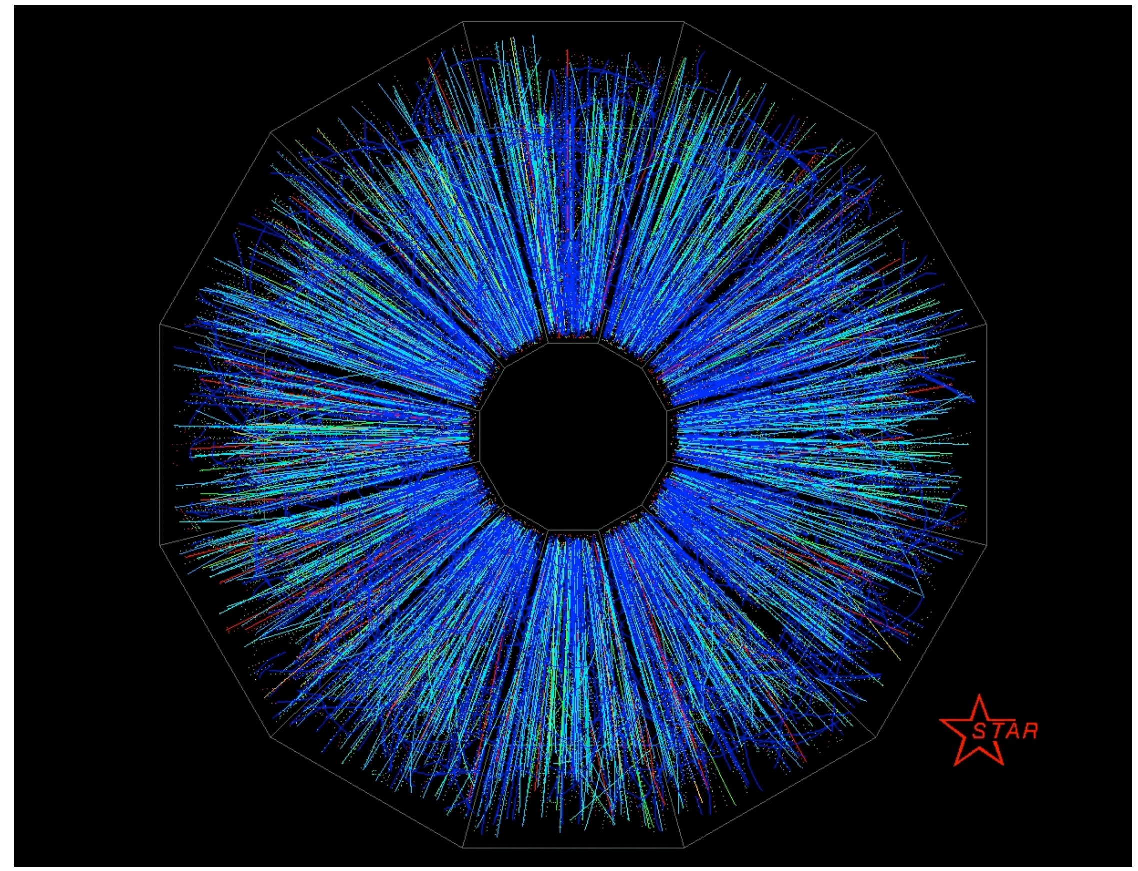
The STAR Experiment: The second decade and beyond

Matthew A. C. Lamont,
(Brookhaven National Lab)
for the
STAR Collaboration



1st Collision: June 12, 2000

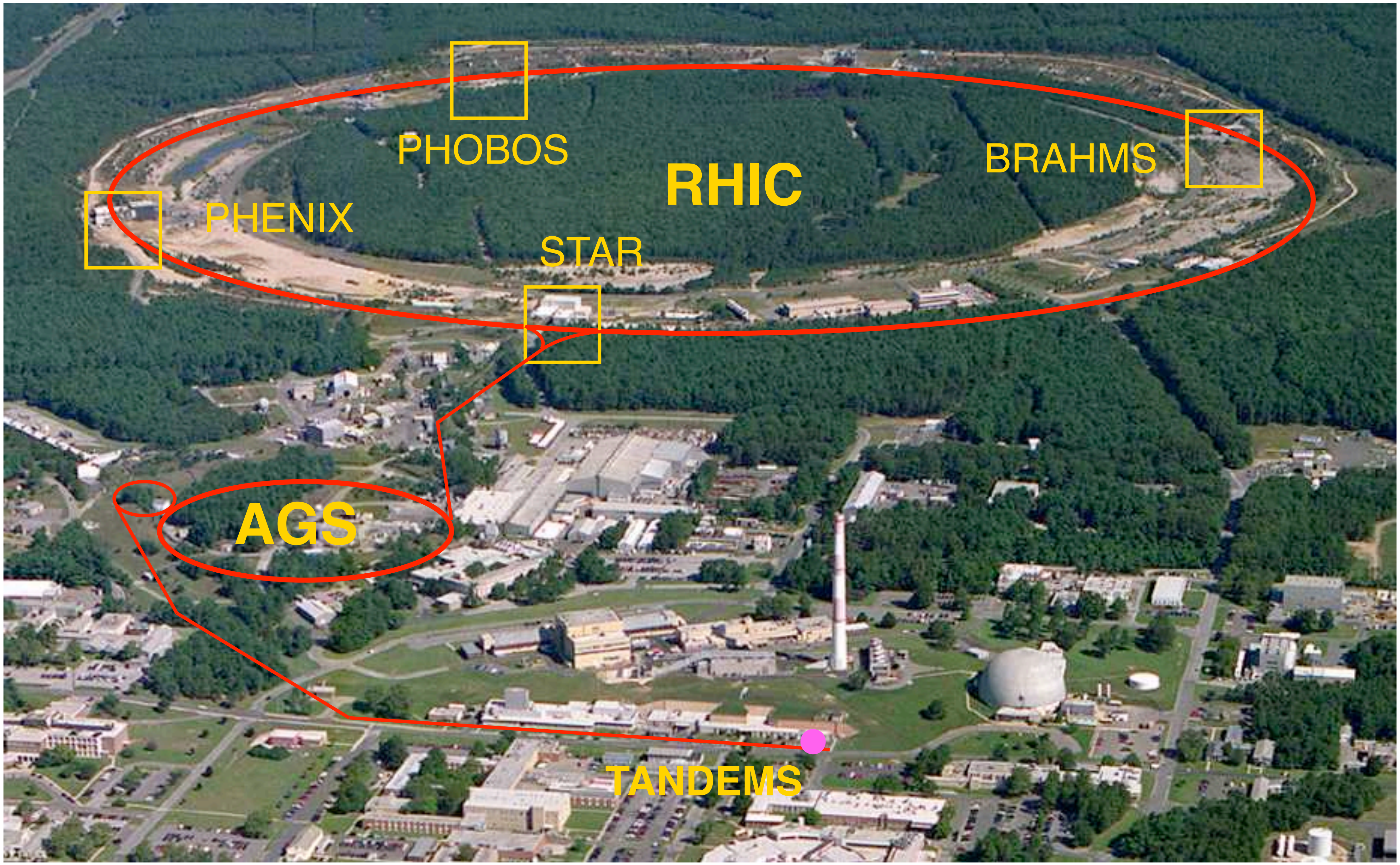
Talk Outline:

1. Introduction to RHIC and STAR
2. Highlights from the first decade
3. Upgrades and near-term future of STAR
4. STAR in the eRHIC era

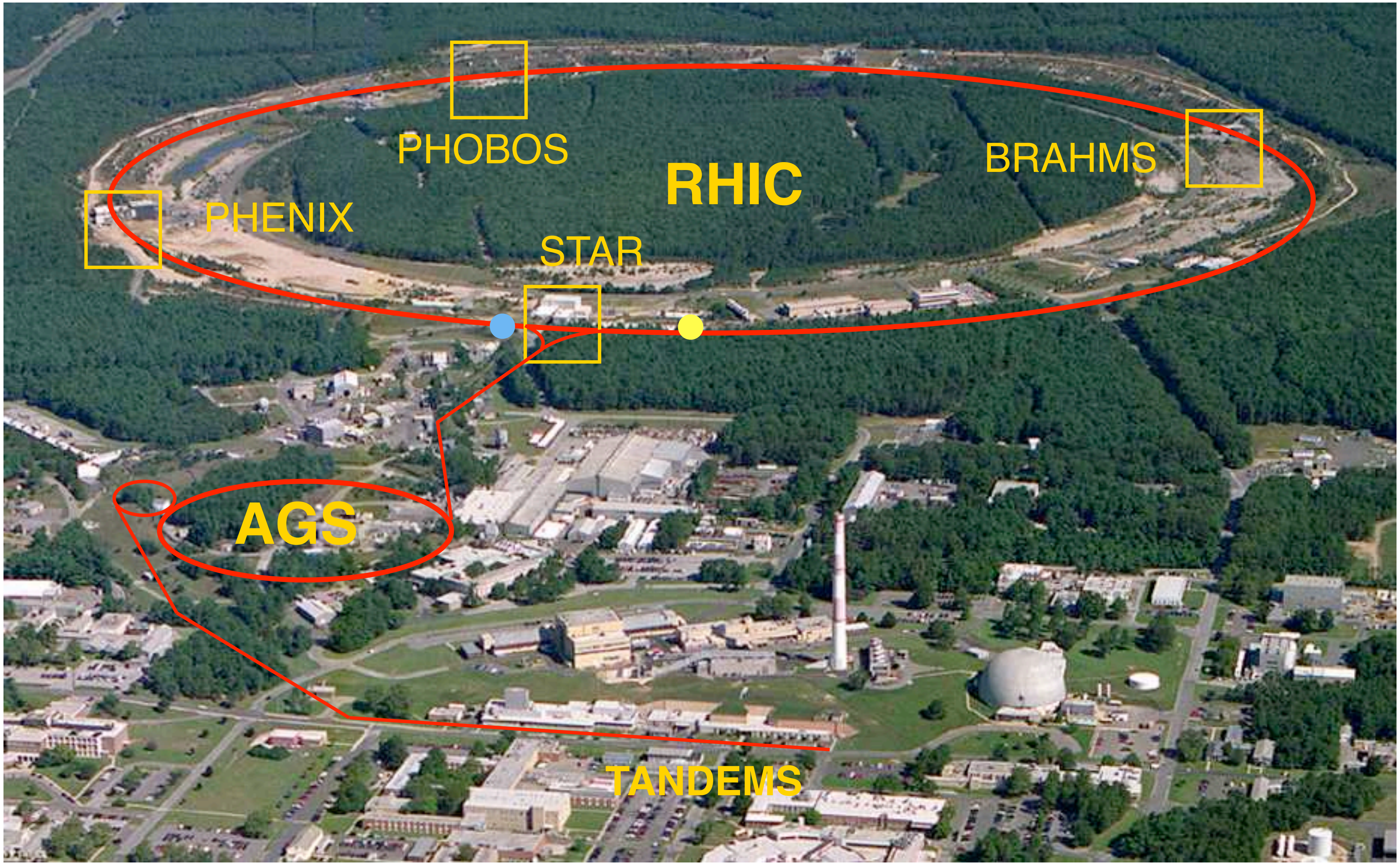
BROOKHAVEN NATIONAL LABORATORY

STAR

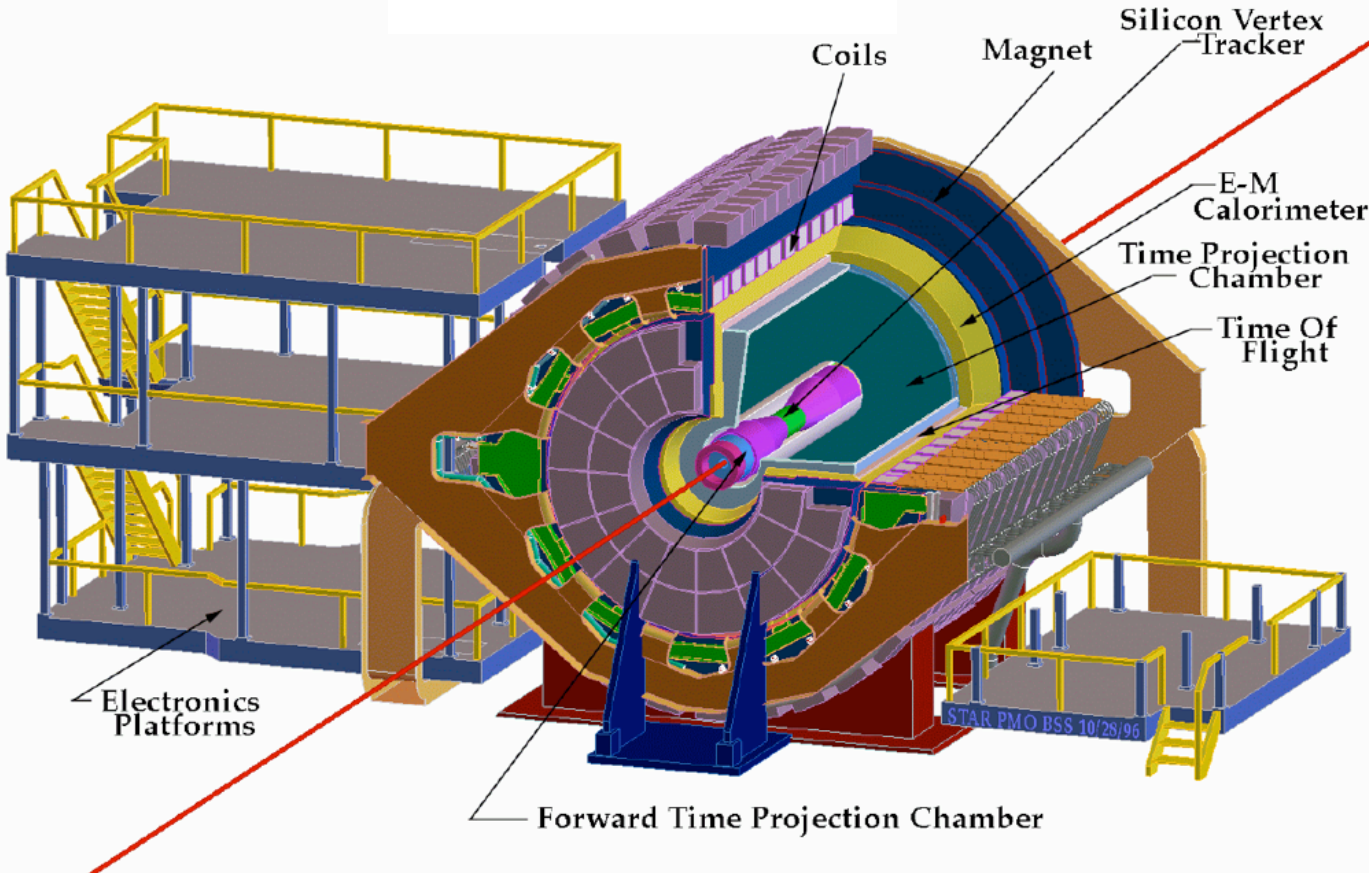
RHIC - Brookhaven Lab



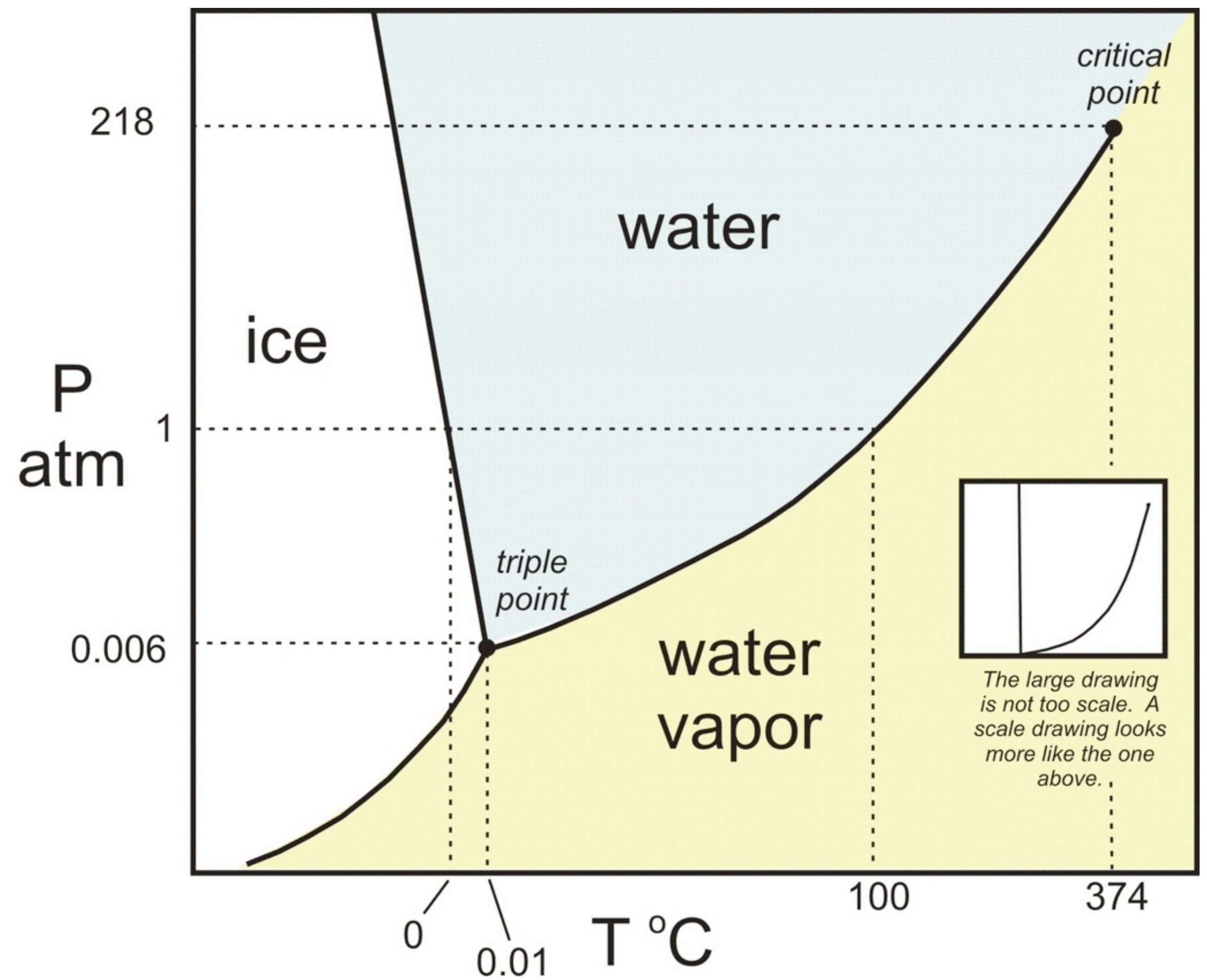
RHIC - Brookhaven Lab



The STAR Detector

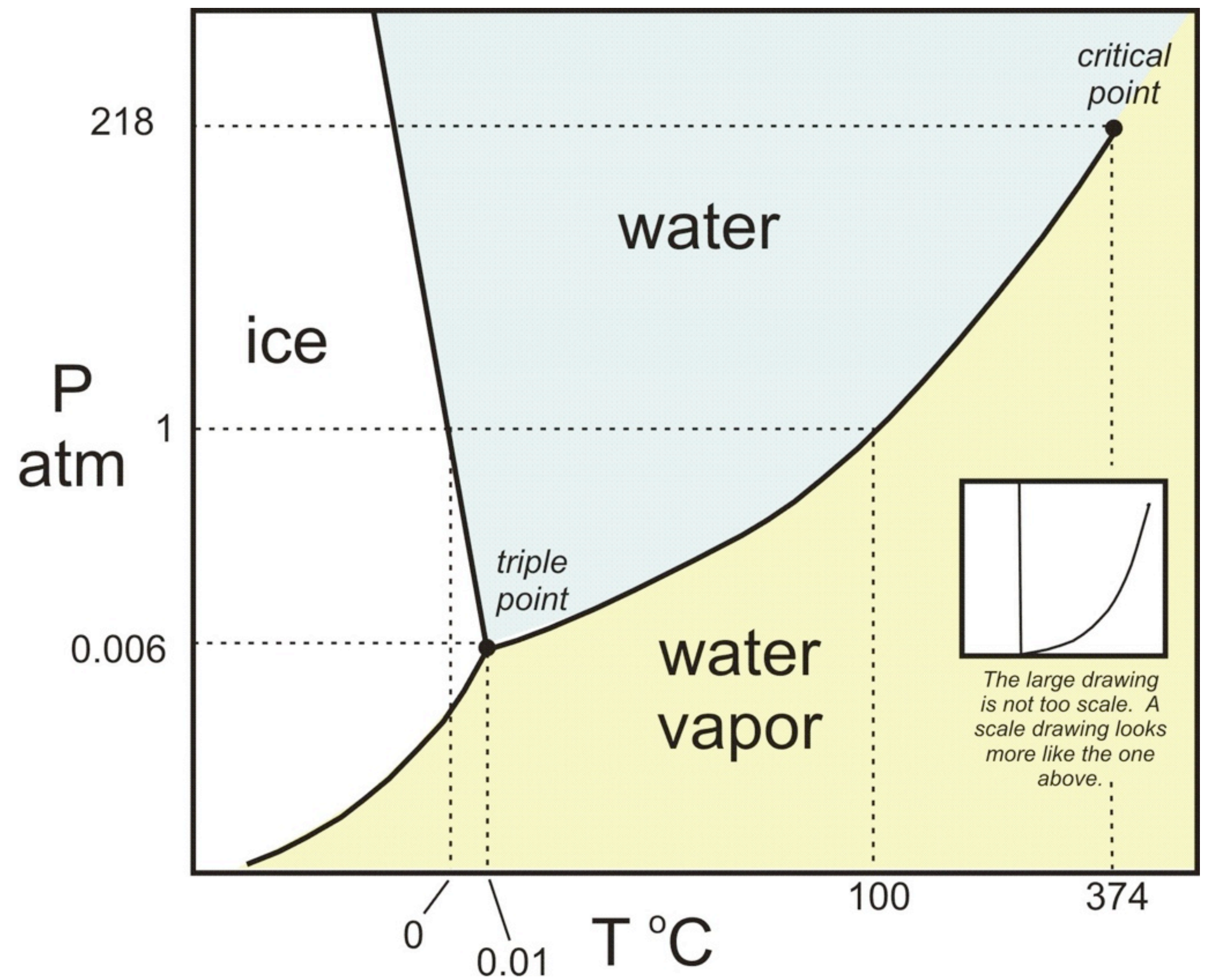


The QCD phase diagram



The QCD phase diagram

Just like with water, QCD has it's own phase diagram, which plots temperature vs net baryon density



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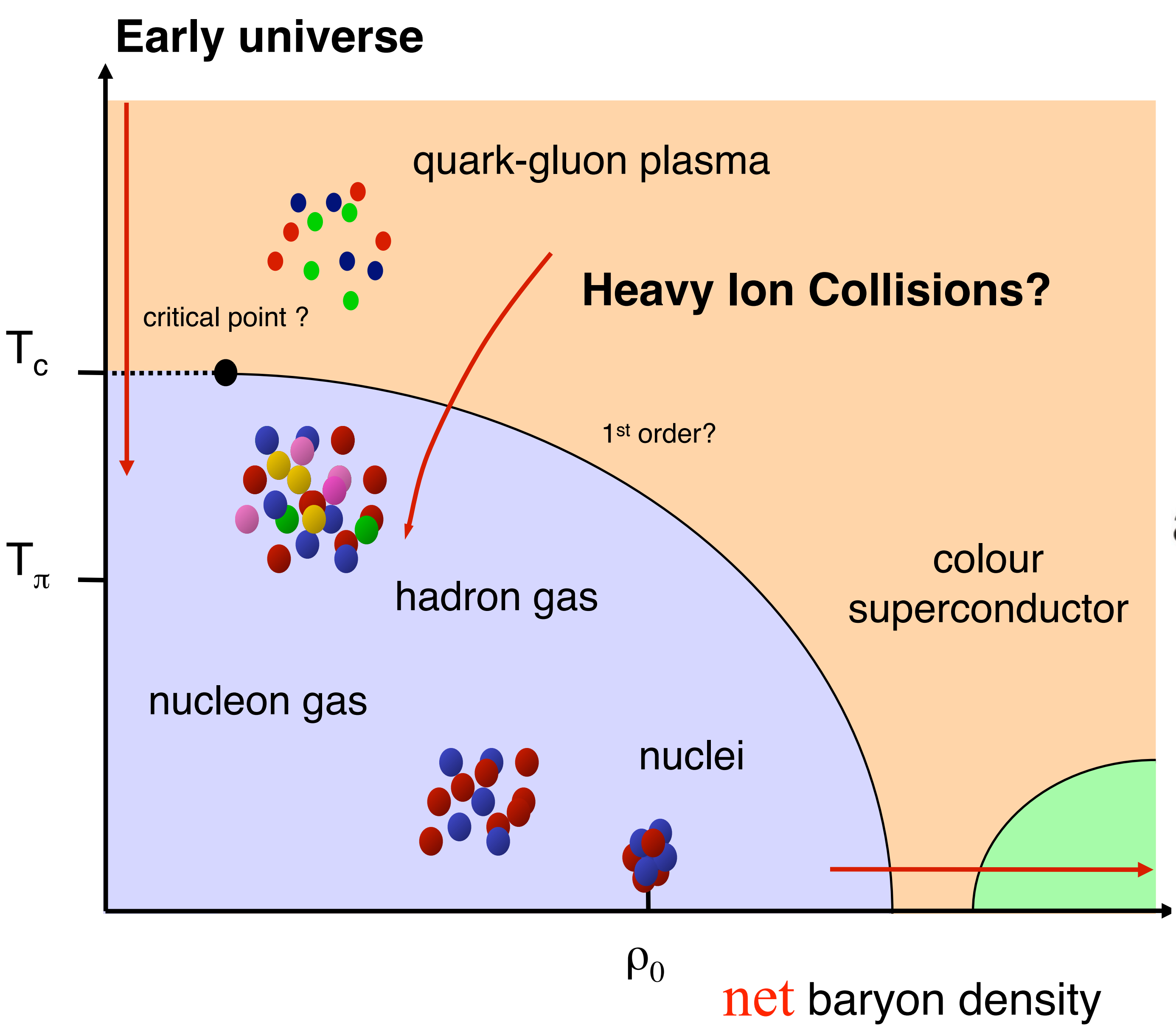

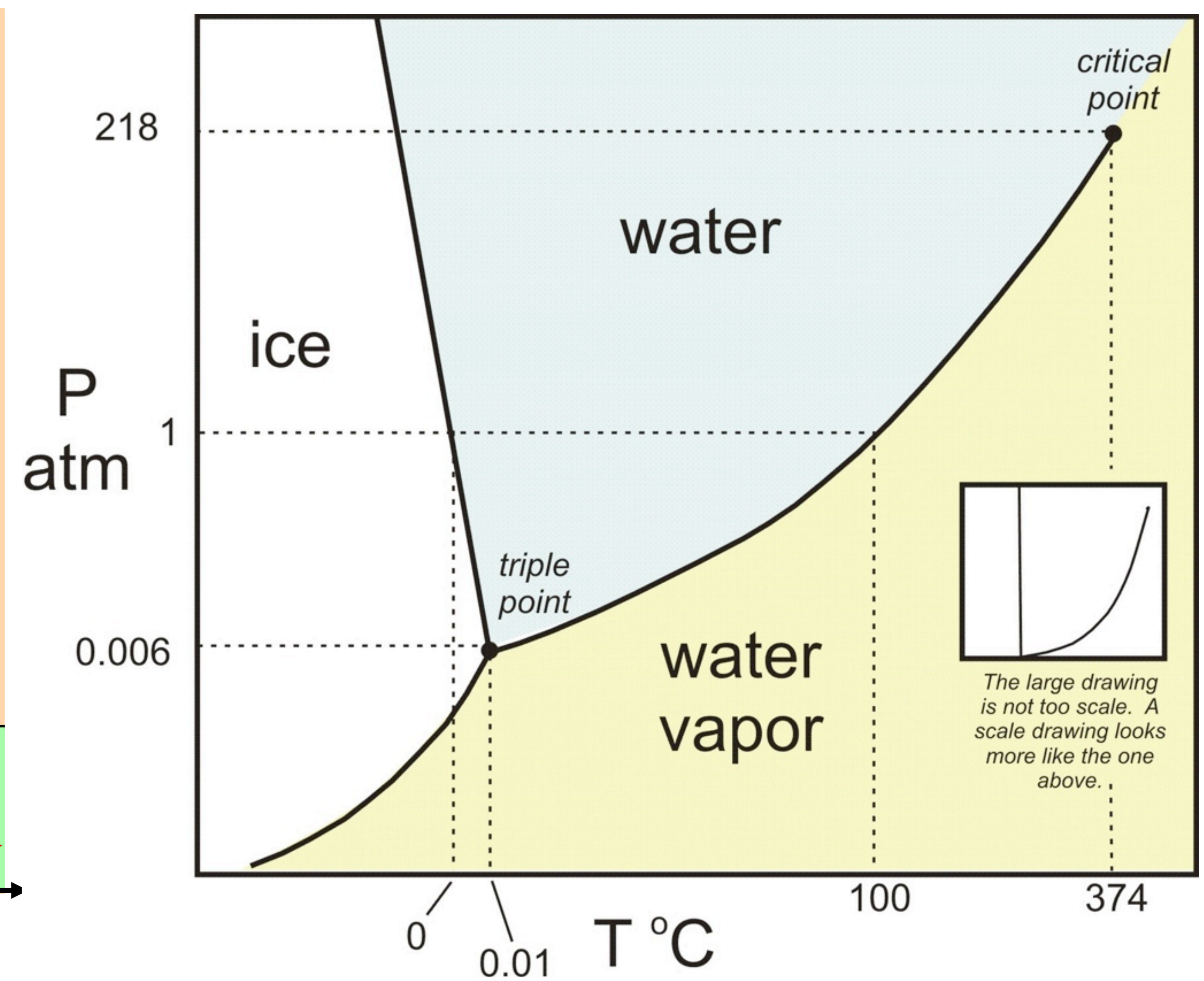

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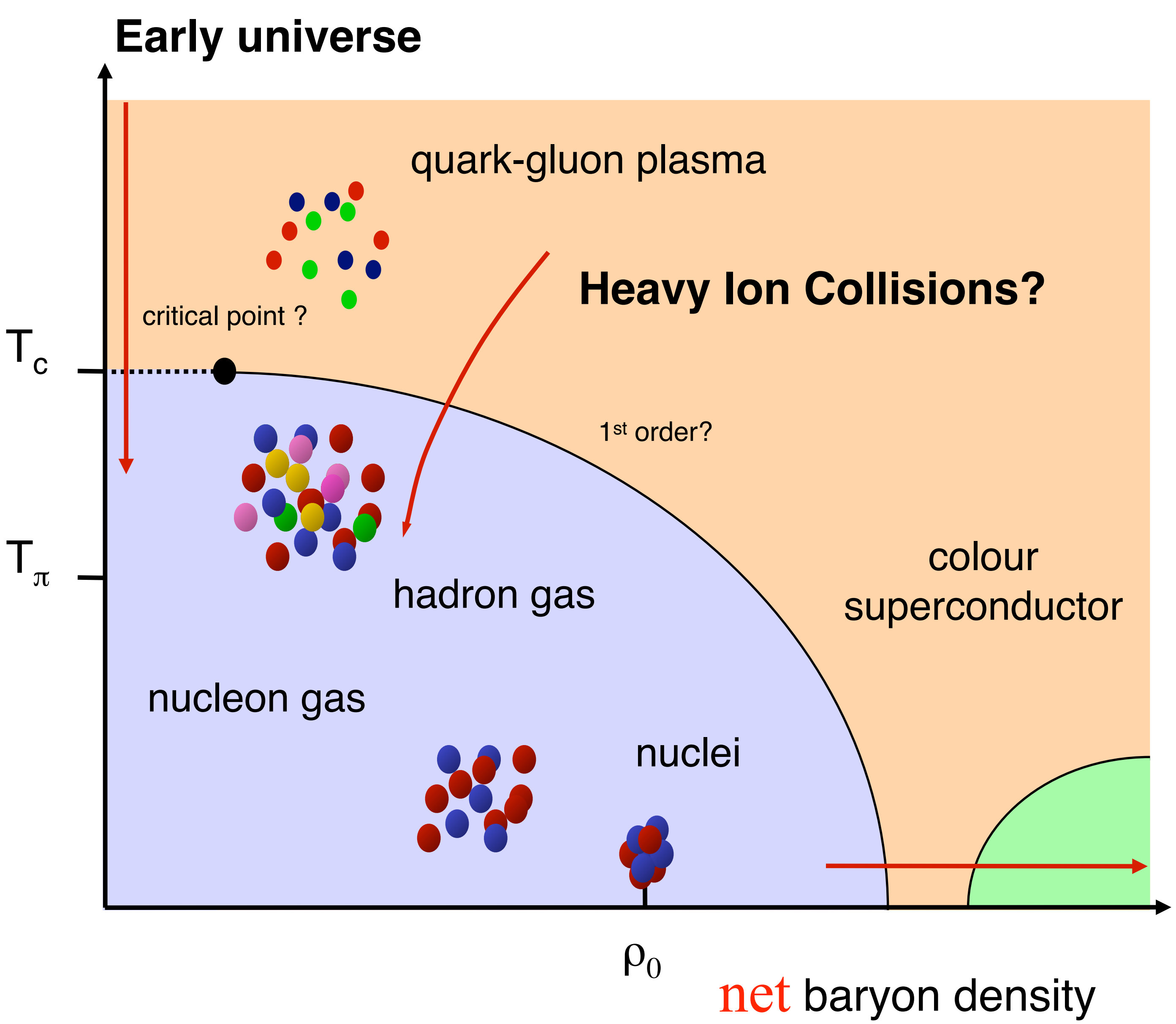

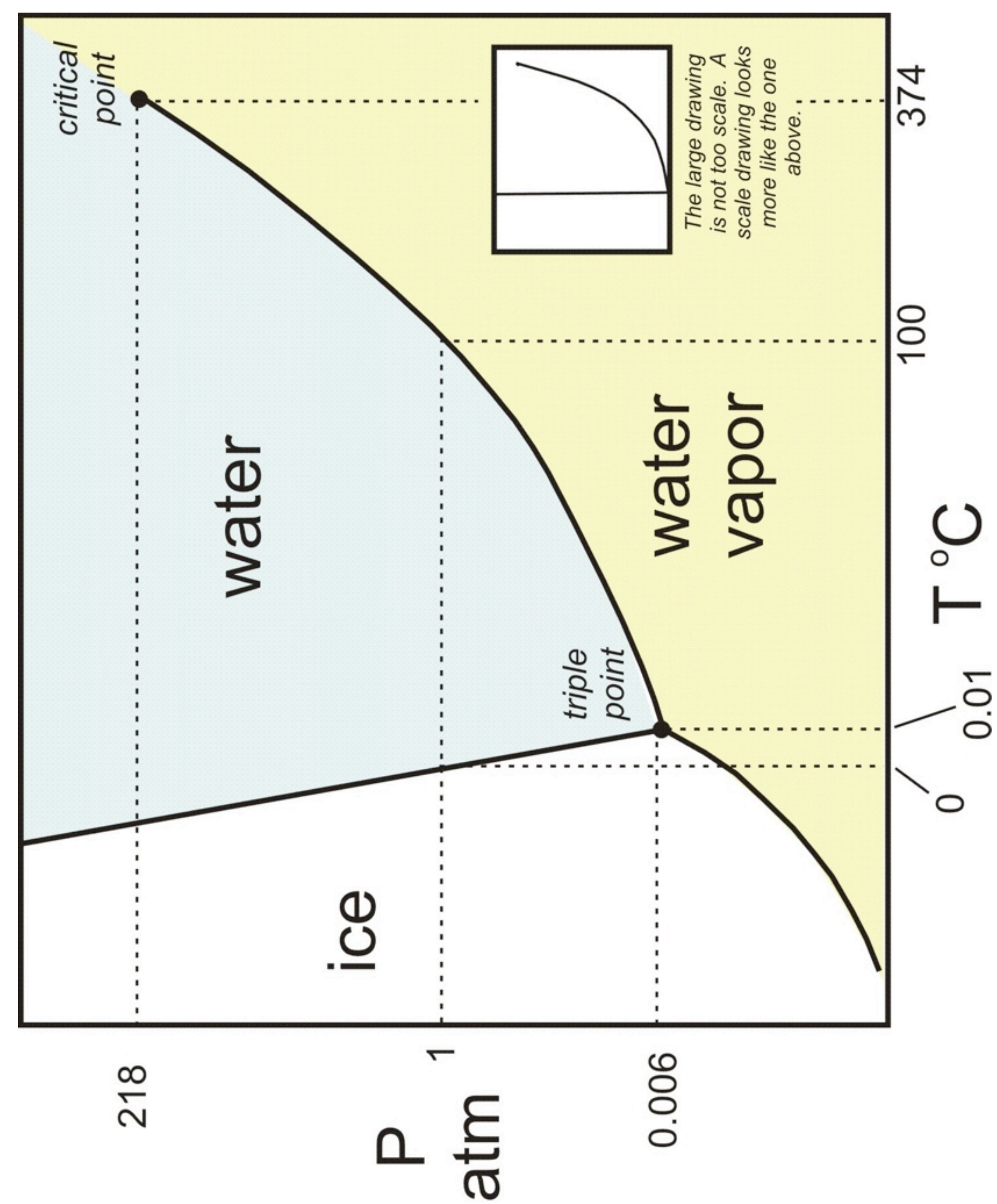

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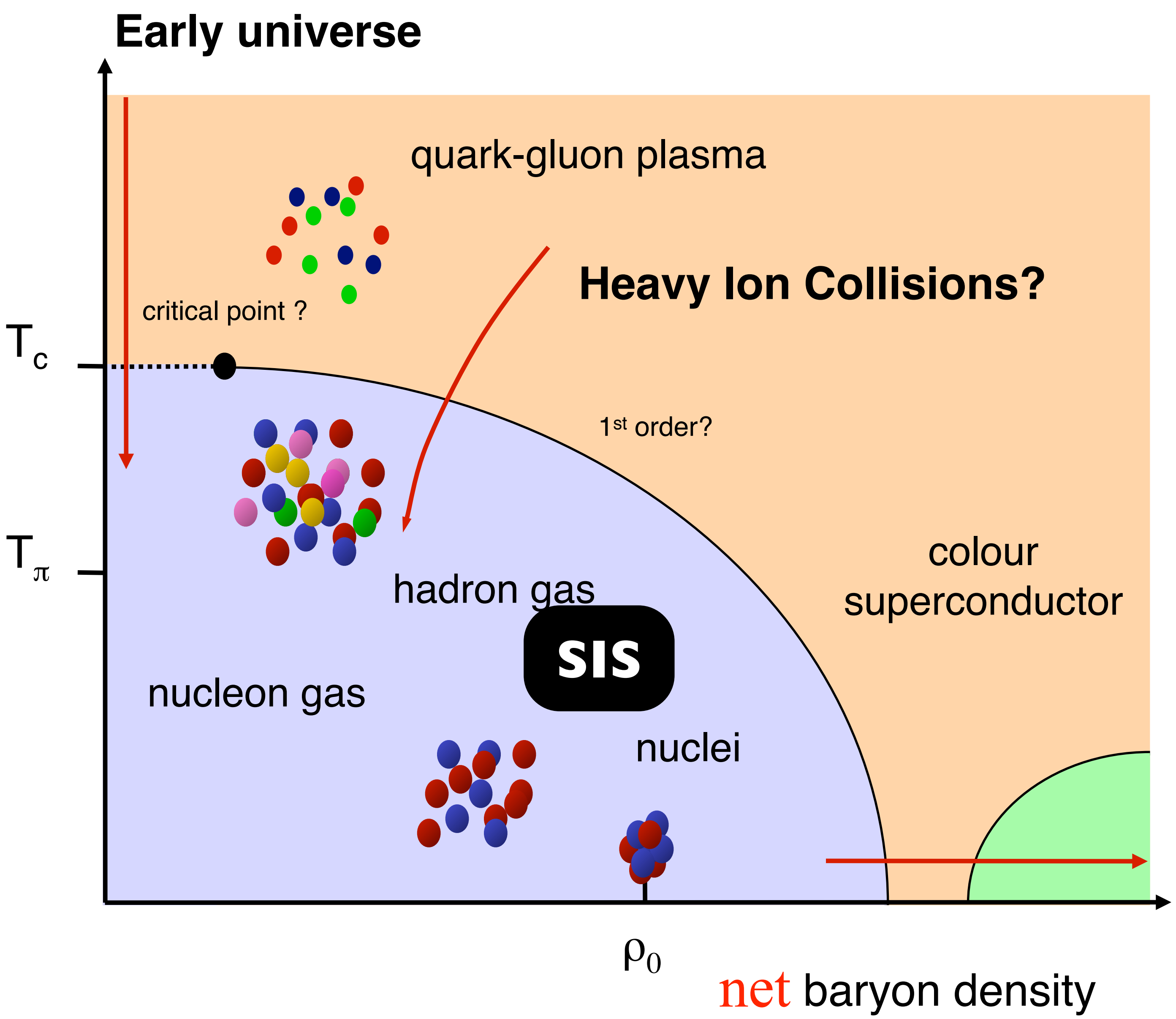

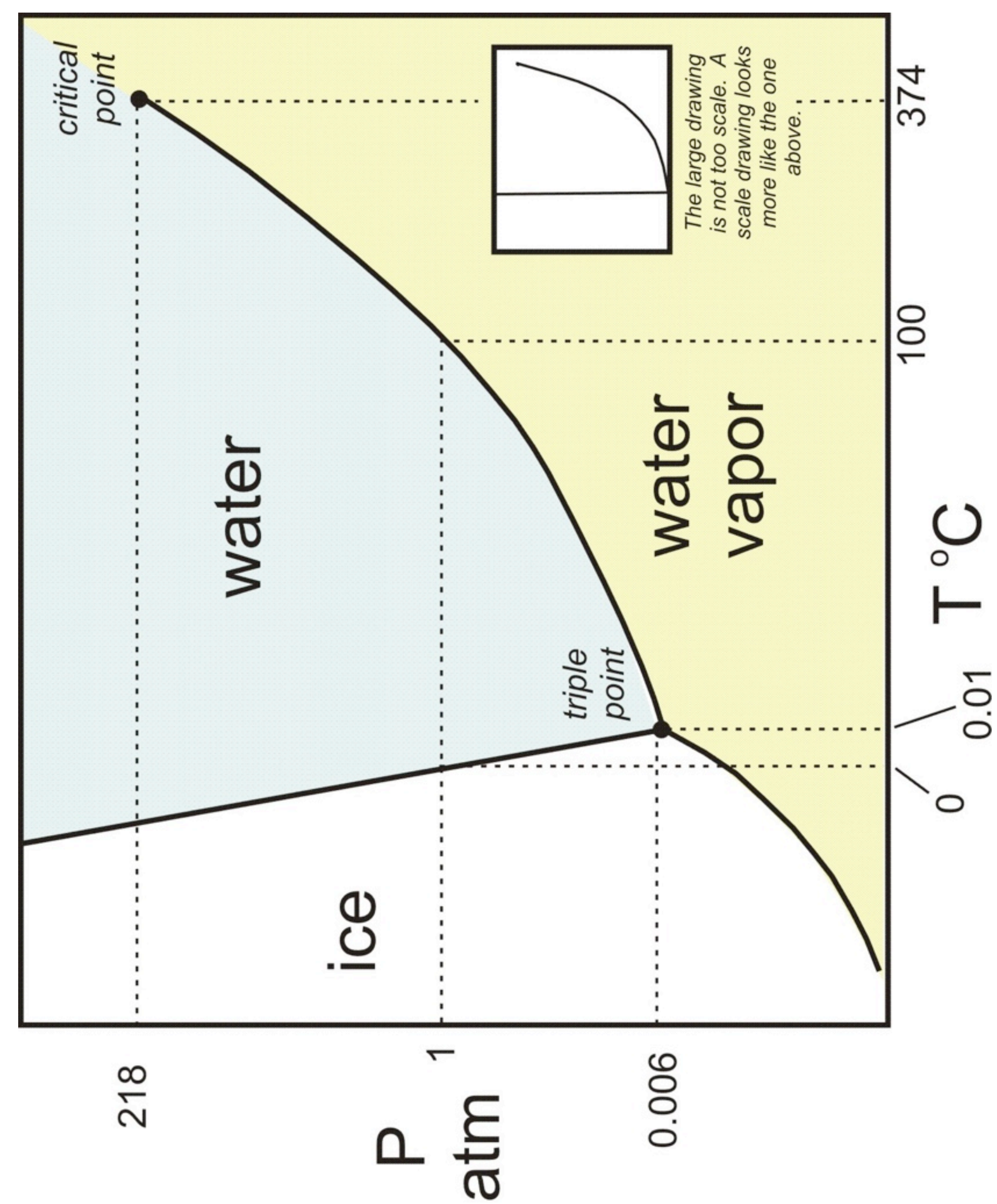

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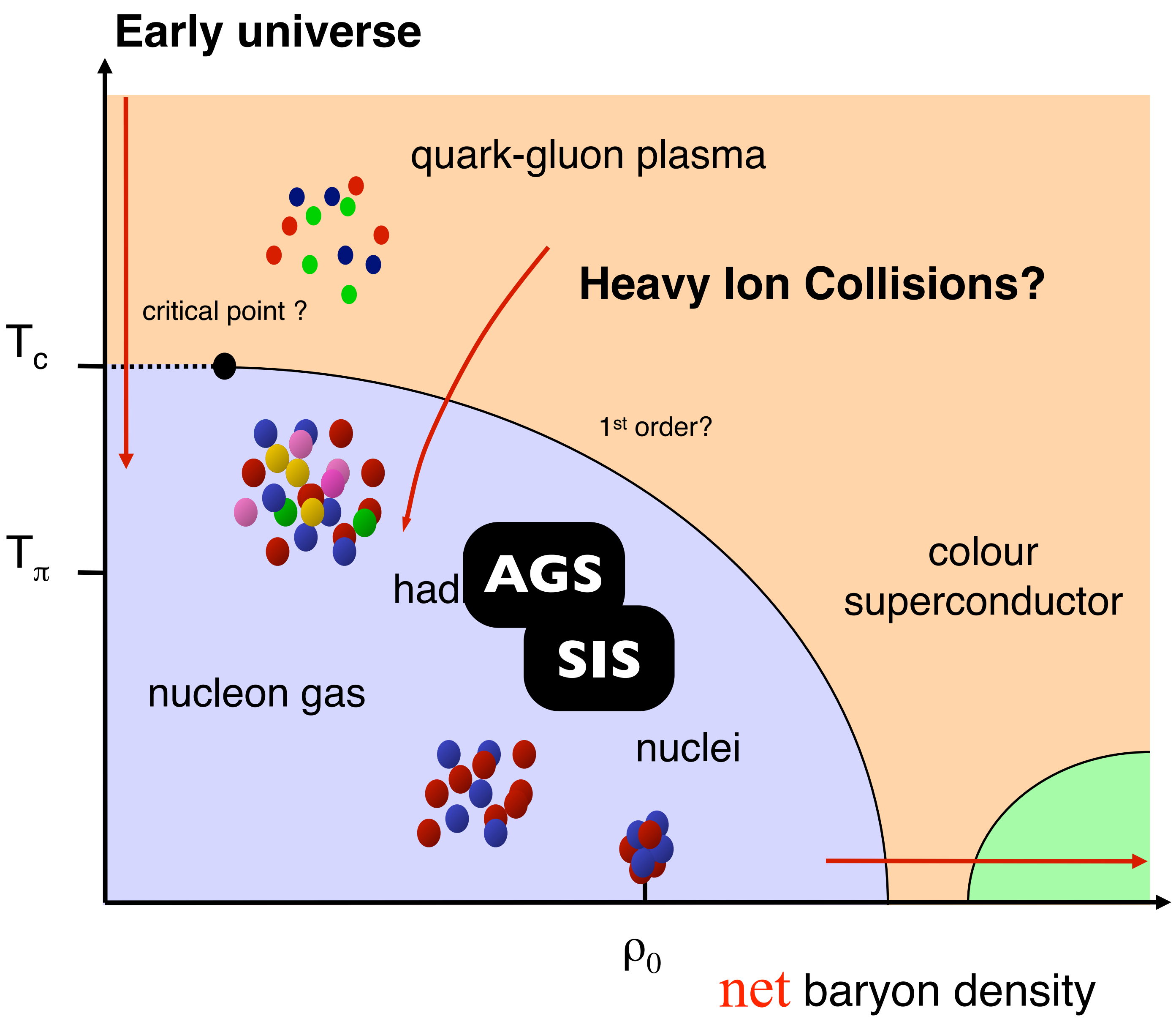

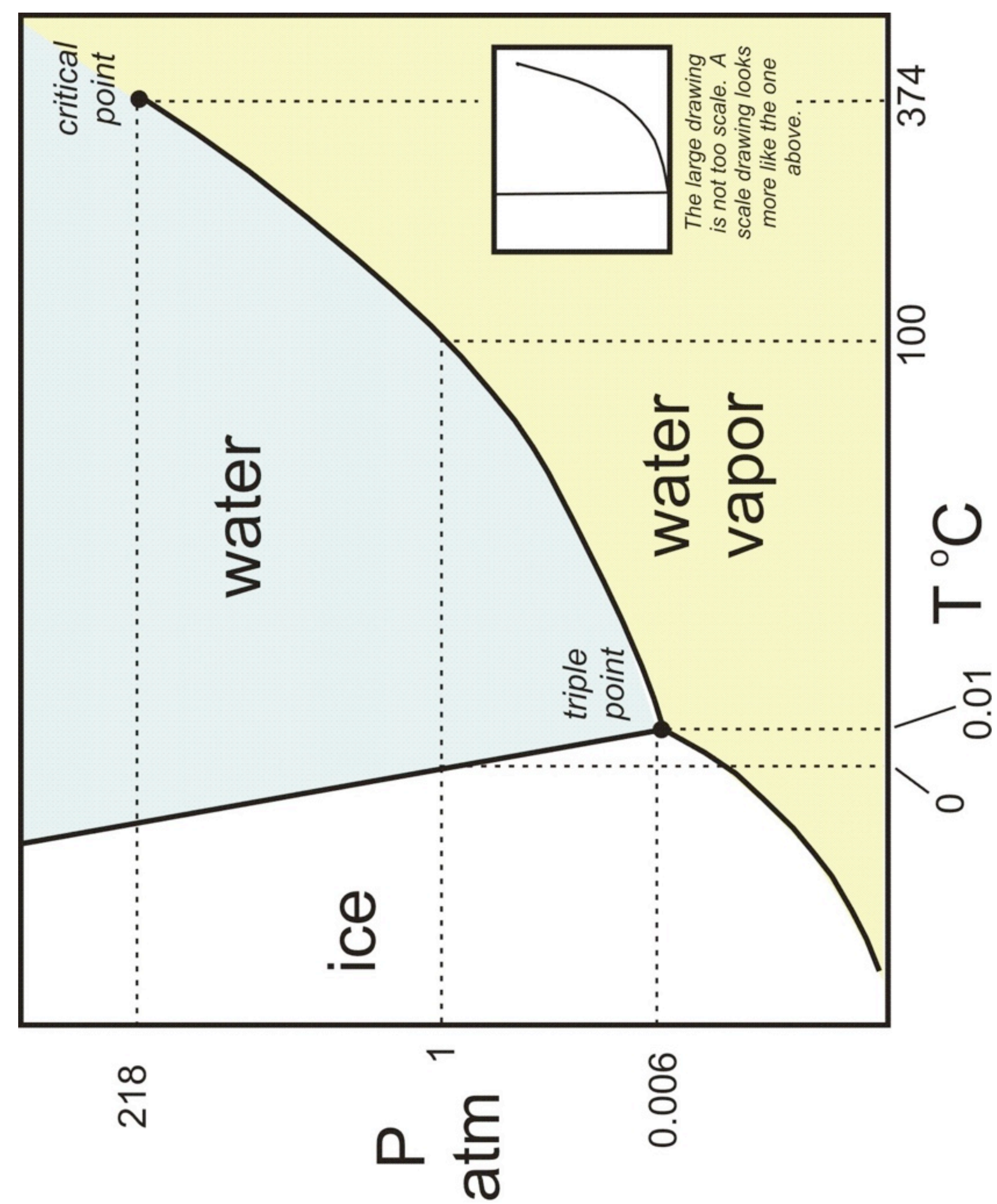

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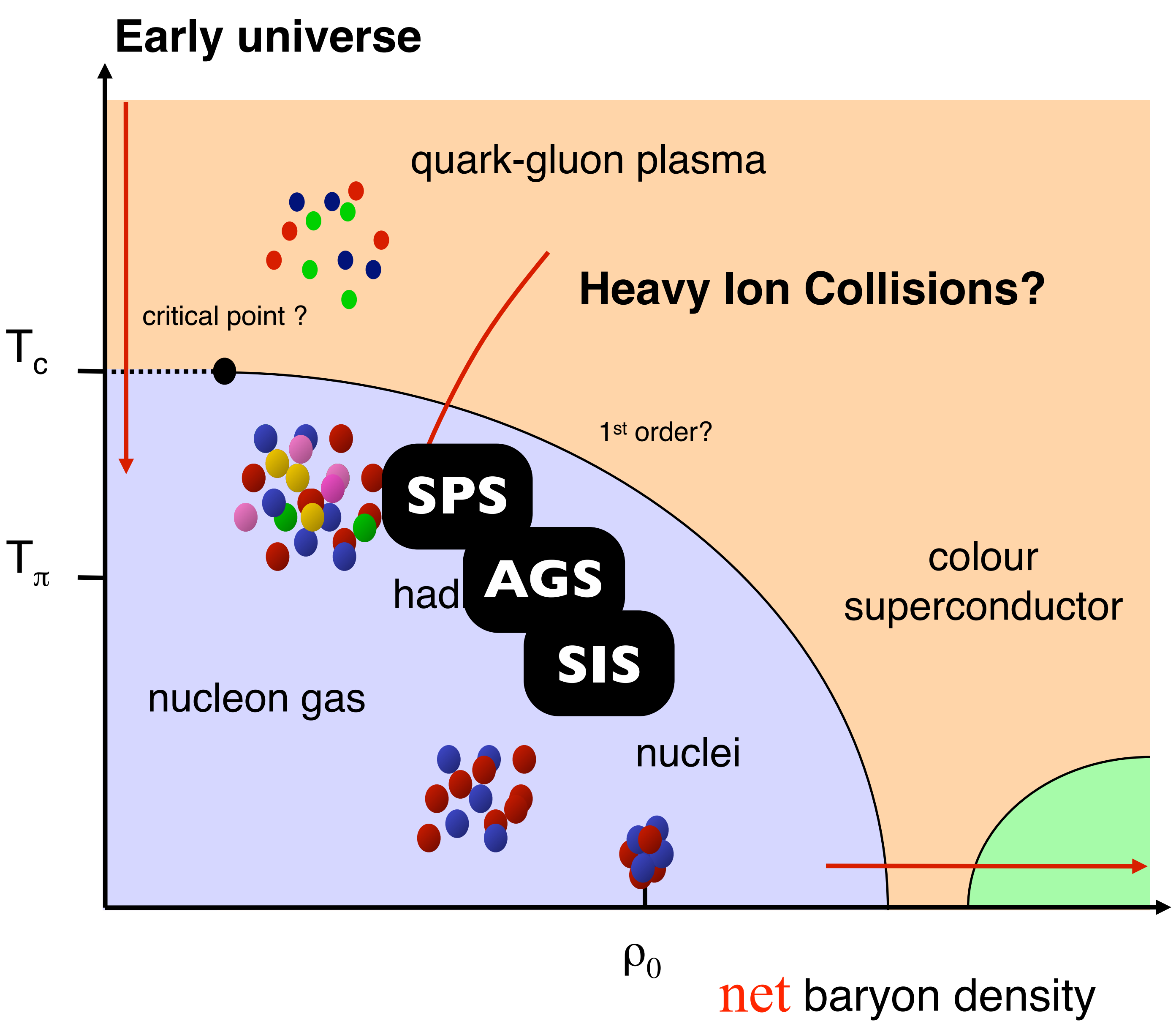

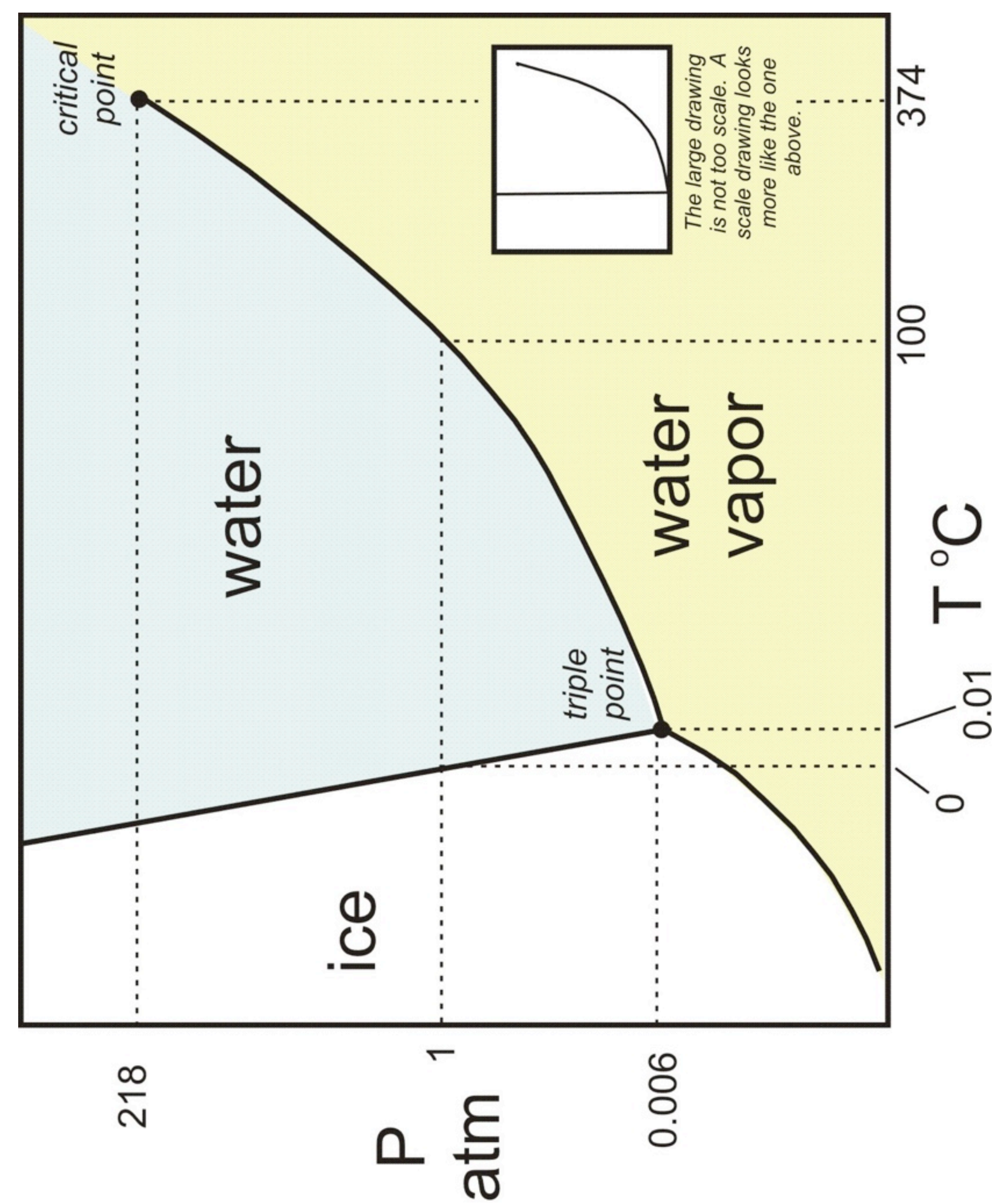

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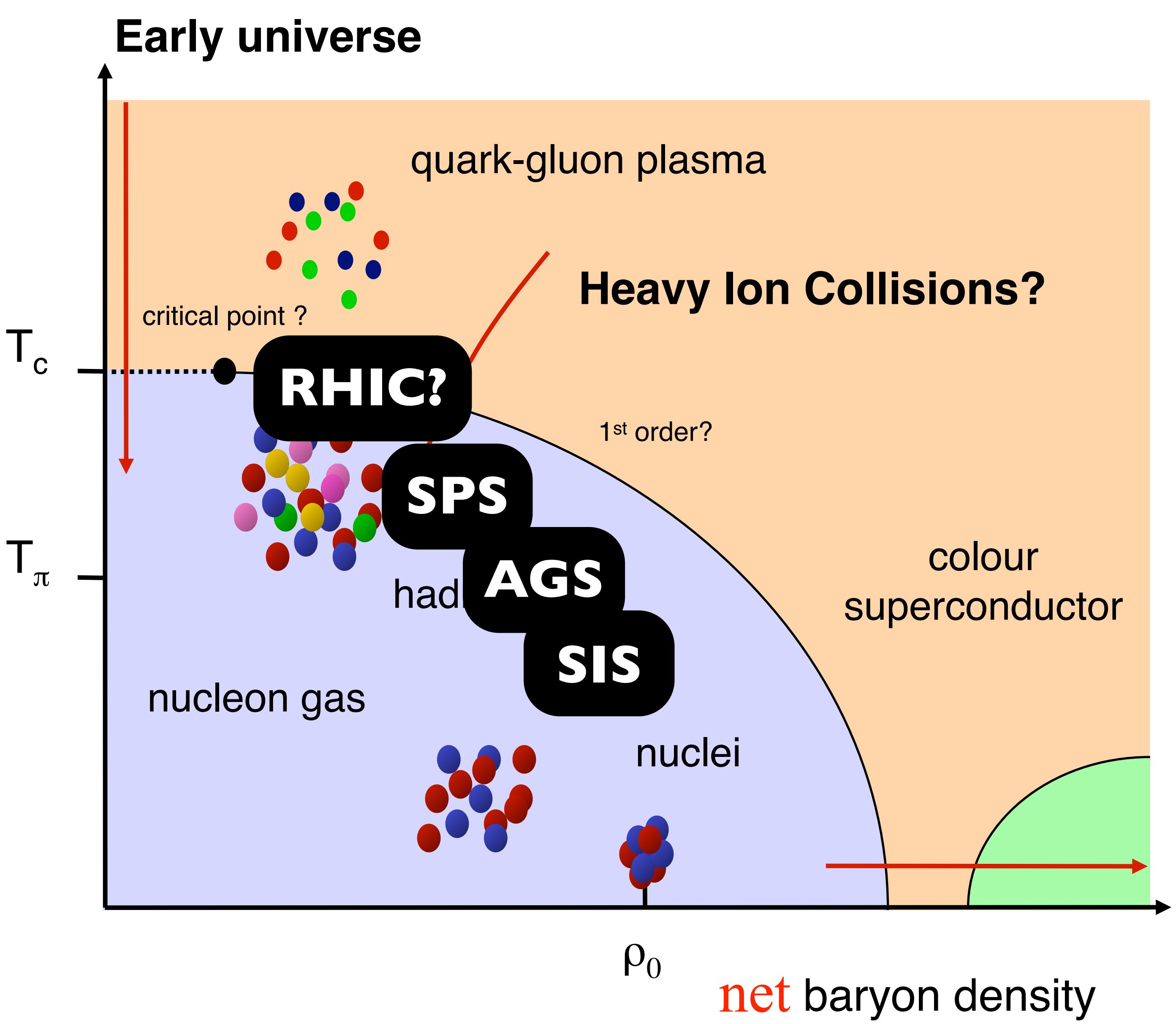

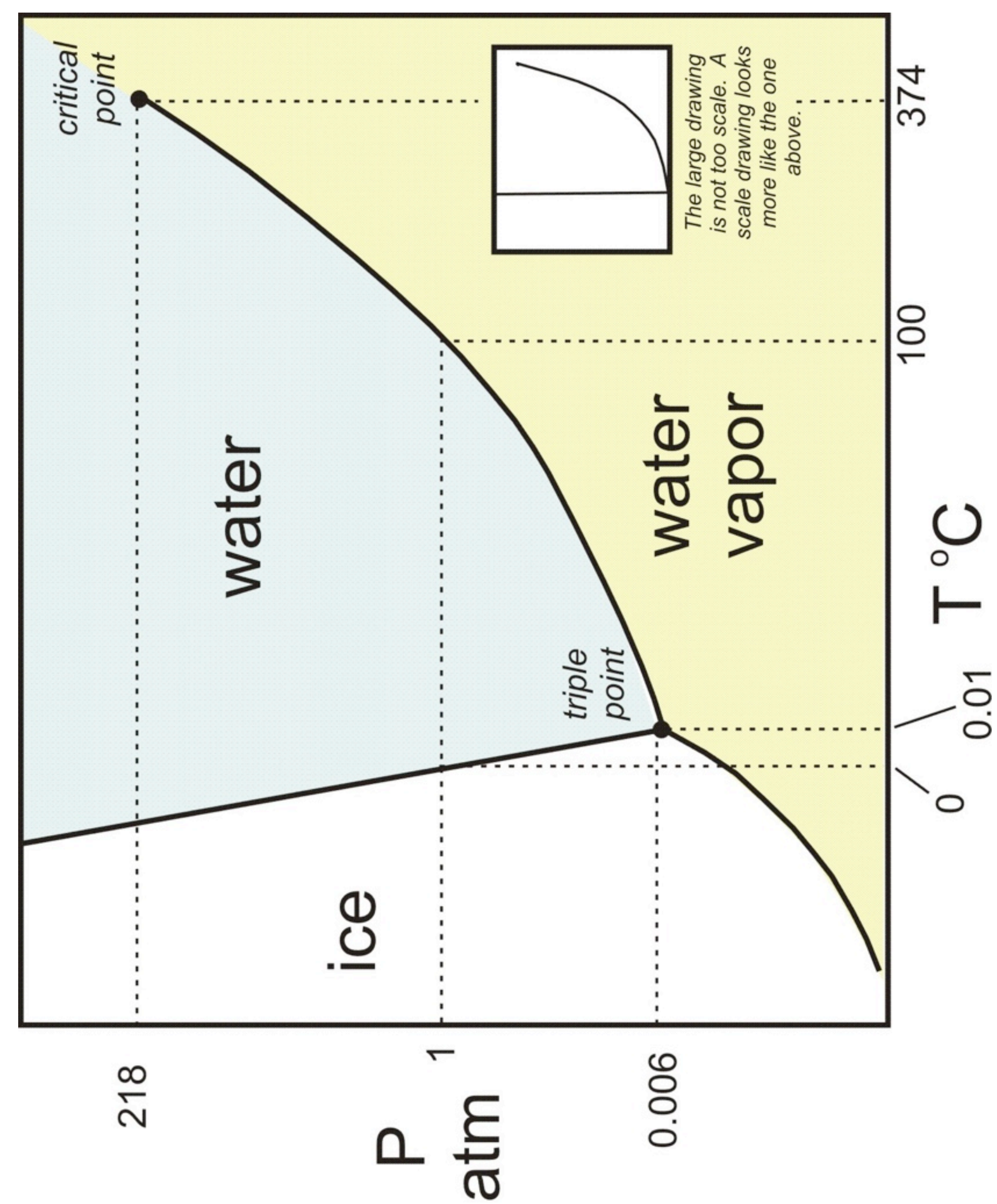

Highlights of the 1st decade of AA collisions in STAR

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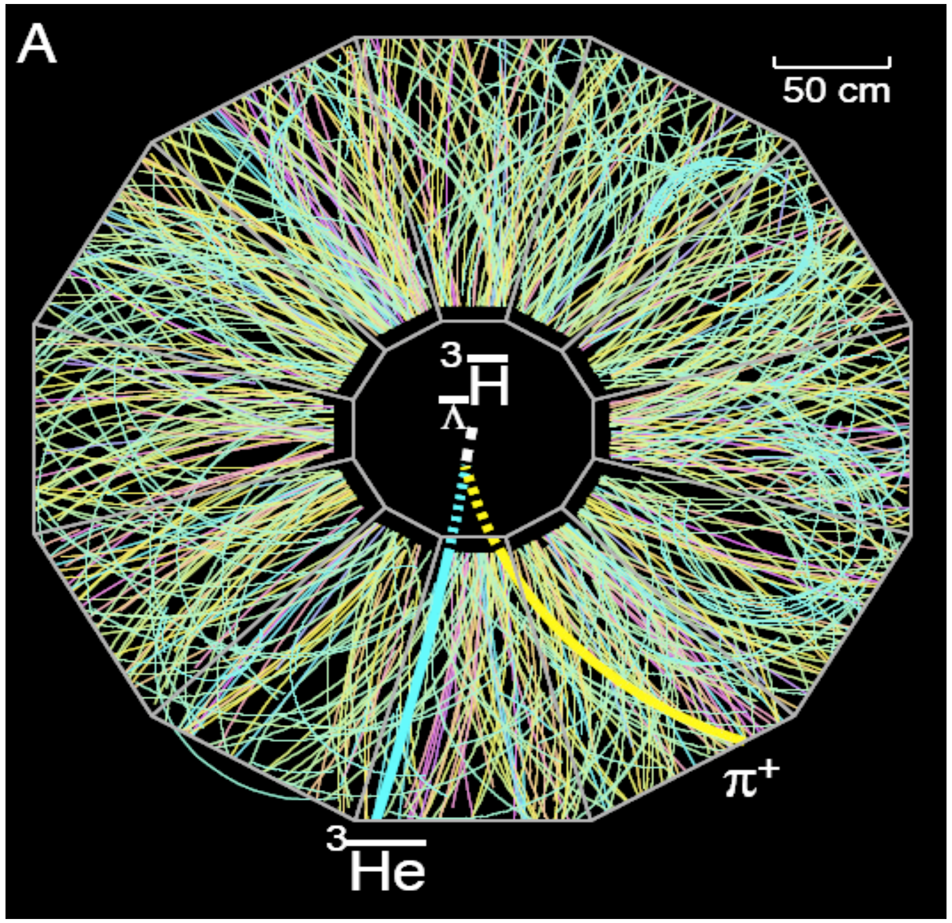
  - First observations of ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$



Science

***Science* 328,** 58 (2010)

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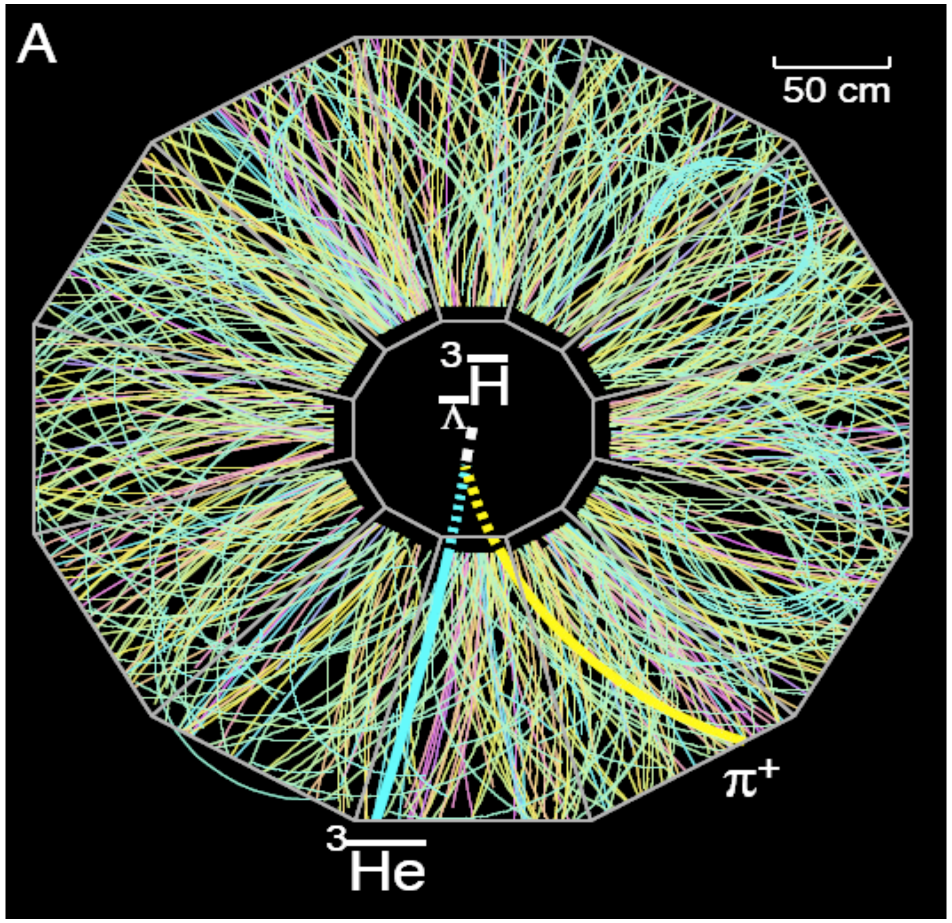

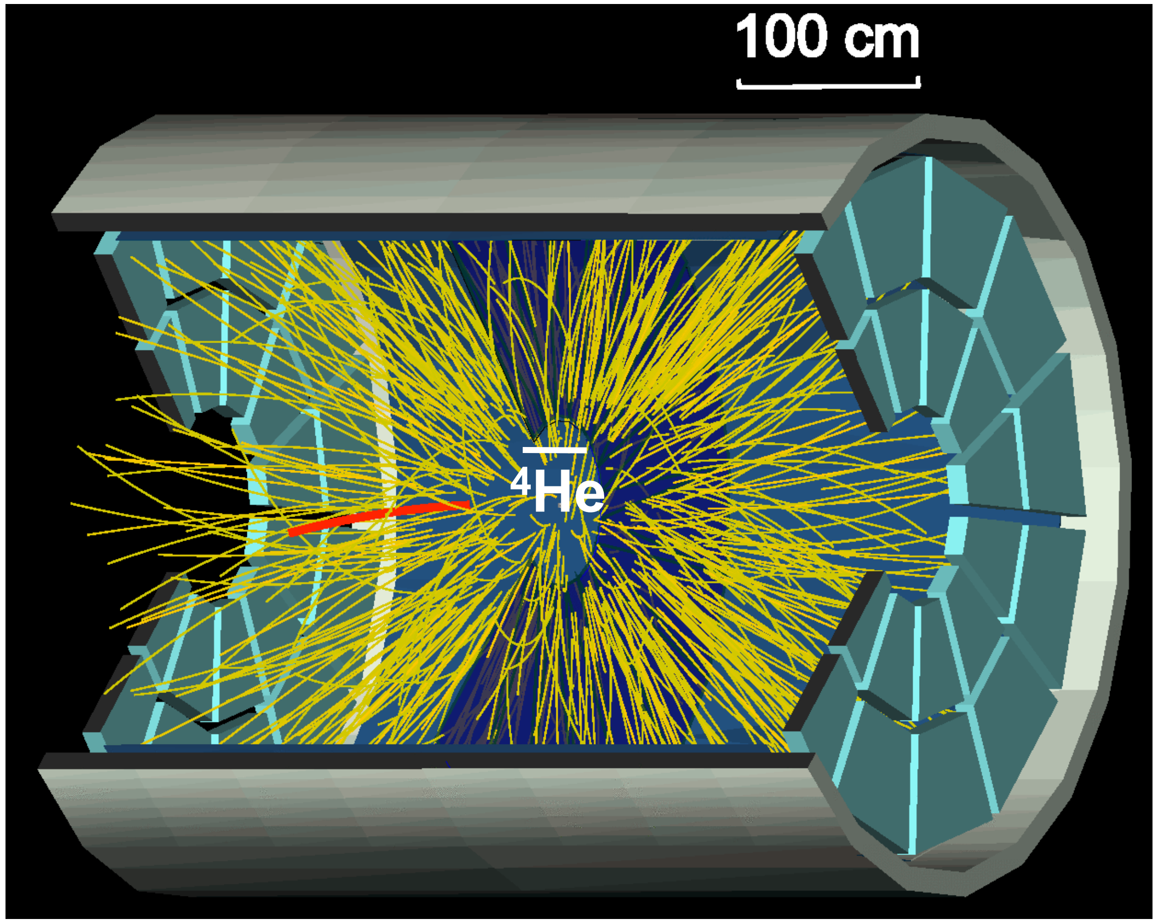

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nature

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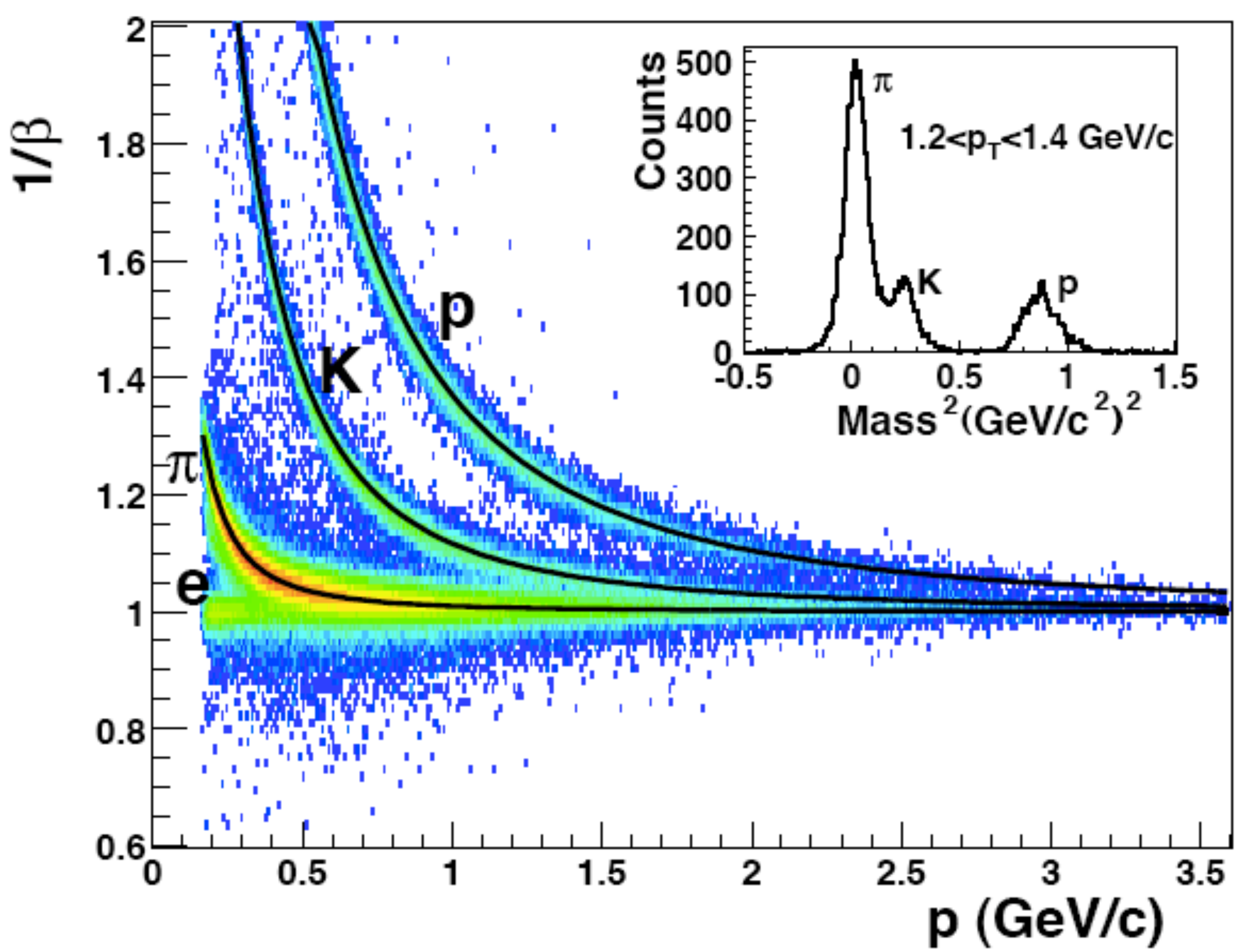

