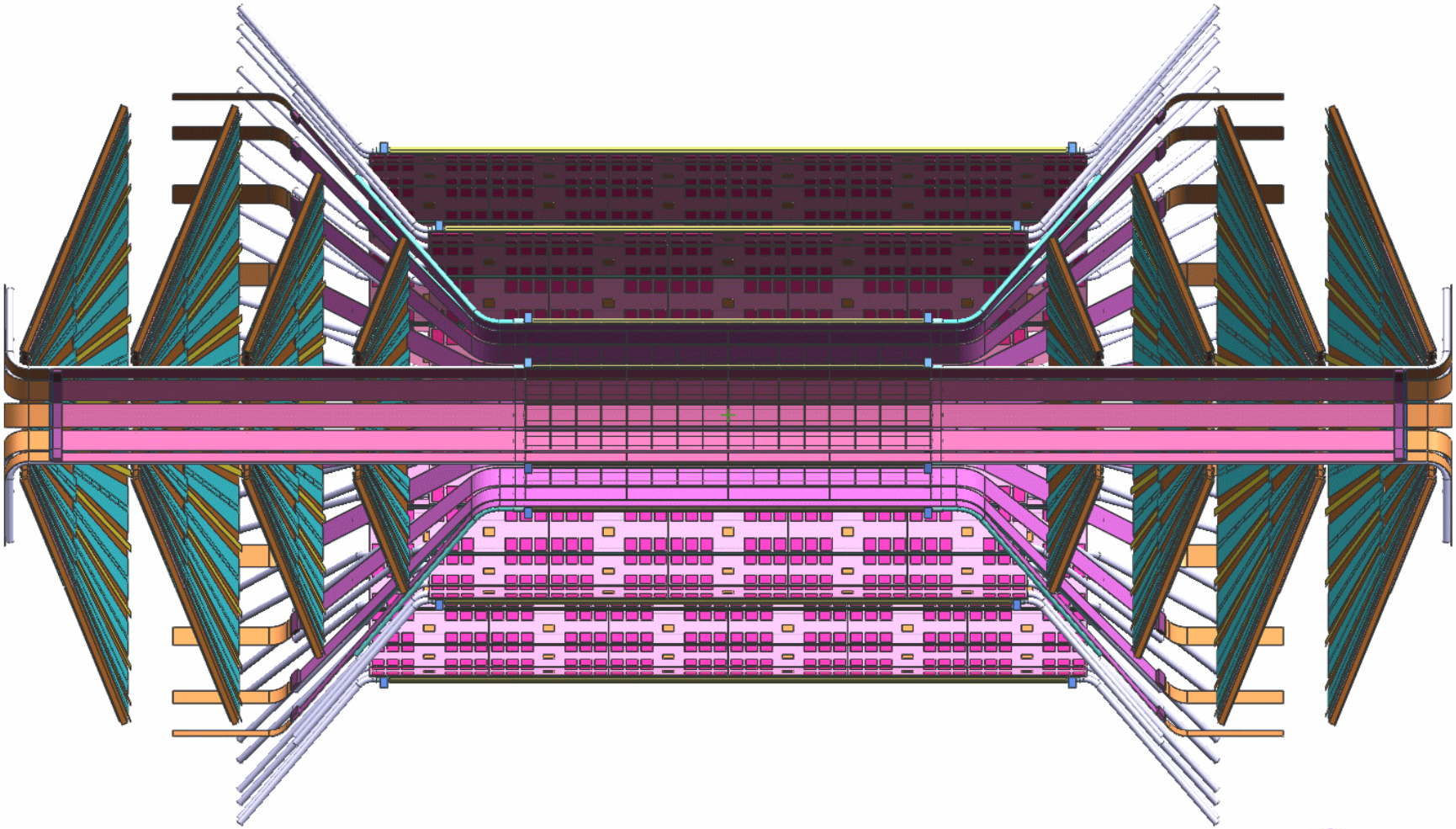
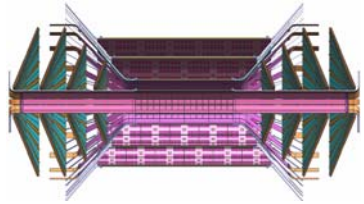
Future of Heavy Quarks at PHENIX or 'The PHENIX Vertex Detector'



The PHENIX VTX Proposal



Proposal for a Silicon Vertex Tracker (VTX) for the PHENIX Experiment

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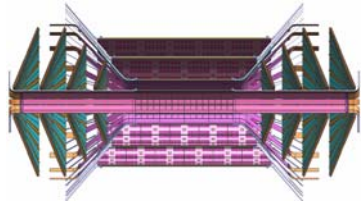
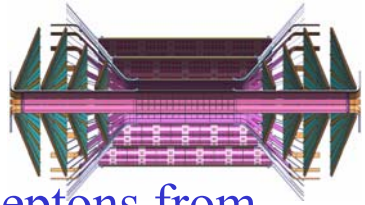
- 117 pages, 73 figures, 18 tables of main part (barrel VTX proposal) plus 20 pages of Appendix (the end-cap).
- 72 authors from 14 institutions
- Major update:
  - 2 pixel + 2 strip
  - Construction: FY06-FY08
    - Ready for RUN8
    - DOE Total Project Cost $4.3M
- The updated proposal was officially submitted from BNL to DOE on 2004/08/09

Physics Case for the VTX

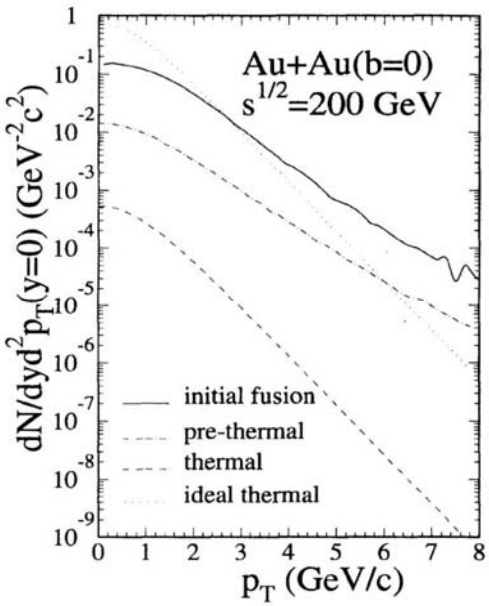


- Hot and dense strongly interacting matter
  - Potential enhancement of charm production
  - Open beauty production
- Flavor dependence of jet quenching and QCD energy loss
  - Accurate charm reference for quarkonium
  - Thermal dilepton radiation
  - High *p*T phenomena with light flavors above 10-15 GeV/c in *p*T
  - Upsilon spectroscopy in the lepton decay channel
- Gluon spin structure of the nucleon
  - $\Delta G/G$ with charm
  - $\Delta G/G$ with beauty
  - x dependence of $\Delta G/G$ with γ-jet correlations
- Nucleon structure in nuclei
  - Gluon shadowing over broad x-range

Charm/Beauty Physics in Au-Au

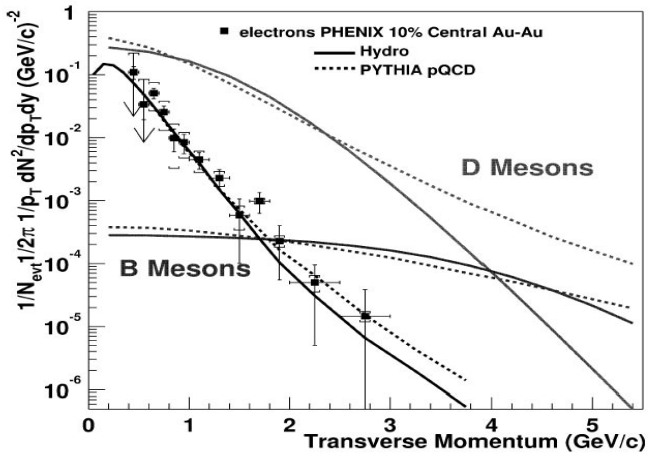


Is there pre-thermal charm production?



