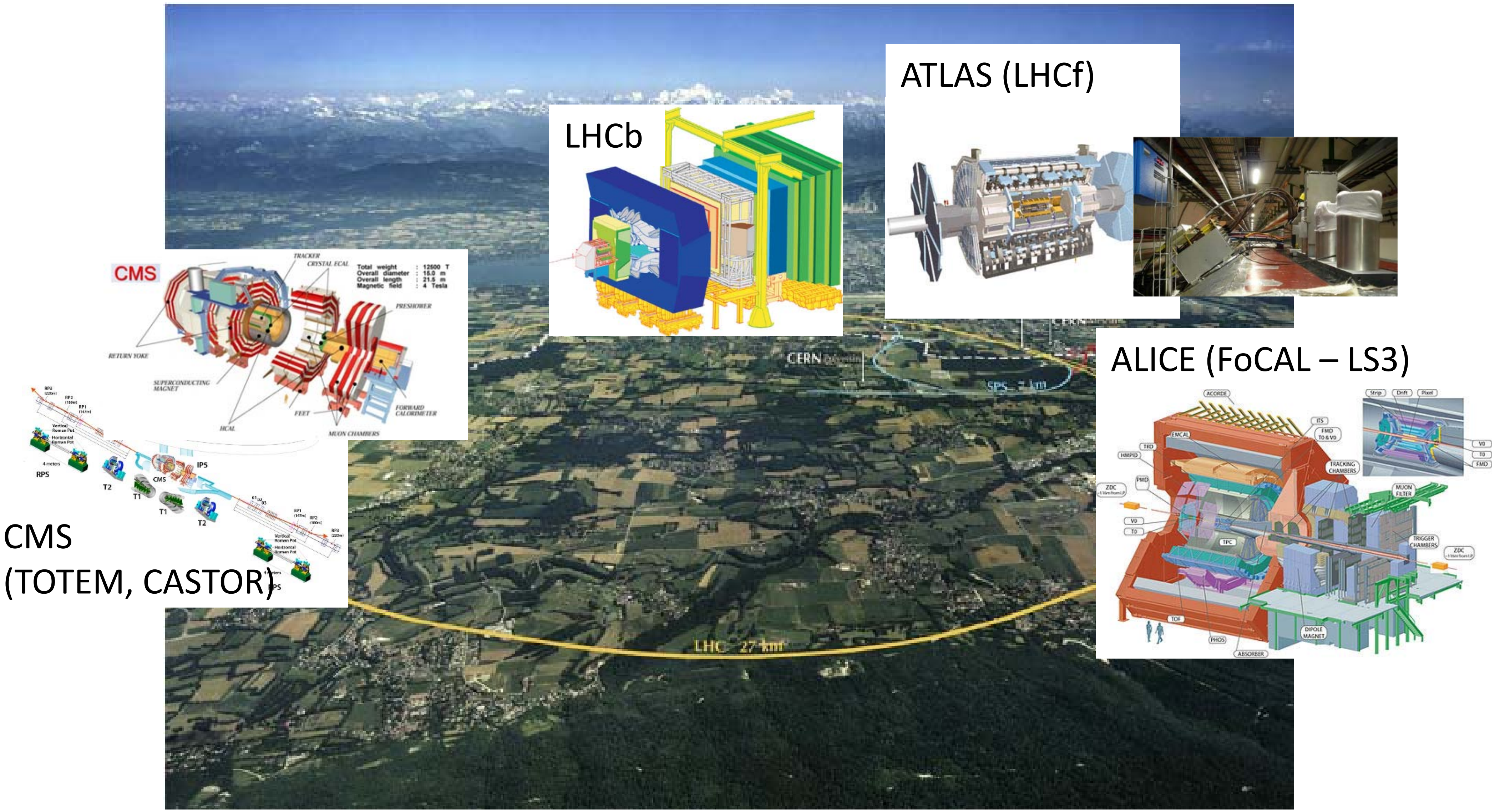

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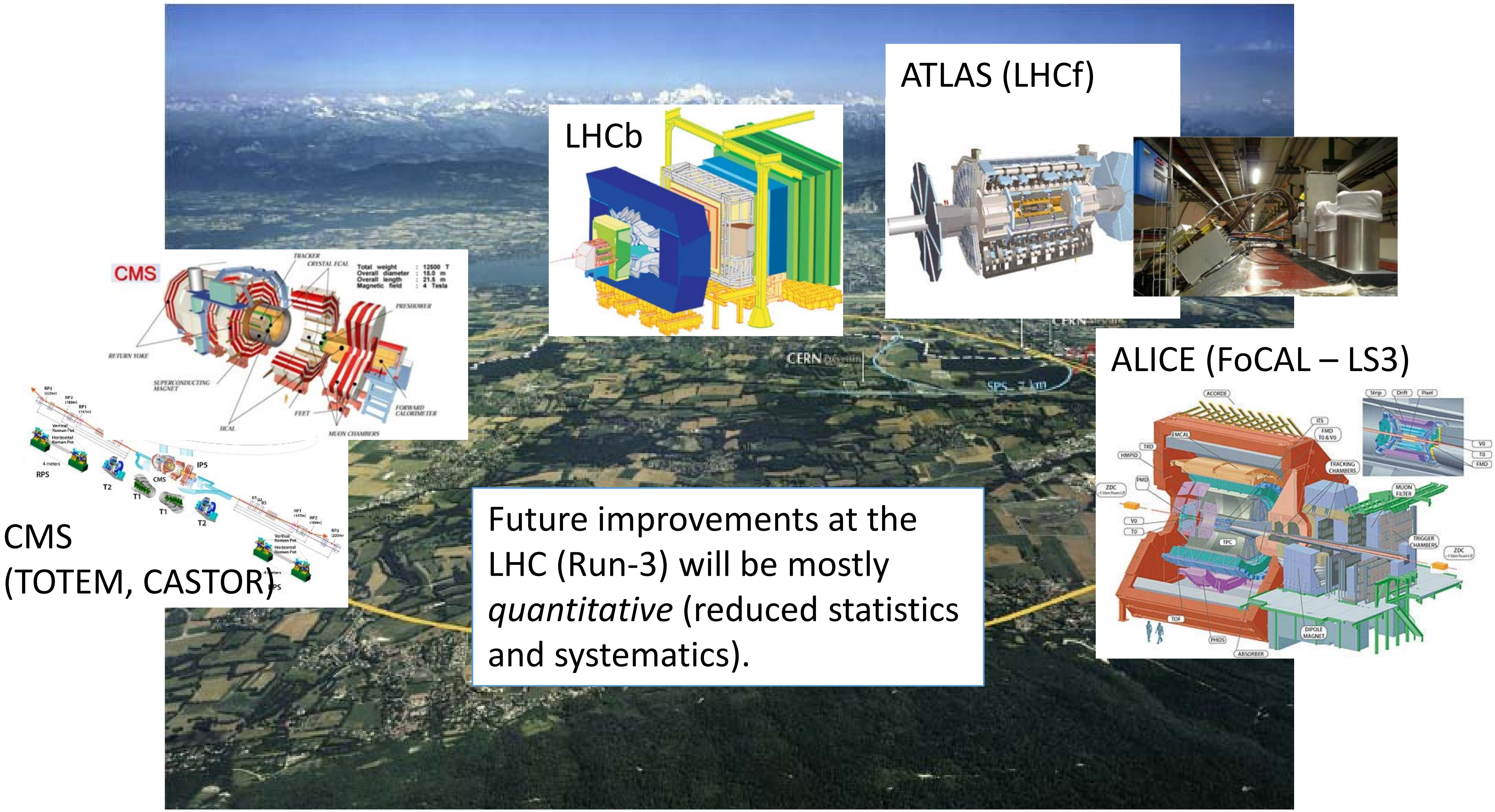
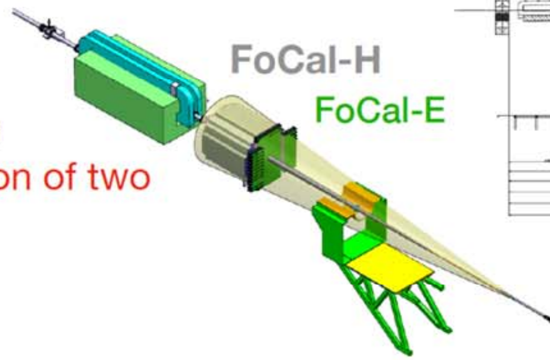


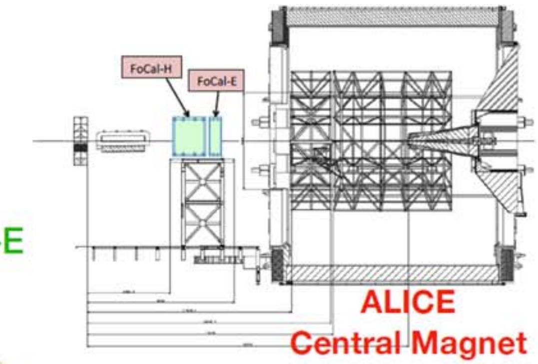
Future improvements at the LHC (Run-3) will be mostly *quantitative* (reduced statistics and systematics).

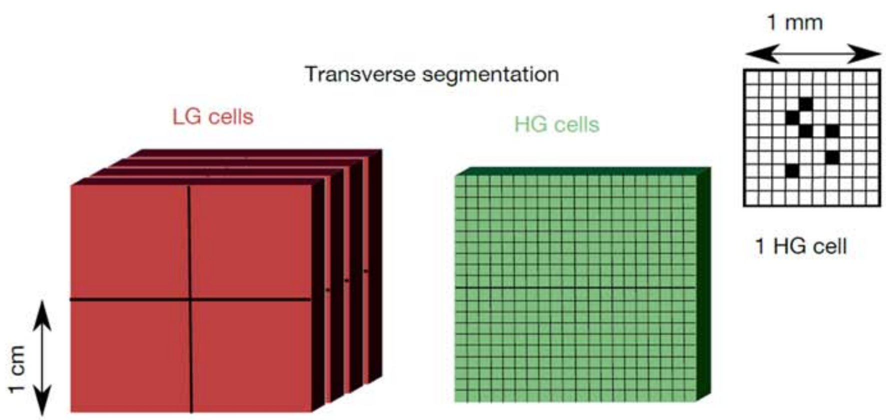
see talk by Martin Rybar (Thursday)

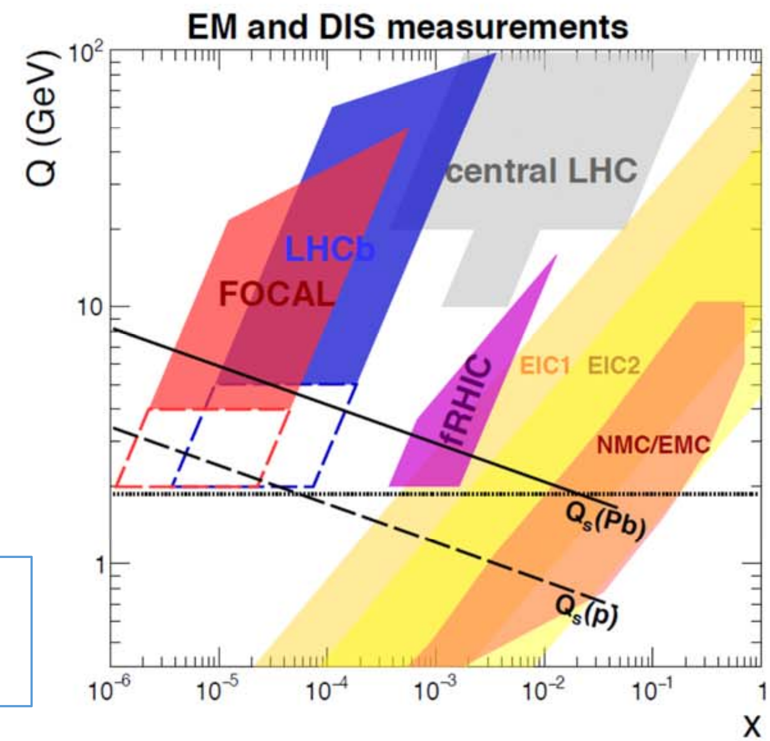
ALICE FoCAL

FoCal Proposal:
- 7 m from the interaction point
  - covering $3.3 < \eta < 5.8$
- FoCal-E - electromagnetic part:
  - **direct-γ and π^0** measurement
  - Main challenge is the separation of two clusters at high energy
- FoCal-H - hadronic calorimeter:
  - Jet measurement
  - Isolation cut





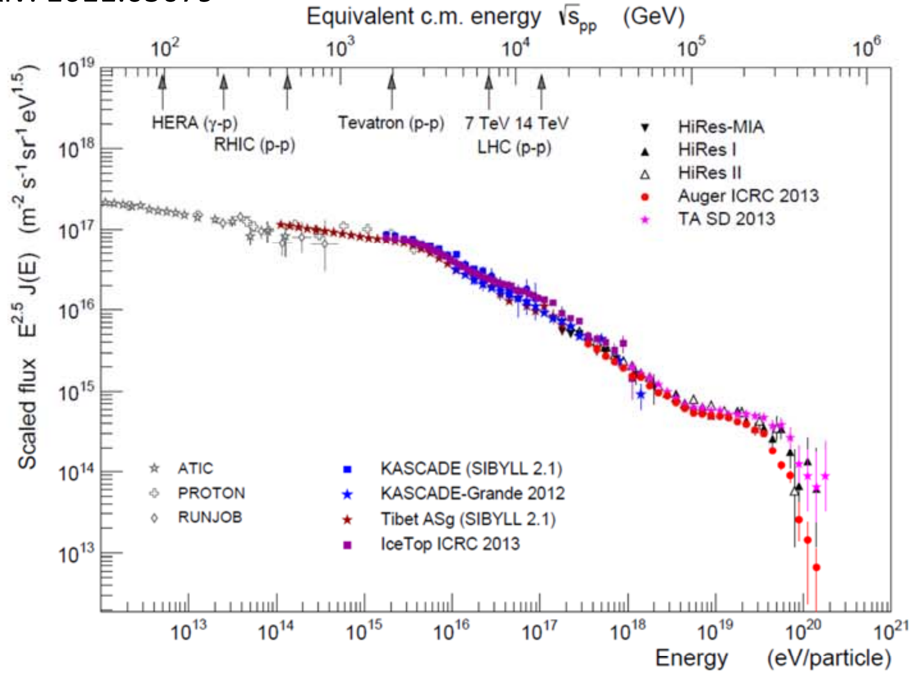


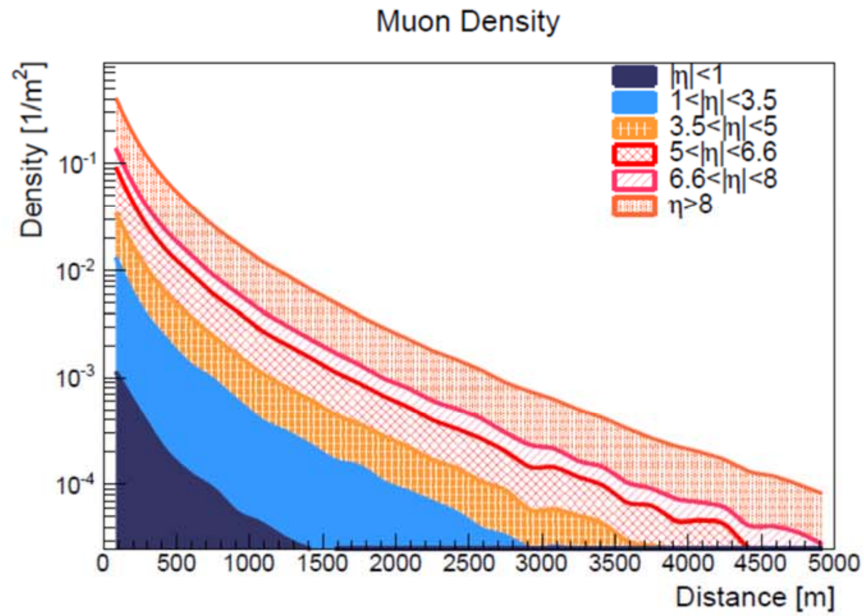


Decision later this year – Installation during LS3 (2024-26) for use in LHC Run-4.

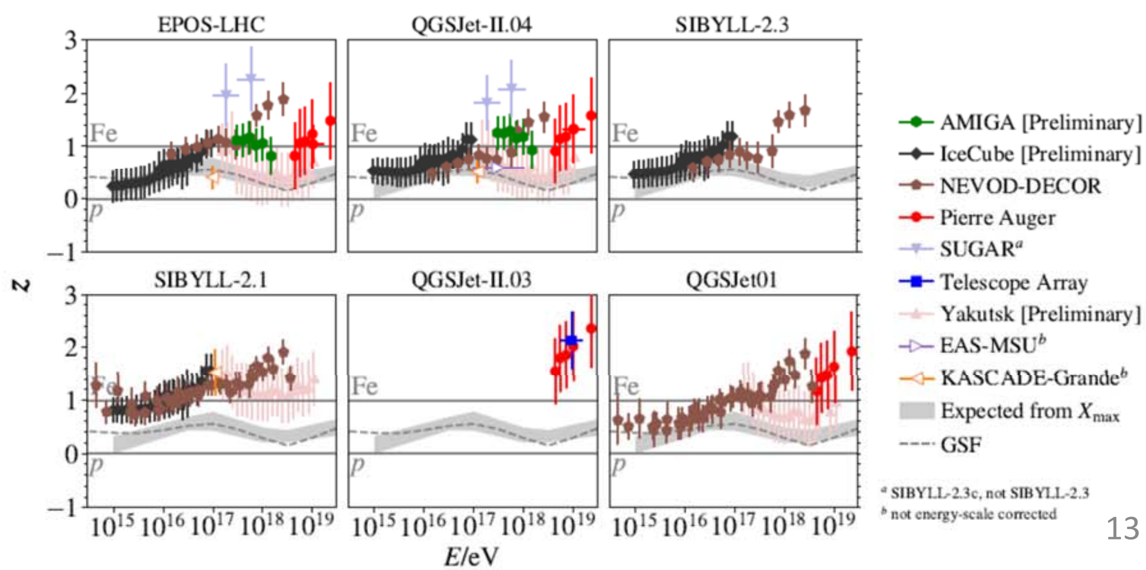
Cosmic Ray Physics

arXiv: 1611.05079





arXiv: 1902.08124

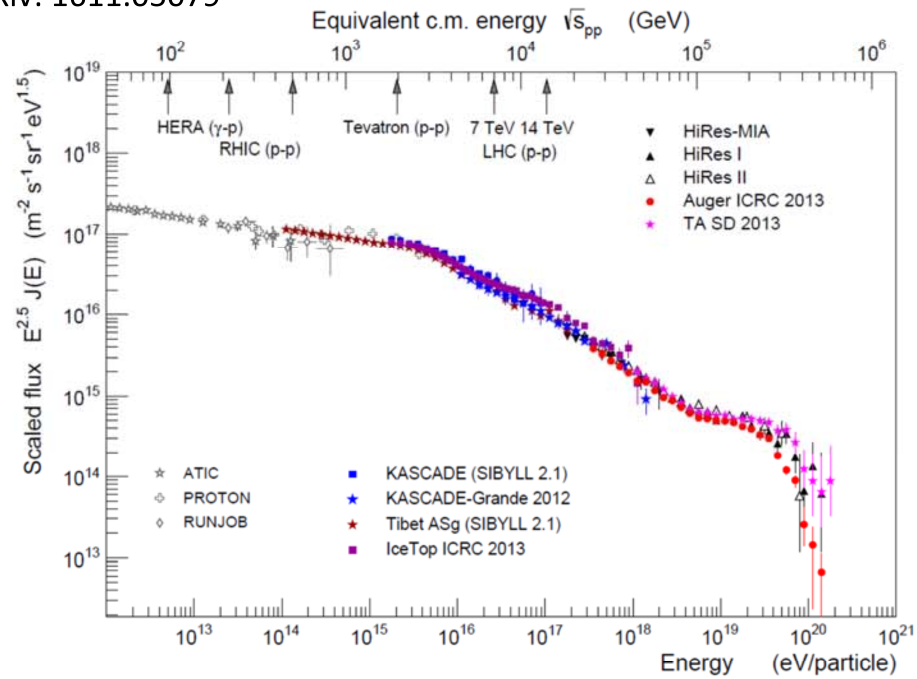


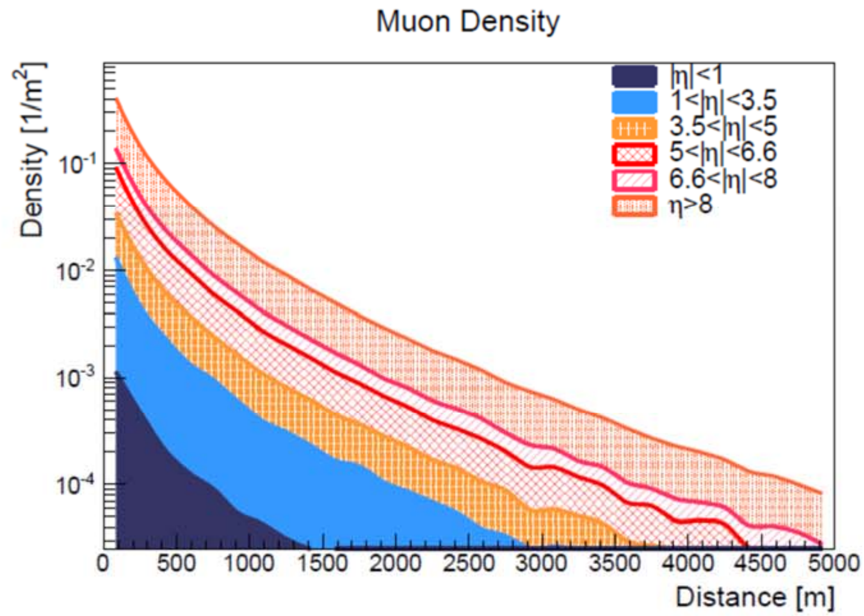
Excess of muons and muon "bundles" at highest cosmic ray energies

see also talk by Pasquale Di Nezza (Wednesday, LHC p+He antiprotons)