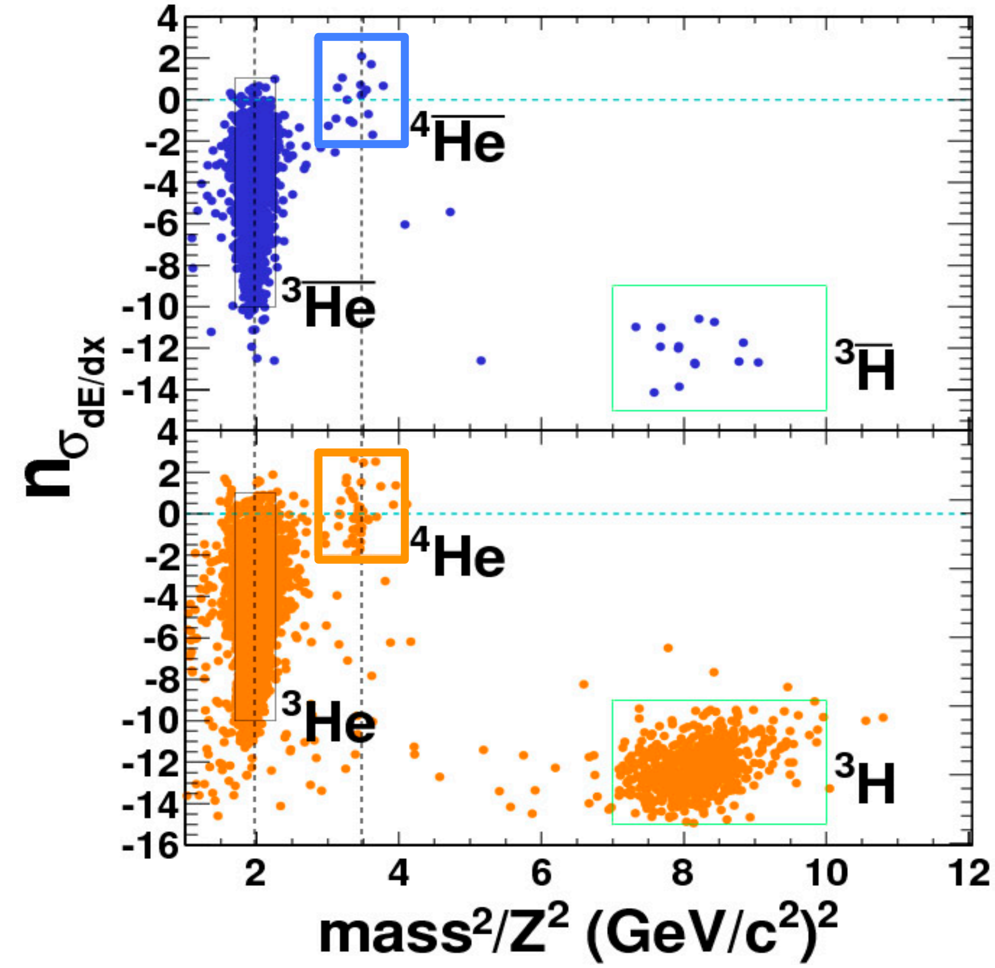

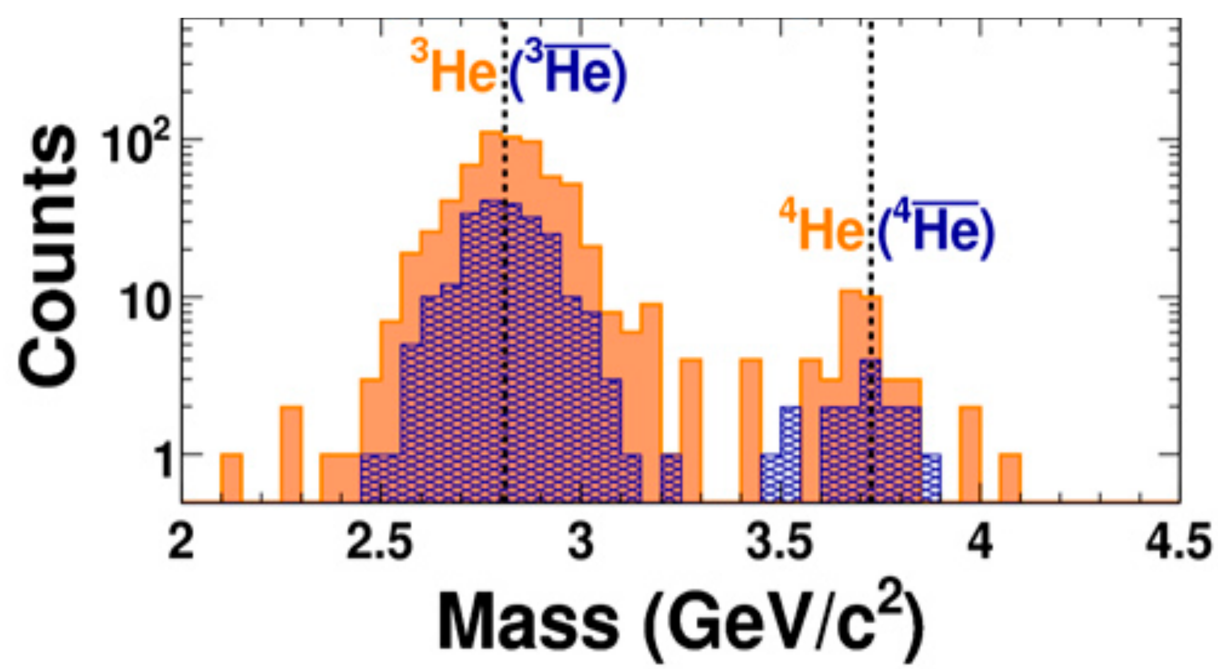

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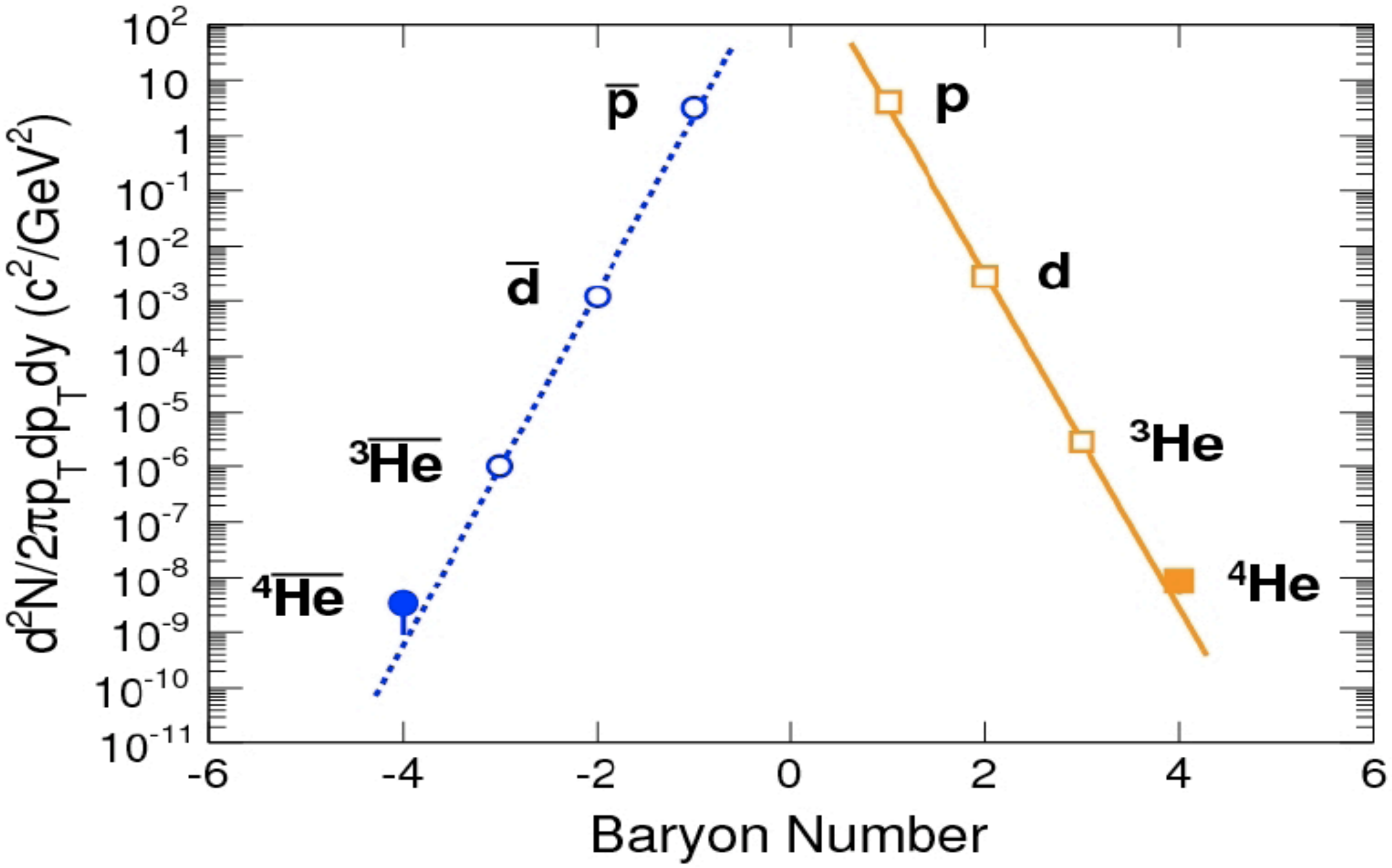

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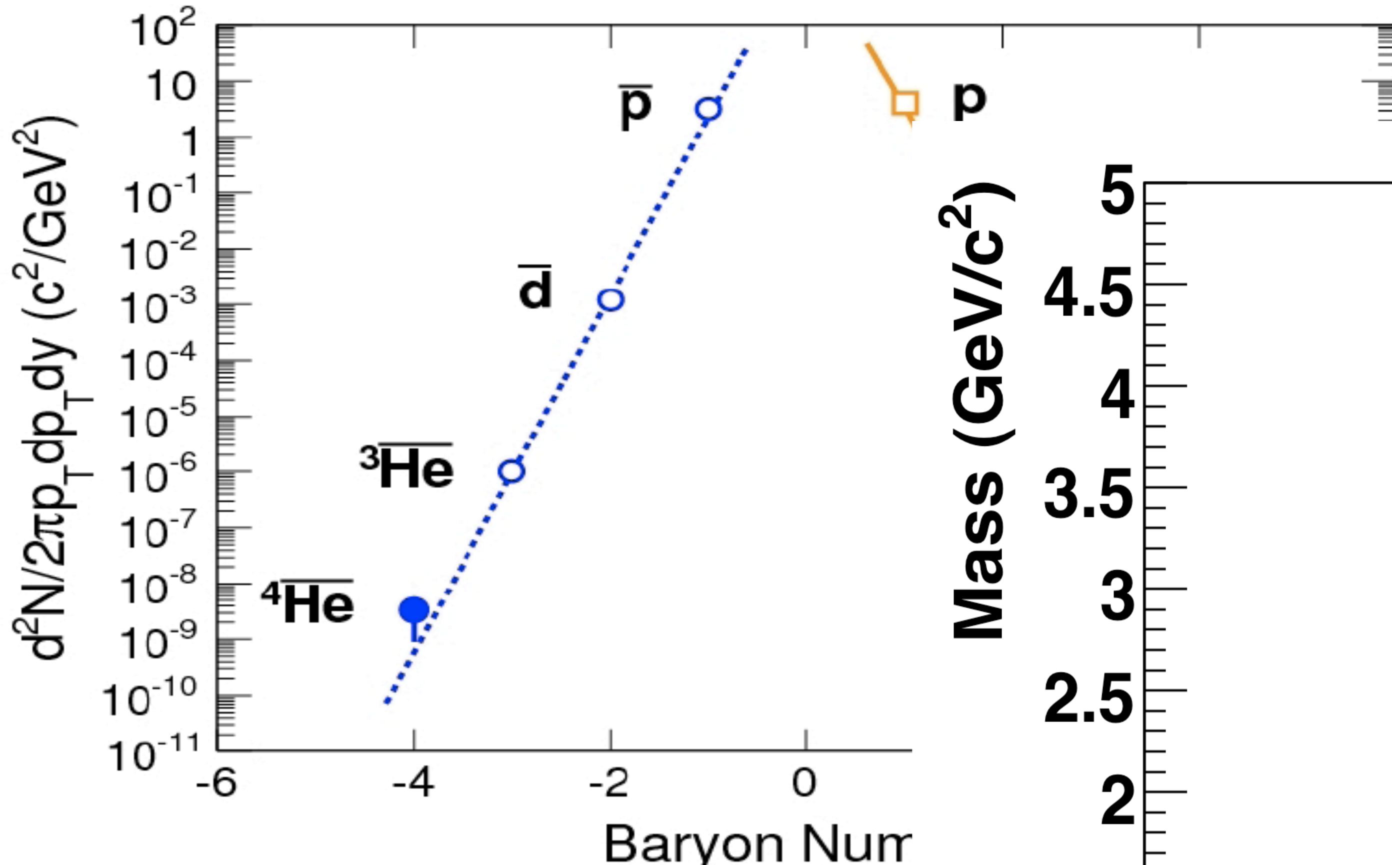

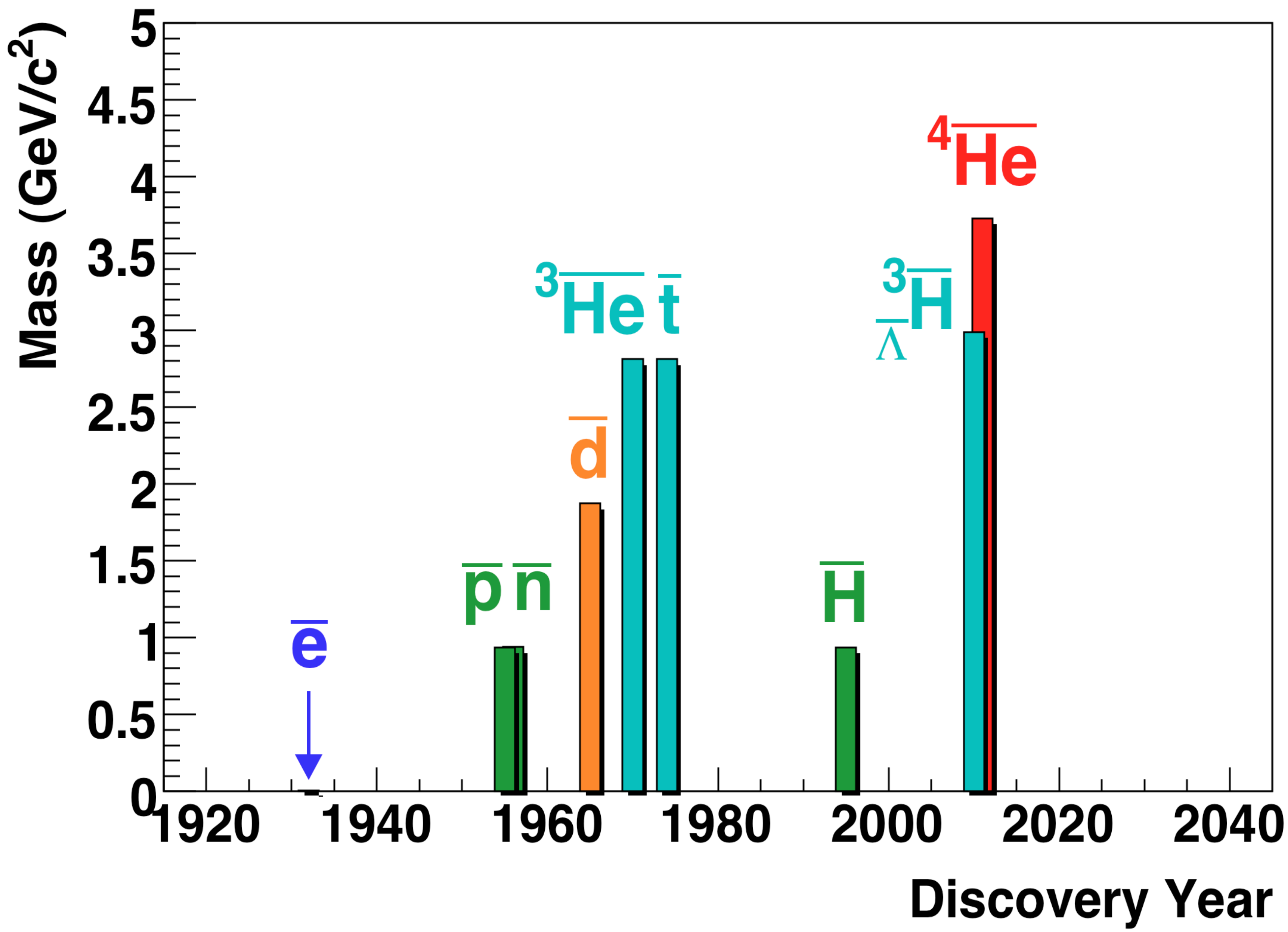

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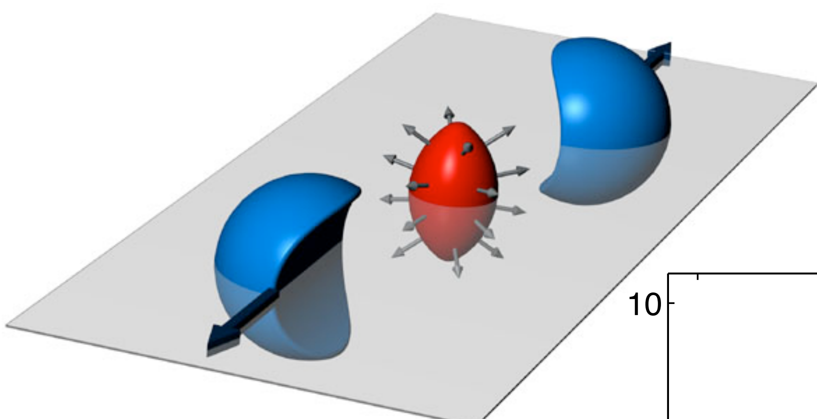

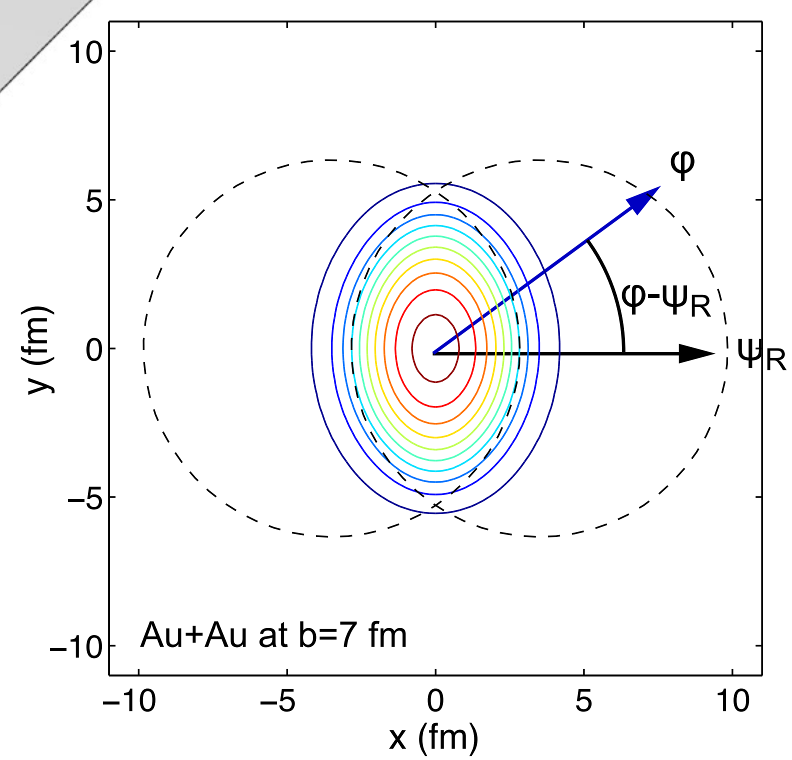

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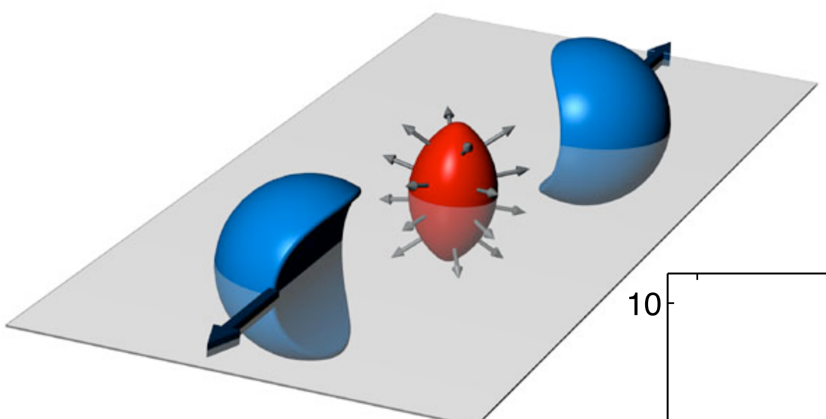

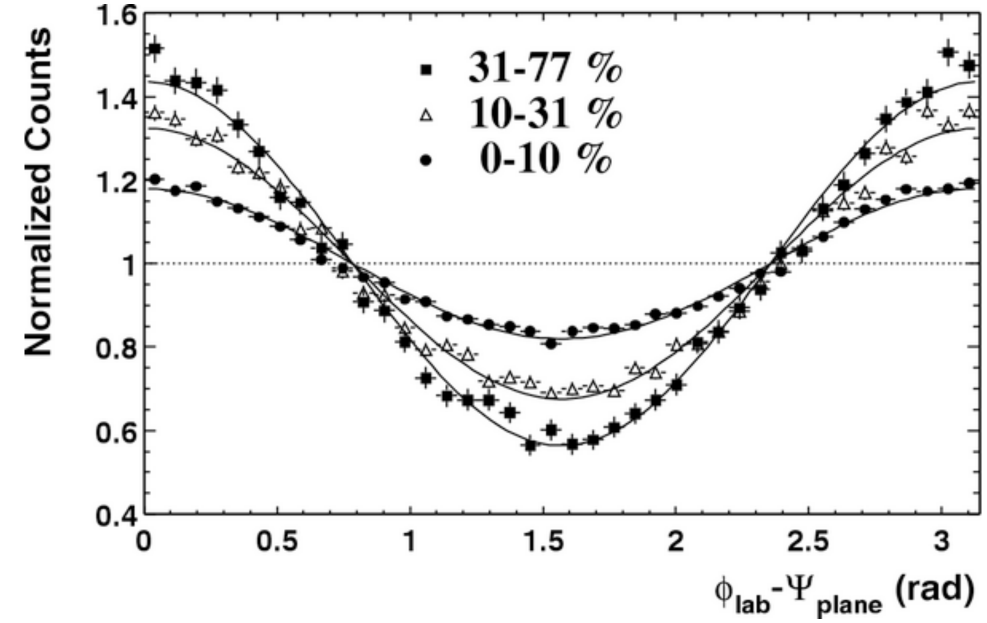

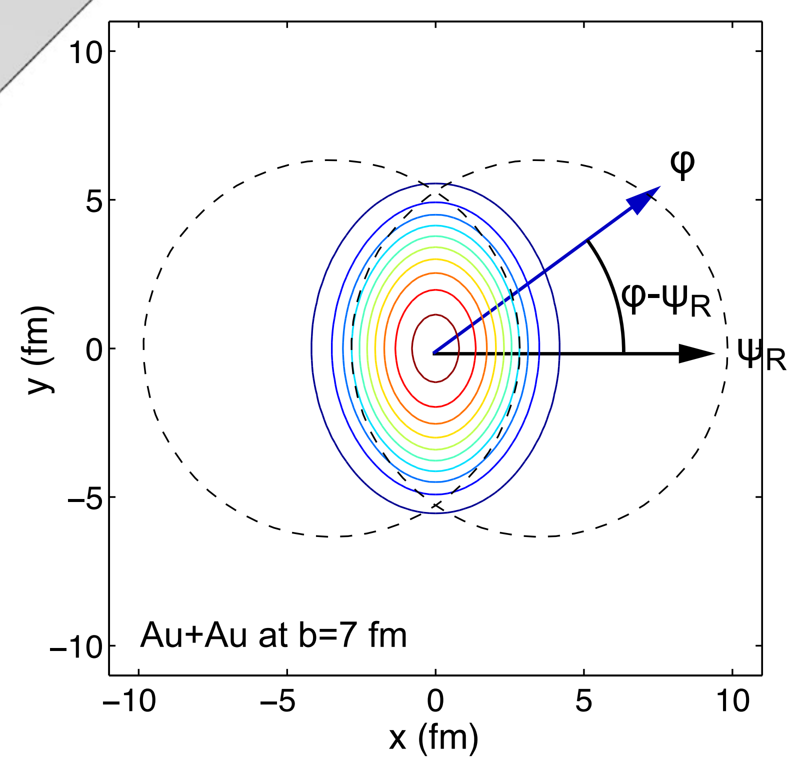

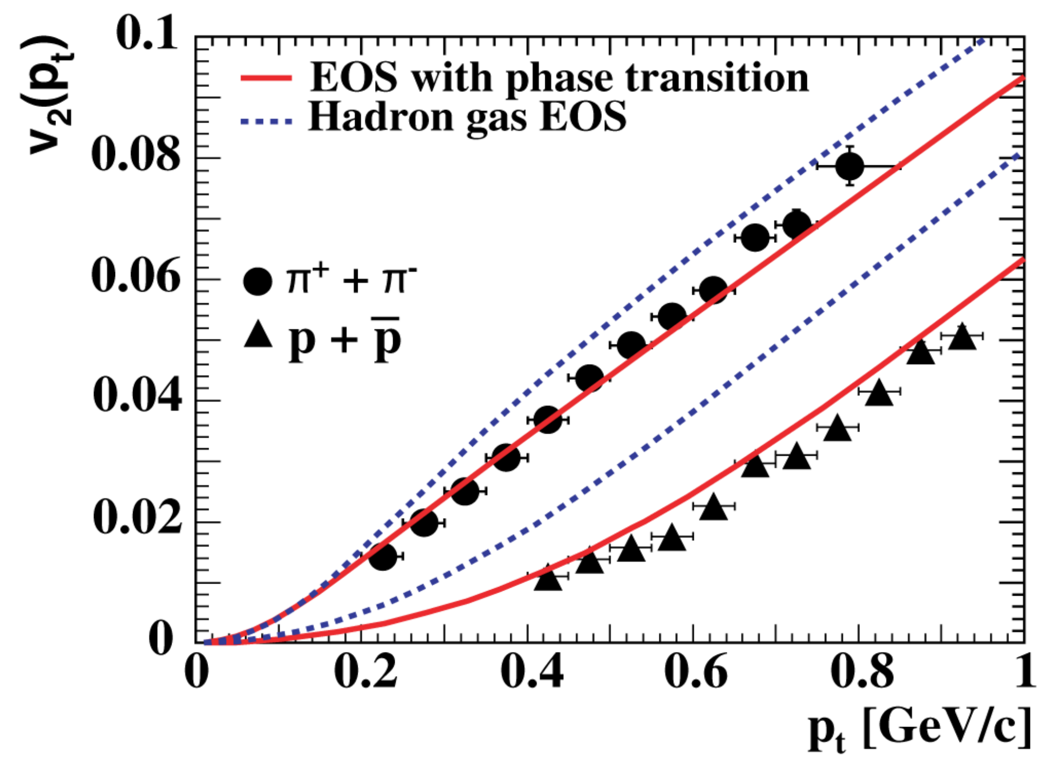

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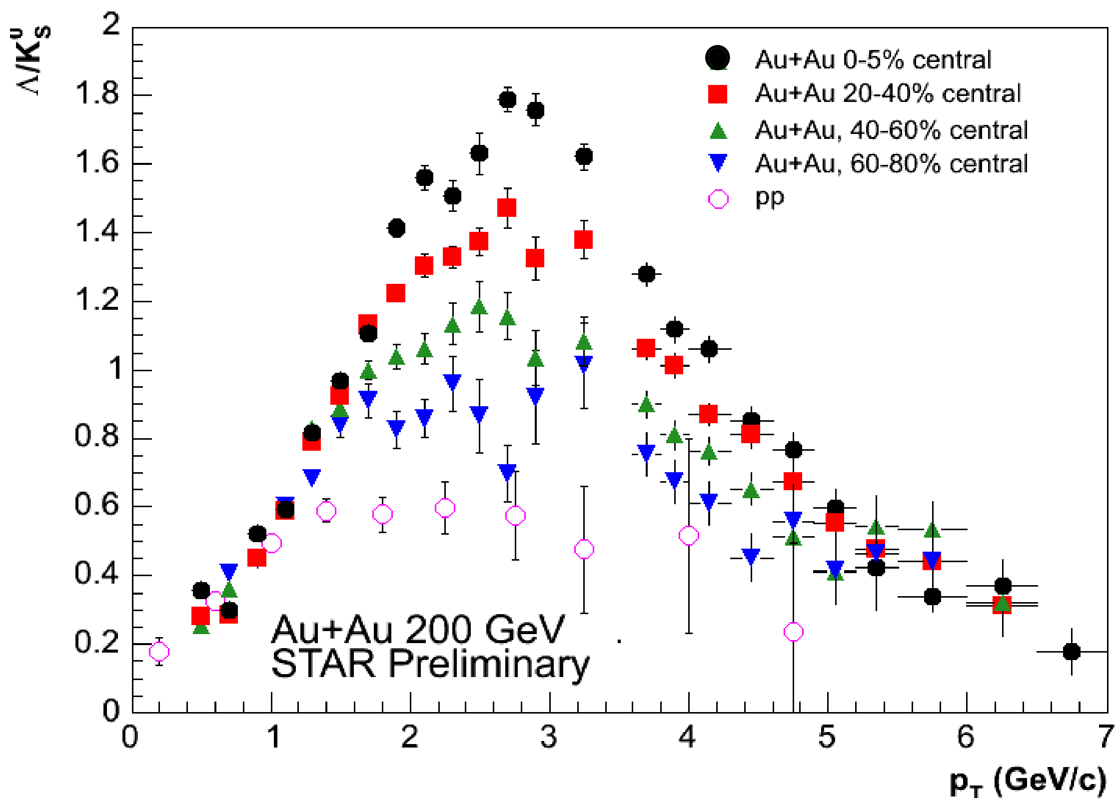

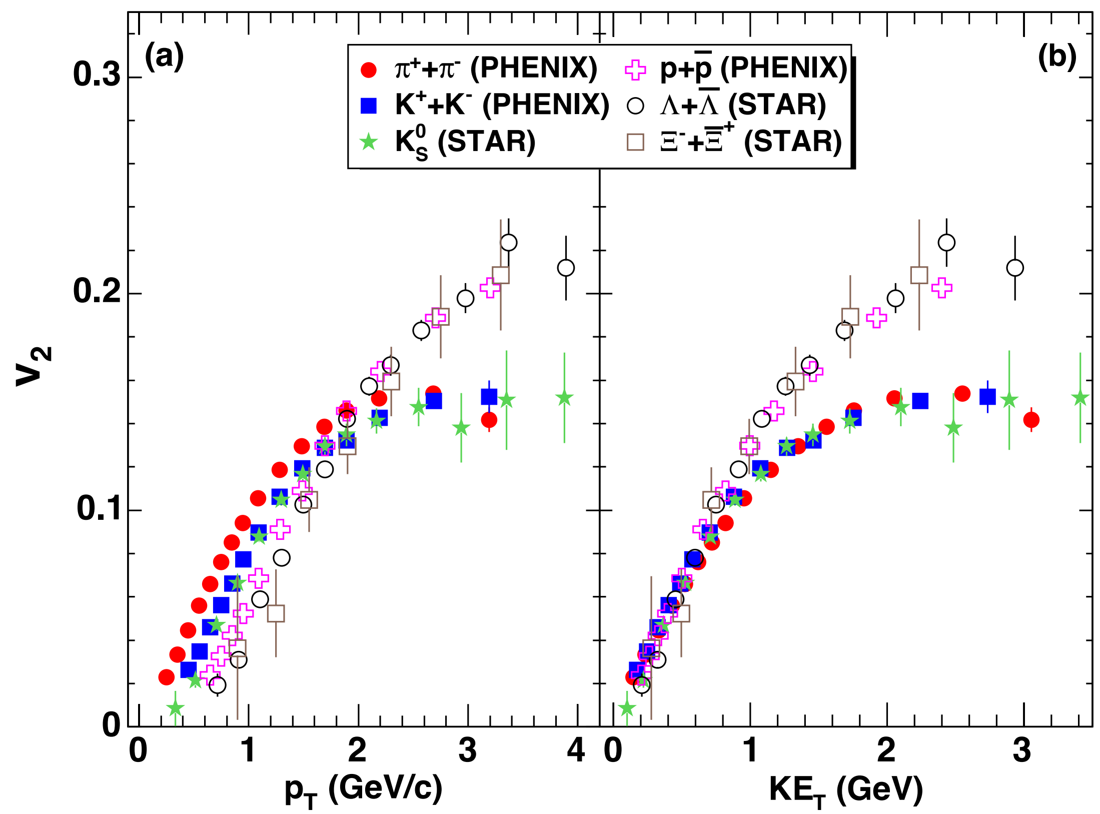

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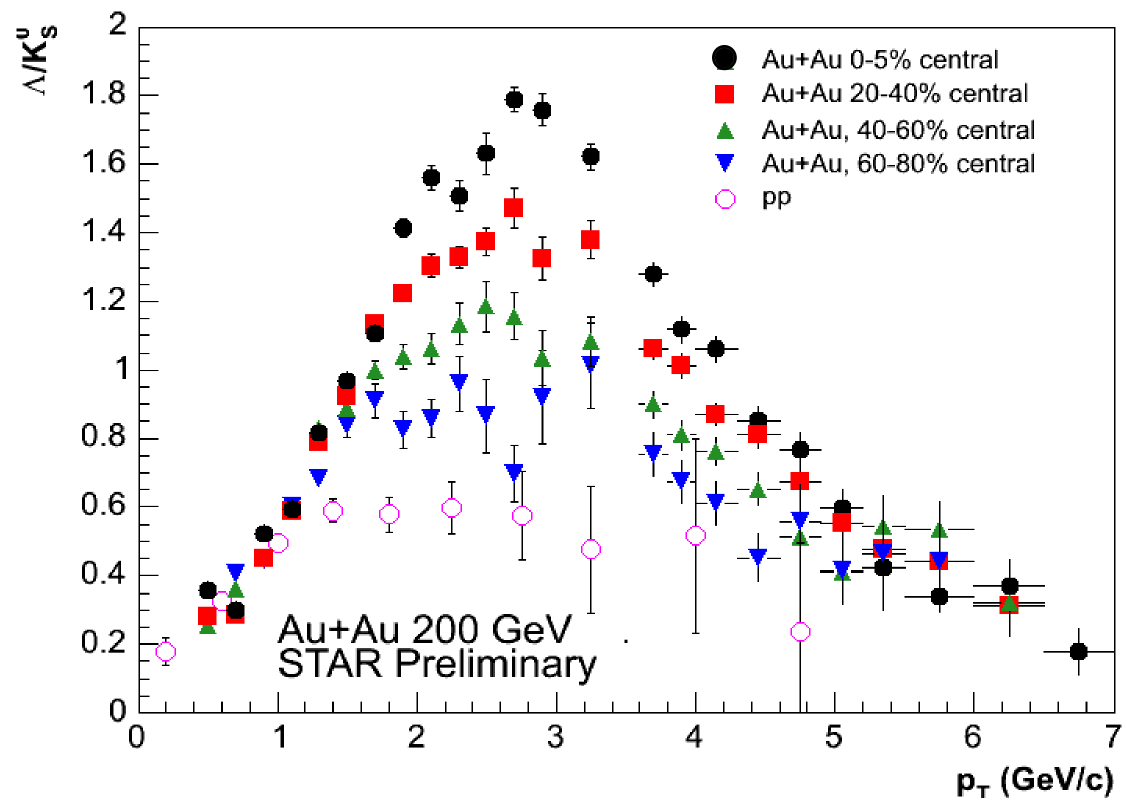

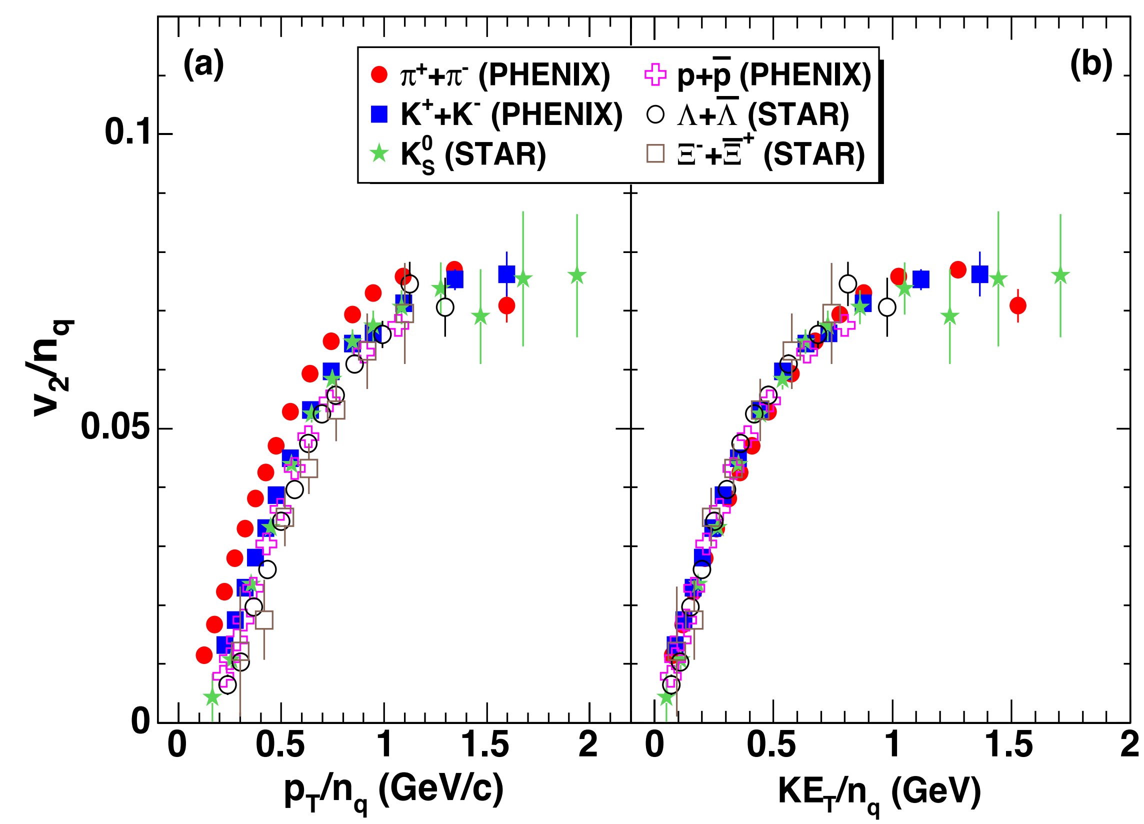

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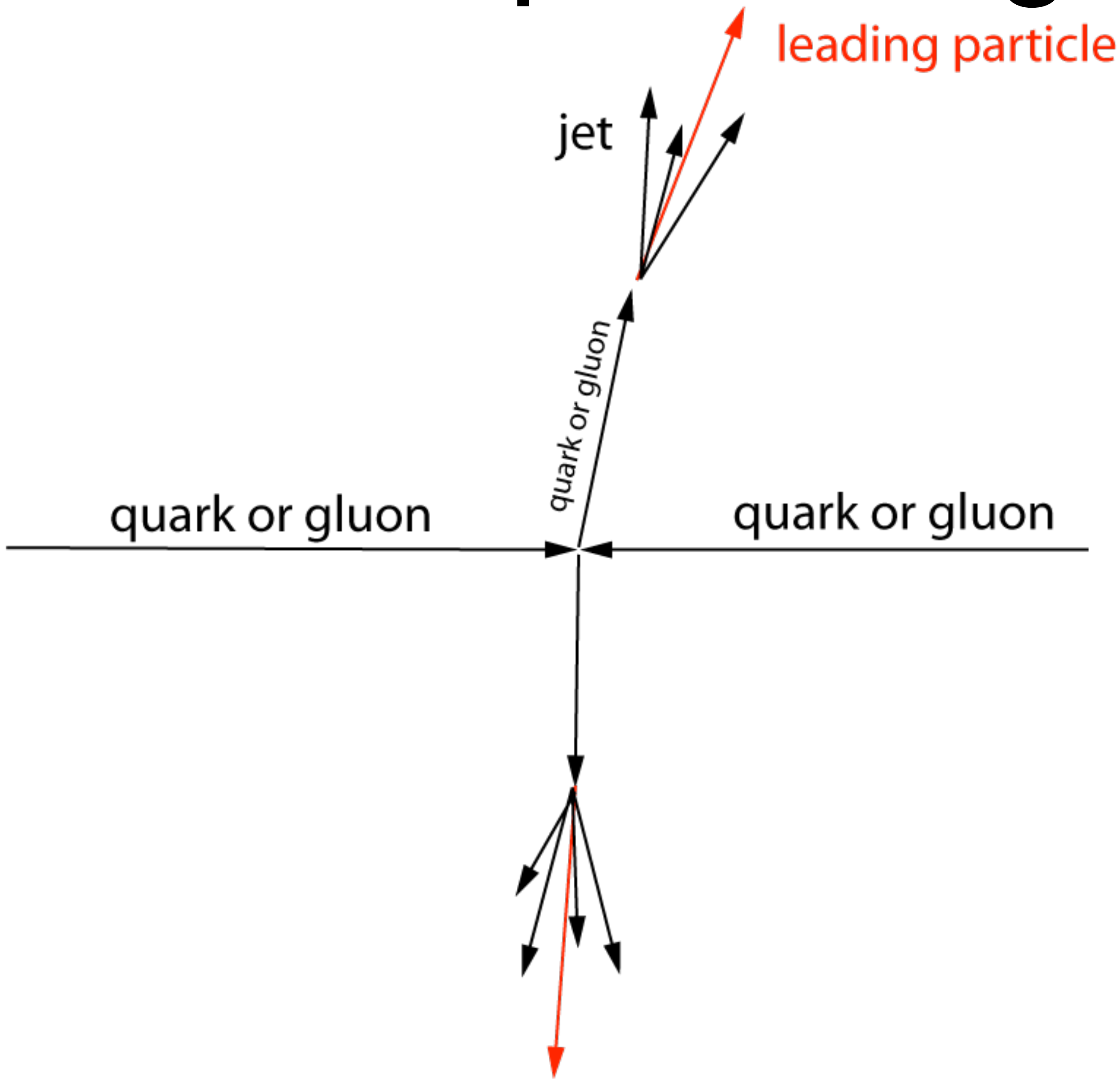
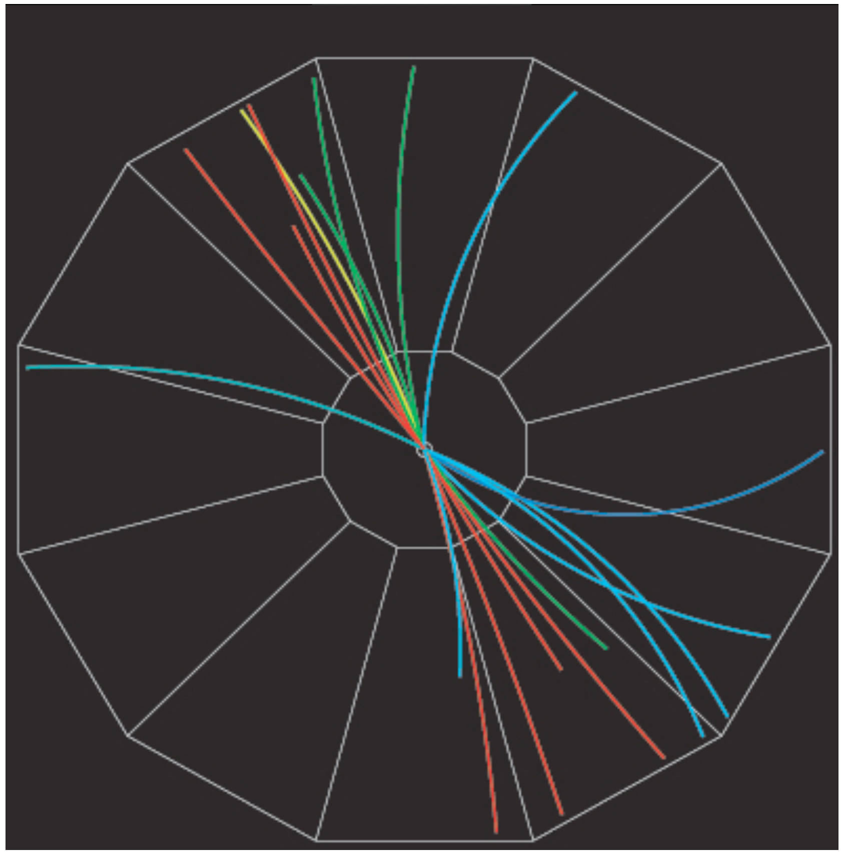
- Jet quenching
  - Energy loss of high-p_T partons traversing the hot and dense matter

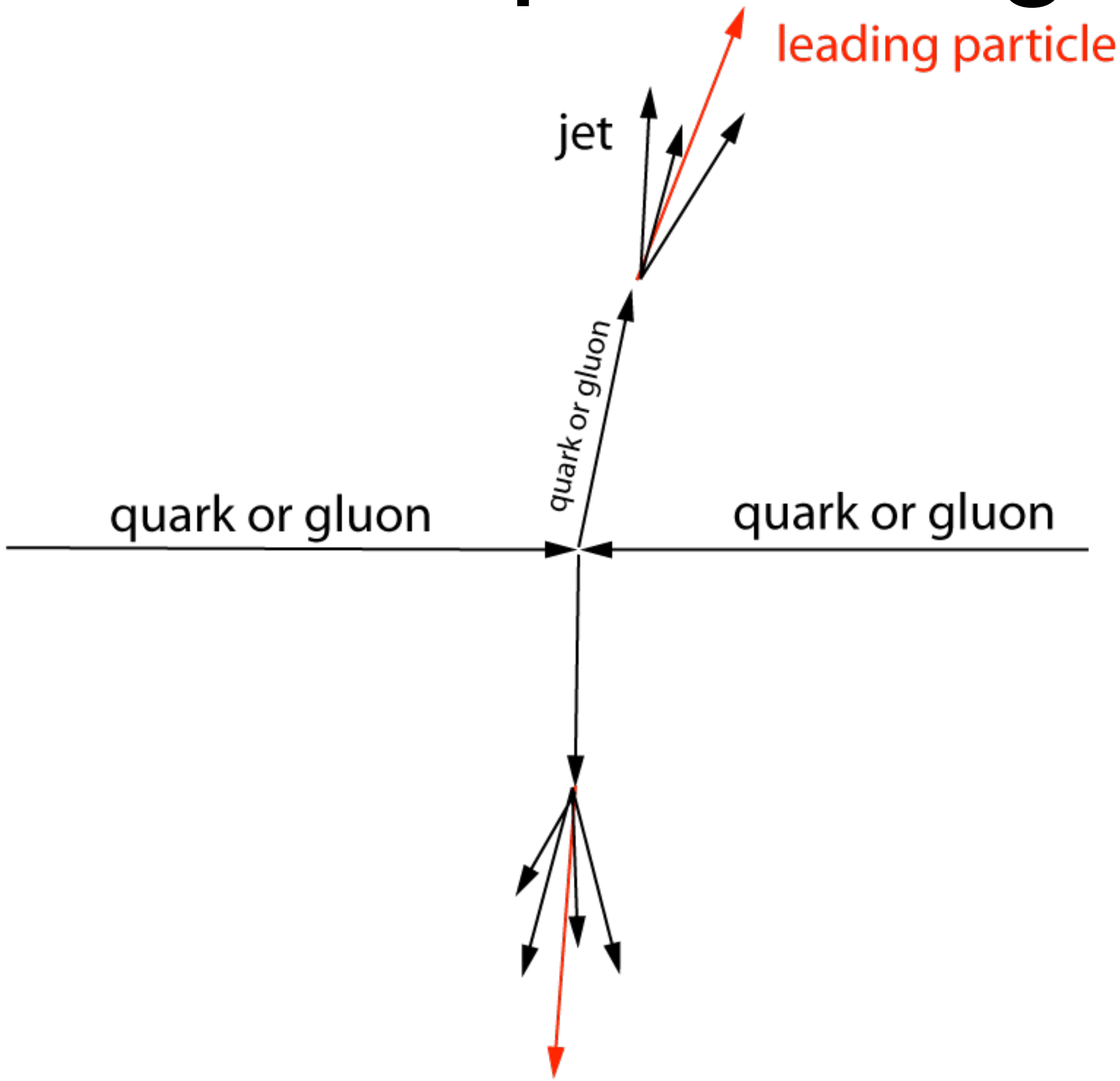
Jet quenching in A+A collisions

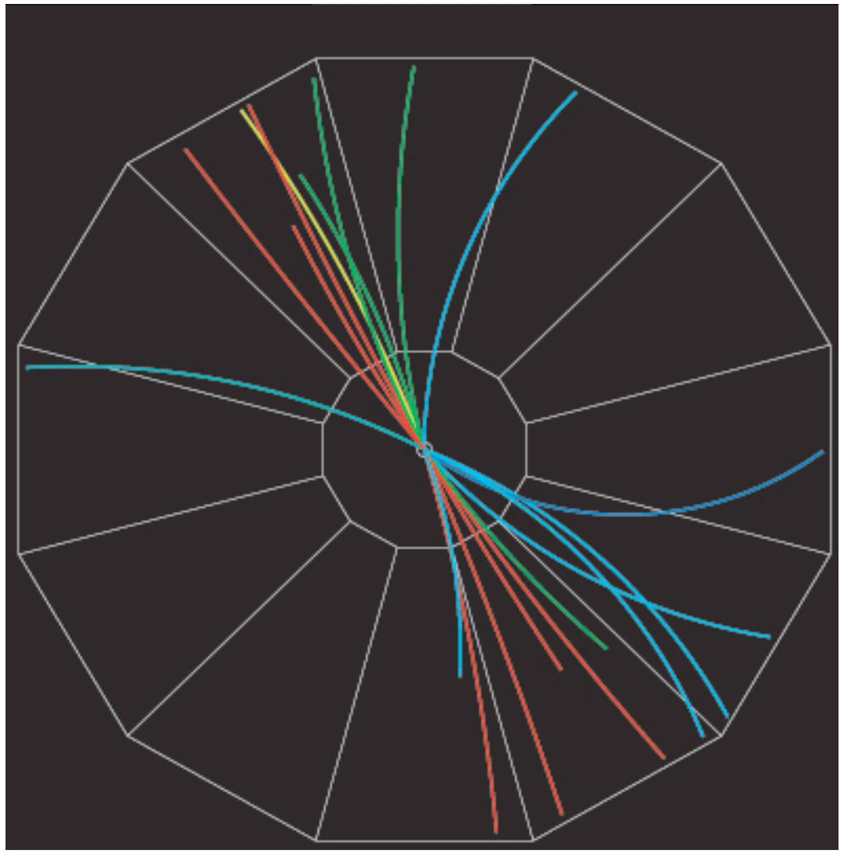




p+p Event

Jet quenching in A+A collisions

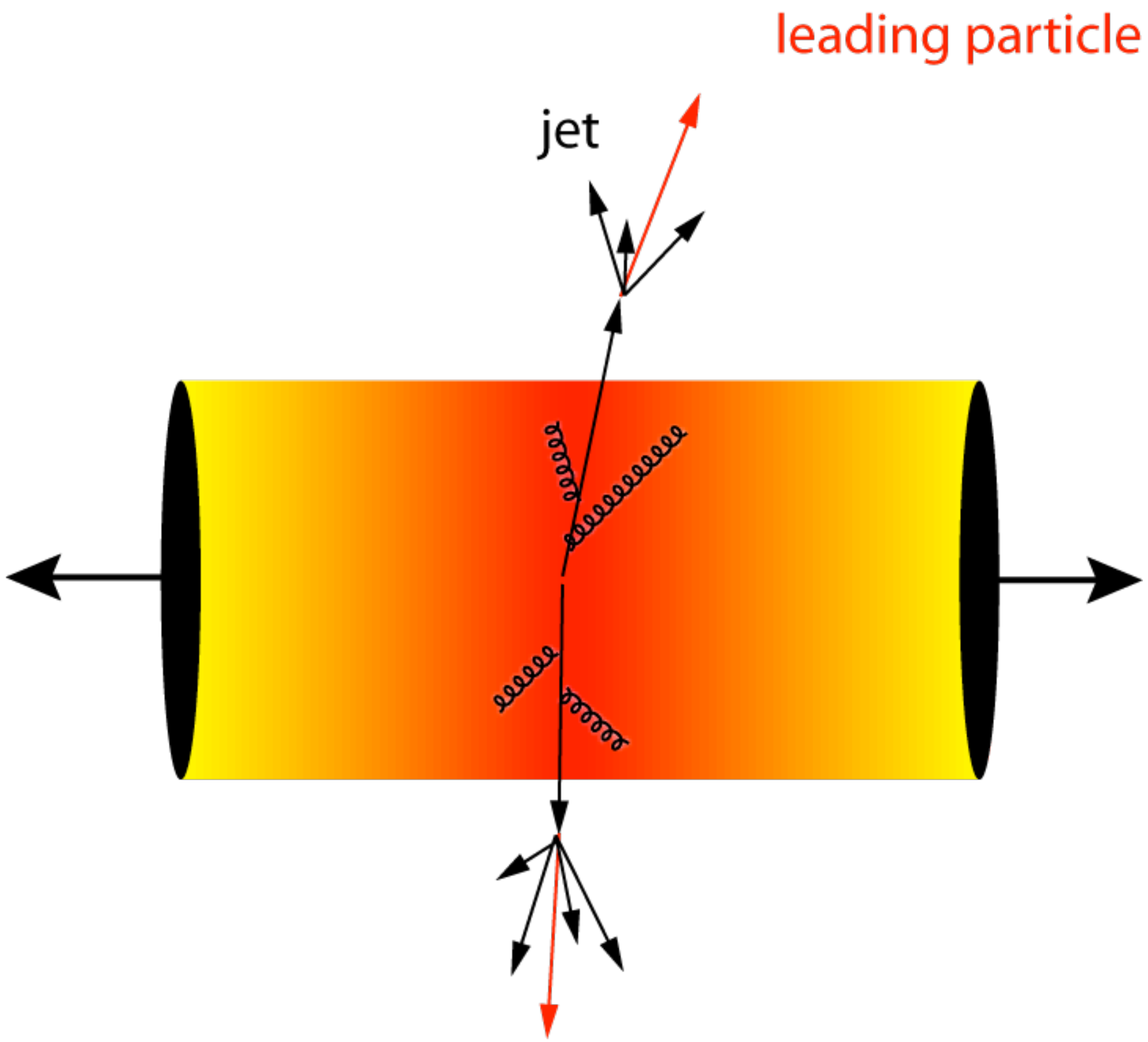


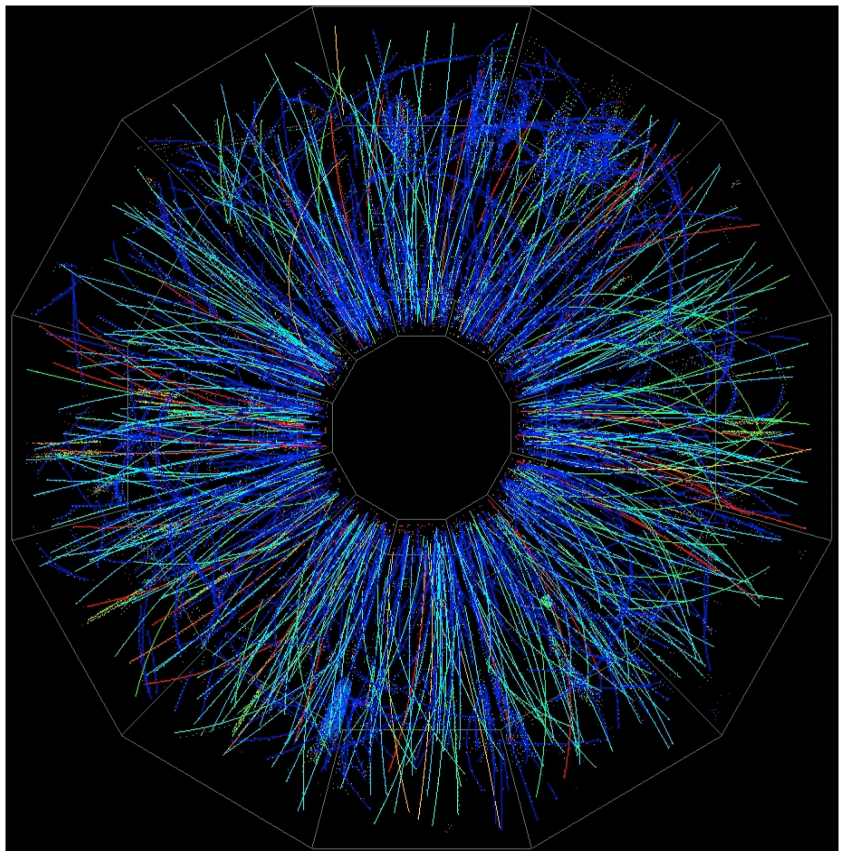


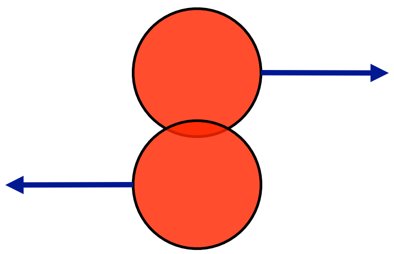
p+p Event

- Jet-finding is relatively straight-forward in low-multiplicity p+p collisions

Jet quenching in A+A collisions



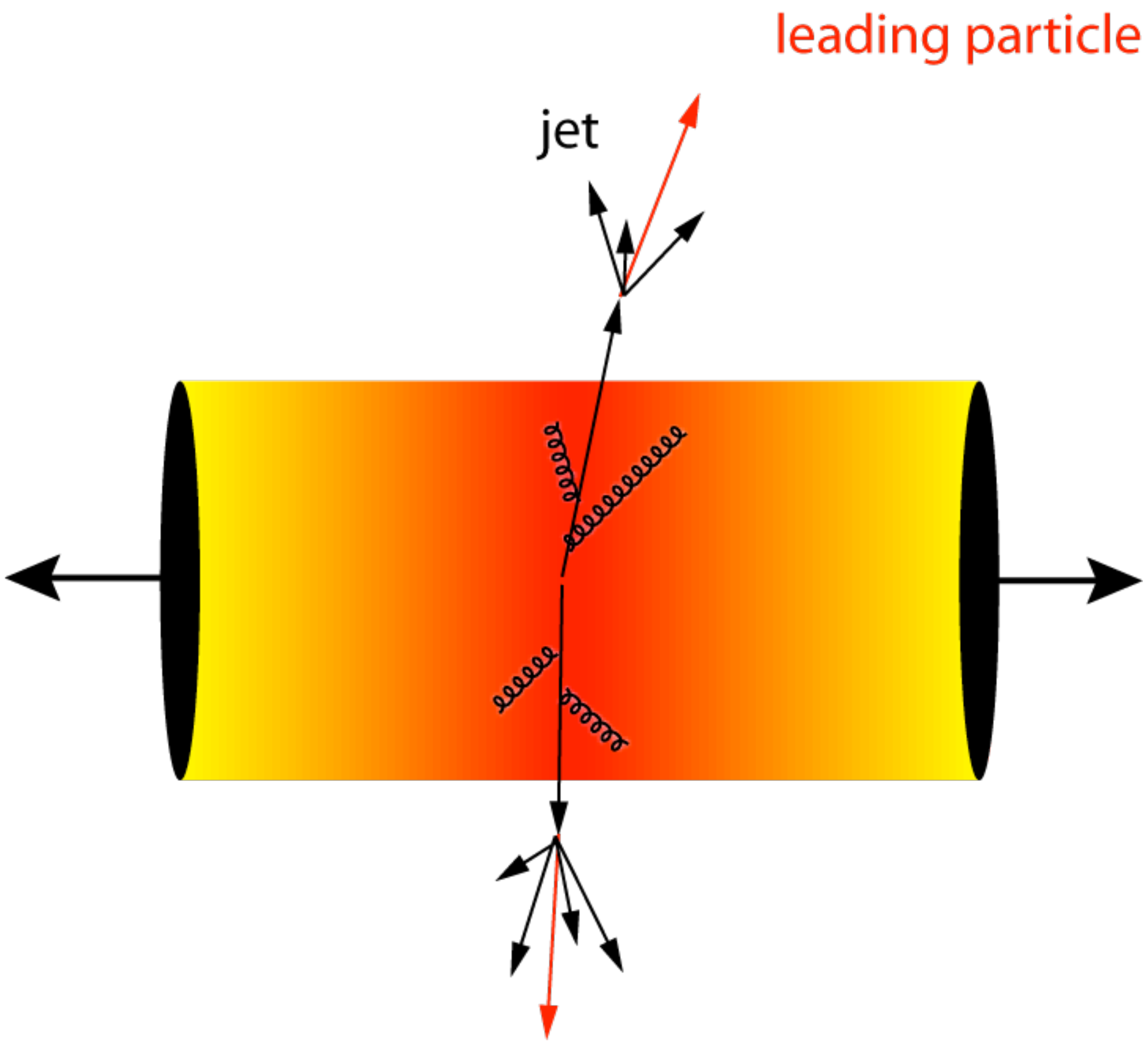


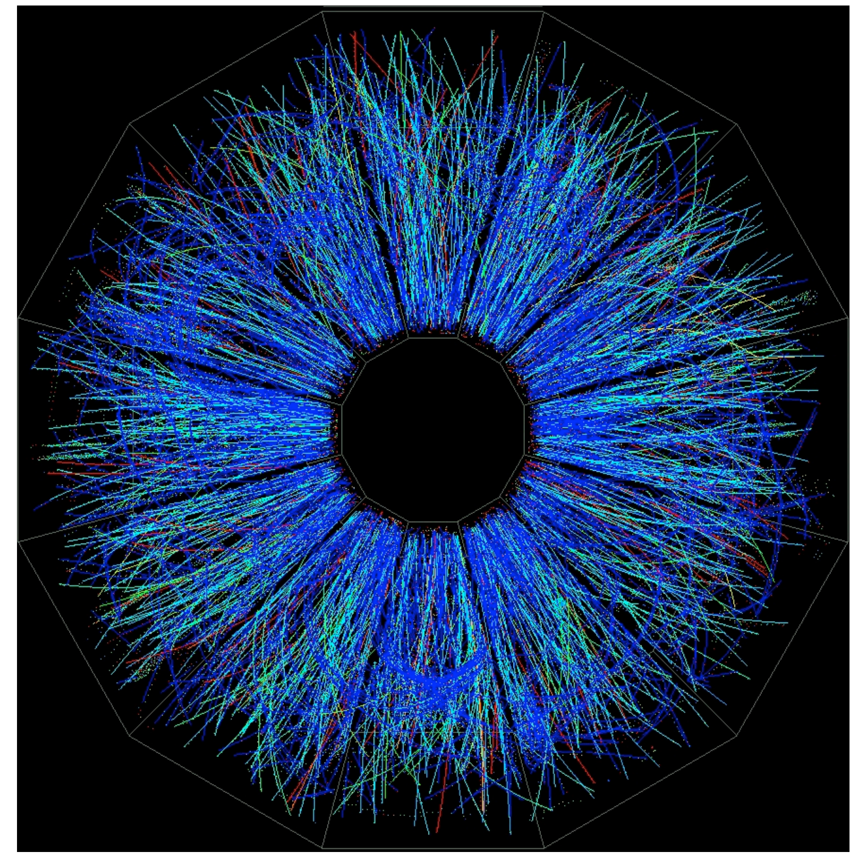


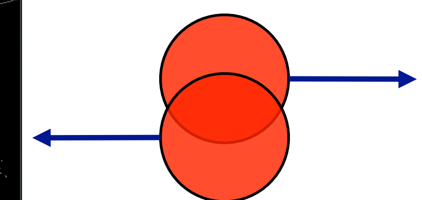
Peripheral Au+Au Event

- Jet-finding is relatively straight-forward in low-multiplicity p+p collisions

Jet quenching in A+A collisions



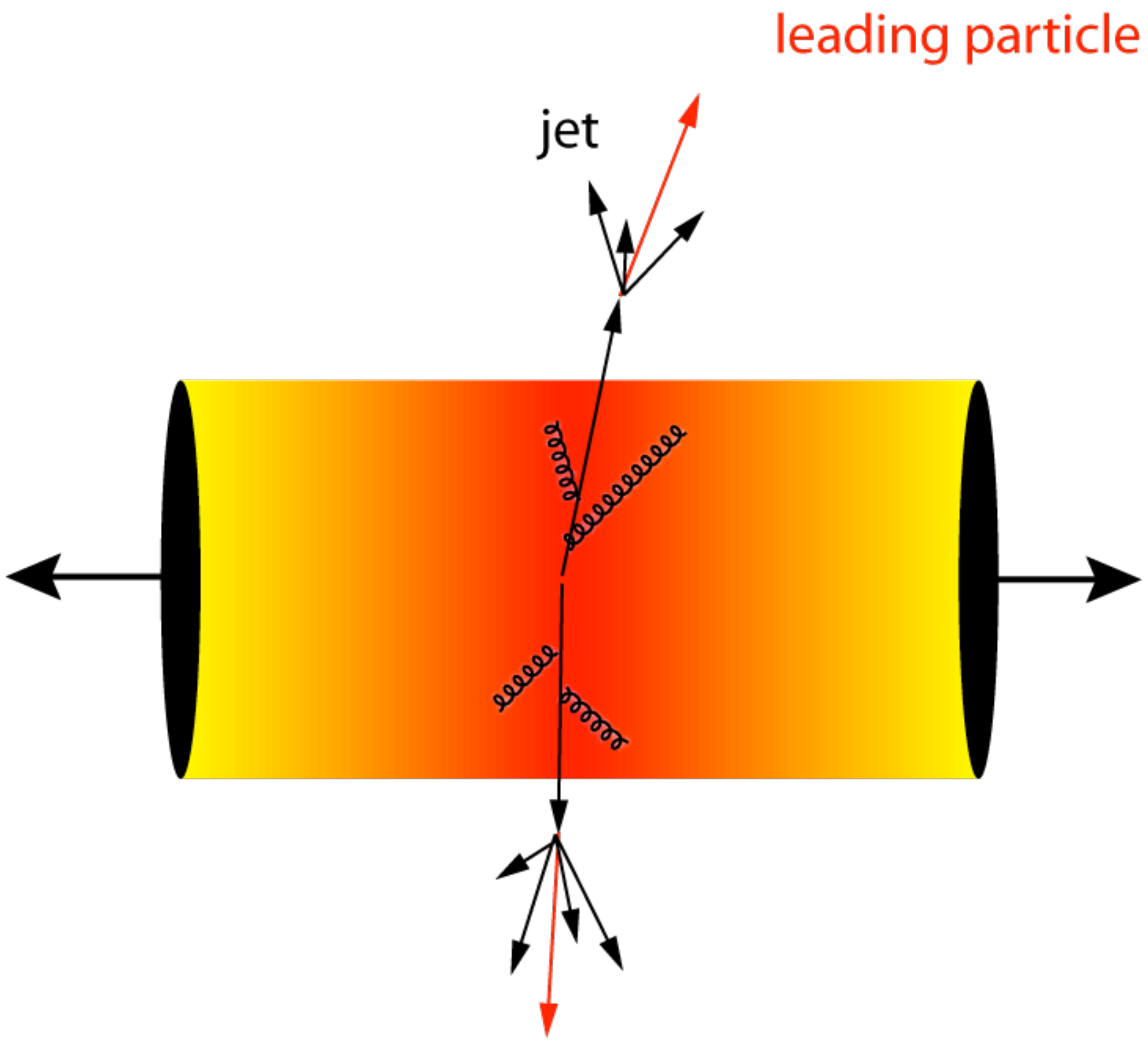


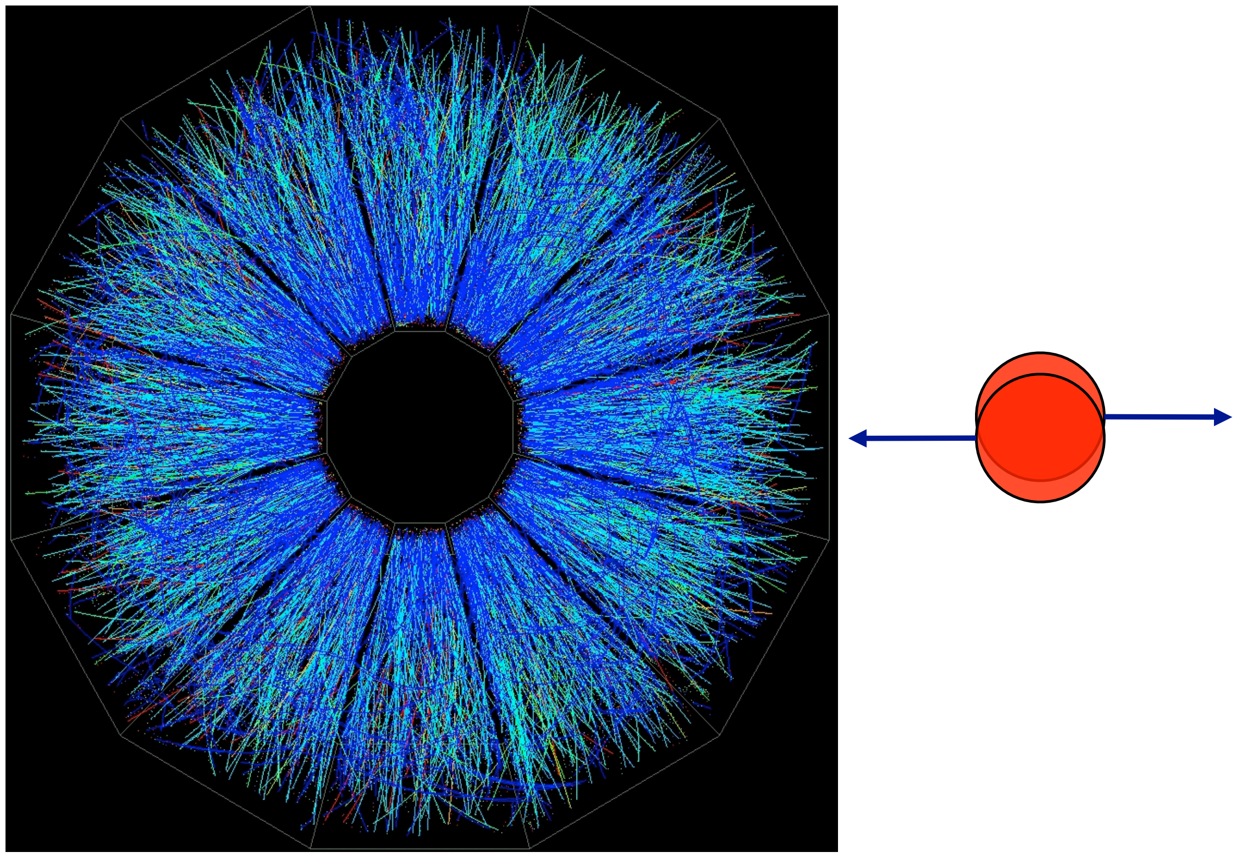


Mid-Central Au+Au Event

- Jet-finding is relatively straight-forward in low-multiplicity p+p collisions

Jet quenching in A+A collisions





Central Au+Au Event

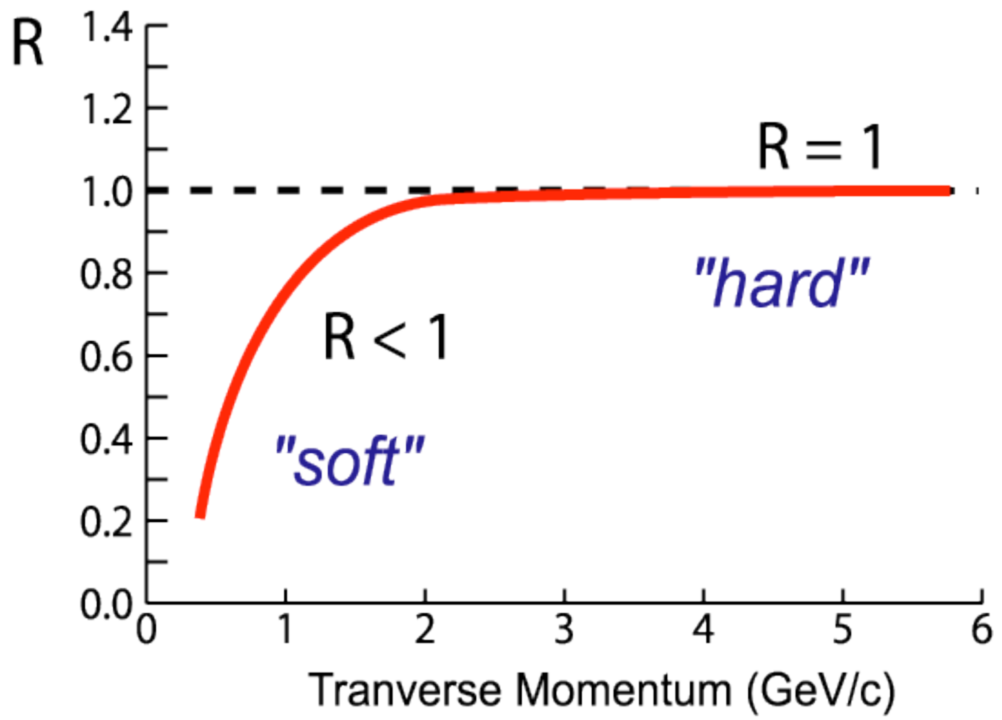
- Jet-finding is relatively straight-forward in low-multiplicity p+p collisions
- How do we do this in high-multiplicity A+A collisions?