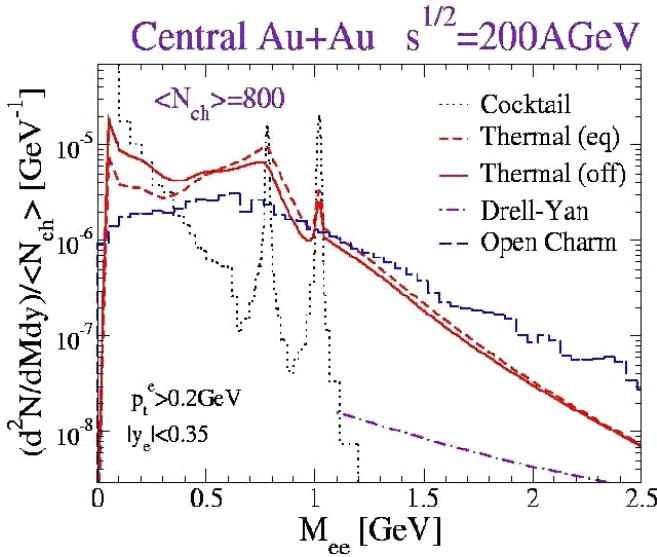
Precise charm measurement is required to detect small enhancement

Does charm flow? Heavy quark energy loss?



Charm measurement in pT>3 GeV/c is required to see energy loss effect

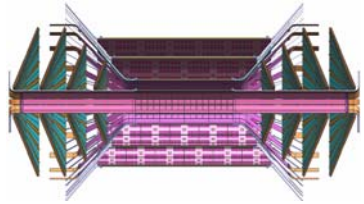
Thermal dileptons from the QGP



Di-leptons from charm decay must be identified and subtracted to detect the thermal di-leptons from the QGP in 1-3 GeV region

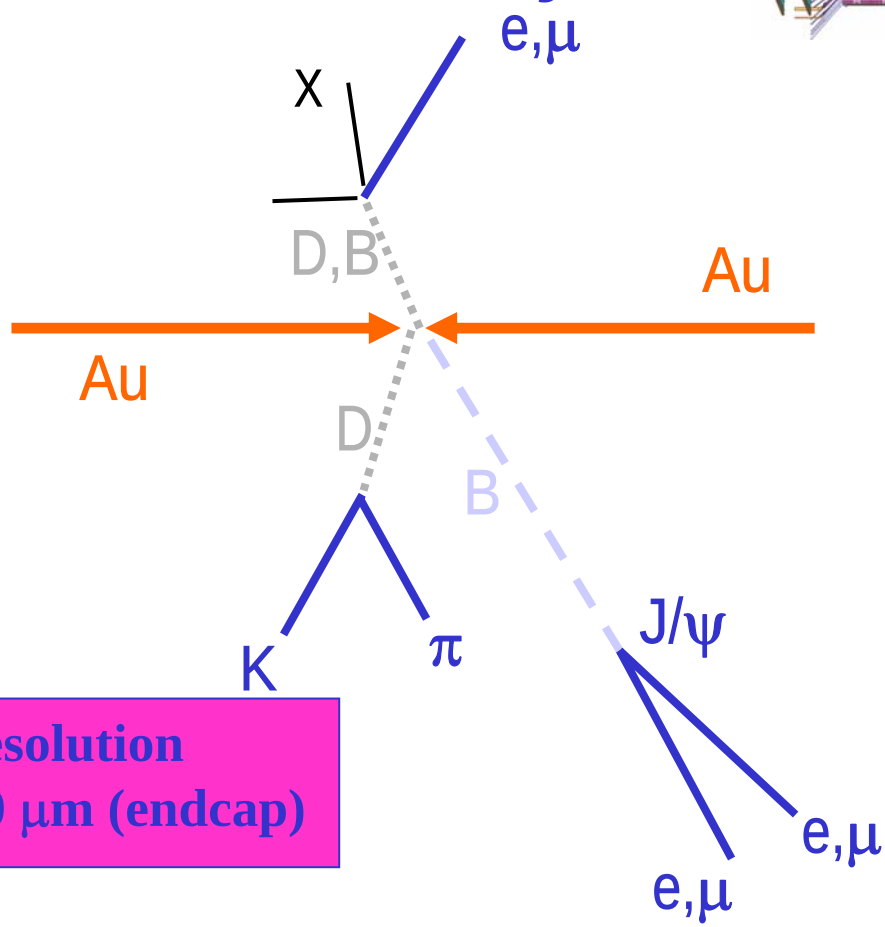
These measurements are not possible or very limited without precise vertex tracking

Direct Observation of Open Charm and Beauty



Detection of decay vertex
will allow a clean identifications of
charm and bottom decays

	m GeV	cτ μm
D^0	1865	125
$D^\pm$	1869	317
B^0	5279	464
$B^\pm$	5279	496

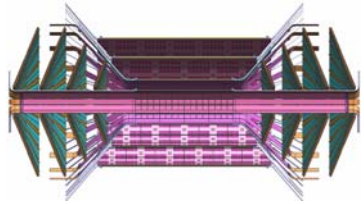


Need secondary vertex resolution
< 50 μm (barrel) < 150 μm (endcap)

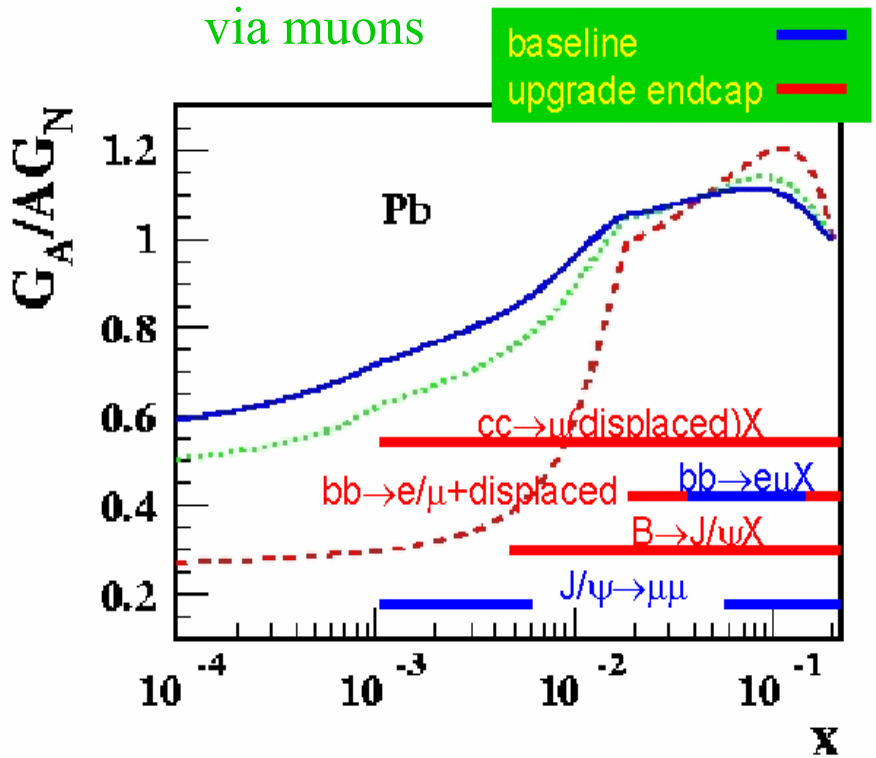
Detection options (PHENIX):