Cosmic Ray Physics

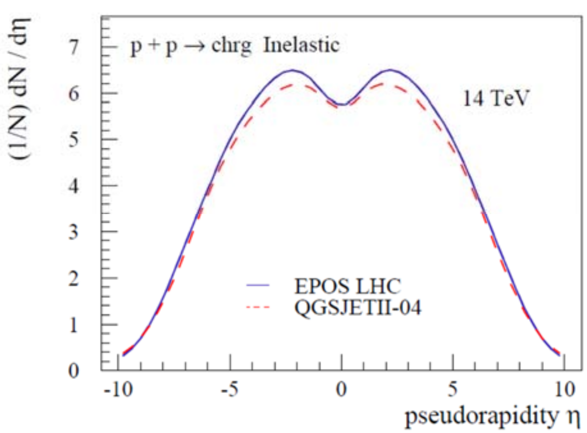
arXiv: 1611.05079

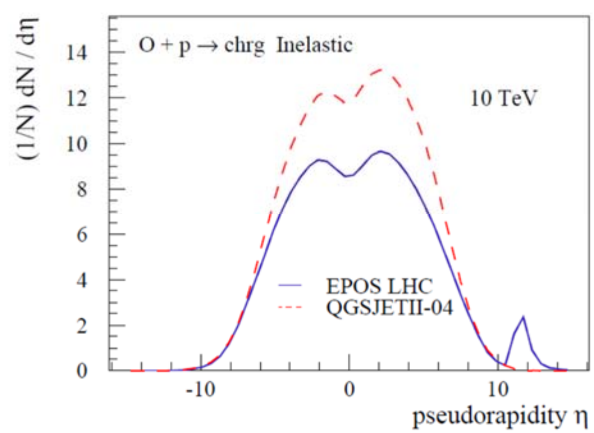


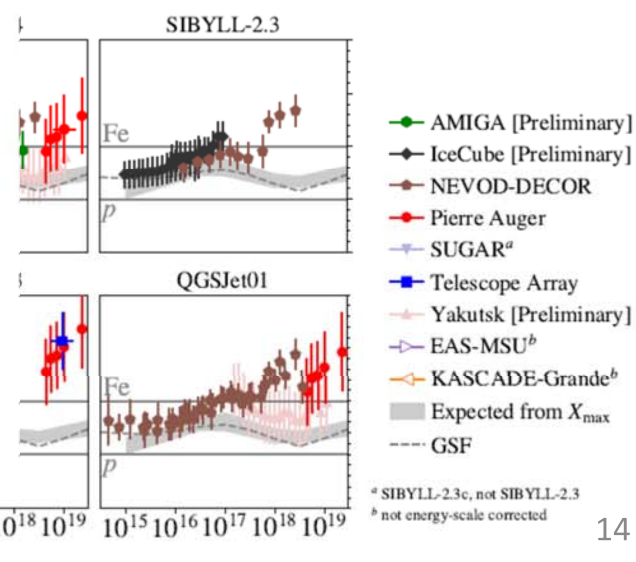


Strong need for p+O collisions to further constrain models for cosmic ray air showers!

arXiv: 1902.08124







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LHC p+He antiprotons)

Forward Facilties/Upgrades at RHIC

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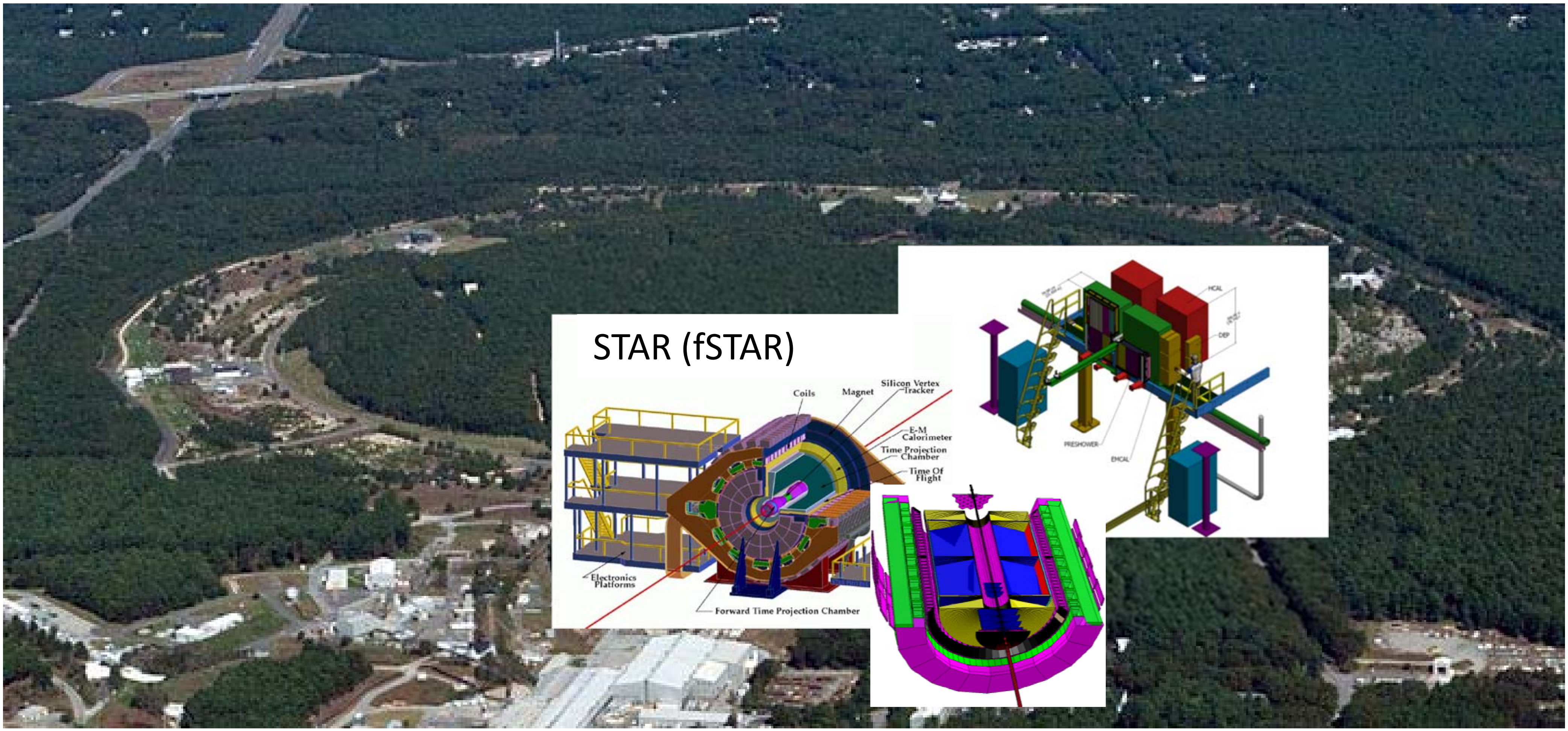

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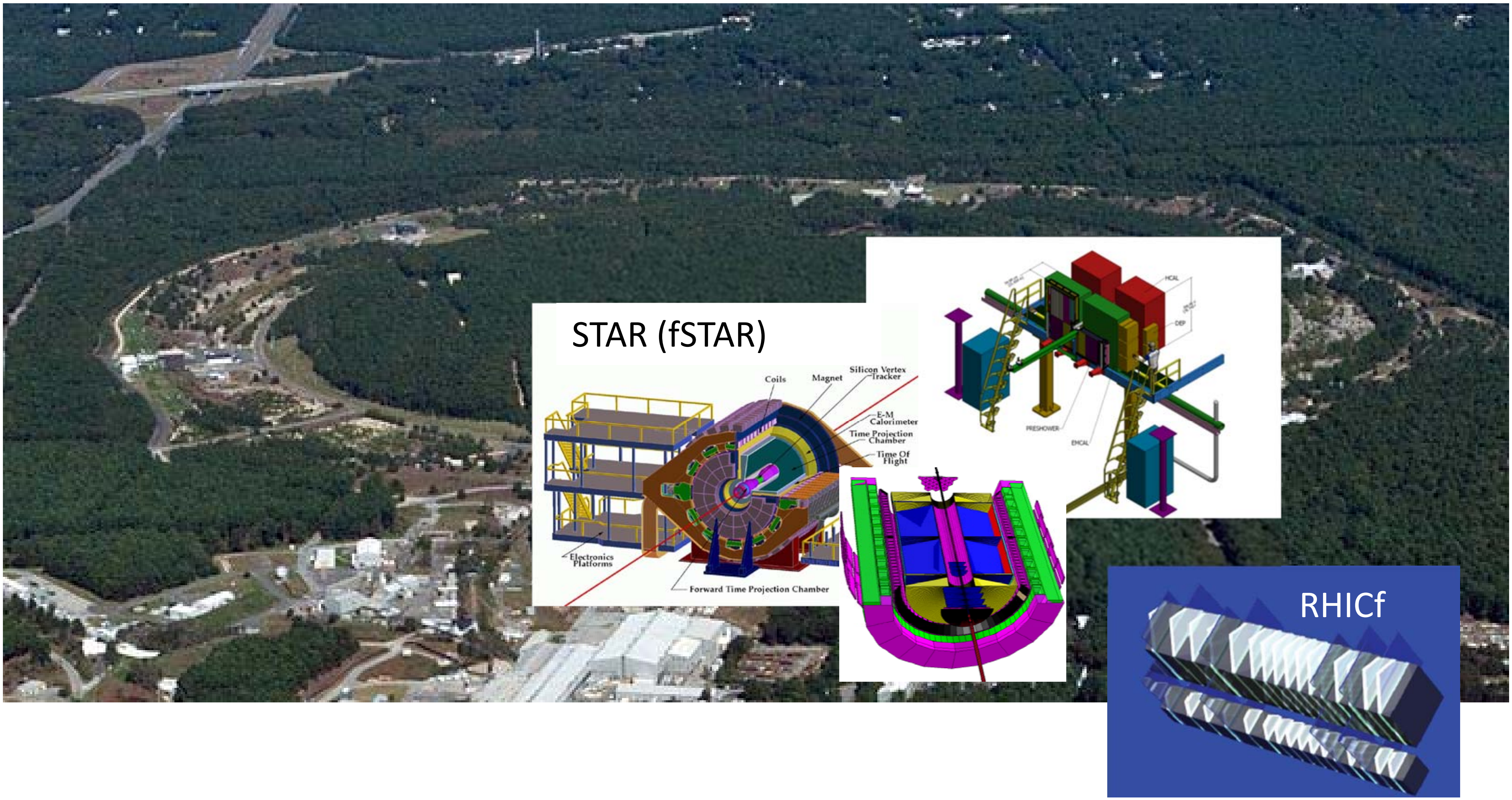

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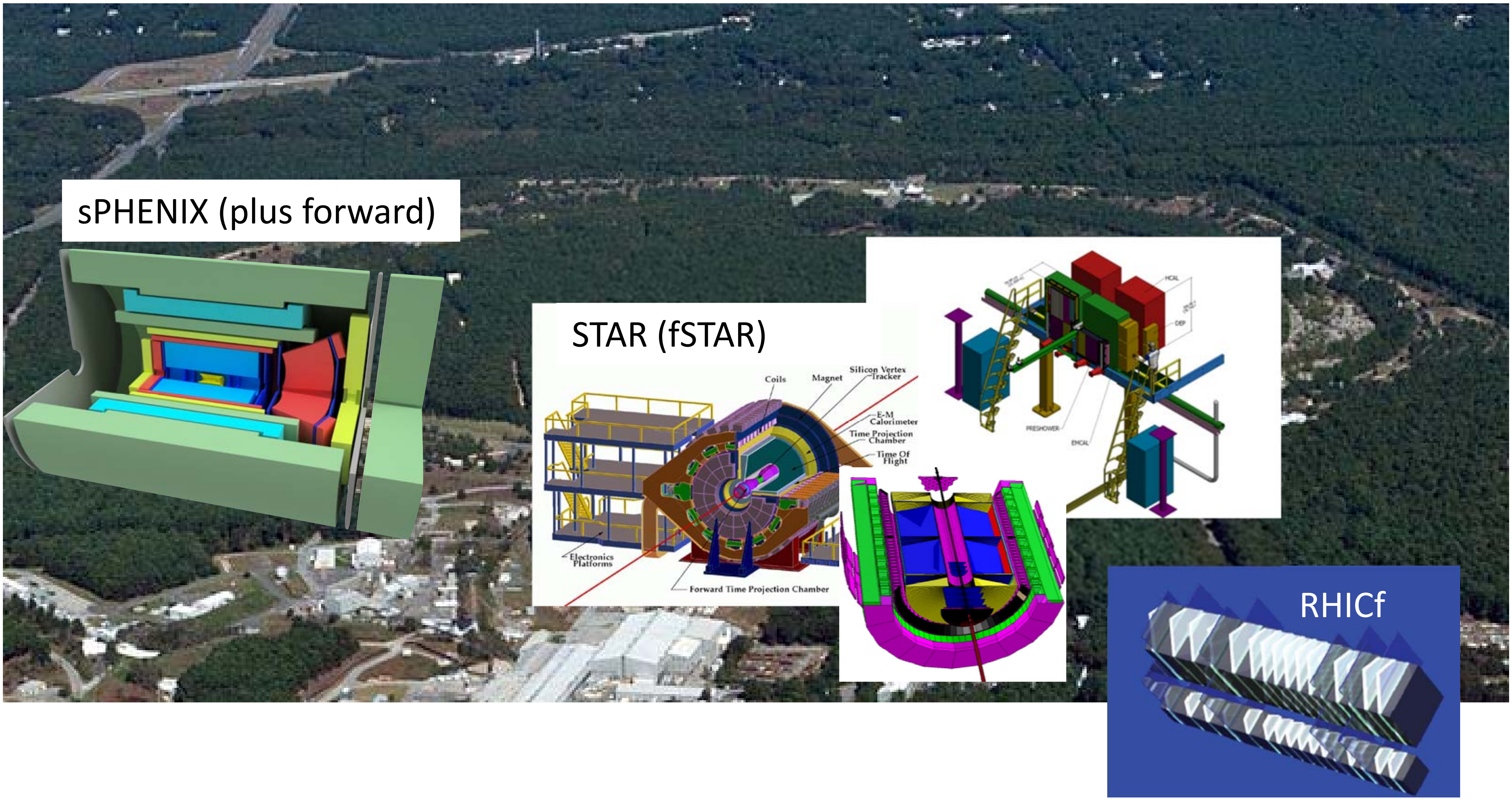


STAR Forward Implementation

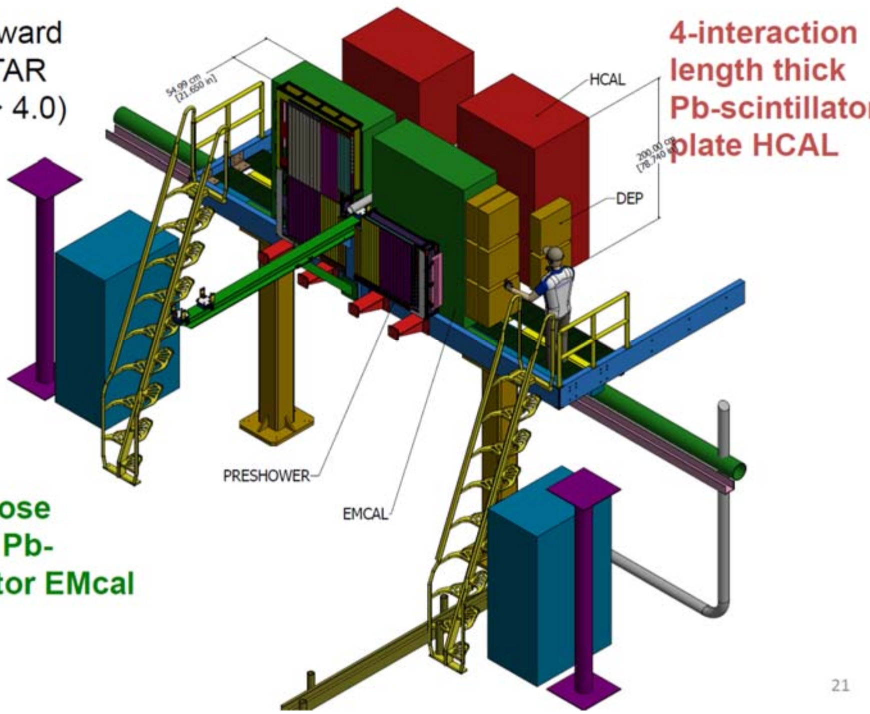
see talk by Daniel Brandenburg (Wednesday)

3 Silicon disks: at 90, 140, 187 cm from IP
Built on successful experience with STAR IST
- Single-sided double-metal mini-strip sensors
  - Granularity: fine in ϕ and coarse in R

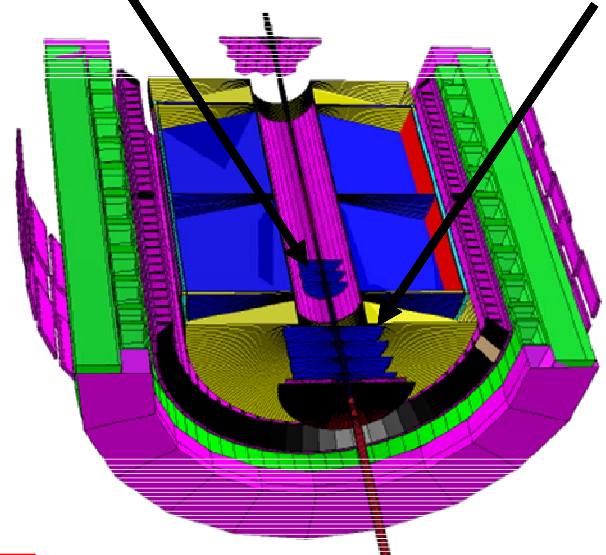
4 sTGC disks: at 270, 300, 330, 360 cm from IP (outside Magnet)
- Position resolution: ~100 μm
- Material budget: ~0.5% per layer, 2 layers / disk
- Readout: reuse current STAR TPC electronics
- 1st sTGC prototype to be installed in STAR in 2019

Install in forward region at STAR (2.3 > eta > 4.0)

4-interaction length thick Pb-scintillator plate HCAL



Re-purpose PHENIX Pb-scintillator EMcal



Substantial re-use of existing equipment and infrastructure. Extensive R&D program underway, leverages STAR and EIC detector R&D.