How to measure high-p_T processes

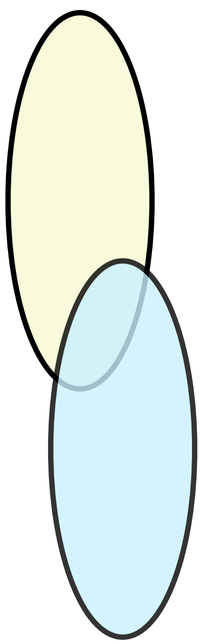
- Single particle spectra

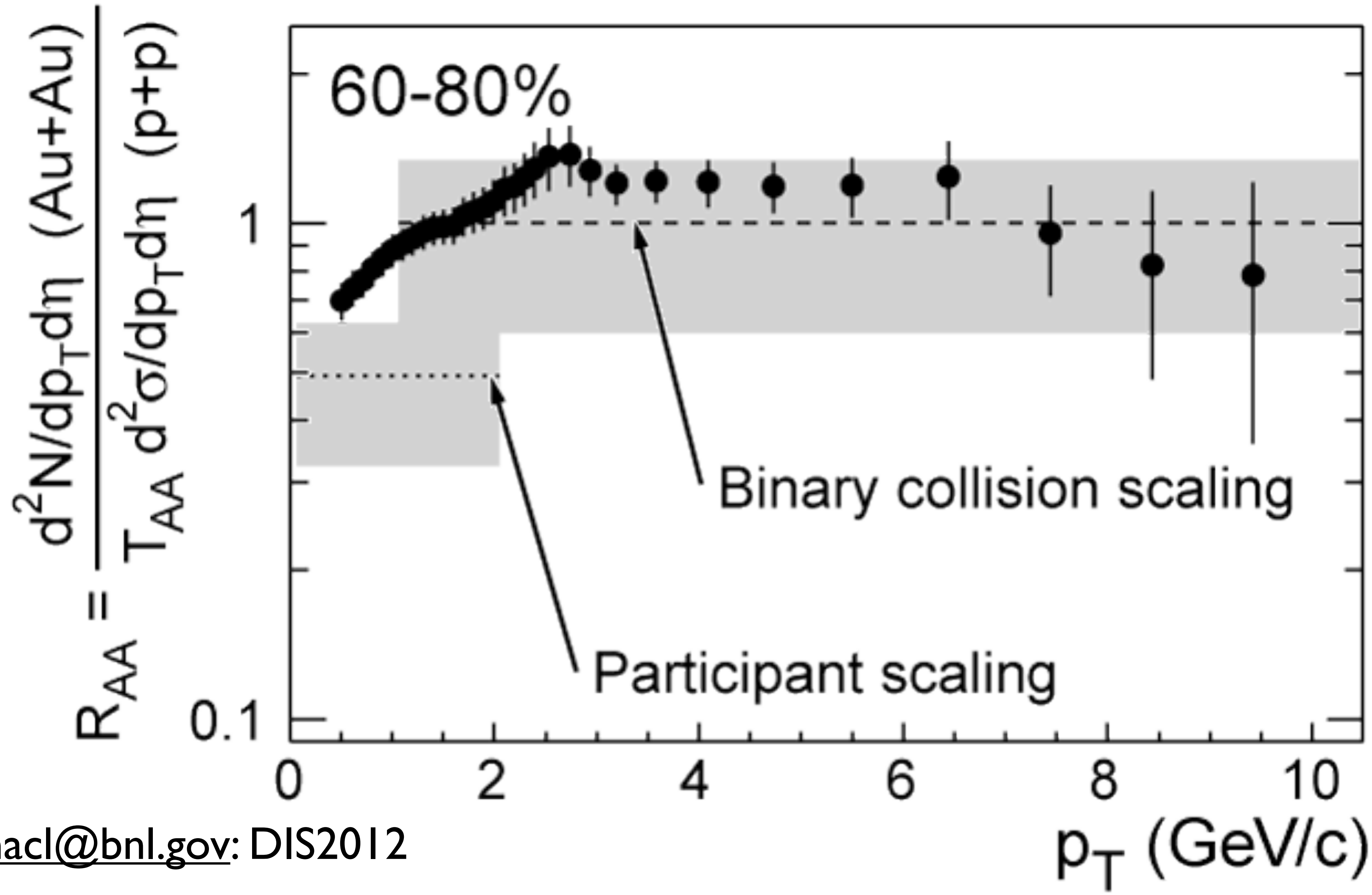
$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times < N_{coll} >}$$

$R_{AA}(p_T)$ = Nuclear Modification Factor



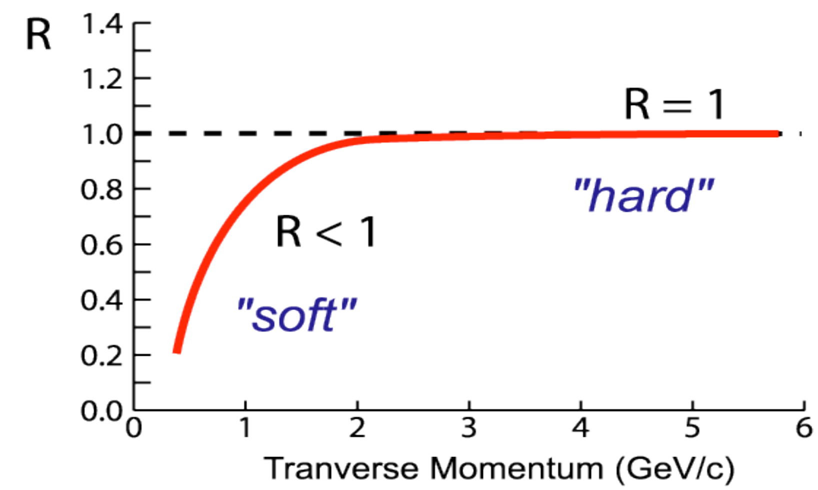
Suppression of inclusive hadron yield at high p_T

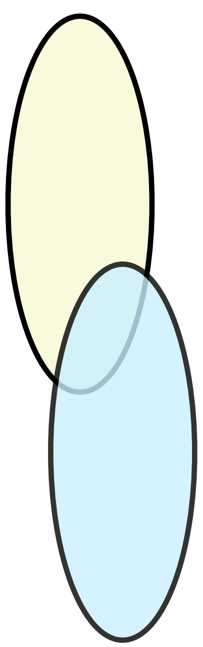


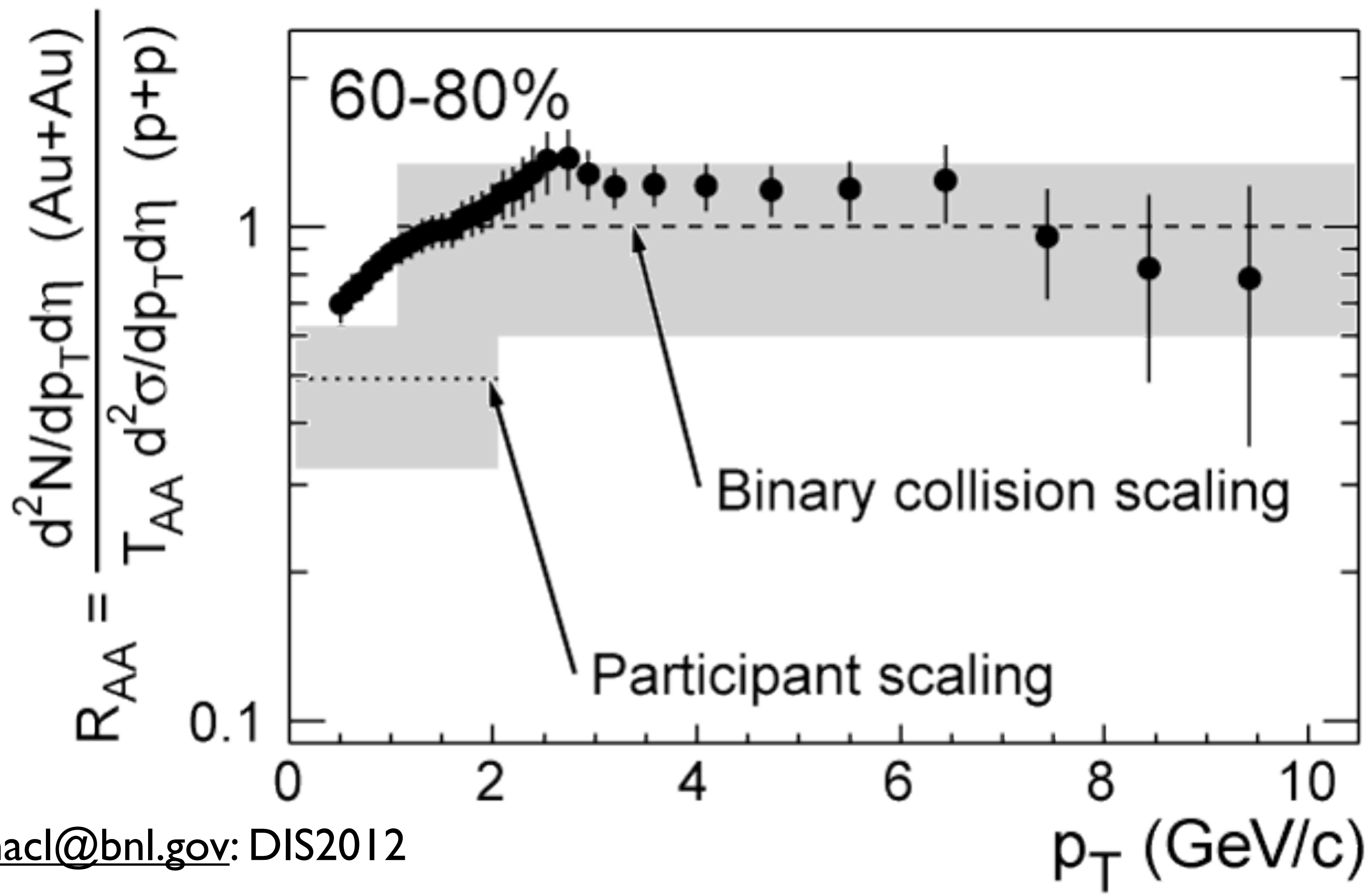


Suppression of inclusive hadron yield at high p_T

- Good quality measurements of single particle spectra as a function of collision centrality

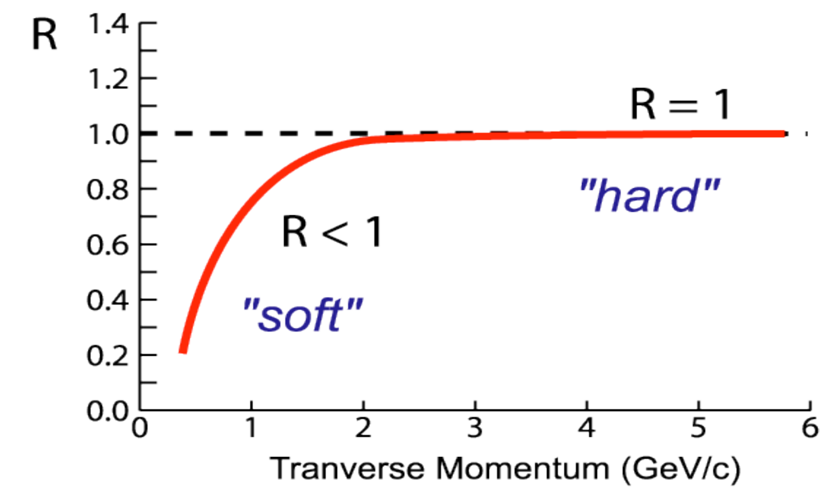


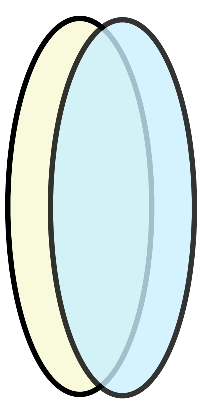


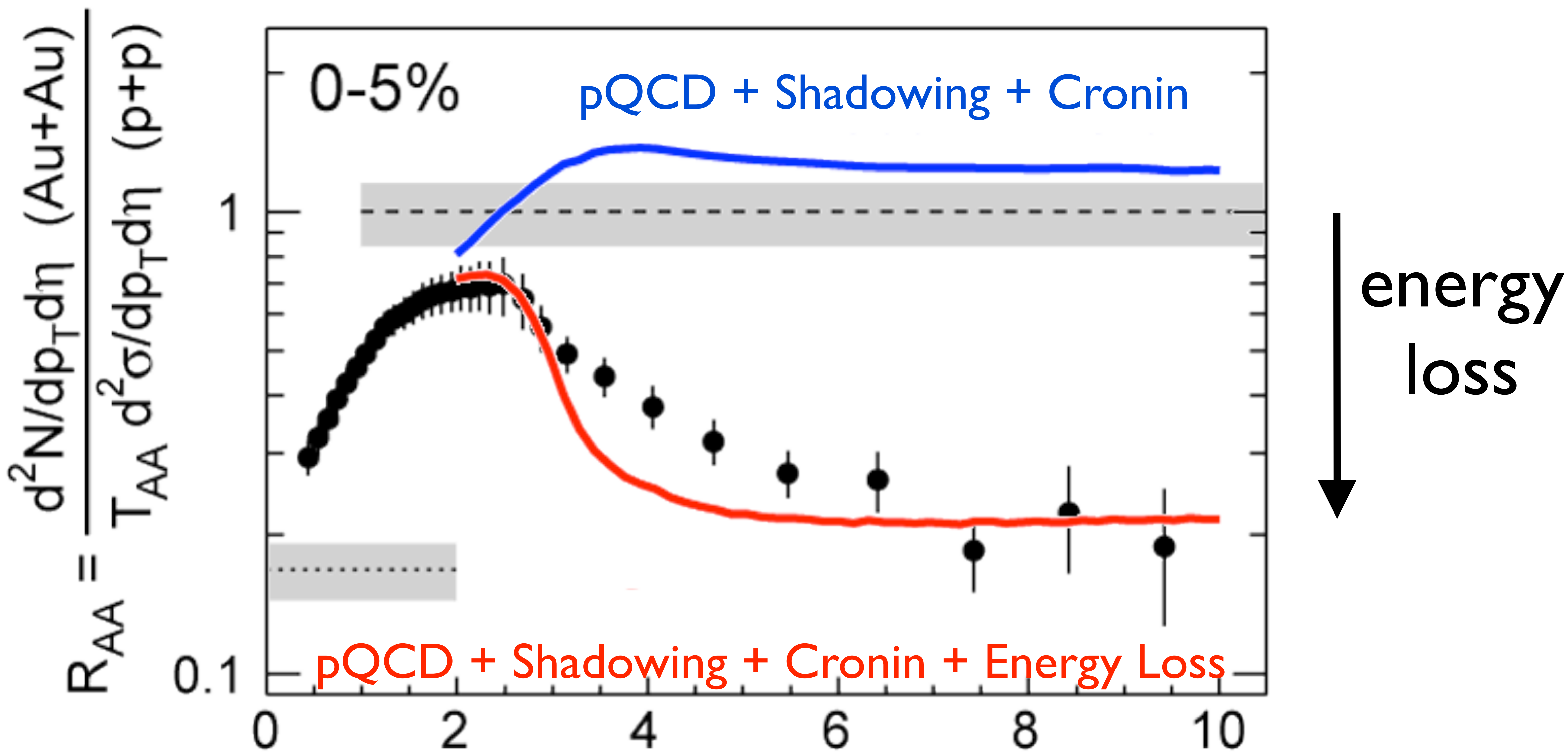


Suppression of inclusive hadron yield at high p_T

- Good quality measurements of single particle spectra as a function of collision centrality
- Increasing suppression as the A+A centrality increases
  - They appear to traverse dense opaque matter







How to measure high-p_T processes

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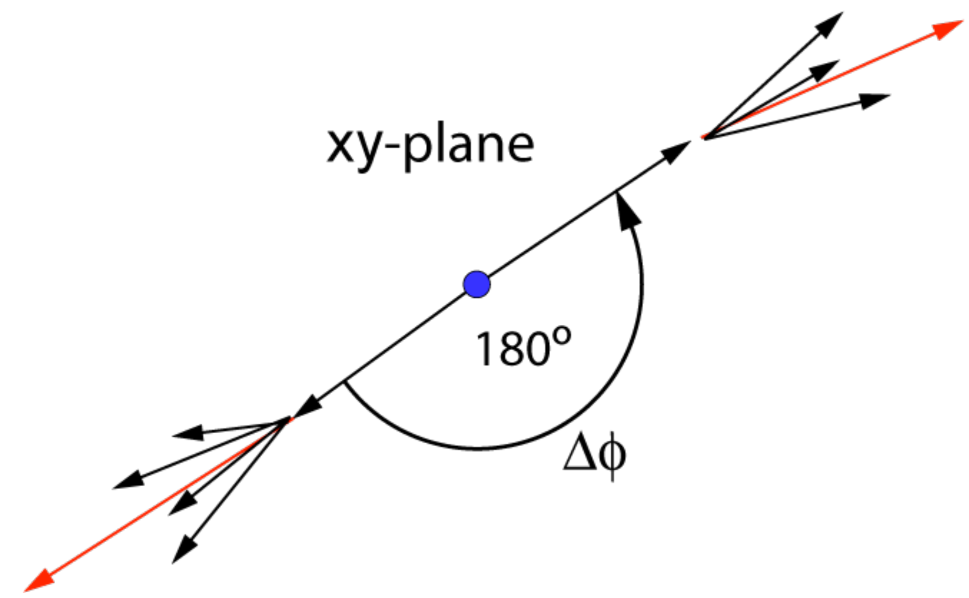
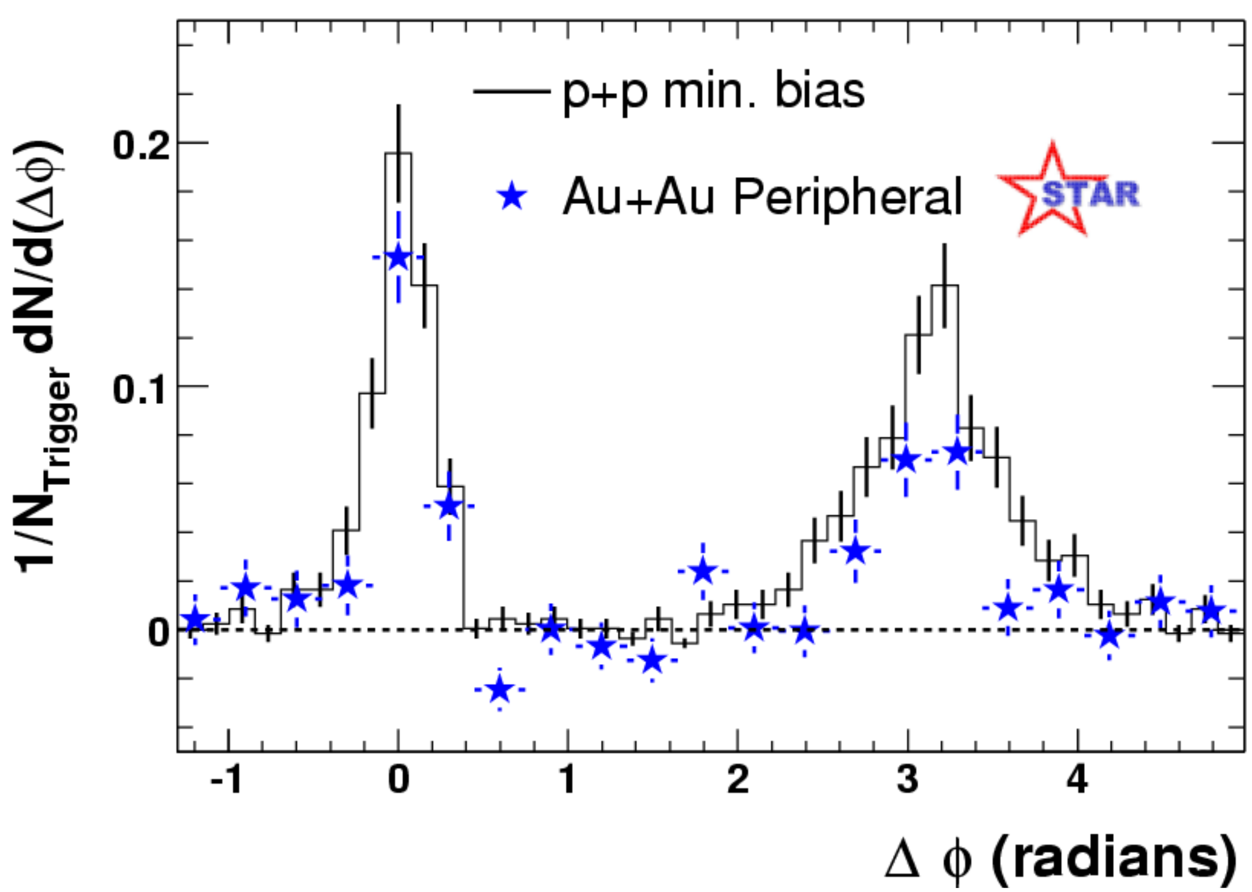
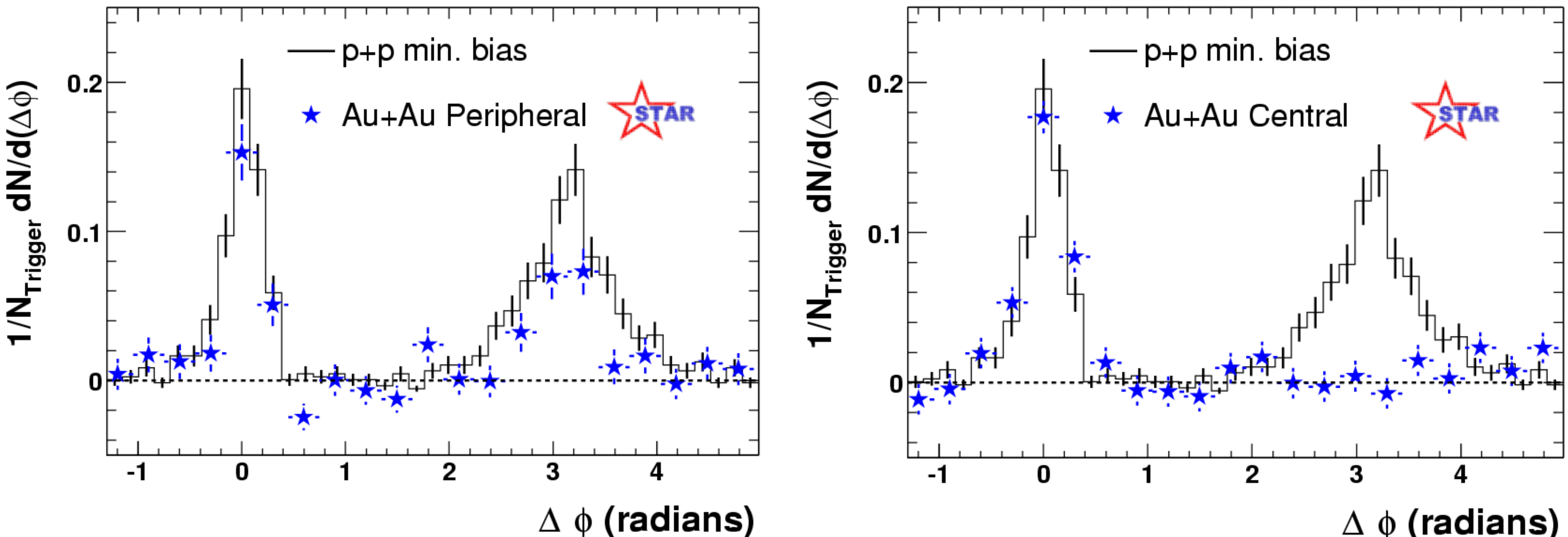
$R_{AA}(p_T)$ = Nuclear Modification Factor



- 2-particle correlations
  - Measure correlations of high-p_T hadrons in azimuth in lieu of jet-finding in high-multiplicity environments

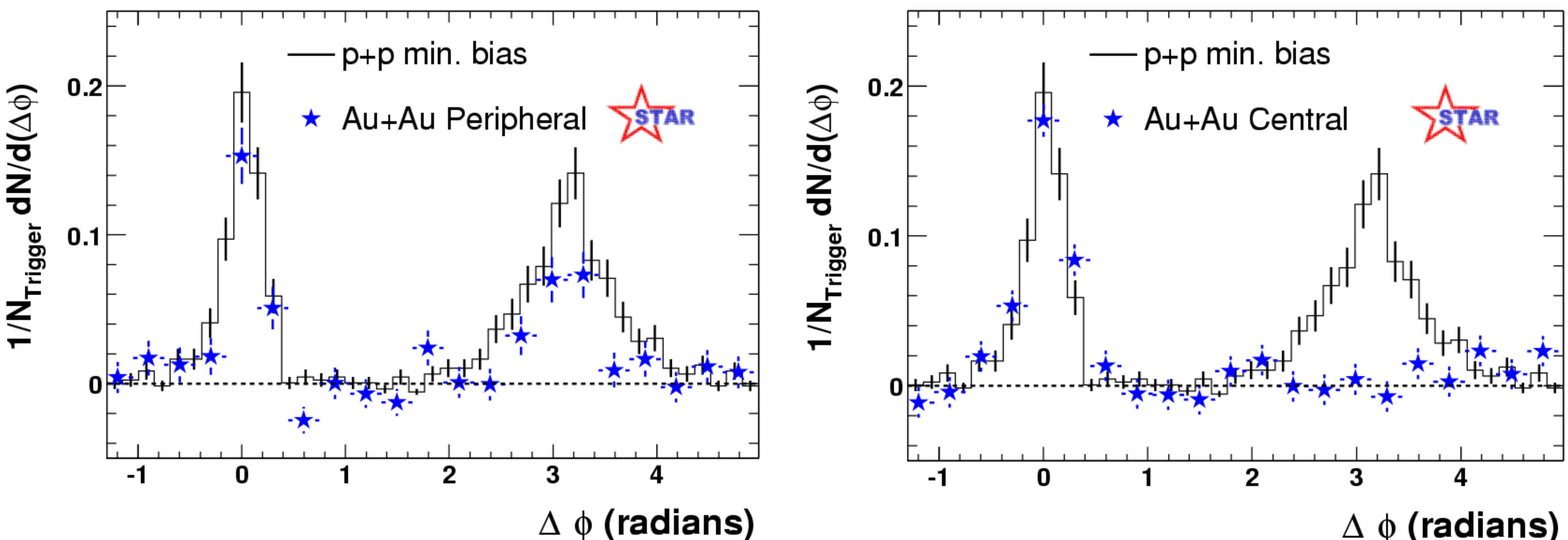


Jet suppression: 2 particle correlations



Jet suppression: 2 particle correlations

- Peripheral collisions look like p+p - suppression observed in central AuAu



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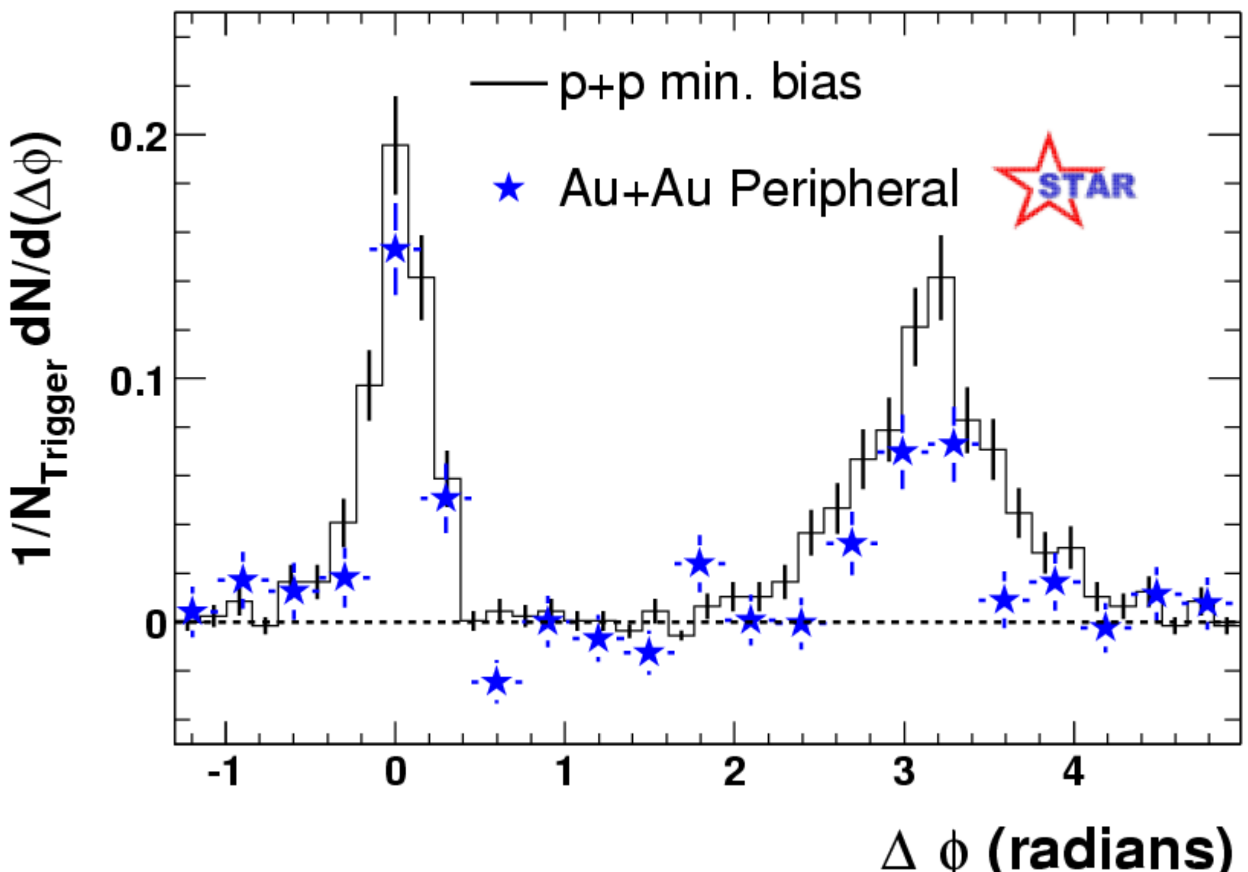

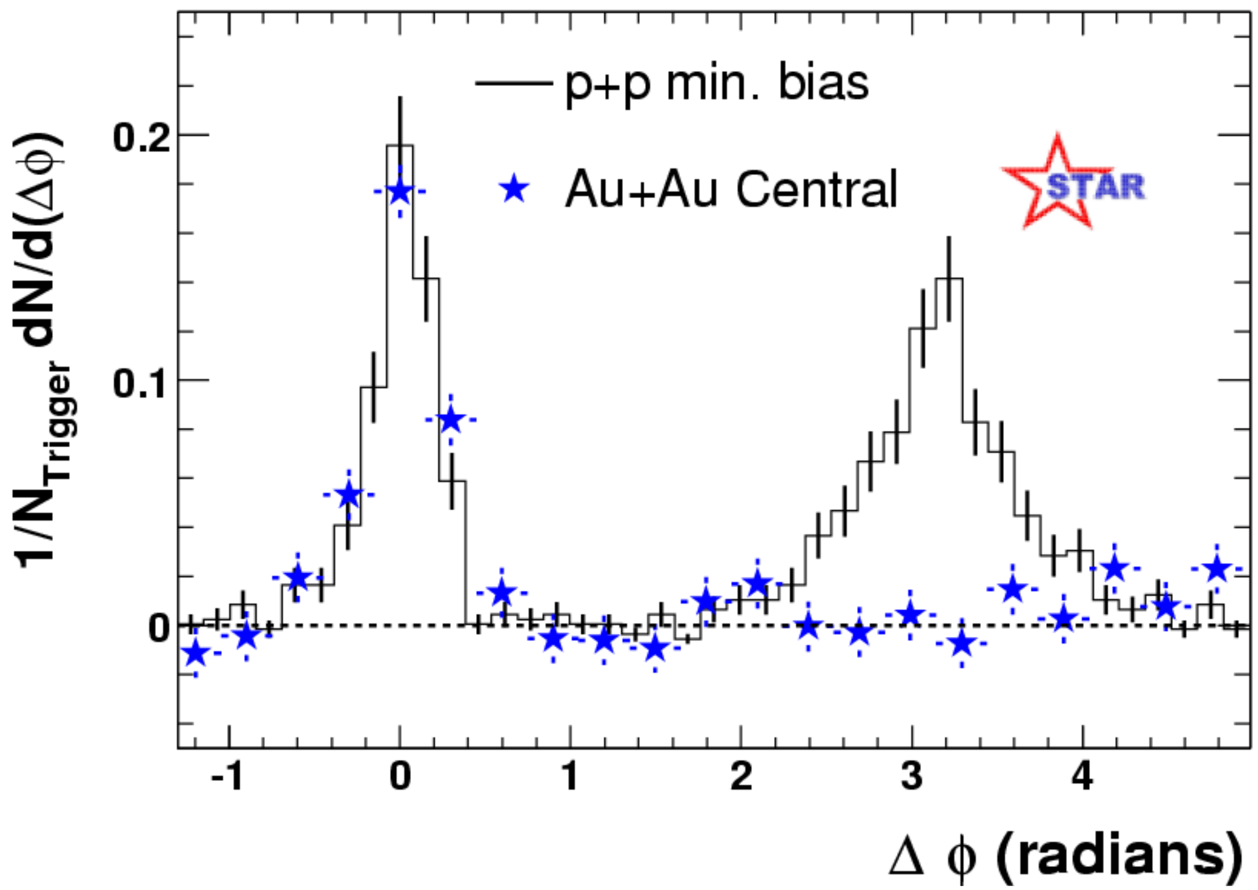

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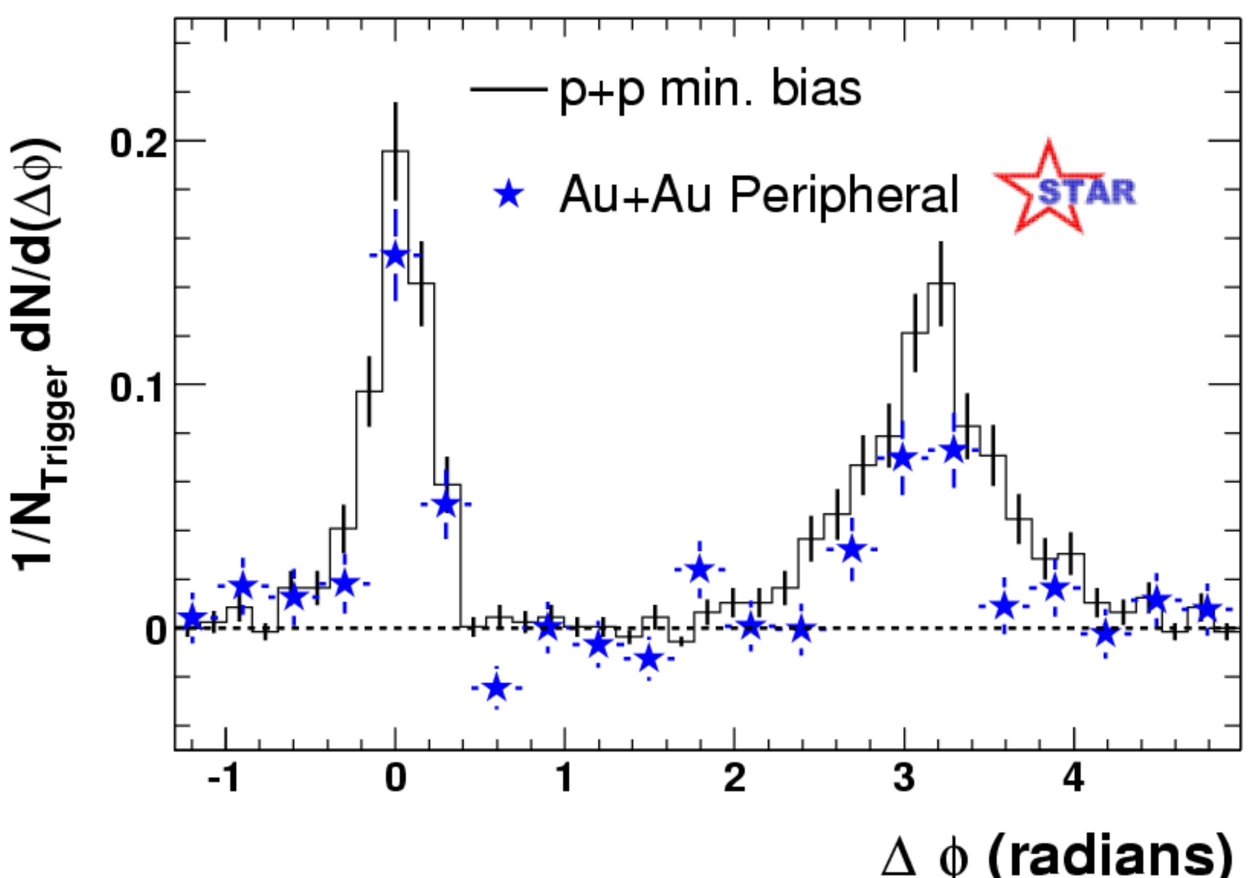
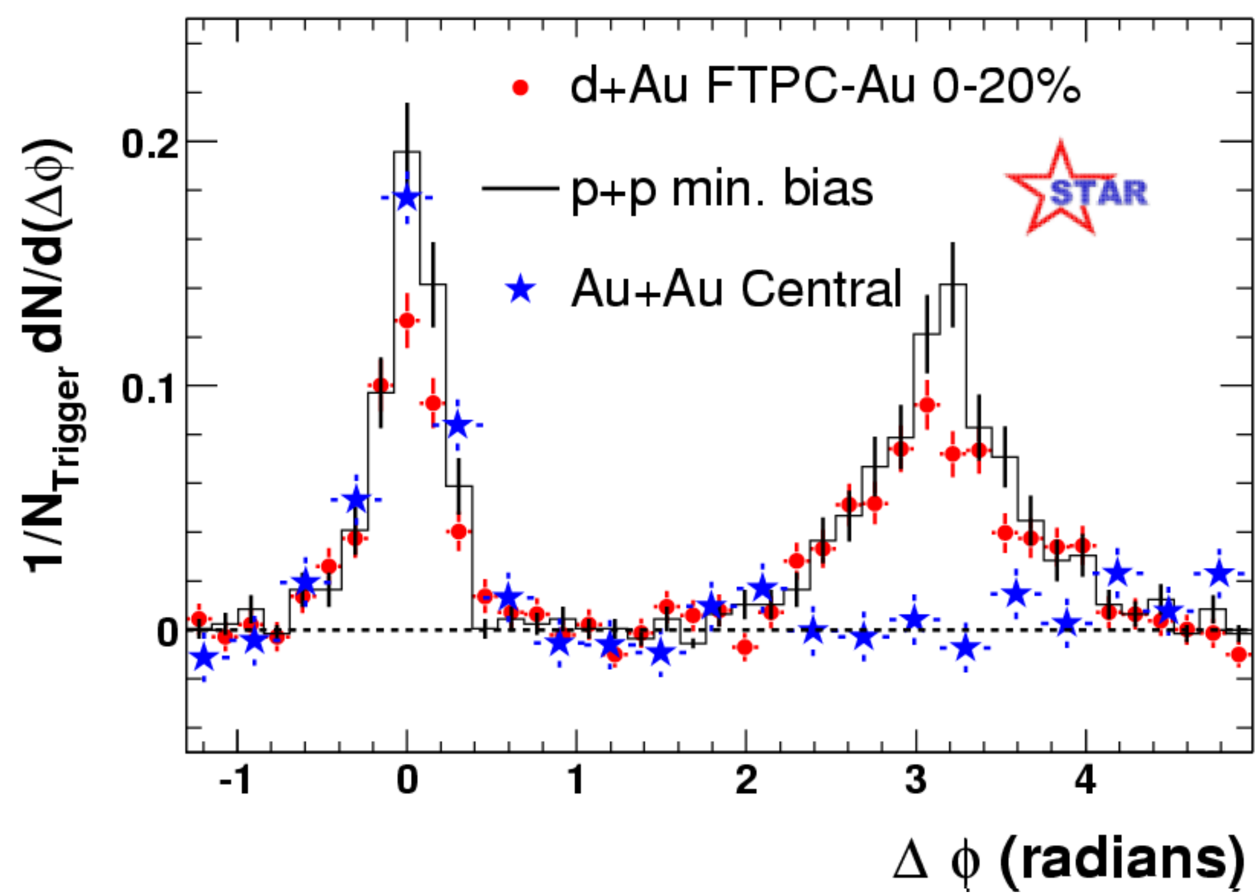
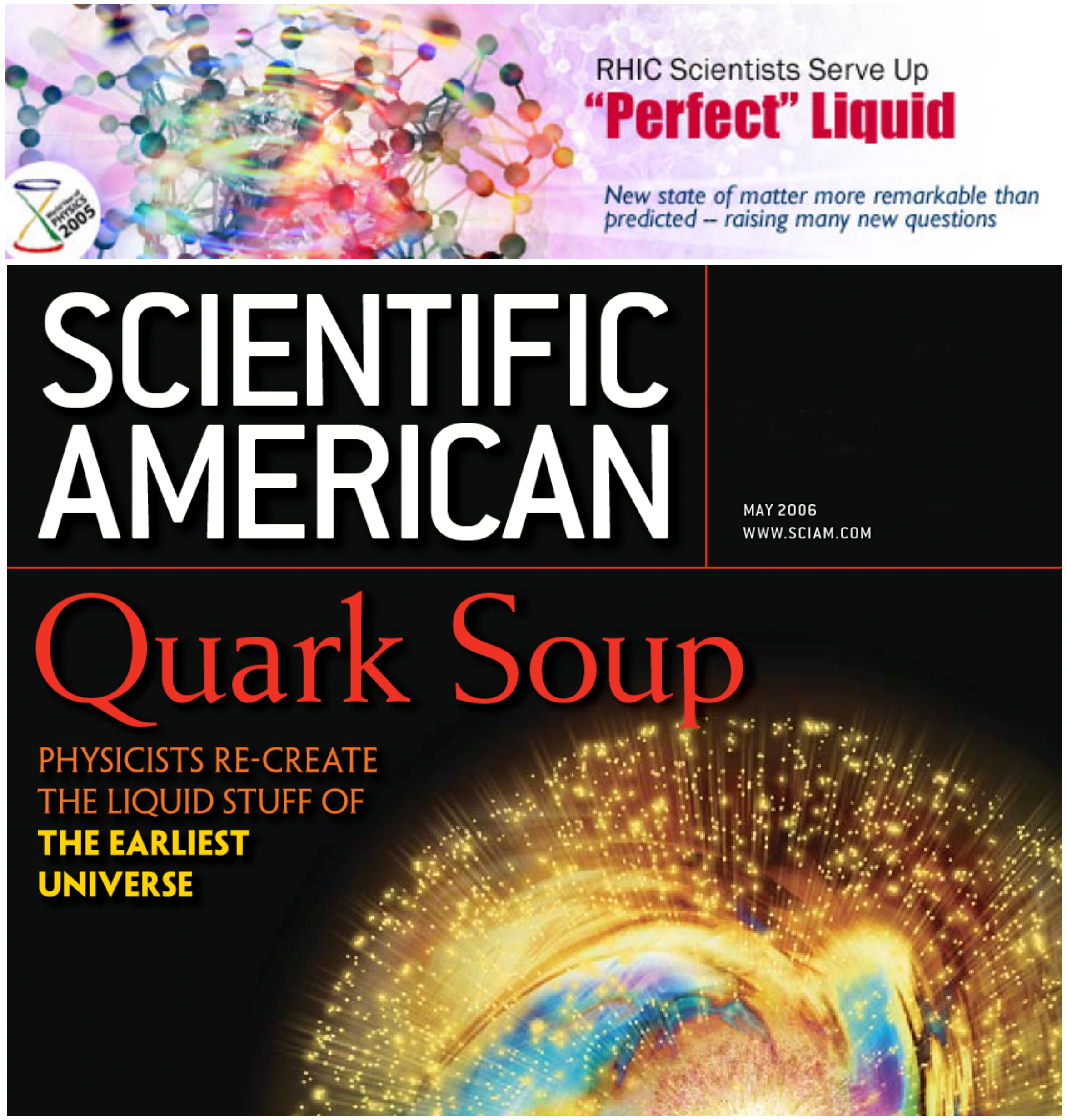
- No suppression is observed in d+Au collisions at **mid-rapidity** at RHIC
  - Jet suppression a final state effect?





Highlights of the 1st decade of AA collisions in STAR

- Exotic particles
  - First observations of $^{3}_{\Lambda}\overline{H}$ and $^{4}\overline{He}$
- Strong Elliptic Flow
  - Collective flow of created matter
  - Constituent quark number degrees of freedom apparent in scaling laws of elliptic flow
- Particle production through recombination/coalescence dominates over fragmentation at medium p_T
- Jet quenching
  - Energy loss of high-p_T partons traversing the hot and dense matter



⇐ these and comparisons to models led to the "perfect fluid" hypothesis

Paradigm shift:

strongly coupled QGP = sQGP

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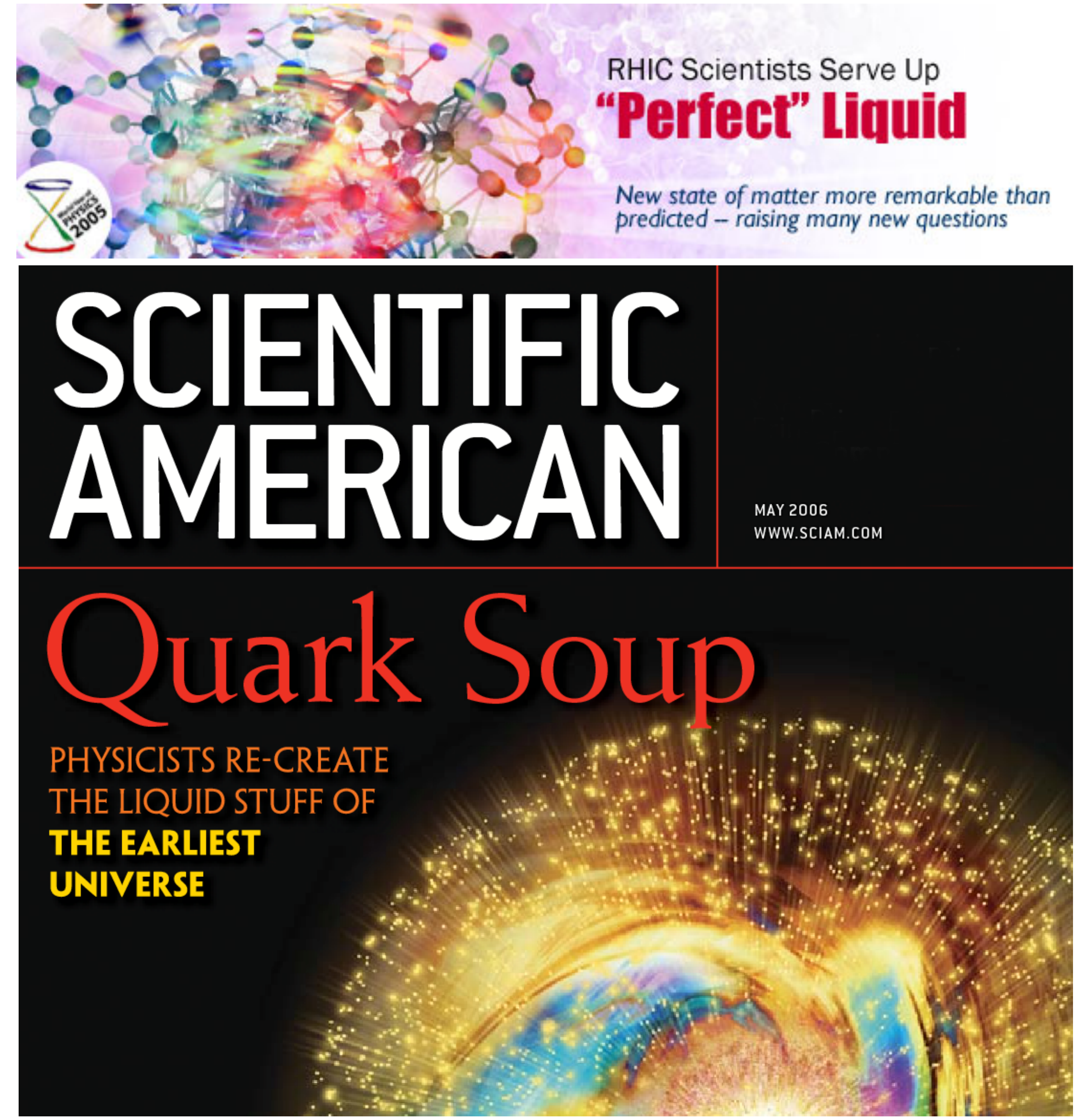
- Gluon saturation at small-x?
  - Tantalising hints of saturation phenomena in d+A collisions



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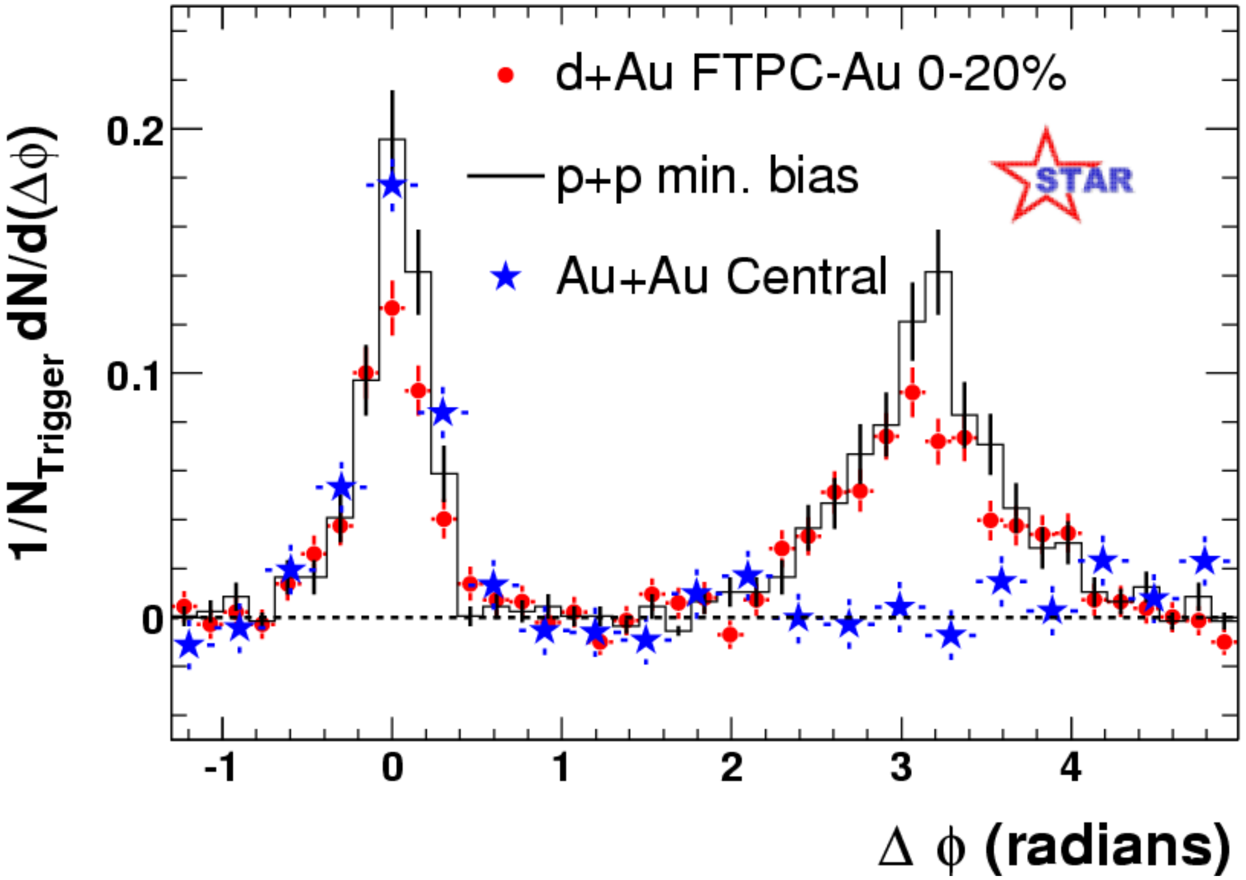
Saturation at RHIC: correlations at forward rapidities

mid-rapidity



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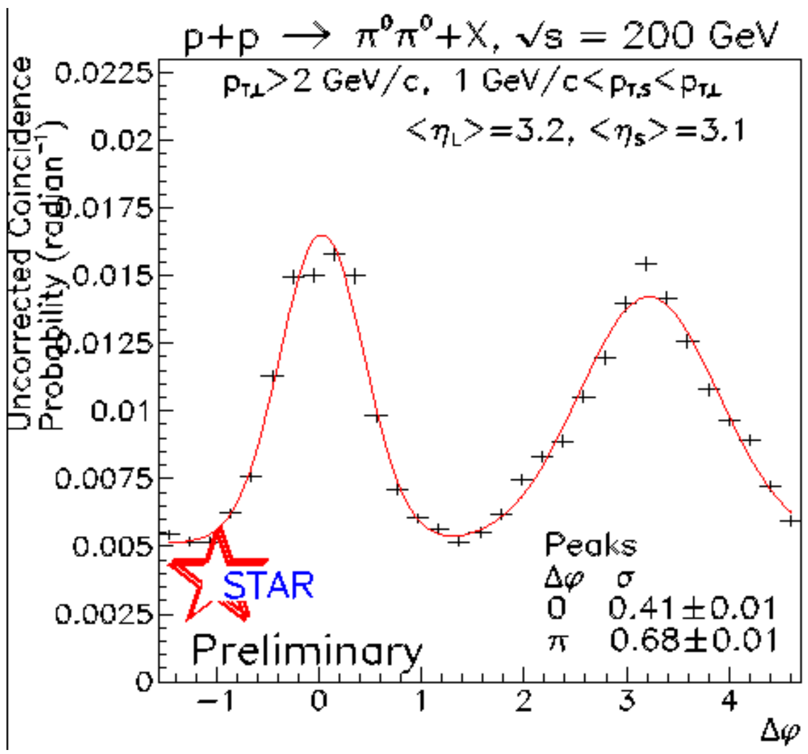

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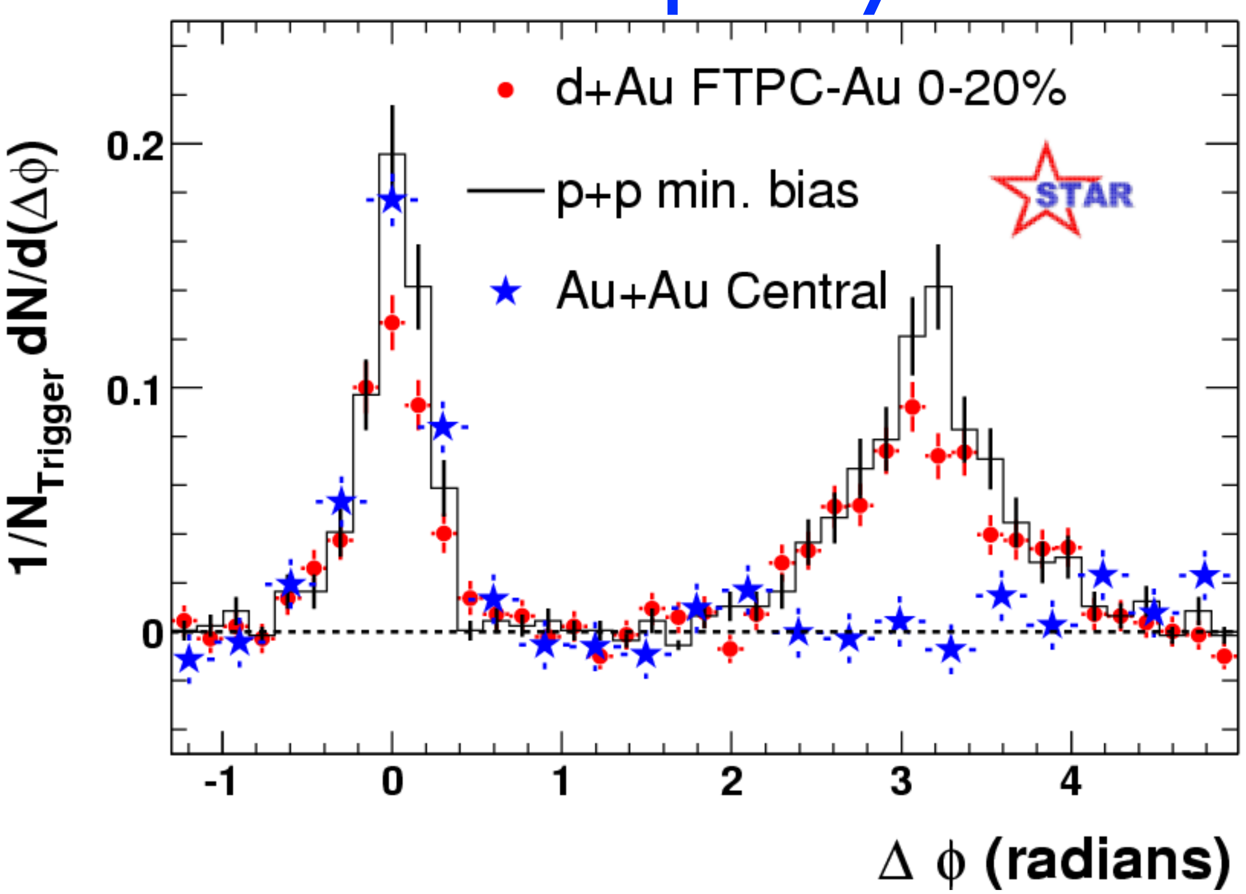

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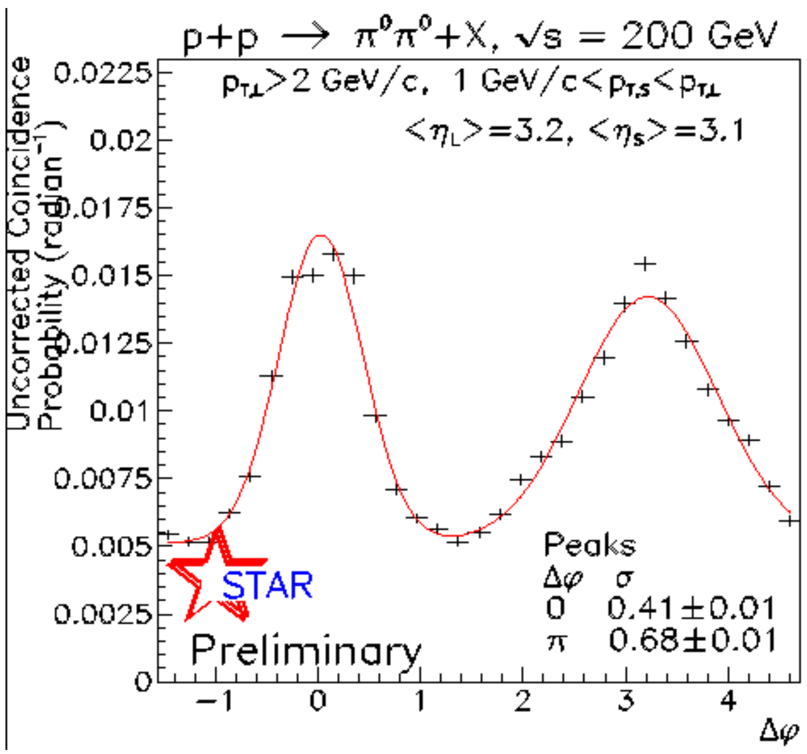
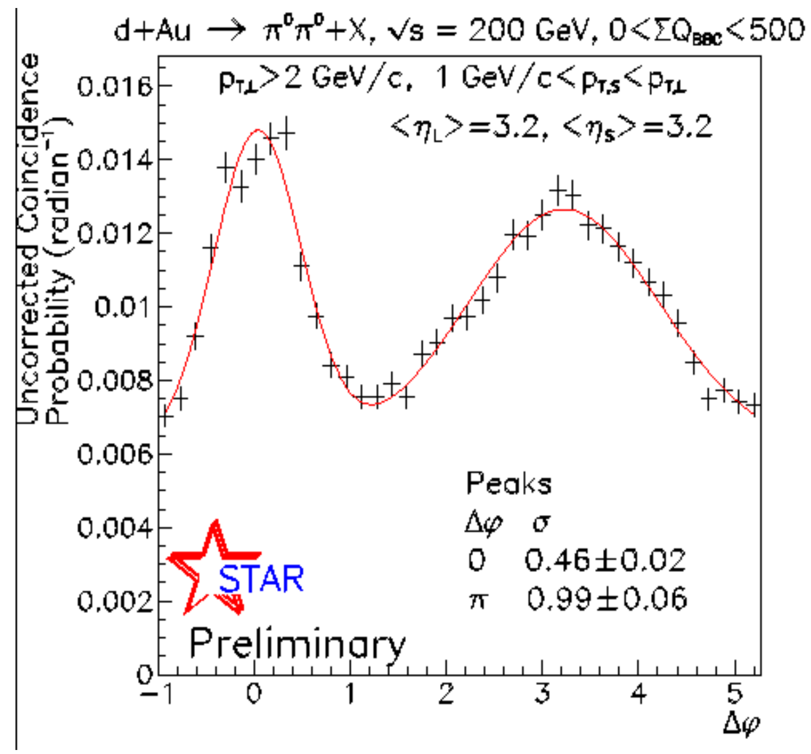


d+Au peripheral



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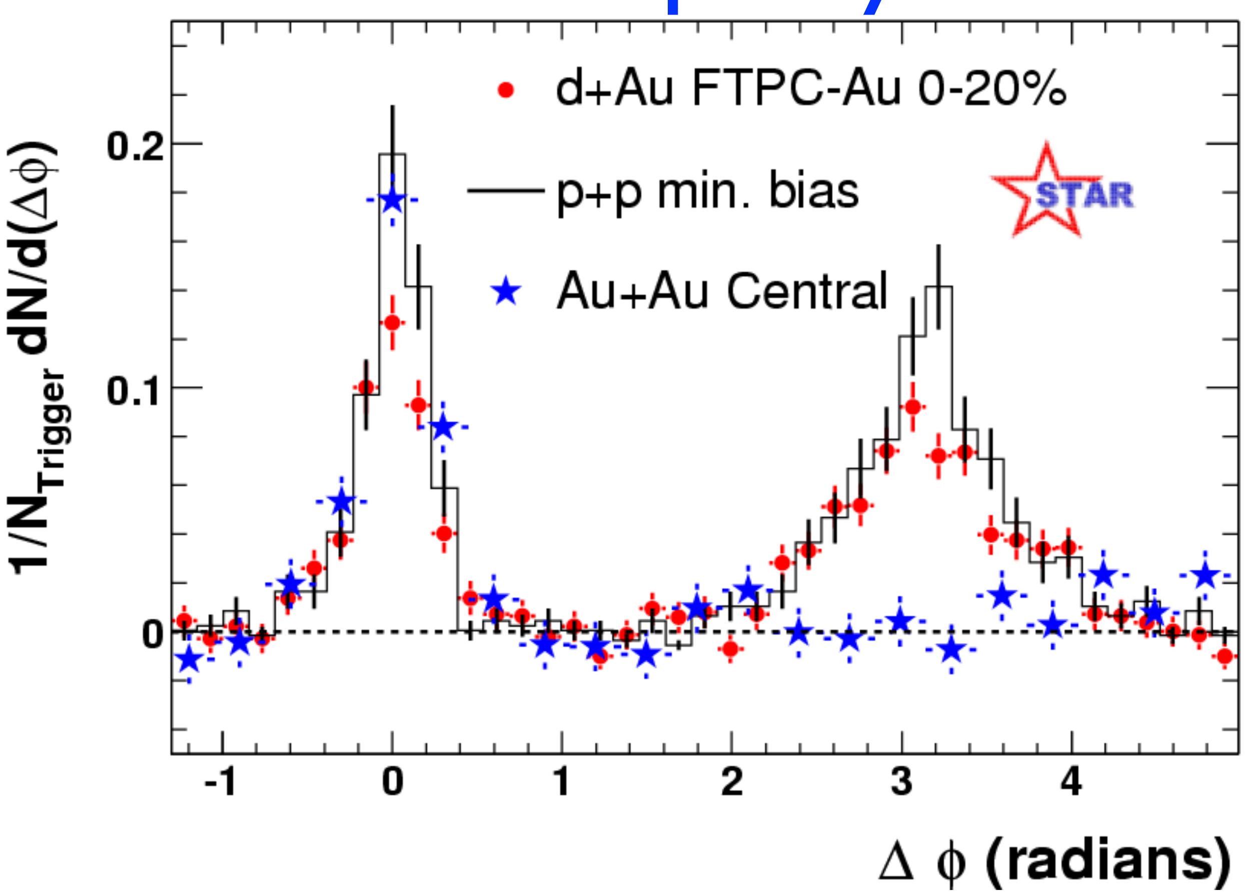

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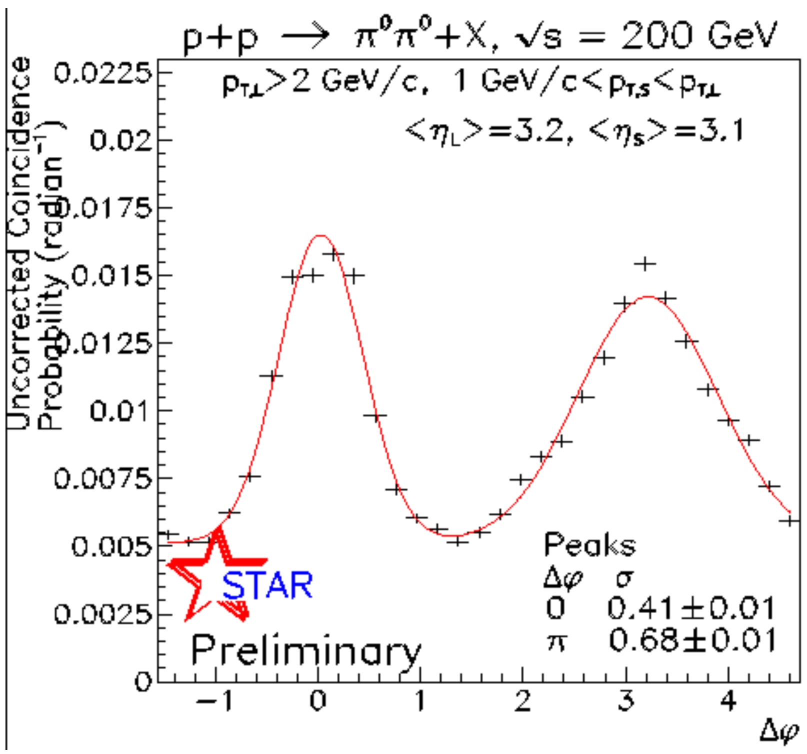

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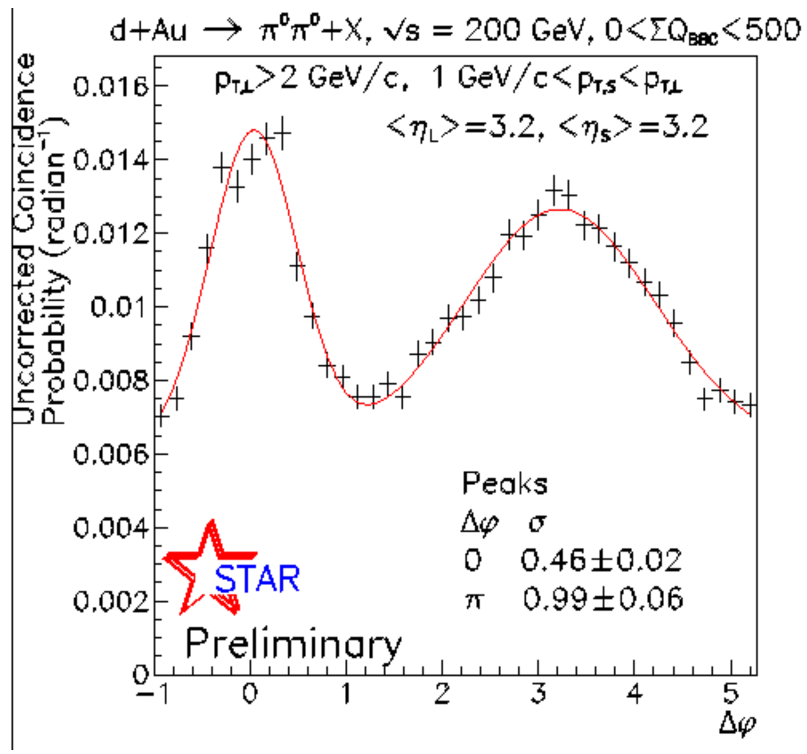
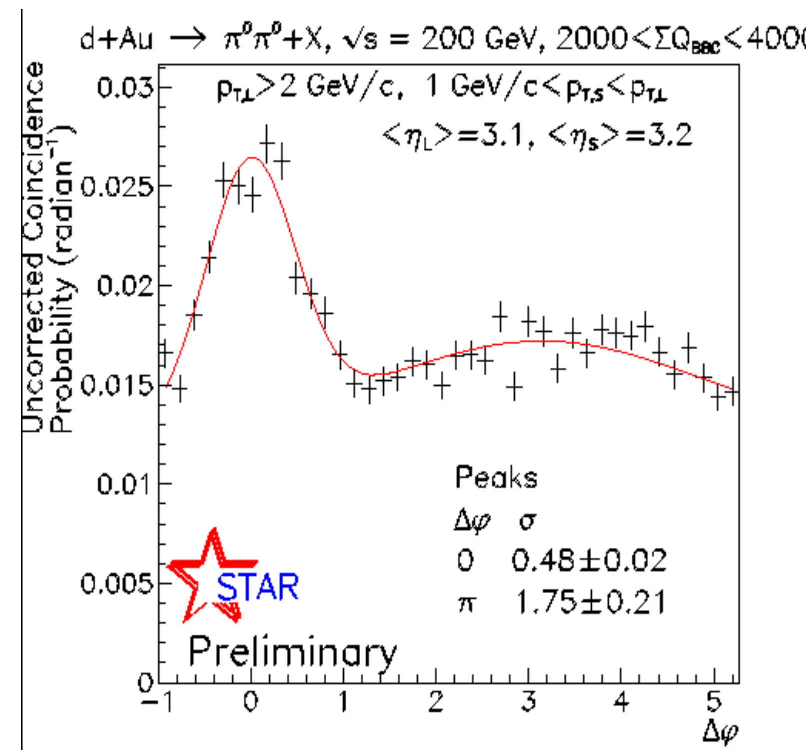


d+Au central



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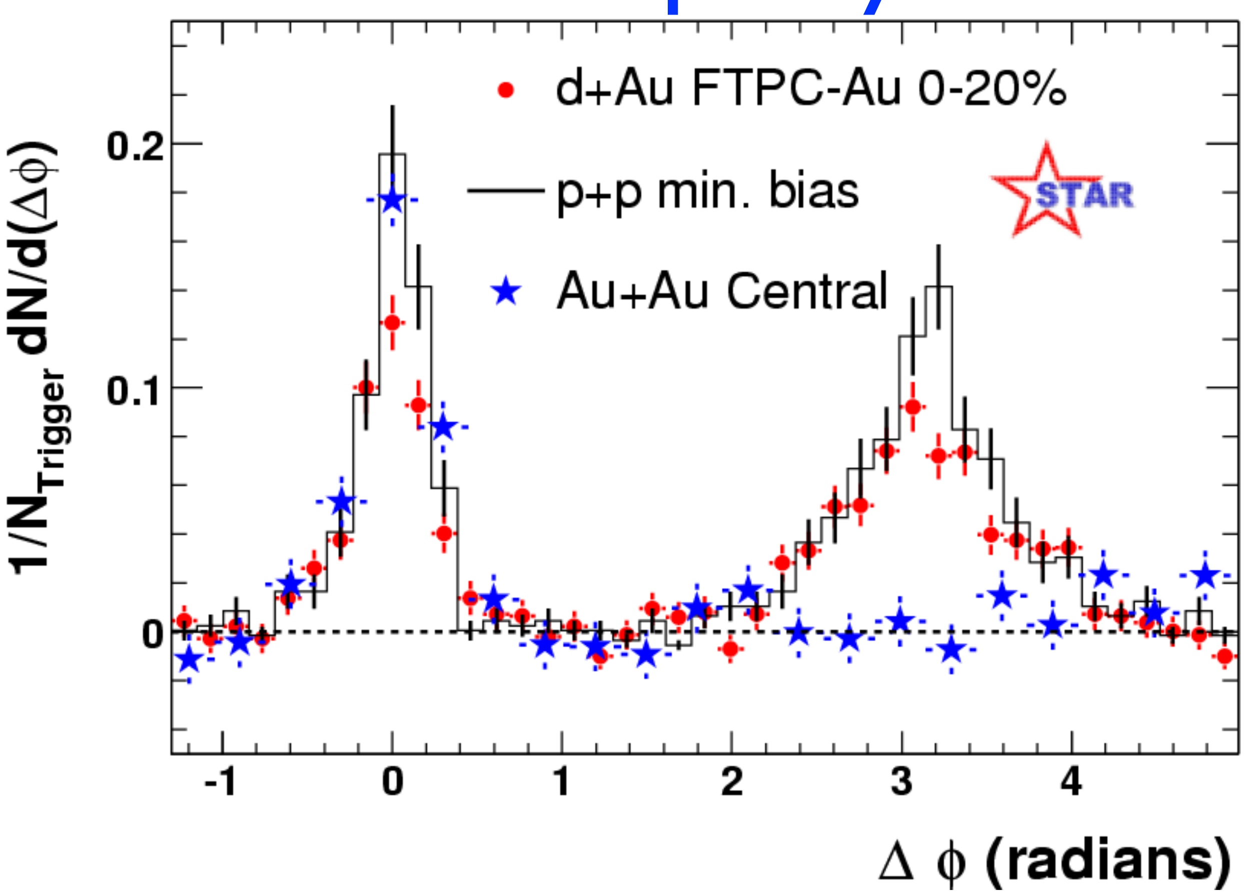

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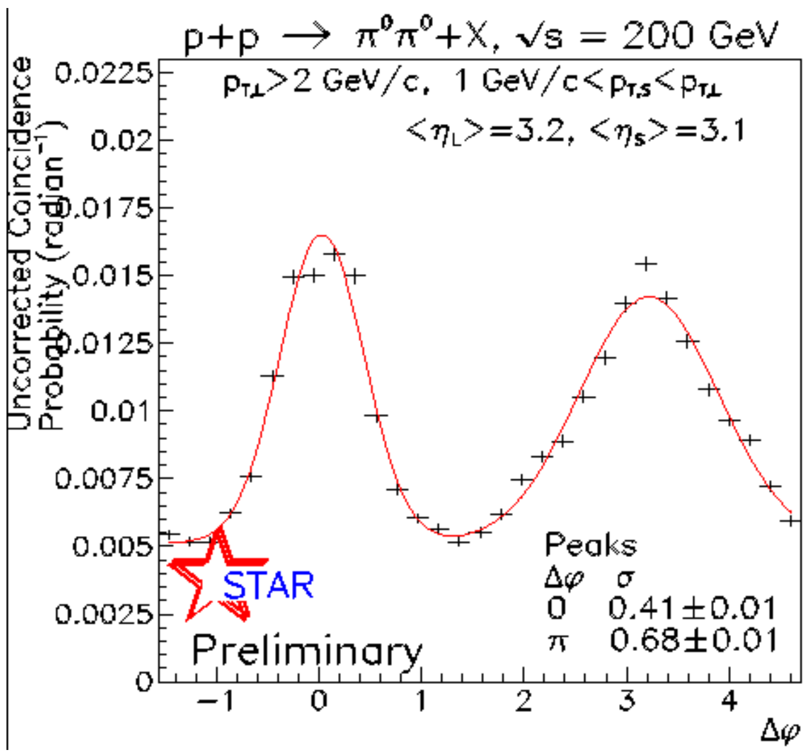

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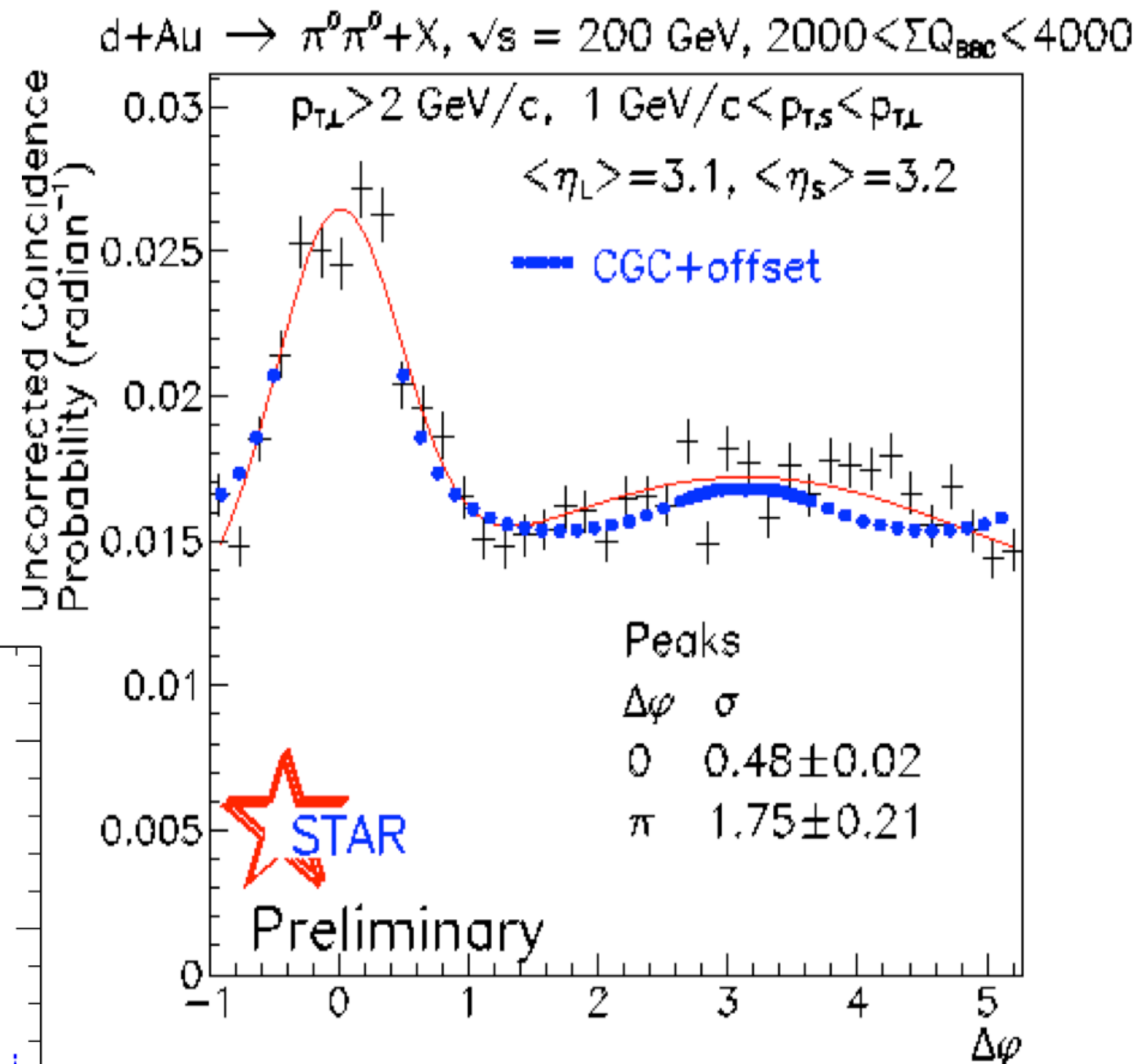

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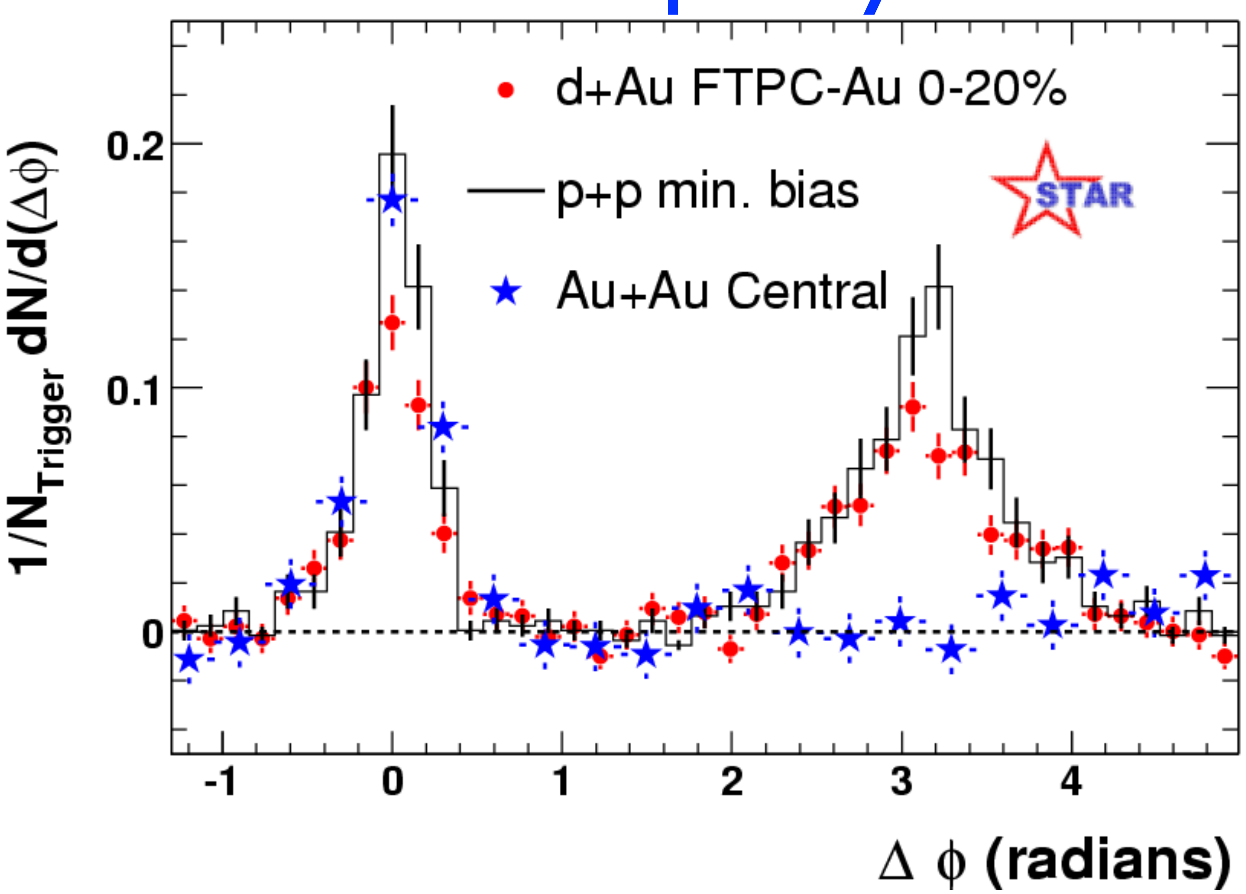
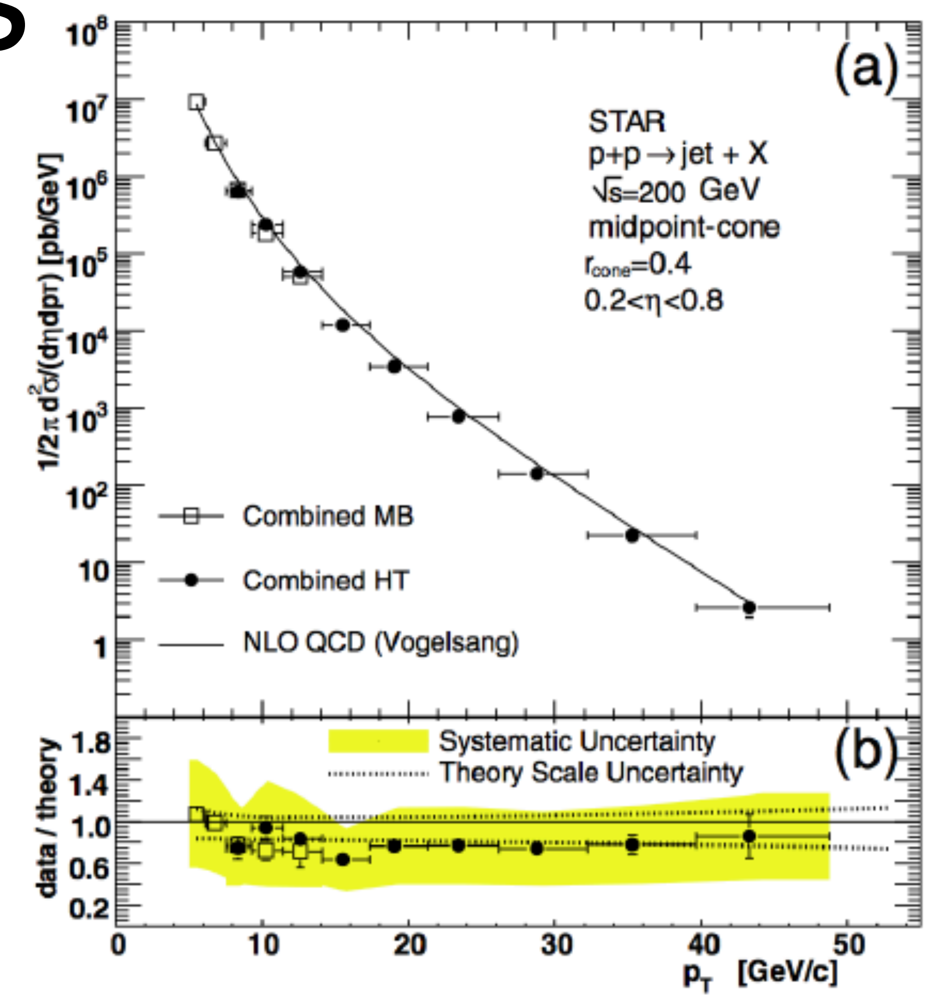
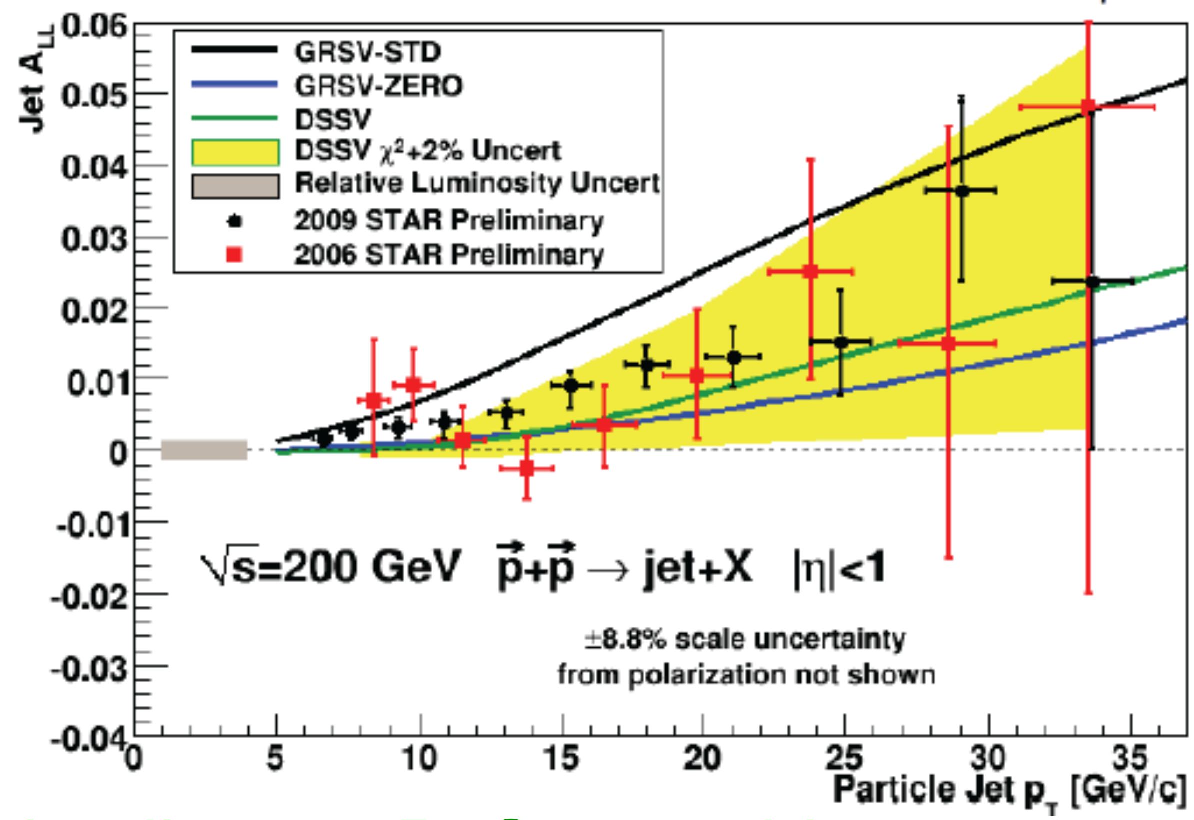


Model: Nucl.Phys.A796:41-60,2007

Spin Results

- The main aim of the RHIC polarised proton running is the measurement of $\Delta g(x)$ at medium-x ($0.01<x<0.3$).
- Inclusive jet-yield is well reproduced by NLO pQCD calculations
  - Can use NLO pQCD to extract $\Delta g(x)$ from measurements of A_{LL}
  - Measurement good enough to discriminate between some GRSV scenarios
- Lot more to do in the spin programme
  - Running at $\sqrt{s}$=500 GeV increases the x-range and available measurements





For more details, see B. Surrow, id:113

Questions remaining to be answered

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- Despite RHIC's successful 1st decade - unanswered questions remain:
- A+A
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  - Are the interactions of energetic partons with QCD matter characterised by strong or weak coupling? What is the detailed mechanism of partonic energy loss?
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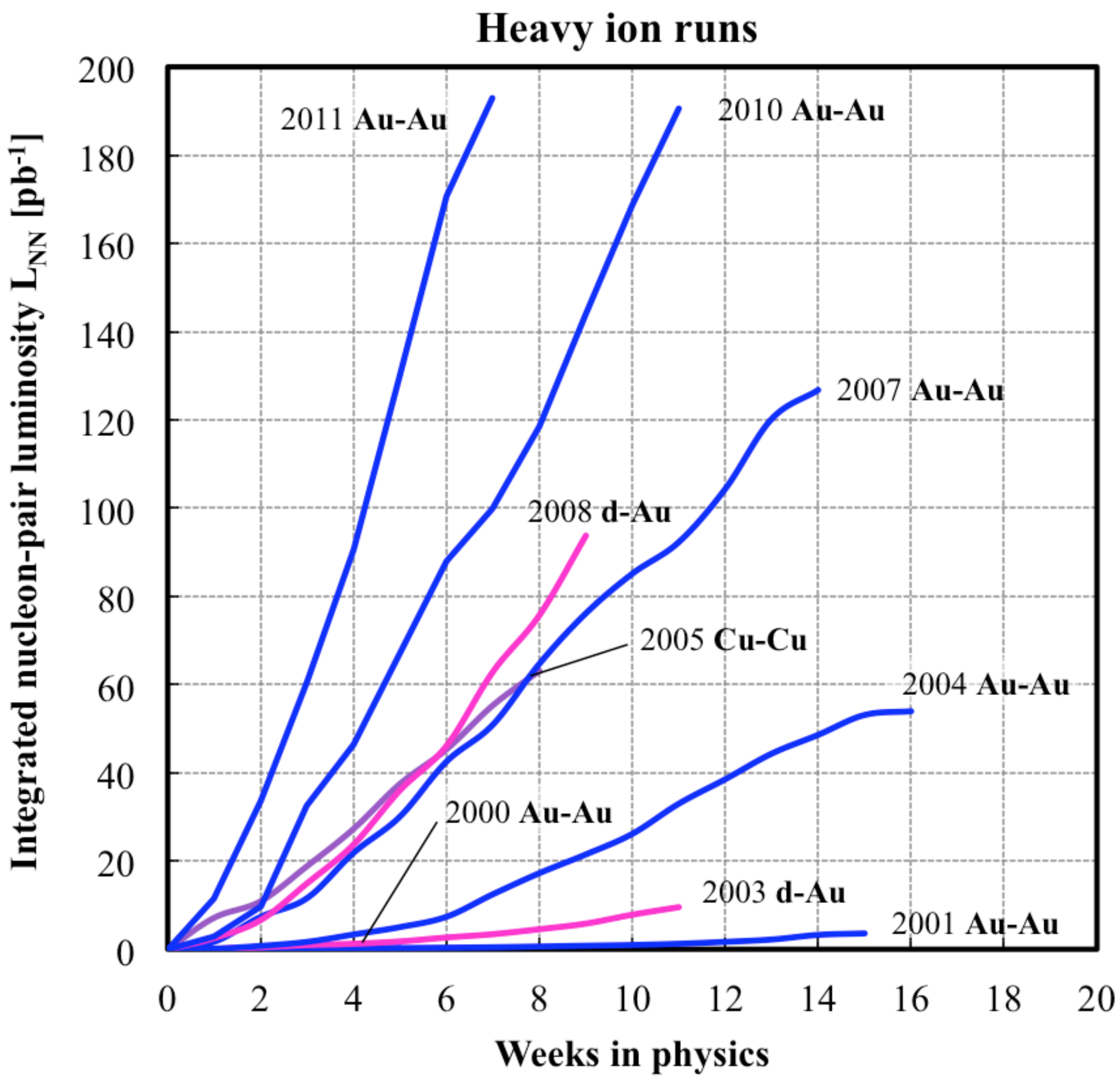
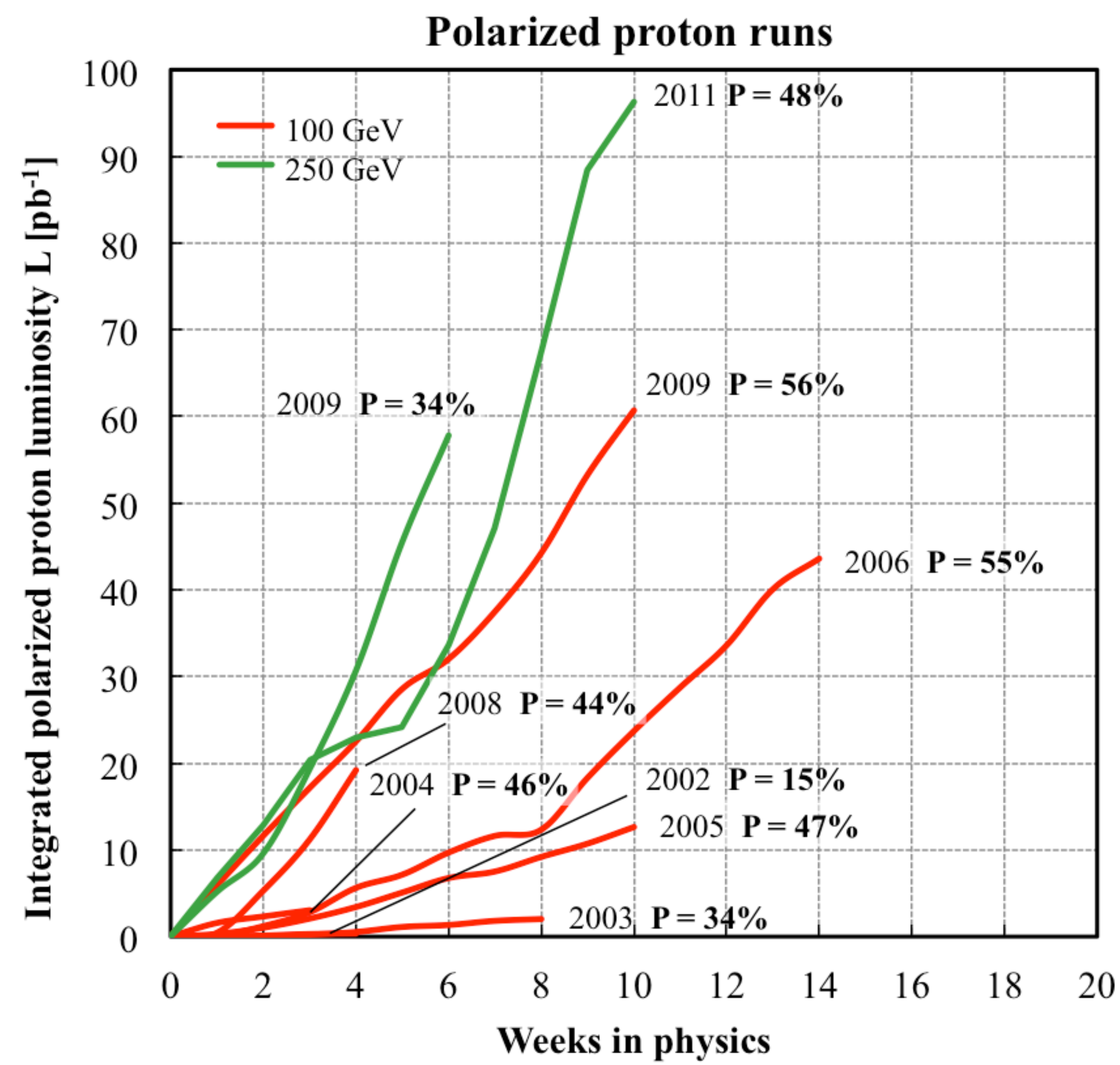
- p/d+A
  - What is the nature of the initial state in nuclear collisions?
- p+p
  - What is the partonic spin structure of the proton?
  - How do we go beyond leading-twist and collinear factorisation in pQCD?