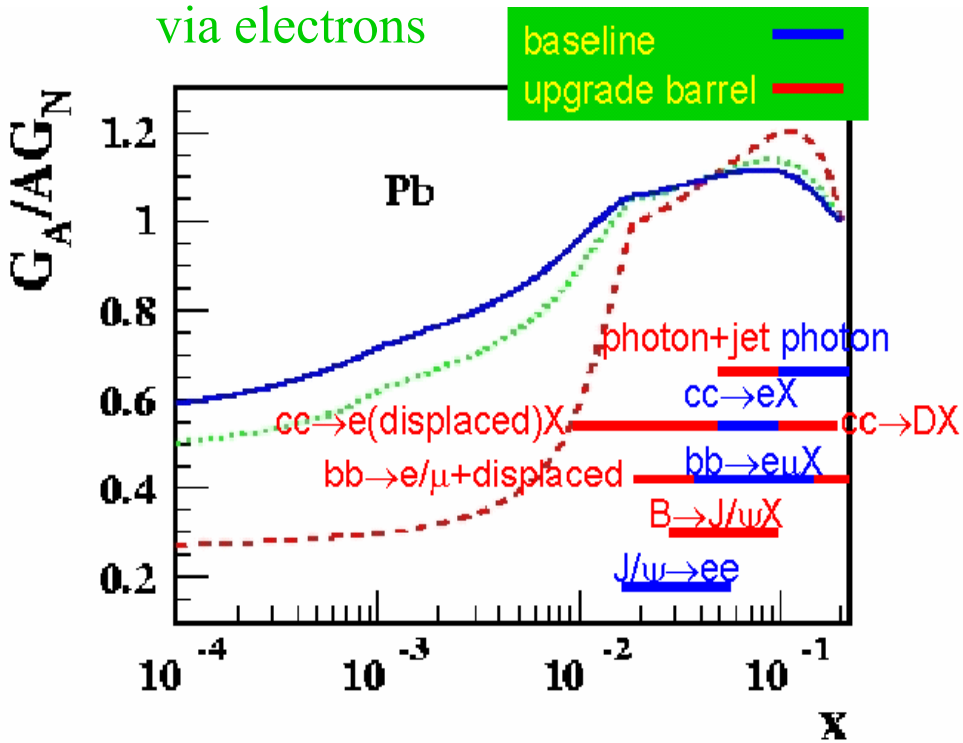
- **Beauty and low p_T charm via displaced e and/or μ** $-2.7<\eta<-1.2$, $|\eta|<0.35$, $1.2<\eta<2.7$
- **Beauty through displaced $J/\psi \rightarrow ee$ (μμ)** $-2.7<\eta<-1.2$, $|\eta|<0.35$, $1.2<\eta<2.7$
- **High p_T charm through $D \rightarrow \pi K$** $|\eta|<0.35$

Measurement of Gluon Shadowing with VTX

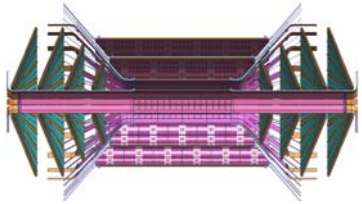


- **Heavy-flavor measurement in p(d)+A**
  - Single lepton and J/Ψ with displaced vertex
- **Extracting gluon structure function in nuclei (shadowing)**
  - Vertex detector provides broader range in x in the predicted shadowing region (x <= 10^{-2})



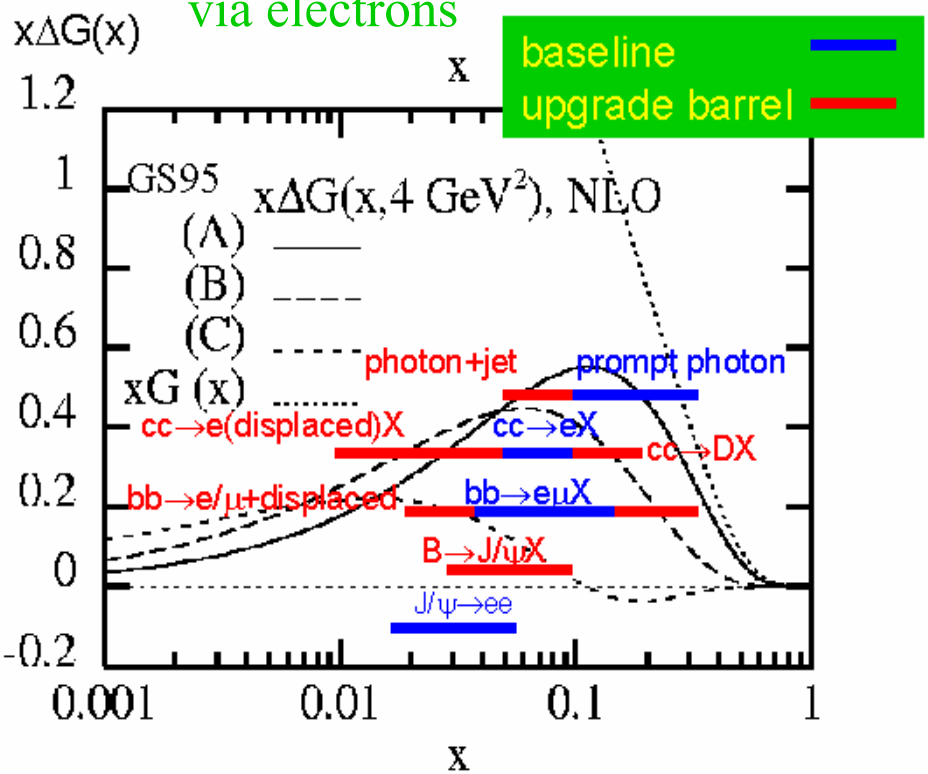


Spin Physics with VTX Upgrade

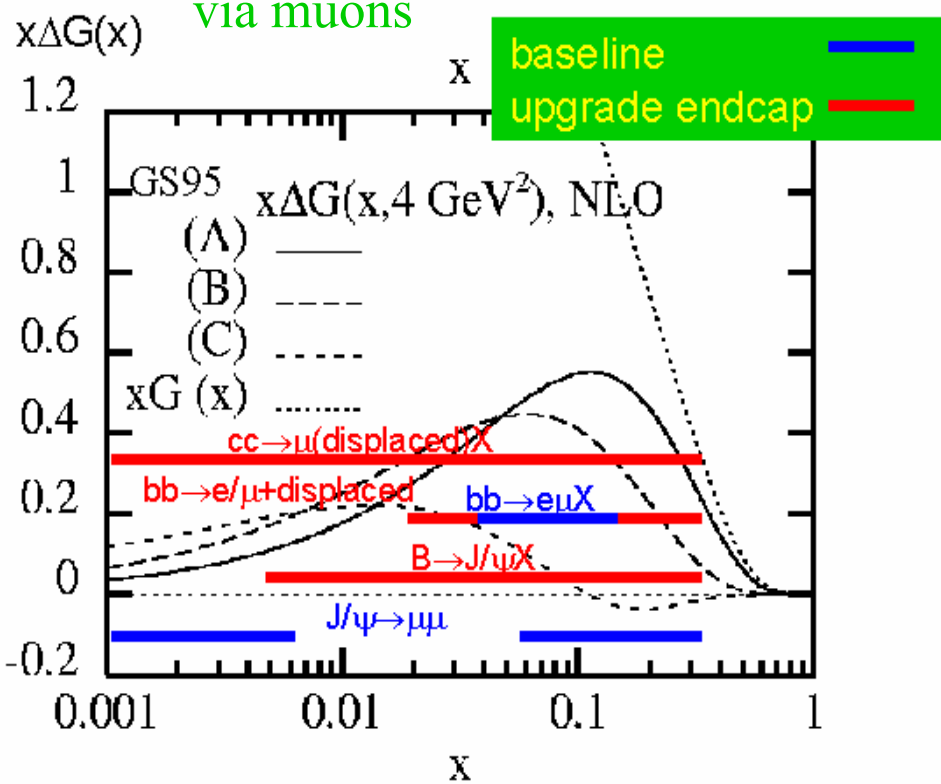


- Measurement of gluon polarization by heavy flavor production using VTX measurement of displaced vertex
  - Improved S/B (rejection of pi and K decays) → higher sensitivity to DG(x)
  - Much broader x-range coverage