Momentum resolution: 20-30%
for $0.2 < p_T < 2$ GeV/c
track finding efficiency: 80%@100 tr/ev

STAR Forward Implementation

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3 Silicon disks: at 90, 140, 187 cm from IP
Built on successful experience with STAR IST

Status of fSTAR

A five-member review panel (S. Boose, C. Miraval, G. van Nieuwenhuizen, A. Tricoli, and chaired by G. Young) conducted a review of the resource requirements for the proposed forward upgrades to the STAR detector on November 19, 2018. The panel noted good progress on the proposed concept for a cold-QCD experiment to run in late 2021 at RHIC, with plausible plans for funding and conservative designs for all detector components, electronics, and support infrastructure. The panel opined that the major project risks are identified and that the experiment appears positioned to be ready for first operation in 2021, with the caveat that the critical path, which is the silicon detector, presently has very little float. BNL management has begun discussions with ONP about the implementation of the proposed upgrade.

from ECA, BNL 2019 PAC presentation

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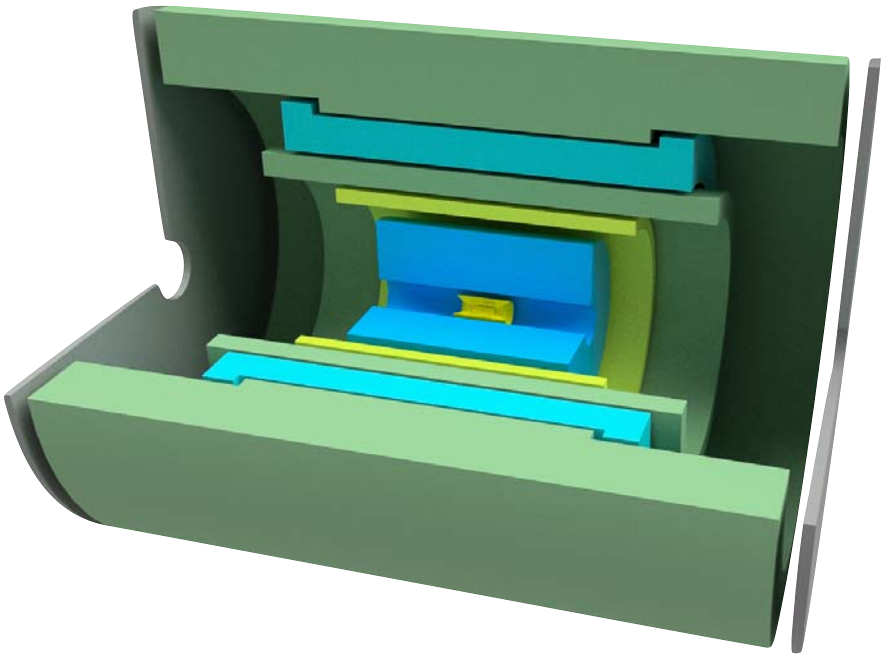
June 2019 : NSF indicates they will fund the HCAL NSF MRI.

from ECA, BNL 2019 PAC presentation

sPHENIX Forward Implementation

A next-generation state-of-the-art jet detector for A+A physics at RHIC. Successful PD-2/3b review!

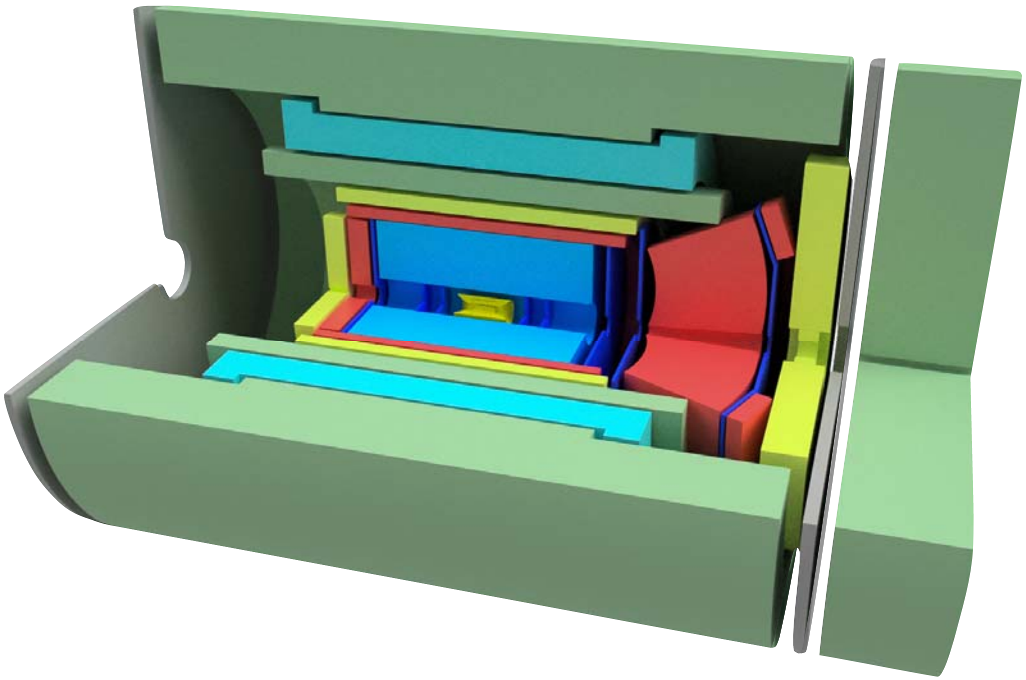


- sPHENIX
  - HCal/Flux return
  - Solenoid
  - Central EMCal
  - Silicon strip tracking
  - TPC
  - MAPS

see talk by Rosi Reed (Wednesday)

sPHENIX Forward Implementation

A solid foundation for EIC physics!!
https://www.sphenix.bnl.gov/web/system/files/eic-sphenix-loi-draft-2018-09-14.pdf



- EIC-sPHENIX detector
  - HCal/Flux return
  - Solenoid
  - Extended Central EMCal
  - Central hadron PID
  - TPC
  - MAPS
  - Forward and backward tracking
  - Forward and backward hadron PID
  - Backward crystal EMCal
  - Forward EMCal
  - Forward HCal

see talk by Rosi Reed (Wednesday)

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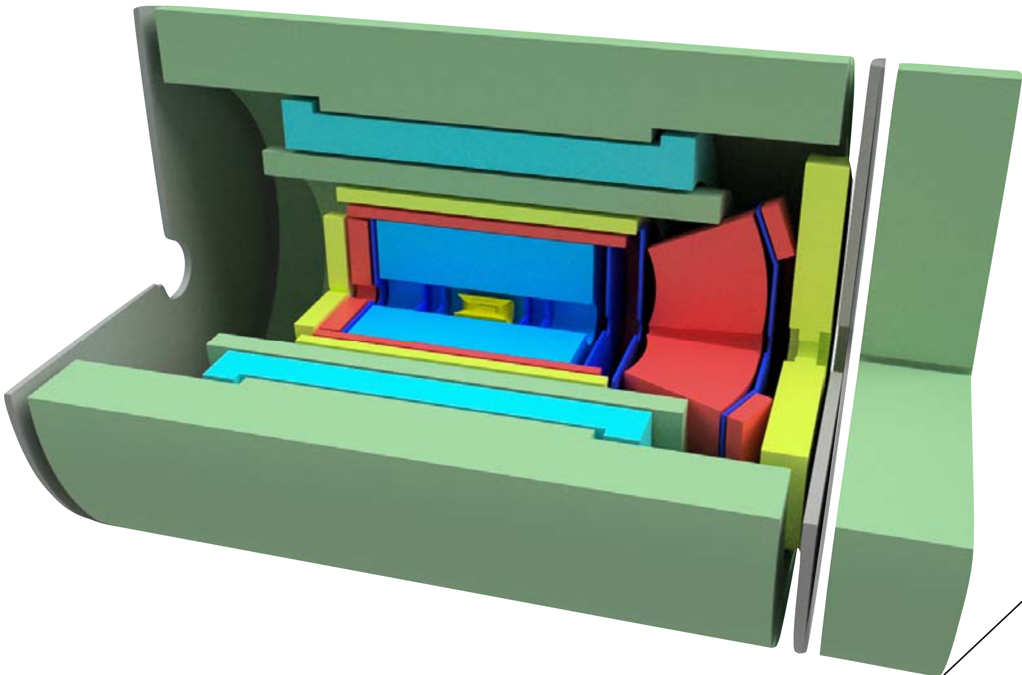

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Cold QCD program enabled by early realization of some EIC-sPHENIX detector components!

see talk by Rosi Reed (Wednesday)

RHIC Forward Hardware Development

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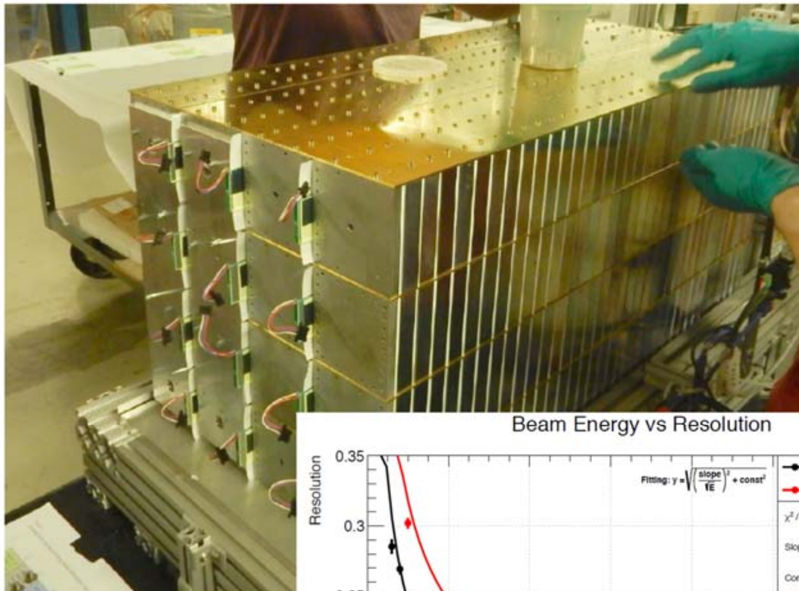
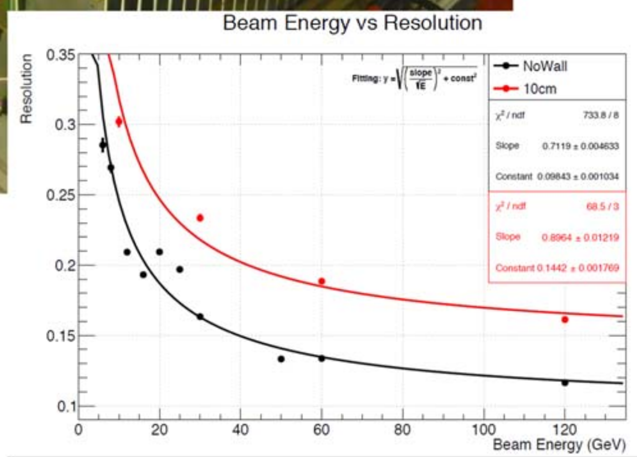
HCAL Prototypes (STAR and sPHENIX)





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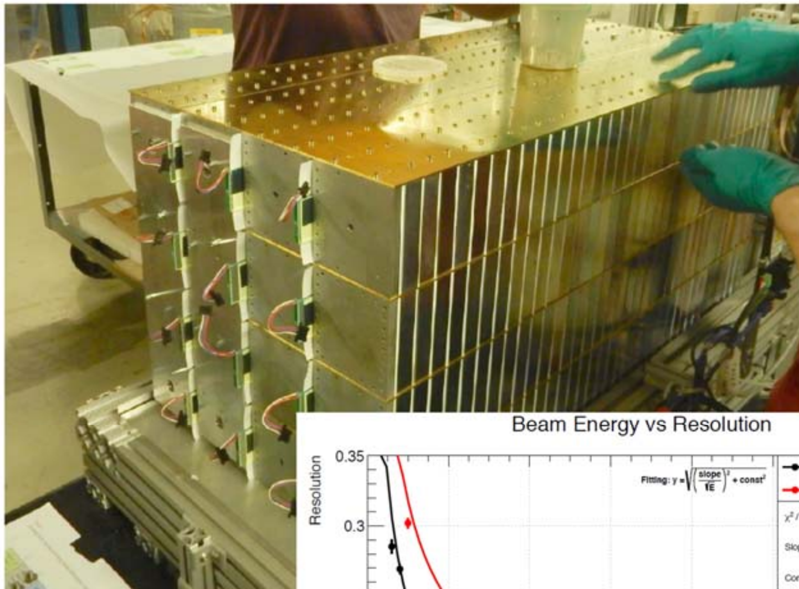
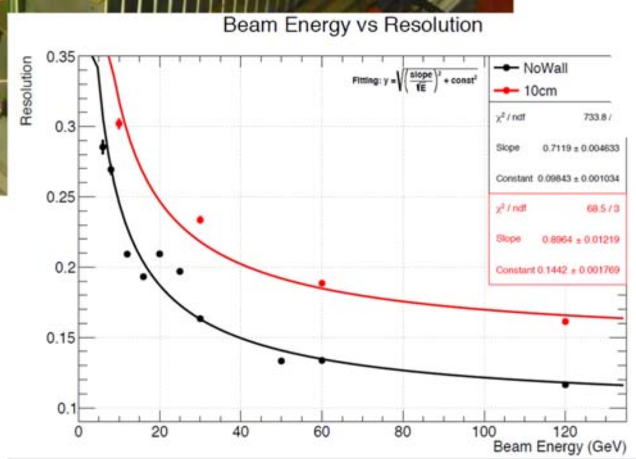
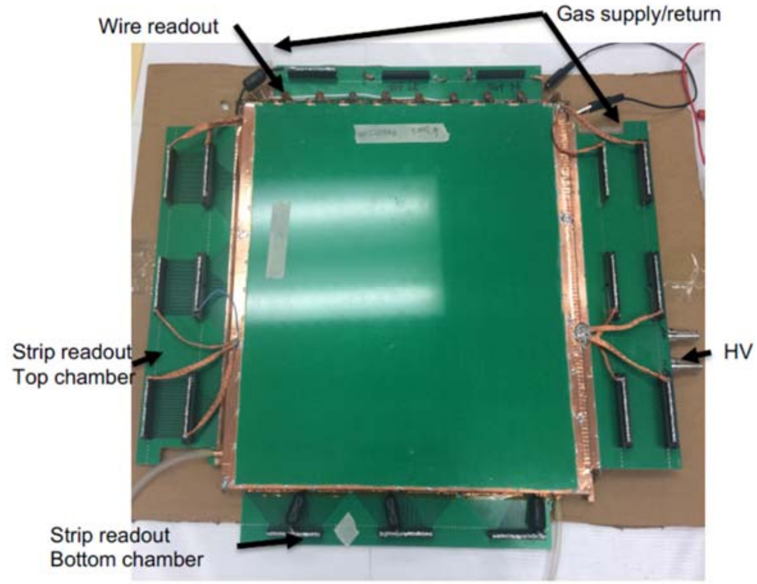




sTGC Development (SDU, China)



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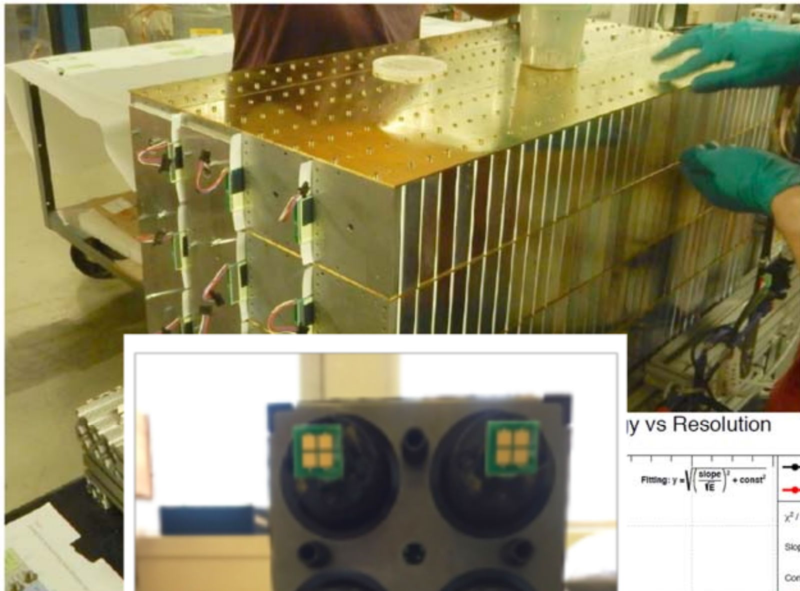

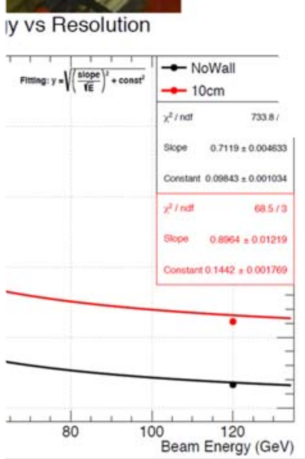

STAR fEMC Prototypes

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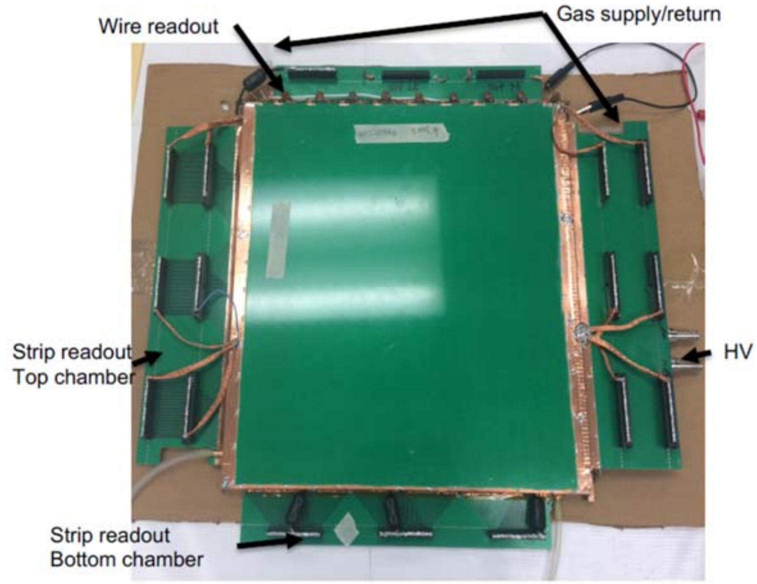

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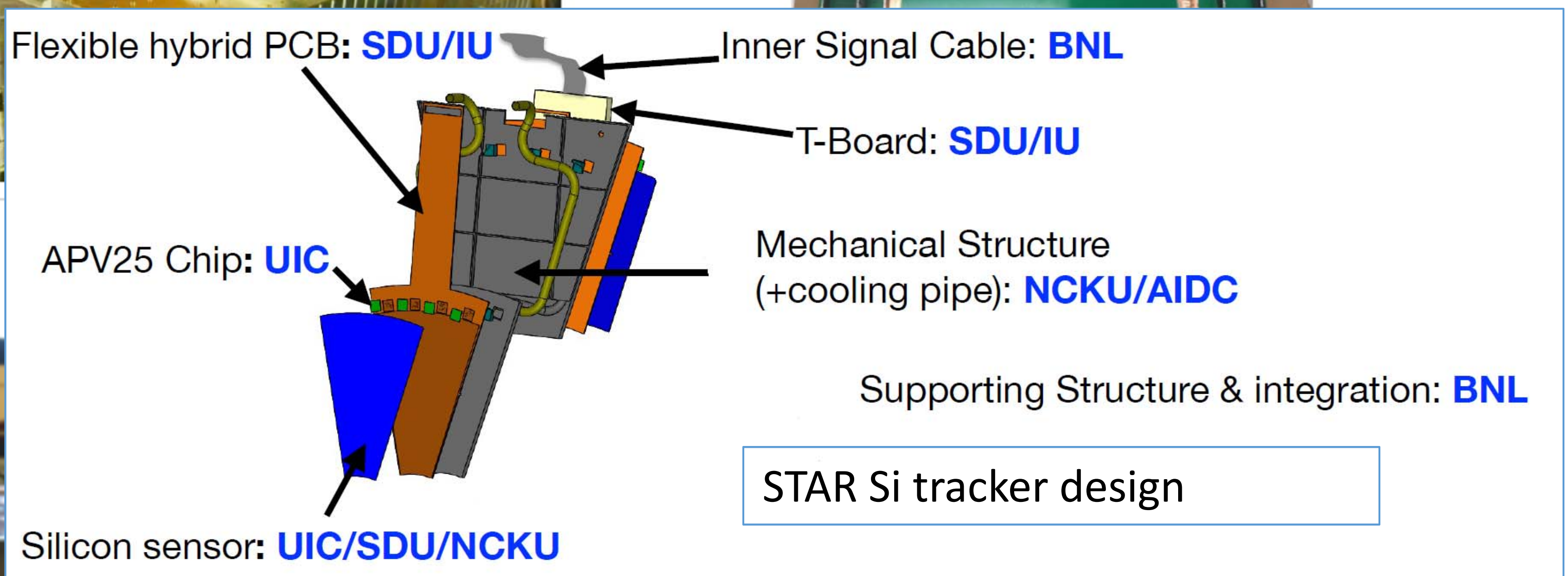
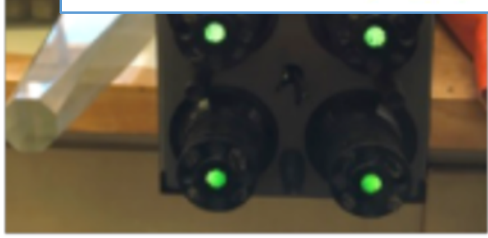
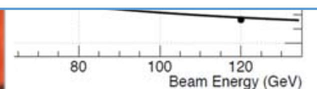