RHIC's improvement with age….

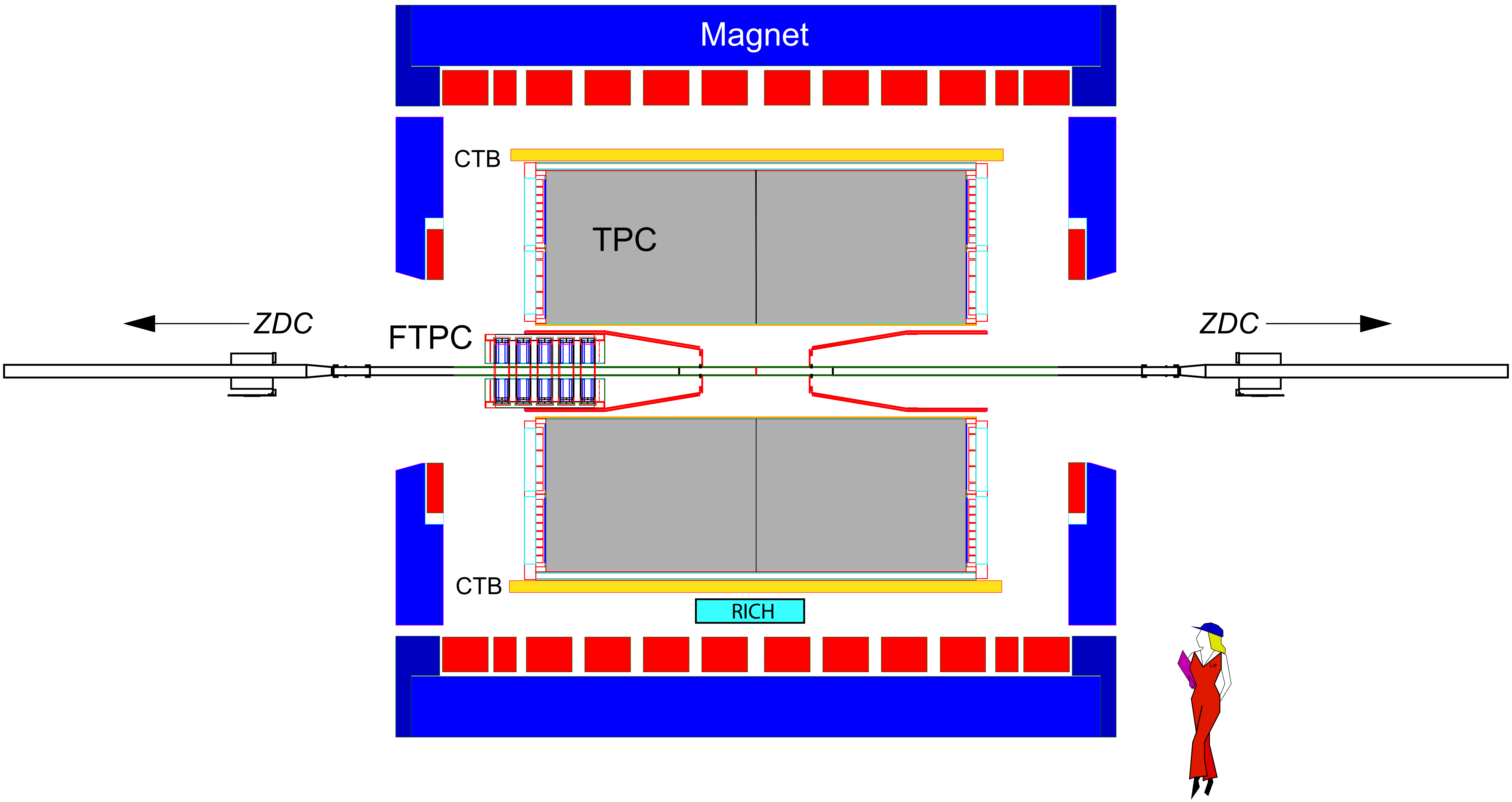




Plots courtesy of W. Fischer, C-AD

- As RHIC has improved luminosity, so STAR has improved
  - 2001: TPC DAQ ~ 8 Hz (when the stars aligned)
  - 2012: TPC DAQ ~ 1.8 kHz

STAR through the ages



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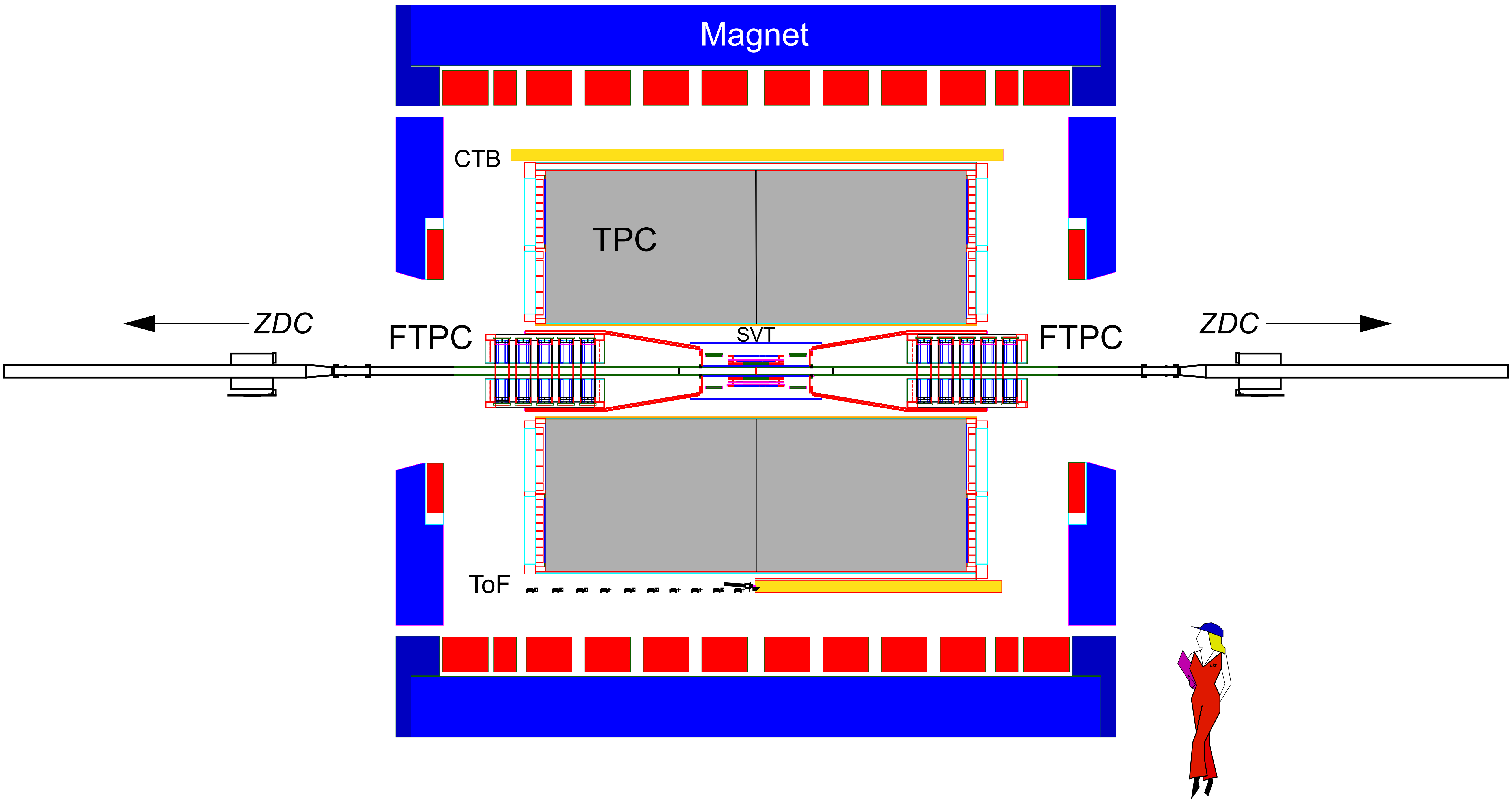

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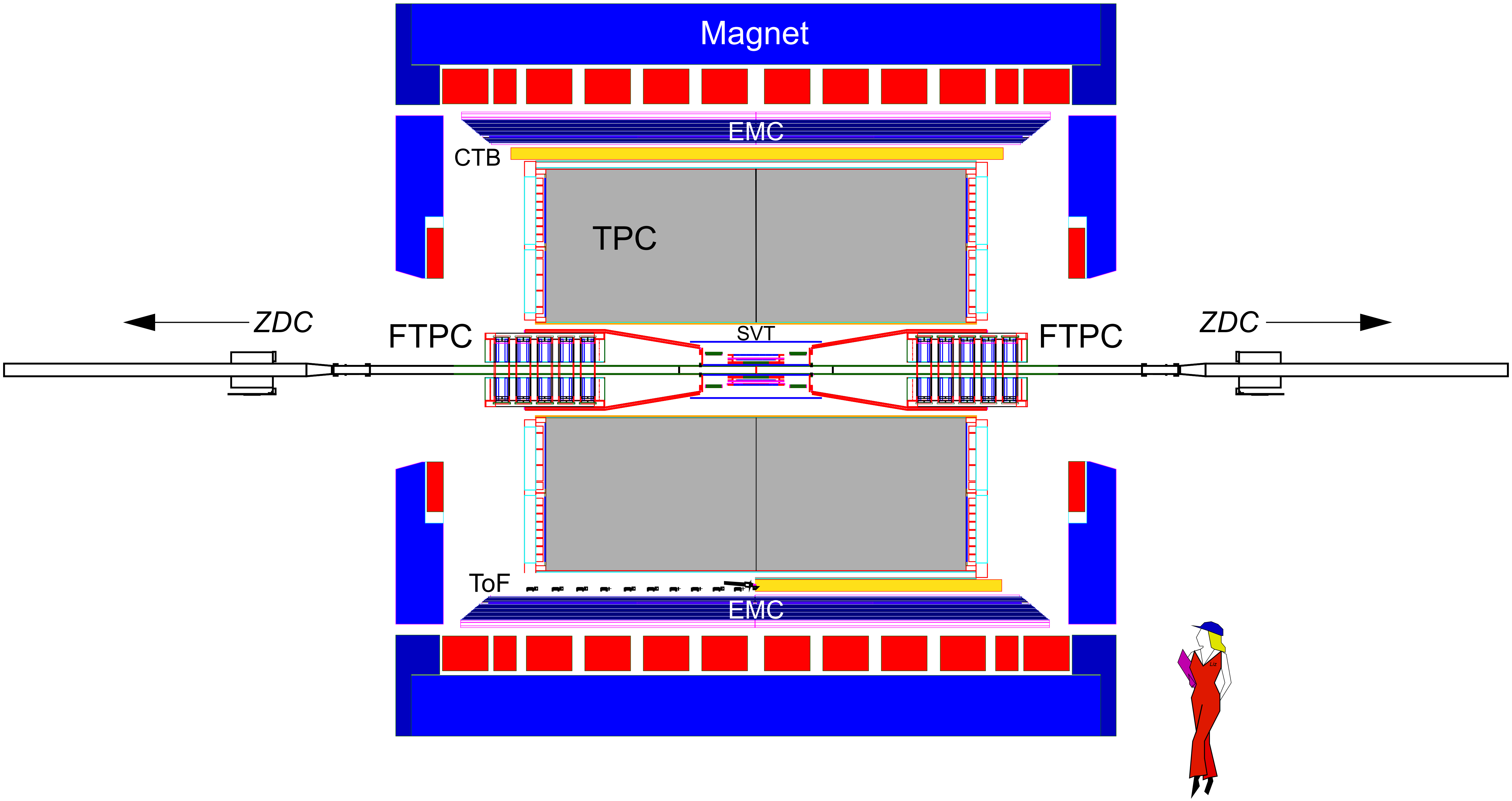

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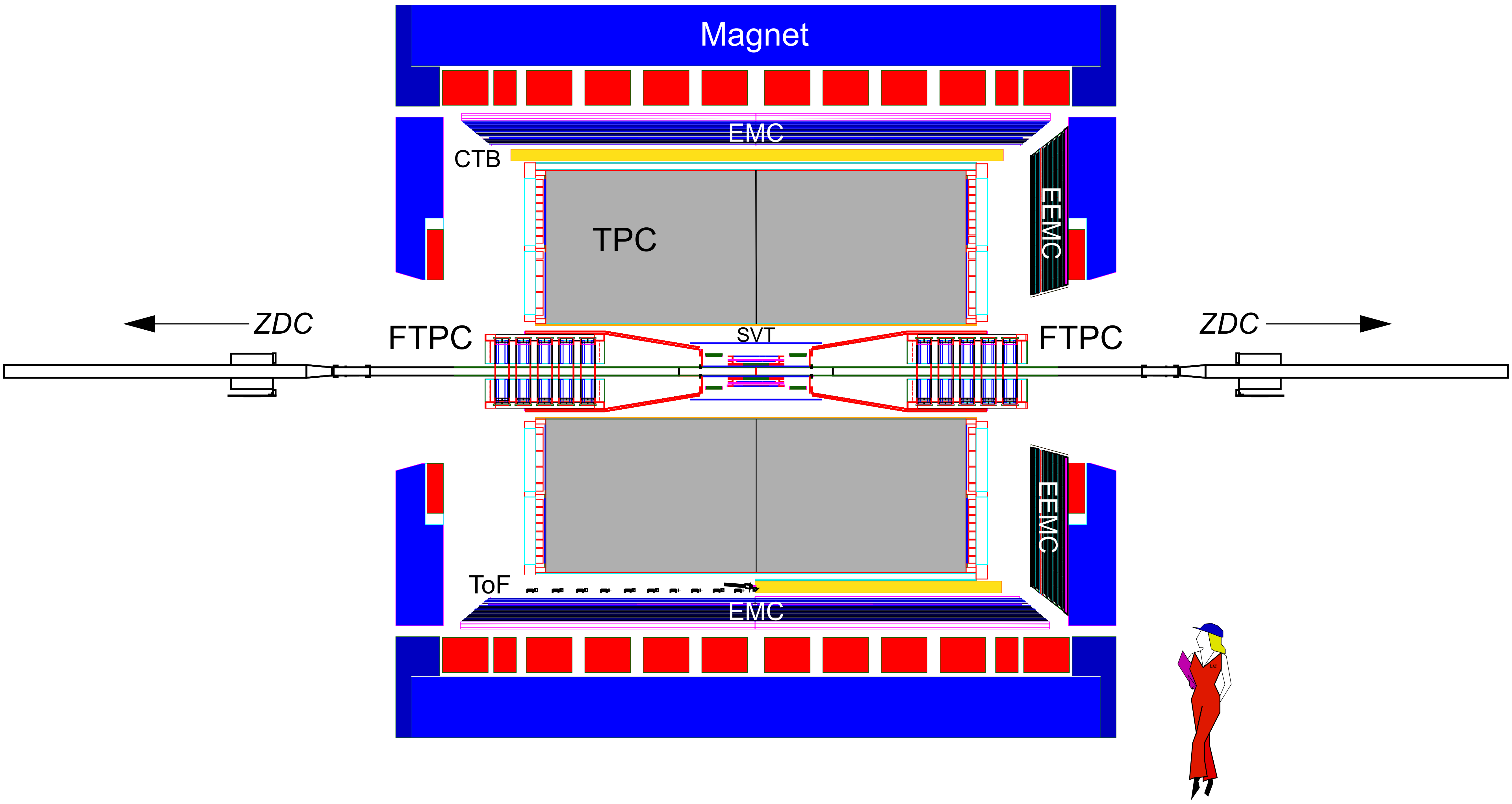

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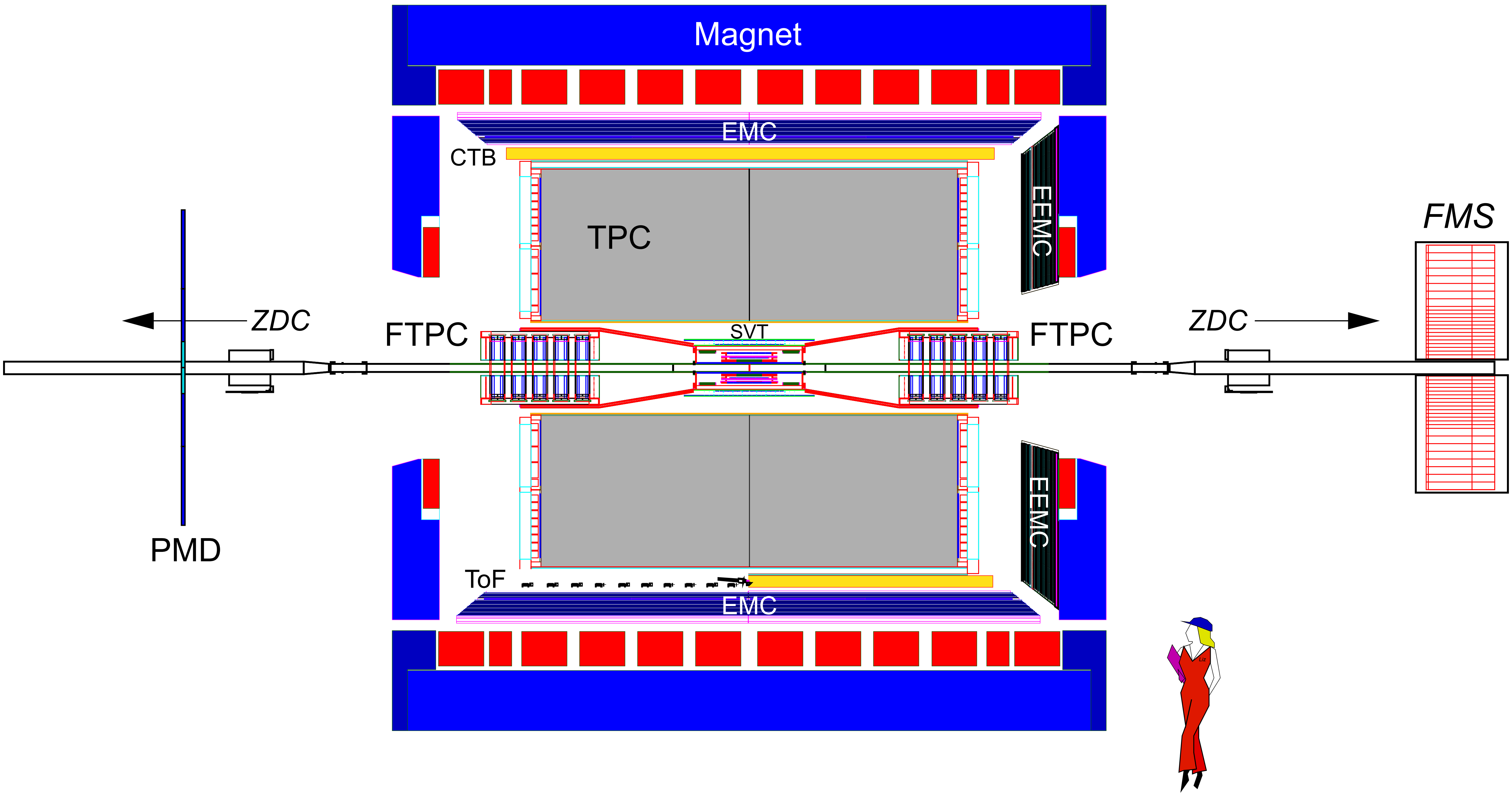

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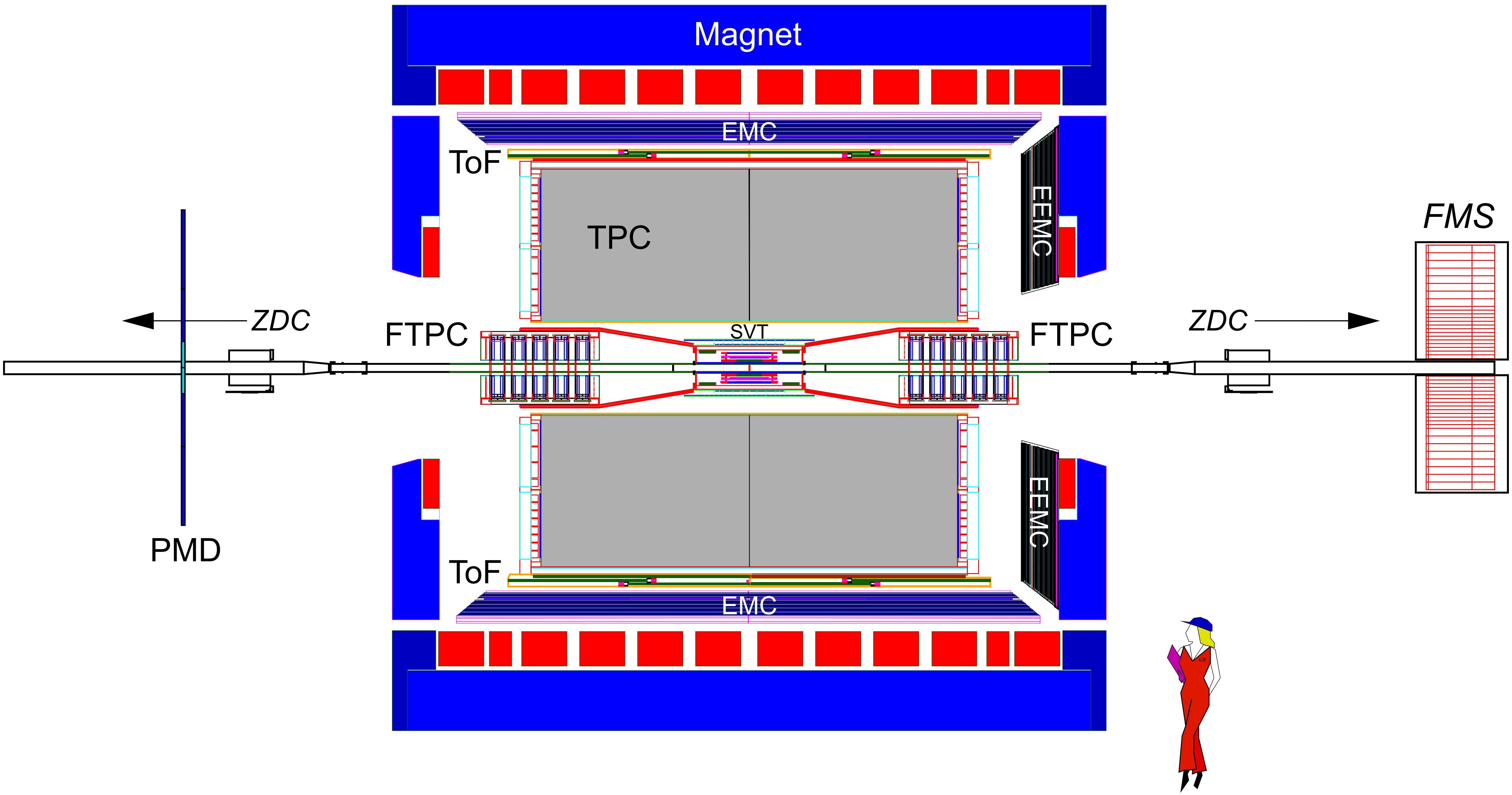

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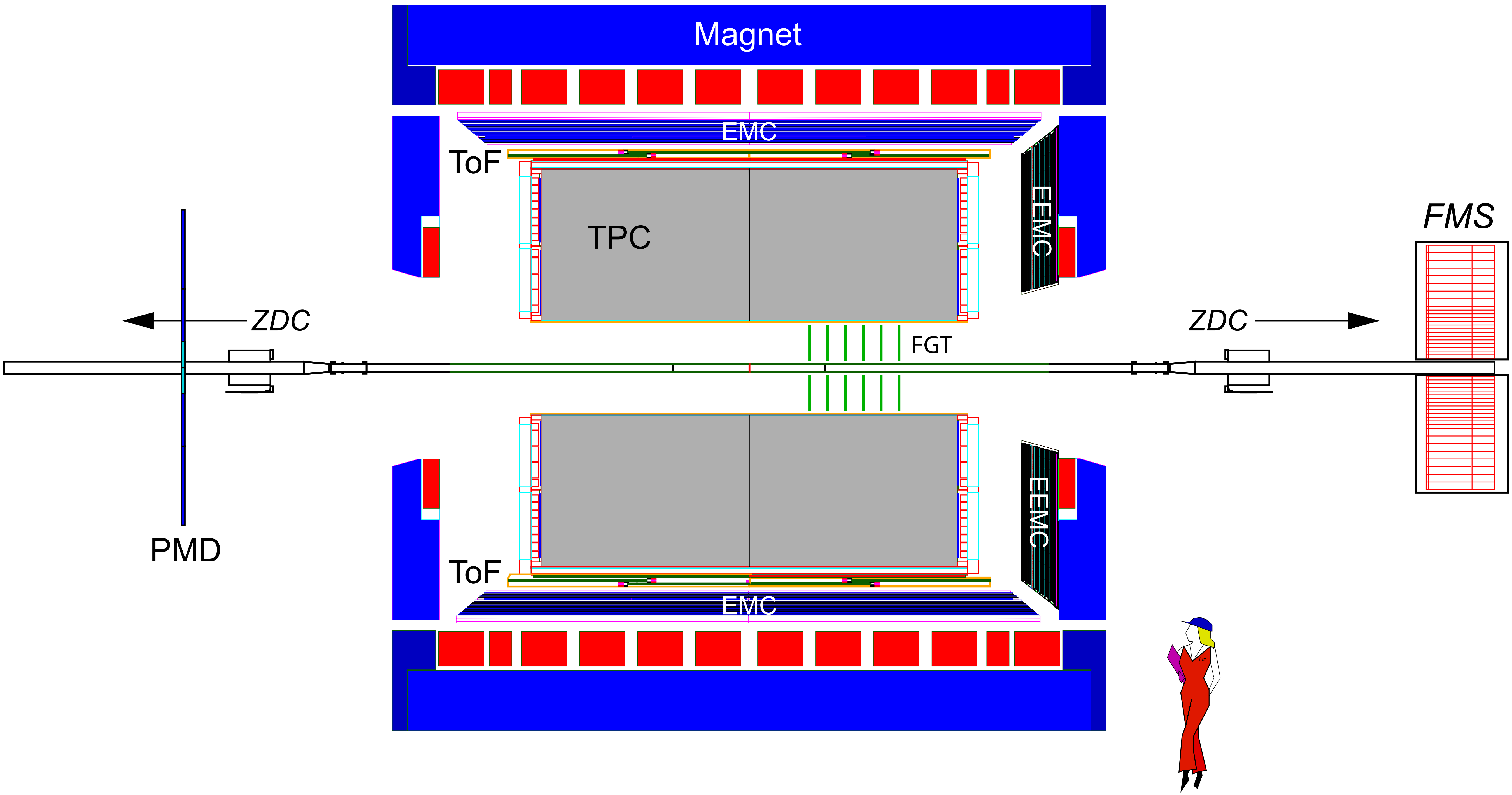
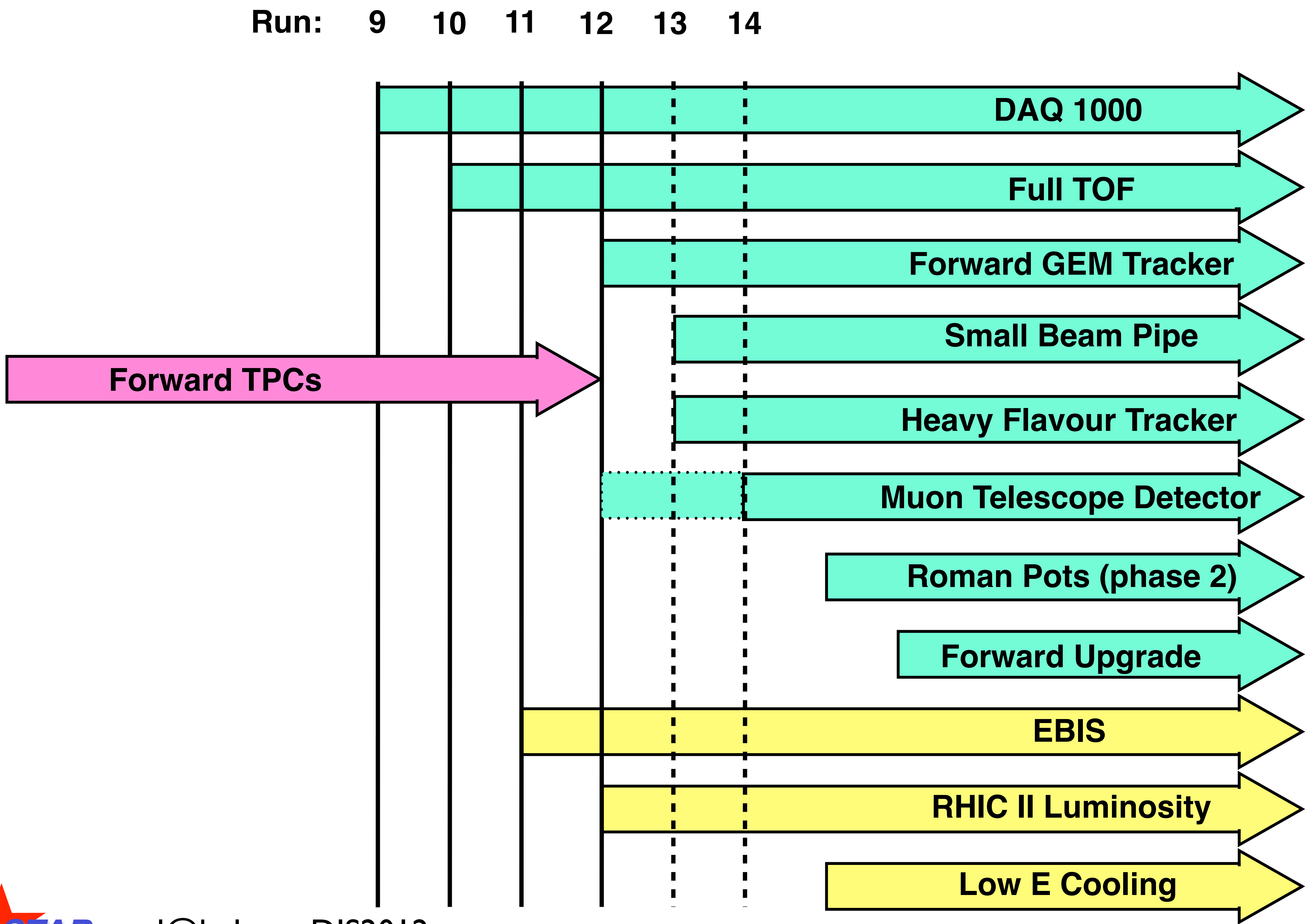


Timeline of STAR detector upgrades



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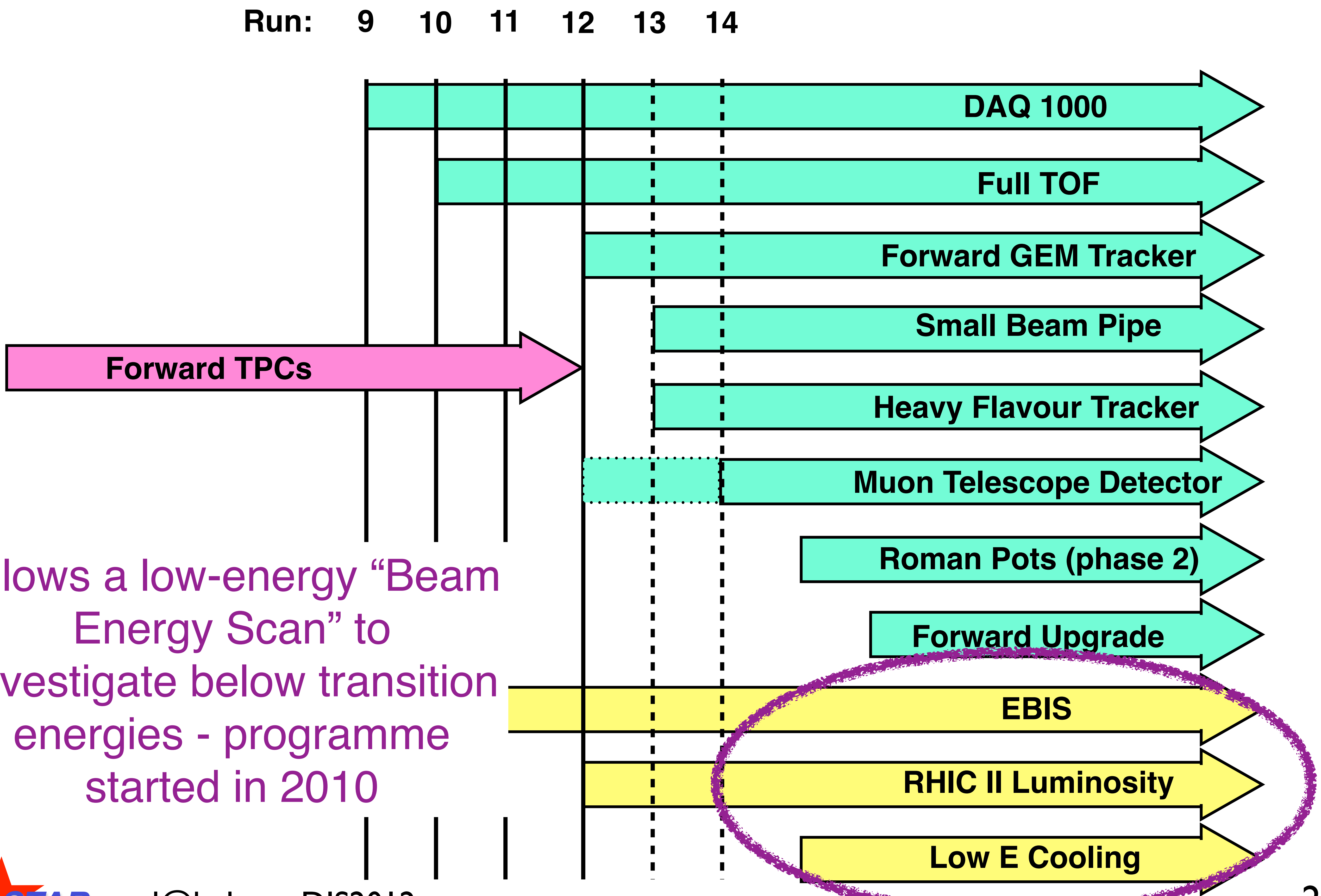
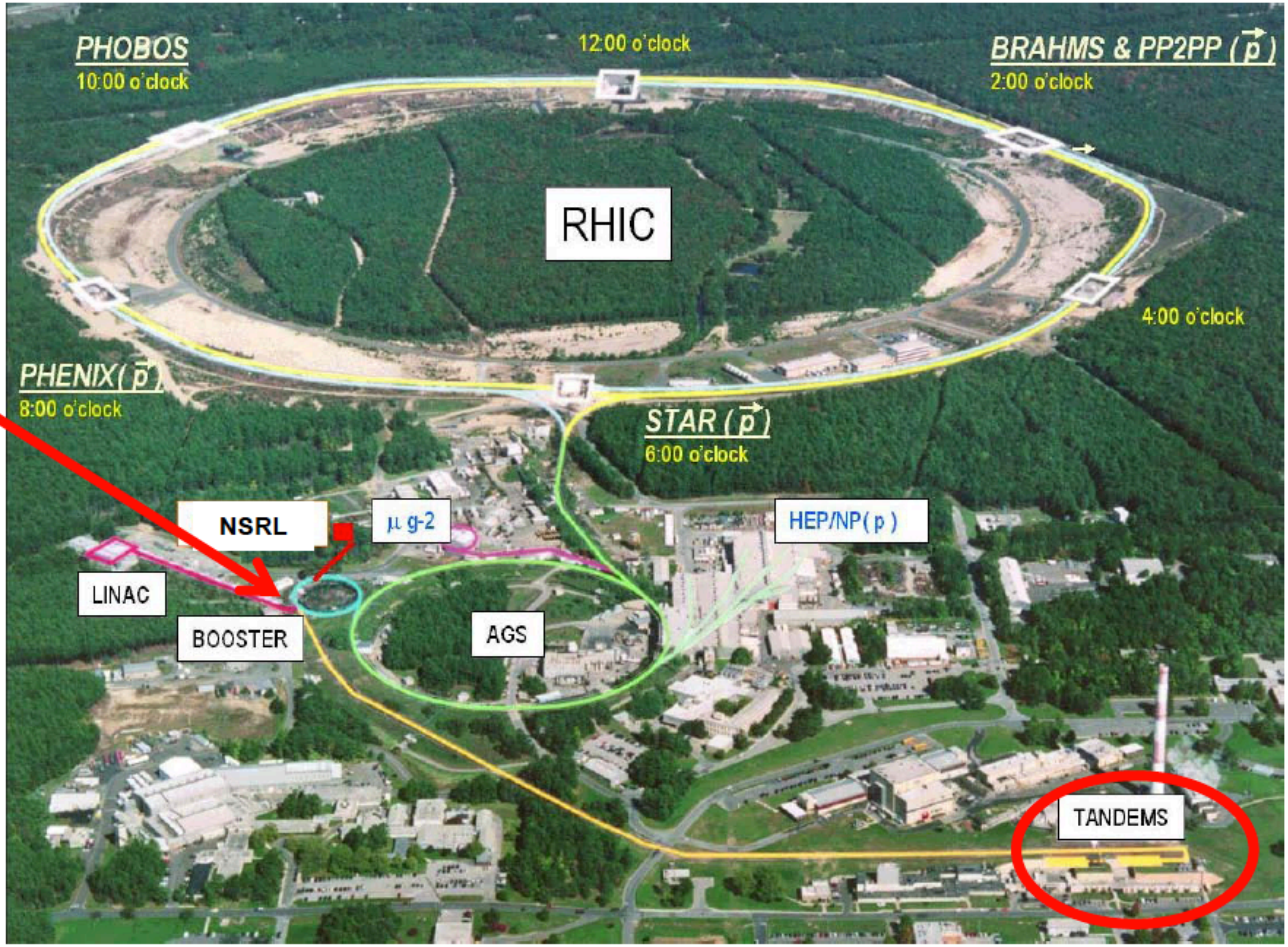


Allows a low-energy “Beam Energy Scan” to investigate below transition energies - programme started in 2010

RHIC Upgrades - EBIS Source

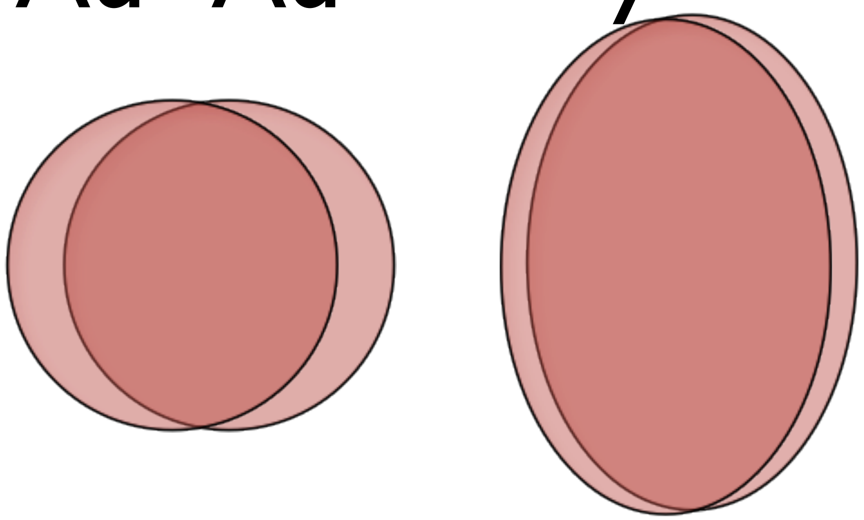
EBIS going here



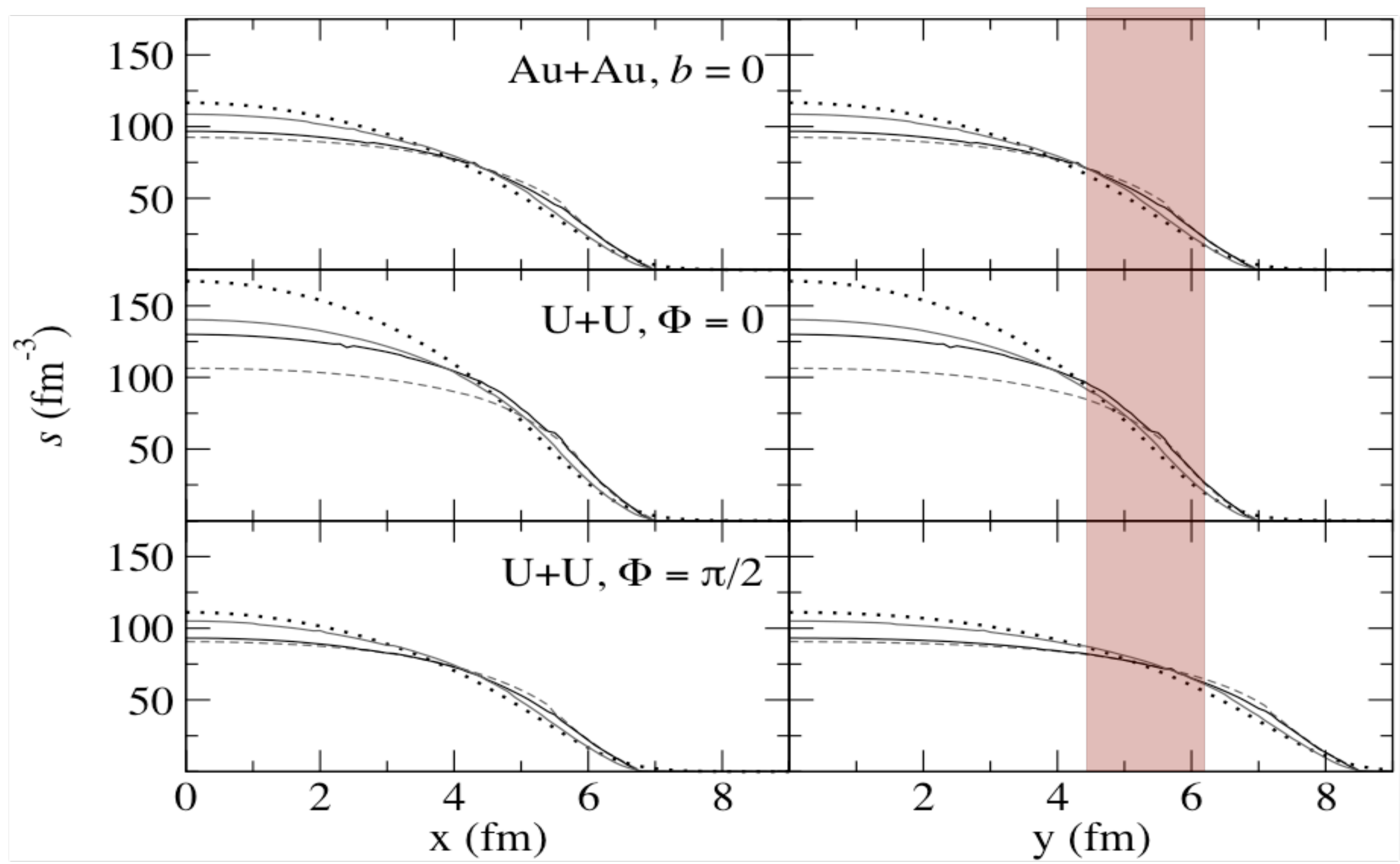
Flexibility: U+U

Au+Au

U+U
Body-Body



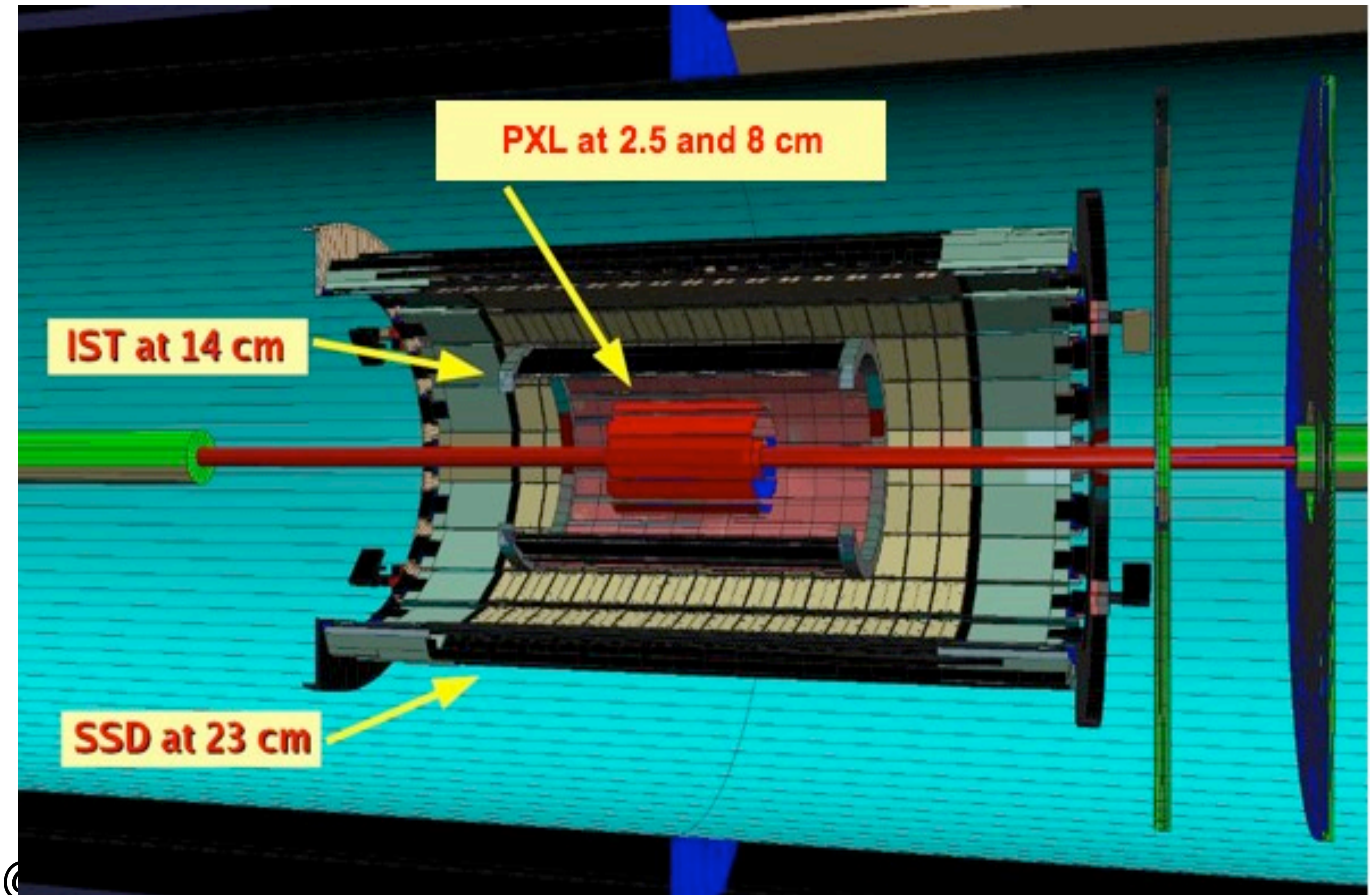
A. Kuhlman, U. Heinz, Y.V. Kovchegov, Phys. Lett. **B638**, 171(2006)



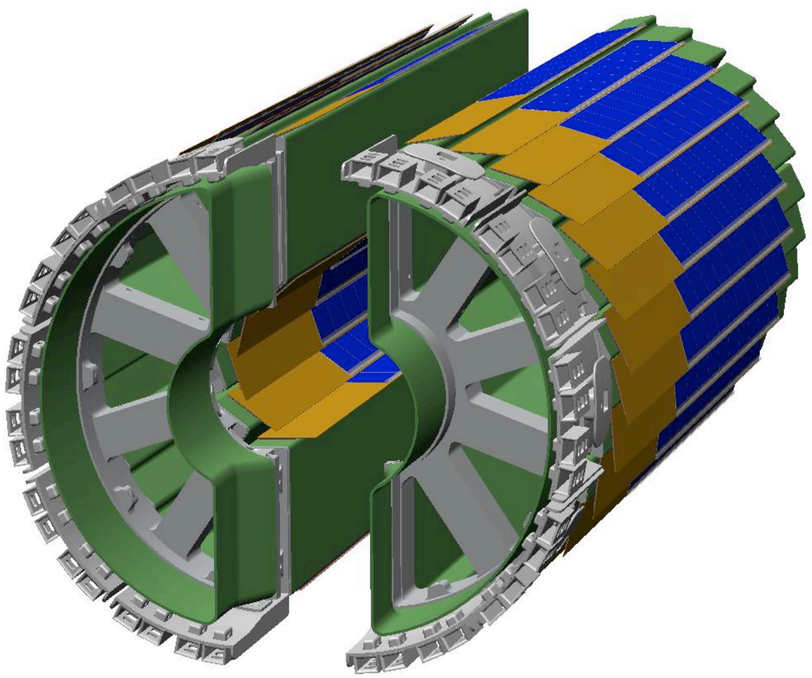
- Run 12: first feasibility studies
- Unique: pathlength dependence of quenching (50% more L)
  - Full range of measurements: γ-jet, b and c, jets, Upsilons, …

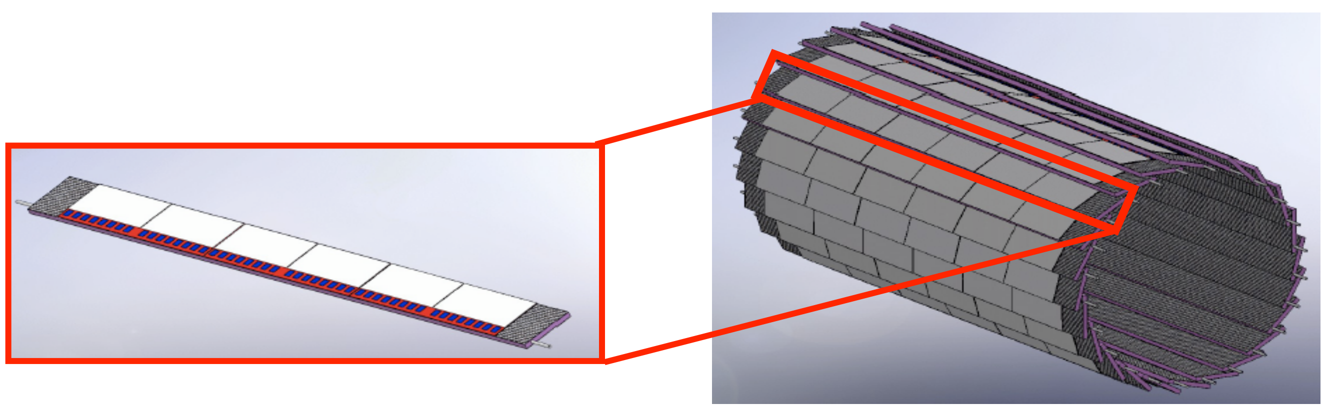
Heavy Flavour Tracker

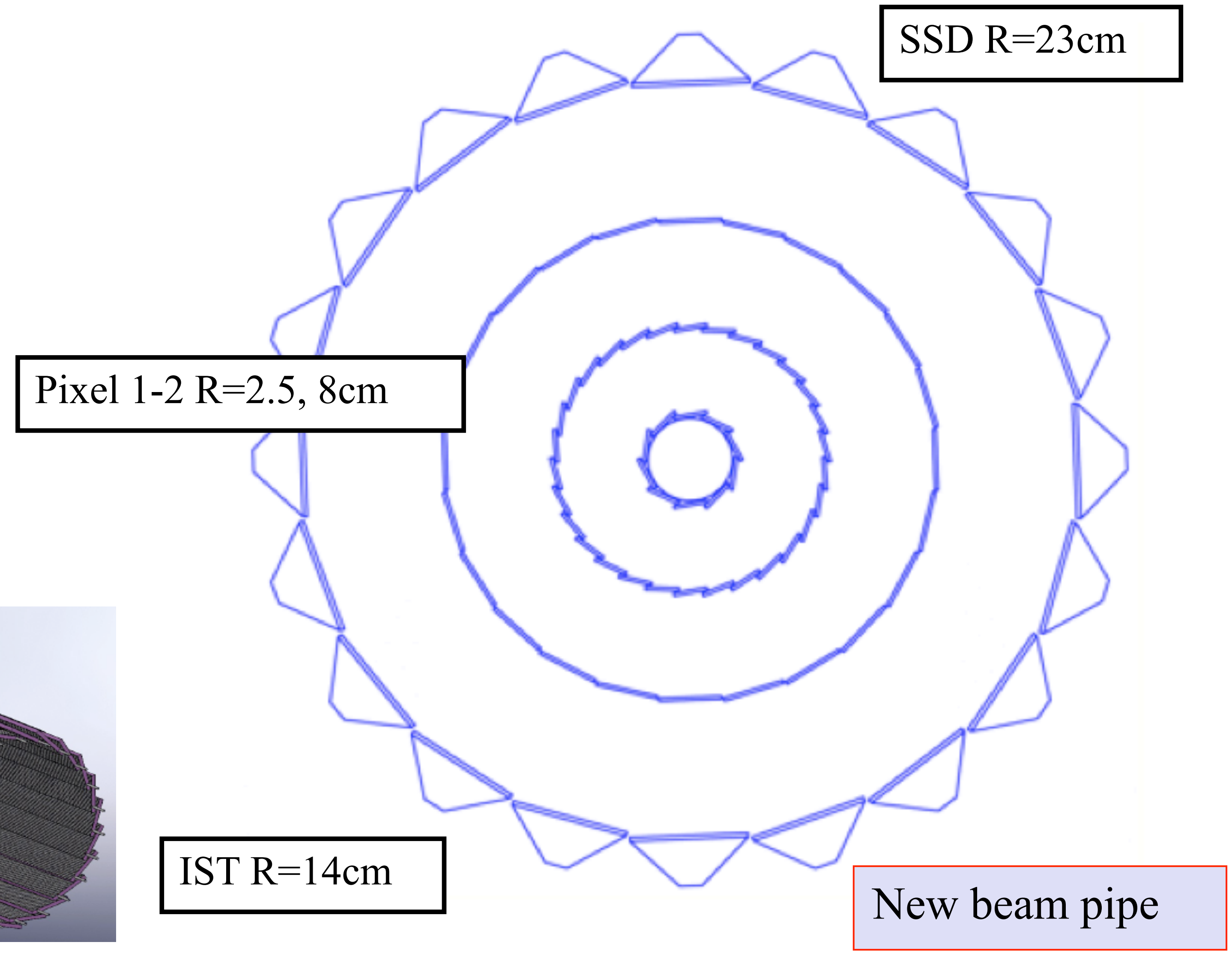
- Original mid-rapditiy Si vertex tracker at STAR not capable of identifying charm and bottom hadrons through direct reconstruction of the displaced vertex
- Heavy Flavour Tracker designed to do this. Installation begins in 2013



HFT Technology

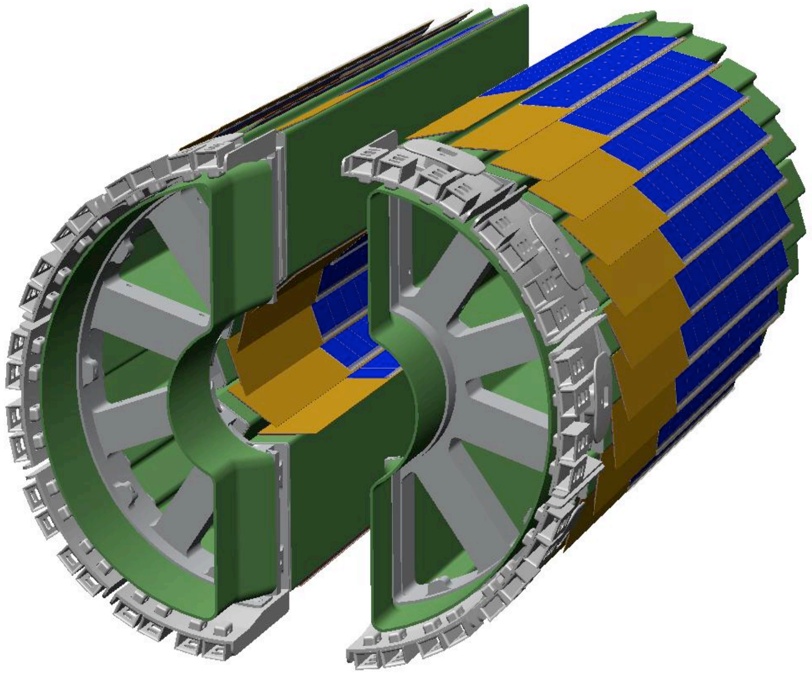


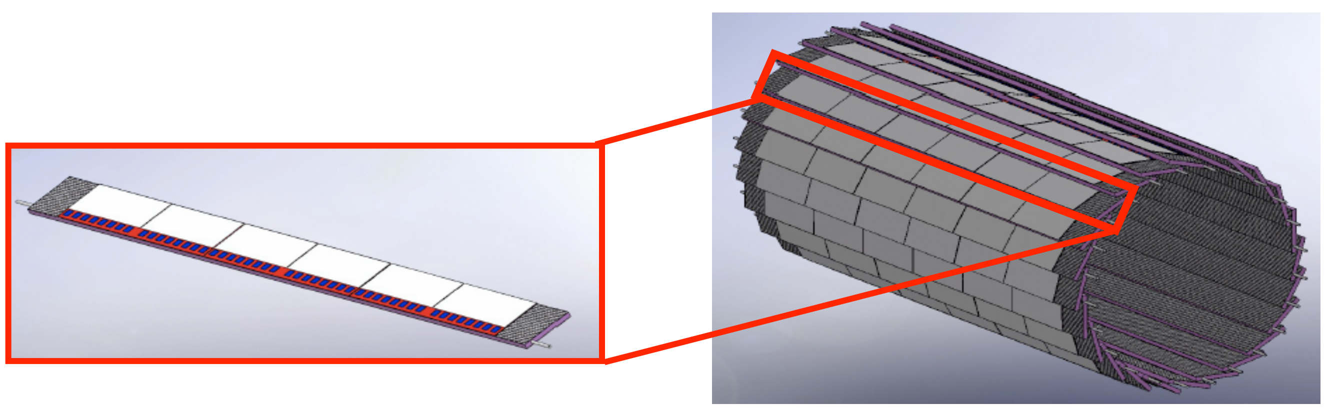


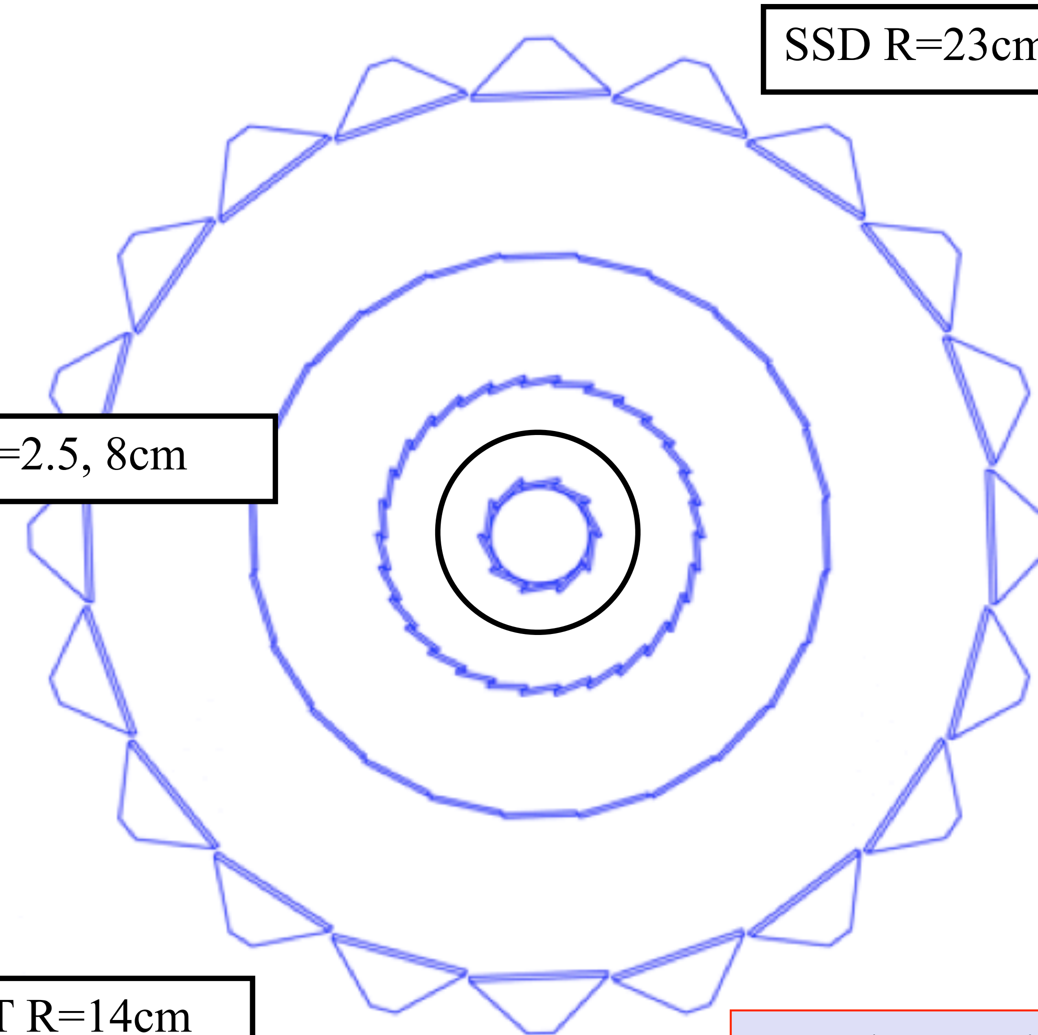


	Technology	Hit resolution R-ϕ (μm - μm)	Radiation Length
SSD	double sided strips	30 - 857	1% X_0
IST	Silicon Strip Pad sensors	170 -1700	1.2% X_0
PIXEL	Active Pixels	8.6 - 8.6	0.4 % X_0

HFT Technology







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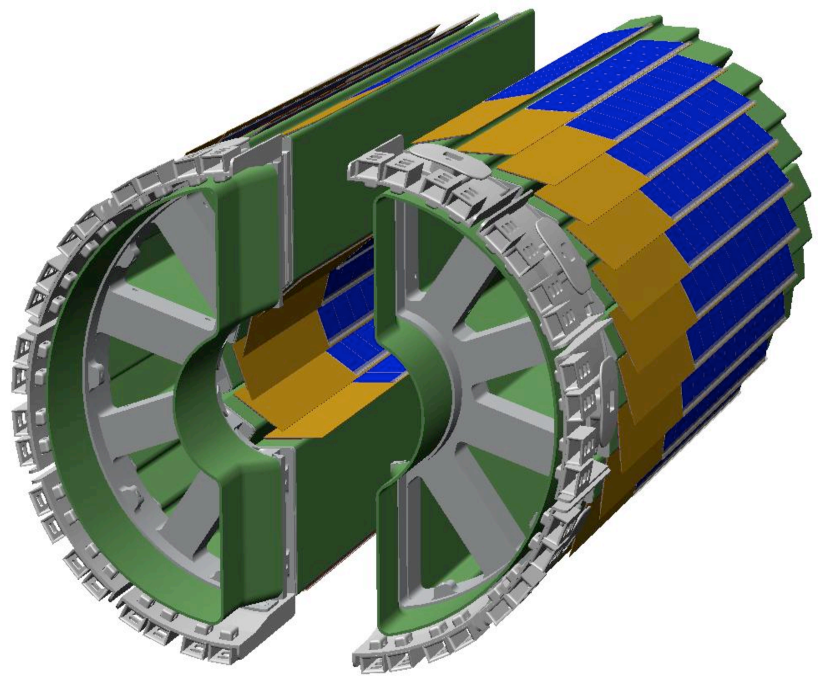

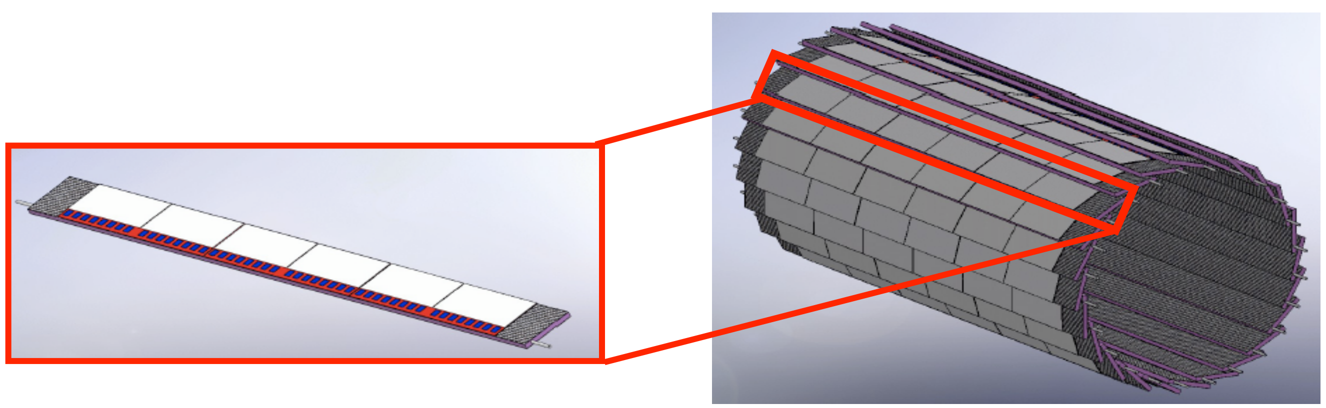

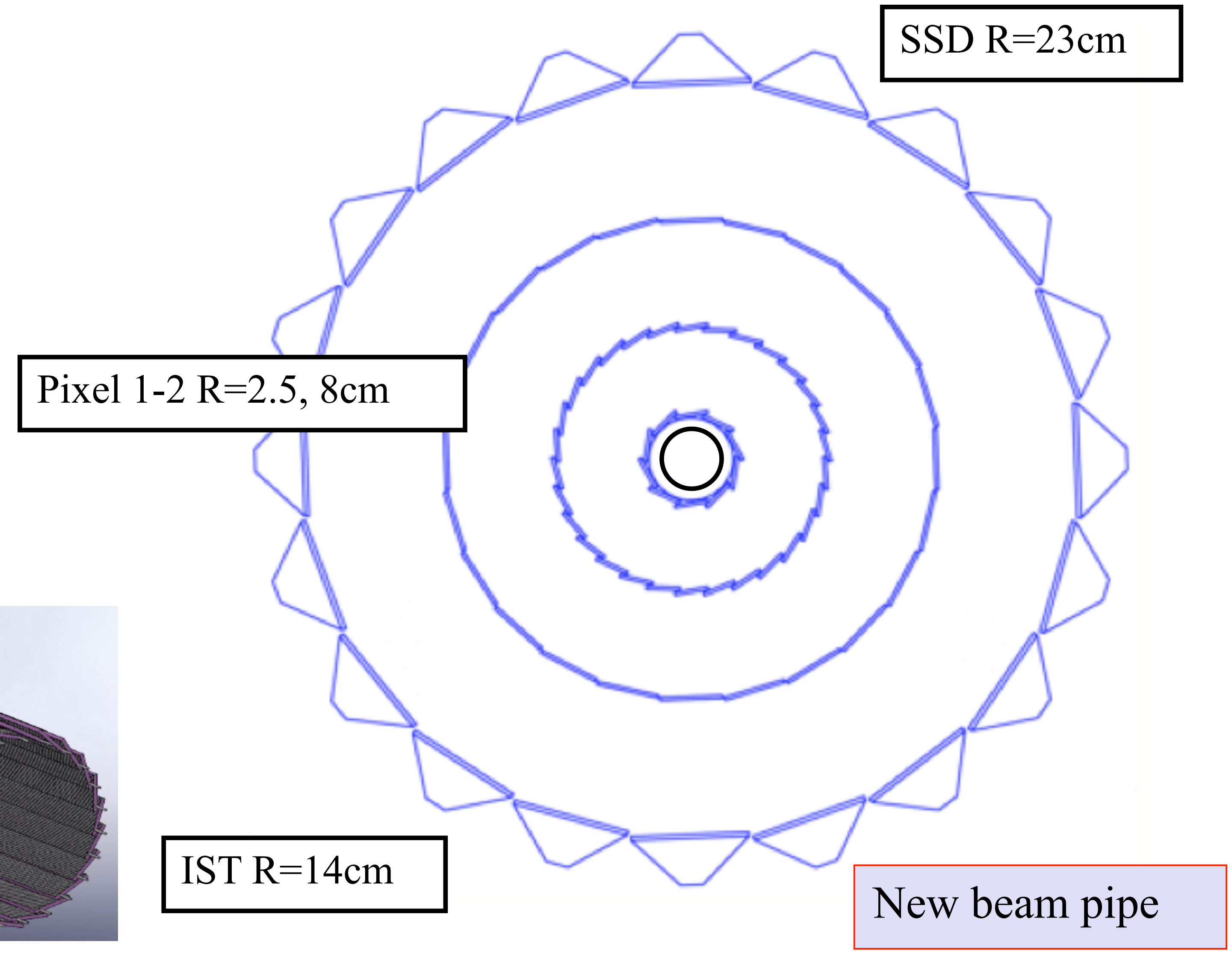

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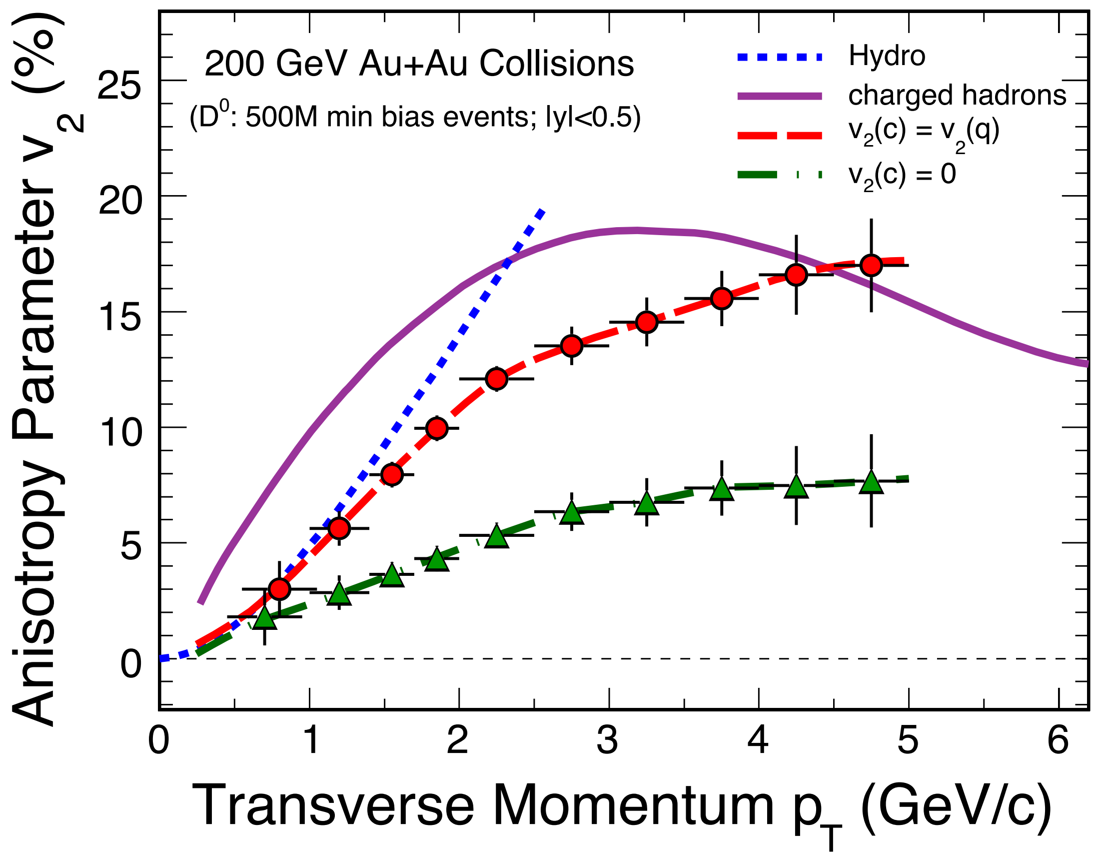
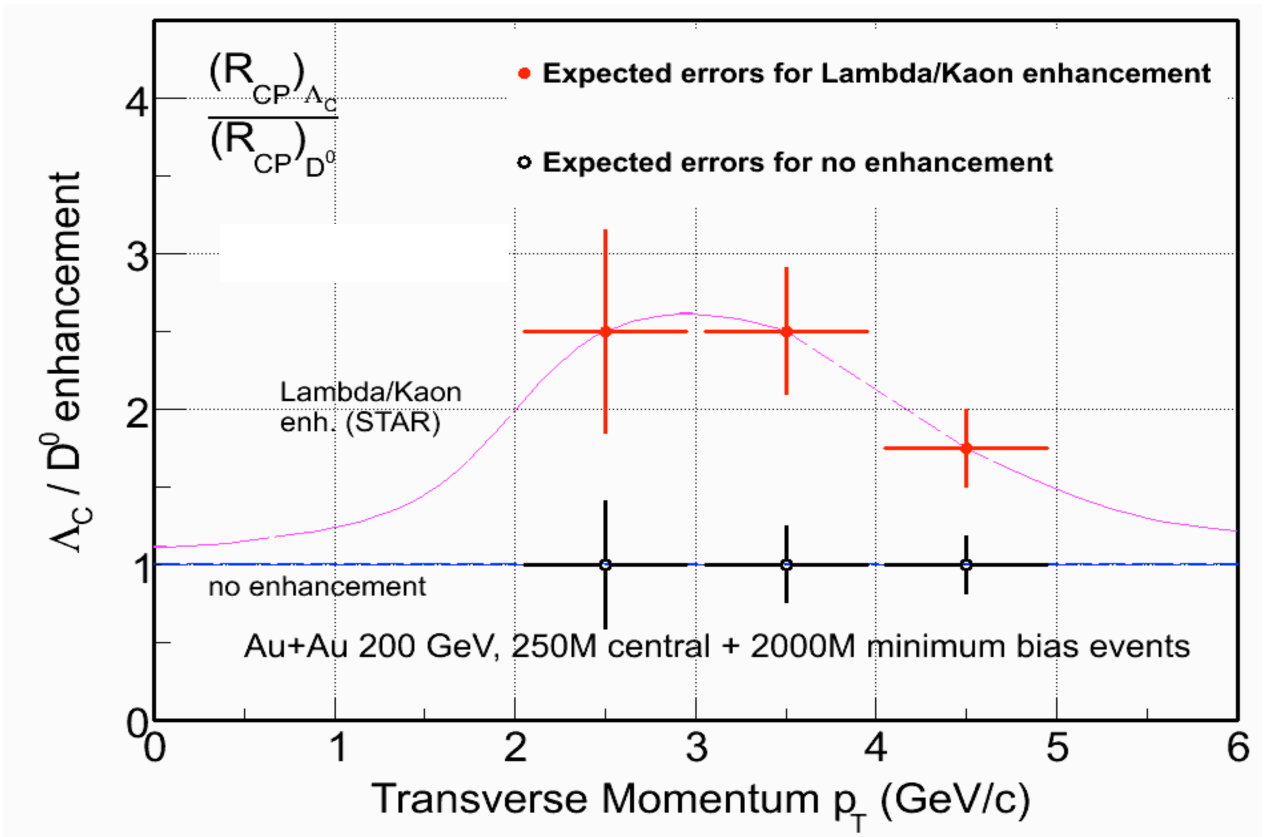
Physics of the HFT