via electrons



via muons

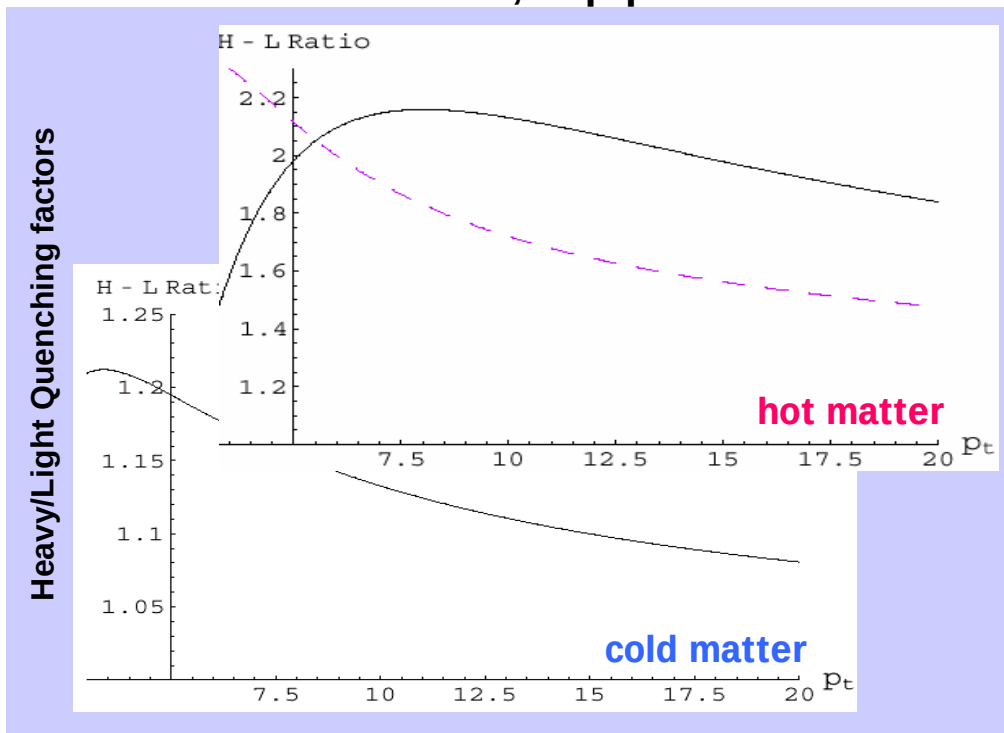


VTX significantly increases the Bjorken-x converage of ΔG(x) measurement

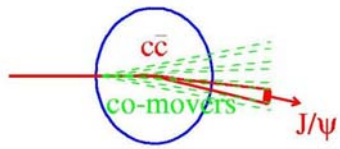
AA Collisions: Charm, Beauty Production

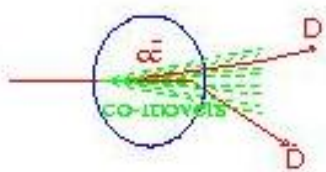
Kharzeev, hep-ph/0106202

- Possible charm enhancement in earliest stage of reaction
- High-pt heavy-quarks may experience a smaller energy energy loss
  - Kharzeev et al. predict reduced gluon Bremsstrahlung

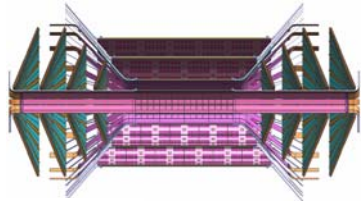


- Charm is critical baseline for J/ψ suppression
  - open vs. hidden charm
- Charm provides key info. for di-lepton continuum





Physics Gained by Barrel Detector

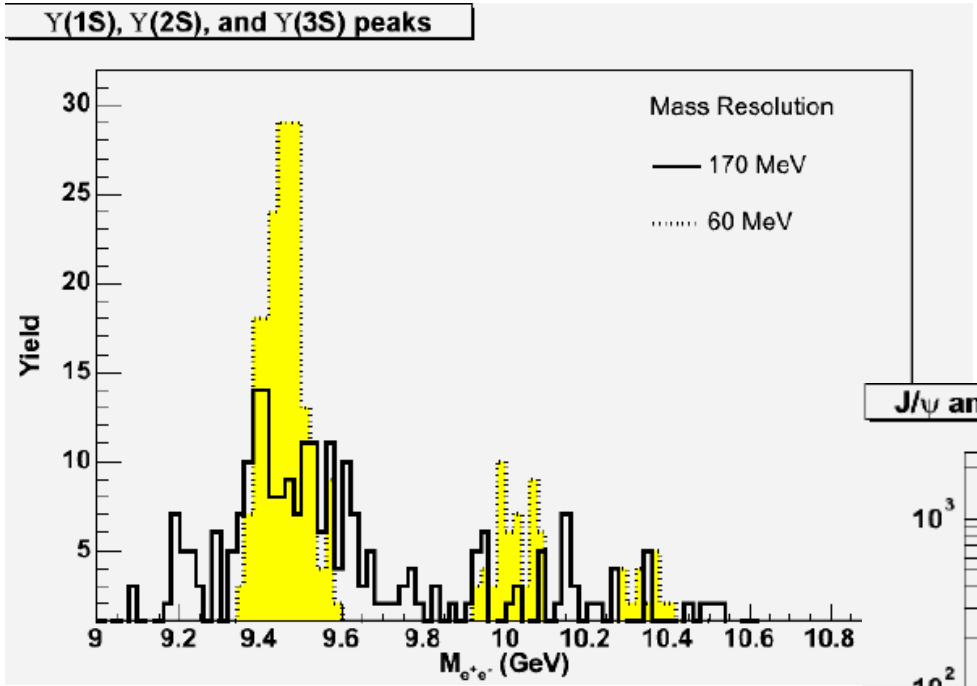


DOE proposal:

Table 5 Summary of physics measurement gained by the VTX detector. The column "without VTX" shows the present capability of PHENIX, while the measurement range with the VTX detector is shown in the column "with VTX". If the process is not measurable, it is marked as "No".

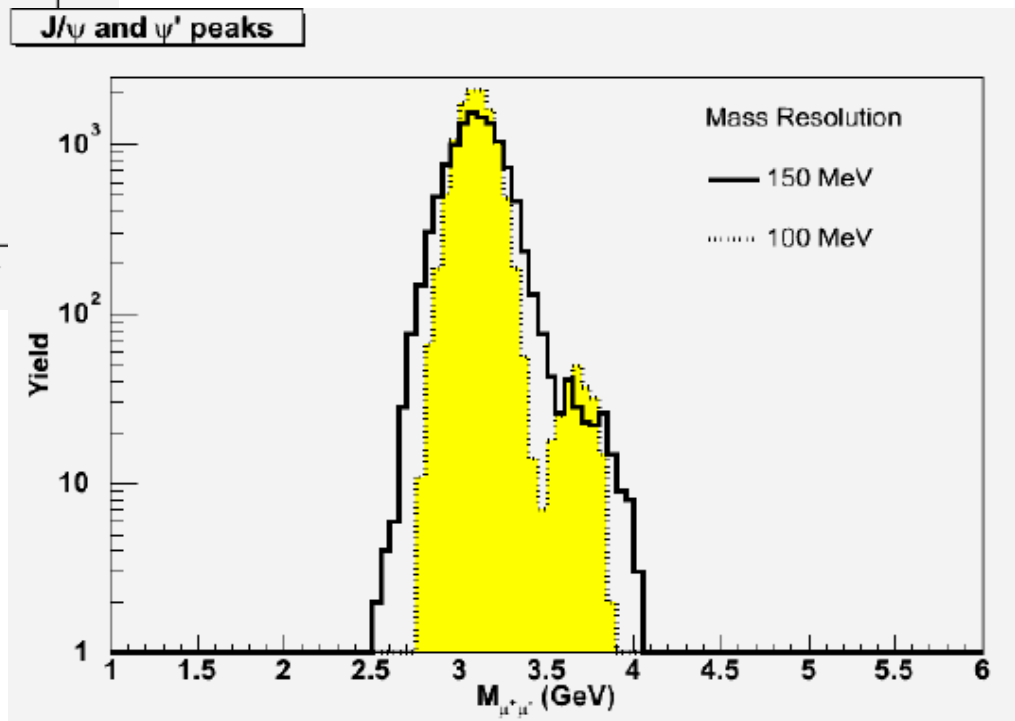
Process	Physics Objectives	Without VTX	With VTX
$c \rightarrow e$	Charm energy loss	$0.5 < p_T < 2.5$ GeV/c	$0.3 < p_T < 6$ GeV/c
$D \rightarrow K\pi$ ($p_T > 2$ GeV/c)	Charm energy loss		$> 7\ \sigma$ significance in central Au+Au
Total charm yield	Charm production	~ 20 %	~ 10 %
$(c \rightarrow e)/(b \rightarrow e)$ ratio	Search for thermal charm produciton		~ 1 %
$b \rightarrow e$	Beauty production Beauty energy loss	$p_T > 3$ GeV/c with model dependence	$1 < p_T < 6$ GeV/c
$B \rightarrow J/\psi$	Beauty production		$\Delta\sigma/\sigma \sim$ 10 - 15 %
Total beauty yield	Beauty production		~ 10 %
High p_T charged	Light quark energy loss	$p_T \leq 10$ GeV/c	$p_T < 15$ -20 GeV/c
$p+p \rightarrow c \rightarrow e$	$\Delta G(x)$	$0.03 < x < 0.08$	$0.01 < x < 0.15$
$p+p \rightarrow b \rightarrow e$	$\Delta G(x)$		$0.02 < x < 0.15$
$p+p \rightarrow \gamma$+jets	$\Delta G(x)$		$0.04 < x < 0.3$
$p+A\ (dA) \rightarrow c/b$	Nuclear shadowing of $G(x)$	$0.03 < x < 0.3$	$0.01 < x < 0.3$