STAR Si tracker design





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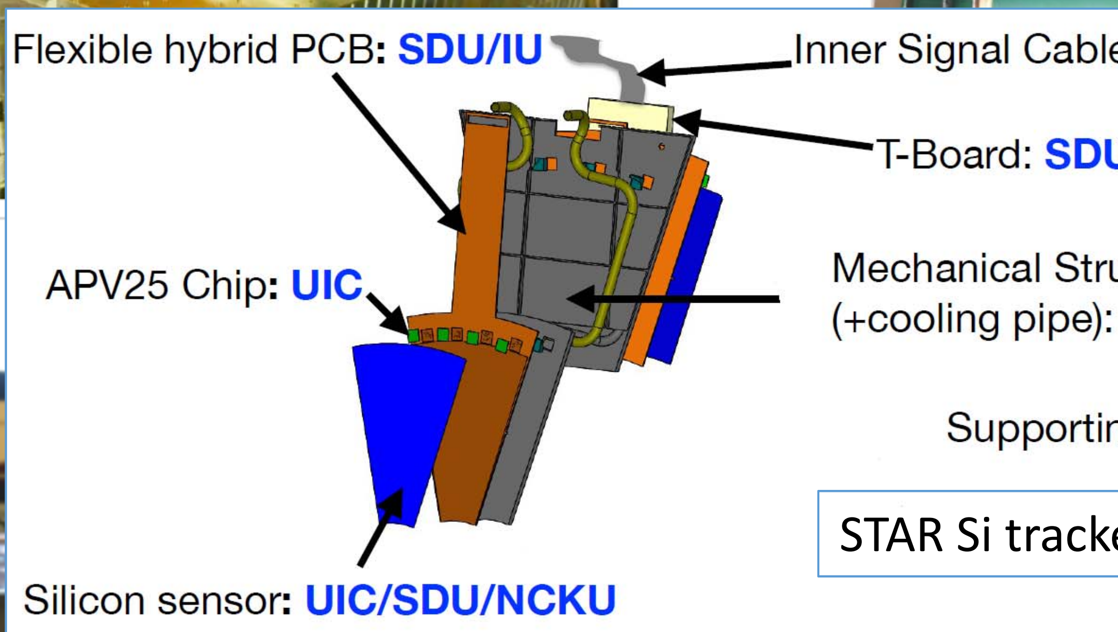
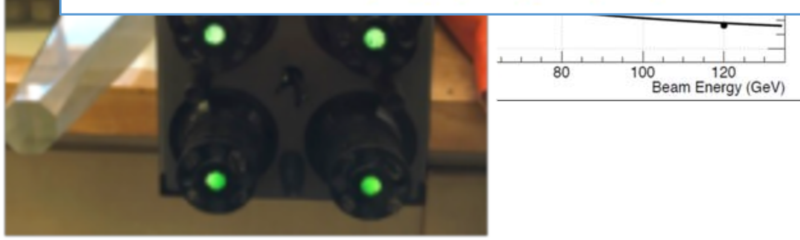
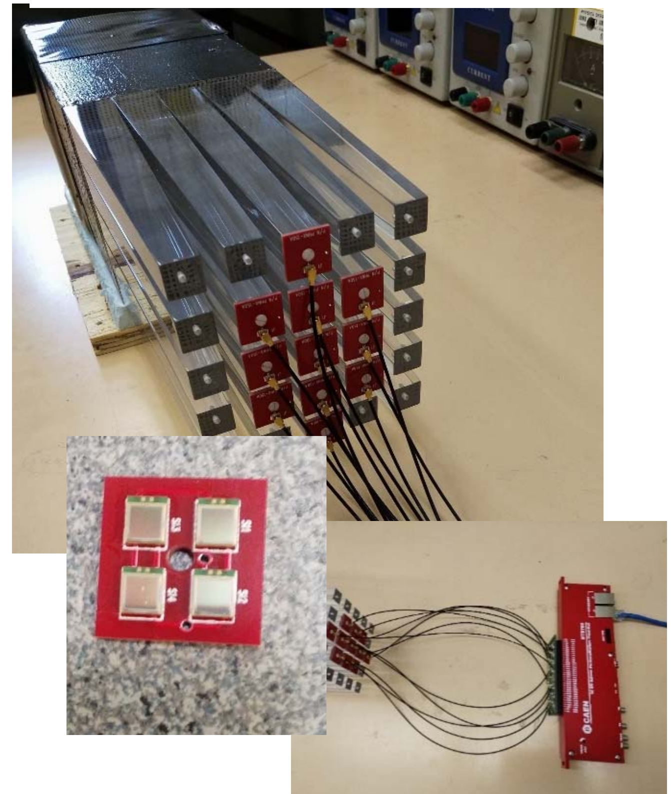




STAR fEMC Prototypes

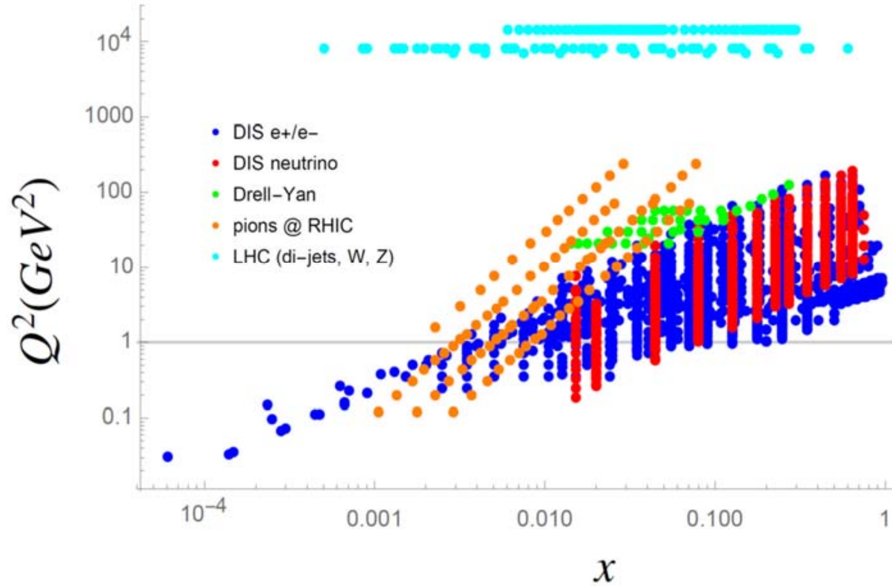
sPHENIX fEMC Prototype

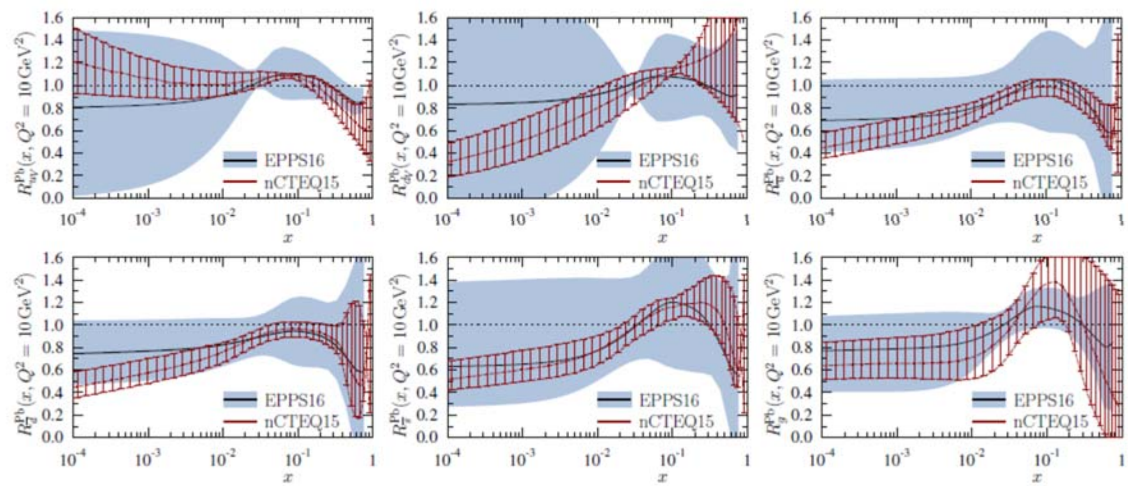


nPDF's

see talk by Maria Zurita (Monday)

- nPDF's are a phenomenological construct that encode information about the measured ratio of hard processes in p+A/p+p
  - Works in a collinear factorization framework (DGLAP)
  - Dependent on parametrization
  - Assumptions made about flavor symmetry, nuclear density/centrality dependence
  - Depend on what data is included
- They tell us nothing about the underlying microscopic mechanism
- Need a wide variety of data in x, Q^2, A, centrality…

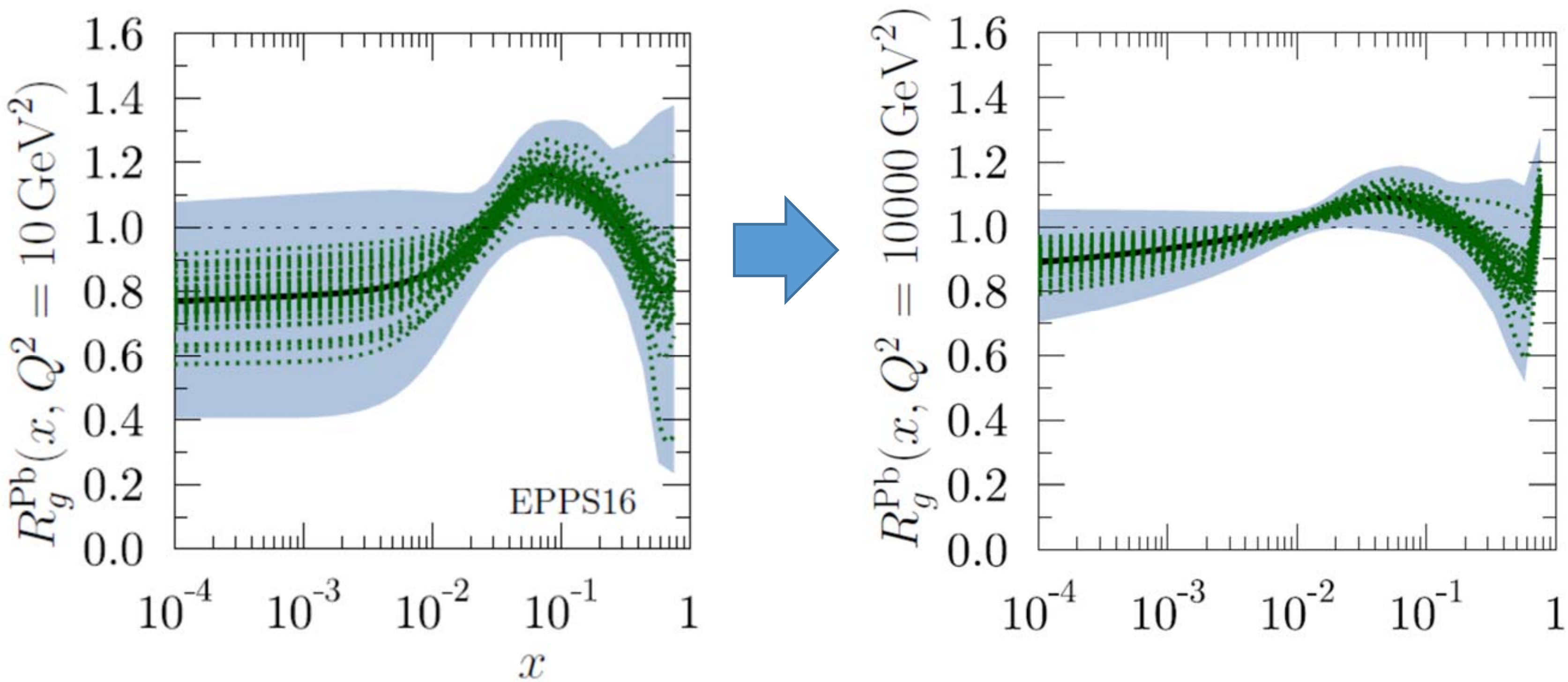




Eskola , Paukkunen, Paakkinen, and Salgado, Eur. Phys. J. C (2017) 77:136

nPDF's at the LHC

Eskola , Paukkunen, Paakkinen, and Salgado,
Eur. Phys. J. C (2017) 77:136



DGLAP evolution suppresses nPDF effects – but high statistics for clean probes!

Dijets, W/Z and photons assumed to be the "key" measurements at the LHC.

nPDF's – Lots of new LHC data!

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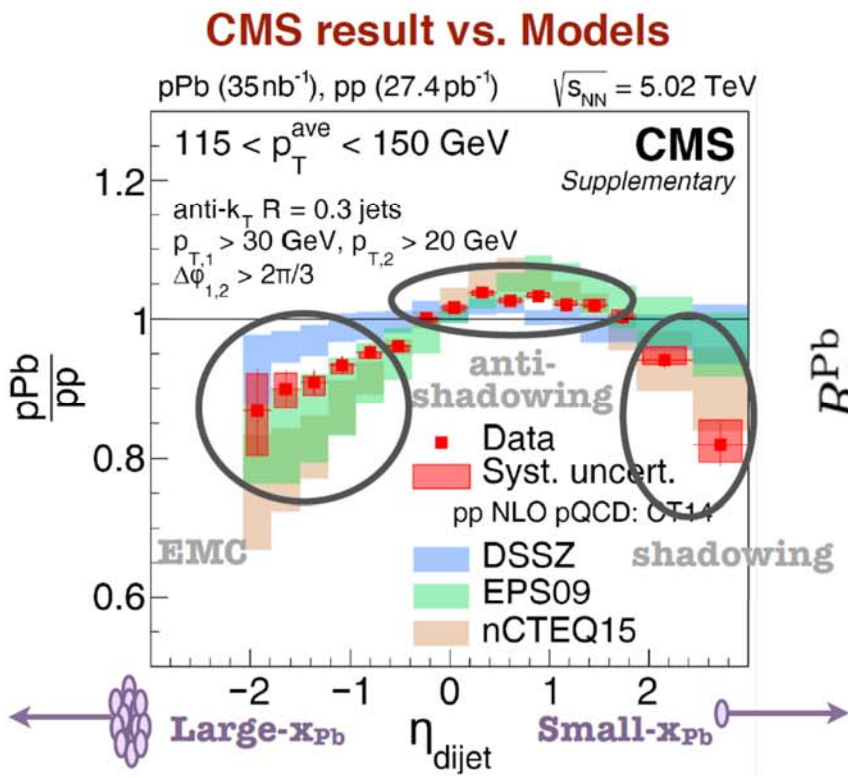
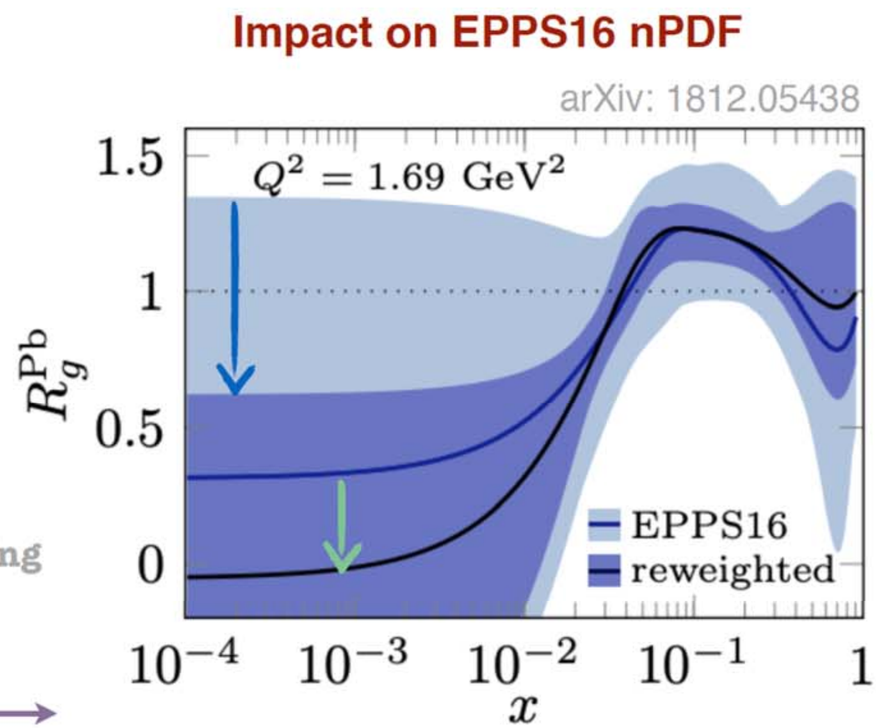
see talk by Jing Wang (Monday)





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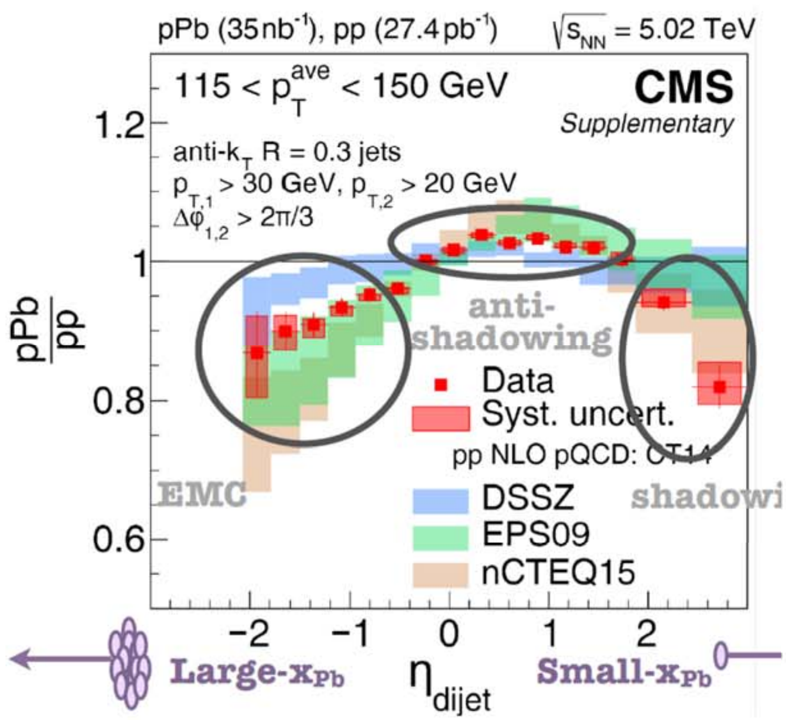
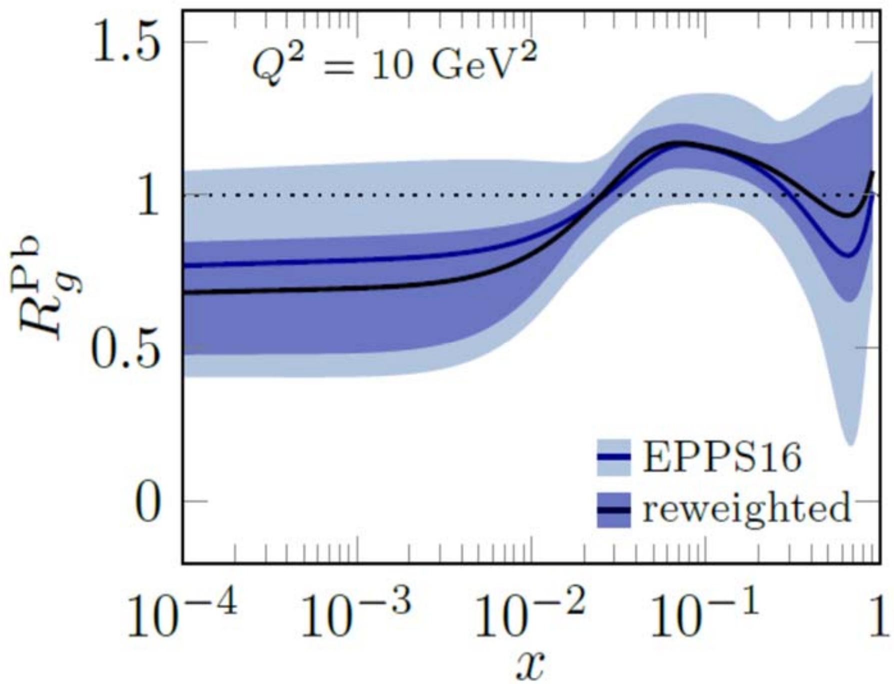


arXiv: 1812.05438



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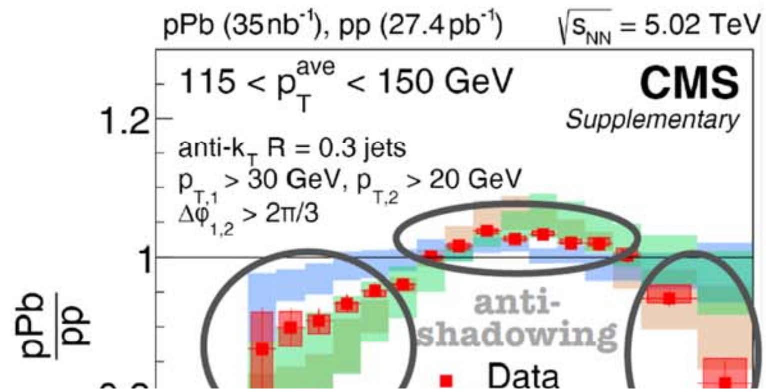
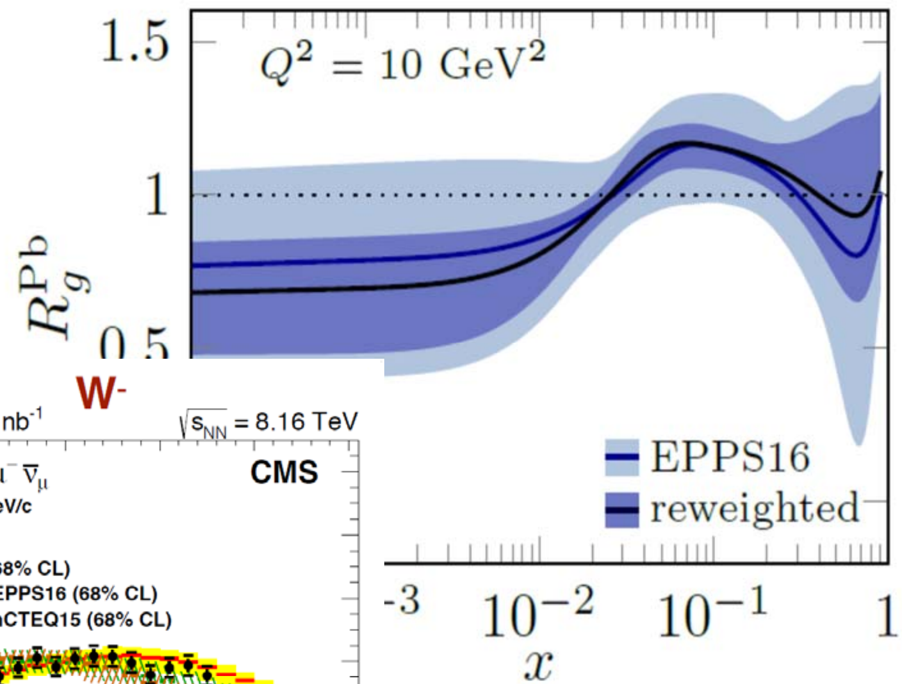
see talk by Jing Wang (Monday)