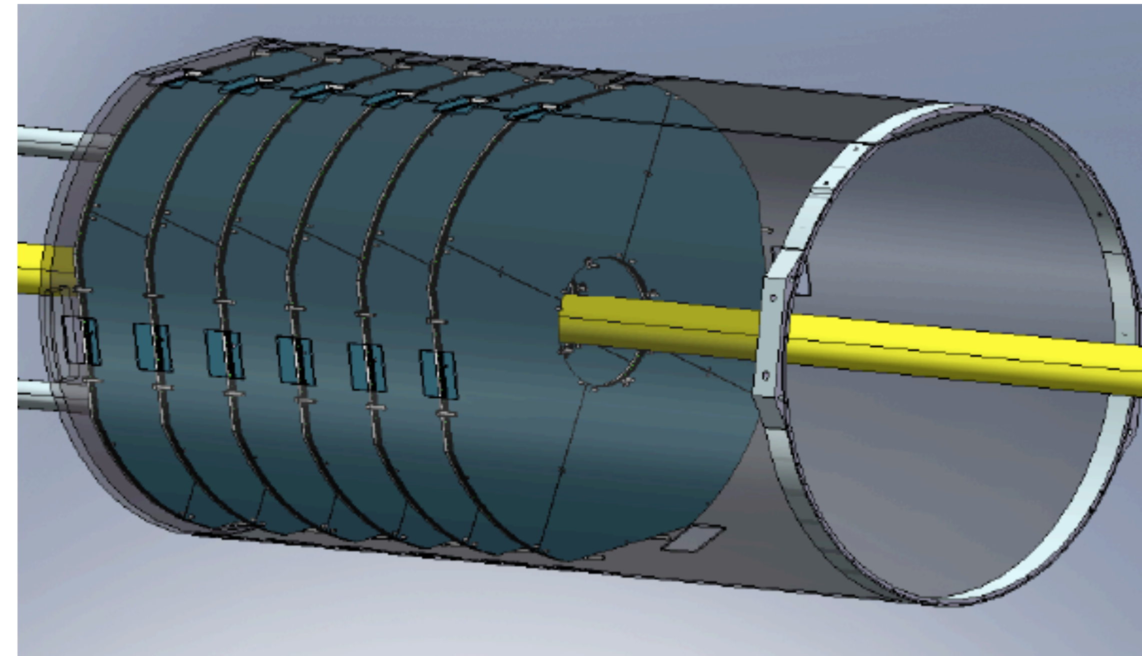


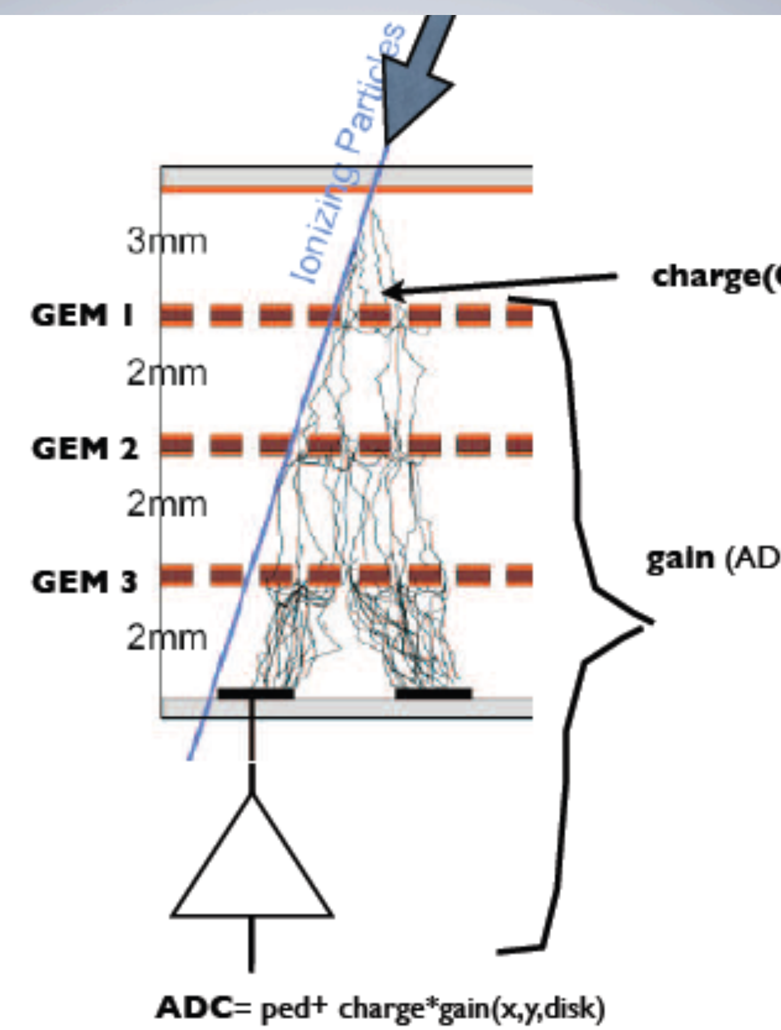


- Very thin vertexer focussed on reconstructing charm:
  - Run 14: does charm flow hydrodynamically?
  - Run 15: reference data in p+p 200 GeV
  - Run 16: baryonic composition
    - Does baryon/meson ratio at intermediate p_T behave as p/π and Λ/K?
      - If so - need to re-visit the interpretation of the non-photonic electrons due to different branching ratios than what was expected

Forward GEM Tracker

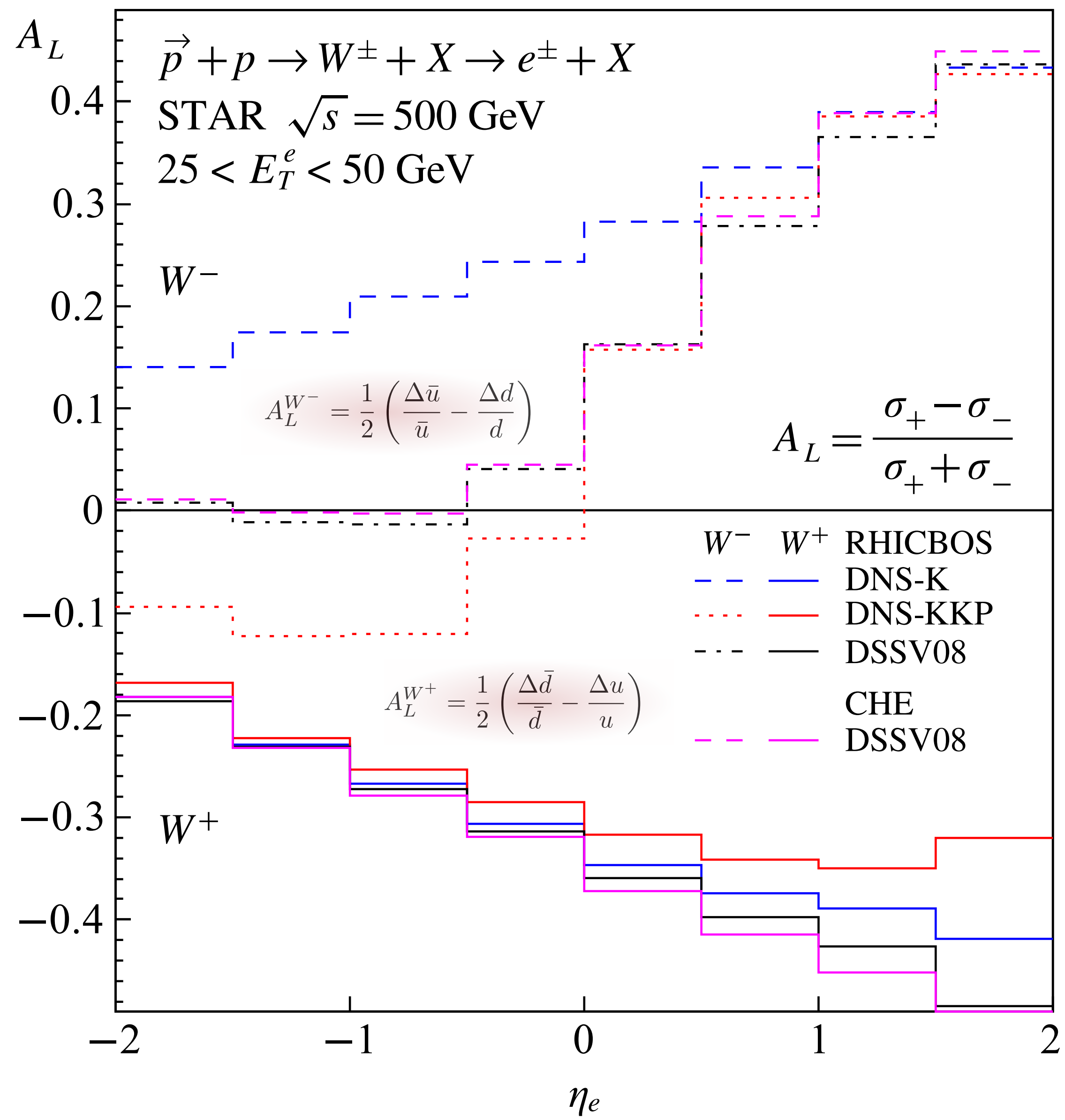
- Small Business Innovative Research (DOE) funded programme (~ $850K)
  - Collaborative effort between Tech-Etch Inc., BNL, MIT and Yale
- Triple GEM Detector
- Coverage: $-1 < \eta < 2$
- Inner radius: 10.5 cm, outer radius: 39 cm
- GEM foils: Hole inner r: 50 μm, outer: 70 μm, 140 μm pitch
- Quoted resolutions in the proposal:
  - ~40 μm in phi (120 μm in R - inclined tracks) from simulations
  - Evaluate performance after this run
- FGT partially installed in current run (12)
  - 14 out of 24 quadrants installed





For more details, see B. Surrow, id:113

Physics of the FGT - Quark Helicities



STAR Collaboration, PRL 106, 062002 (2011)

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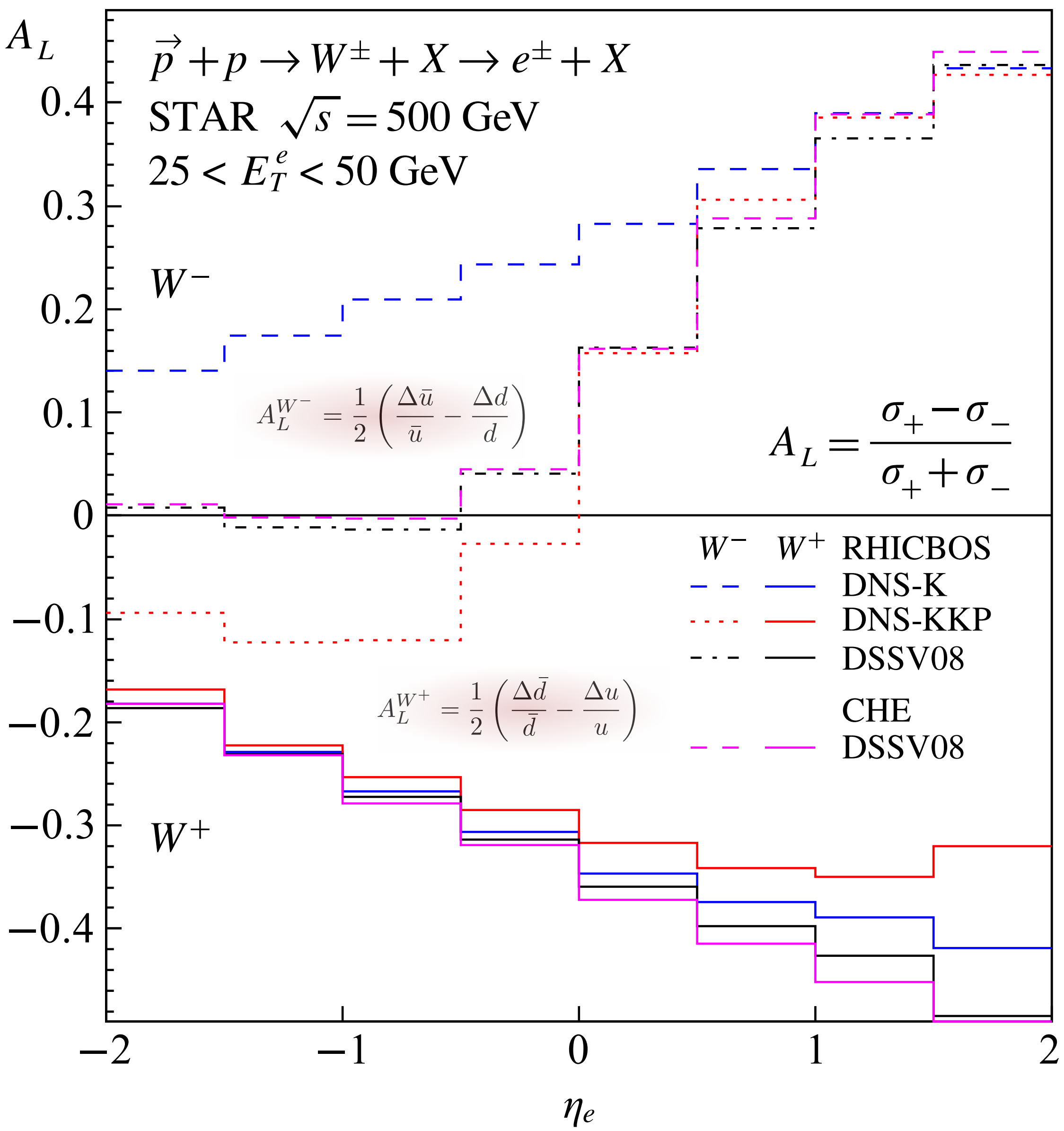
Physics of the FGT - Quark Helicities

- u,d,anti-q helicity distributions obtained through A_L measurements of $W^\pm$
- $W^\pm \rightarrow e^\pm + X$ (11% BR) provides a clean signature with high efficiency



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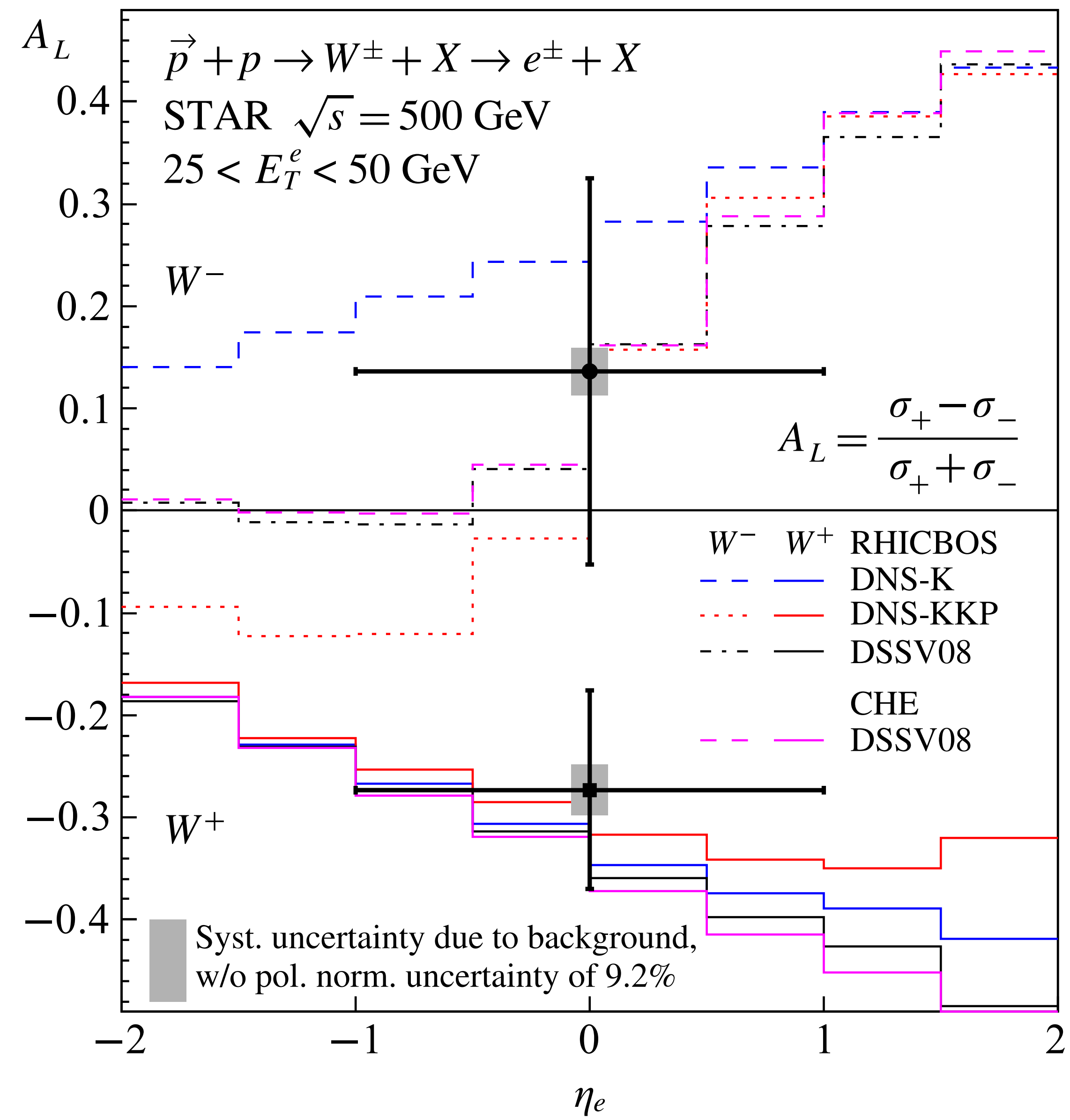

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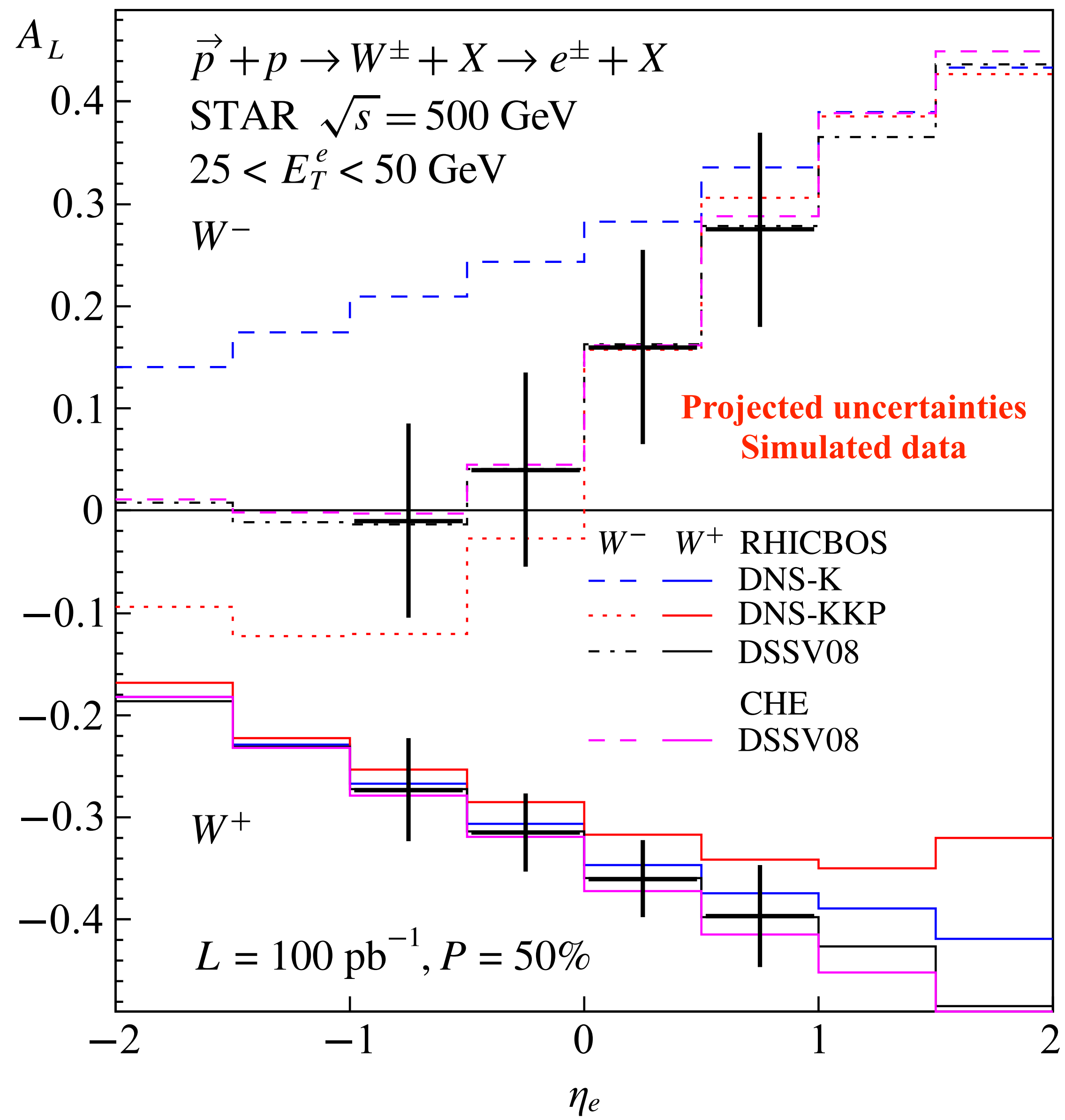
  - A_L^{W+} = -0.27 ± 0.10 ± 0.02 ± 0.03
- Upgrades to add the FGT significantly improve this measurement and allow for charge-sign discrimination

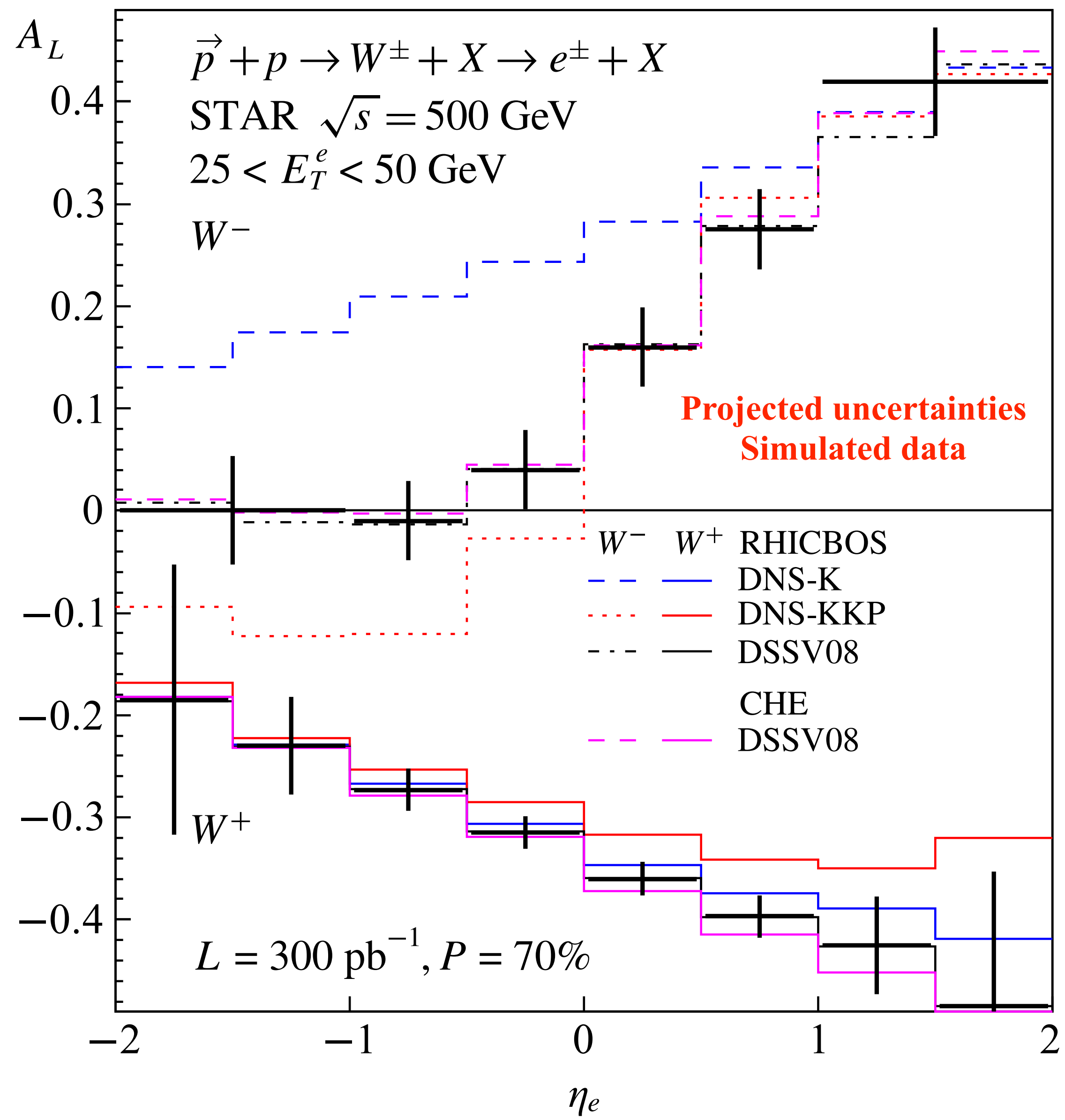


STAR Collaboration, PRL 106, 062002 (2011)

For more details, see B. Surrow, id:113

Physics of the FGT - Quark Helicities

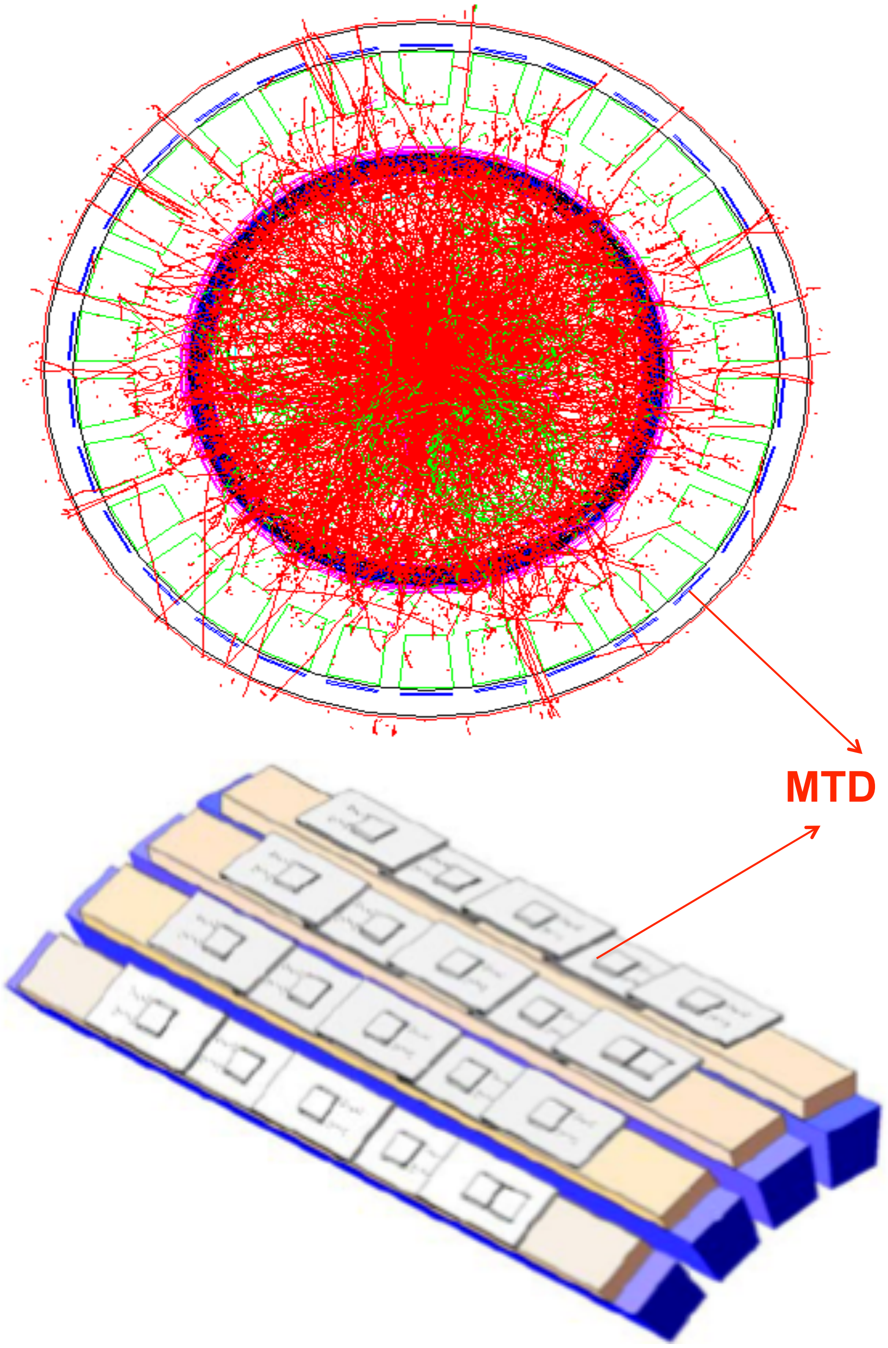
- u,d,anti-q helicity distributions obtained through A_L measurements of $W^{\pm}$
- $W^{\pm} \rightarrow e^{\pm}+X$ (11% BR) provides a clean signature with high efficiency
- Initial measurements of A_L utilised STAR's barrel and end-cap calorimeters sampled 12 pb^{-1}
  - $A_L^{W-} = 0.14 \pm 0.19 \pm 0.02 \pm 0.01$
  - $A_L^{W+} = -0.27 \pm 0.10 \pm 0.02 \pm 0.03$
- Upgrades to add the FGT significantly improve this measurement and allow for charge-sign discrimination

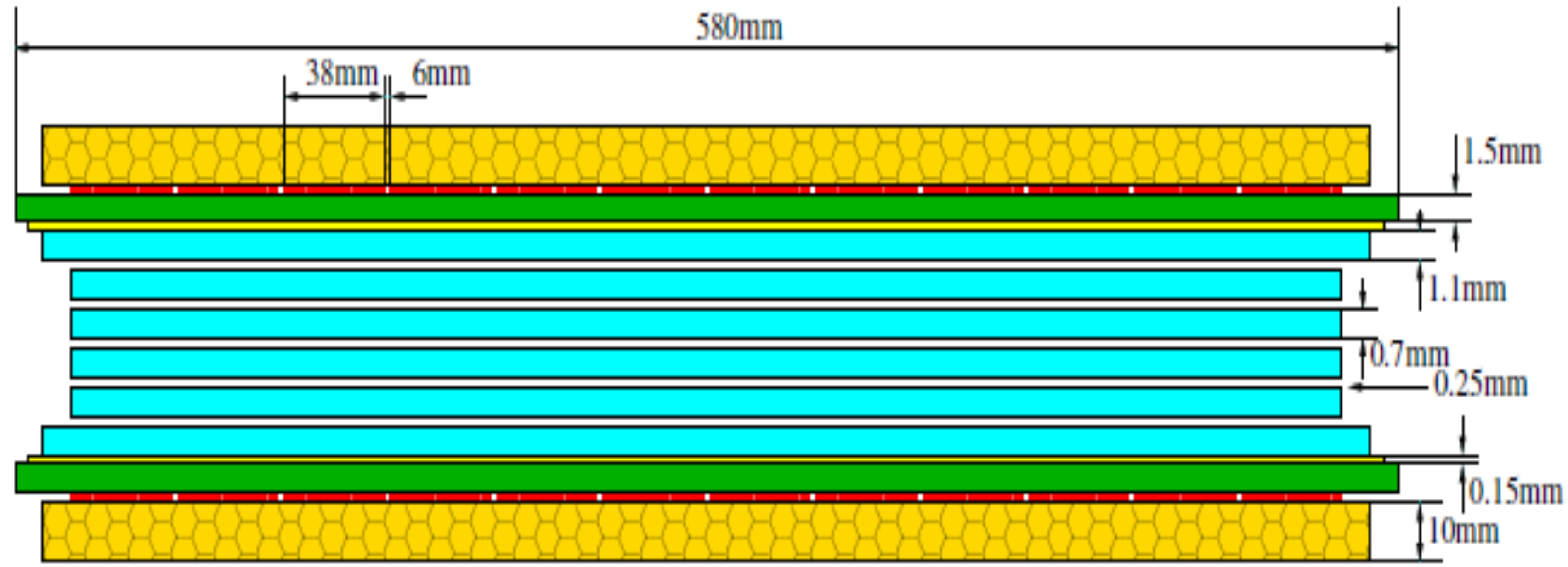


STAR Collaboration, PRL 106, 062002 (2011)

 For more details, see B. Surrow, id:113

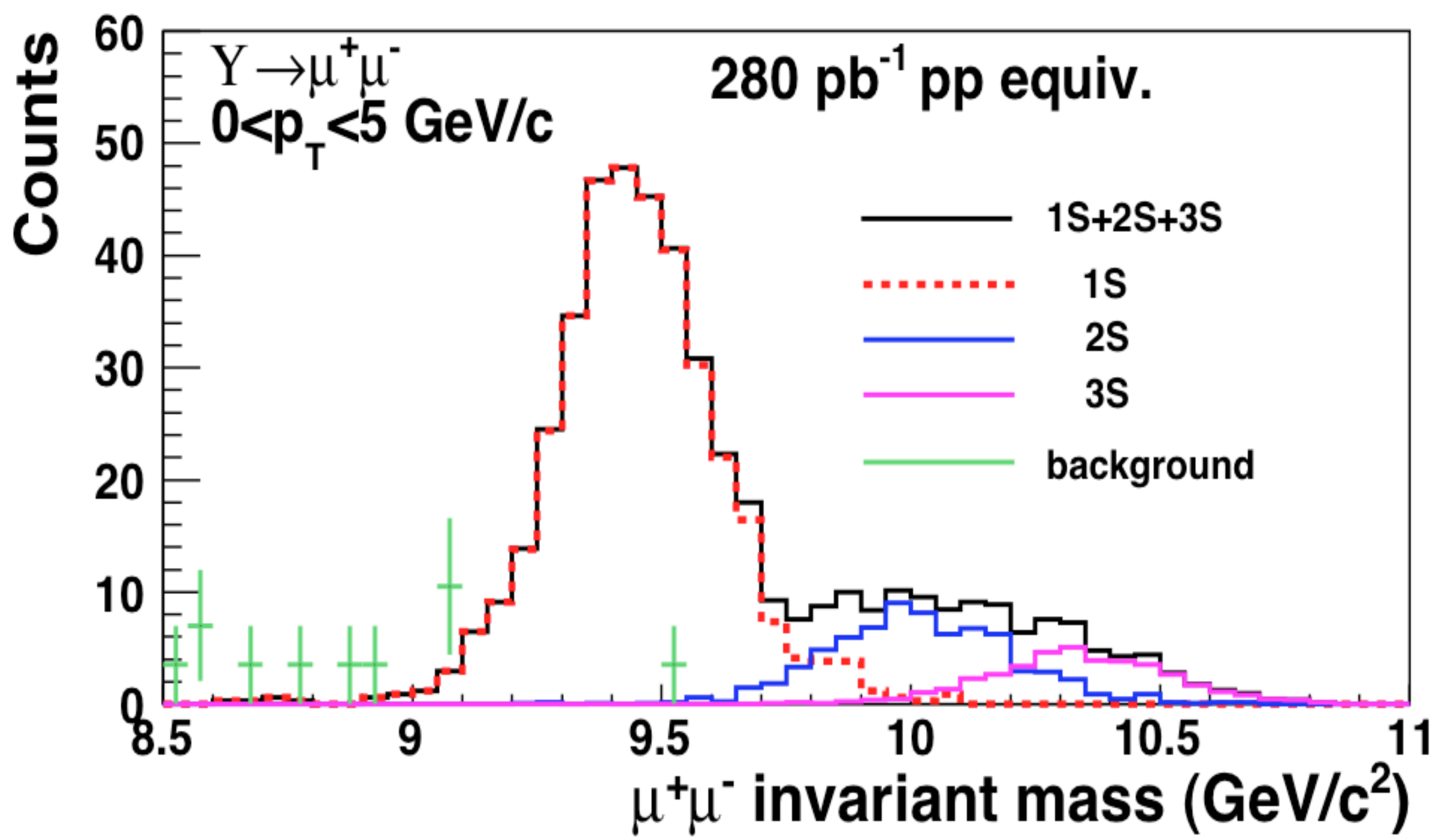
Muon Telescope Detector

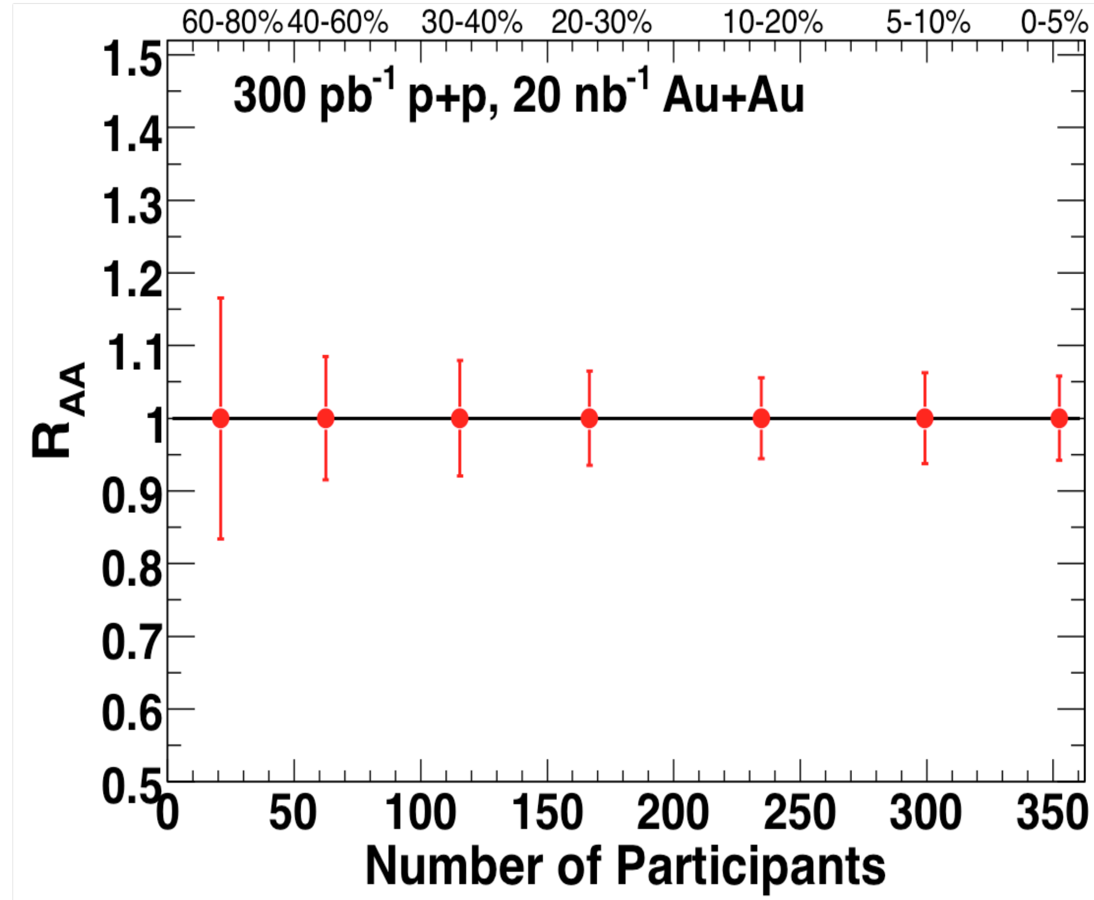




- MTD is a Multi-gap Resistive Plate Chamber gas detector
- Long MRPCs cover the whole iron bars - gaps inbetween are not covered
  - Acceptance: 45% at $|\eta|<0.5$
- 118 modules, 1416 readout strips, 2832 readout channels
- MRPC technology and electronics is the same as that used in the STAR TOF

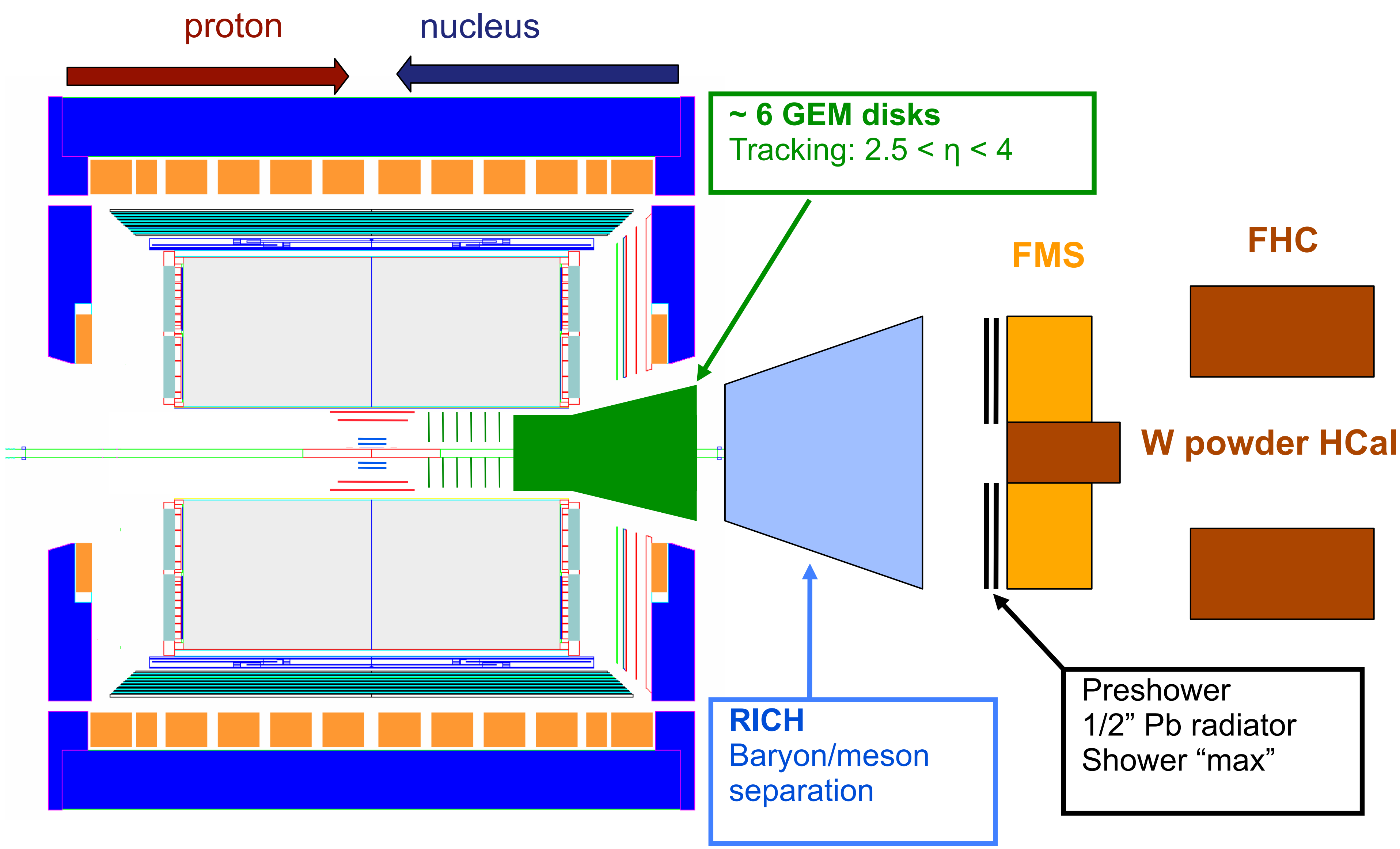
Physics capabilities with the MTD





- MTD can measure muons at mid-rapidity
  - di-leptons of a different flavour
- High-precision Upsilons, J/Psi,...
  - No Bremsstrahlung tails allows effective separation of Upsilon states
    - Allows a handle on melting of lightly bound Upsilon states in hot and de-confined matter
- e-μ correlations
  - Distinguish heavy flavour production from initial lepton pair production
    - S/B ~ 8 with electron pairing and TOF association

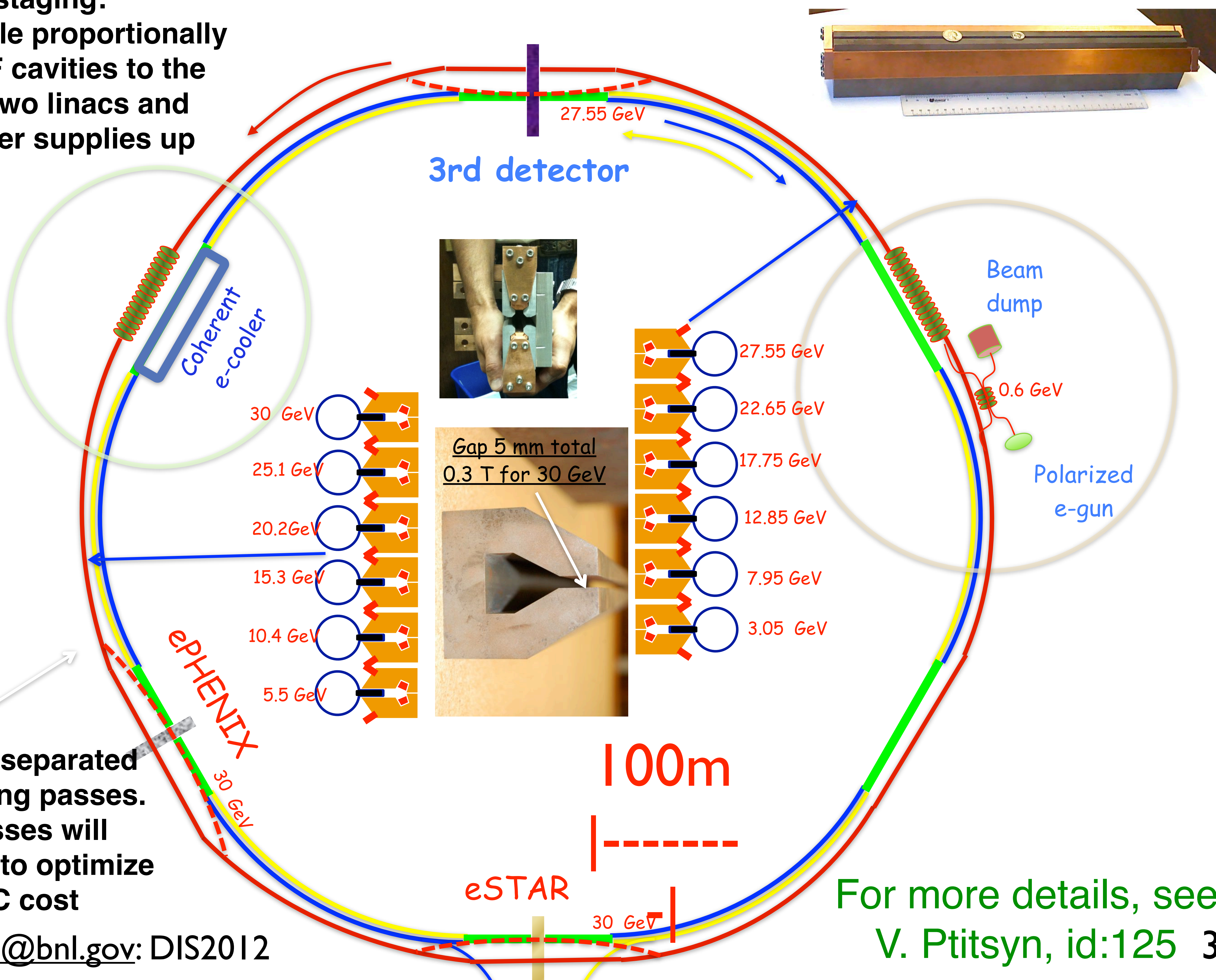
Forward instrumentation upgrade concept



- Forward instrumentation optimised for p+A and transverse spin physics
  - charged particle tracking
  - e/h and γ/π discrimination
  - baryon/meson separation

eRHIC - the future of RHIC

eRHIC staging:
All energies scale proportionally by adding SRF cavities to the injector and two linacs and cranking power supplies up



Vertically separated recirculating passes. # of passes will be chosen to optimize eRHIC cost

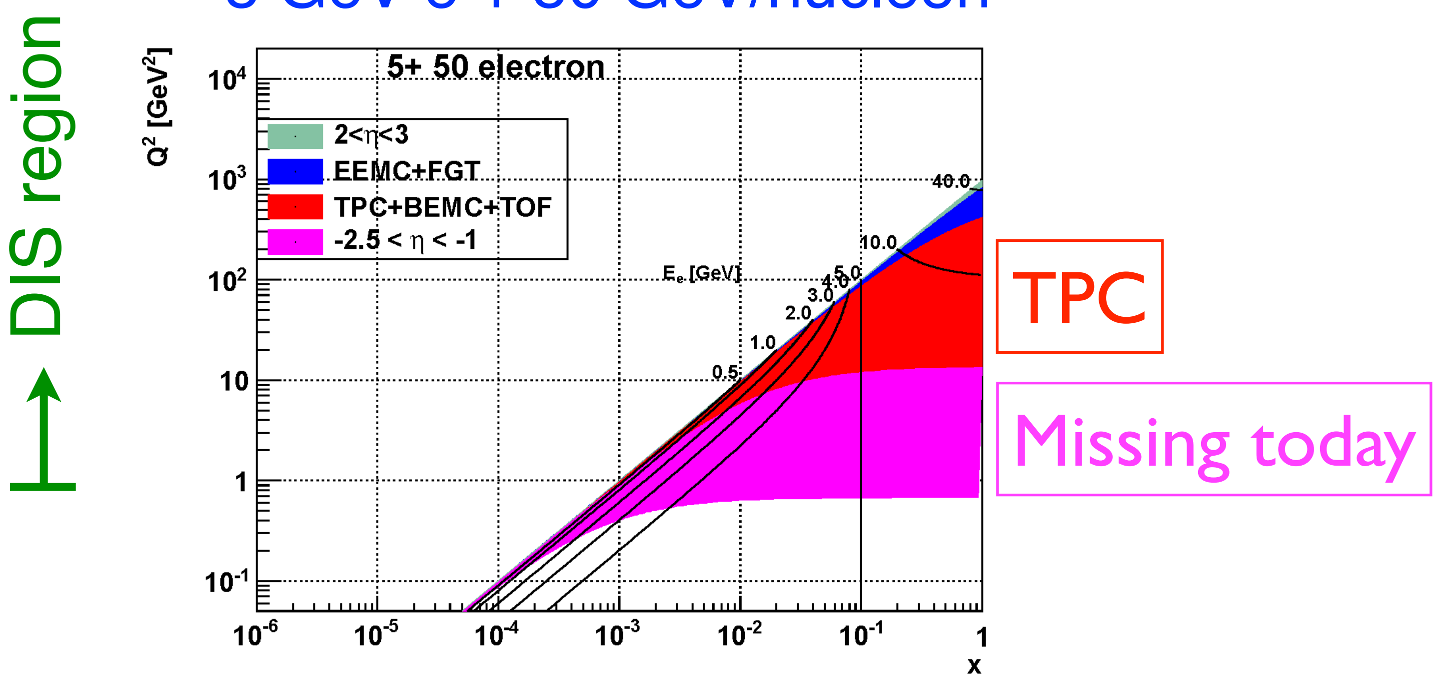
For more details, see V. Ptitsyn, id:125

eSTAR - the future of STAR?

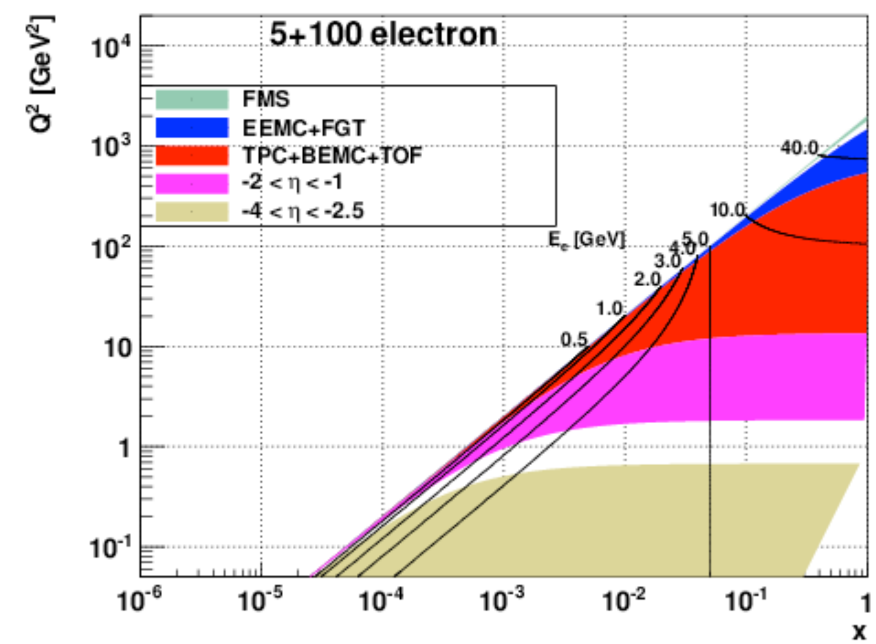
- STAR will need to be optimised/modified for its current setup for e+A collisions
  - 5 GeV electron beams currently being studied with p(A) energies from 50 GeV to 250(100) GeV
- Key measurements:
  - Inclusive scattering over the entire DIS region
    - F_L in e+A - a direct measure of nuclear gluon densities
    - F_2^A/F_2^p - parton distributions in nuclei
  - Semi-inclusive DIS over a broad (x,Q^2) range
    - Flavour-separated parton distributions in nuclei, including strangeness
    - Parton energy loss in cold nuclear matter
- What's needed?

eSTAR kinematics in phase 1: 5 GeV electrons

5 GeV e + 50 GeV/nucleon



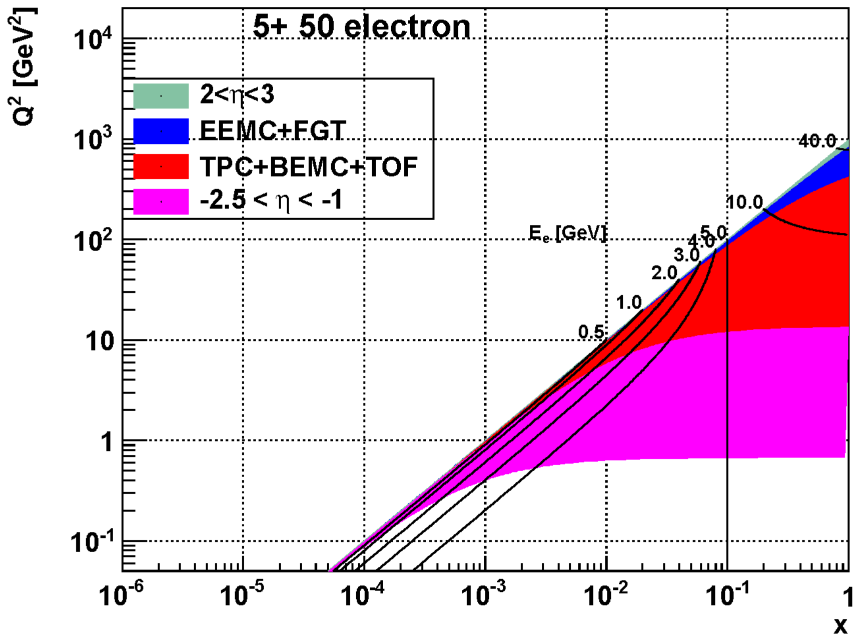
5 GeV e + 100 GeV/nucleon



eSTAR kinematics in phase 1: 5 GeV electrons

DIS region

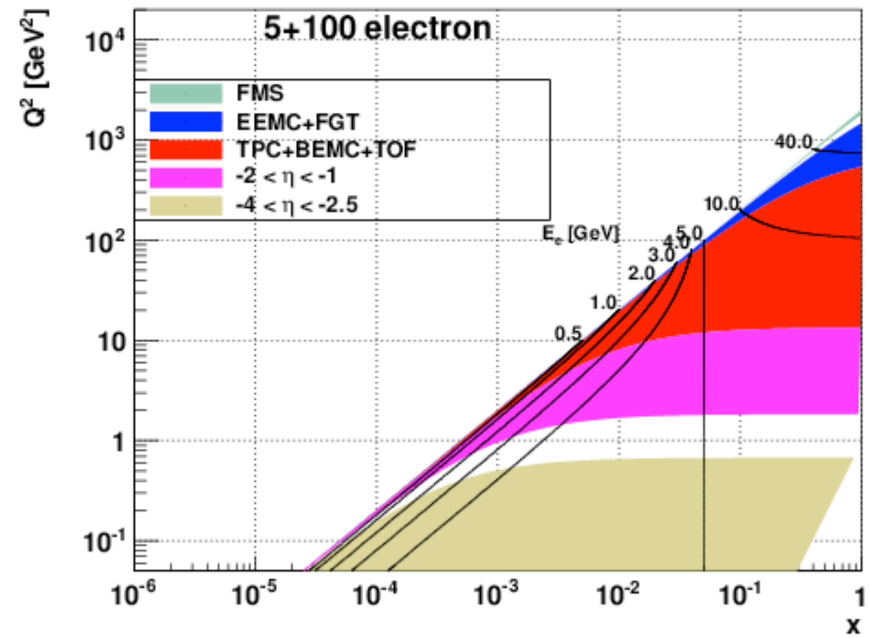
5 GeV e + 50 GeV/nucleon



TPC

Missing today

5 GeV e + 100 GeV/nucleon



- "Forward" (-2.5 < h < -1) electron acceptance is essential in order to span the DIS regime

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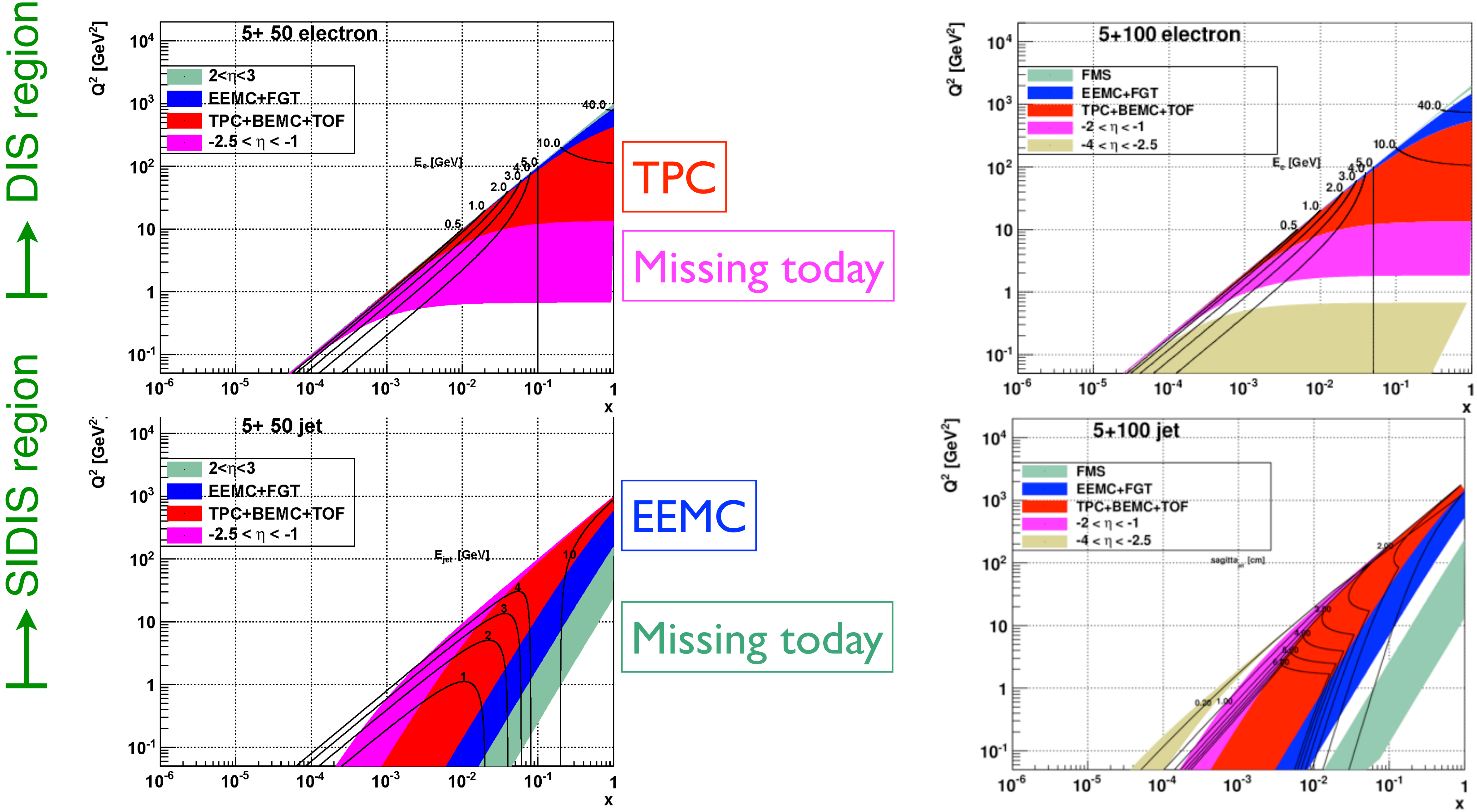
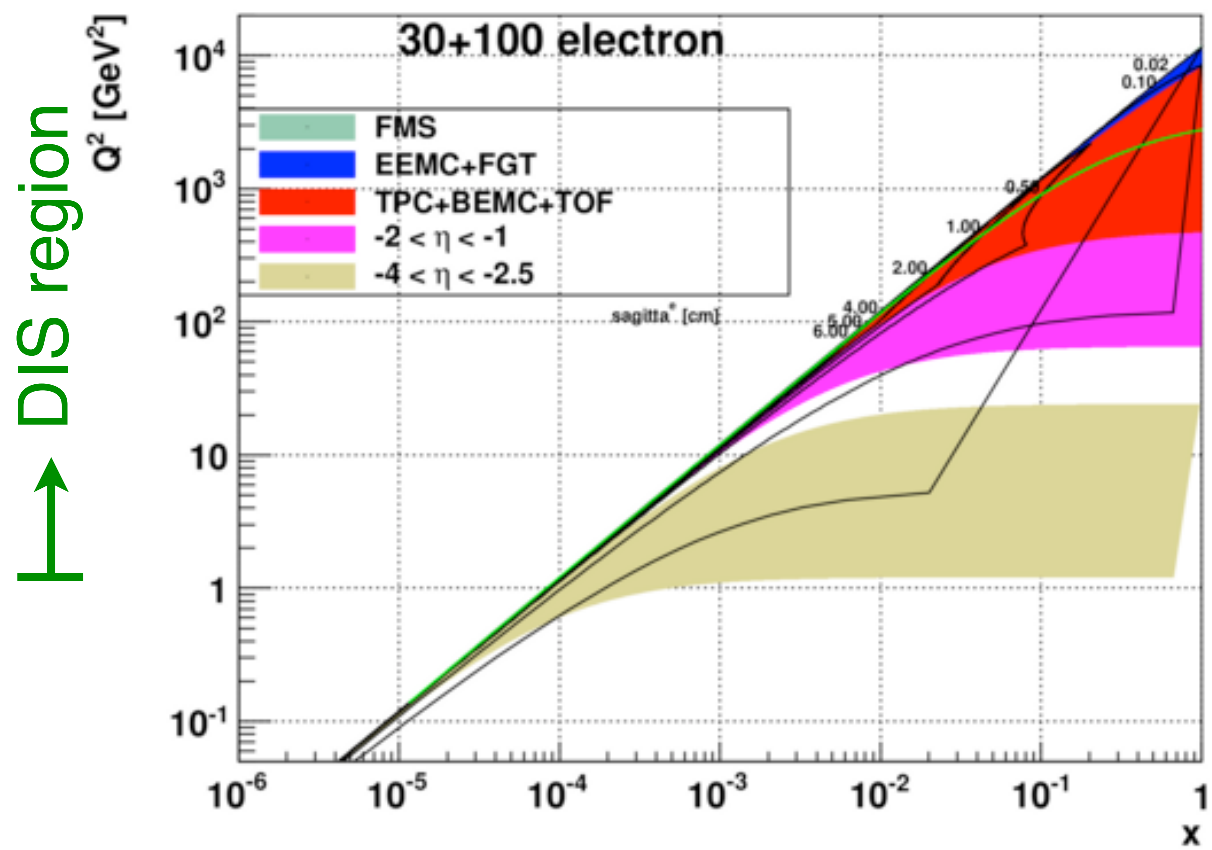
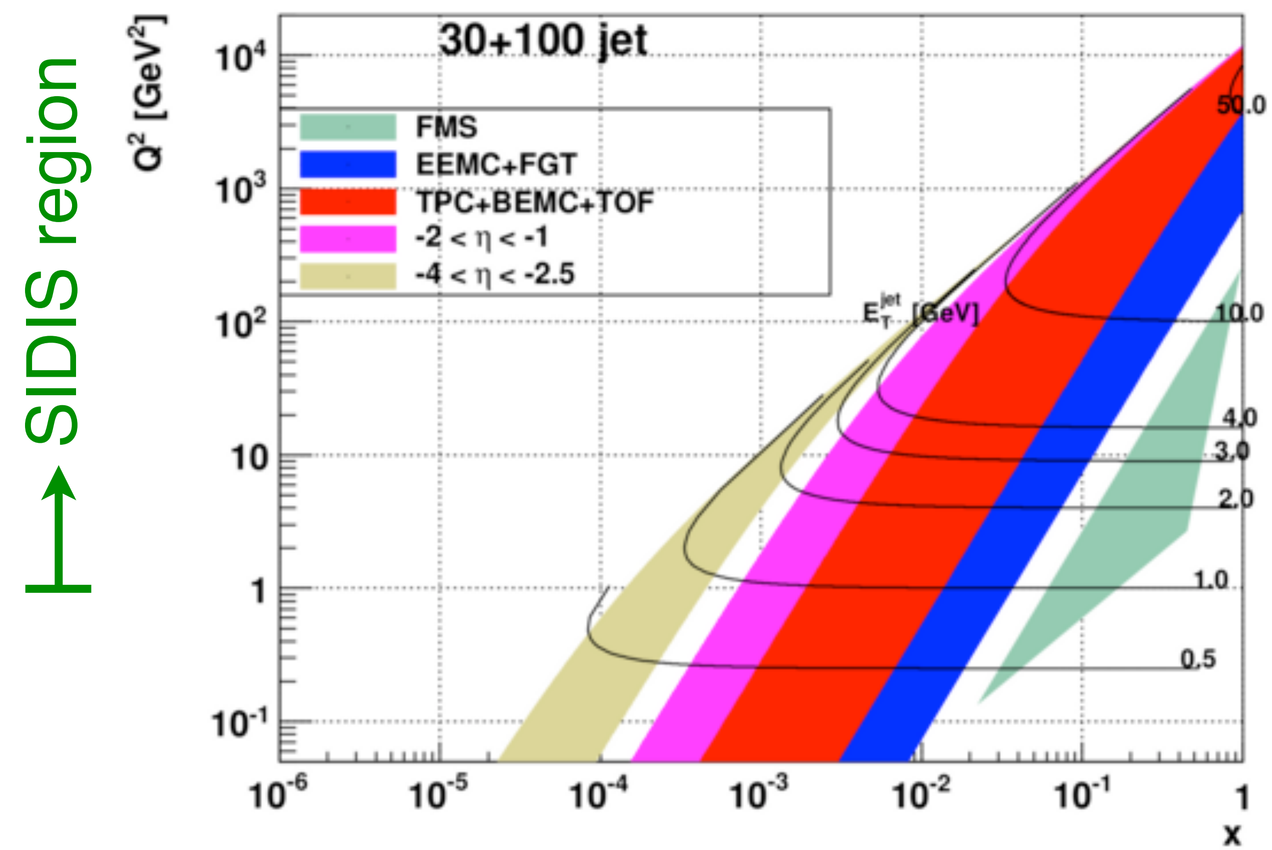


- “Forward” (-2.5 < h < -1) electron acceptance is essential in order to span the DIS regime
- Both “forward” and “backward” hadron coverage is needed for SIDIS physics

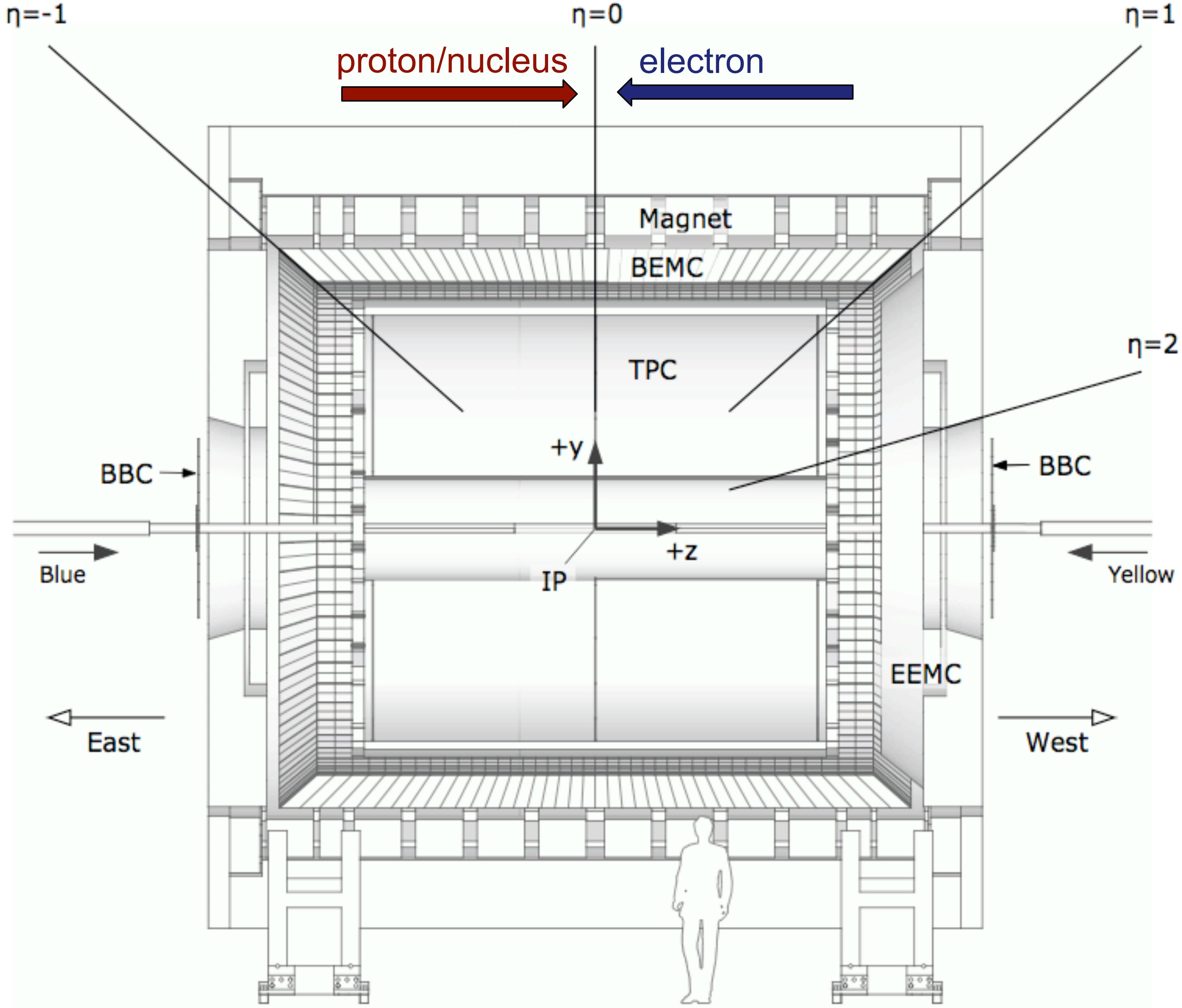
eSTAR kinematics in phase-II: 30 GeV electrons





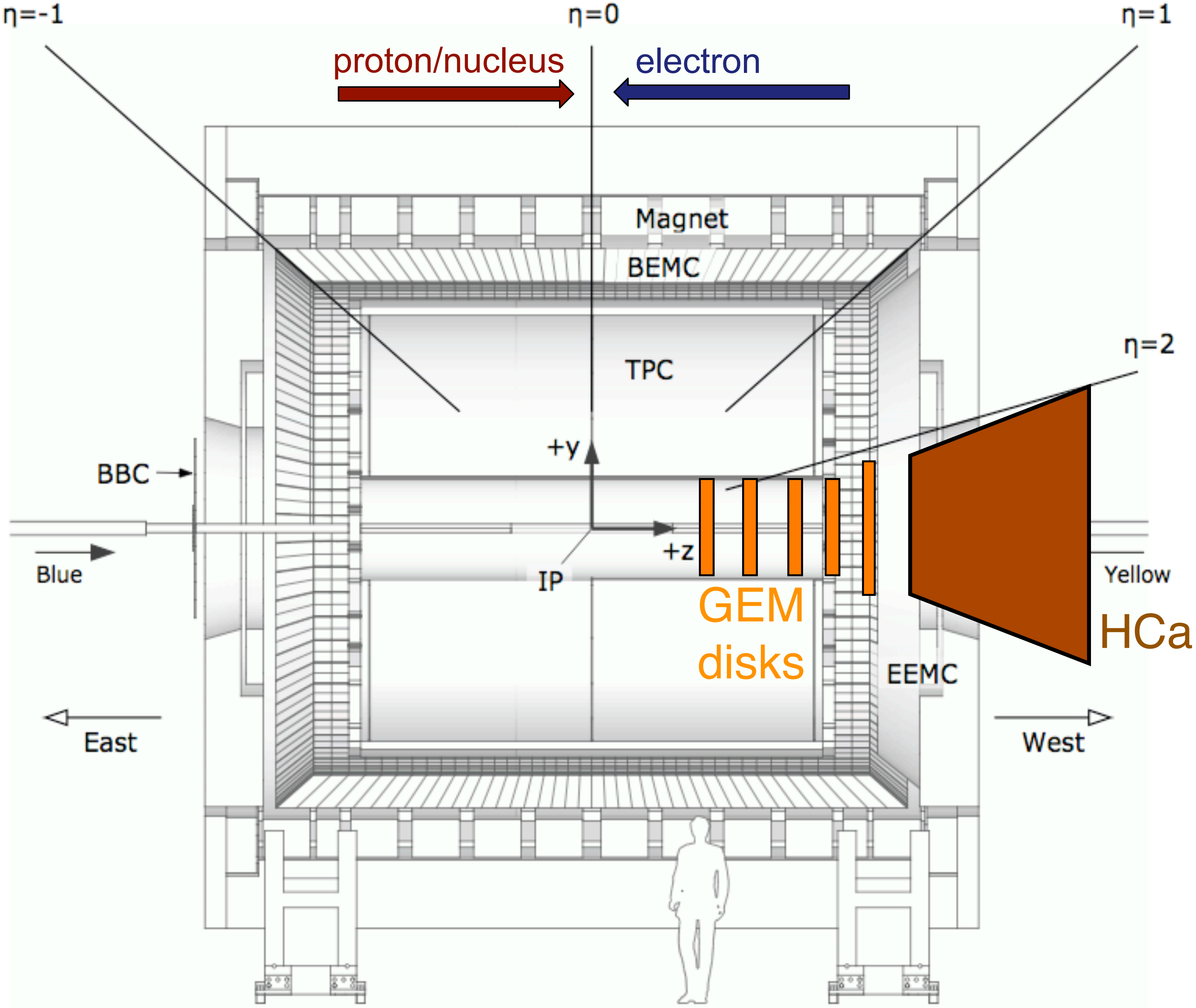
- With 30 GeV electrons, need very forward coverage
- eSTAR is unsuitable for this energy regime
  - Will need a fully comprehensive detector, which eSTAR can complement in the first phase.