Improved Onium Mass Resolution

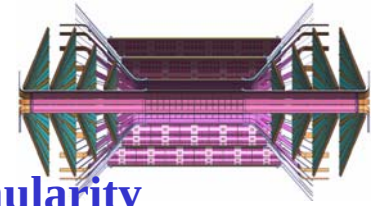


Barrel

Endcap



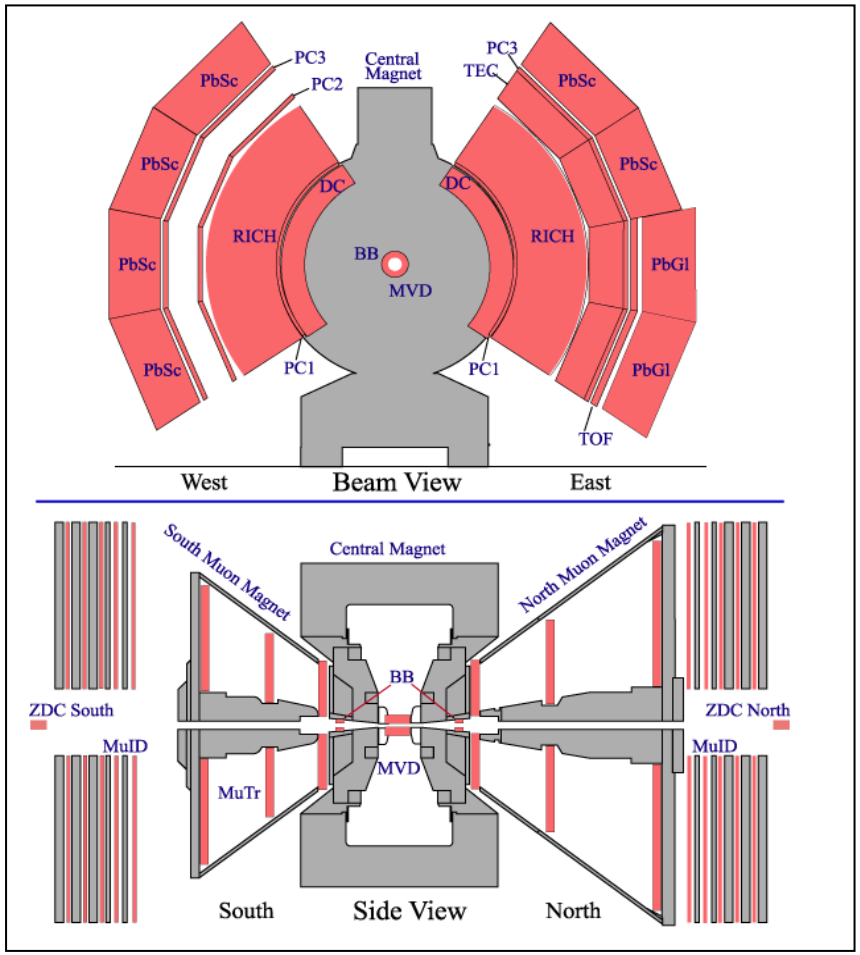
The PHENIX Detector



Designed to measure rare probes:

Au-Au & p-p (spin)

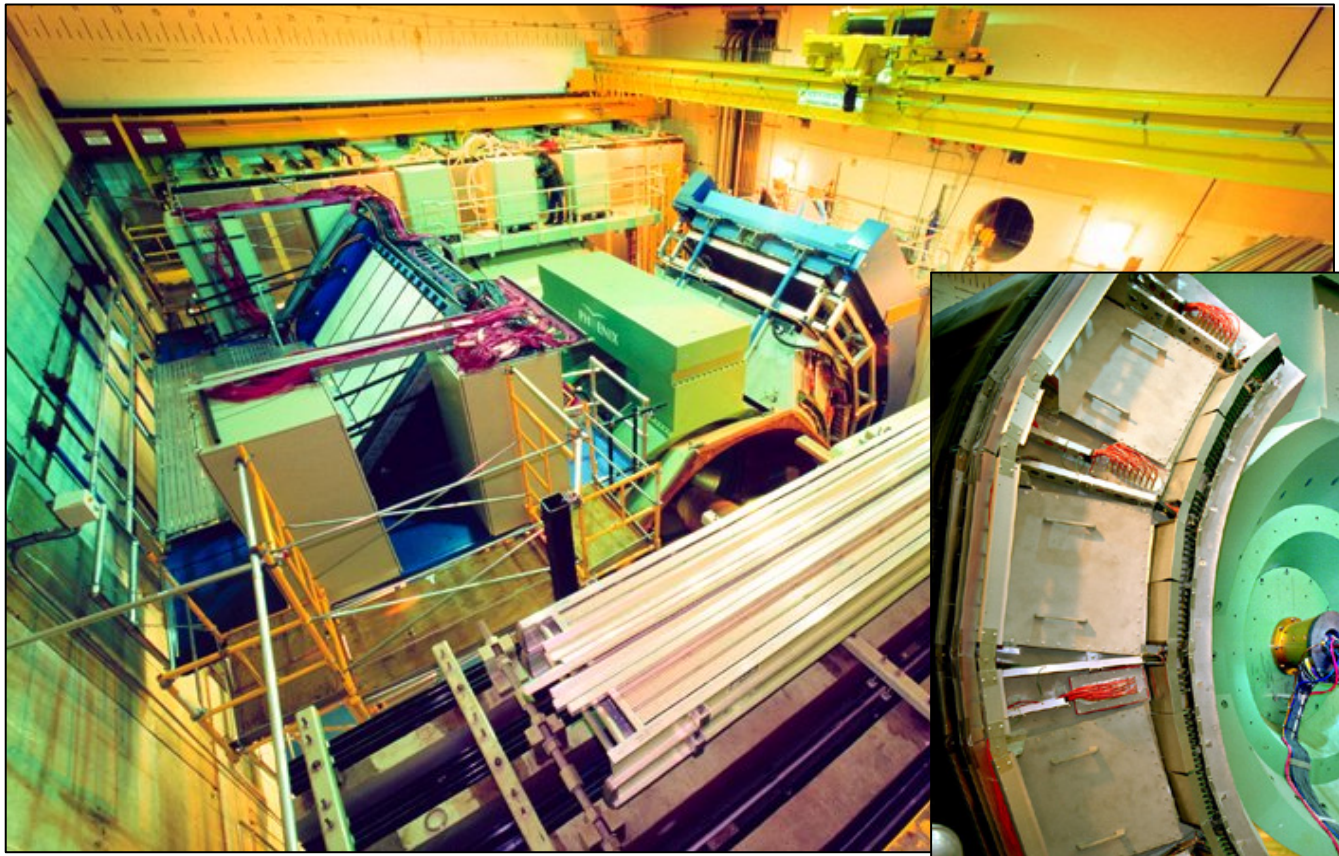
+ high rate capability & granularity
+ good mass resolution and particle ID
- limited acceptance