CMS result vs. Models

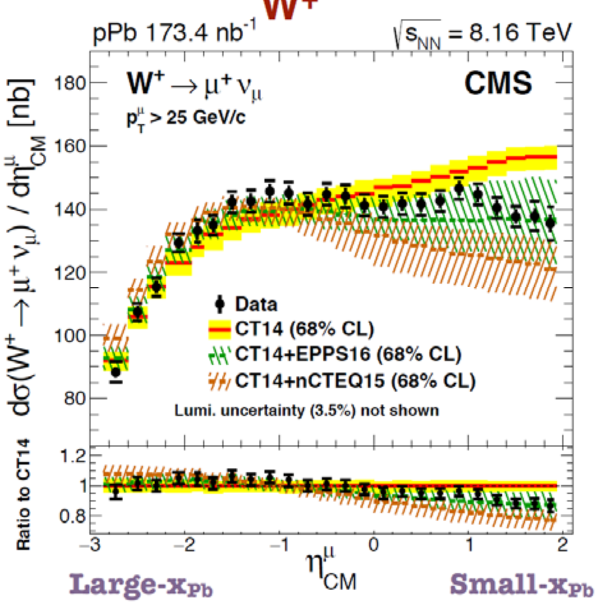


Impact on EPPS16 nPDF

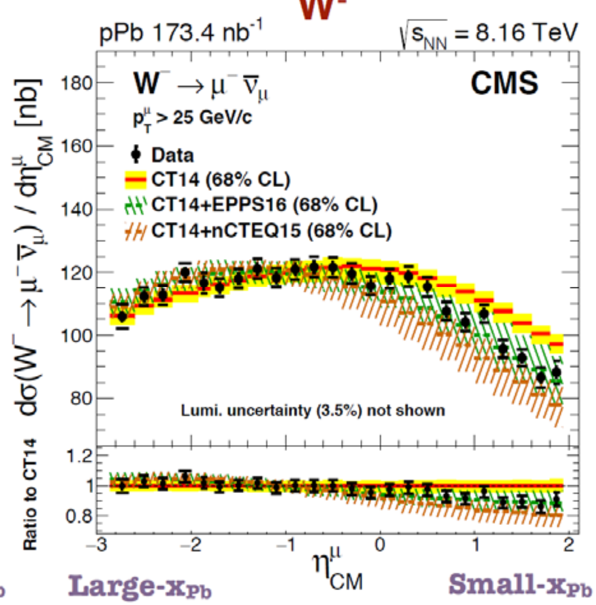
arXiv: 1812.05438



W+



W-



see talk by Jing Wang (Monday)

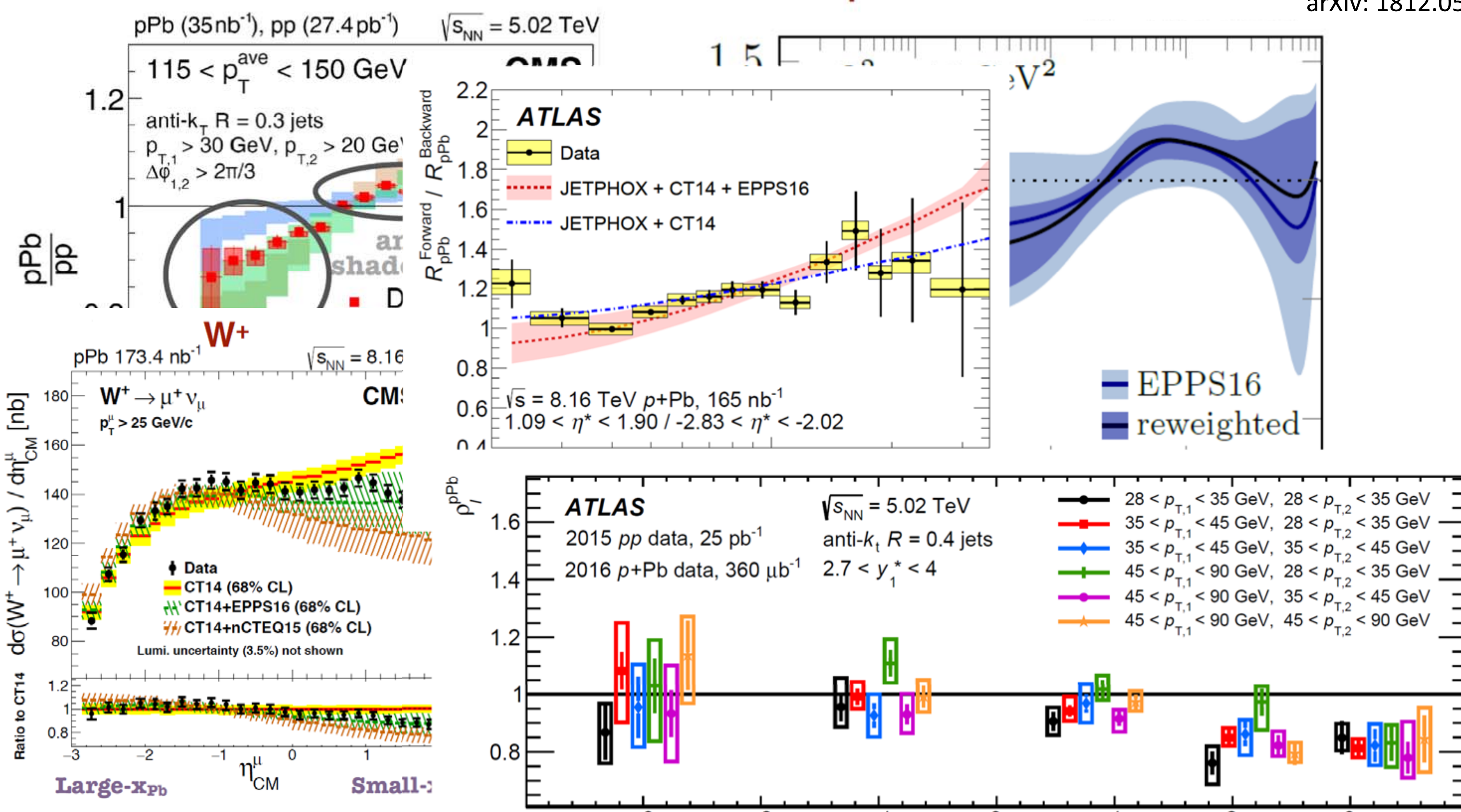
nPDF’s – Lots of new LHC data!

see talk by Jing Wang (Monday)

CMS result vs. Models

Impact on EPPS16 nPDF

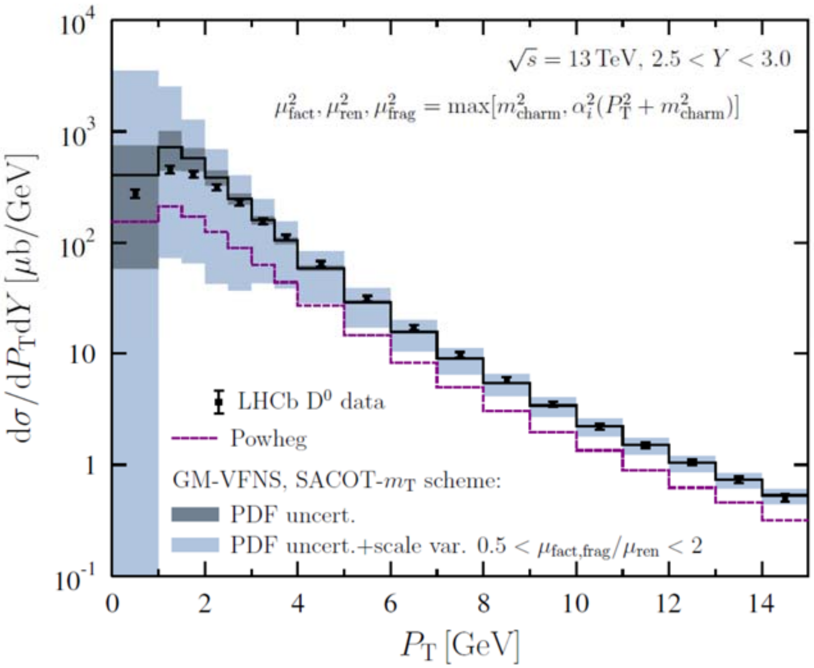
arXiv: 1812.05438



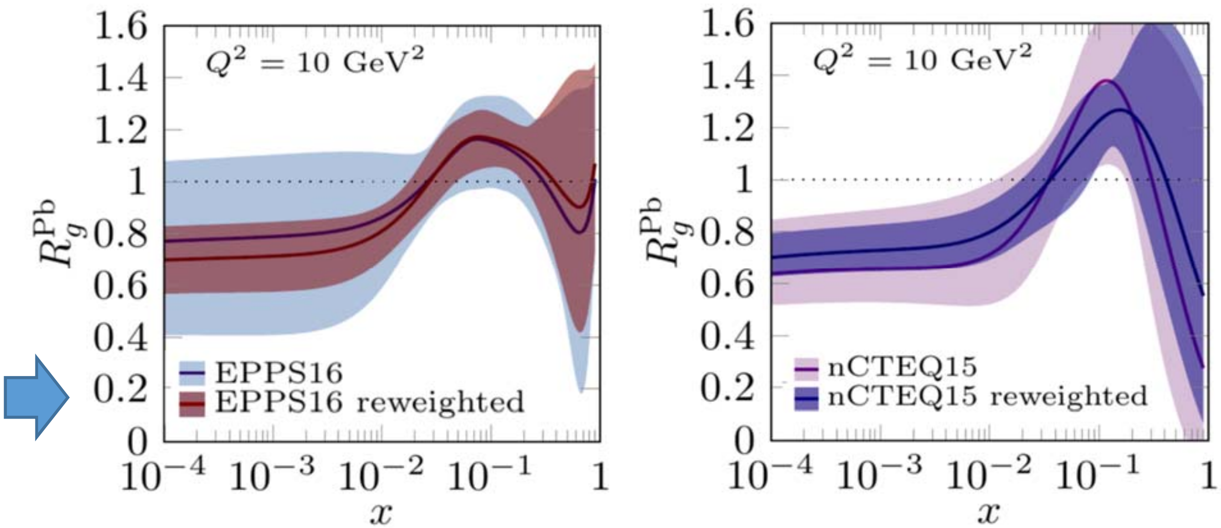
see talk by Jing Wang (Monday)

see talk by Jiangyong Jia (Monday), Dennis Perepelitsa (Wednesday)

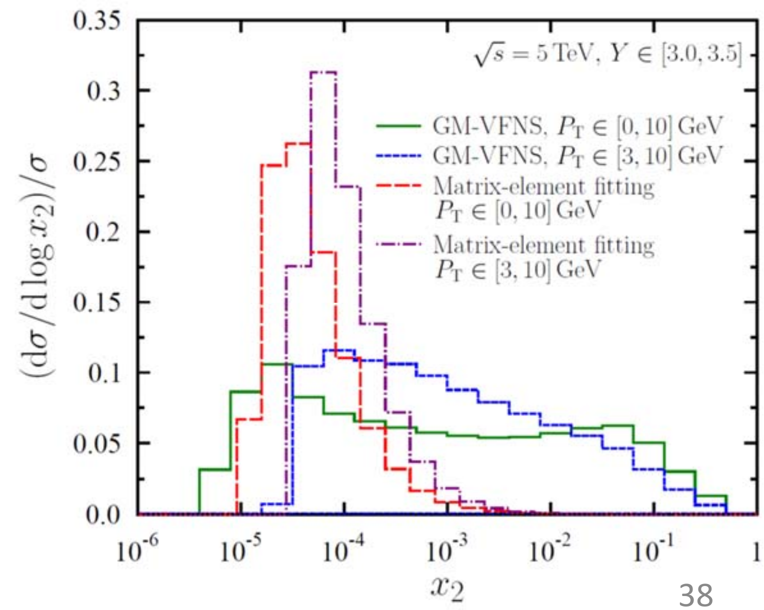
nPDF’s – D^0 in LHCb



arXiv 1906.3943



arXiv 1906.02512



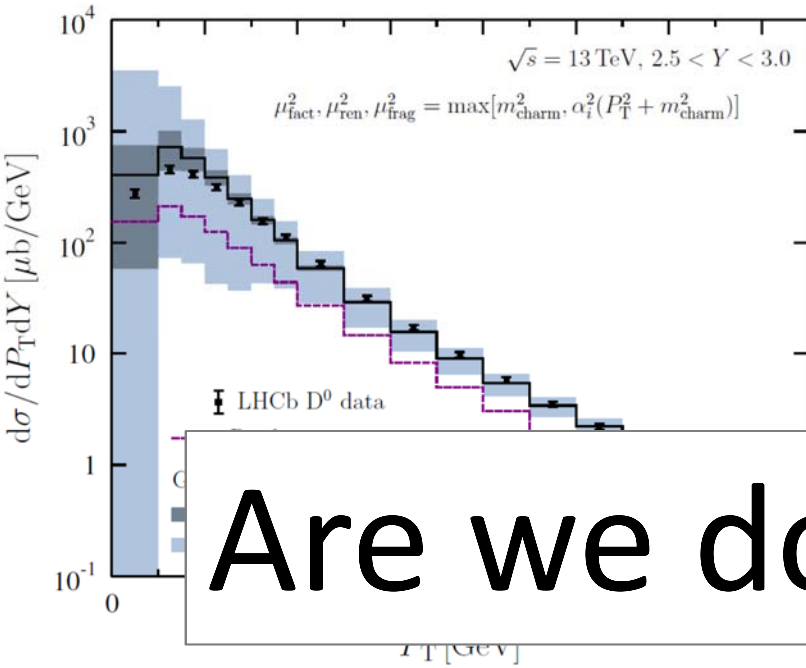
New LHCb D^0 data and improved theory provides significant new constraints on the gluon nPDF in Pb.

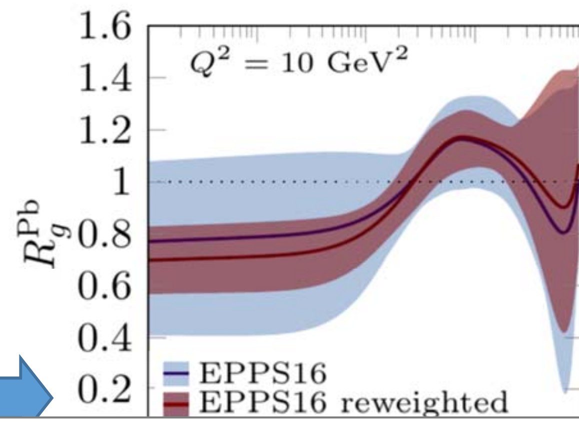
First real constraint on gluons at low-x!

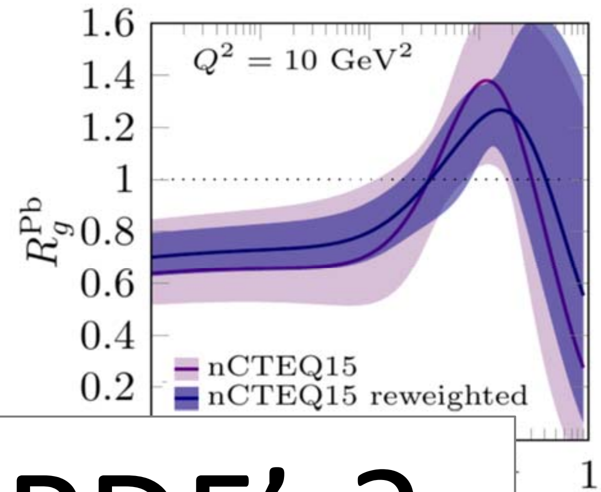
see talk by Burkhard Schmidt (Monday)

nPDF's – D^0 in LHCb

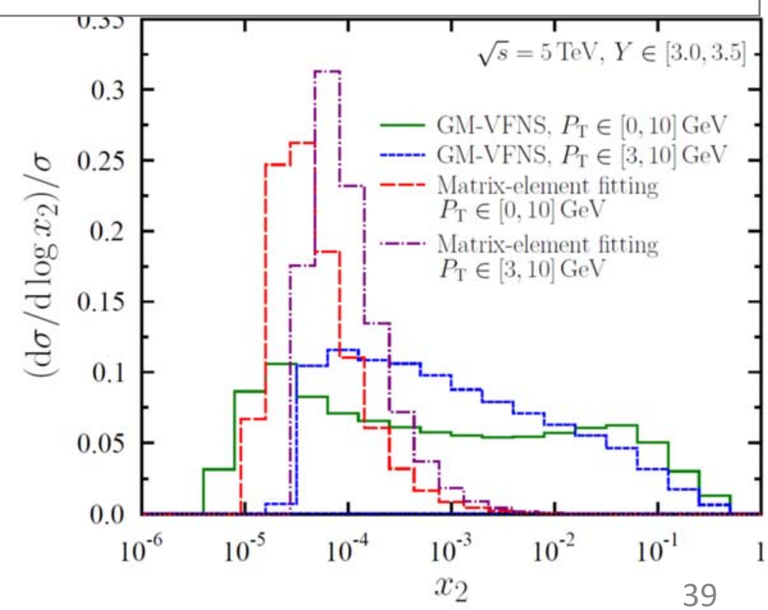
arXiv 1906.3943







Are we done with nPDF's?



New LHCb D^0 data and improved theory provides significant new constraints on the gluon nPDF in Pb.

First real constraint on gluons at low-x!