The realisation of an eSTAR detector



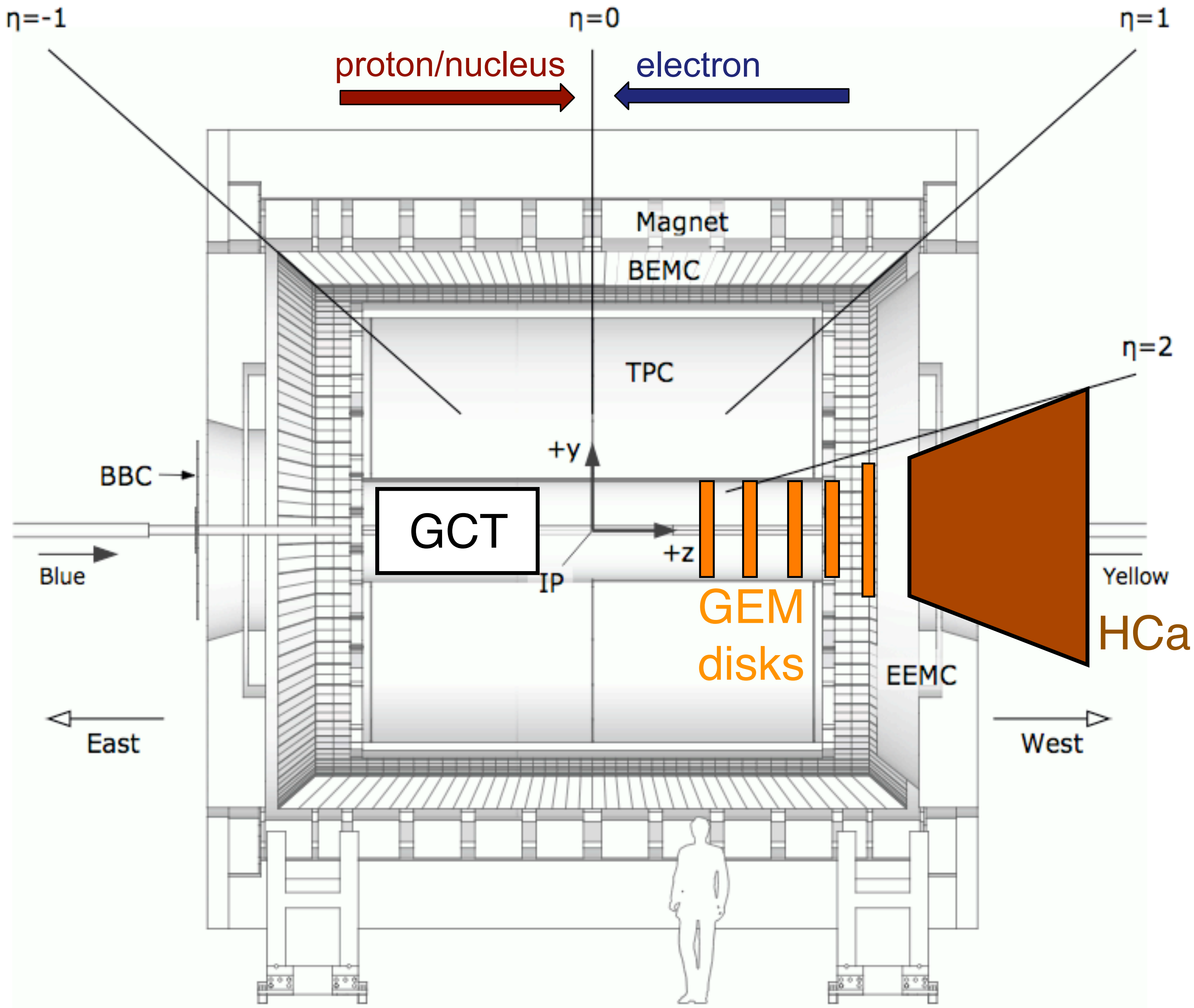
The realisation of an eSTAR detector

- HCal: W powder, spaghetti calorimeter



The realisation of an eSTAR detector

- HCal: W powder, spaghetti calorimeter
- GCT: compact tracker with enhanced electron capability
    - combine high-threshold (gas) Cherenkov with TPC-like tracking



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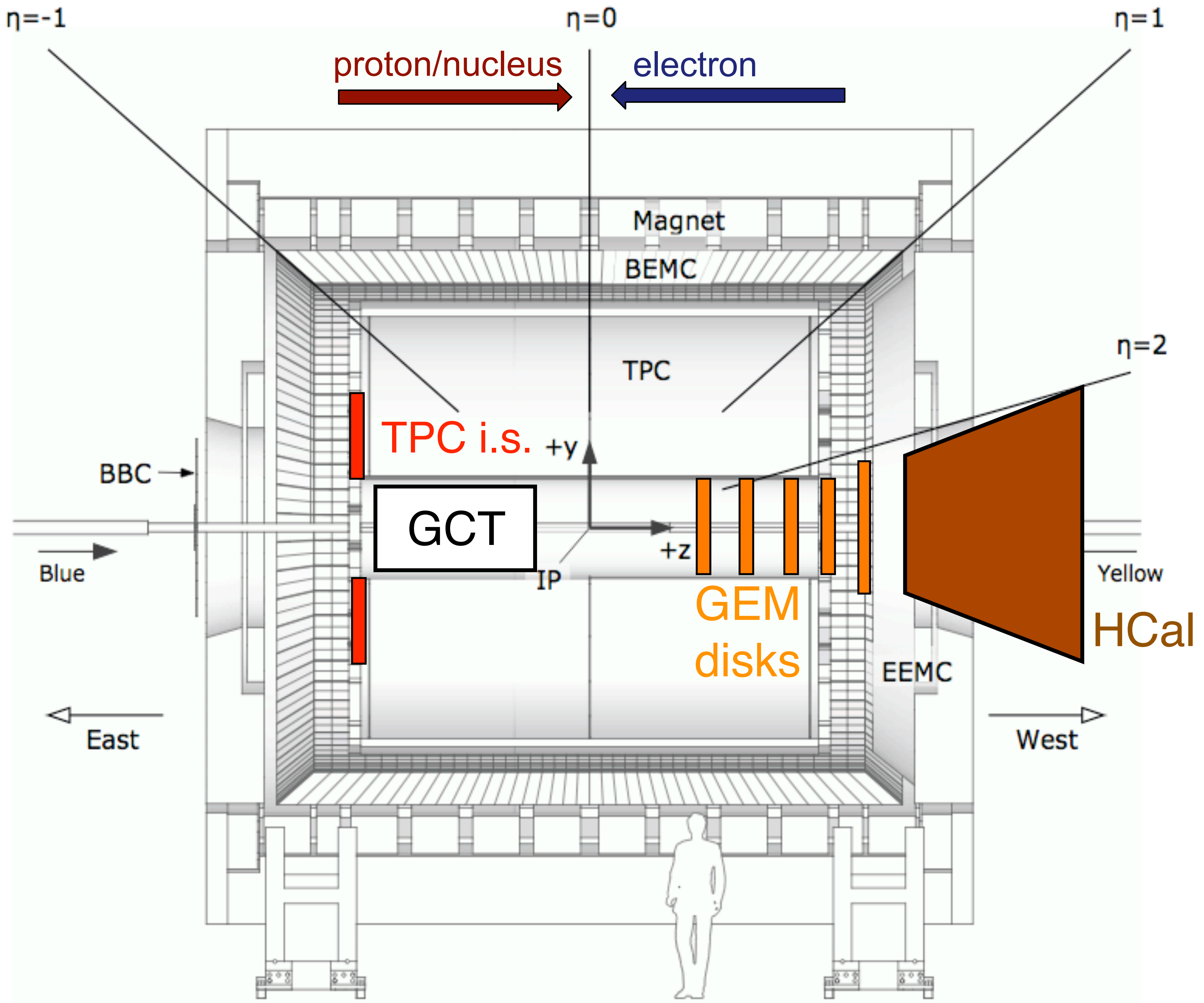
- TPC: replace inner sectors
  - make a greater density of pad rows



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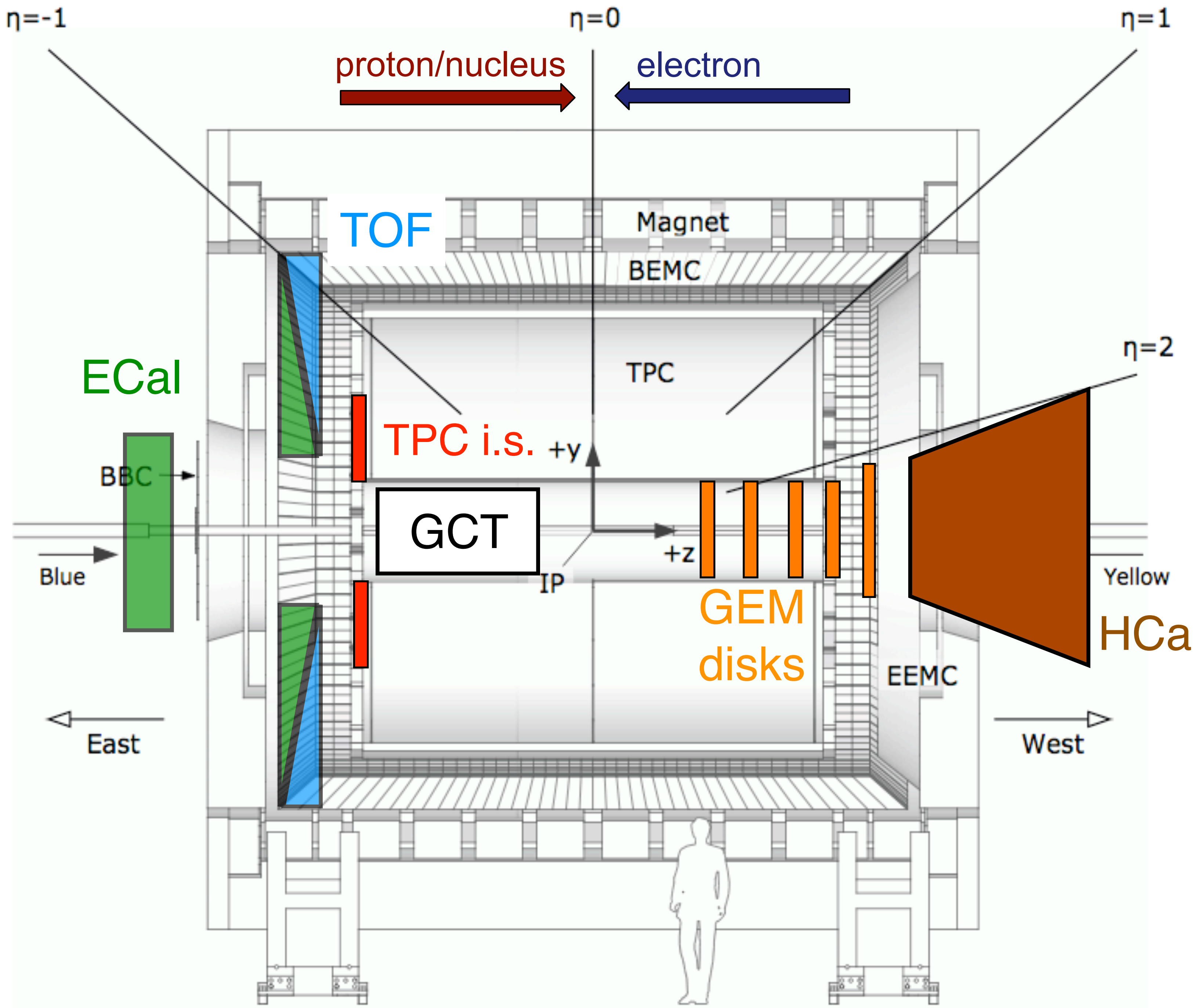
- TOF: π, K i.d., t_0, electron
- ECal: electrons, photons



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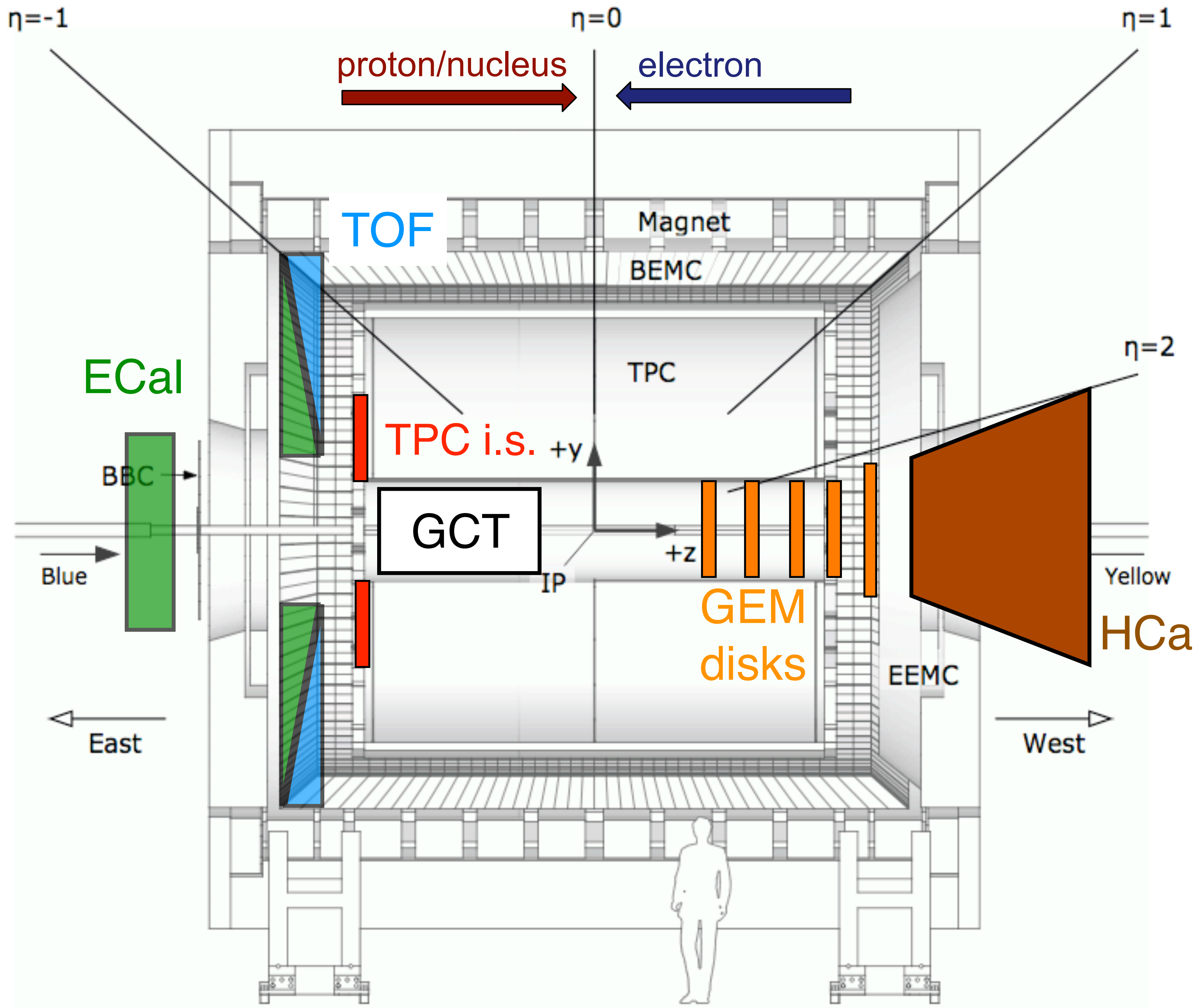
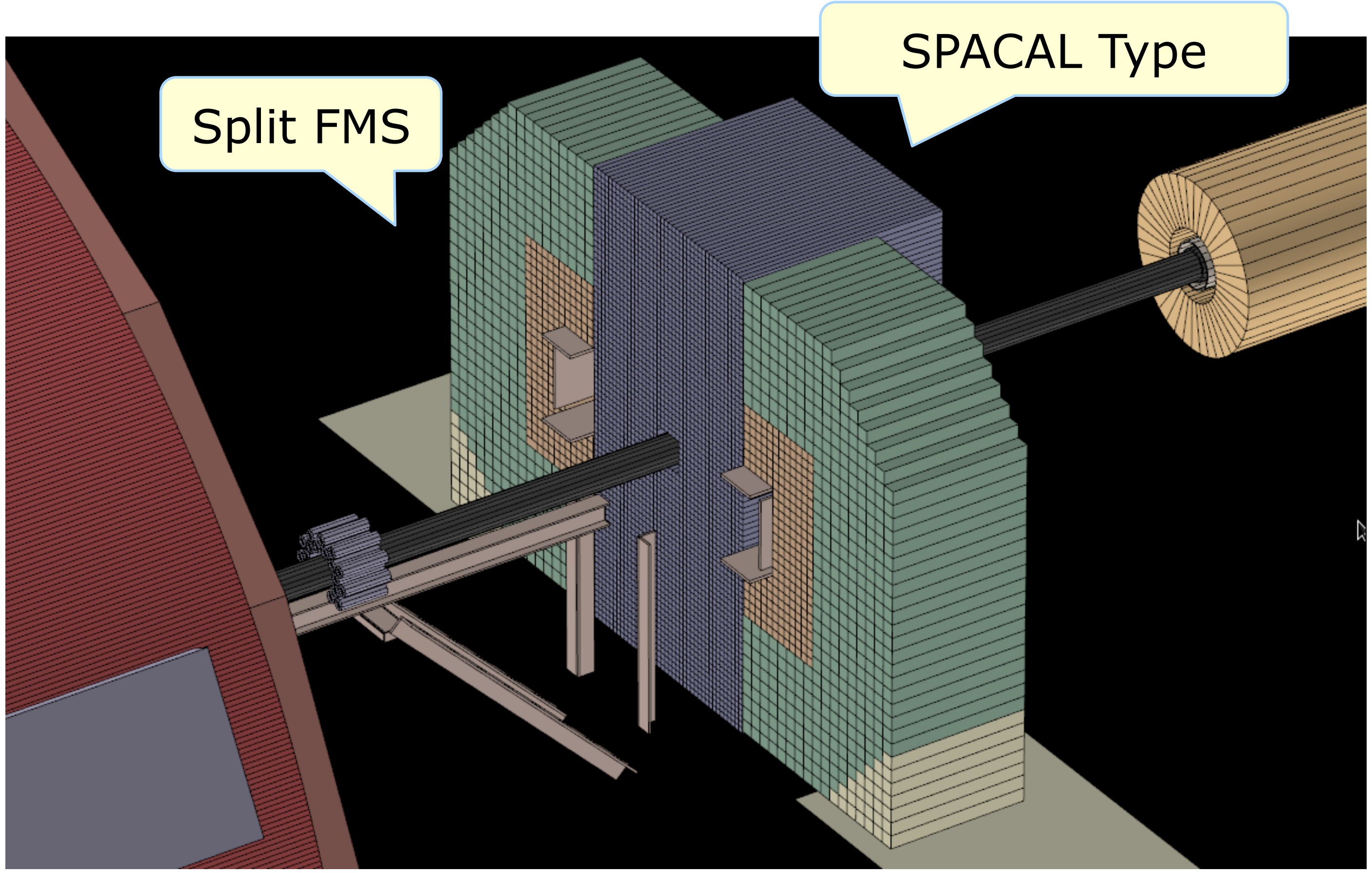


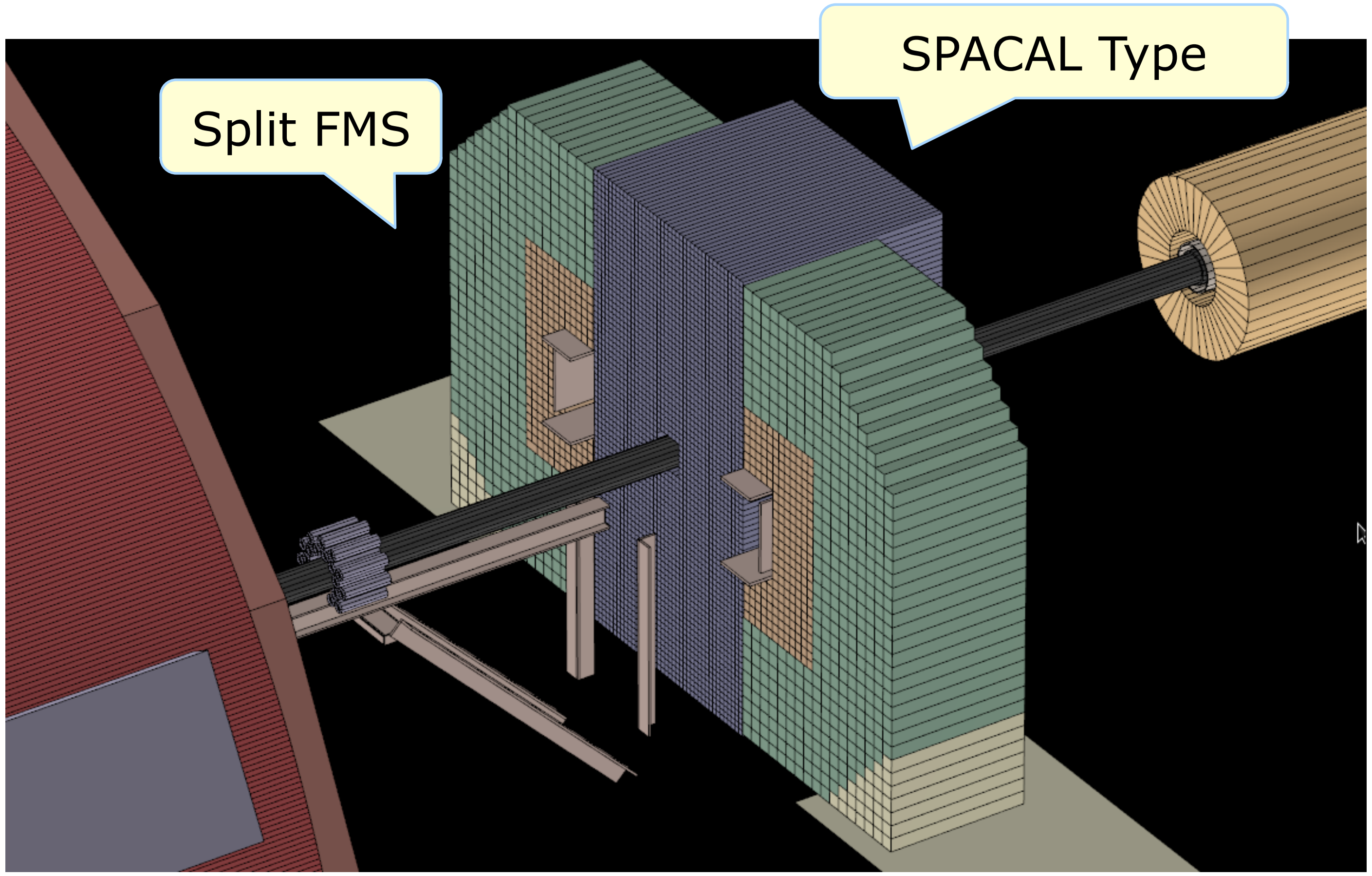
R&D ongoing thanks to BNL-directed EIC generic detector R&D funds

New Calorimeter R&D



- Requirements:
  - Efficient π^0 reconstruction at 100 GeV
  - Good γ/π^0 discrimination
  - Good e/h separation (~1000) with high electron efficiency
  - Reasonable energy resolution for jets and single hadrons
  - Provide trigger (high tower…)
  - Fit into available space
  - Readout insensitive to magnetic field

New Calorimeter R&D



- Solution
  - W powder, fibre readout
  - 1m x 1m x 2m detector with ~ 3k readout channels, weight ~ 20 tonnes
  - Compact Hadronic and EM calorimeter

- Requirements:
  - Efficient π^0 reconstruction at 100 GeV
  - Good γ/π^0 discrimination
  - Good e/h separation (~1000) with high electron efficiency
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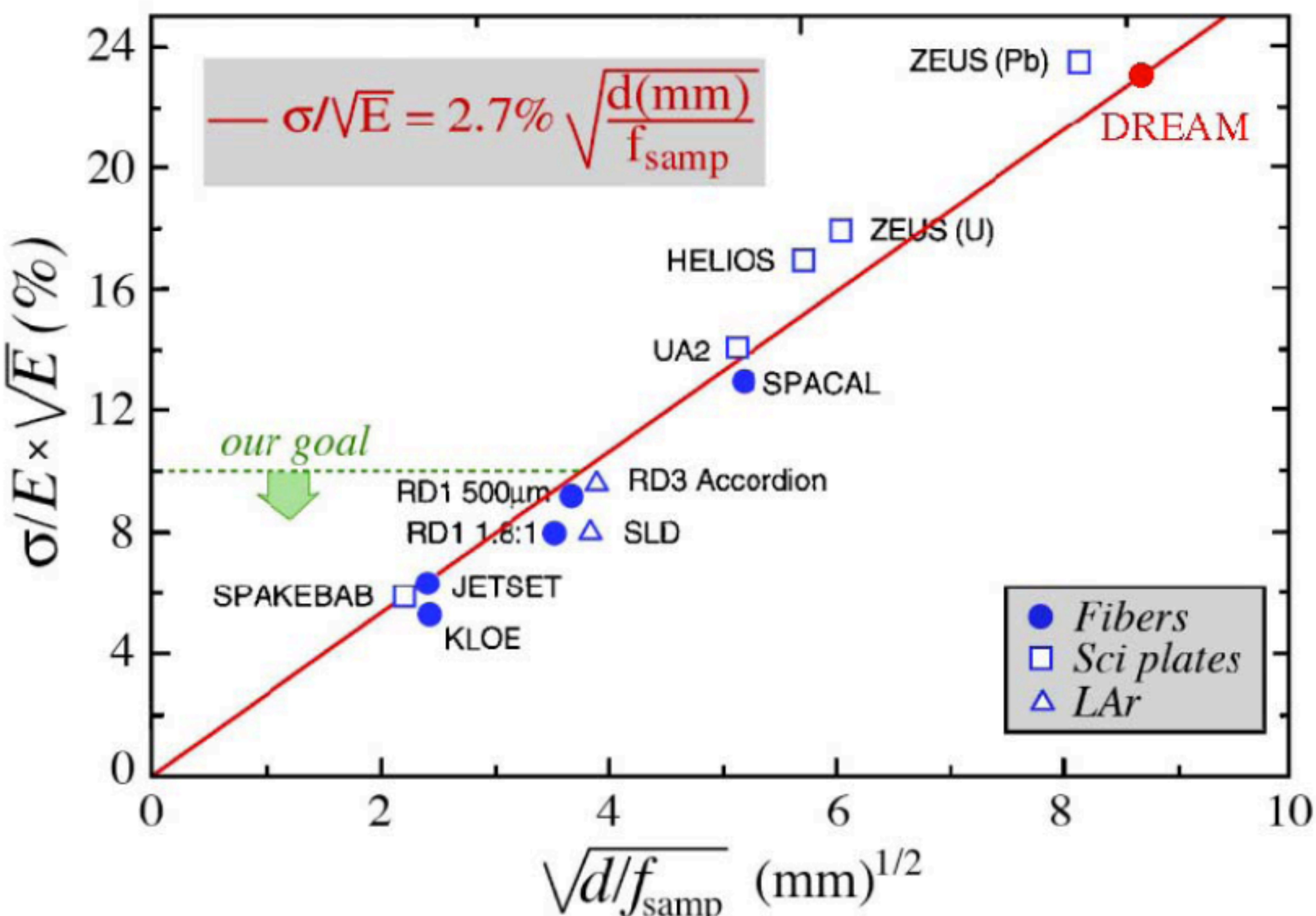
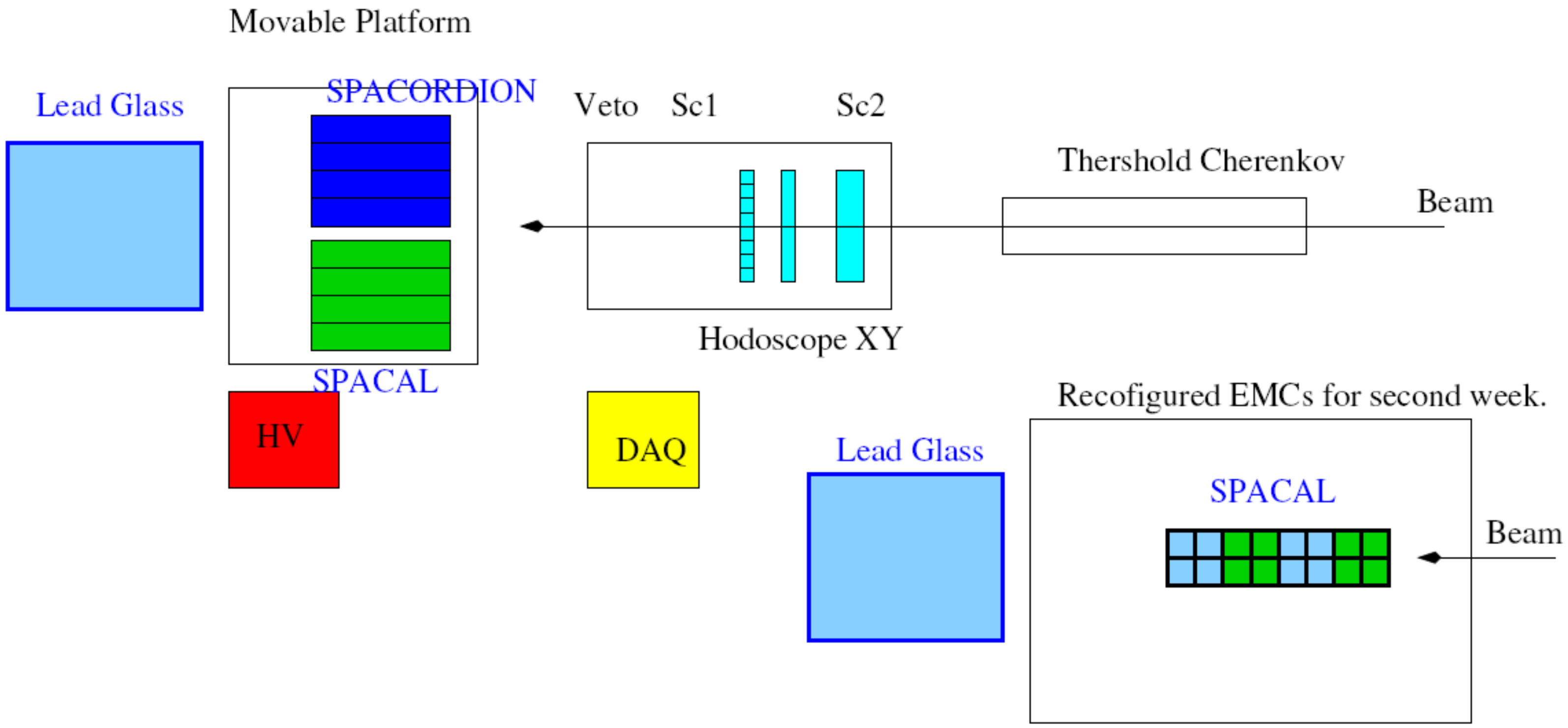
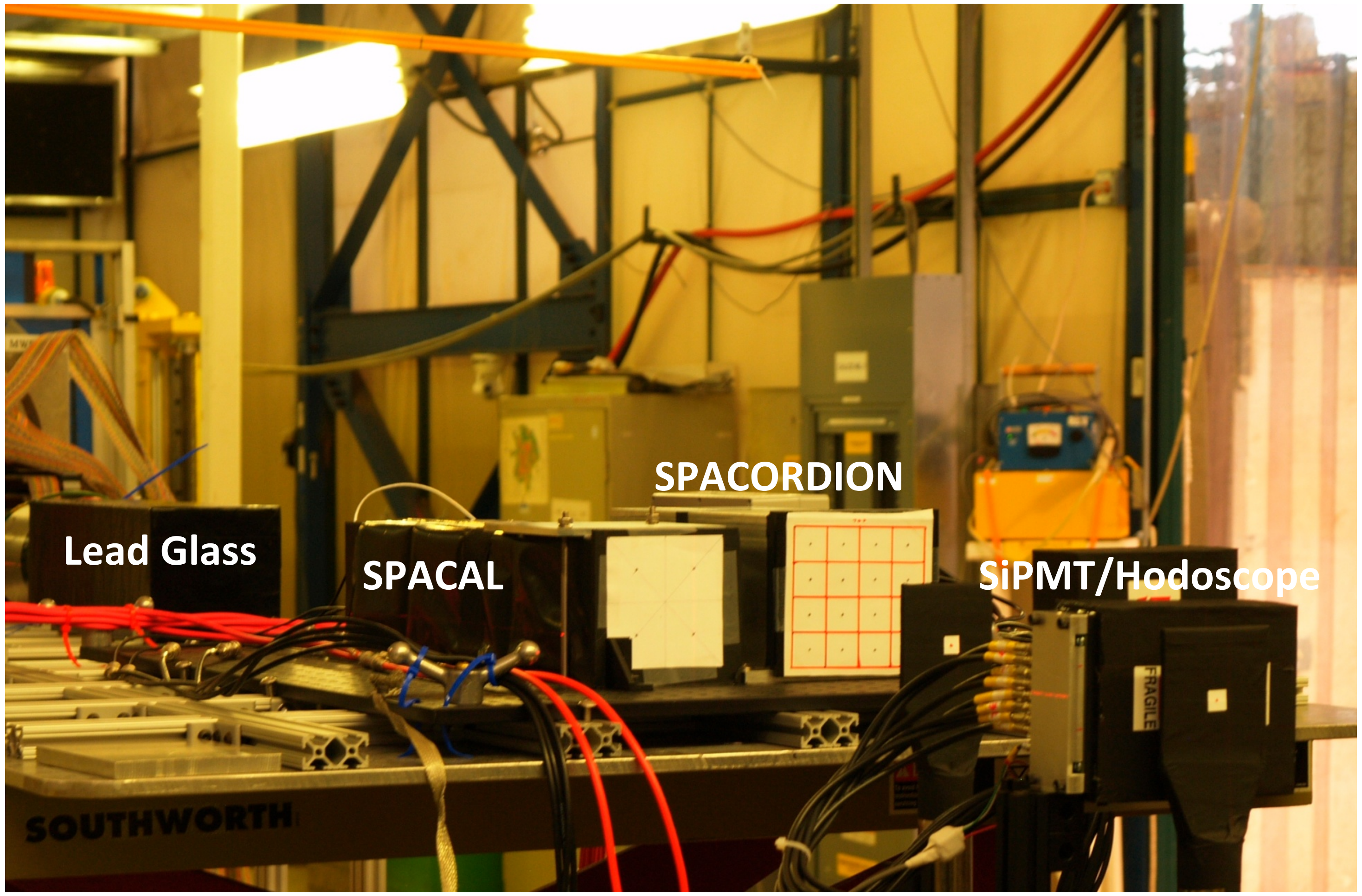
New Calorimeter R&D



Not just an idea on paper...



T-1018, FNAL
MT6 beam line
Jan 18-31



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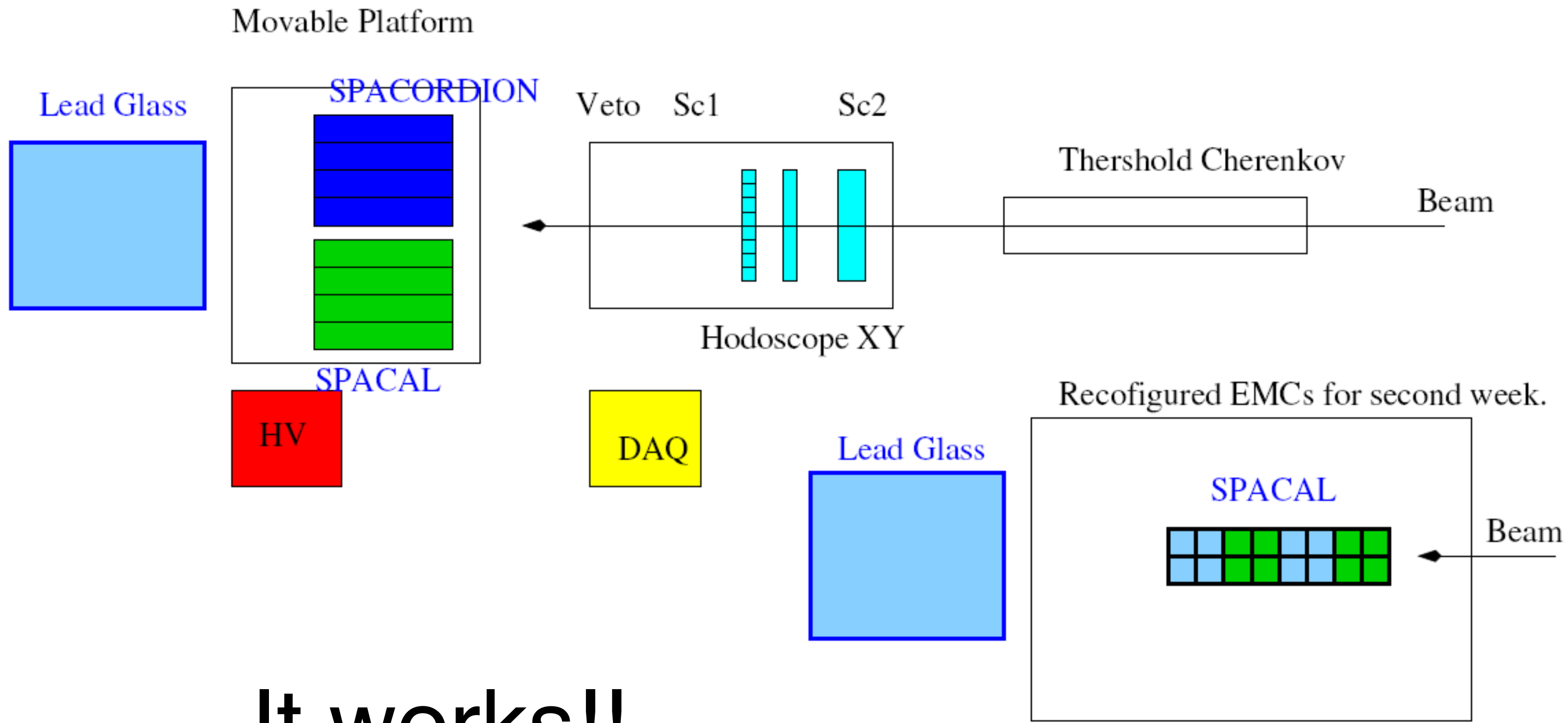
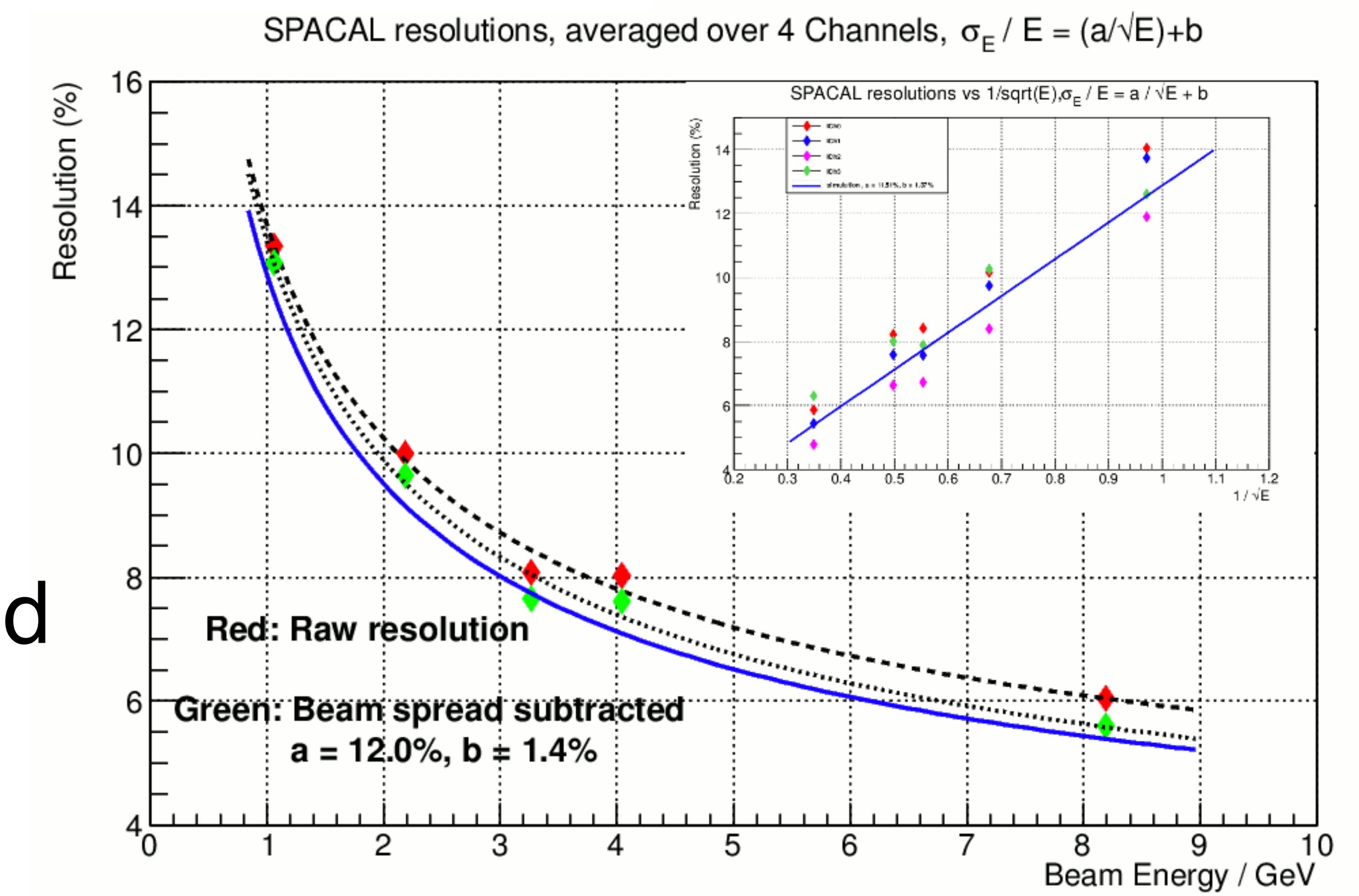


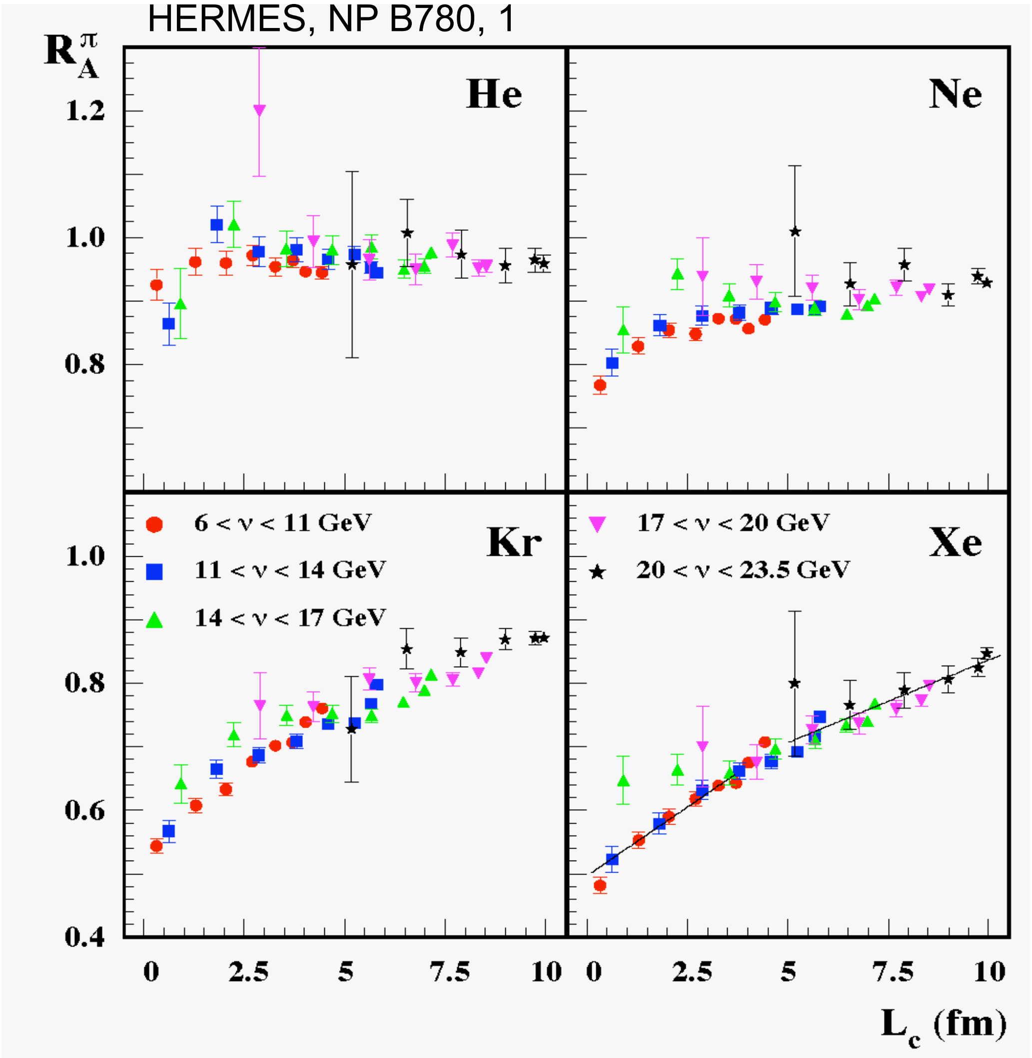
T-1018, FNAL
MT6 beam line
Jan 18-31

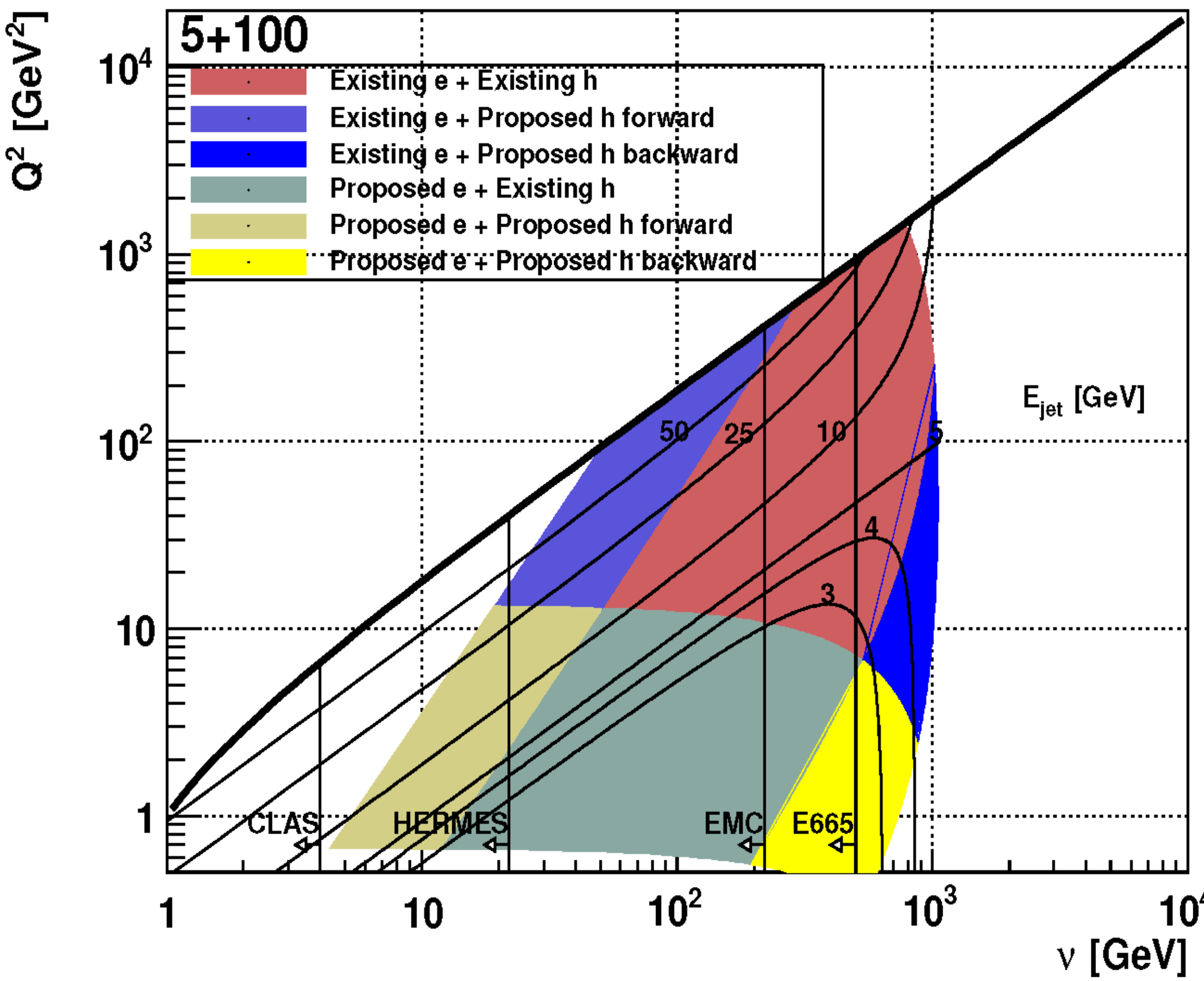
It works!!

- Resolution is close to what is expected (~12% at 1 GeV)
- Light yield is very good (~ 4000 Phe/GeV)



Example physics: parton energy loss in cold QCD matter





- HERMES: limited range in ν
  - hadrons form partially inside the medium
- eRHIC: large range in ν (L_c up to a few 100 fm)
  - light quarks form well outside the medium
  - also ability to explore heavy-quark formation
- Day-1 measurement for e+A

Summary and Conclusions

- STAR has completed it's first decade of physics with exciting and unexpected results
  - A strongly coupled plasma is formed in heavy-ion collisions, creating a perfect liquid
- STAR has a clear path of upgrades to build on the physics already learned, together with the upgrades of the machine
  - New detectors, new electronics
- In the long term (STAR's 3rd decade), a role is foreseen for STAR → eSTAR
  - STAR has an active eSTAR task force
  - Calorimetry R&D progressing with test beam at FNAL in January 2012

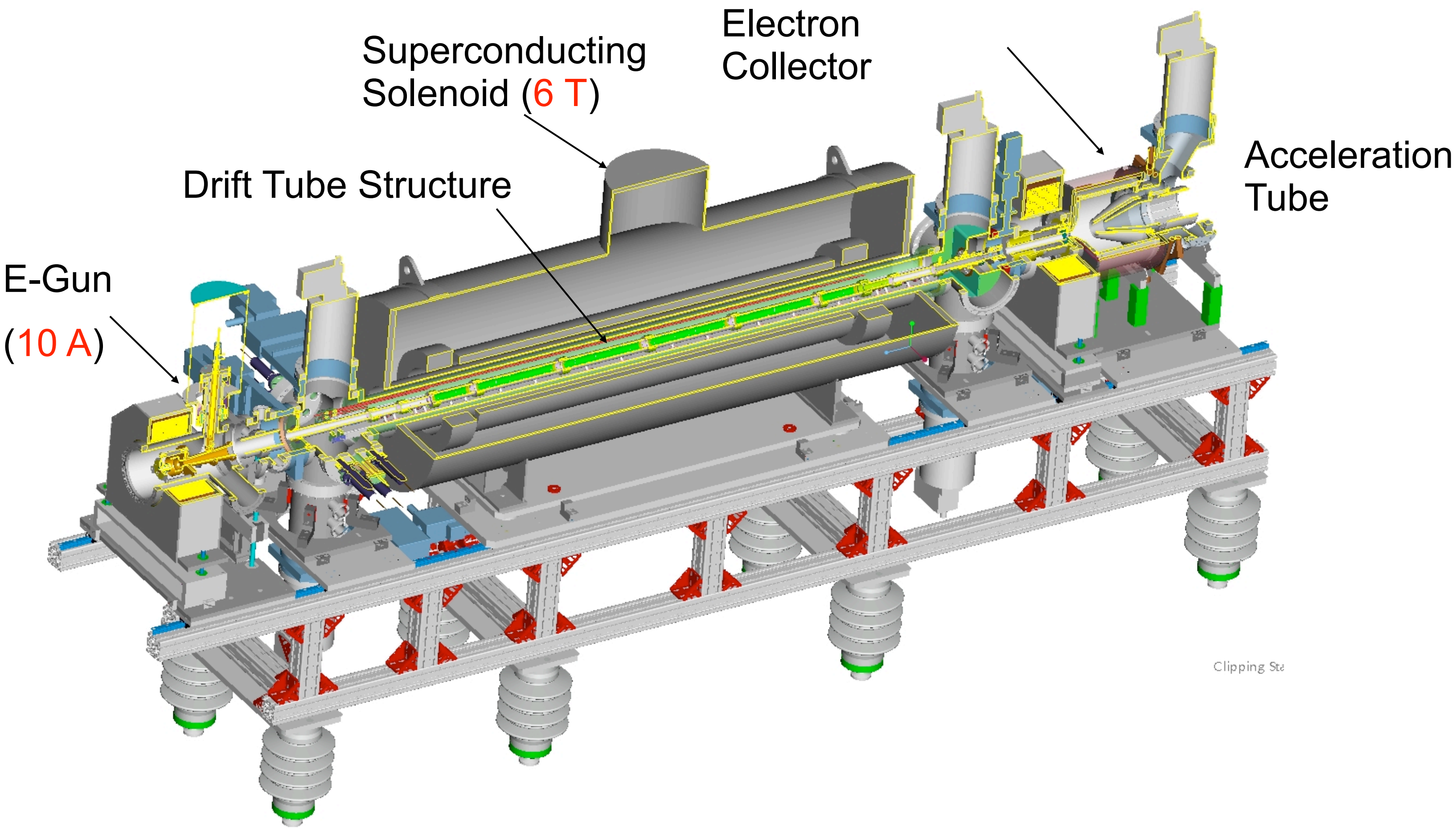
The future physics programme of STAR

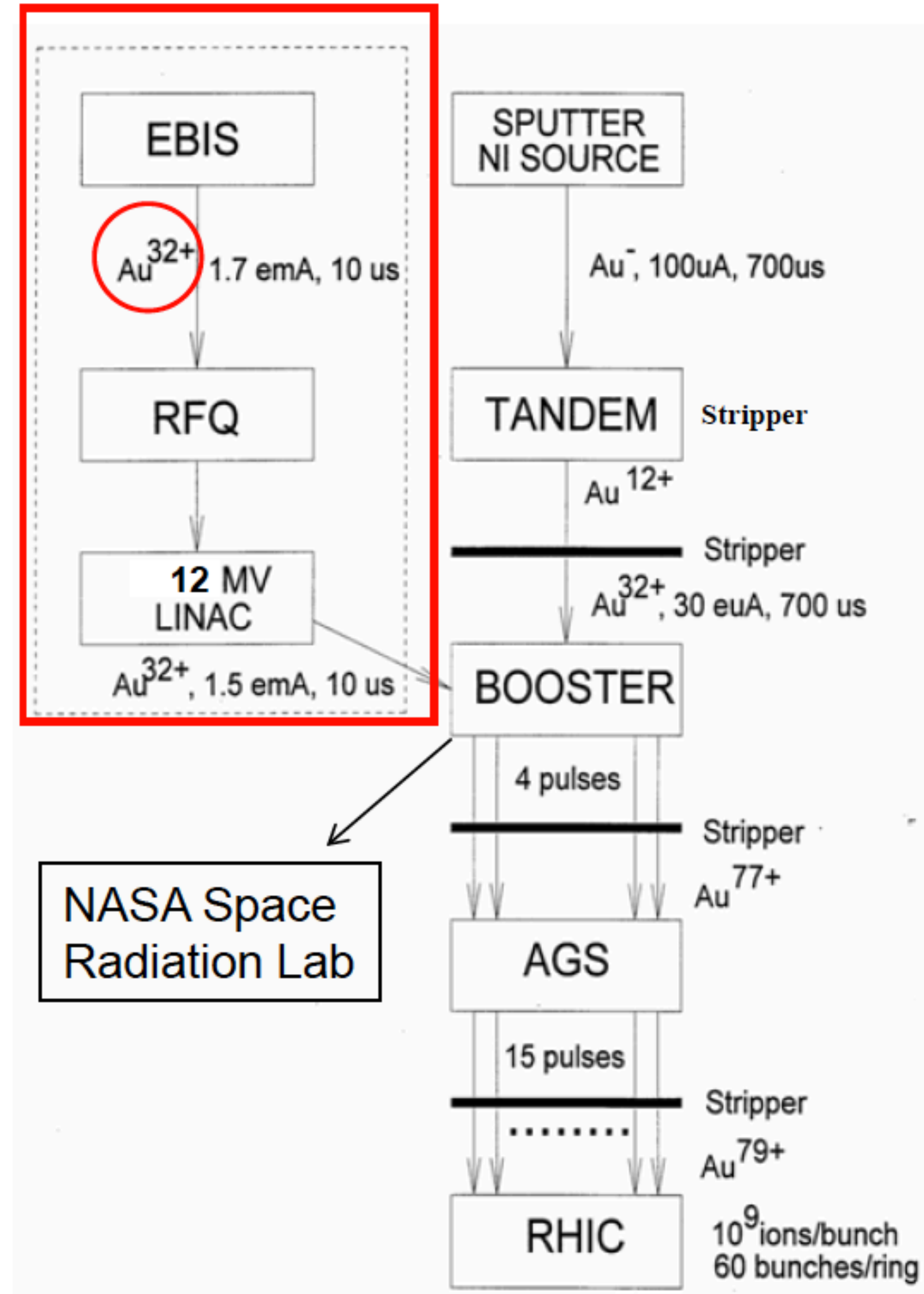
	Near term (Runs 11–13)	Mid-decade (Runs 14–16)	Long term (Runs 17–)
Colliding systems	p+p, A+A	p+p, A+A	p+p, p+A, A+A, e+p, e+A
Upgrades	FGT, FHC, RP, DAQ10K, Trigger	HFT, MTD, Trigger	Forward Instrum, eSTAR, Trigger
(1) Properties of sQGP	$\Upsilon, J/\psi \to ee$, m_{ee}, v_2	$\Upsilon, J/\psi \to \mu\mu$, Charm v_2, R_{CP}, Charm corr, Λ_c/D ratio, μ-atoms	p+A comparison
(2) Mechanism of energy loss	Jets, γ-jet, NPE	Charm, Bottom	Jets in CNM, SIDIS, c/b in CNM
(3) QCD critical point	Fluctuations, correlations, particle ratios	Focused study of critical point region	
(4) Novel symmetries	Azimuthal corr, spectral function	$e-\mu$ corr, $\mu-\mu$ corr	
(5) Exotic particles	Heavy anti-matter, glueballs		
(6) Proton spin structure	W A_L, jet and di-jet A_{LL}, intra-jet corr, $(\Lambda+\bar{\Lambda})$ D_{LL}/D_{TT}		Λ D_{LL}/D_{TT}, polarized DIS, polarized SIDIS
(7) QCD beyond collinear factorization	Forward A_N		Drell-Yan, F-F corr, polarized SIDIS
(8) Properties of initial state			Charm corr, Drell-Yan, J/ψ, F-F corr, Λ, DIS, SIDIS

BACKUP SLIDES

EBIS

RHIC Upgrades - EBIS Source



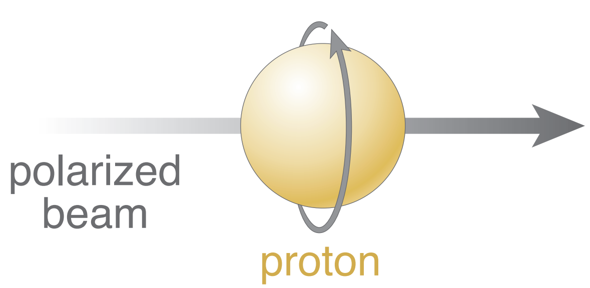


- EBIS advantages:
  - Low cost/maintenance, modern
  - Can produce any ion (e.g. ^{3}He↑, U)
  - Fast switching between species

FGT

Physics of the FGT - Quark Helicities

Physics of the FGT - Quark Helicities



For more details, see B. Surrow, id:113

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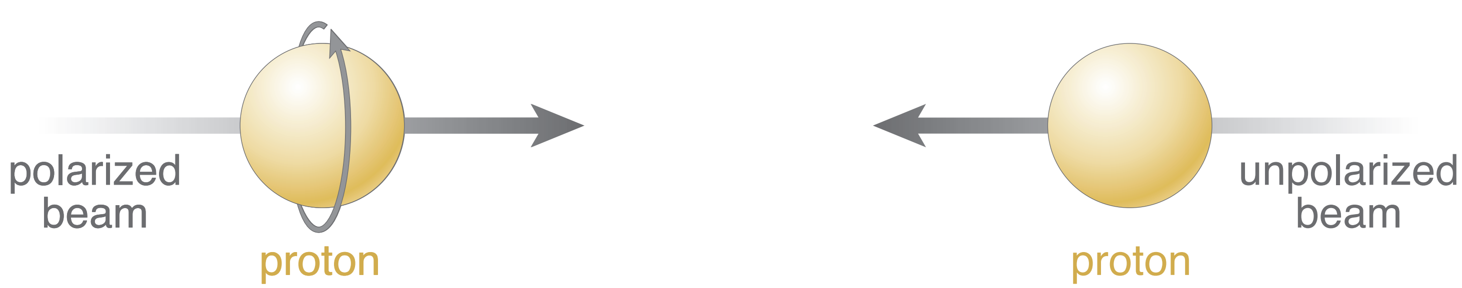

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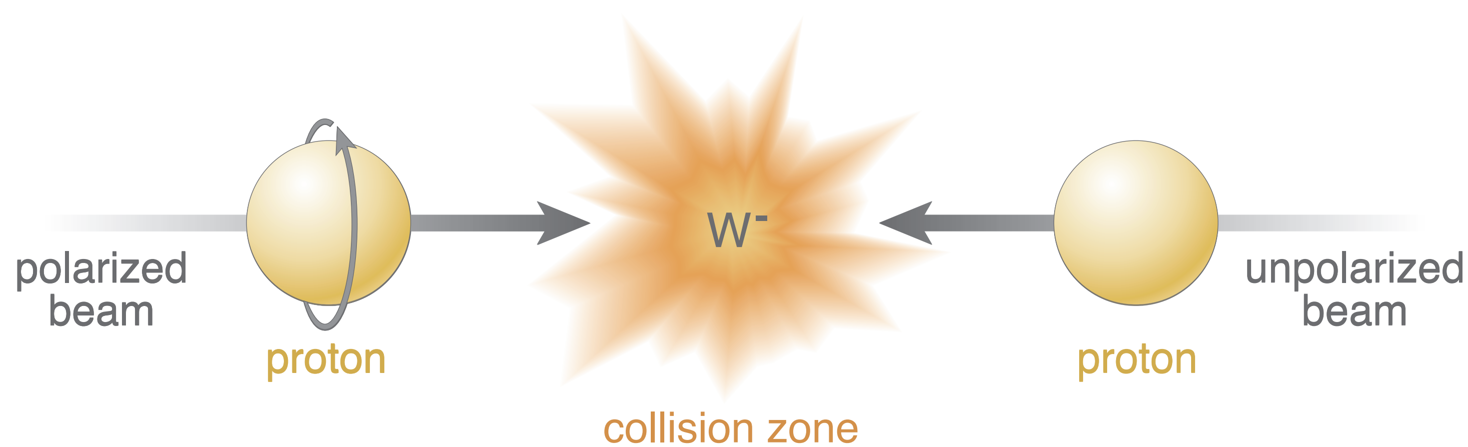

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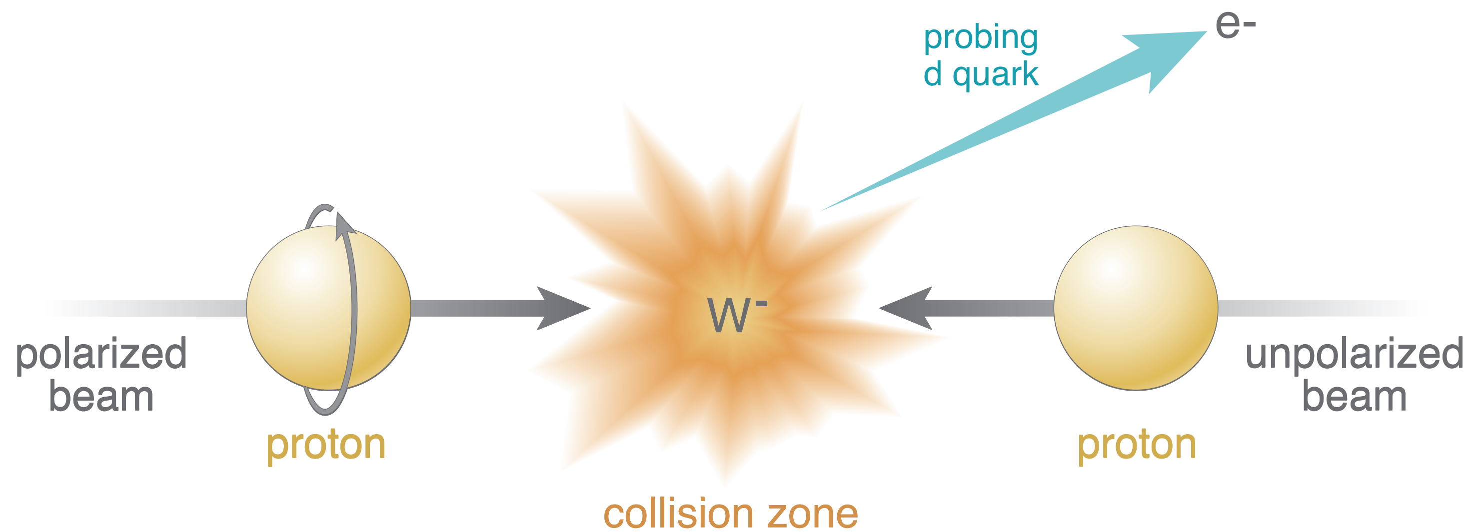

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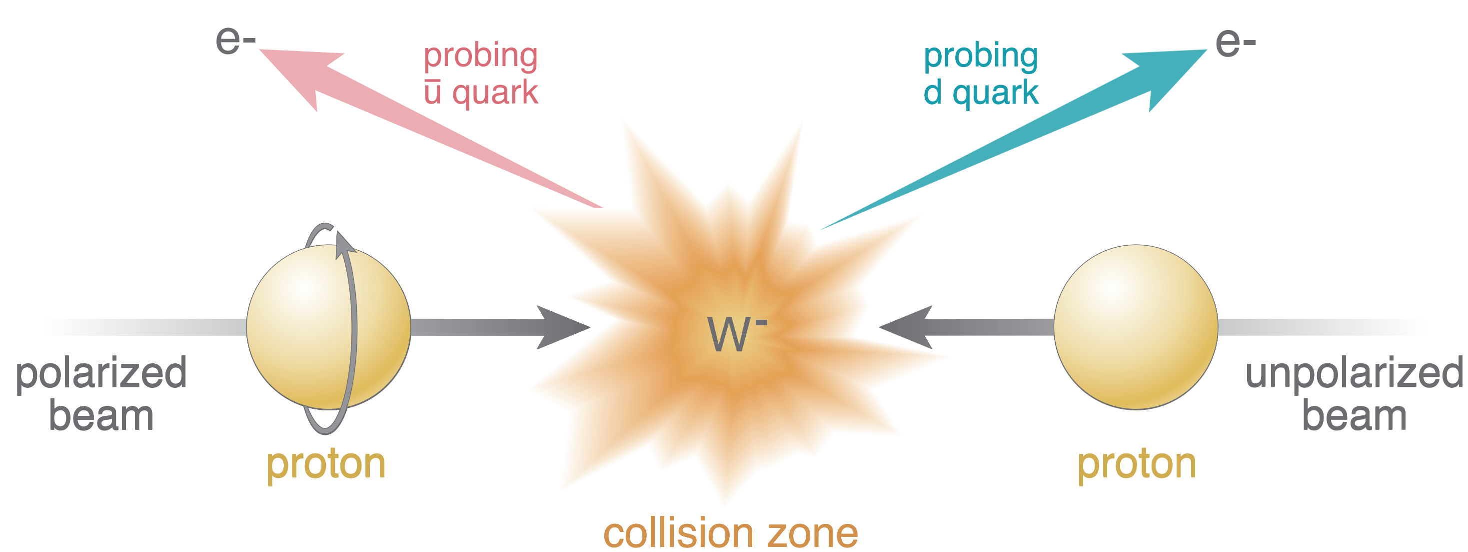

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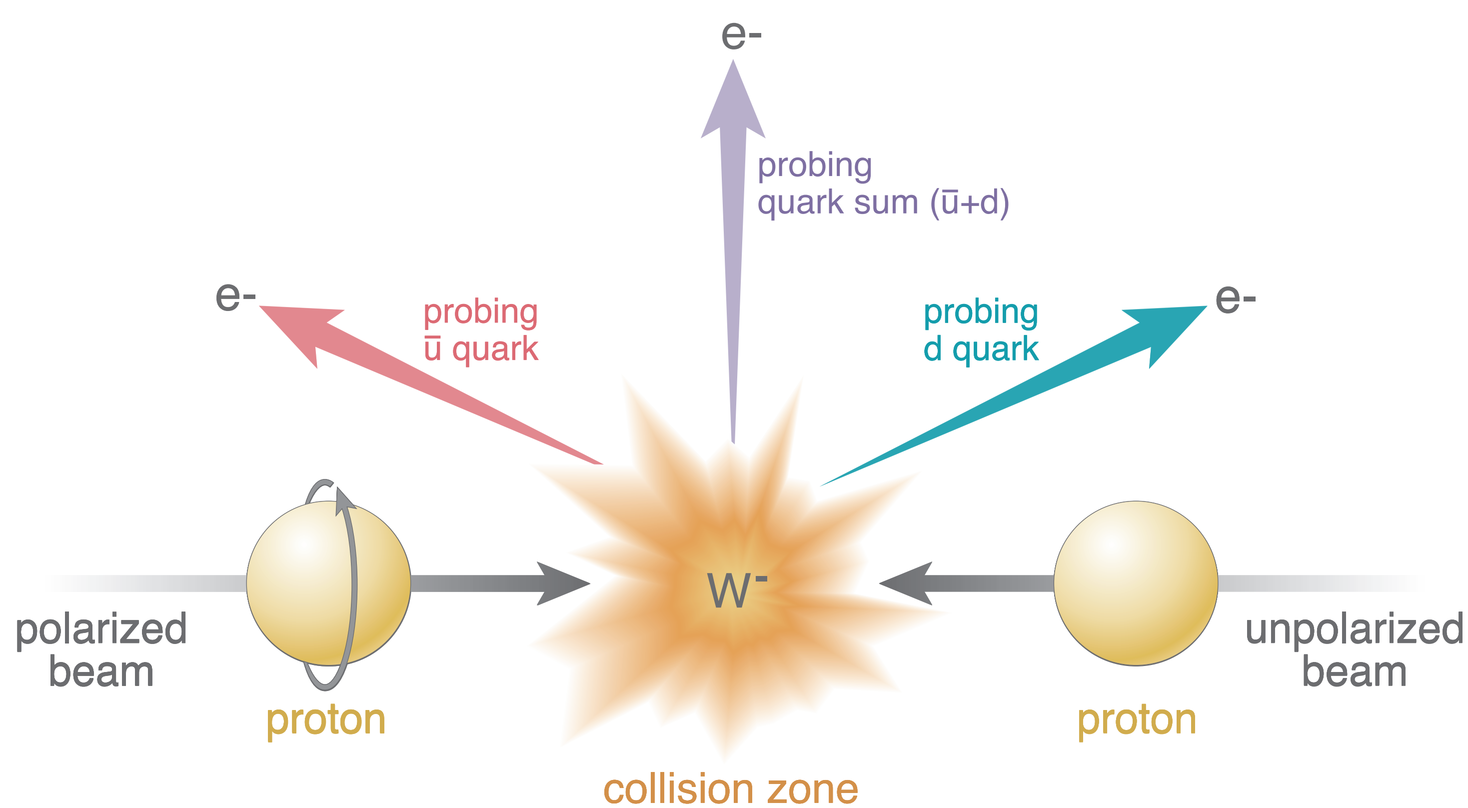

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- $W^{\pm} \rightarrow e^{\pm} + X$ (11% BR) provides a clean signature with high efficiency

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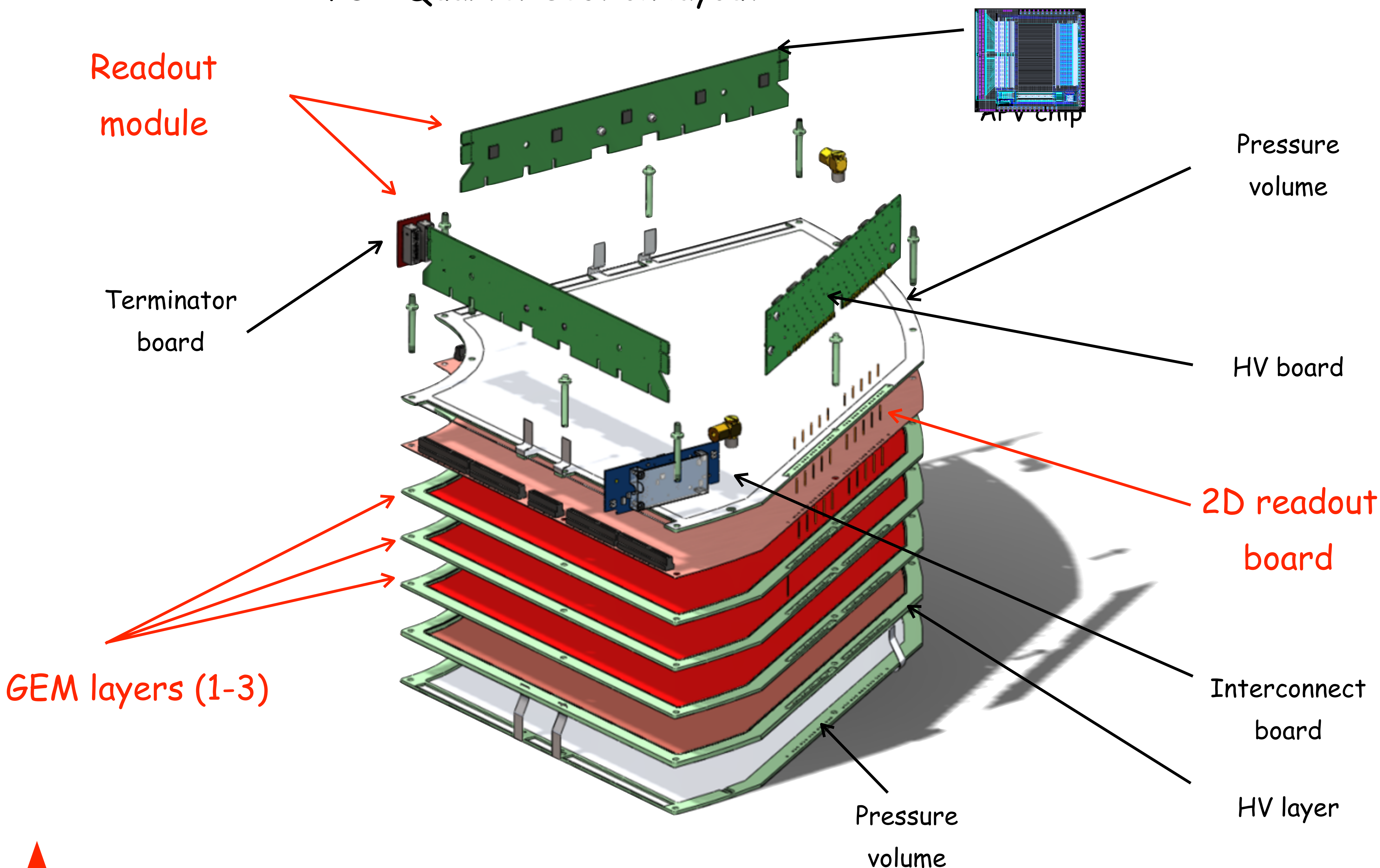
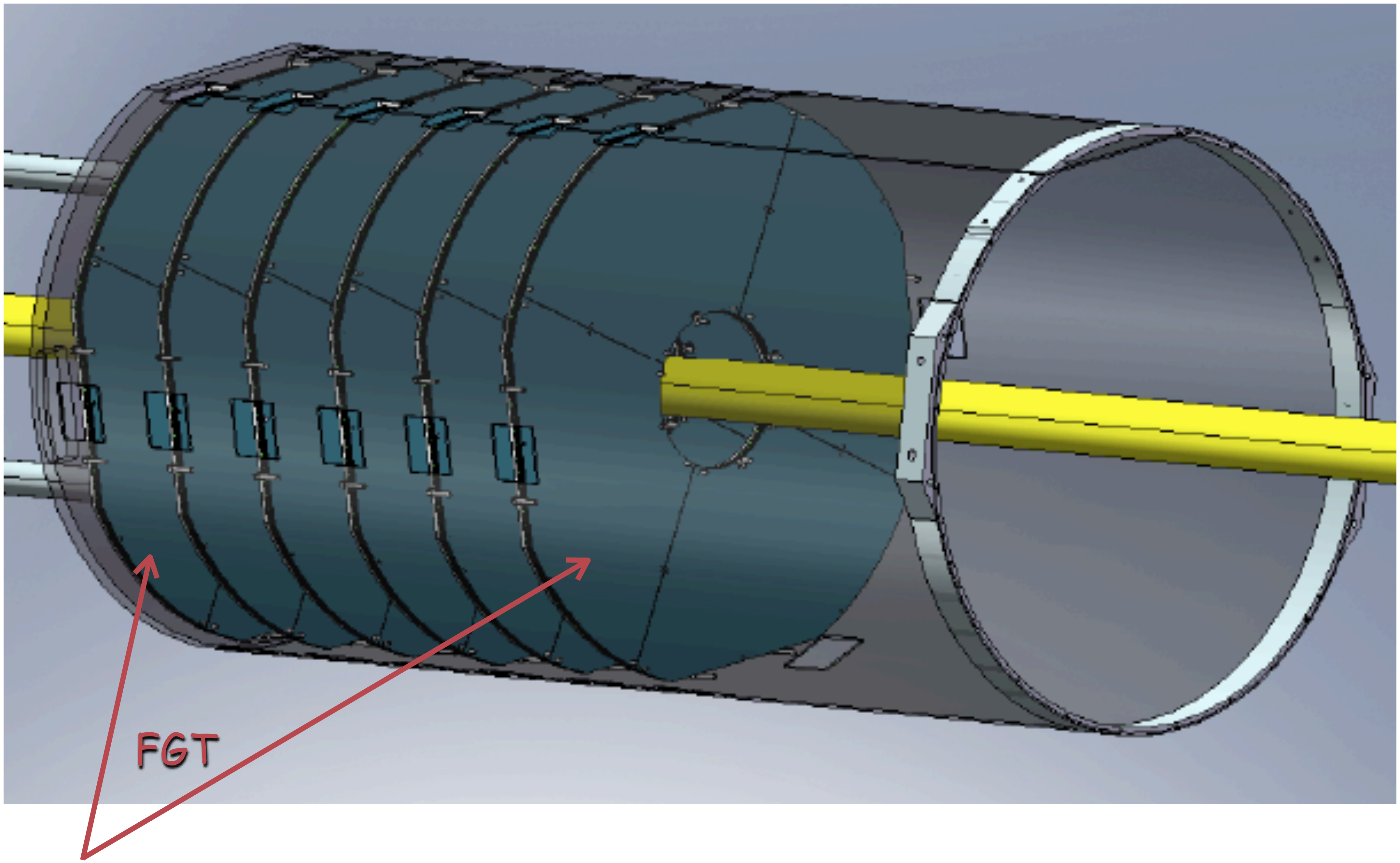
FGT Overview

FGT Quarter section layout



FGT Technical realization / Design

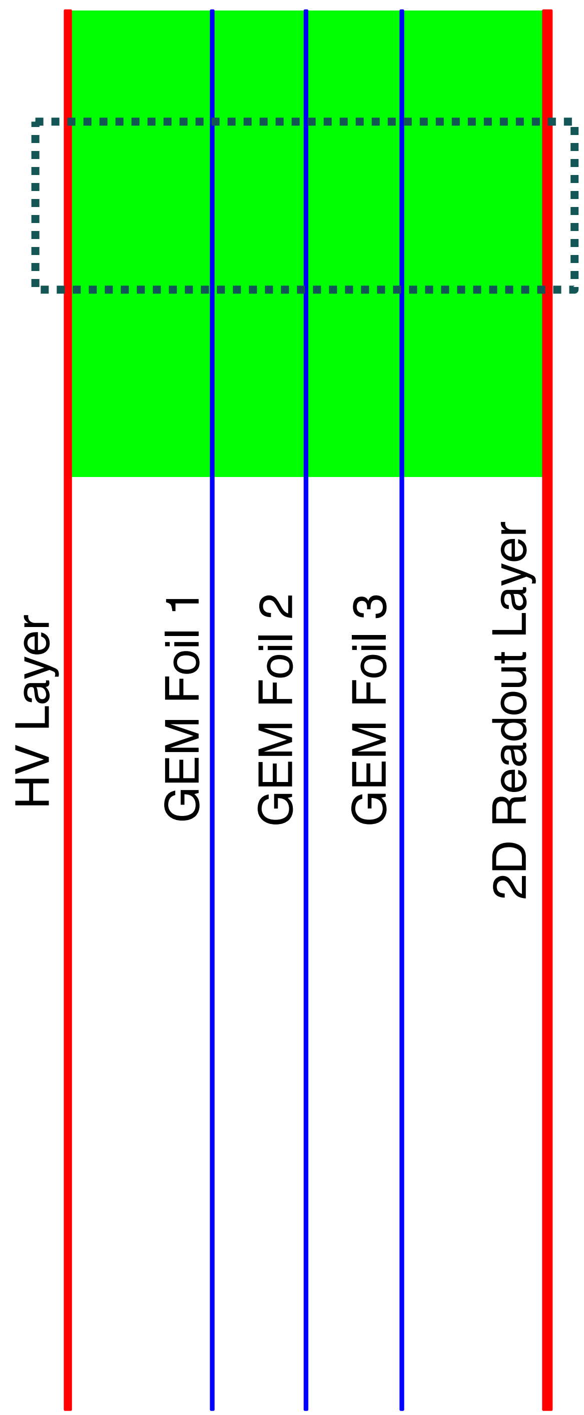
- Overview FGT Layout

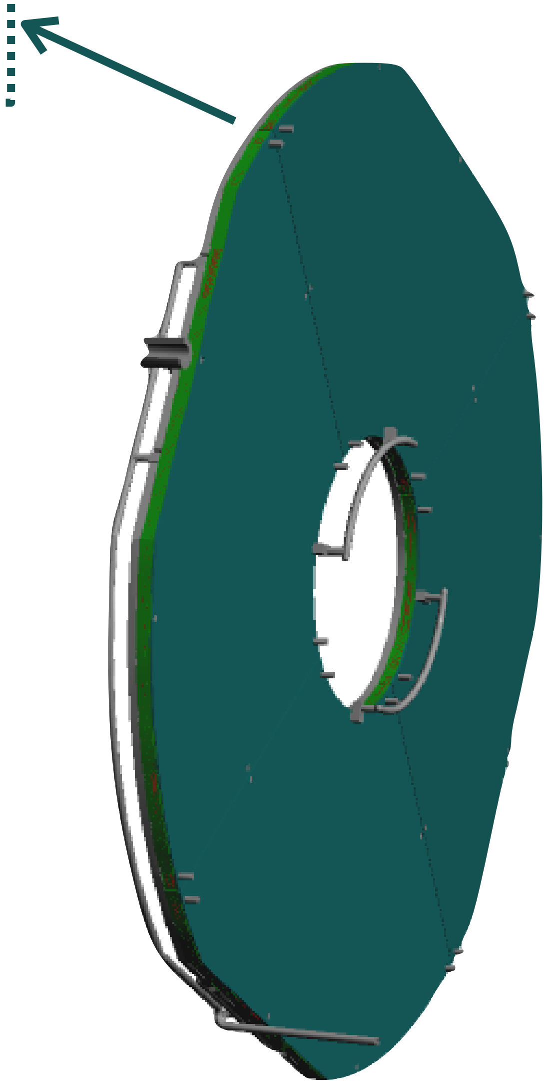


- FGT: 6 light-weight disks
- Each disk consists of 4 triple-GEM chambers (Quarter sections)

FGT Technical realization / Layout

- Triple-GEM: Quarter section / Disk design (2)



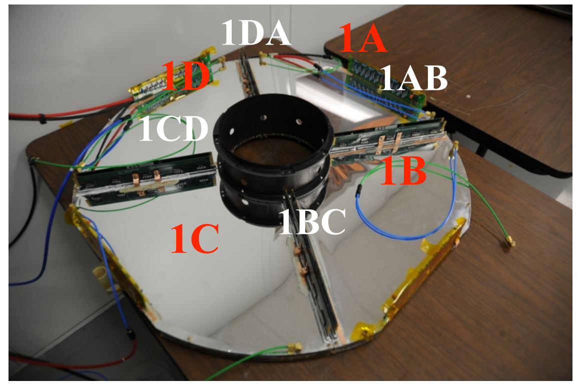


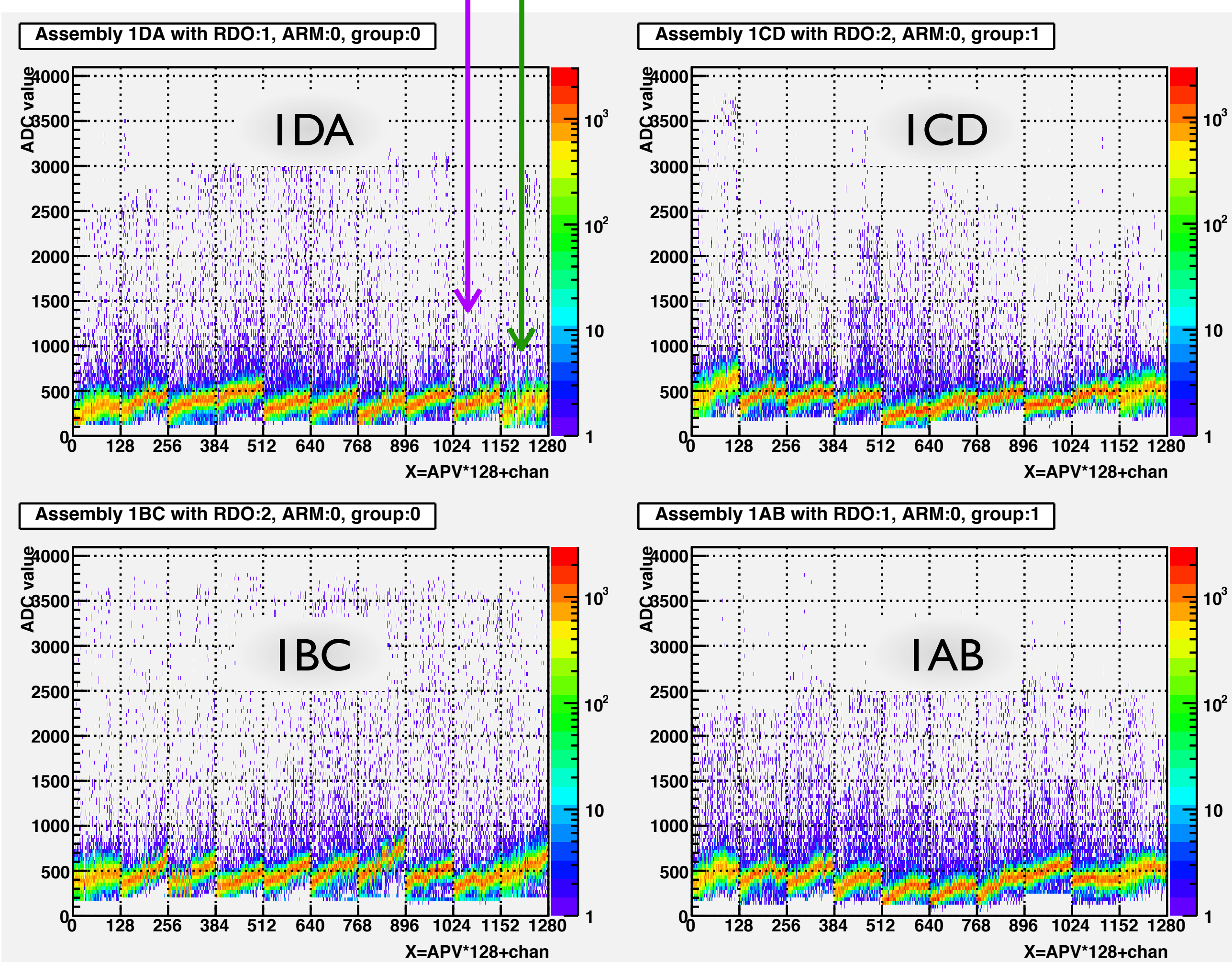
Component	Material	Radiation Length [%]
Support plate	5 mm Nomex	0.040
	2x250 µm FR4	0.257
HV layer	5 µm Cu	0.035
	50 µm Kapton	0.017
GEM foils	6x5 µm Cu (70%)	0.147
	3x50 µm Kapton (70%)	0.036
Readout	5 µm Cu (20%)	0.007
	50 µm Kapton (20%)	0.003
	5 µm Cu (88%)	0.031
	50 µm Kapton	0.017
	5 µm Cu (10%)	0.004
	5 µm Cu (10%)	0.004
Drift gas	10 mm CO_2 (30%)	0.002
	10 mm Ar (70%)	0.006
Total		0.606