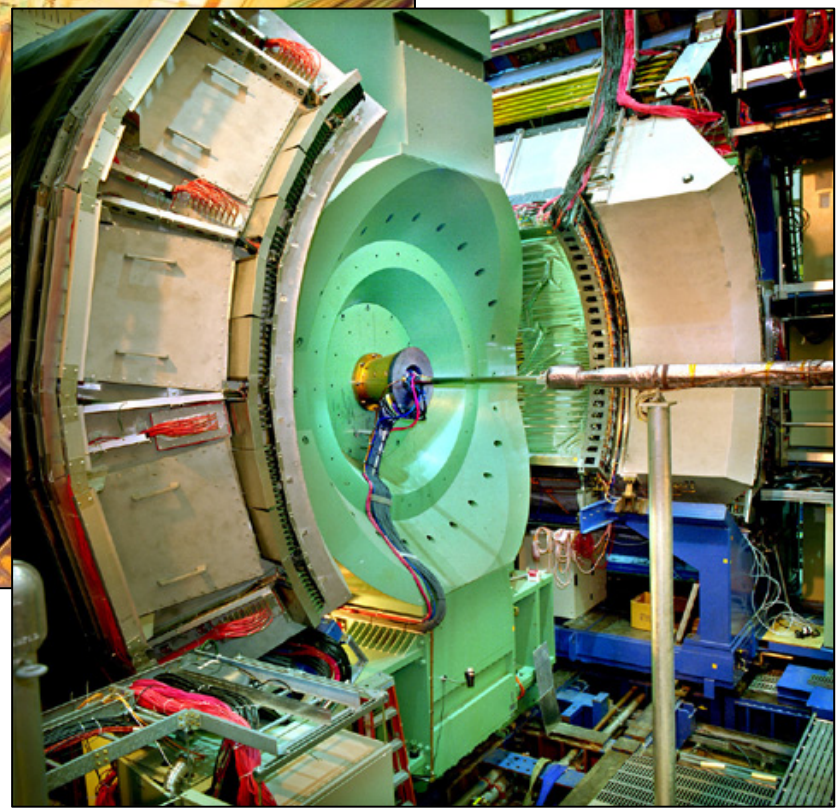


- 2 central arms:
  electrons, photons, hadrons
  - charmonium J/ψ, $\psi' \rightarrow e^+e^-$
  - vector meson $\rho, \omega, \phi \rightarrow e^+e^-$
  - high p_T π^o, π^+, π^-
  - direct photons
  - open charm, beauty $(D,B \rightarrow e)$
  - hadron physics

- 2 muon arms: muons
  - "onium" J/ψ, ψ', $\Upsilon \rightarrow \mu^+\mu^-$
  - open charm, beauty $(D,B \rightarrow \mu)$

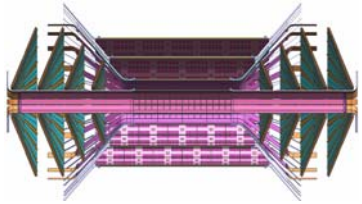
PHENIX - Pictures

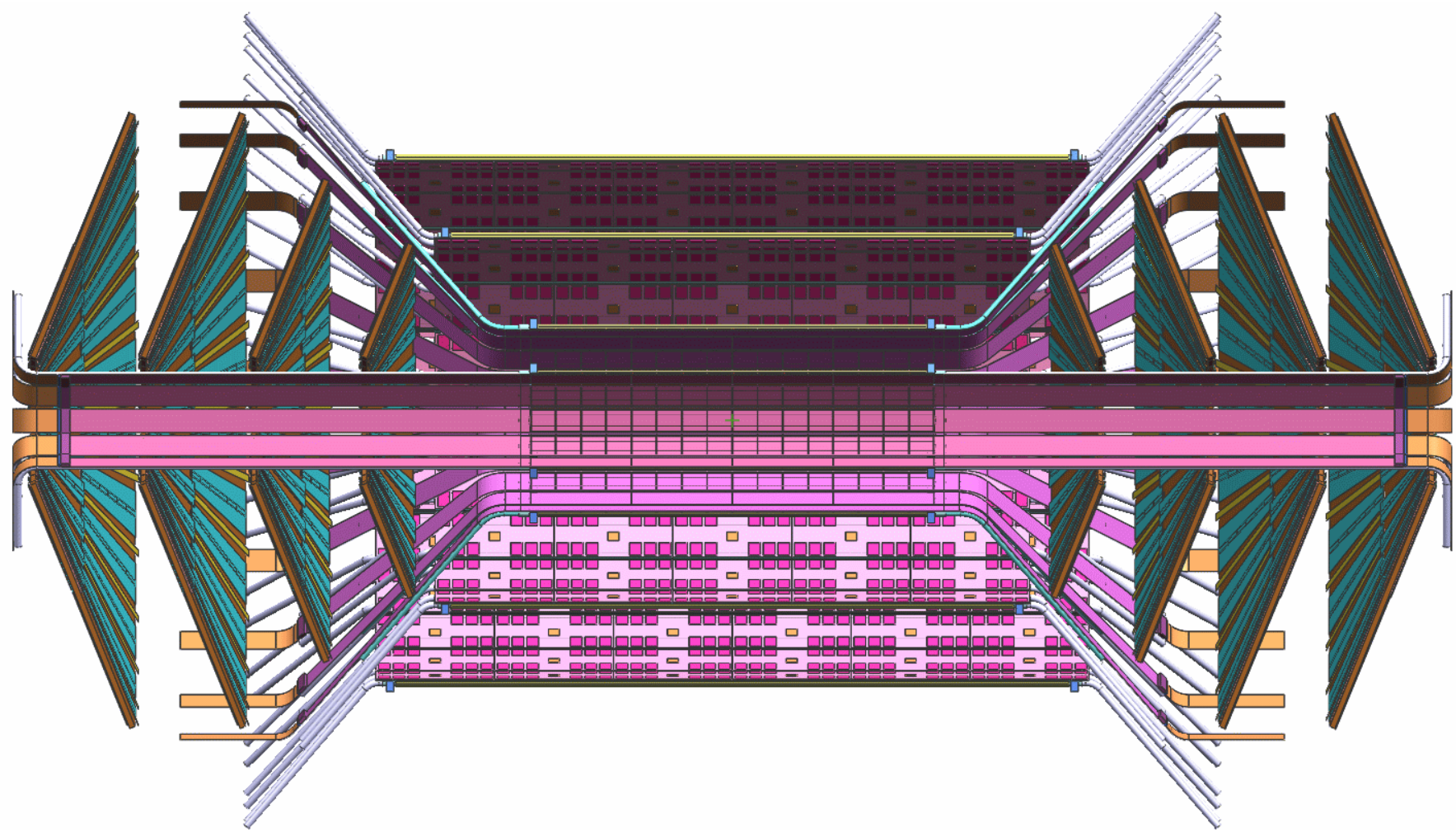




Baseline detector completed since Run-III (2003)

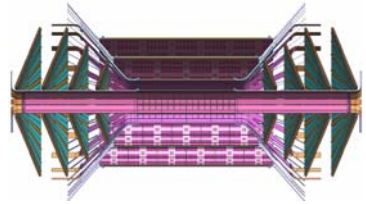
The Complete VTX System for PHENIX

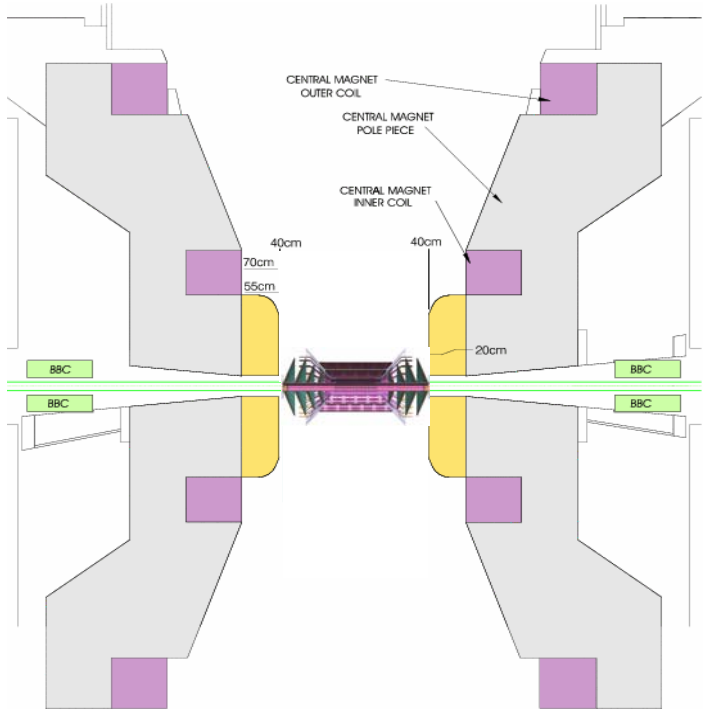




Barrel Proposal submitted to DOE in 2004
Endcap will follow in 2005

Integration into Phenix





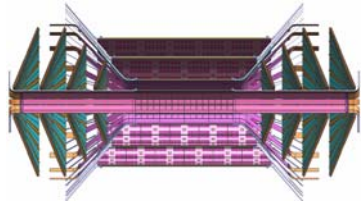
General Integration

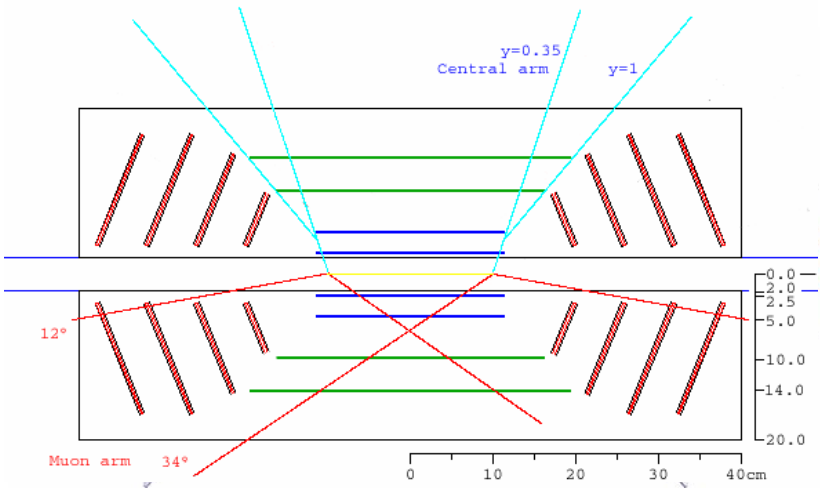
beam pipe radius, 0.5mm Be	1.5 cm
pole tips, +-z	41 cm
Al-Mylar around beam pipe	~ microns