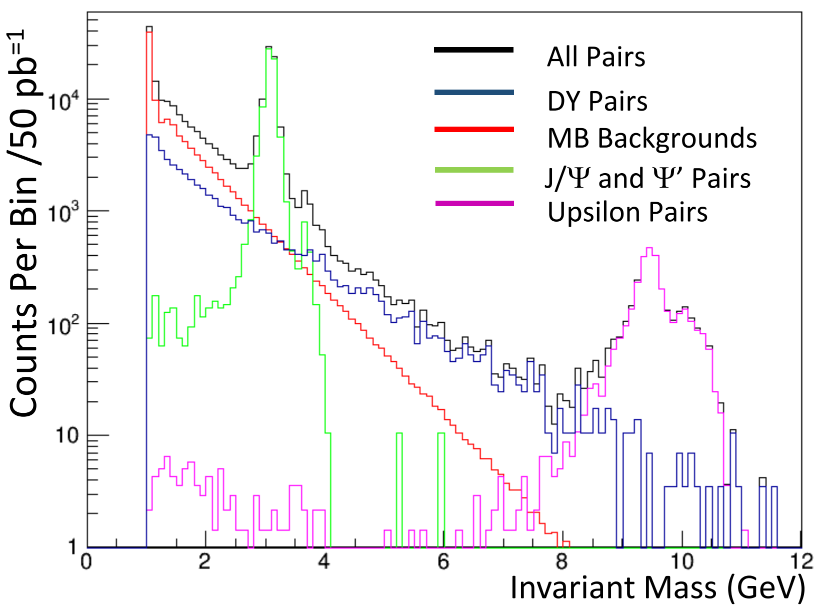
see talk by Burkhard Schmidt (Monday)

Future nPDF's at RHIC (sPHENIX)

Assumptions:

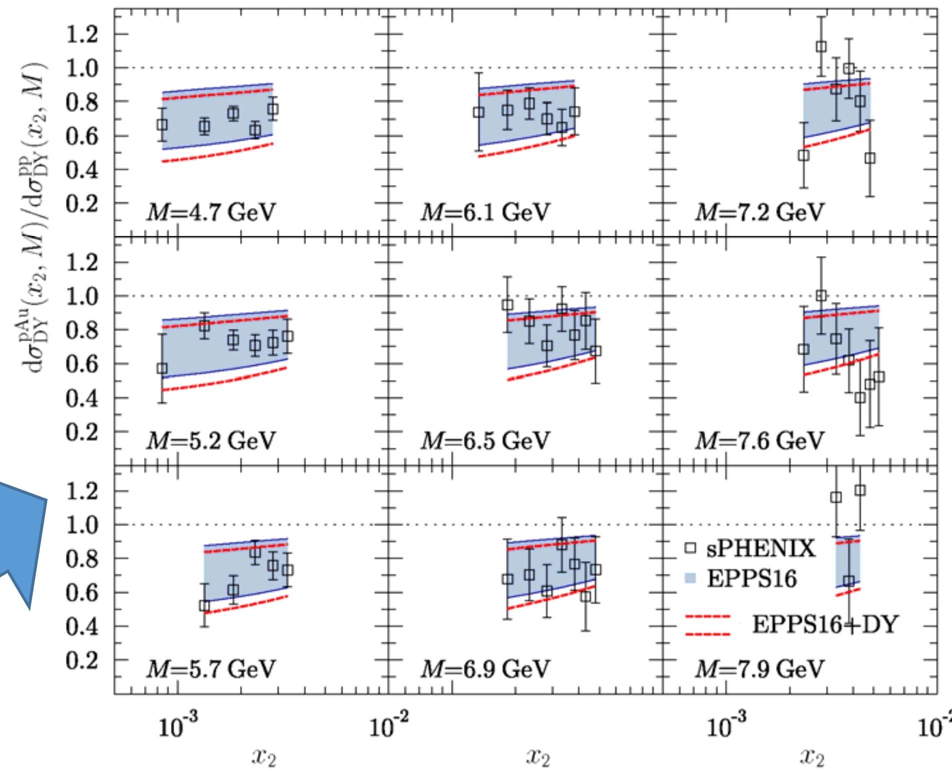
- Forward EM and HAD calorimetry ($1.4<\eta<4.0$)
- Low-mass tracking with good momentum resolution: $(\eta = 2.5 \quad 2.2\% \oplus 0.21\% \times p(GeV))$
- $197 pb^{-1}$ of p+p sampled lumi., $330 nb^{-1}$ of p+Au sampled lumi.

Full G4 Simulation:



access down to x~10^{-3}

Include pseudo data in EPPS16



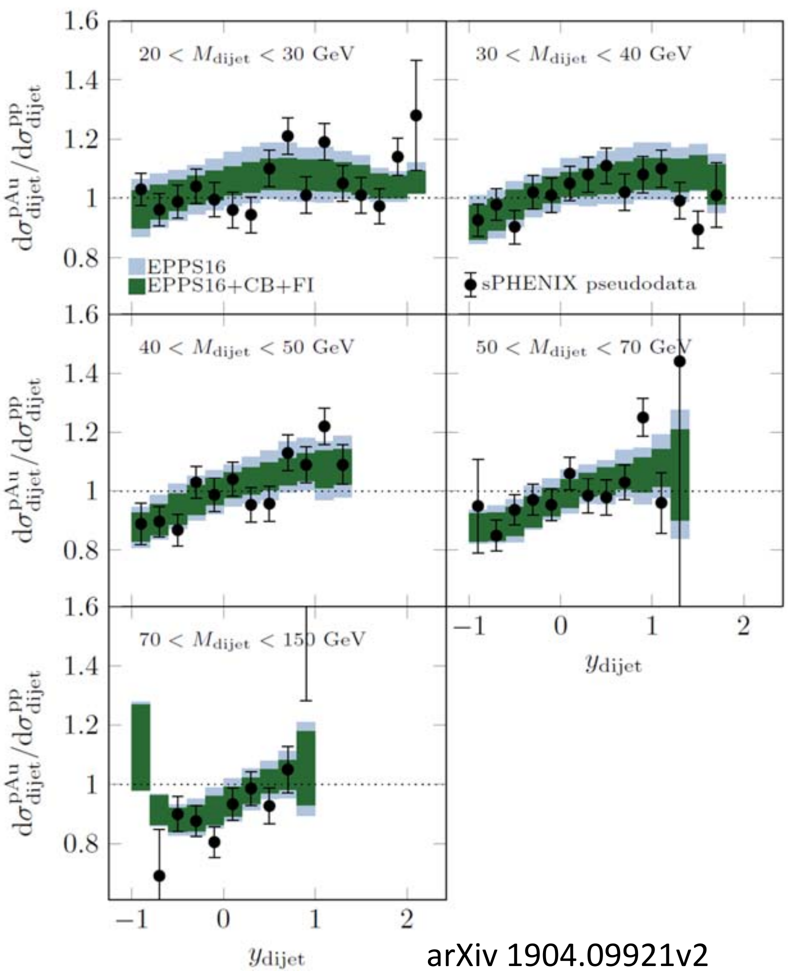
Pseudo data included with statistical uncertainties and a 10% normalization systematic error – the normalization error defeats the power of the data!

$$R_{pA} = \frac{\dfrac{d\sigma_{p+A\to X}}{2\pi p_T dp_T dy}}{A\dfrac{d\sigma_{p+p\to X}}{2\pi p_T dp_T dy}} = \frac{\dfrac{1}{N^{inel}_{p+A}}\dfrac{dN_{p+A\to X}}{2\pi p_T dp_T dy}}{\langle N_{coll}\rangle \dfrac{1}{N^{inel}_{p+p}}\dfrac{dN_{p+A\to X}}{2\pi p_T dp_T dy}}$$

A Multiobservable Approach (I)

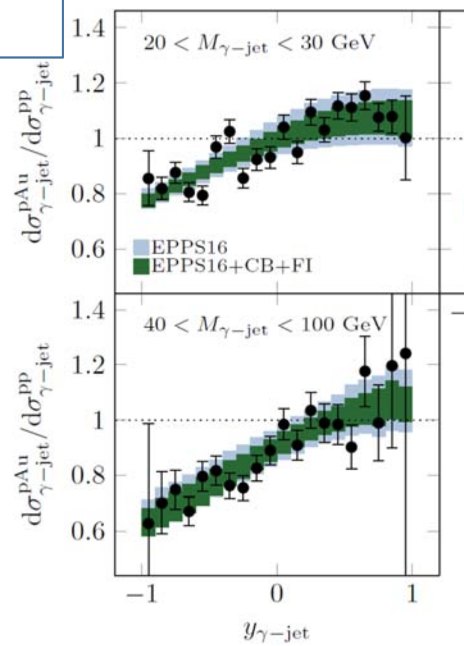
Can we use multiple datasets (with similar systematics) to overcome the normalization limitation?

Central (|η|<1) + Forward dijets (1.6<η<3.6)
(used primarily to fix normalization)



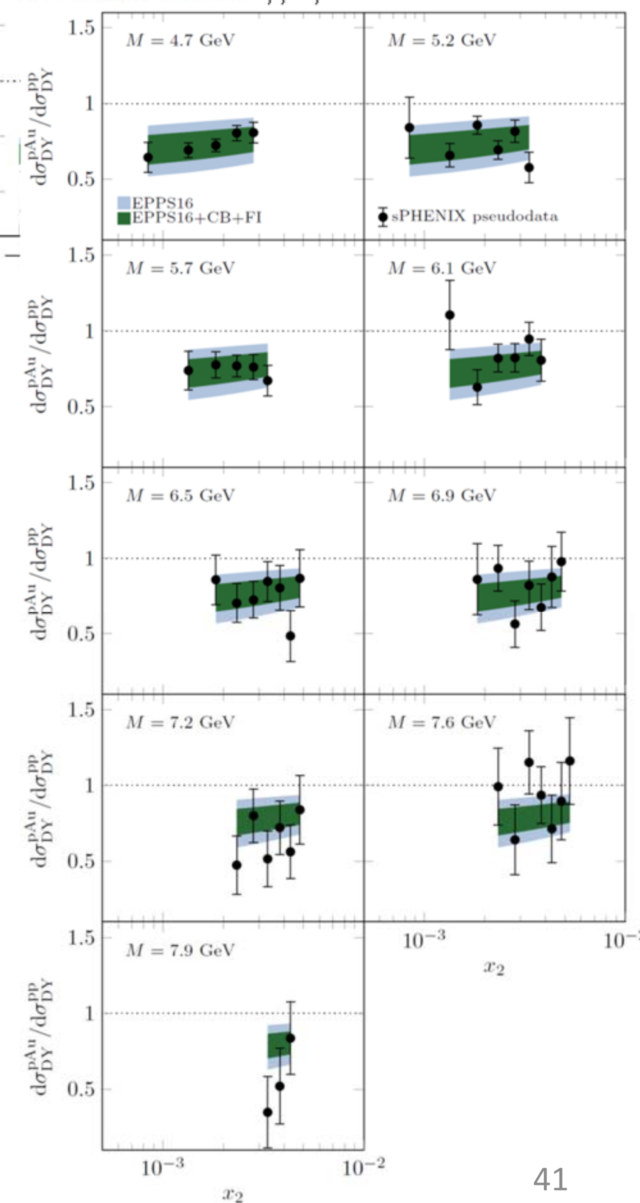
arXiv 1904.09921v2

Central (|η|<1) gamma+jet

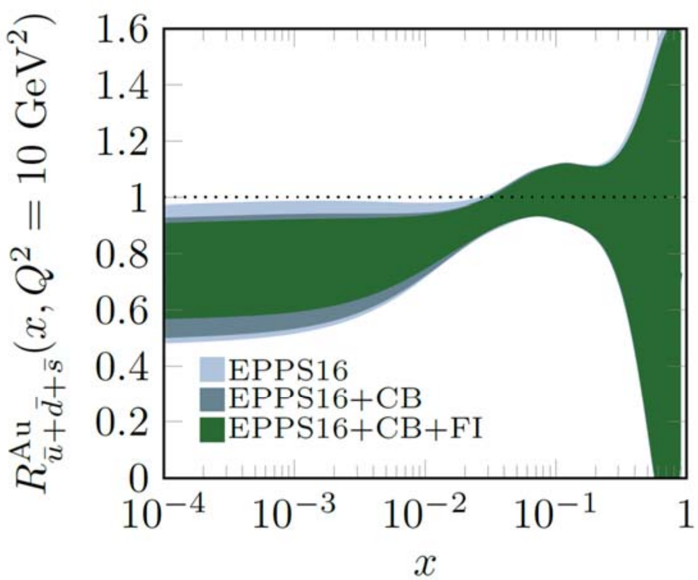


Forward DY
(same pseudo data as before)

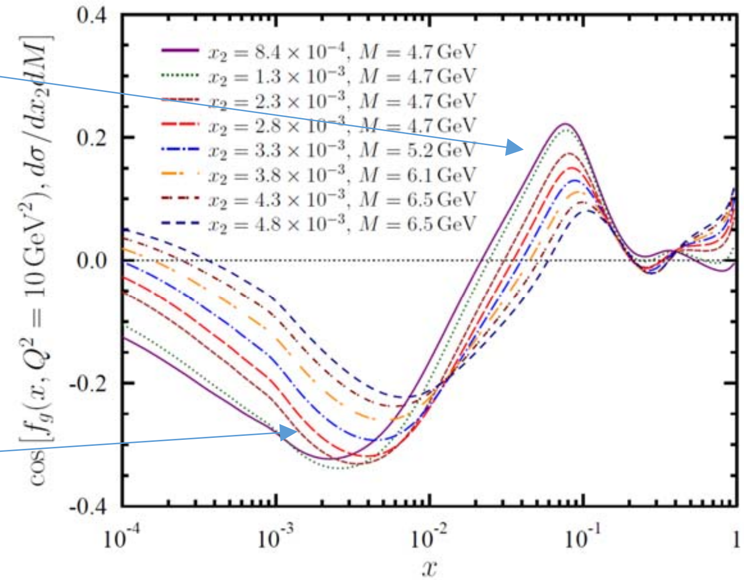
(Central DY not shown)



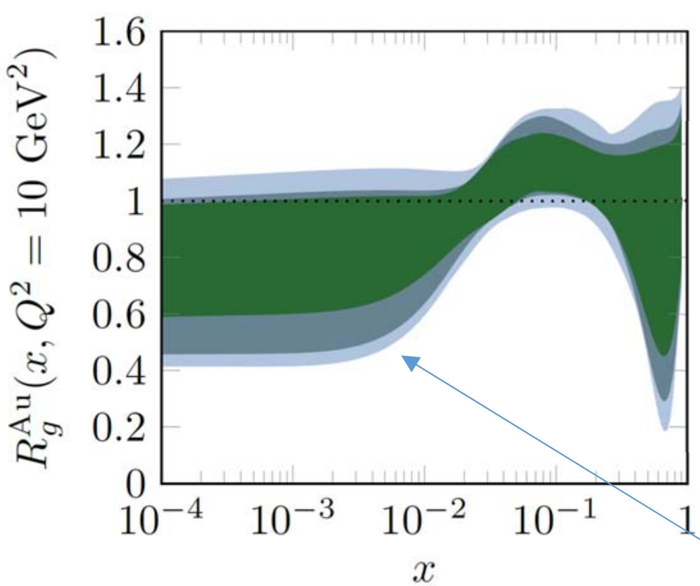
A Multiobservable Approach (II)



Indirect (LO) by scale evolution

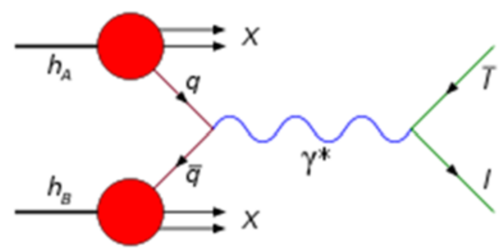


Direct (NLO) contribution

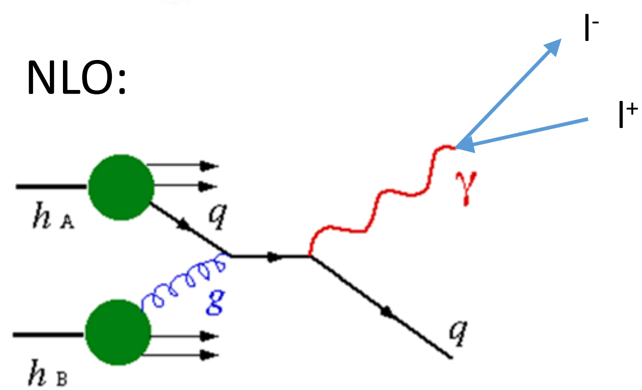


arXiv 1904.09921v2

LO:



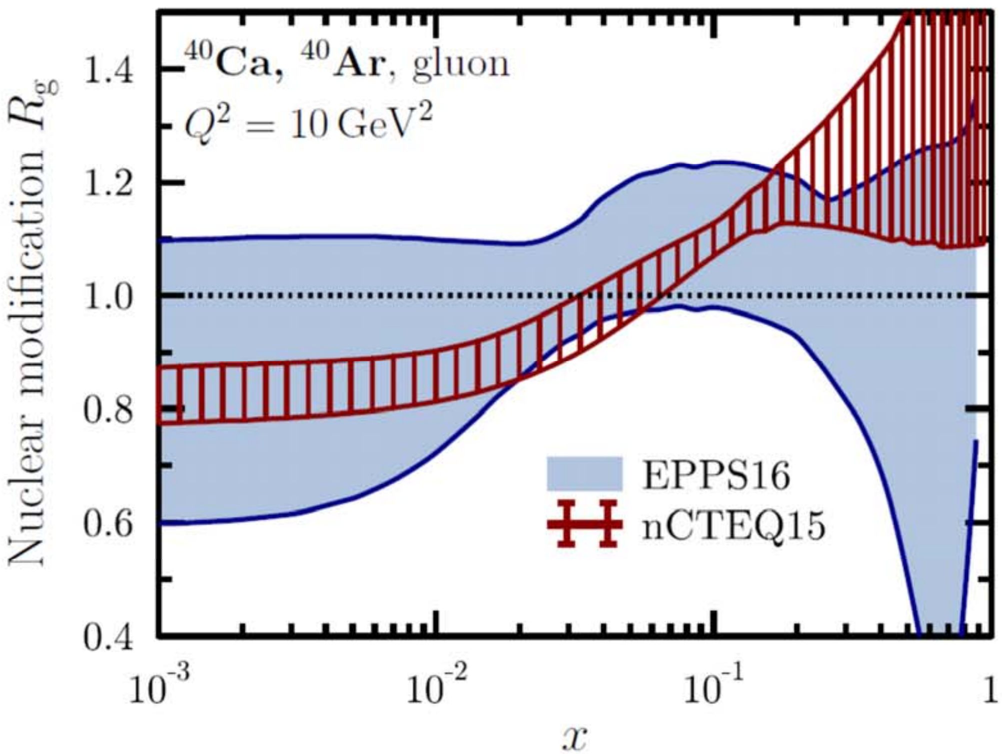
NLO:



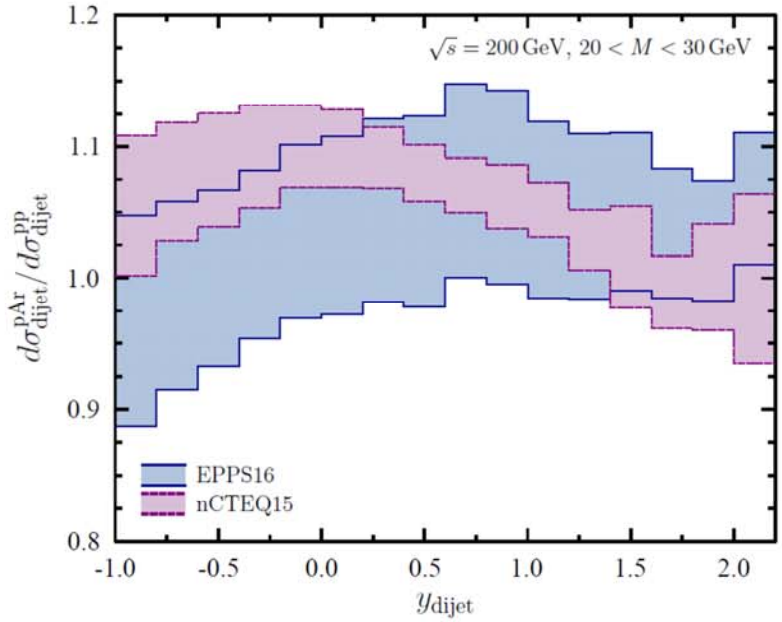
~15-40% of cross section

50% reduction in gluon nPDF uncertainties!

Other nPDF benefits at RHIC



Prediction for Dijets at RHIC:



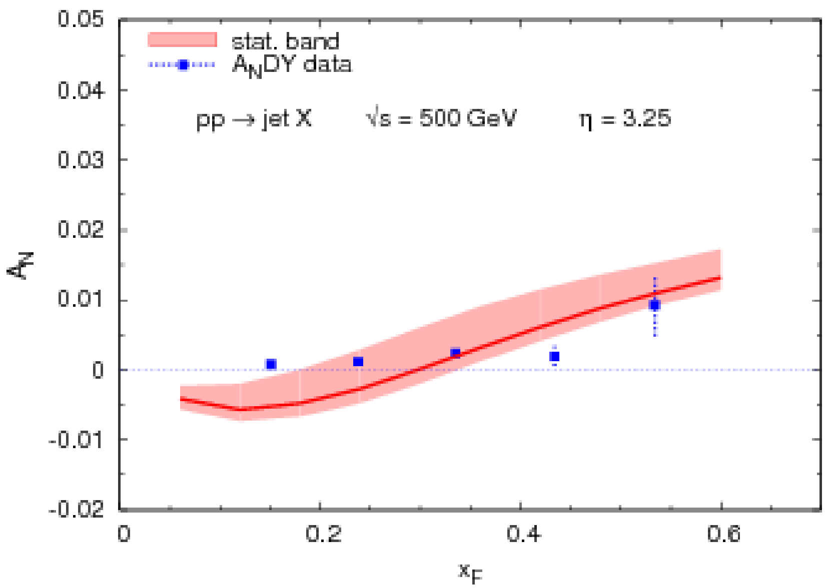
arXiv 1904.09921v2

Mass-number (A) dependence is not well-constrained between nPDF models. Light ion data at RHIC should have the power to improve this.