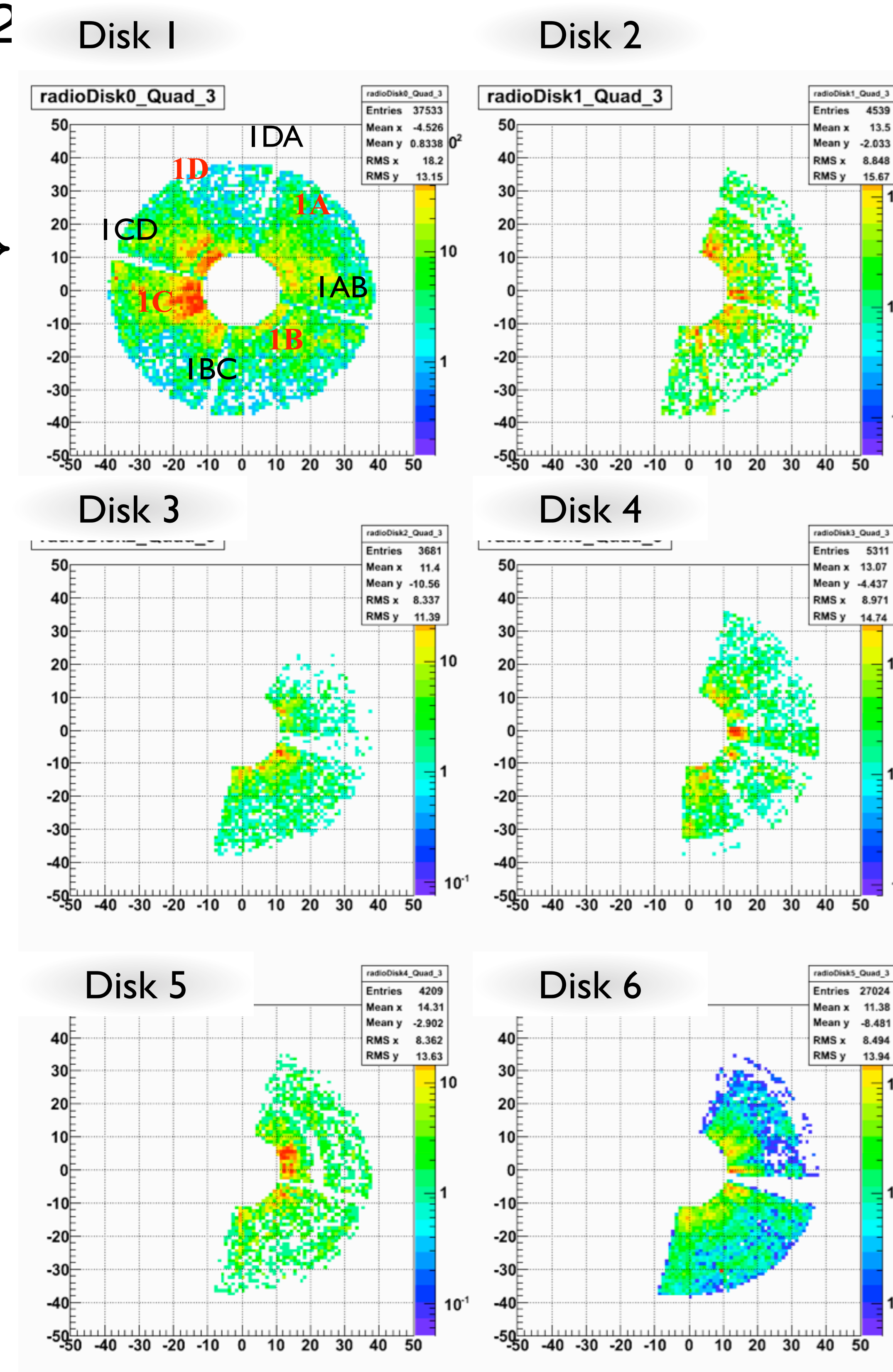
FGT Performance - Run 12

- Snapshot of FGT raw performance (Run 12

Ready for data taking in Run12







Summary / Outlook

Summary / Outlook

- Summary

Summary / Outlook

- Summary
  - Extensive R&D period:

Summary / Outlook

- Summary
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    - Commercial GEM foil production by Tech-Etch Inc. (SBIR funding)

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    - Optical CCD scan

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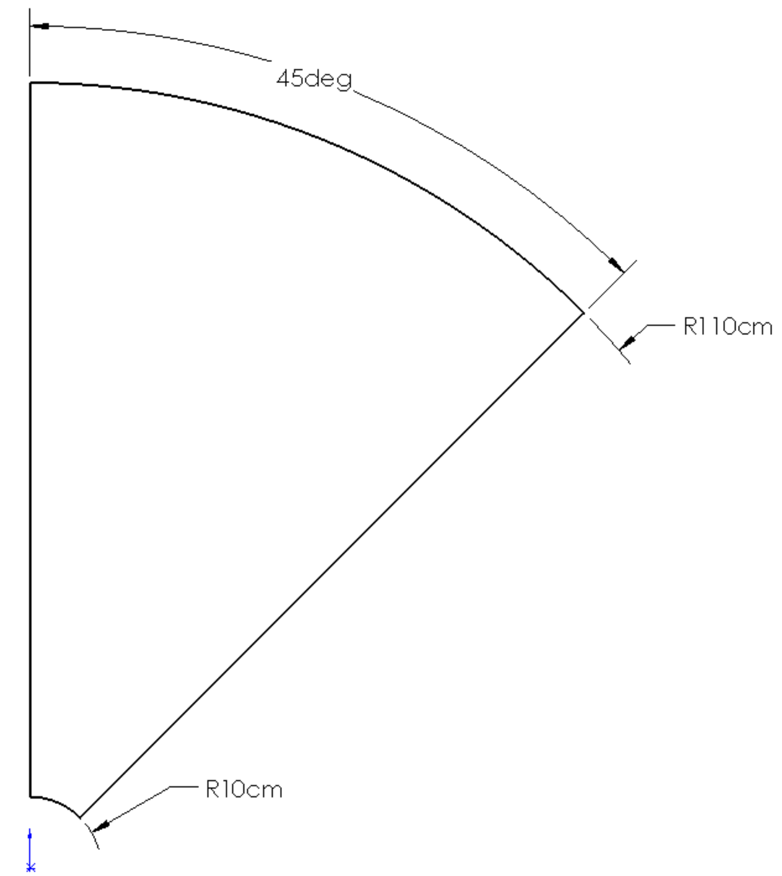

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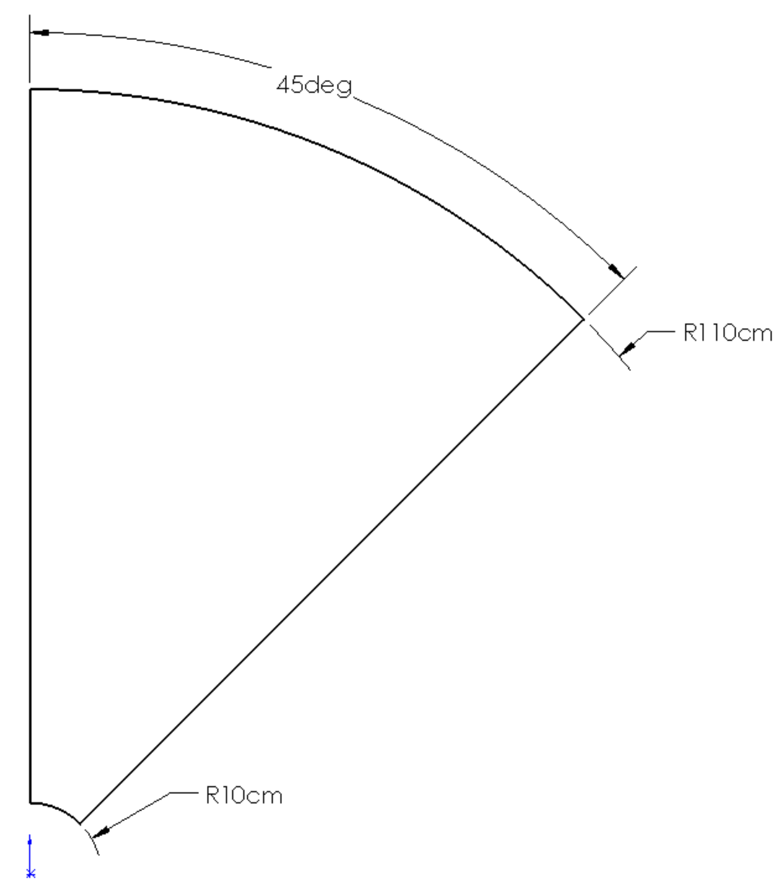

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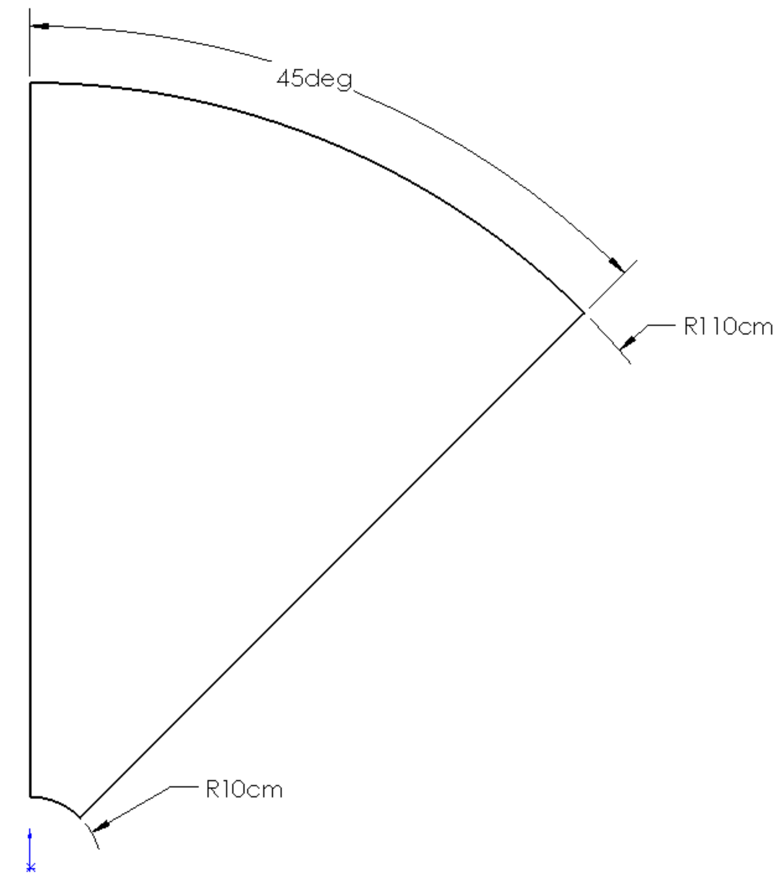

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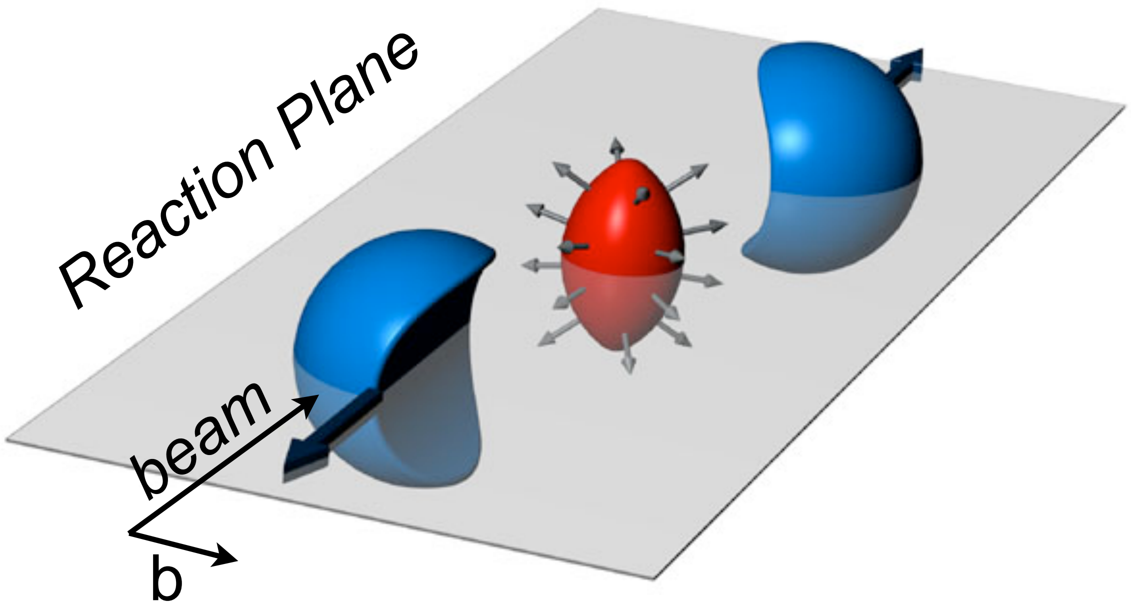
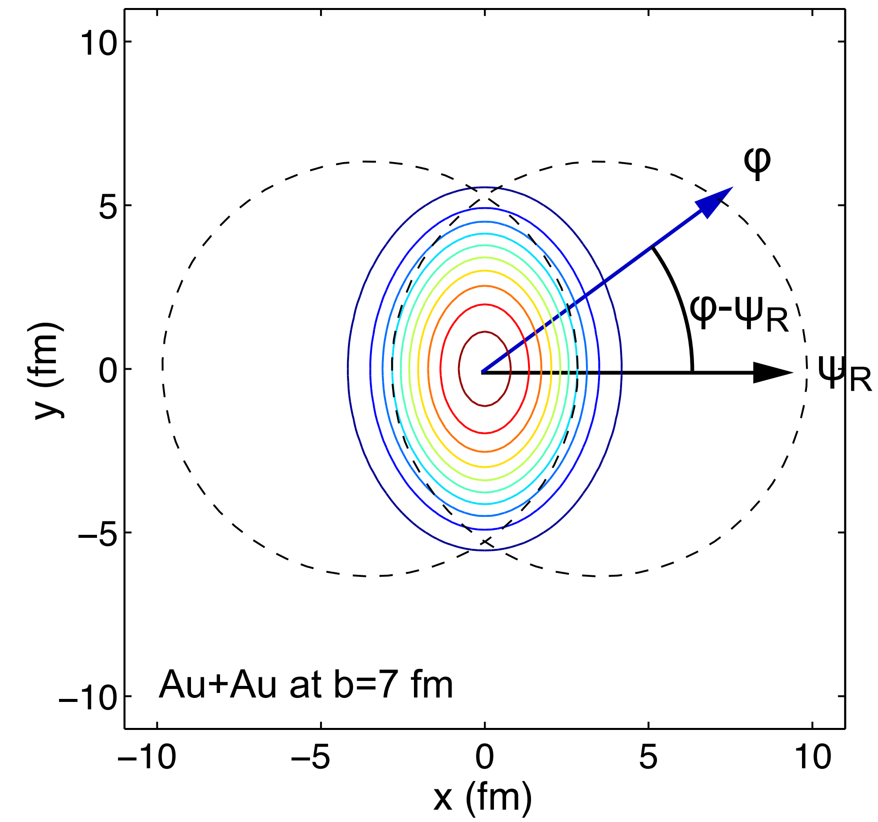
Looking forward to long-term collaboration with Saclay v2

Strong Elliptic Flow





Initial spatial anisotropy → Interactions → Final state anisotropy in momentum space

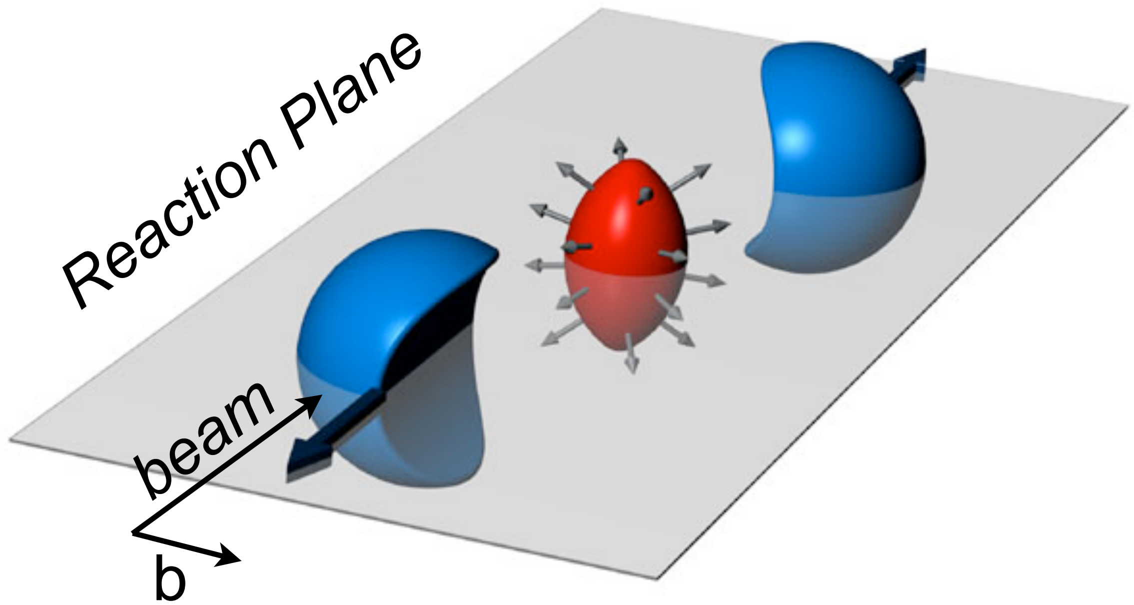
Use a Fourier expansion to describe the angular dependence of the particle density

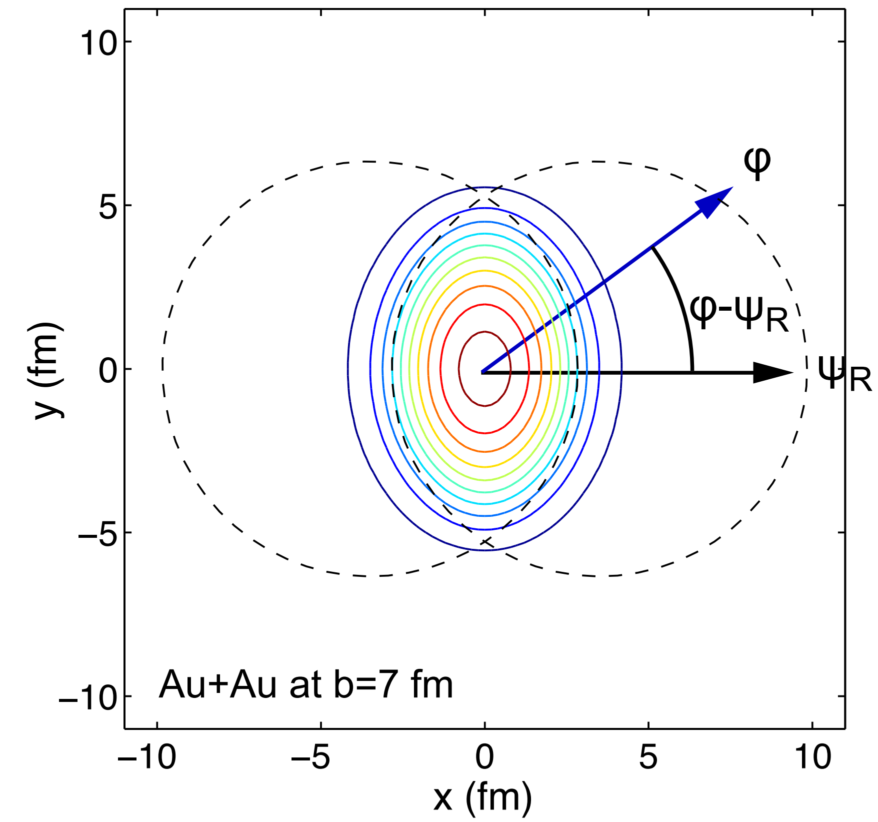
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi - \Psi_r\right)\right]\right)$$

Fourier coefficient

Angle of reaction plane

Strong Elliptic Flow

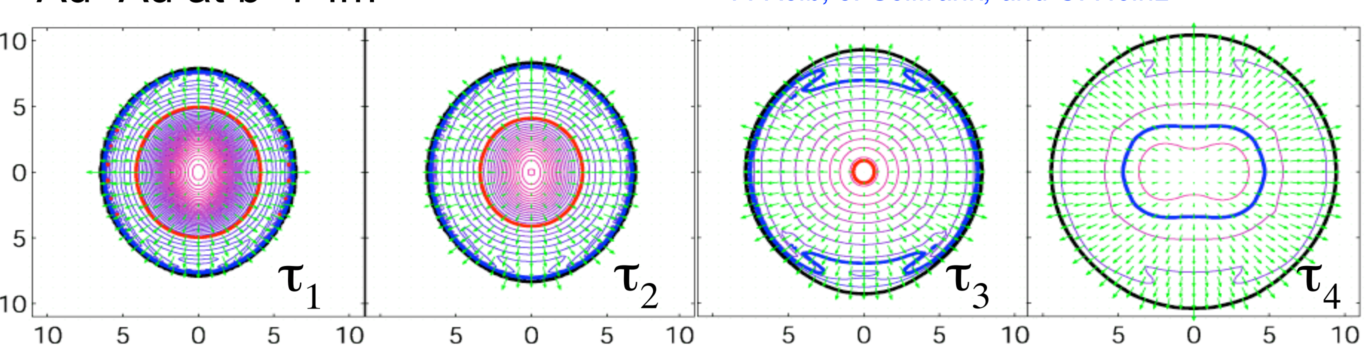




Initial spatial anisotropy → Interactions → Final state anisotropy in momentum space

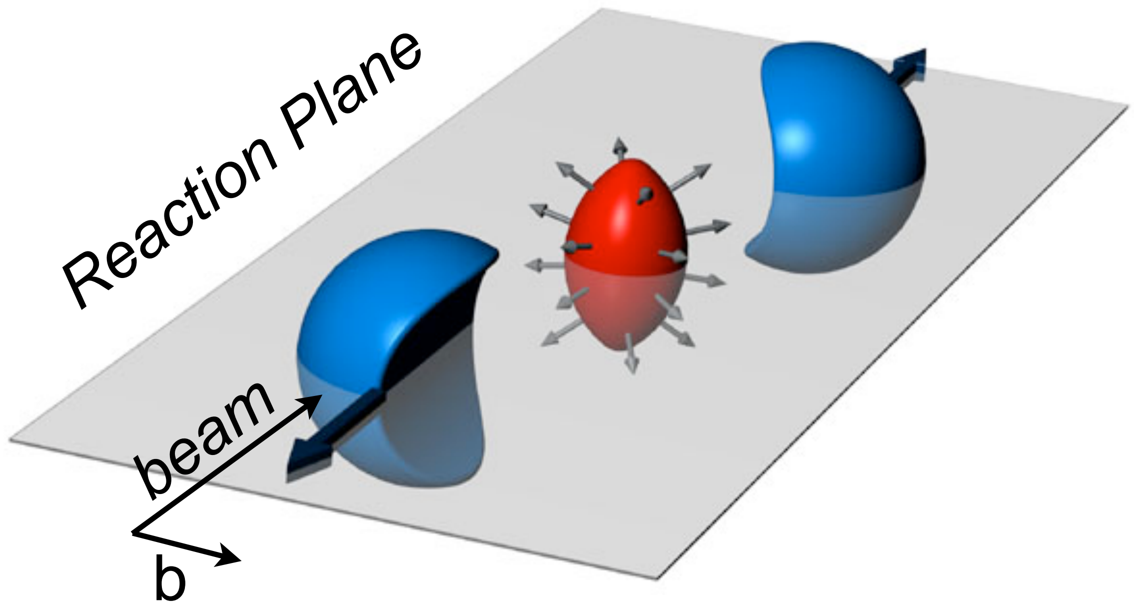
Au+Au at b=7 fm

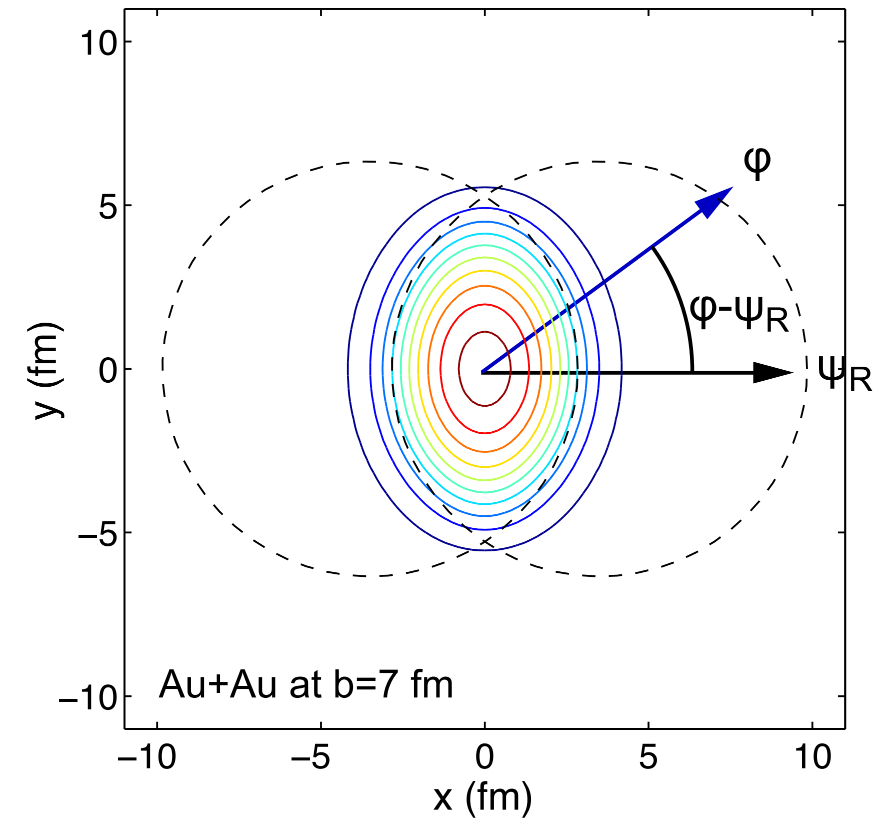
P. Kolb, J. Sollfrank, and U. Heinz

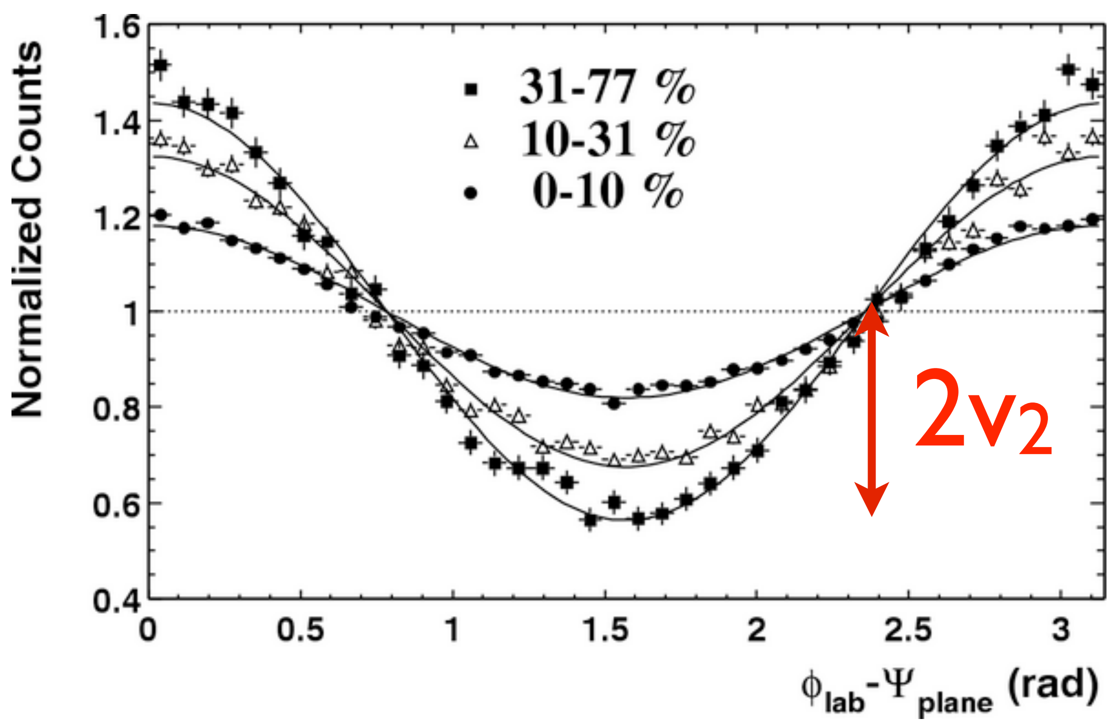


- driving spatial anisotropy vanishes ⇒ self quenching
- v_2 → sensitive to **early** interactions and pressure gradients

Strong Elliptic Flow

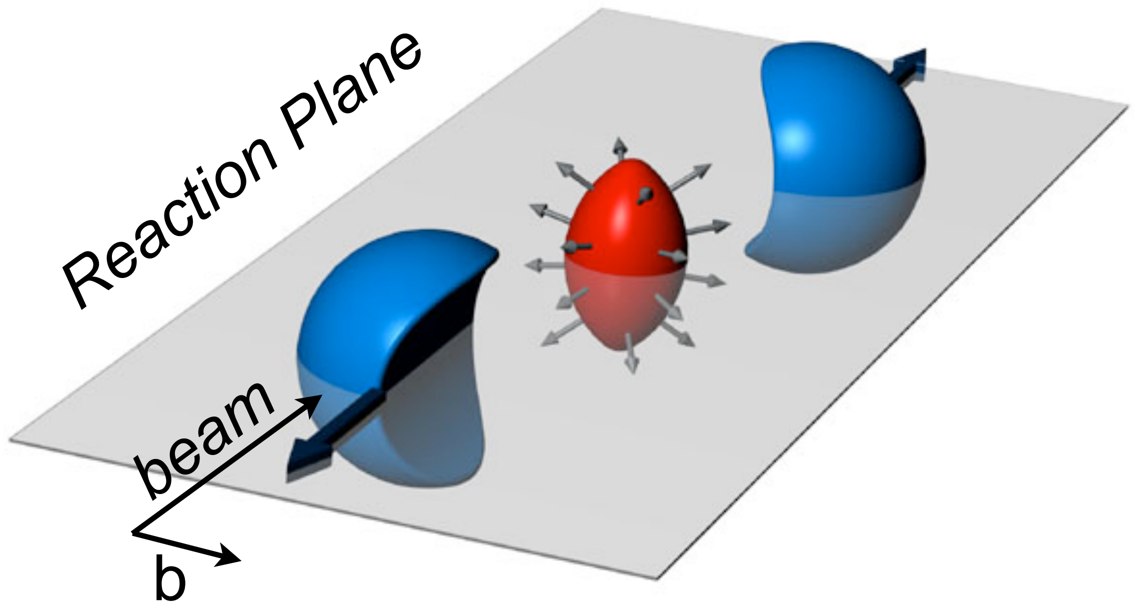


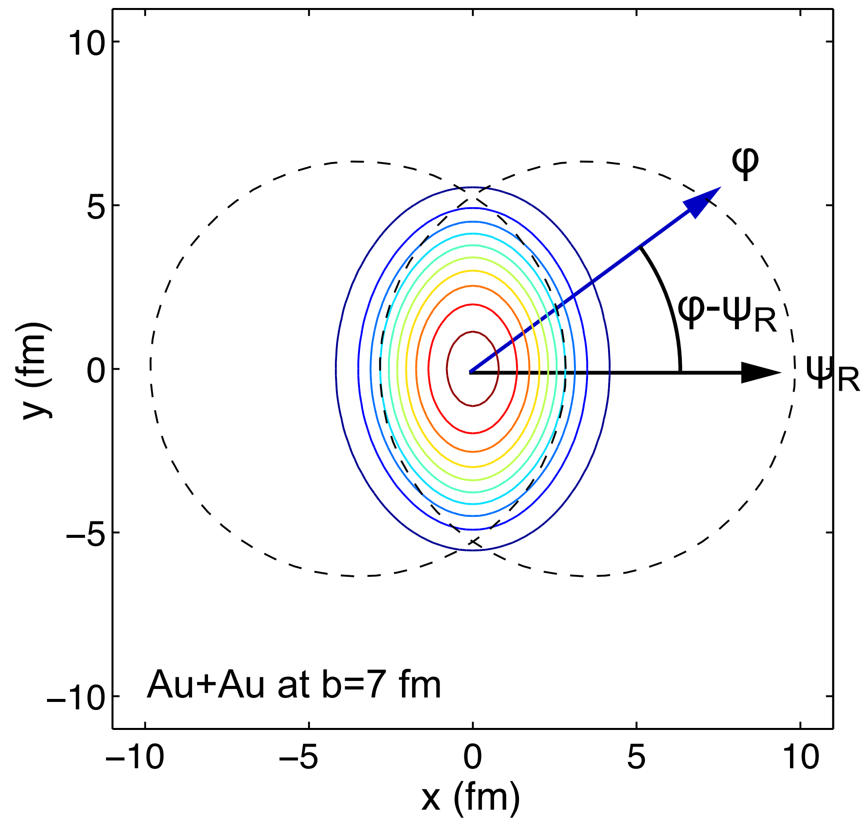


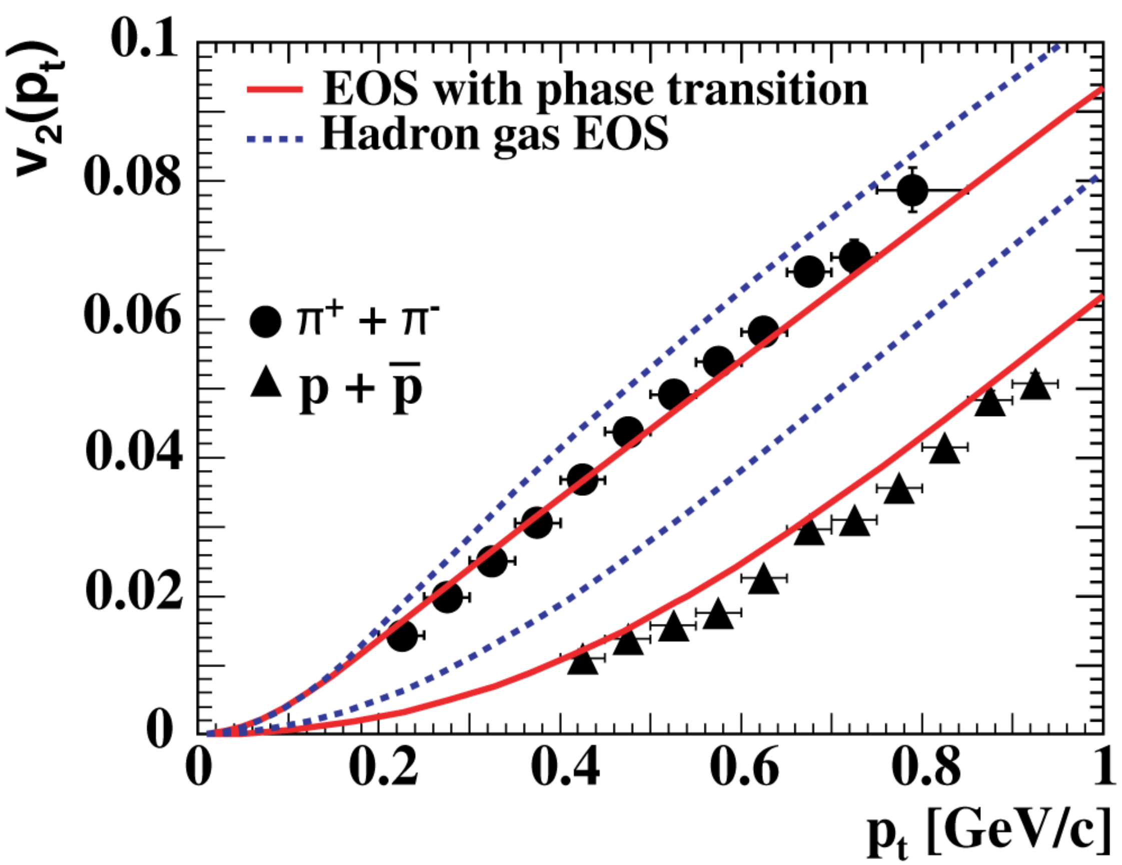


Huge asymmetry found at RHIC !!

Strong Elliptic Flow



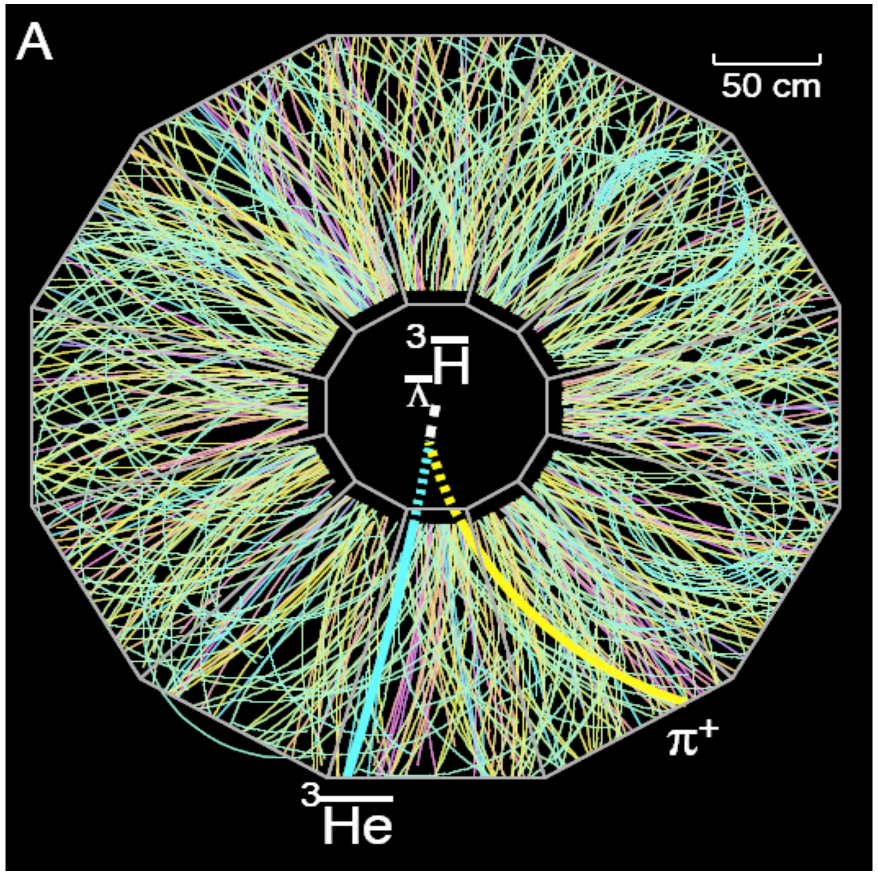




- v_2 shows particle type dependence
- Good agreement between data and ideal (zero viscosity) hydrodynamics

Exotic particles

Exotic particle search with STAR



Science **328,** 58 (2010)

- By utilising the high anti-baryon density and temperature of A+A collisions, coupled with special high-level trigger algorithms, have been able to find:
  - $^{3}_{\bar{\Lambda}}\overline{H}$ - 2010

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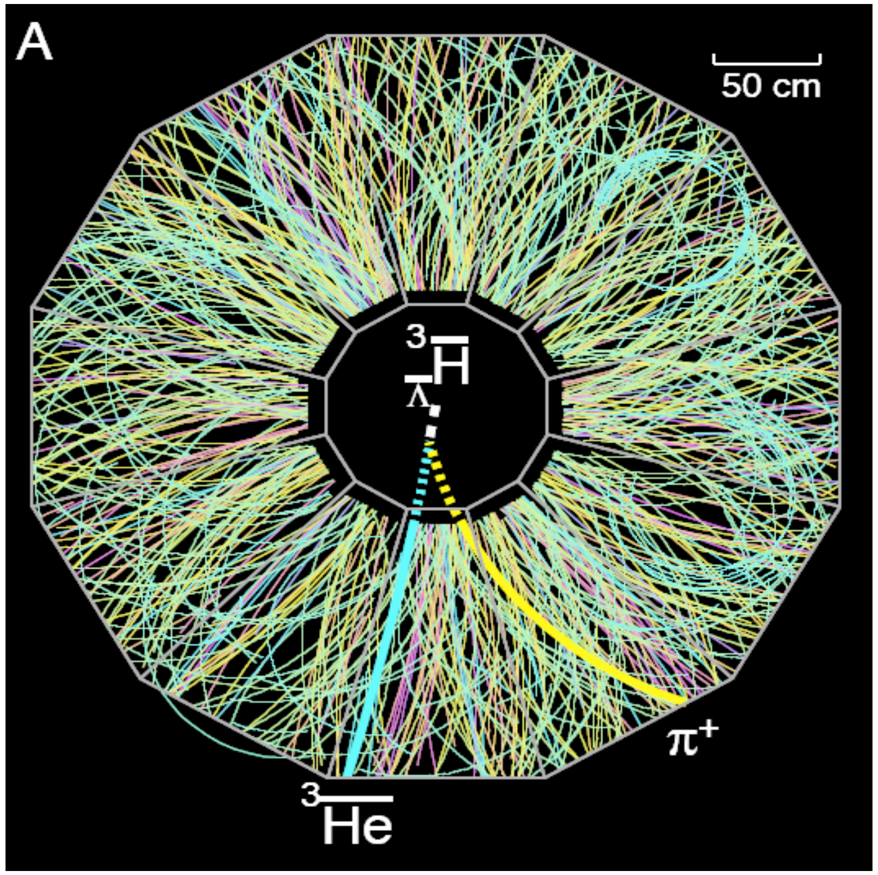
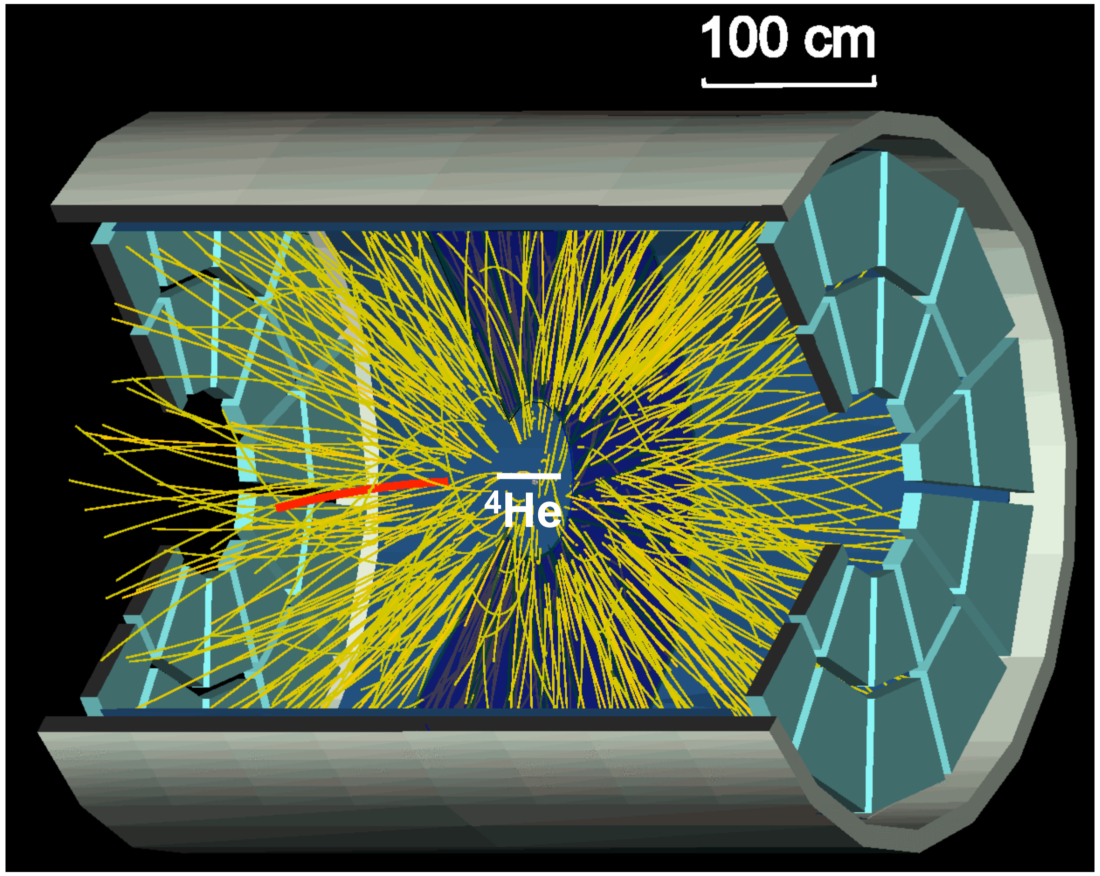




Science

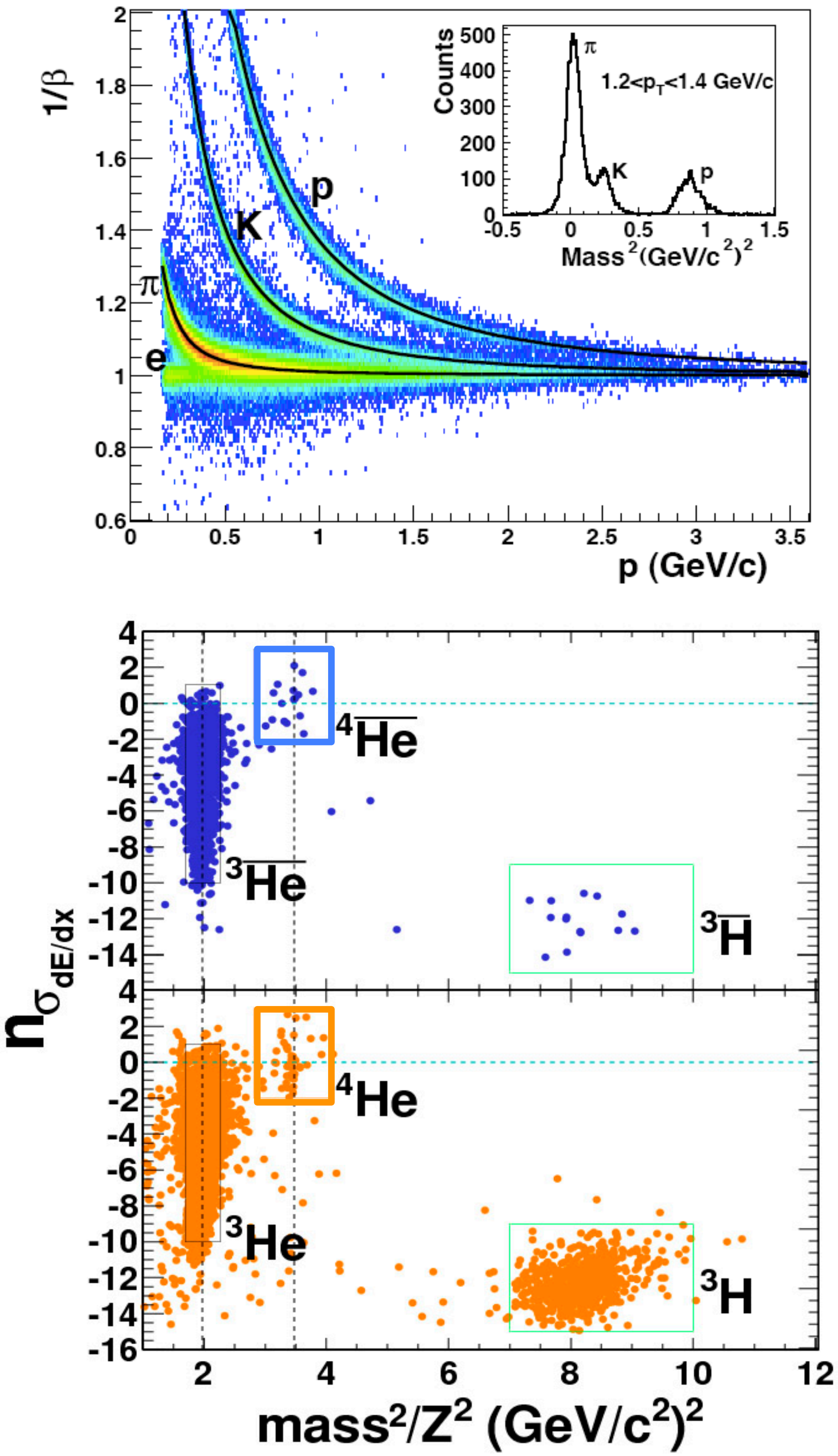
***Science* 328,** 58 (2010)

nature

***Nature* 473,** 353 (2011)

- By utilising the high anti-baryon density and temperature of A+A collisions, coupled with special high-level trigger algorithms, have been able to find:
  - $^{3}_{\bar{\Lambda}}\bar{H}$ - 2010
  - $^{4}\overline{He}$ - 2011

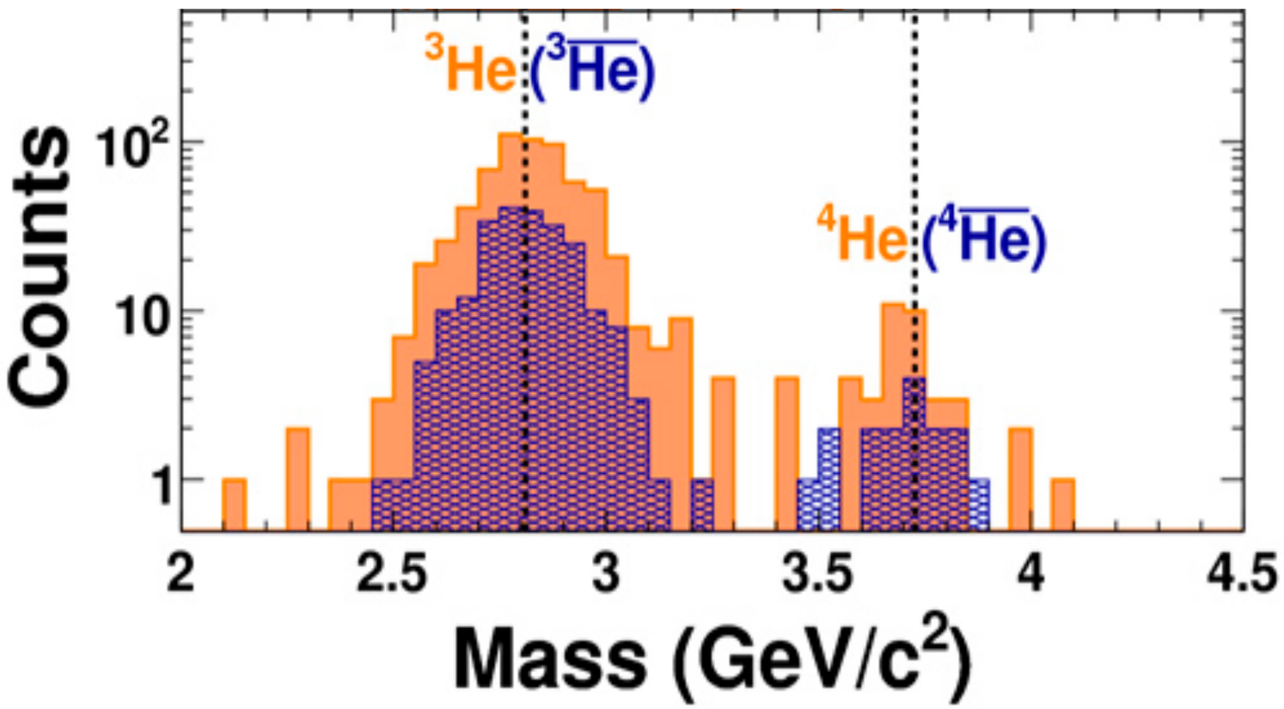
The search for exotic particles

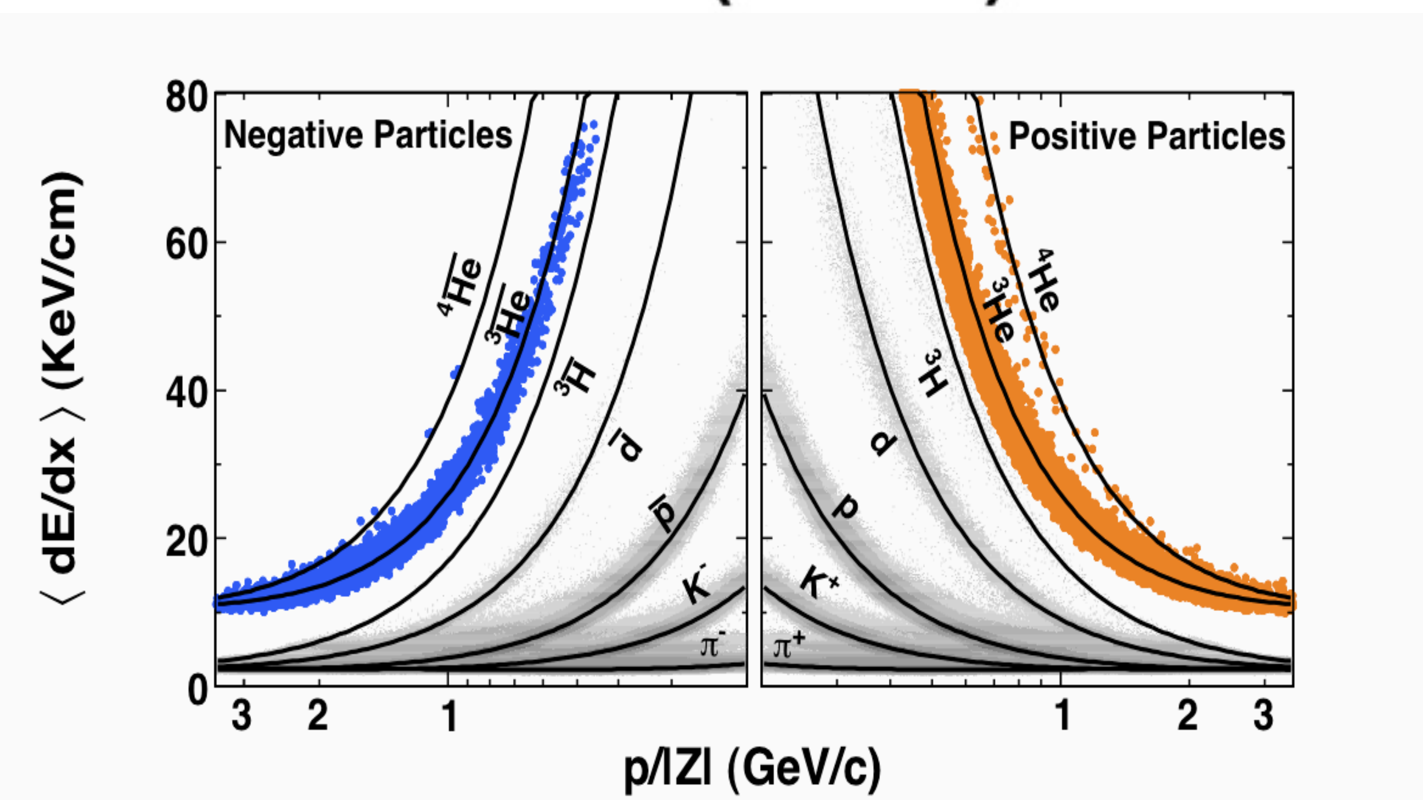


- By utilising STAR upgrades (both DAQ rate and detectors), have been able to search for exotic particles
- Combining TPC and TOF PID techniques, get clean PID out to relatively large p_T
- By measuring $n_{\sigma dE/dx}$ - the deviation from the expected energy loss of anti-^{4}He - can separate well the heavy nuclei produced
- Currently measured 18 counts of anti-^{4}He.

The search for exotic particles

nature **473,** 353 (2011)





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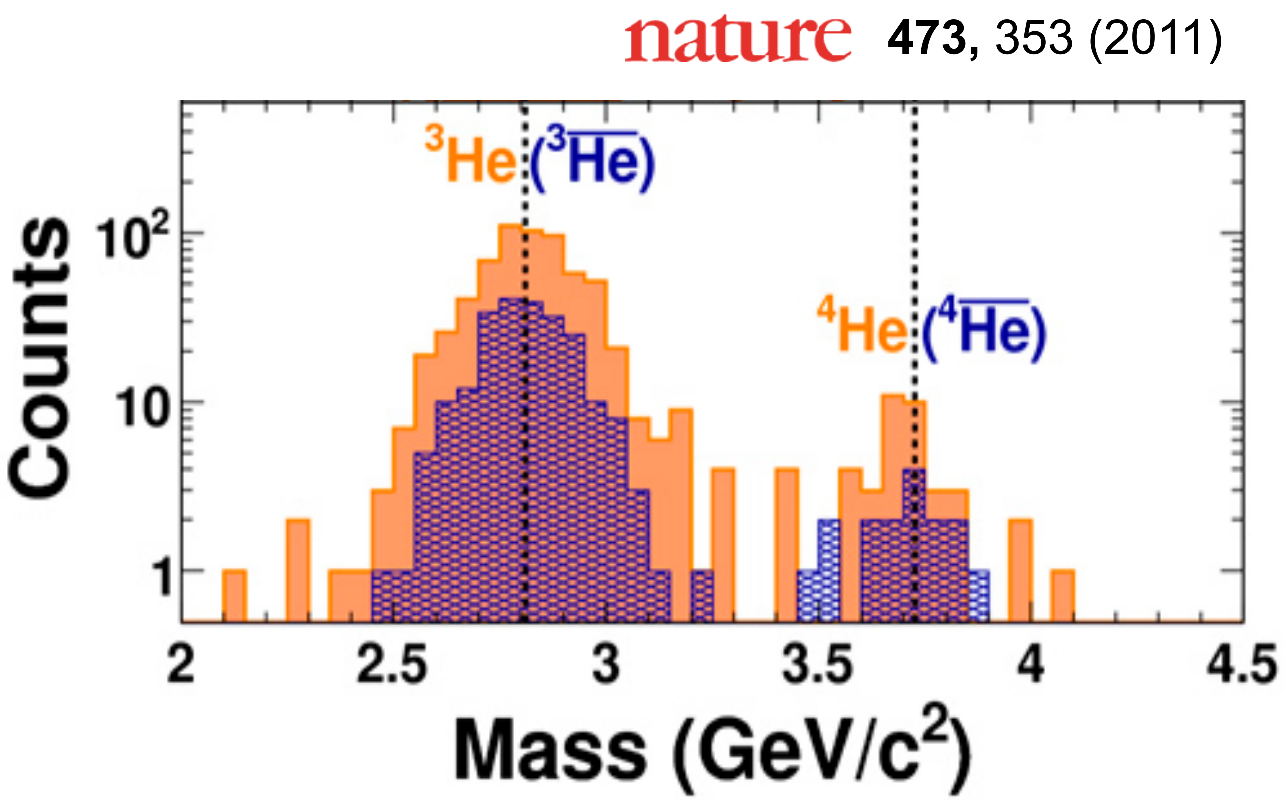
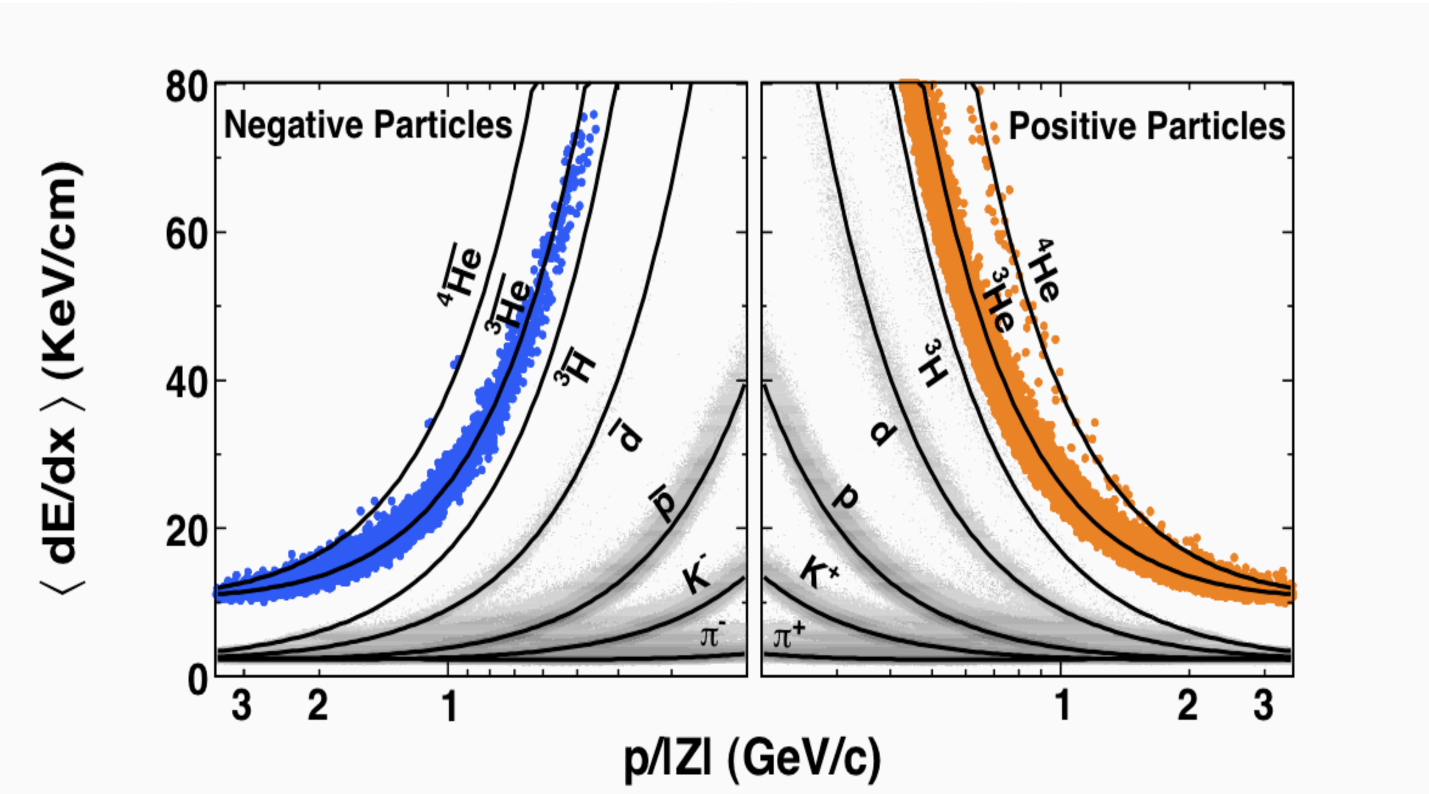
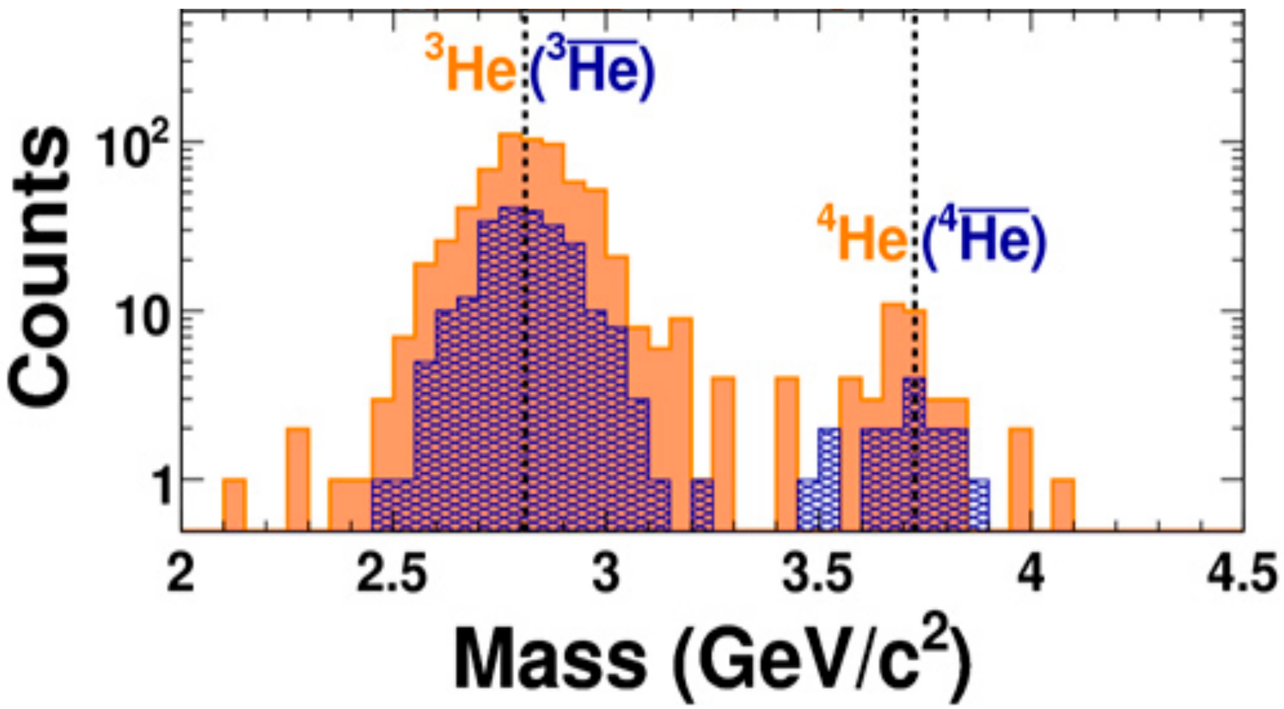


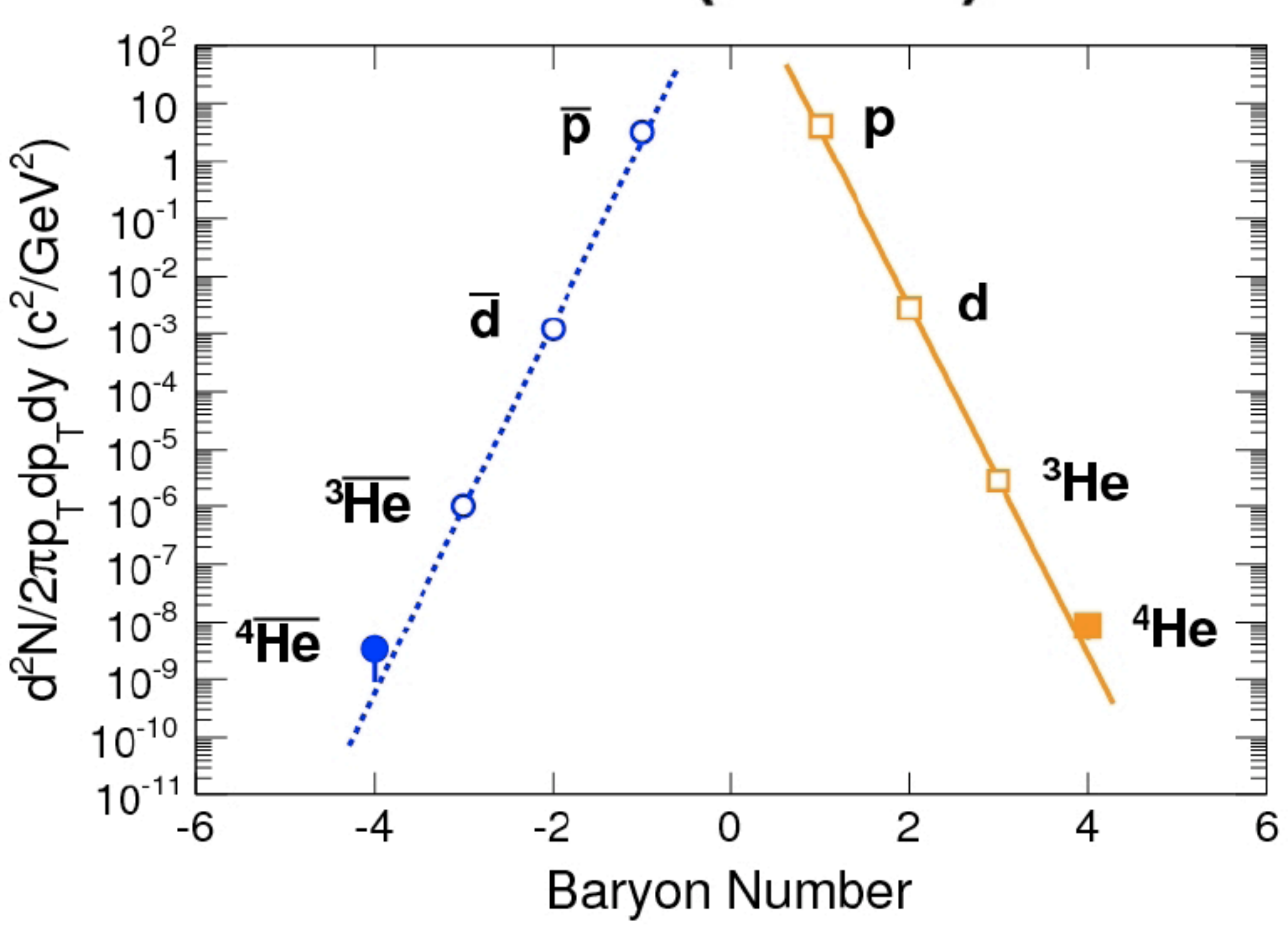


- Very clean identification after searching > 5×10^8 tracks from 10^7 Au+Au collisions!!

The search for exotic particles

nature 473, 353 (2011)

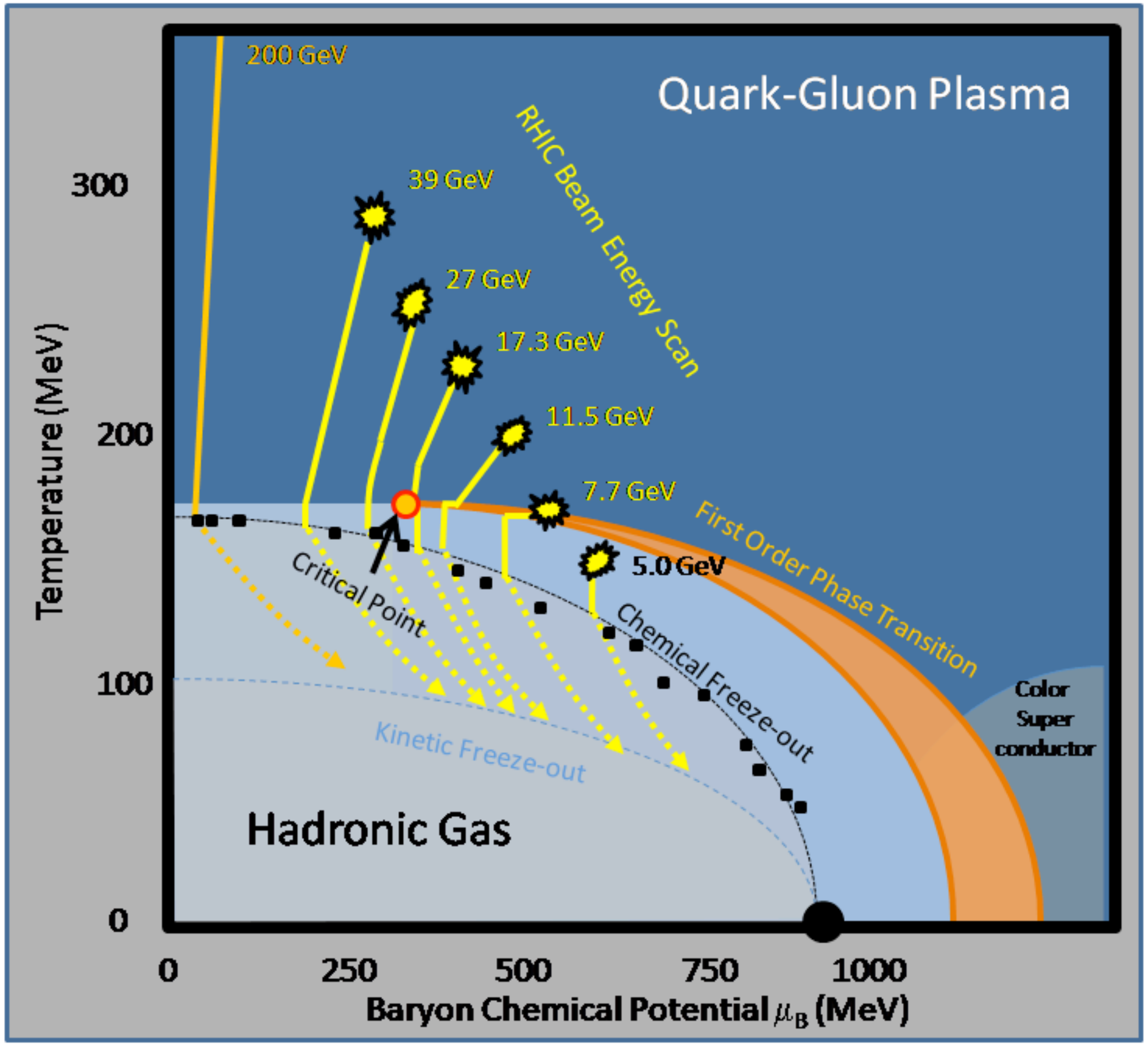




- Very clean identification after searching > $5x10^8$ tracks from 10^7 Au+Au collisions!!
- Production rate reduces by a factor of $1.6x10^3$ ($1.1x10^3$) for each additional anti-nucleon (nucleon) added to the anti-nucleus (nucleus).
  - Searching for heavier anti-nuclei becomes problematic due to required statistics
    - There are ideas and searches which can be done here (DAQ10K, H^0..)

Critical Point

Flexibility: Critical Point Search



- Phase 1: 2010, 2011
  - ~5 million events per energy and more already taken
    - Fluctuations, constituent quark scaling, HBT…
- Phase 2: 2014 and beyond
  - Luminosity improvement with electron cooling at RHIC
  - Scan to even lower energies
  - Increase event counts at energies already scanned

Flexibility: Critical Point Search

Collision Energies (GeV)	5	7.7	11.5	~~17.3~~ 19.6	27	39
Mevents taken (2010/11)		~5	~11	~17	~37	~170
Observables	Millions of Events Needed					
v_2 (up to ~1.5 GeV/c)	**0.3**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**
v_1	0.5	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Azimuthally sensitive HBT	4	**4**	**3.5**	**3.5**	**3**	**3**
PID fluctuations (K/p)	1	**1**	**1**	**1**	**1**	**1**
net-proton kurtosis	5	**5**	**5**	**5**	**5**	**5**
differential corr & fluct vs. centrality (e.g. bal. fctn)	4	**5**	**5**	**5**	**5**	**5**
n_q scaling p/K/p/L $(m_T-m_0)/n$<2GeV	8.5	**6**	**5**	**5**	**4.5**	**4.5**
f/W up to p_T/n_q=2 GeV/c		56	25	**18**	**13**	**12**
R_{CP} up to p_T ~4.5 GeV/c (at 17.3) 5.5 (at 27) & 6 GeV/c (at 39)				**15**	**33**	**24**
untriggered ridge correlations		27	13	**8**	**6**	**6**
parity violation		**5**	**5**	**5**	**5**	**5**

Perfect Liquid

How perfect is the "perfect" liquid?