Silicon Tracker

outer envelope radius	< 25 cm
inner envelope radius	> 2.0 cm and < 2.5 cm
silicon outer radius	18 cm
silicon inner radius	2.5 cm
maximum z extent	40 cm

Current VTX Specifications *01-2005*



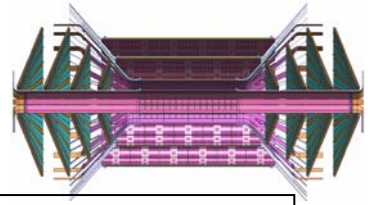


Barrel Section	i-radius	length	strips/pixel	
layer 1	2.5 cm	21.8 cm	pixel	1.2%
layer 2	5 cm	21.8 cm	pixel	
layer 3	10 cm	31.8 cm	strip	2.0%
layer 4	14 cm	38.2 cm	strip	

Occupancy 1&2 <1% 3&4 ~4.5%

Endcap (north and south)	z-start(+-)	o-radius	tilt = 22 deg
disk 1	20 cm	6.6 cm	ministrip
disk 2	26 cm	10.6cm	ministrip
disk 3	32 cm	18 cm	ministrip
disk 4	38 cm	18 cm	ministrip

Silicon Pixel Detectors



Development and production of PHENIX pixel sensor ladders and module readout electronics in collaboration of RIKEN with the ALICE experiment.

ALICE1LHCb readout chip:

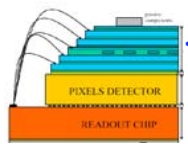
- Pixel: 50 μm x 425 μm.
- Channels: 256 x 32, 10 MHz r/o clock.
- Output: binary, not zero-suppressed, in 25.6μs.

$\Delta r\Phi$ = 1.36cm

Δz = 1.28 cm

Sensor ladder:

- 4 ALICE1LHCb readout chips.
- Bump-bonded (VTT) to silicon sensor.
- Thickness: r/o chips 150 μm, bumps 13 μm, sensor 200 μm.



< 240 μm — < 0.24% X_0

200 μm (13 μm) — 0.36% X_0

150μm

support + cooling — ~0.30% X_0

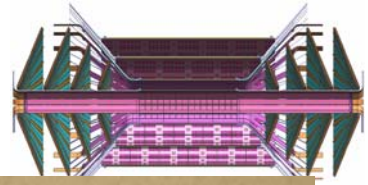
Half-module (2 sensor ladders, bus + Pilot module):

- 1.36 cm x 10.9 cm + bus extender to ~z = 40cm.
- Thickness bus: < 240 μm.

Module, two half-modules in z-direction:

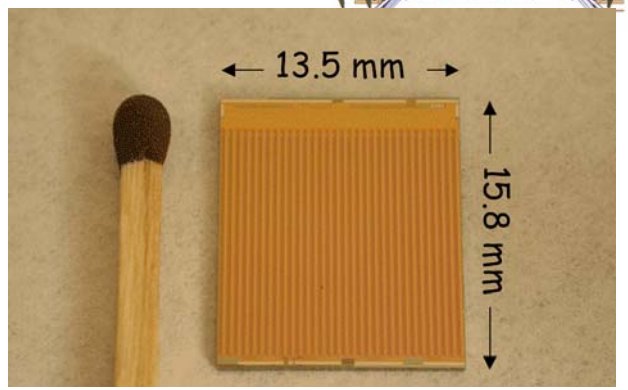
- Δz = 24 cm.
- detector resolution in $r\Phi$: ~14 μm r.m.s.

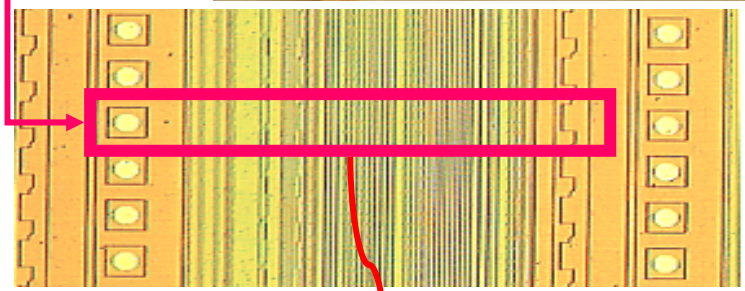
Readout Pixel Chip

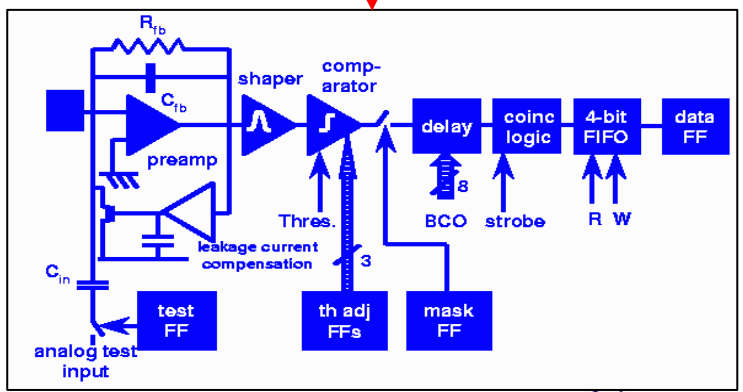


ALICE1/LHCB chip

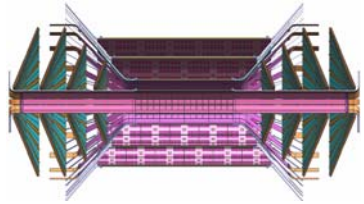
- Active area: 12.8mm x 13.6mm
- pixel size 50 x 425 μm^2
  - CMOS 0.25 µm (8” wafers)
  - transistors : designed with a radiation-tolerant geometry
- 8192 channels (32 x 256)
- 4-event buffer; 10 MHz clock
- radiation hard up to ~30 Mrad
- ~100 µW/channel
- General OR of 8192 pixels will be produced for trigger info every clock cycle (10MHz)