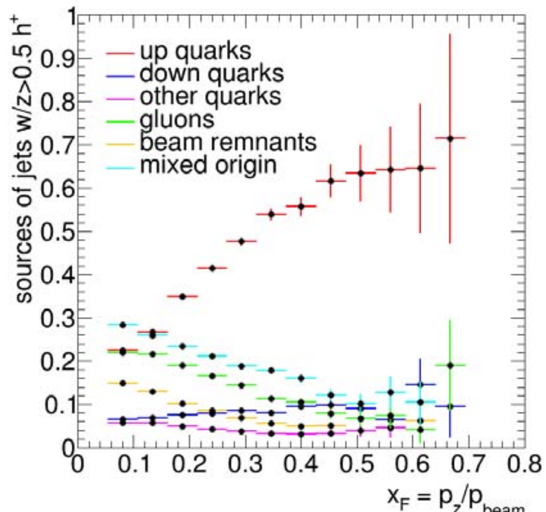
Test isospin asymmetry with (p+Ru)/(p+Zr) ratios.

Unresolved Mysteries…

AnDY: Phys. Lett. B750 (2015) 660



Jets with positive hadron z>0.5



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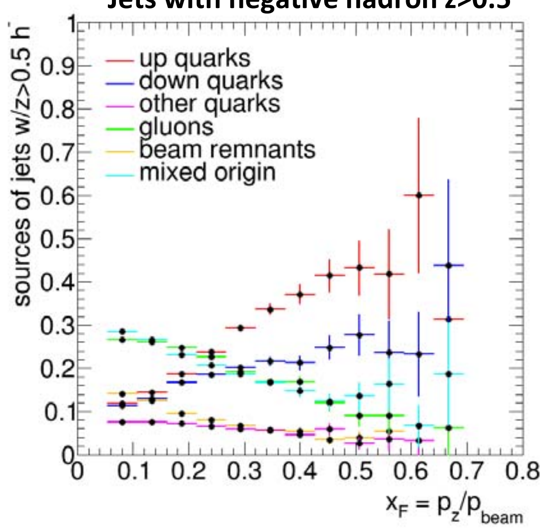

A cut on the charge of the leading hadron changes the composition of the jet sample (Pythia simulation).

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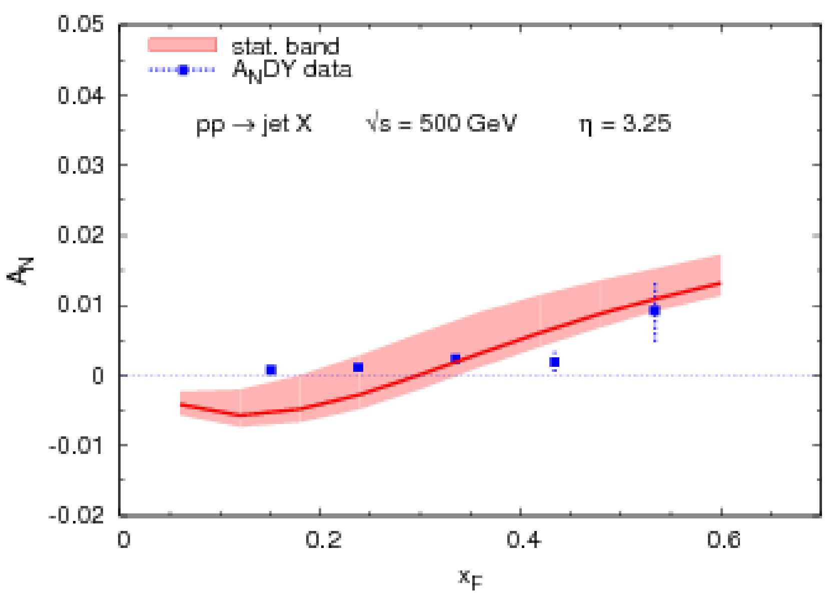

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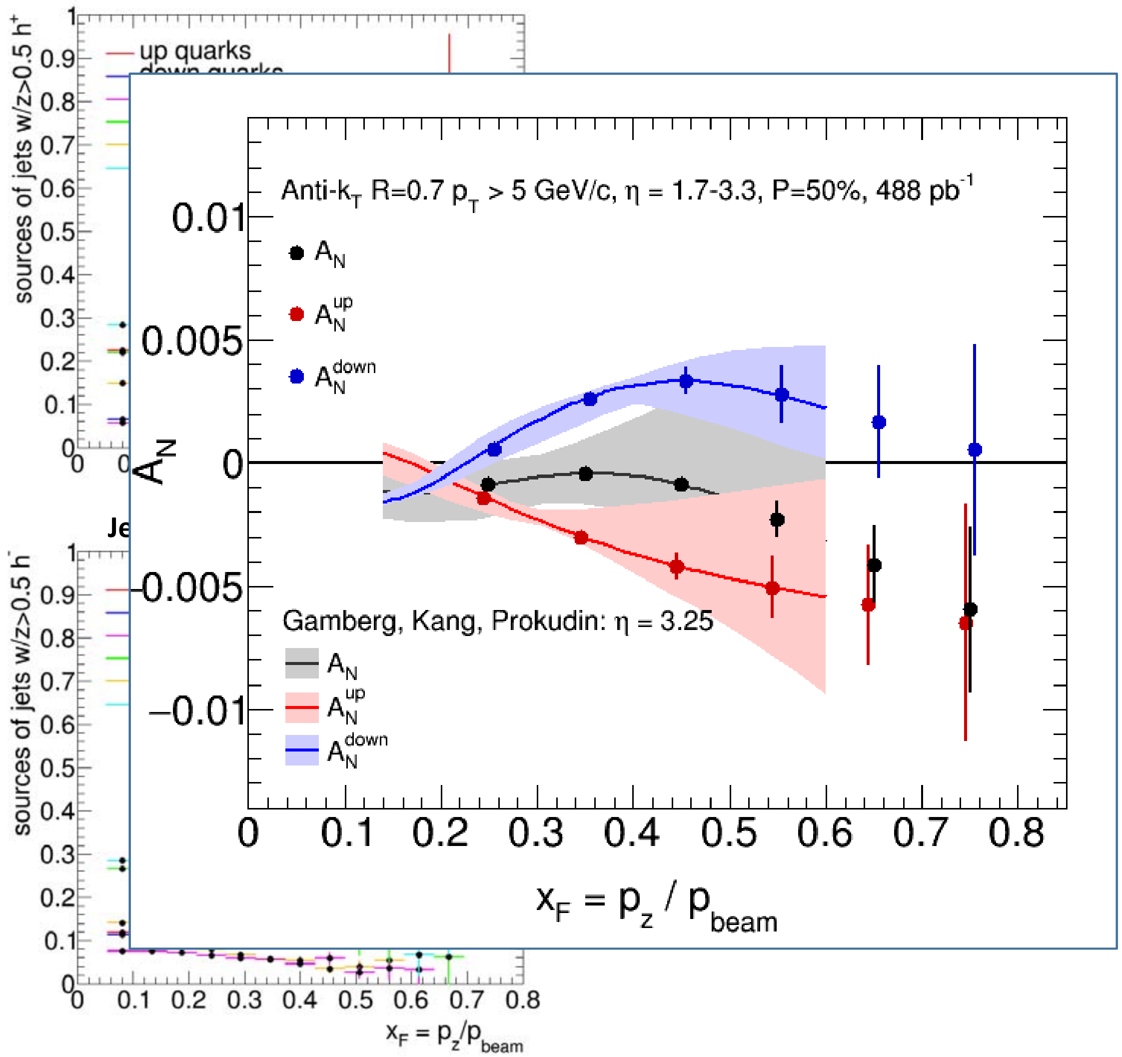

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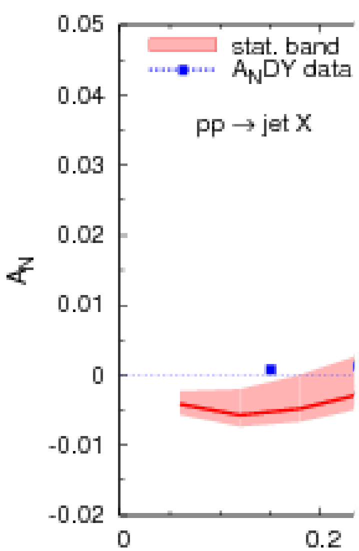
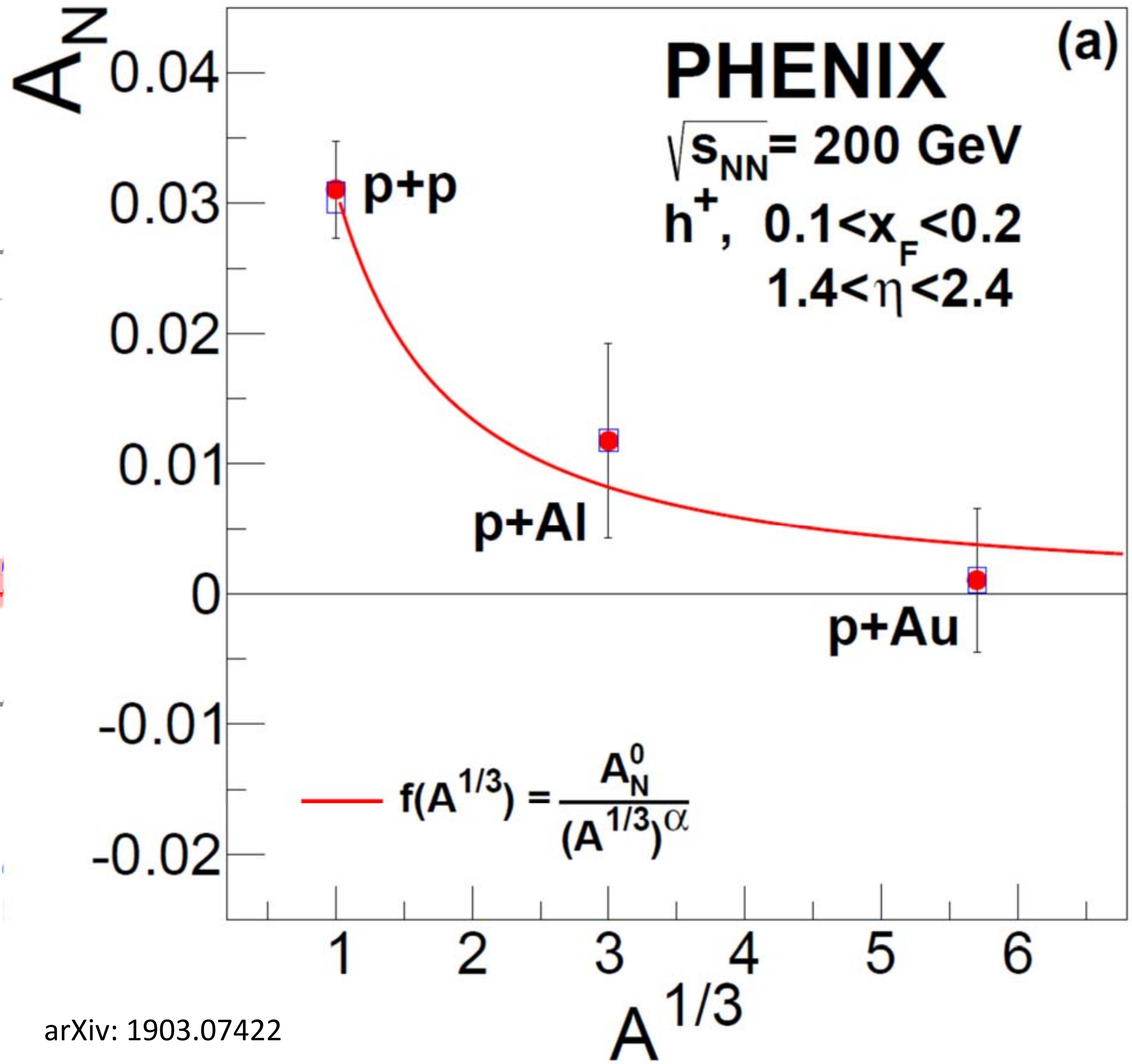
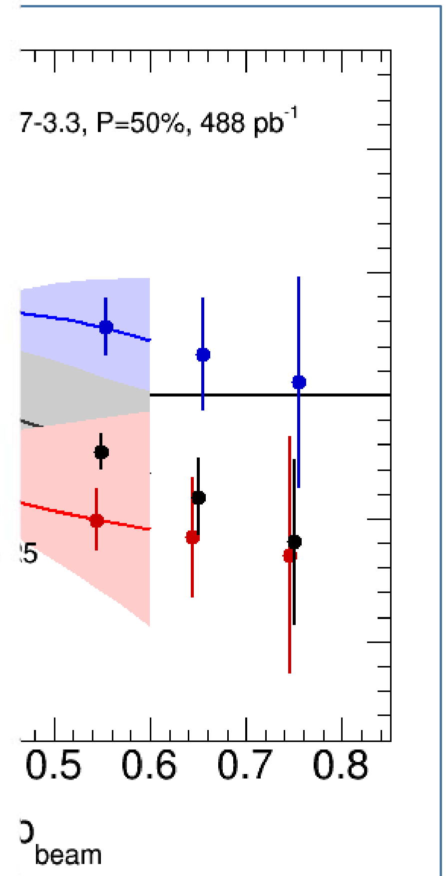


A cut on the
changes the
(Pythia simu





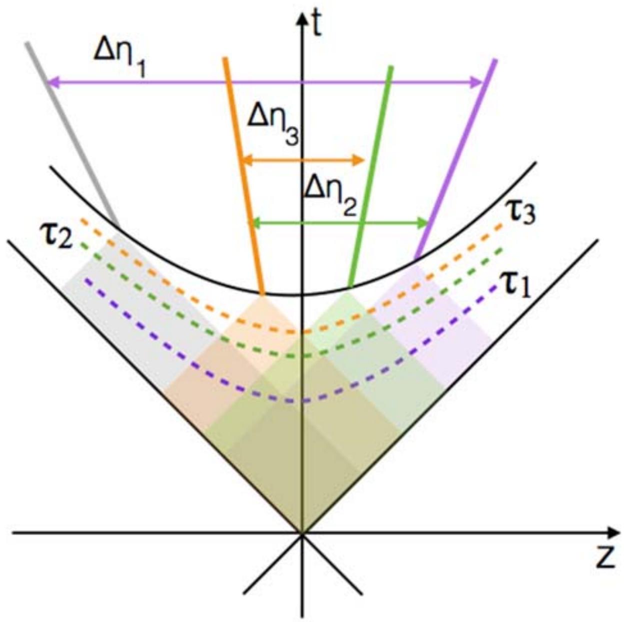
arXiv: 1903.07422

Summary

- Upgrades in capabilities and data at the LHC and RHIC coming soon…
  - LHC:
    - HL-LHC, increase in statistics, possible O+O (p+O), FoCAL(?)
  - RHIC upgrades
    - Both STAR and sPHENIX working to add forward instrumentation
      - fSTAR first run in 2022, sPHENIX in 2023
    - Broad program in Cold QCD and spin
    - Will enhance the planned A+A program
    - Investment could be recovered for a future EIC detector
- An era of *high-precision nPDF's* is available
  - Multiobservable approach with multiple measurements from the same detector can limit systematics
  - Test A-dependence, isospin, centrality, spin …
  - RHIC and LHC data permit tests of evolution
  - Allows tests of universality with EIC data

BACKUP

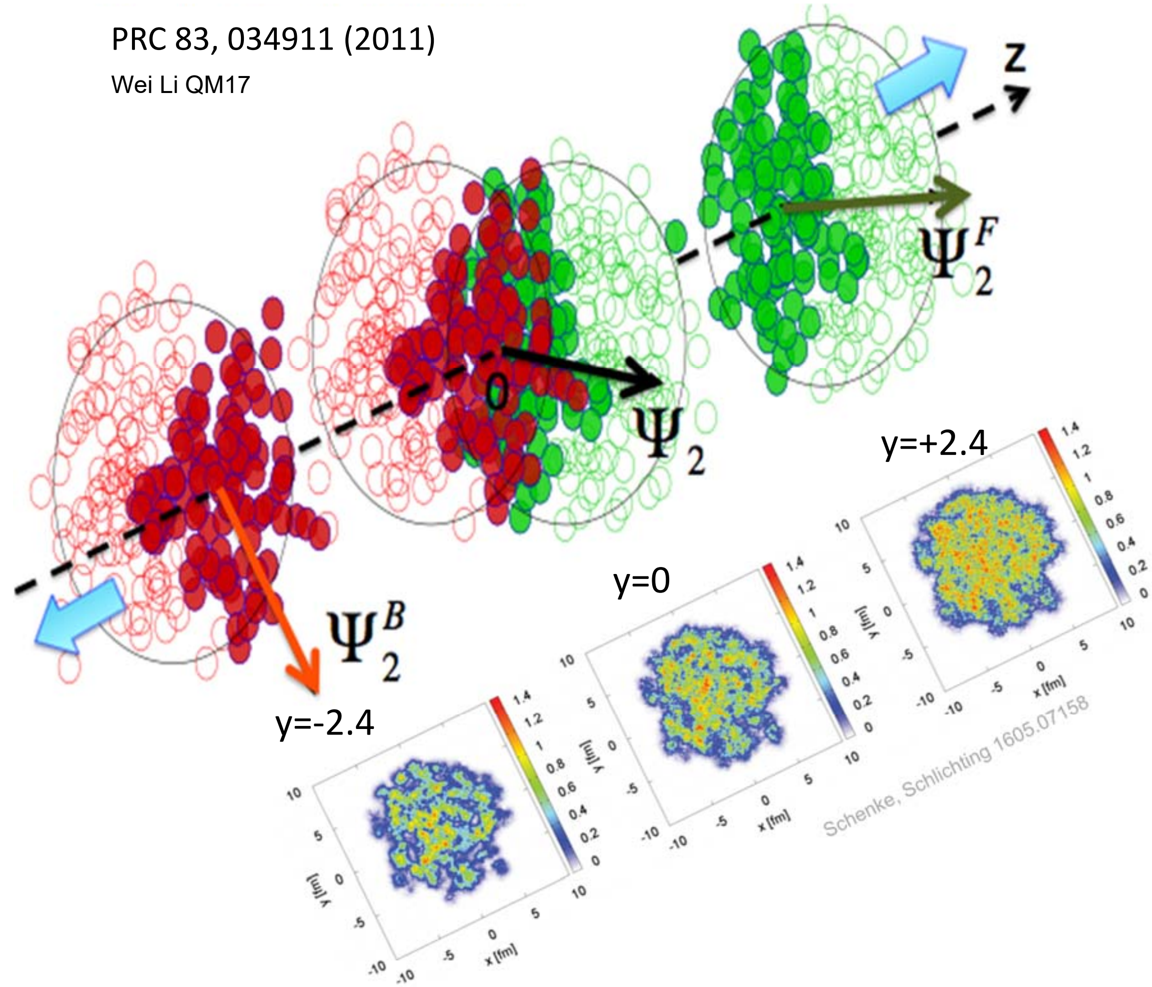
What about A+A?



Due to causality, correlations that are widely separated in rapidity probe the earliest times.

PRC 83, 034911 (2011)

Wei Li QM17



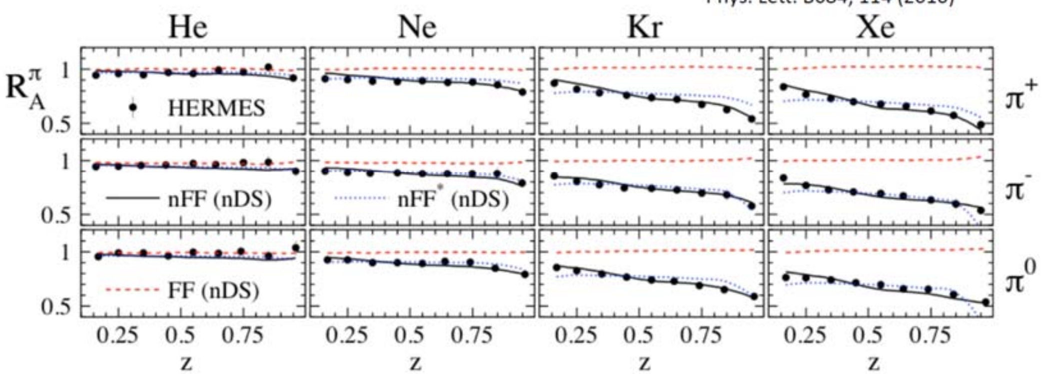
Adding forward capabilities at RHIC will enable a new, complementary physics program to study the initial conditions in HI collisions.

De-correlation of the event plane can result from quantum fluctuations in the initial state.

Need to understand this to be able to extract $\eta/s(T)$ from hydrodynamic models.