Conjectured quantum limit: $\eta \geq \frac{\hbar}{4\pi}(Entropy\ Density) \equiv \frac{\hbar}{4\pi}s$

Ideal hydro $v_2 \propto$ spatial eccentricity ε: $\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$

v_2/ε is a sensitive probe of the system:
(S is transverse area of collision, h is ideal hydro limit of v_2/ε and $B \propto \eta/s$)

$$\frac{v_2}{\epsilon} = \frac{h}{1 + B/(\frac{1}{S}\frac{dN}{dy})}$$

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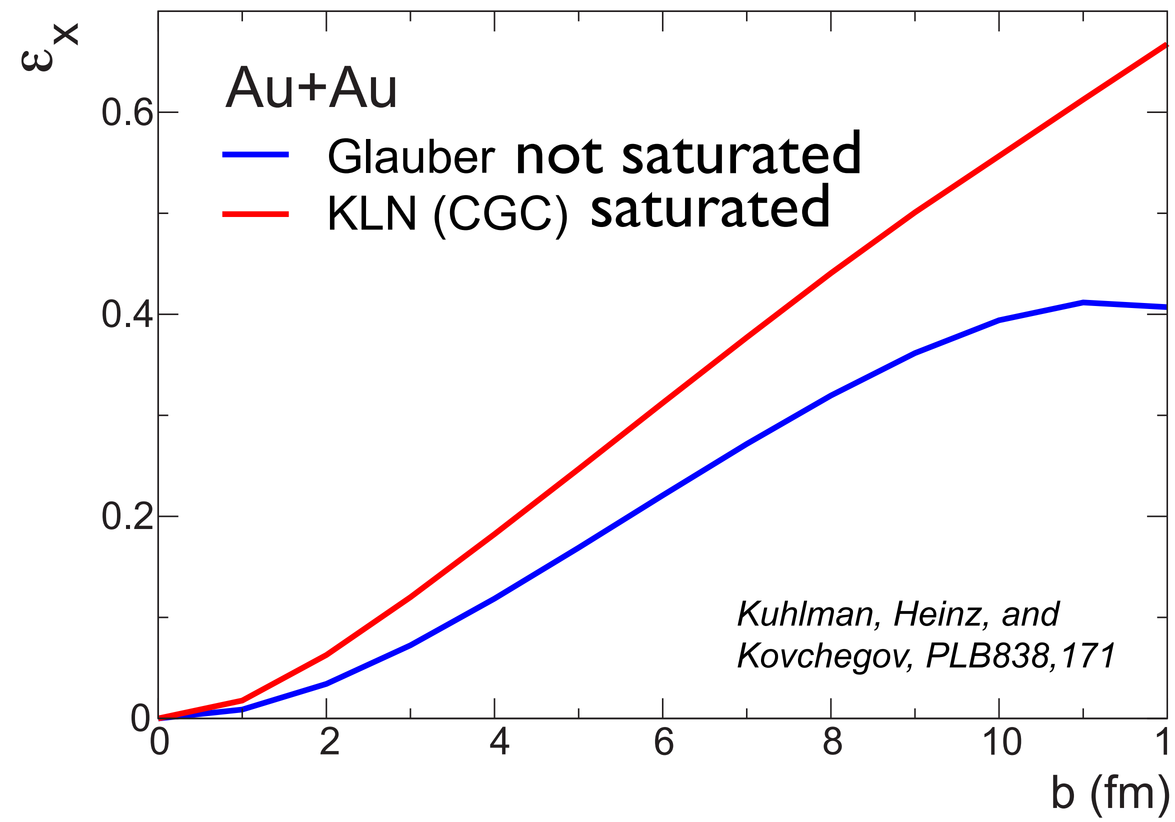

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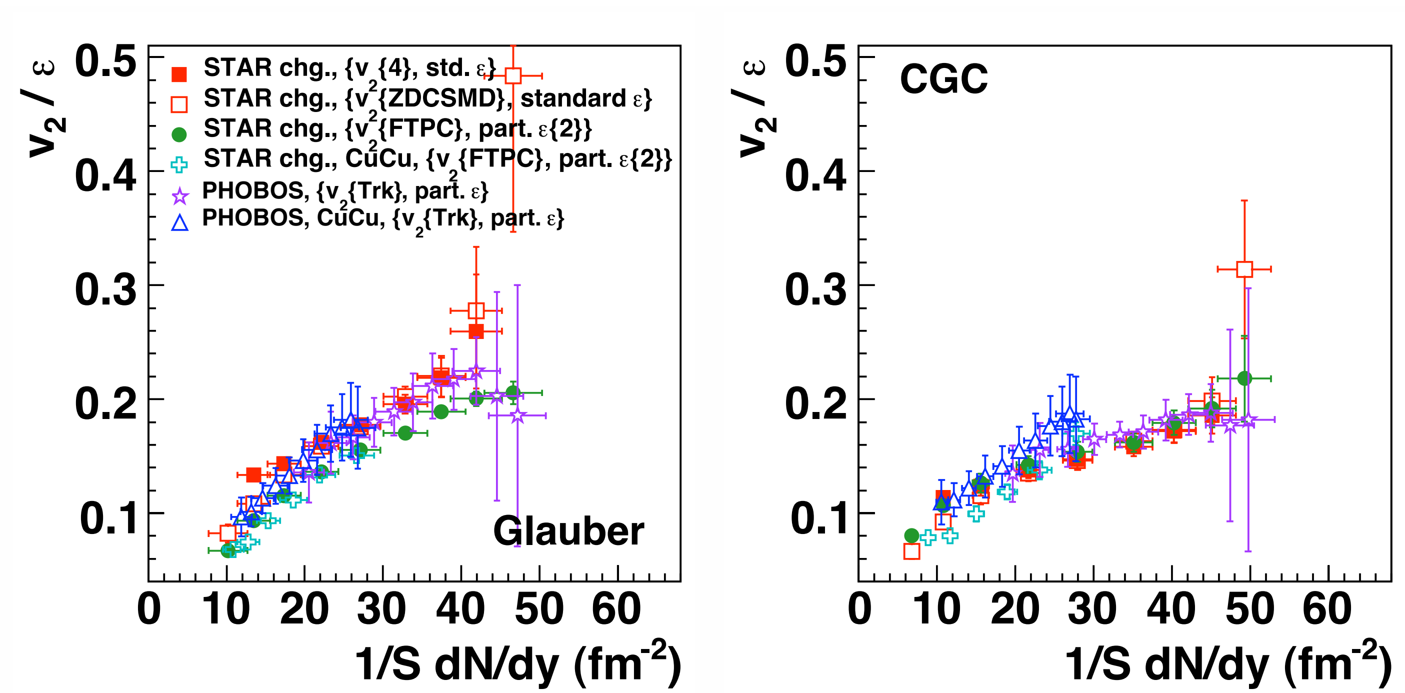

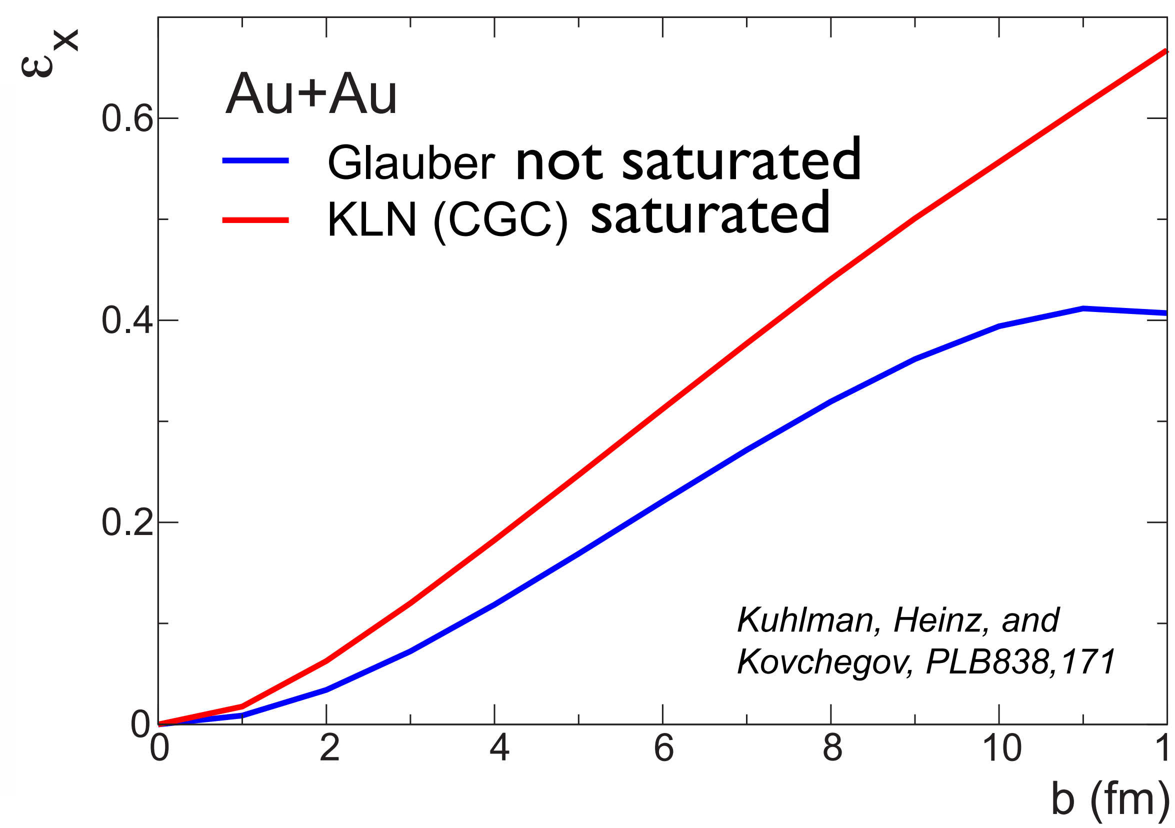

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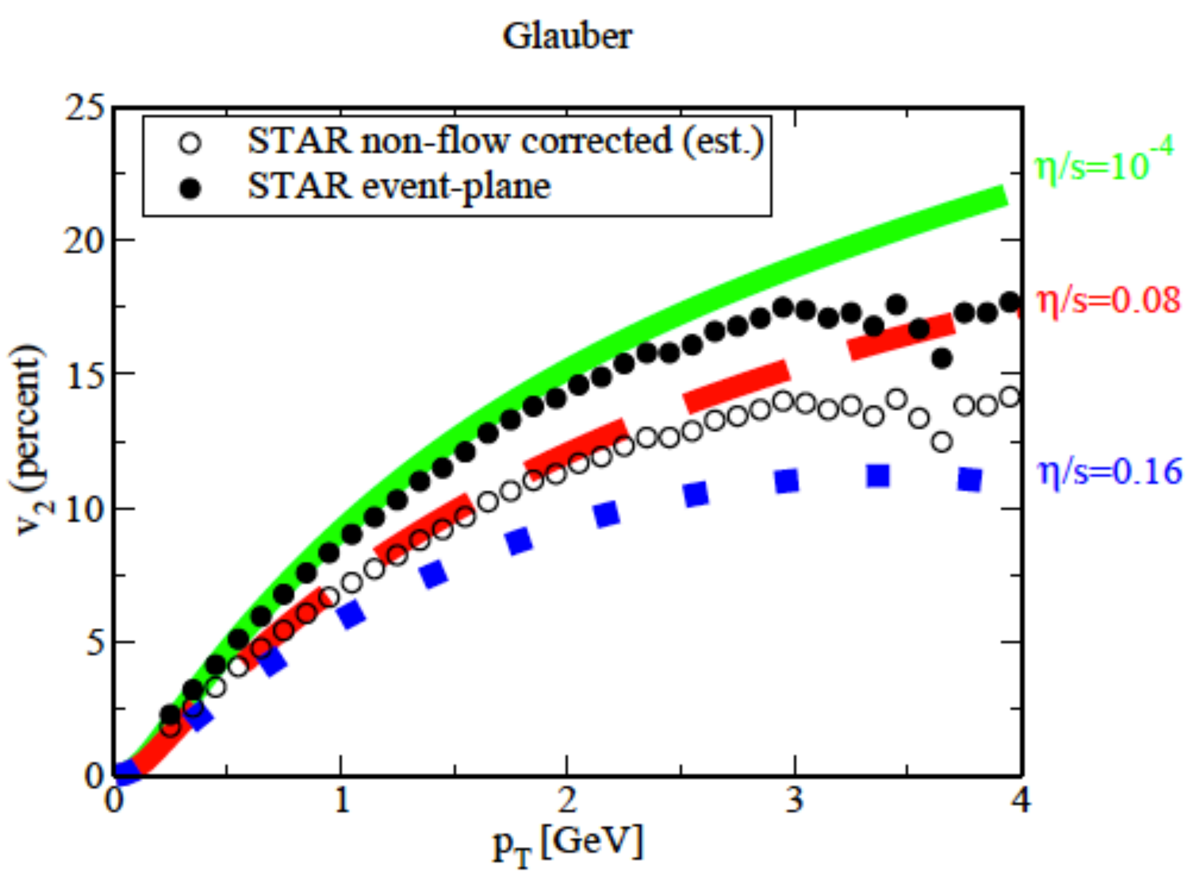

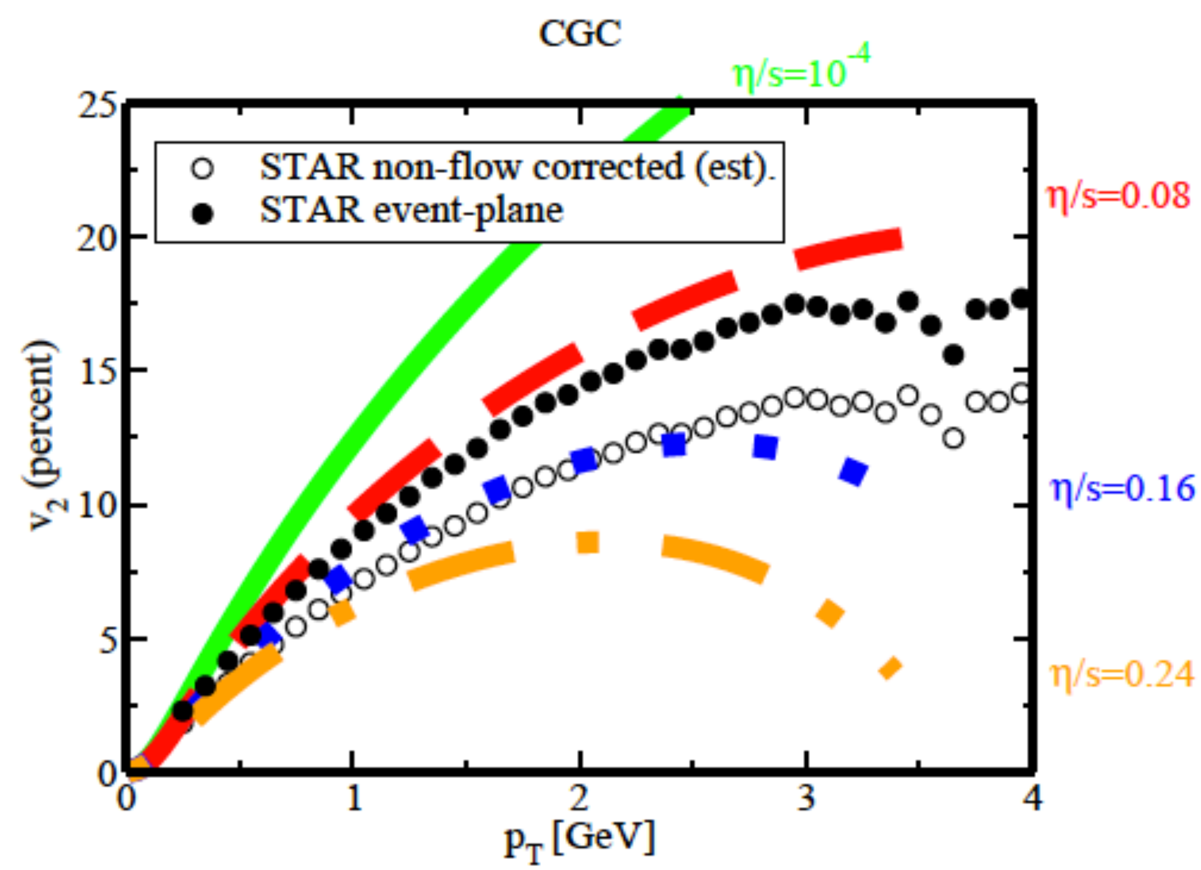

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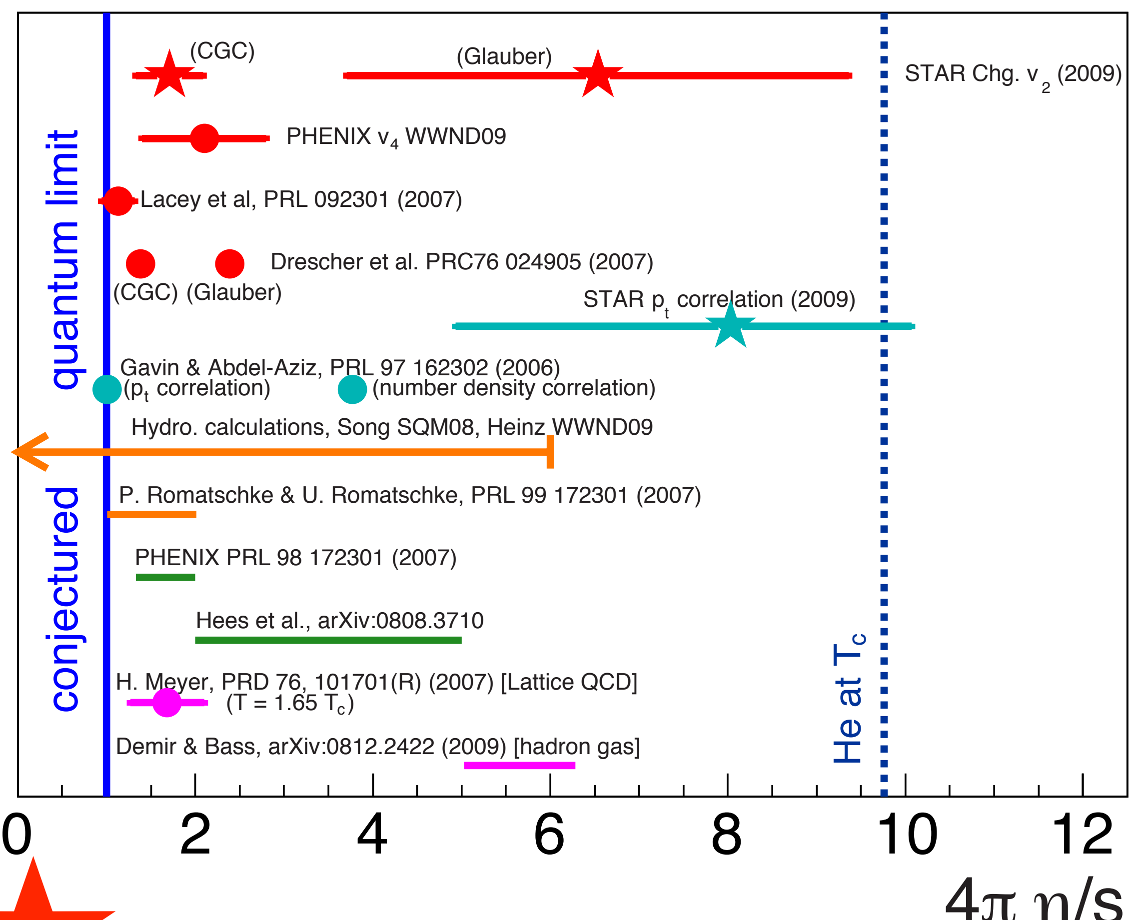
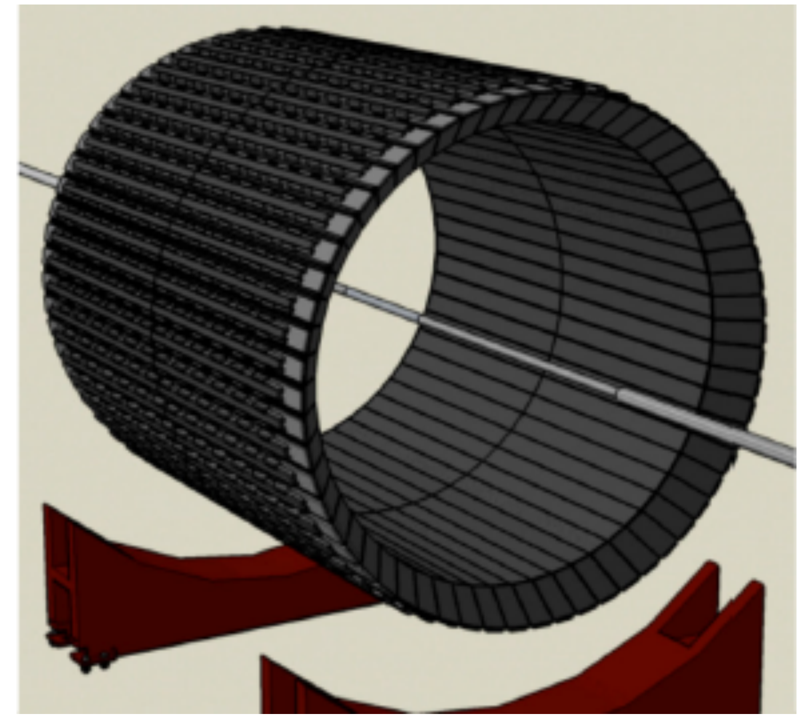


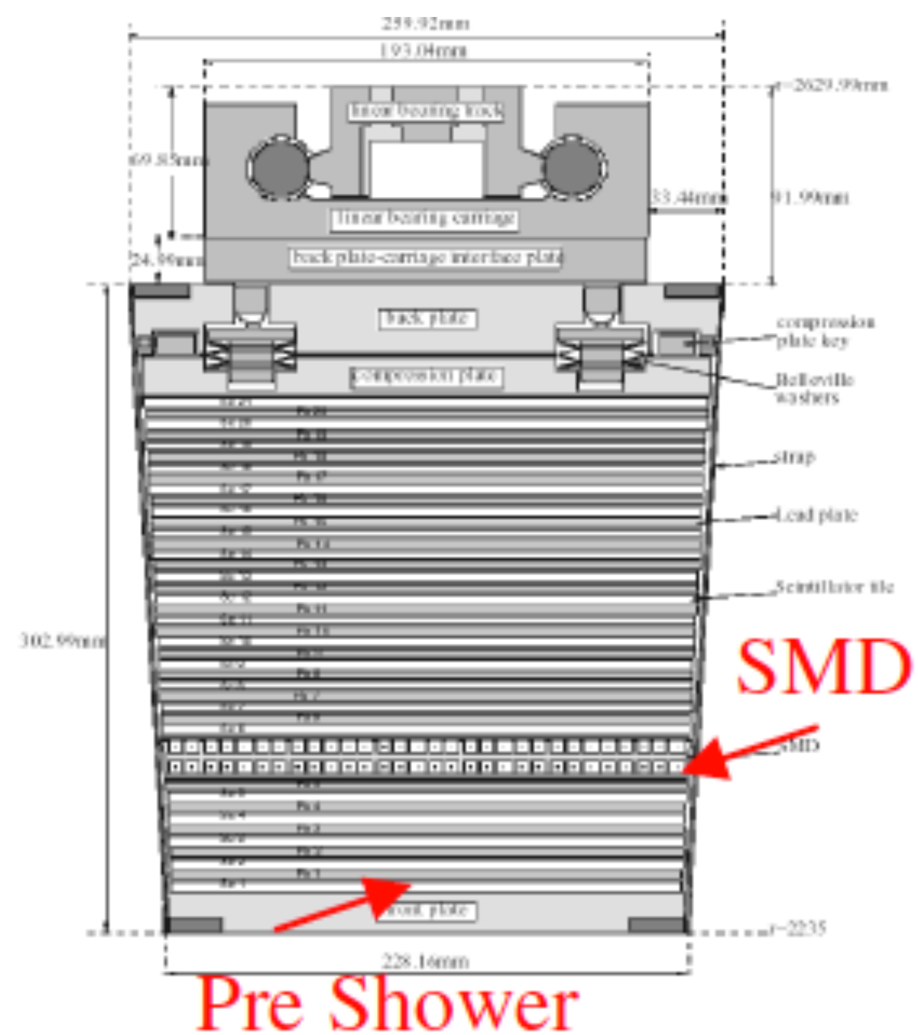
- η/s well below superfluid He for all models
- Can’t yet distinguish between initial conditions - need e+A at an EIC !

Calorimeters

Barrel EMC

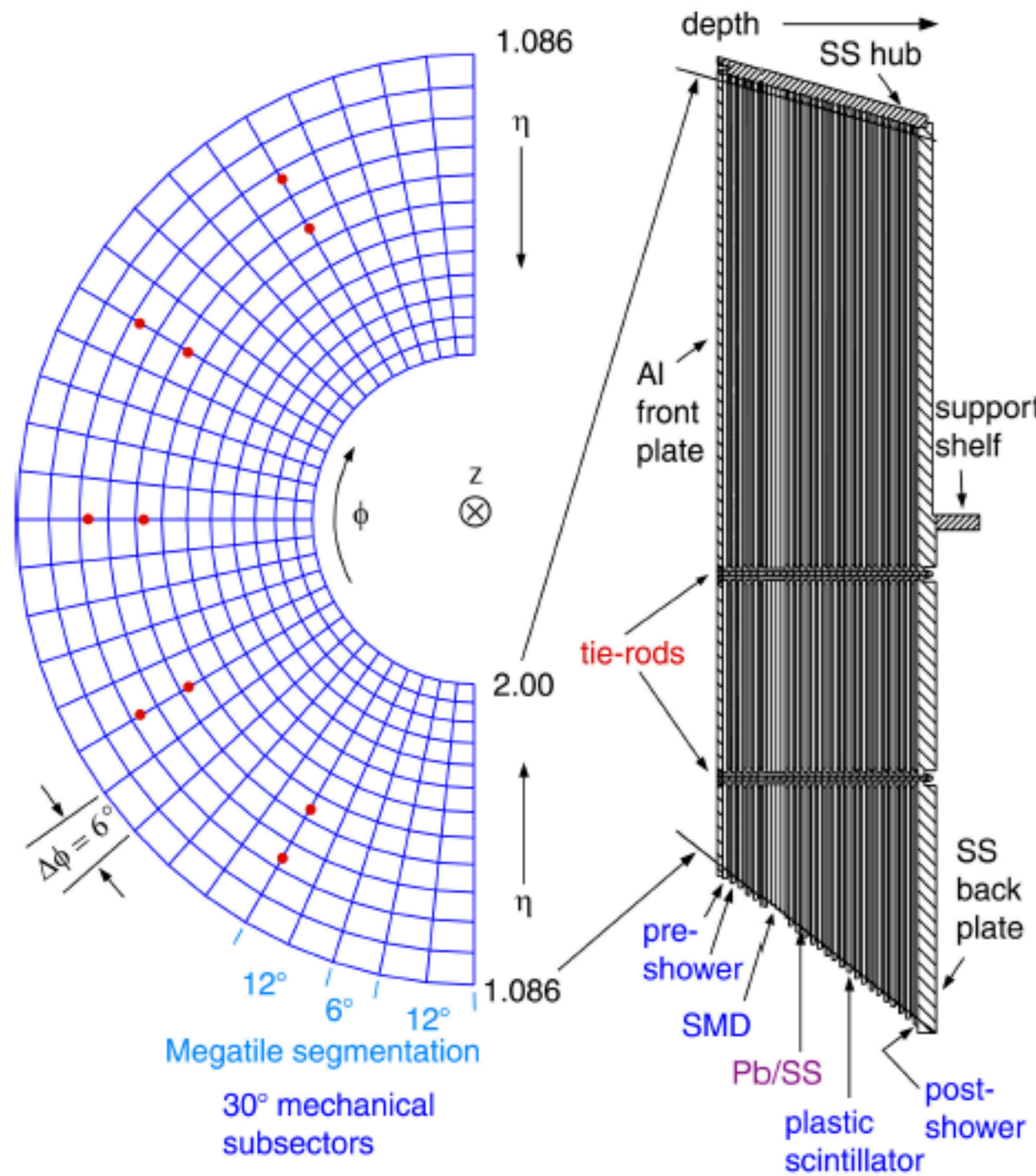
- 120 modules Pb/plastic sampling calorimeter
  - Coverage: $-1 < \eta < 1$;
  - $dE/E \sim 14\%/\sqrt{E}$
- 4.8k towers (40/module), 36k SMD strips, 4.8k preshowers
- $(\Delta\eta,\Delta\phi)$:
  - module: $\sim (1.0, 0.1)$; depth = 21 X_0
  - tower: $\sim (0.05, 0.05)$
- SMD at a depth 5 X_0:
  - $(\Delta\eta,\Delta\phi) \sim (0.007, 0.007)$
- Preshower: first 2 scintillator layers (depth 2 X_0)





Endcap EMC

- Mounted on the inside of the west magnet poletip (~2.7m from nominal interaction point)
- Same technology as BEMC
  - Coverage: $1 < \eta < 2$;
  - $dE/E \sim 16\%/\sqrt{E}$
  - 23 layers Pb/SS laminate
- 720 projective towers (24 layers)
  - 6^o and 12^o megatile: ~ 100% coverage
  - $(\Delta\eta,\Delta\phi)$ tower ~ (0.057-0.099,0.01):
- Depth segmentation:
  - 2 separate pre-shower layers
  - high position resolution SMD at 5 X0
    - 6912 triangular-shaped scint strips; base 10mm, height 7mm
    - "u", "v" stereo planes in 30^o sectors w/ overlap
- Postshower 24^{th} layer



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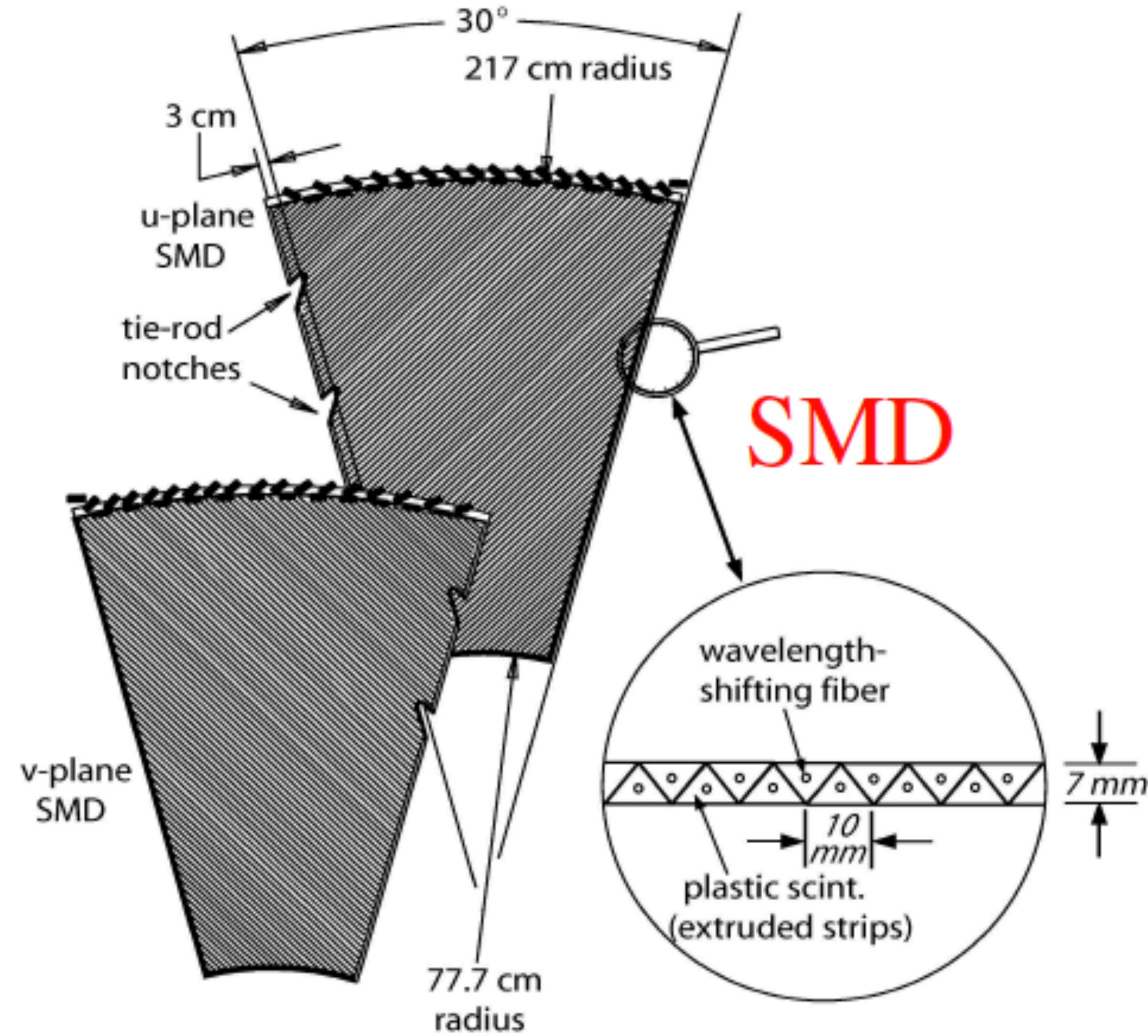
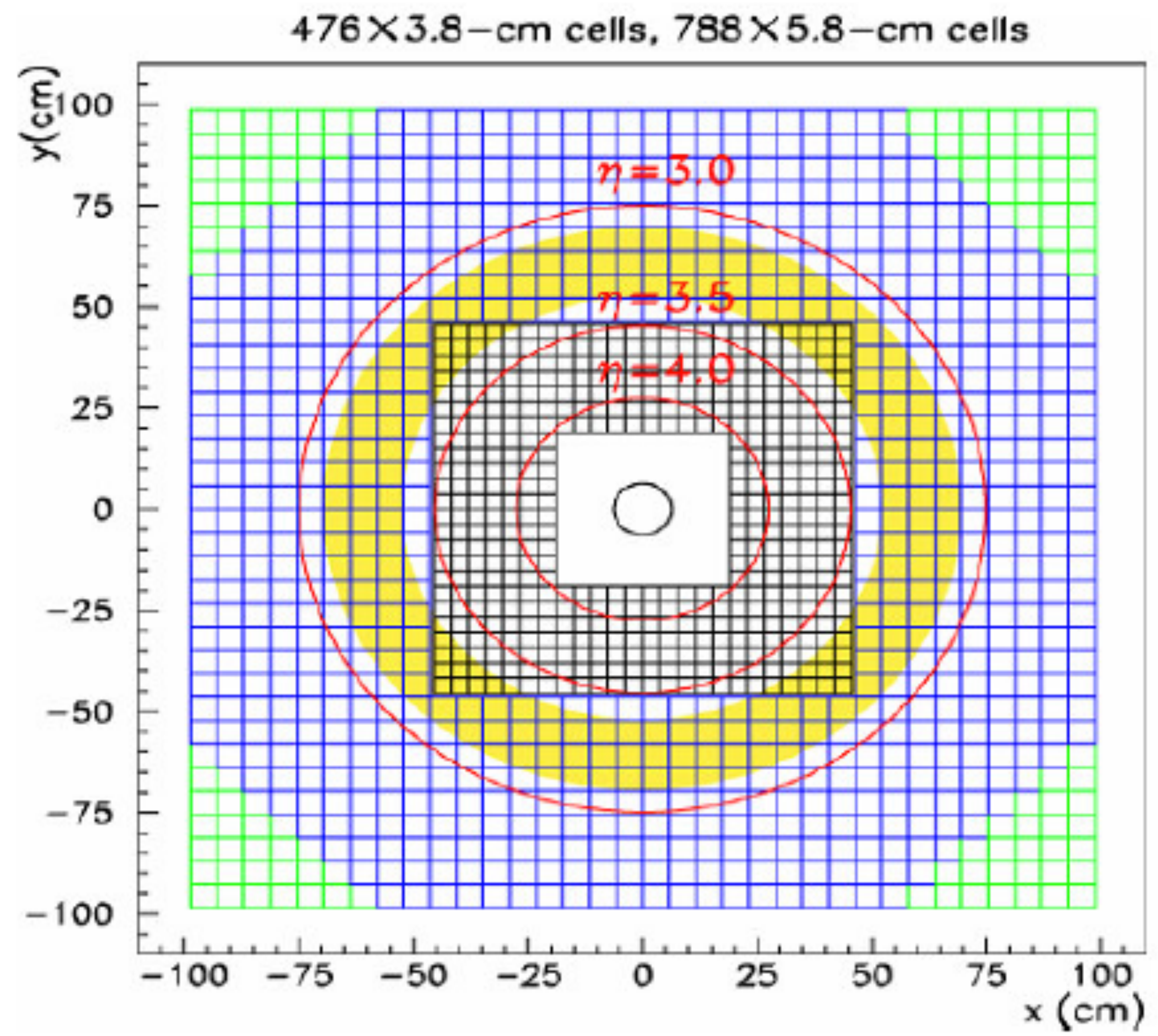


Forward Meson Spectrometer

- Hermetic EMC with finely segmented Pb-glass detectors
- Mixture of re-cycled parts from E831(FNAL), IHEP and JLAB
  - A very green detector!
- 7.5 m west of the interaction point in STAR
  - 2 m square, 1264 cell Pb-glass array
  - small cells (476 total):
    - 3.8 cm square x 60.2 cm;
    - π^0/γ to 60 GeV
  - large cells (788 total):
    - 5.8 cm square x 45 cm;
    - π^0/γ to 40 GeV



SPACAL

- Tungsten powder used as absorber
  - Particle size distribution 90% between 40 and 150 microns
  - Bulk density: 18.5 g/cm3
  - Tap densityL 11.25 g/cm3
  - Chemical composition:
    - W > 99.3%
    - Fe < 0.05%, Ni < 0.05%, O_2 < 0.5% Others (Co, Mo, Cu, Cr)
- Fast and cheap
- Can get as low as $6\%/\sqrt{E}$

SPACAL

W/ScFi

SPACORDION

Wiggled fibers
Tower made from few sub–assemblies
Bundled fibers

SPACAL

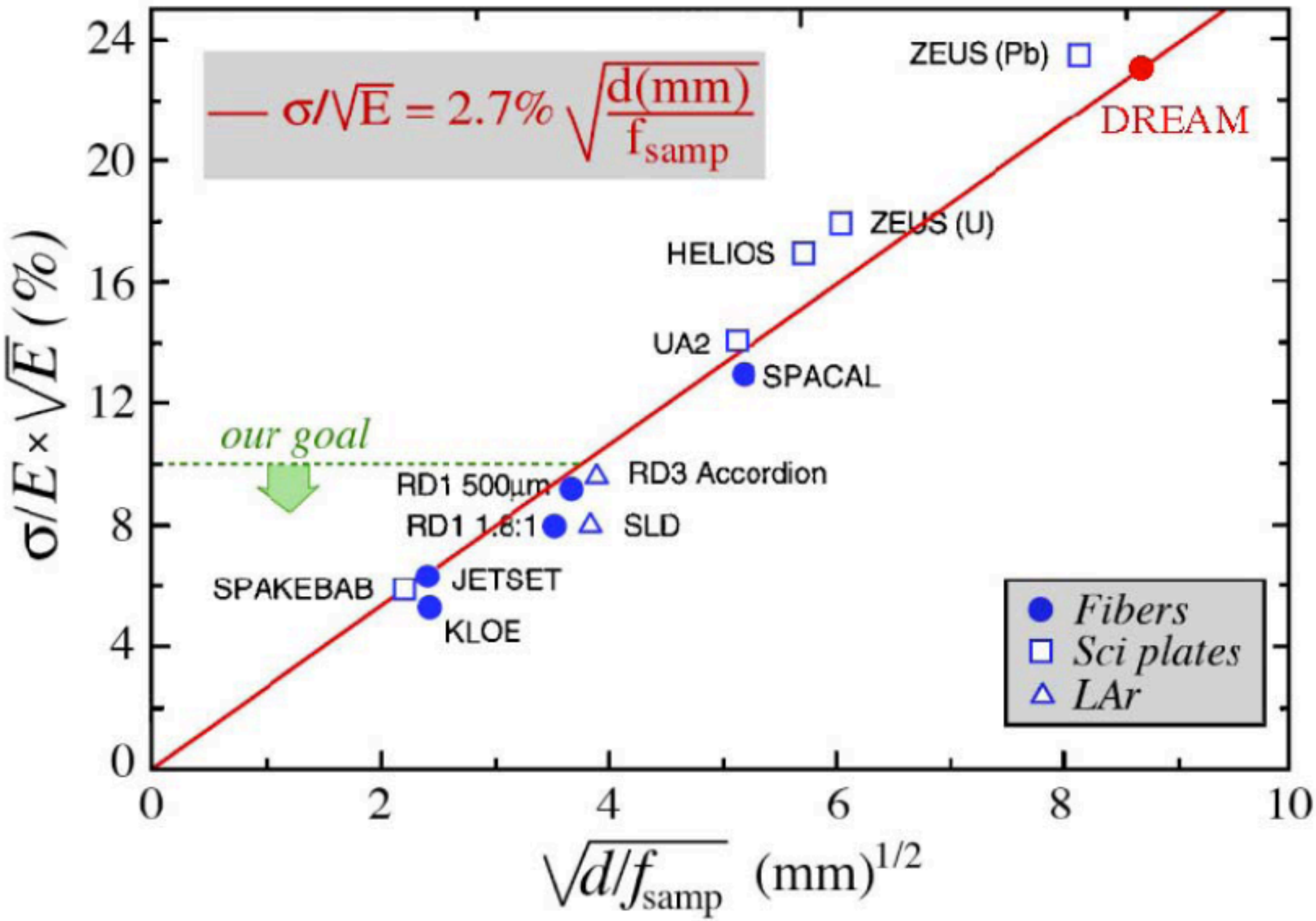
Straight Fibers
Two towers made at once.
Non–bundled fibers.

Ver. 2004	Ver. 2011	Ver. 2011
Two sub–assemblies Light guide to match APD (4.9 mm x 4.9 mm) W powder ("PLUS") Mirror glued with BC600 Optical coupling GE silicone	Four sub–assemblies No Light guide 14 mm x 14 mm W powder ("ULTRA") Mirror glued (Silgard 184 Optical coupling BC–630	Four towers readout by a single PMT Long light guide with mirror pipe. Mirror will be sputteredby FNAL Optical coupling BC–630 W powder ("ULTRA")

Perforated meshes 0.88 mm center to center,
BCF 12 fibers, 0.33 mm diameter.

Precision meshes by PHOTOFAB 1mm
center to center. KURARAY SCFS –78,
0.47 mm diameter.

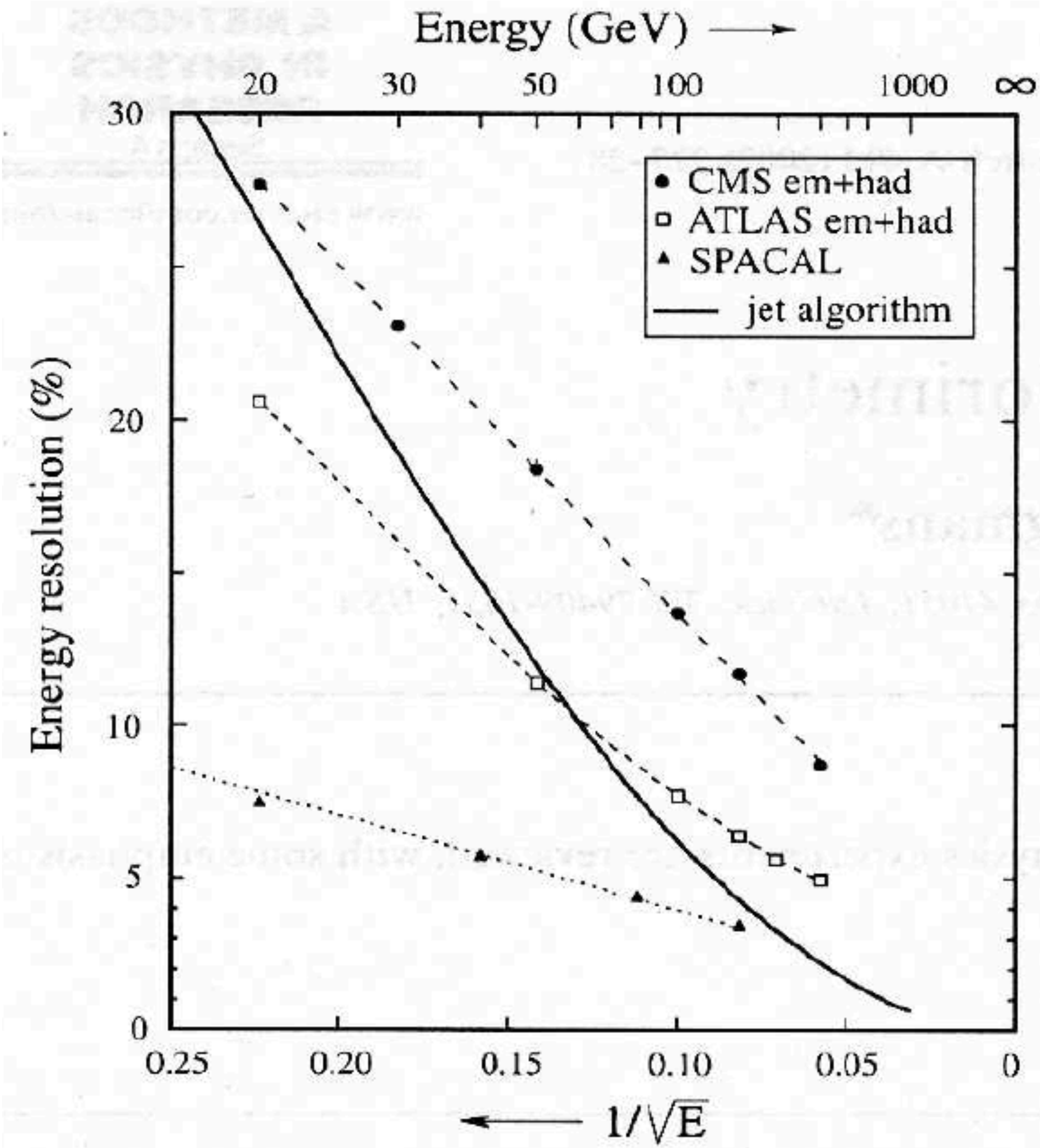
SPACAL



— σ/√E = 2.7% √(d(mm)/f_samp)
ZEUS (Pb)
DREAM
ZEUS (U)
HELIOS
UA2
SPACAL
our goal
RD3 Accordion
RD1 500μm
RD1 1.6:1
SLD
SPAKEBAB
JETSET
KLOE
Fibers
Sci plates
LAr
σ/E × √E (%)
√(d/f_samp) (mm)^1/2
0
4
8
12
16
20
24
0
2
4
6
8
10

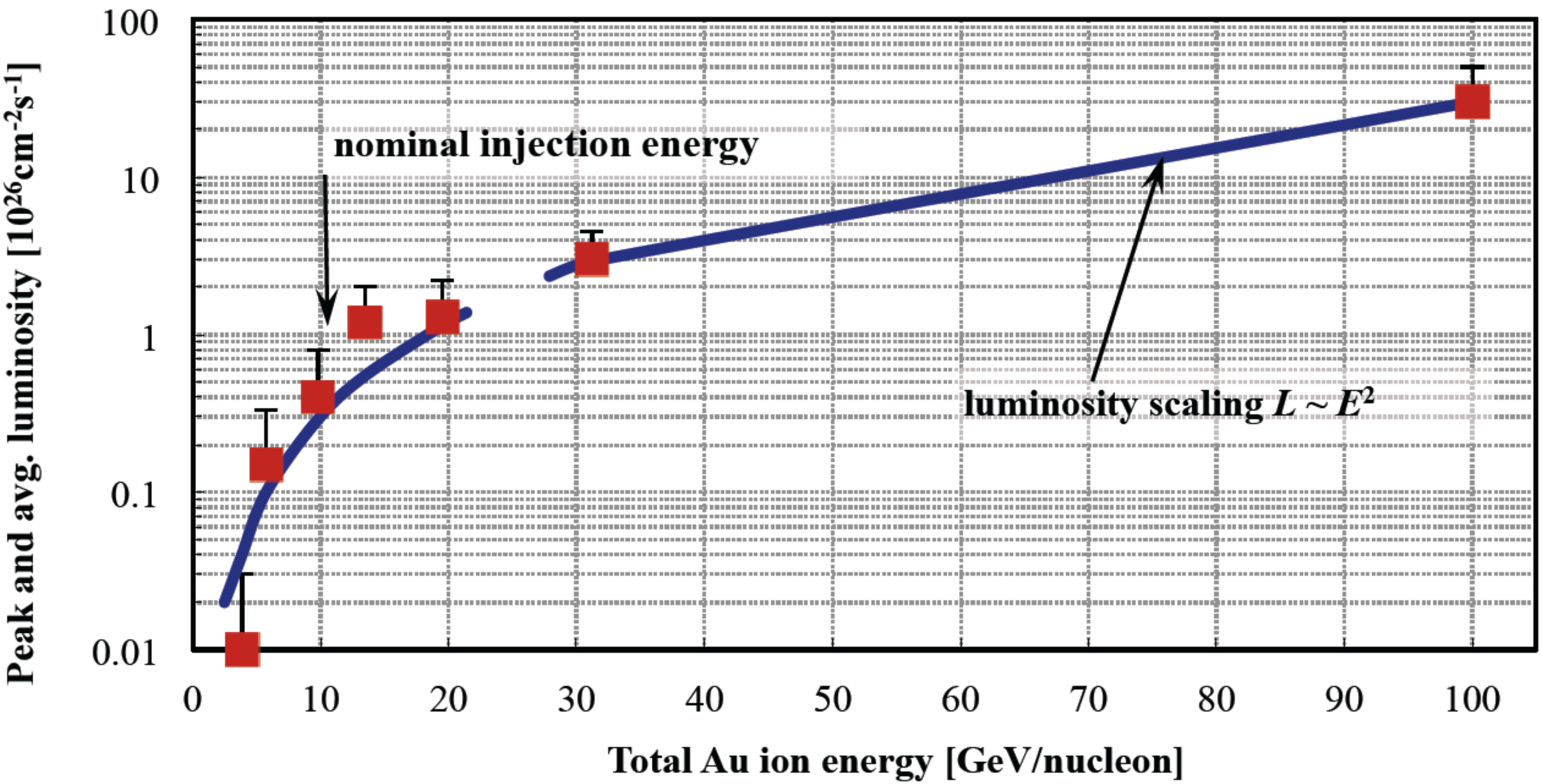
SPACAL

- Trade-off between EM and hadronic calorimeters
  - ZEUS: high-resolution hadronic calorimeter → 18%/√E EMCal
  - Small sampling fraction → large sampling fluctuations

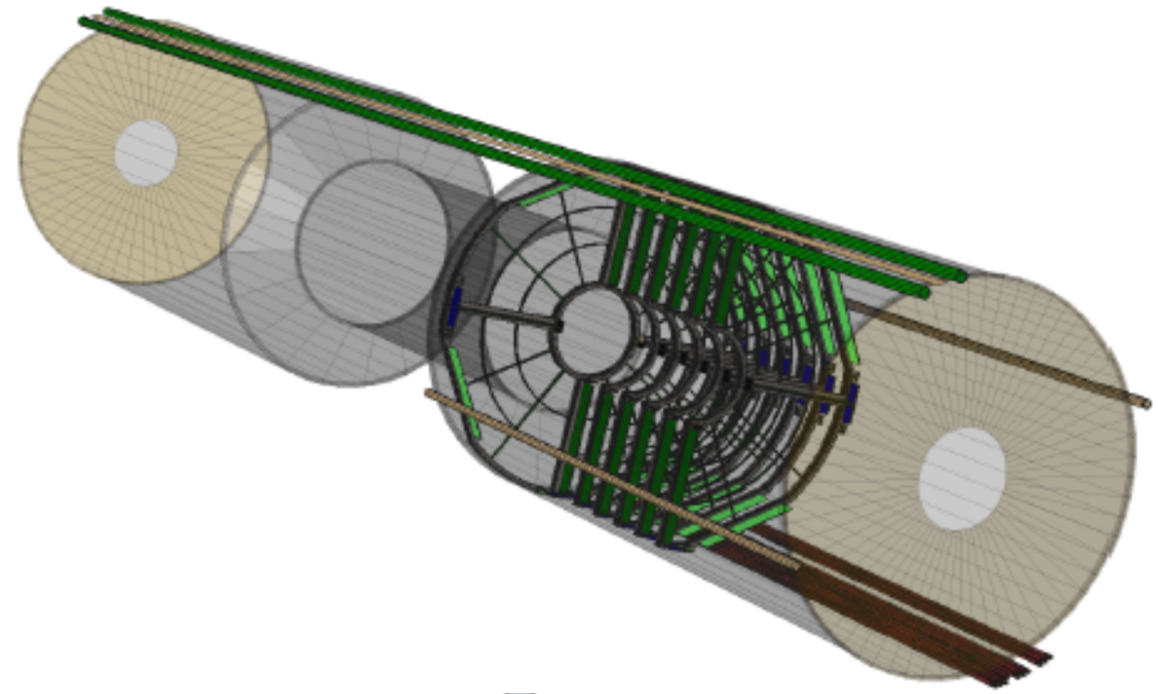


Miscellaneous

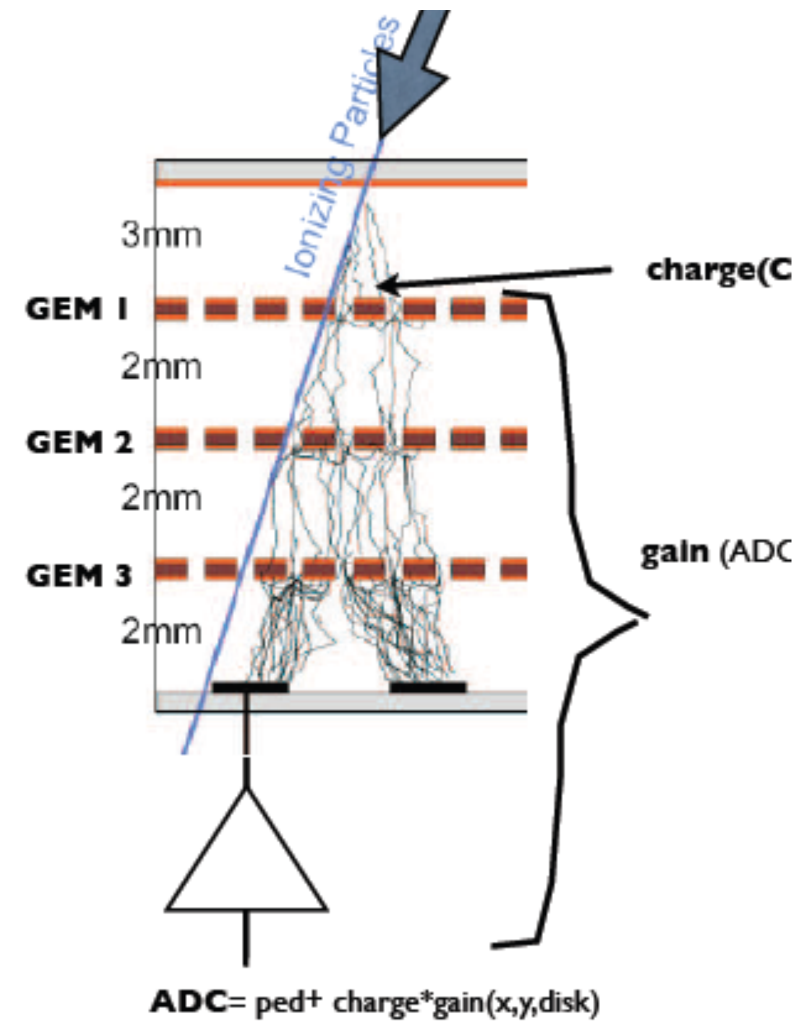
RHIC luminosity vs energy



Forward GEM Tracker

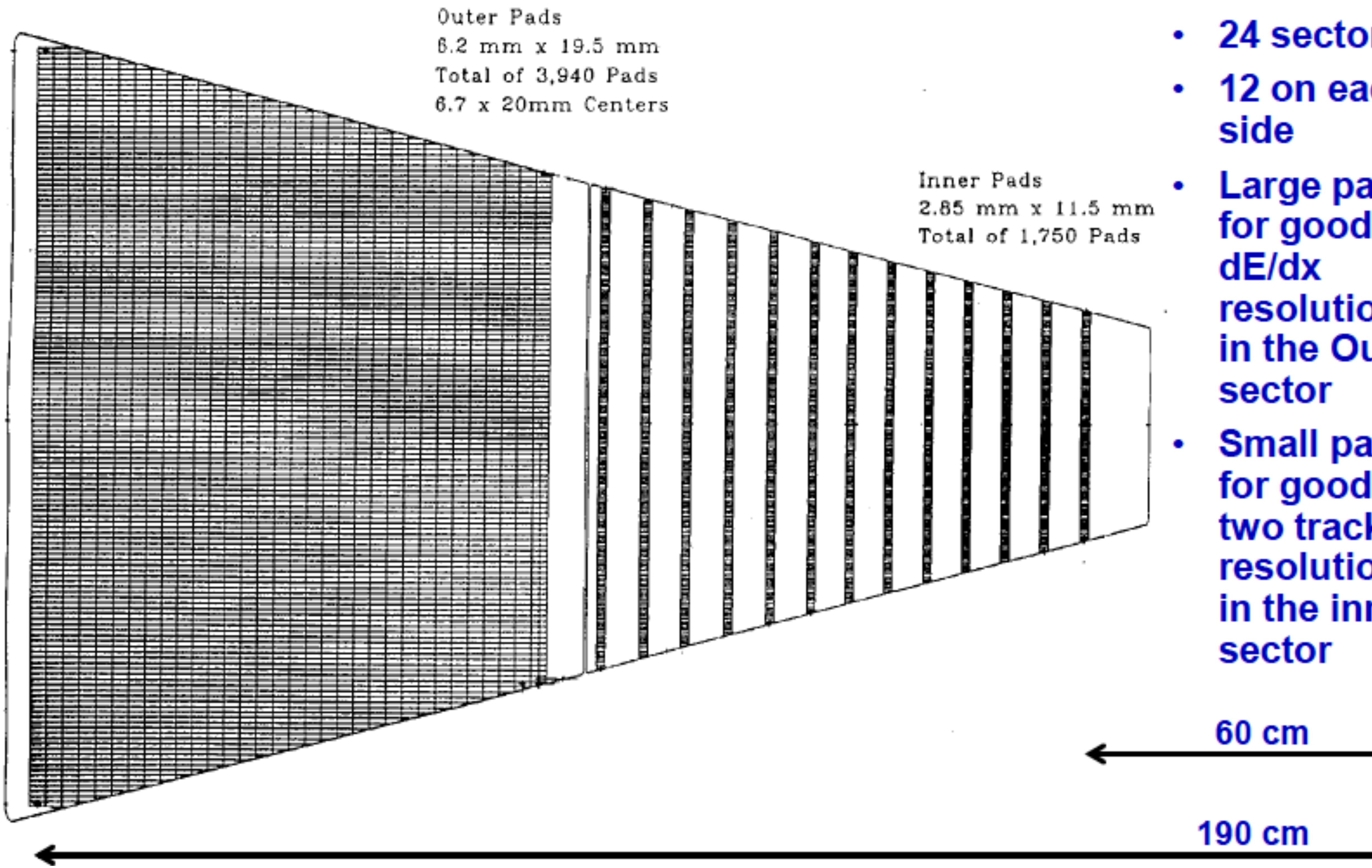


- Small Business Innovative Research (DOE) funded programme (~ $850K)
  - Collaborative effort between Tech-Etch Inc., BNL, MIT and Yale
- Triple GEM Detector
- Coverage: $-1 < \eta < 2$
- Inner radius: 10.5 cm, outer radius: 39 cm
- GEM foils: Hole inner r: 50 μm, outer: 70 μm, 140 μm pitch
- Quoted resolutions in the proposal:
  - ~40 μm in phi (120 μm in R - inclined tracks) from simulations
  - Evaluate performance after this run
- FGT partially installed in current run (12)
  - 14 out of 24 quadrants installed



For more details, see B. Surrow, id:113

TPC Inner Sector



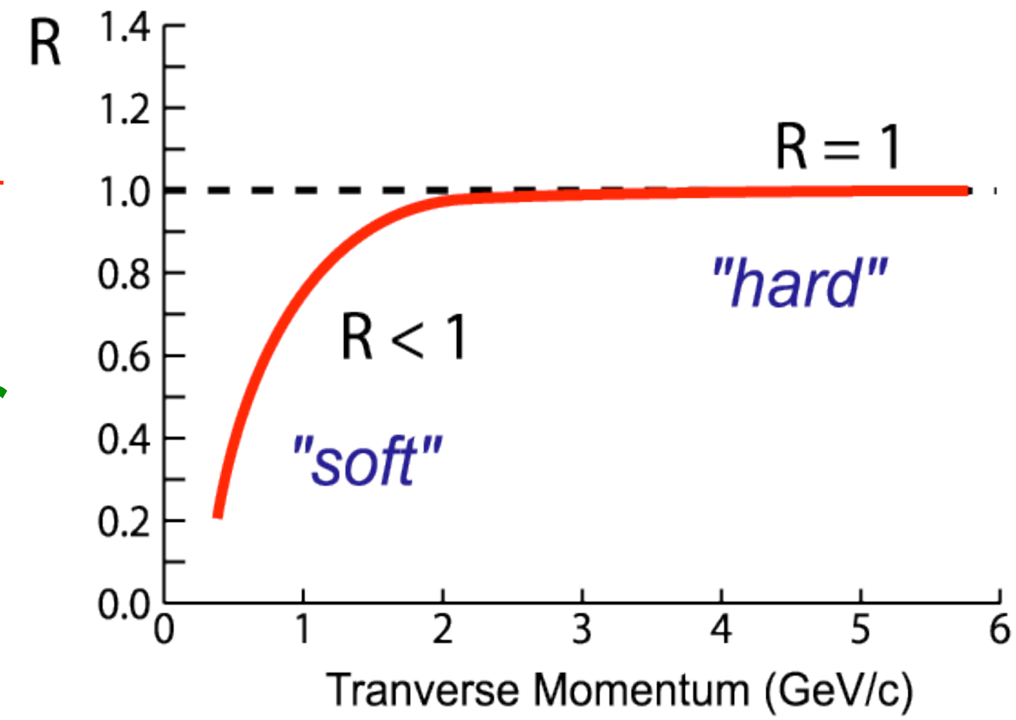
- 24 sectors
- 12 on each side
- Large pads for good dE/dx resolution in the Outer sector
- Small pads for good two track resolution in the inner sector

How to measure high-p_T processes

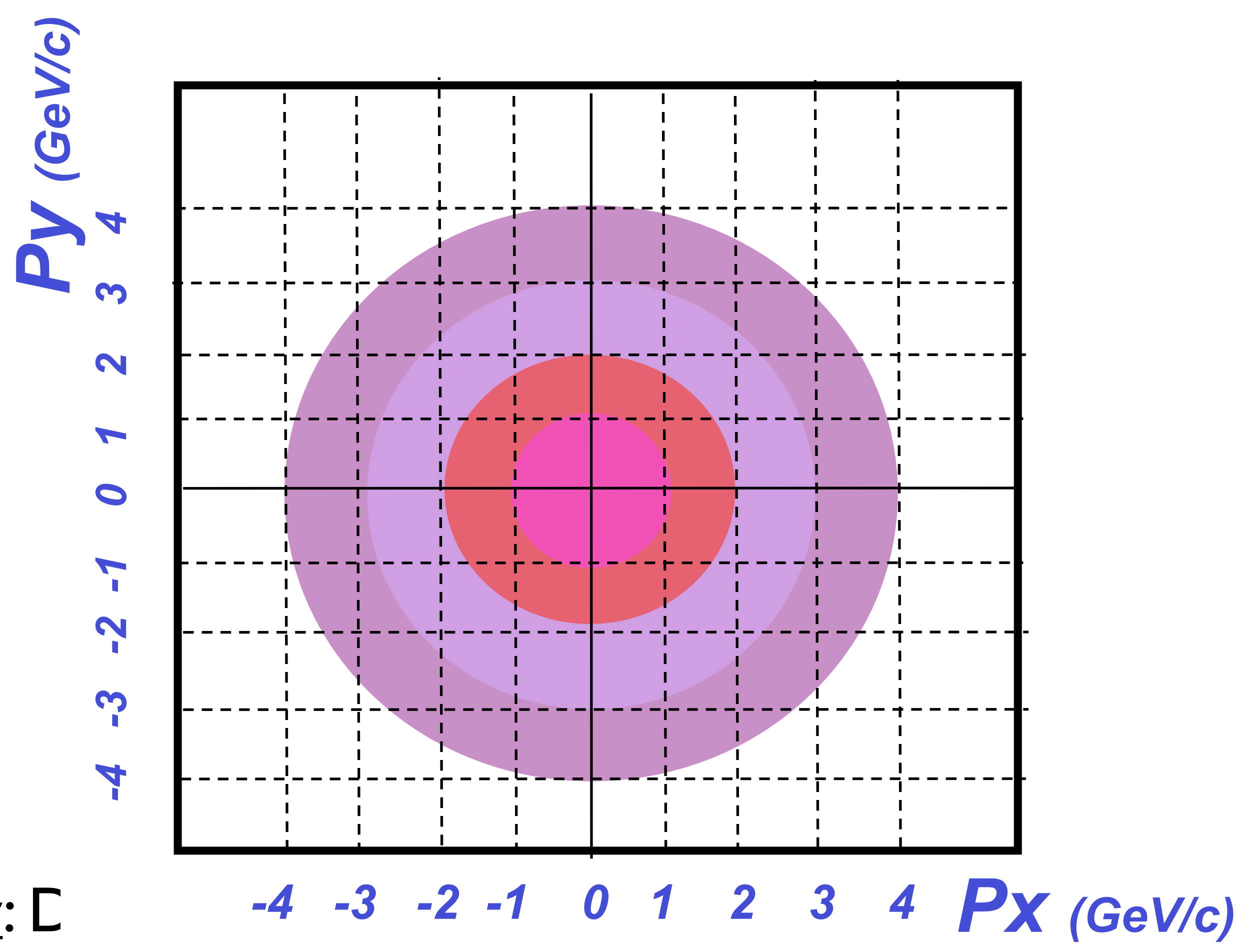
- Single particle spectra

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times < N_{coll} >}$$

$R_{AA}(p_T)$ = Nuclear Modification Factor



- 2-particle correlations



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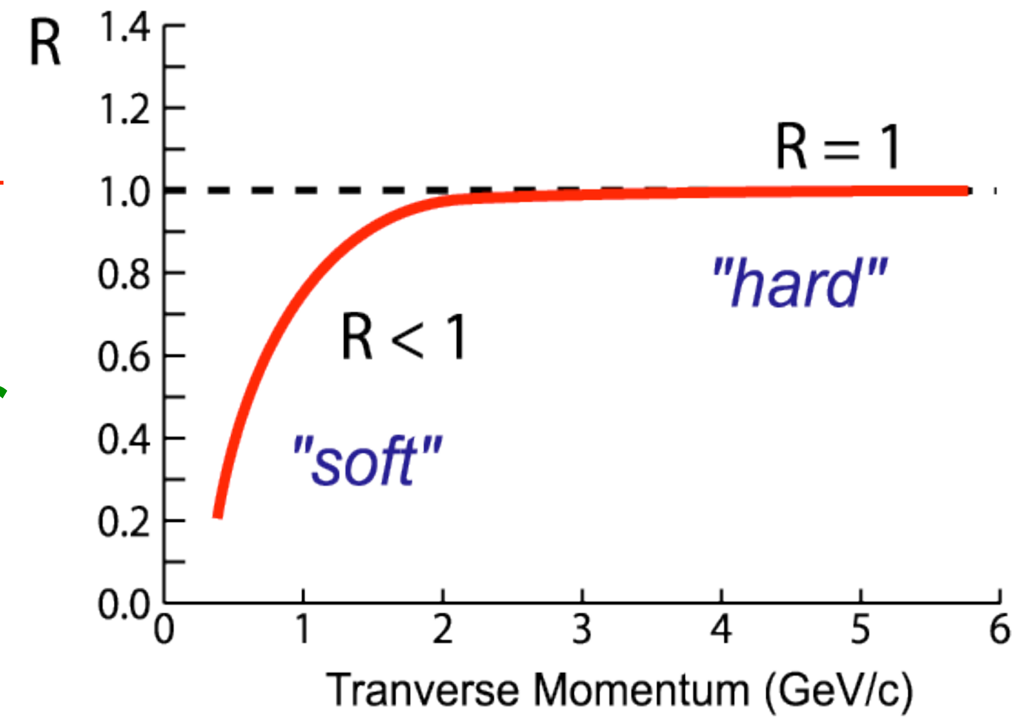

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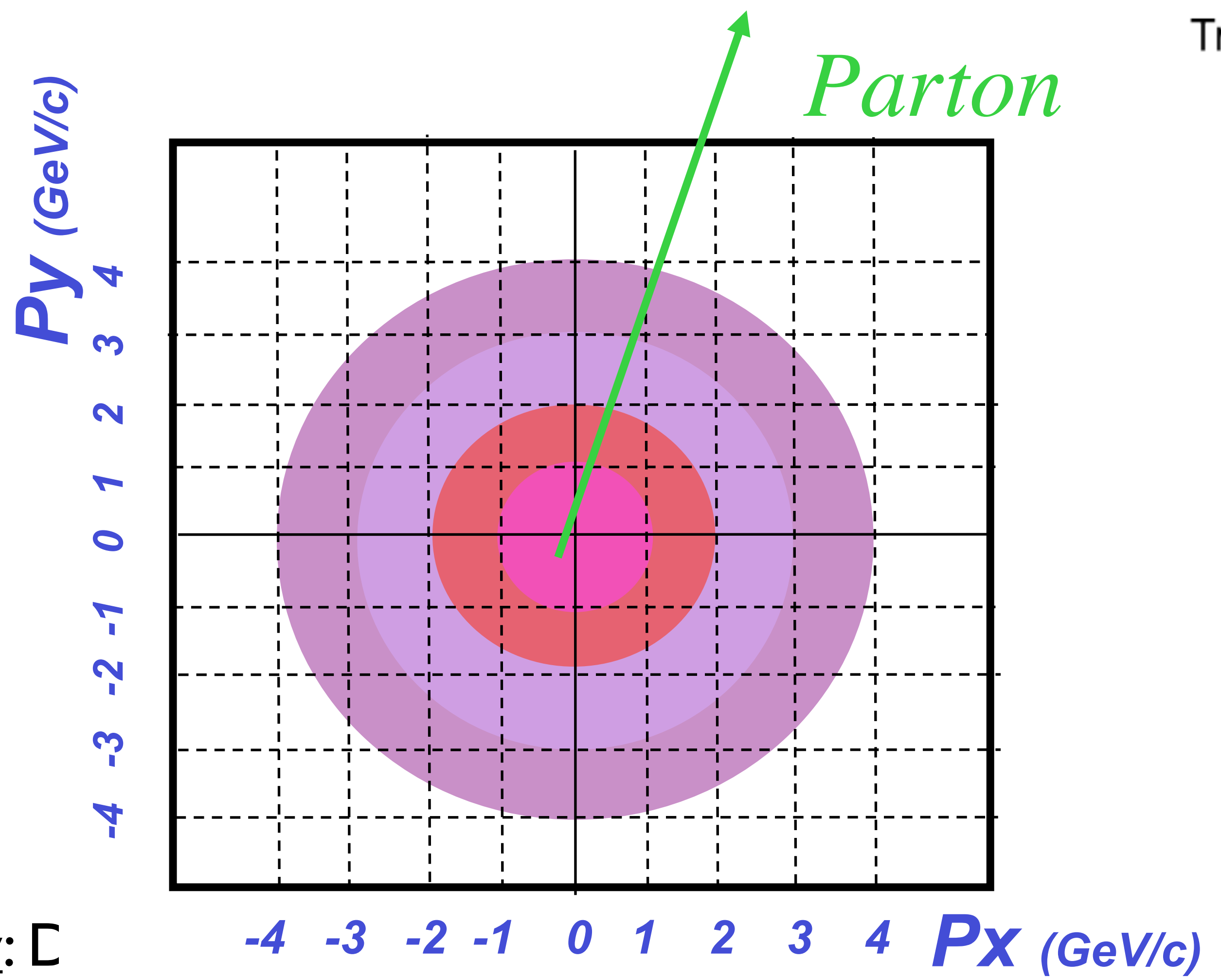

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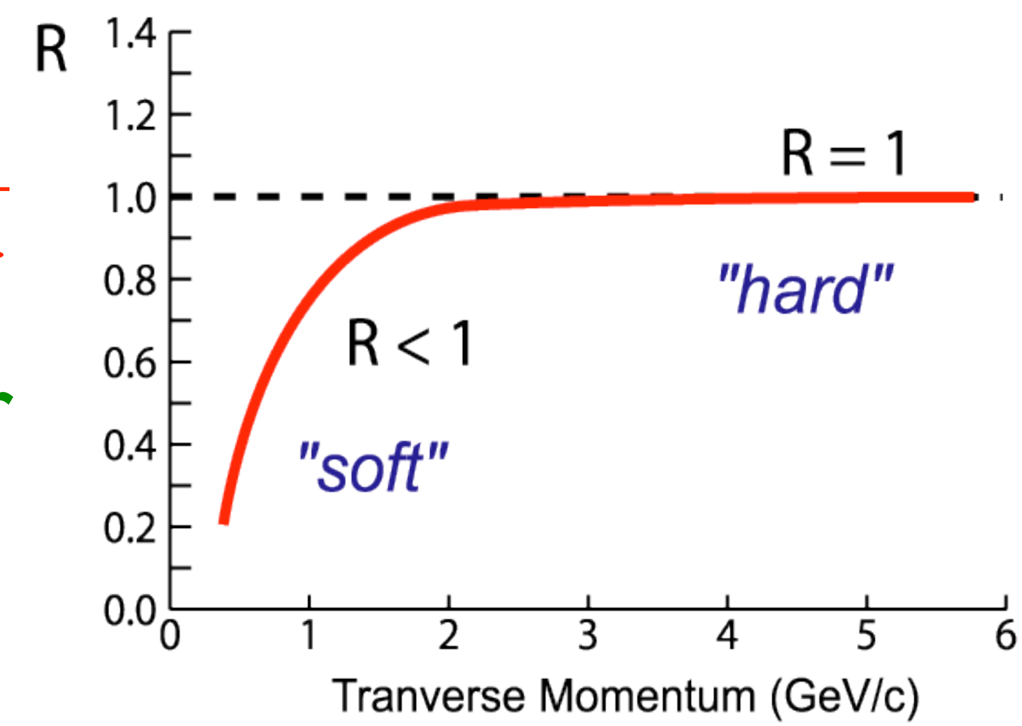

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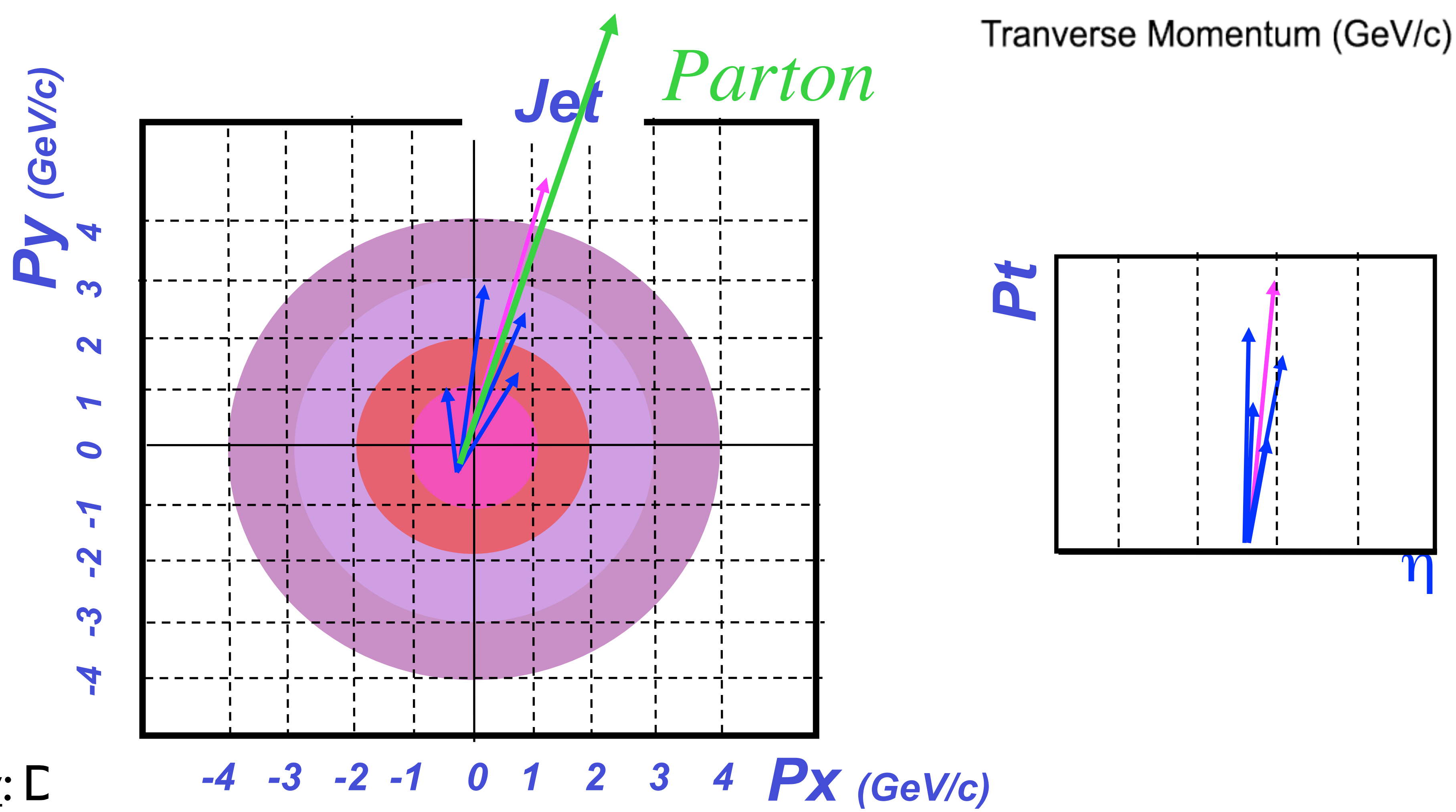

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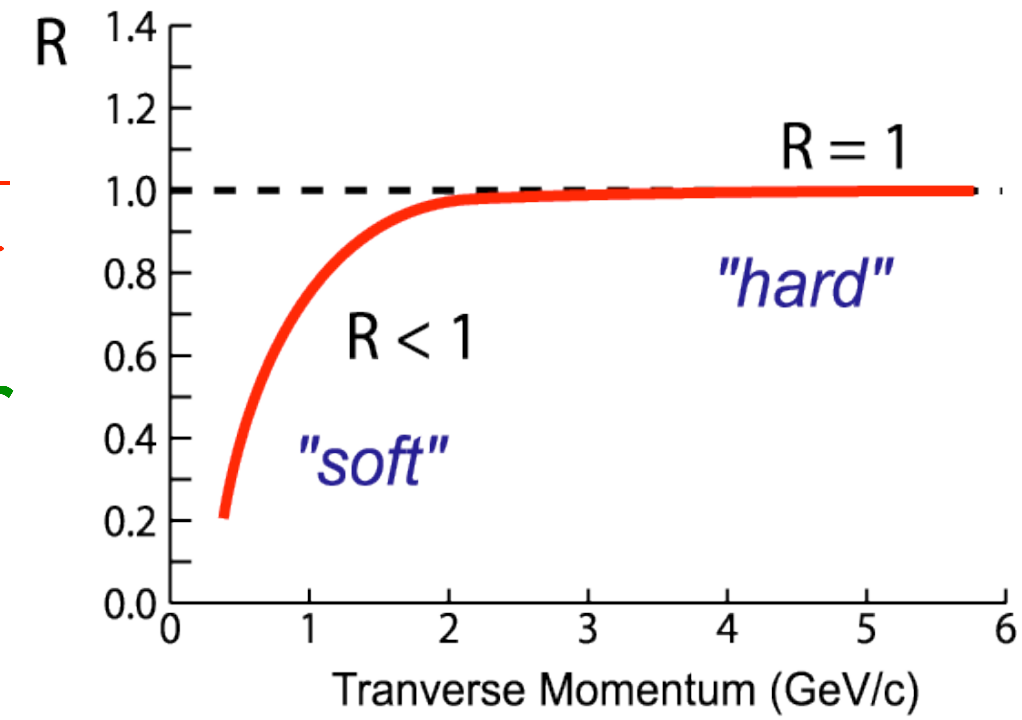

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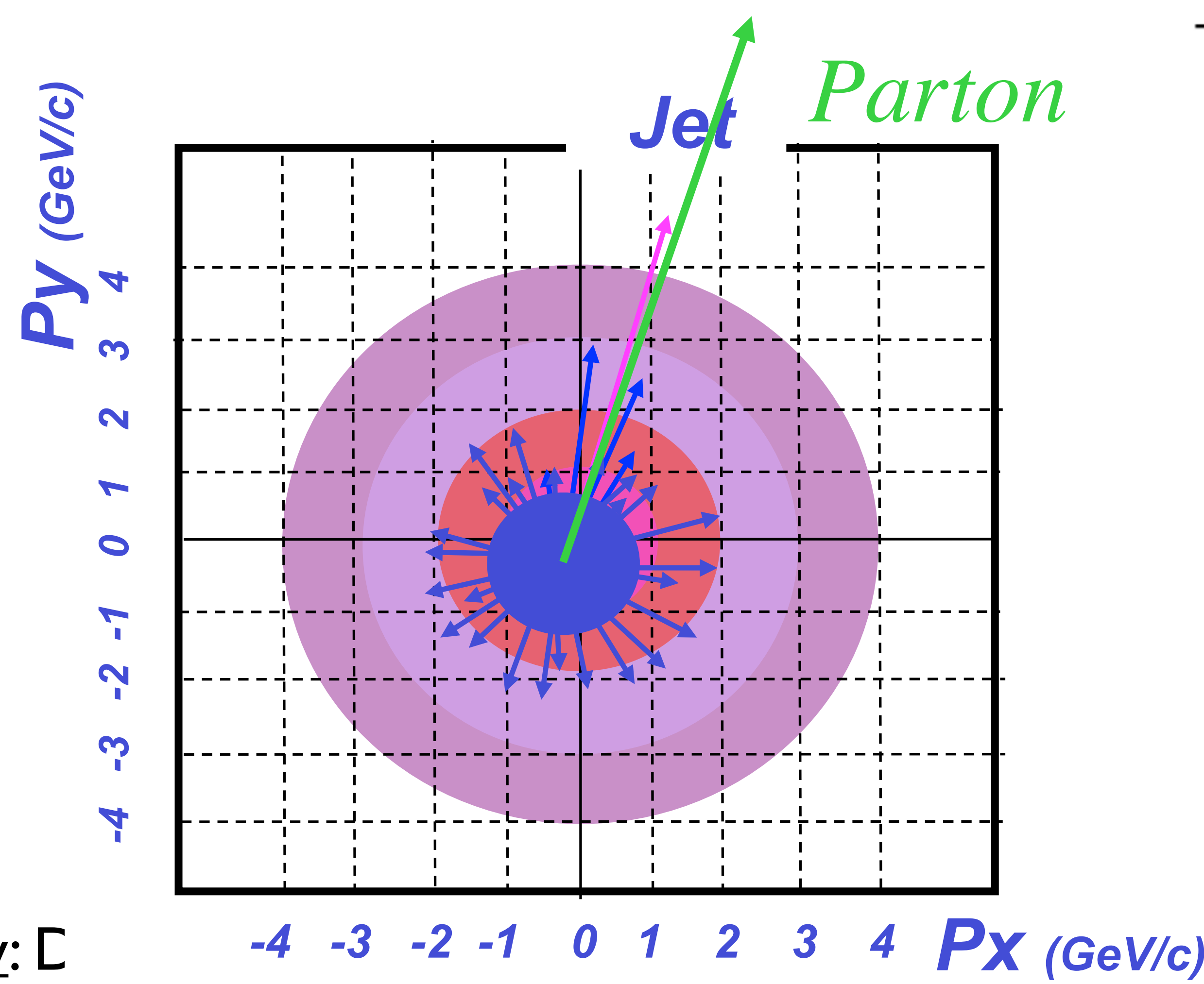

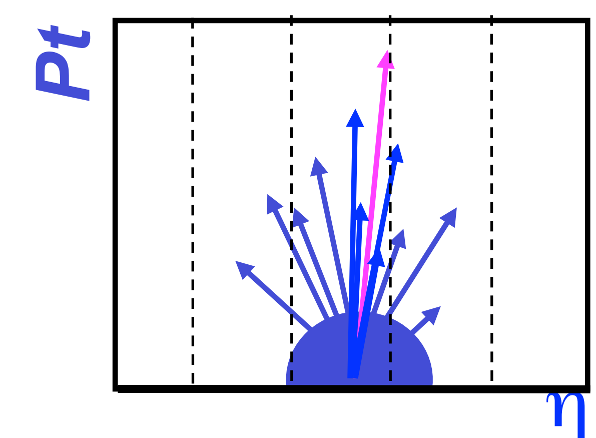

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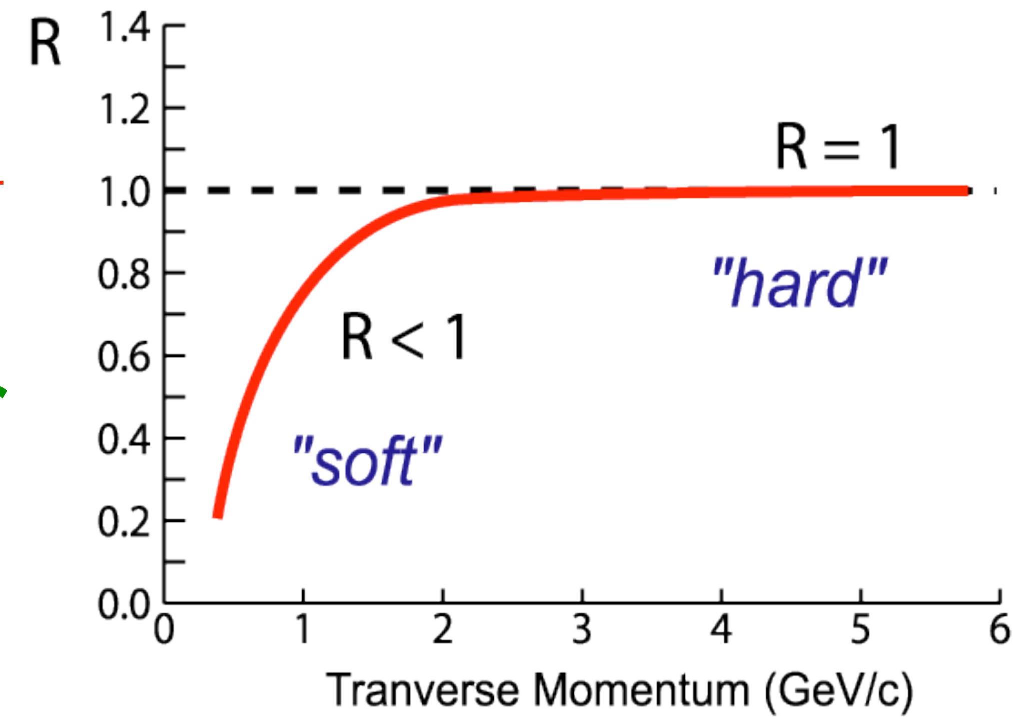

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