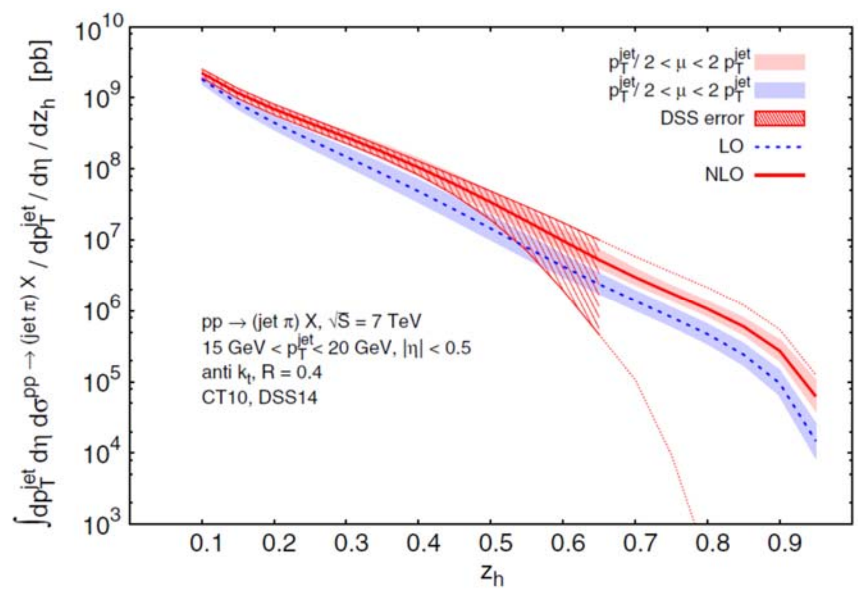
Fragmentation in a Nuclear Environment

Phys. Lett. B577, 37 (2003)
Phys. Lett. B684, 114 (2010)

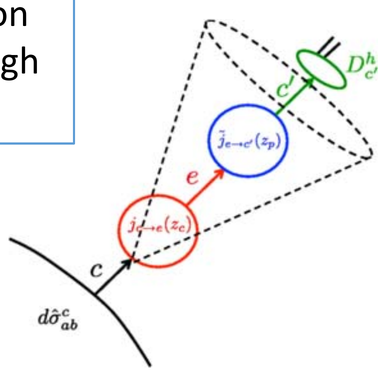


Hadron production in e+A suppressed compared to e+p – must be a fragmentation effect!

Kaufmann, Mukherjee and VogelsangPhys.Rev.D 92 5, 054015



Access fragmentation functions (FF) through p+p(A) -> (jet *h*) X



see talk by Ivan Vitev (Wednesday)

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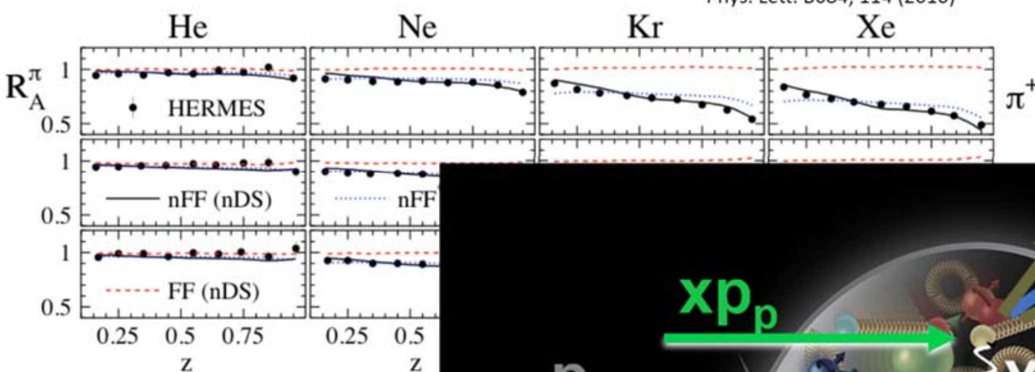

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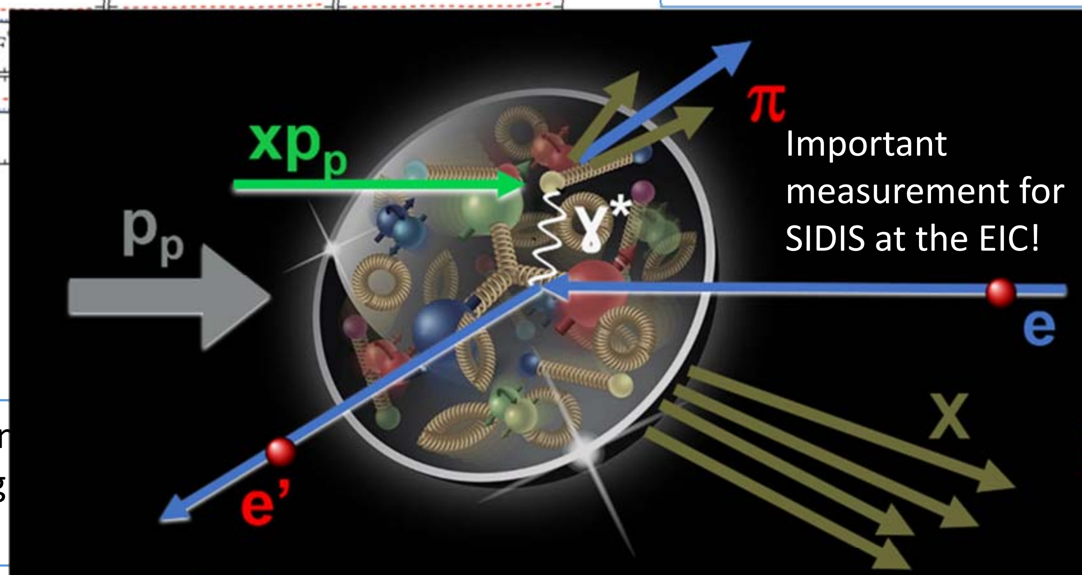
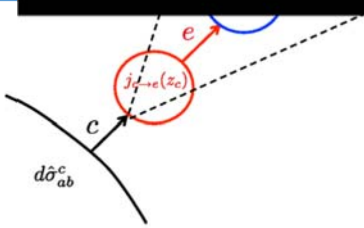
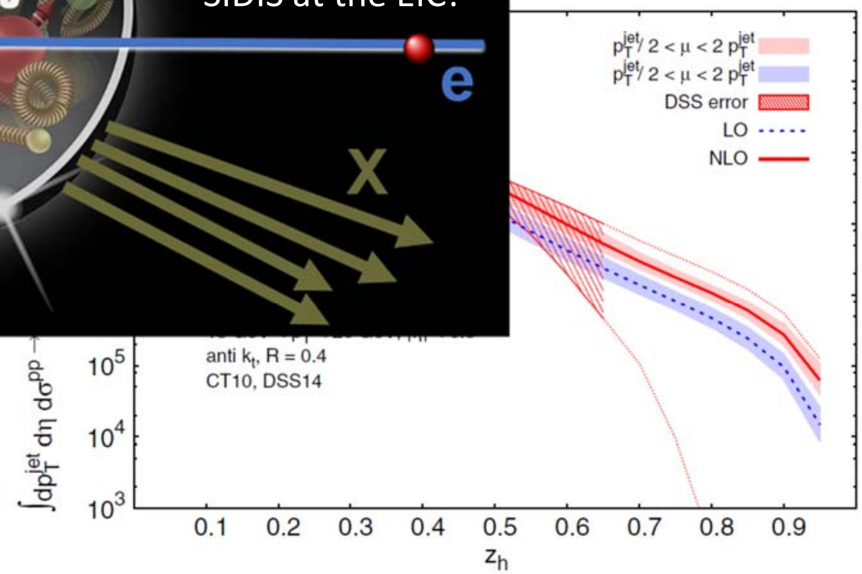


… and VogelsangPhys.Rev.D 92 5, 054015

Access fragmentation functions (FF) throug… p+p(A) -> (jet *h*) X

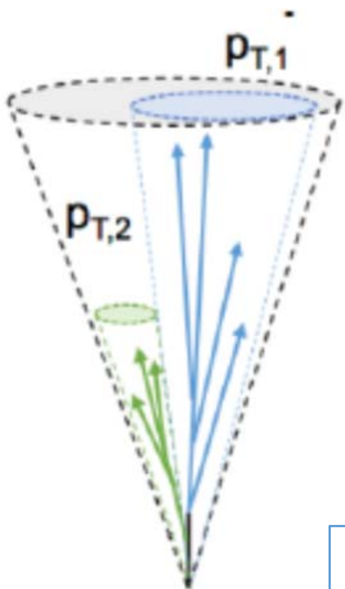




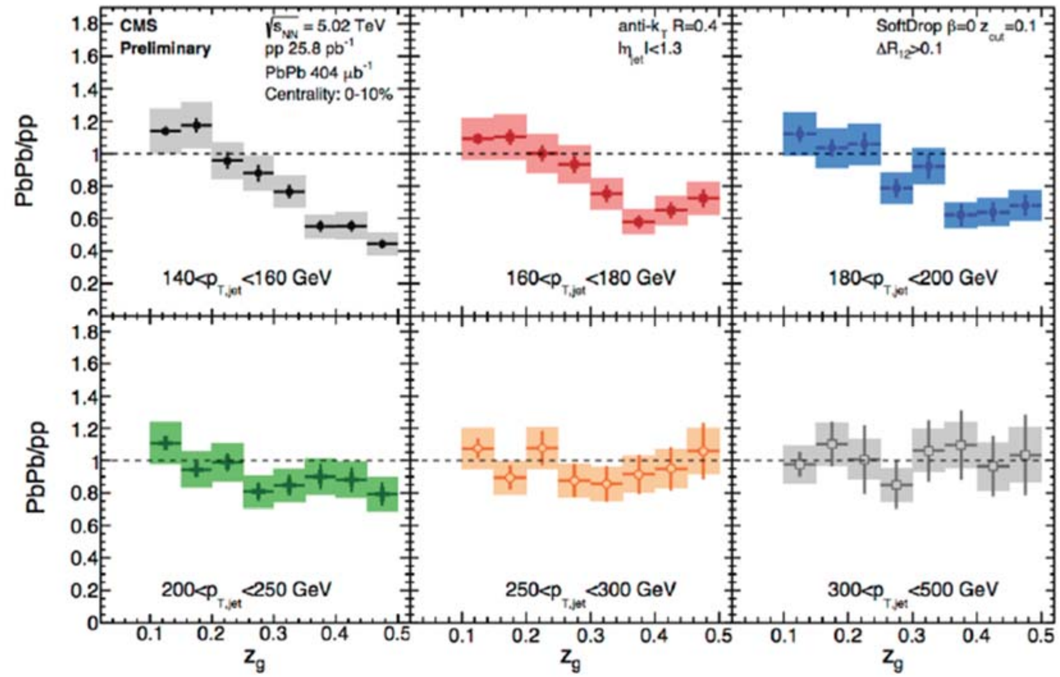
see talk by Ivan Vitev (Wednesday)

Jet Substructure

CMS PAS HIN-16-006



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

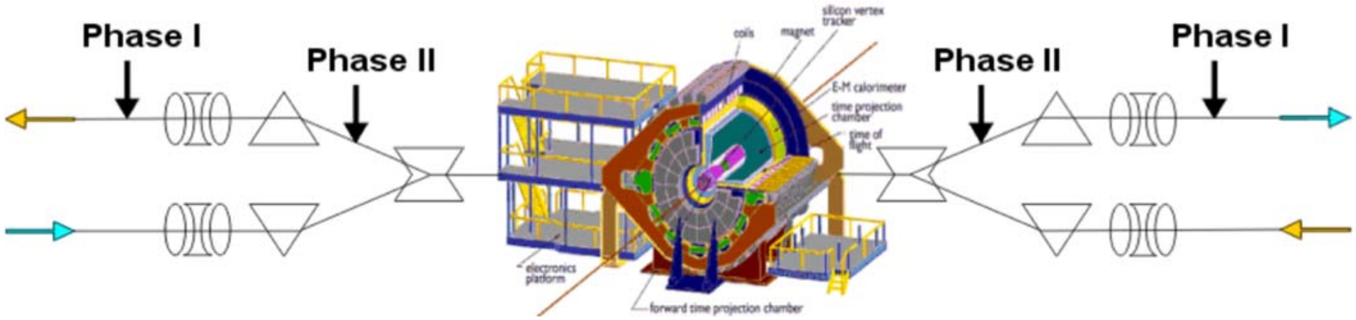


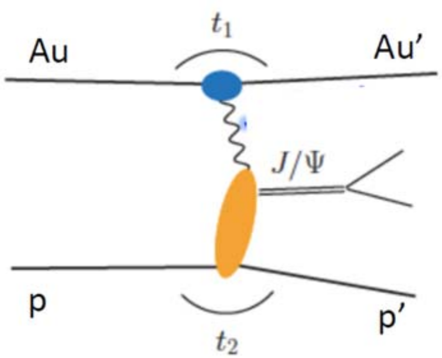
Soft-drop grooming combined with a Cambridge-Aachen type decomposition of a jet found with an anti-k_T algorithm – provides detailed information about the first parton splitting!

An excellent way to study cold QCD effects in fragmentation in detail!

Diffraction/UPC

Data taken in 2015/17 by STAR will elucidate the diffractive contribution to A_N at RHIC.





$$A_{UT}(\tau,t) \sim \frac{\sqrt{t_0 - t}}{m_p}\frac{\mathrm{Im}(E*H)}{|H|} \qquad t = \frac{M^2_{J/\Psi}}{s}$$

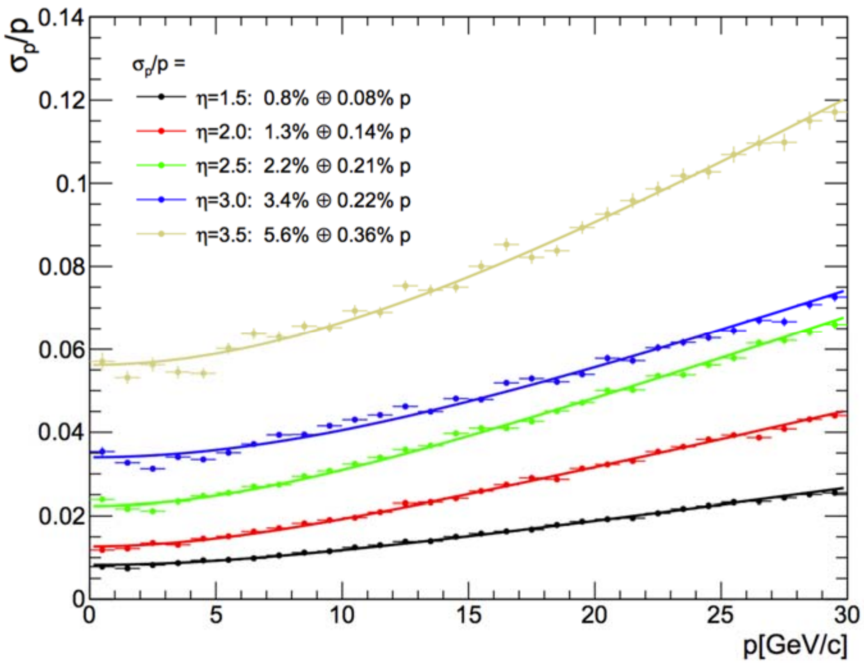
UPC collisions in p+A will allow study of:

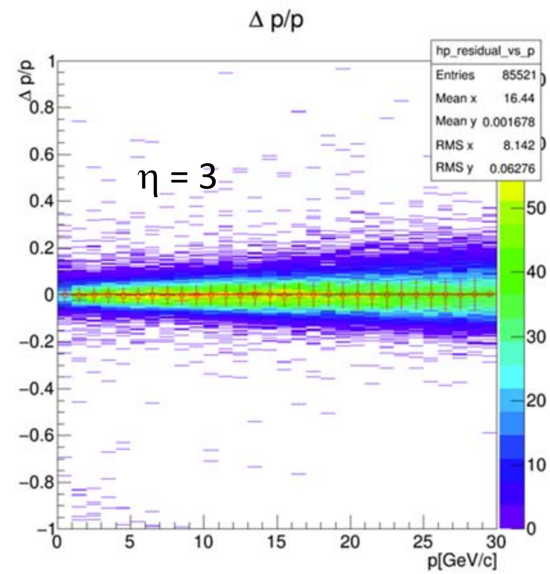
- The gluon spatial distribution in nuclei (“proton shine”)
- The gluon helicity flip Generalized Parton Distribution (GPD) E_g (“A-shine”)

Requires Roman Pots, good t-acceptance and high luminosity

Forward Tracking

- **G4 Simulation and (PH)GenFit** to extract $(p_{Reco} - p_{True})/p_{True}$ vs. p_{True} (right plot)
- For each slice of p_{True}, fit with Gaussian, extract mean as offset, sigma as resolution





Excellent momentum resolution!

Tracking simulations by Haiwang Yu

Multi-year sPHENIX run plan

Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

- Guidance from ALD to think in terms of a multi-year run plan
- Consistent with language in DOE CD-0 "mission need" document
- Based on BNL C-AD guidance on projected luminosity
- Incorporates commissioning time in first year
- Structured so that first three years delivers at least minimum science program

Minimum bias Au+Au at 15 kHz for |z| < 10 cm:
47 billion (Year-1) + **96 billion** (Year-2) + **96 billion** (Year-3) = Total **239 billion events**

For topics with Level-1 selective trigger (e.g. high p_T photons), one can sample within |z| < 10 cm a total of 550 billion events. One could sample events over a wider z-vertex for calorimeter only measurements, 1.5 trillion events.

9

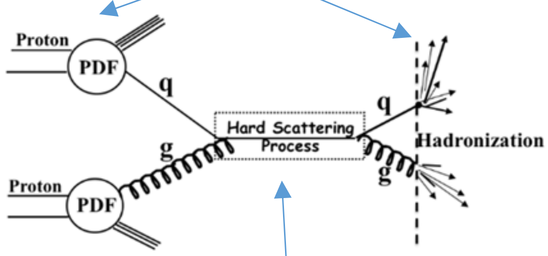
The Big Picture at RHIC (and the EIC…)

The Big Picture at RHIC (and the EIC…)

Two Pillars of QCD:

The Big Picture at RHIC (and the EIC…)

Long-distance physics



pQCD

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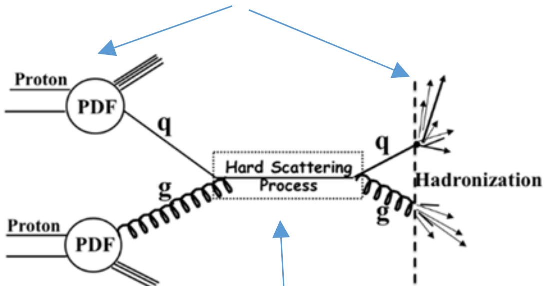
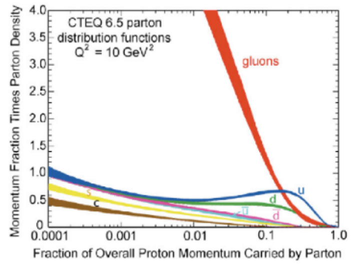
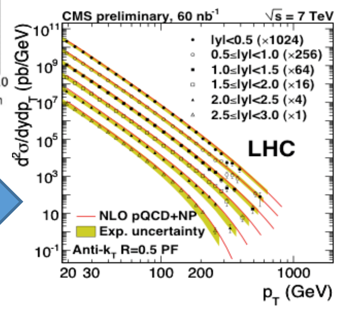


pQCD



Extract PDF's from Hera..

Calculate cross sections at LHC



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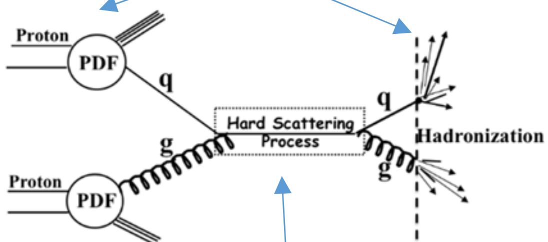
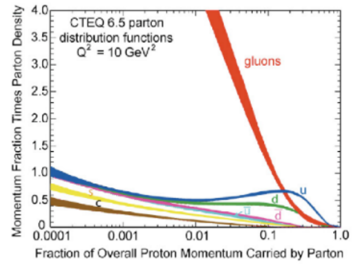


pQCD



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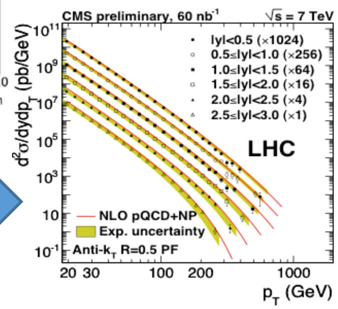

Two Pillars of QCD:

Advances in QCD theory over the past two decades have pushed us away from a simple collinear factorization approach and towards extreme regimes that challenege our underlying assumptions.