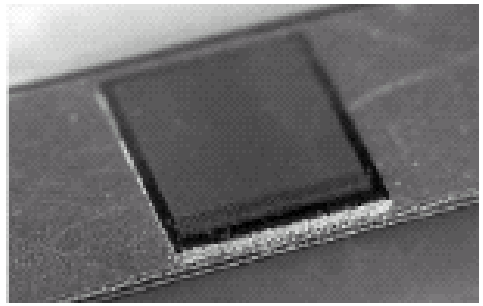


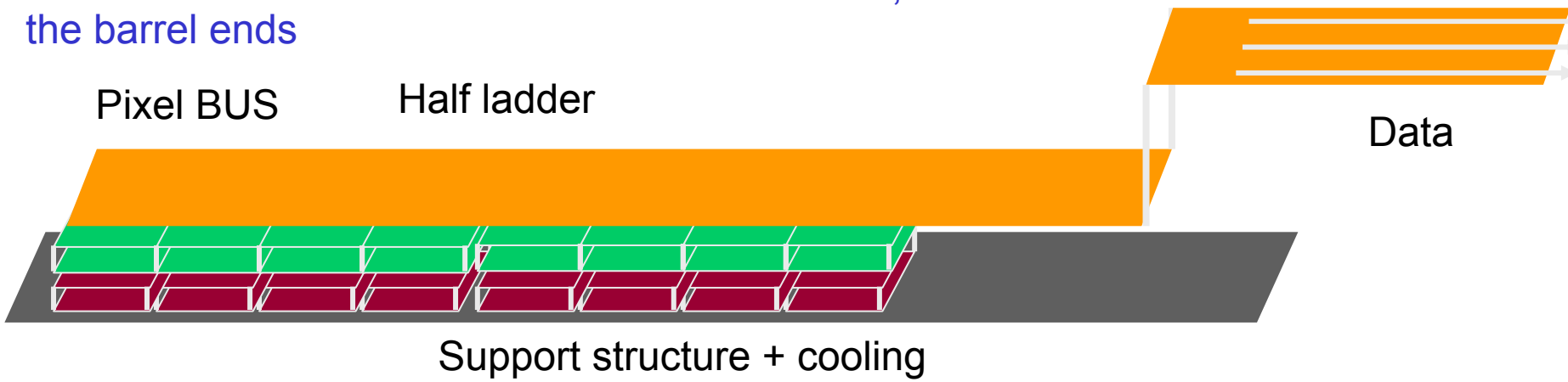


Pixel Detector Module

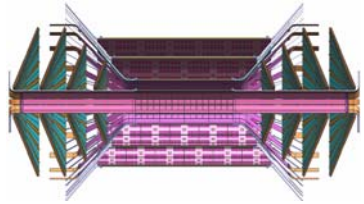


- 4-chip Ladder consists of 4 ALICE Pixel readout chips Bump-bonded to silicon sensor
- One readout unit, half ladder, made from two 4 –chip ladders
- Half module is mounted on the support structure
- Pixel BUS to bring data out and send control signal into the readout chip is mounted on the half ladder
- Each detector module is built of two half ladders, read out on the barrel ends



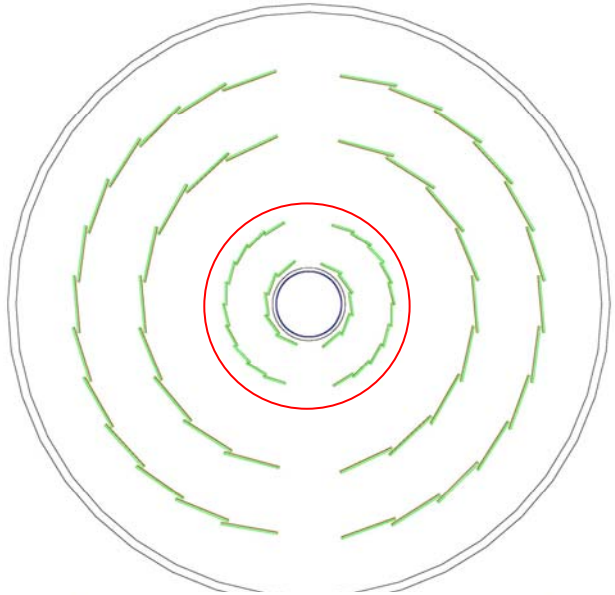


VTX Barrel Layout



- Inner 2 layers will be equipped with silicon pixel detectors
  - Inner most layer
    10 full ladders (at 2.5 cm)
  - Second layer will
    20 full ladders (at 5.0 cm)

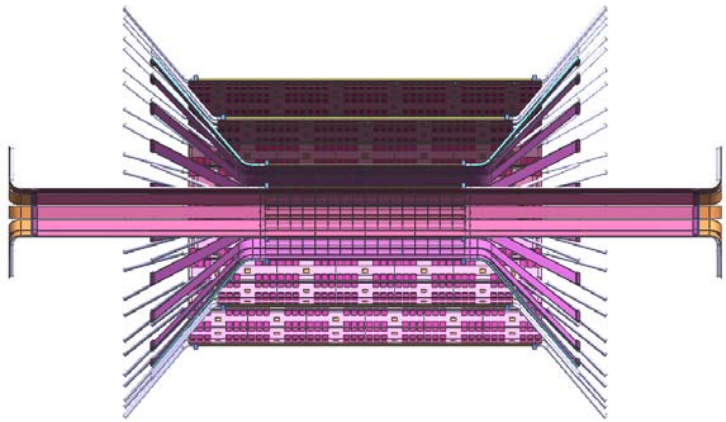
end view



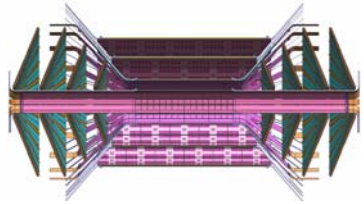
In total, 30 full ladders

= 120 4-chip ladders

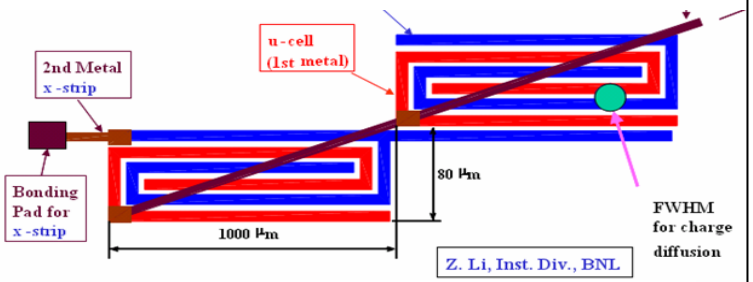
= 480 ALICE pixel readout chips



Strip Detectors

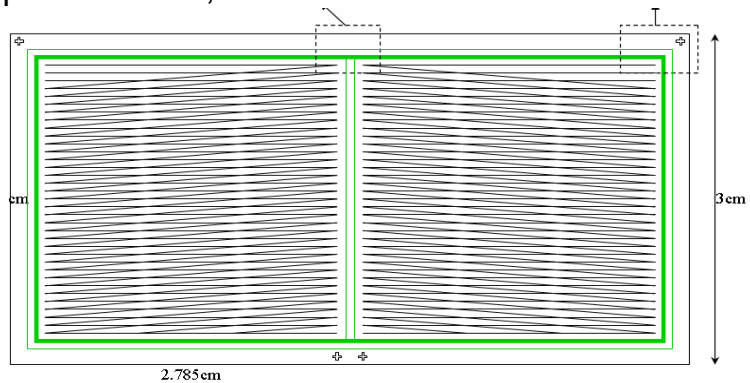


Sensor elements: Developed at BNL



Pixels: 80 μm × 1 mm, projective readout via double metal XU/V "strips" of ~3 cm length.

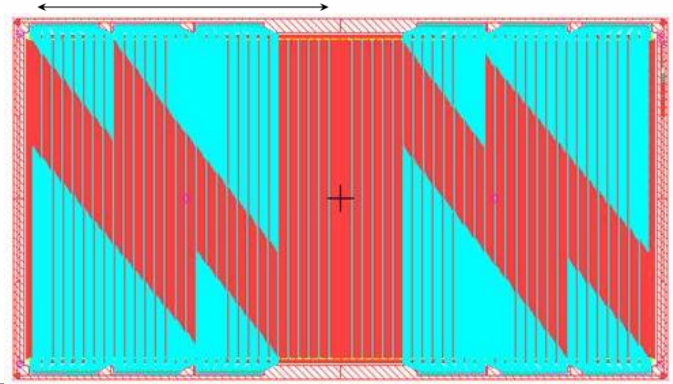
Two strip-pixel arrays on a single-sided wafer of 250 (400) μm thickness, with 384 × 384 channels on 3 x 3 cm^2 area.



Initial design:

"longitudinal" readout.

Made by SINTEF

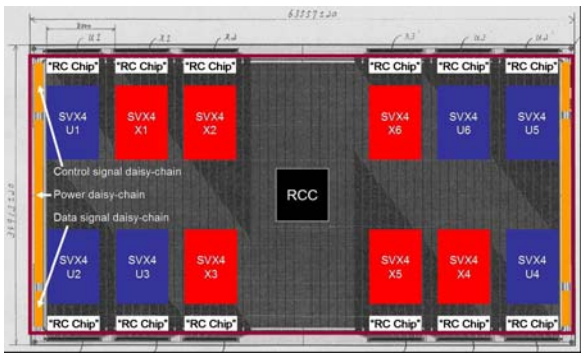


new design:

"lateral" SVX4 readout.

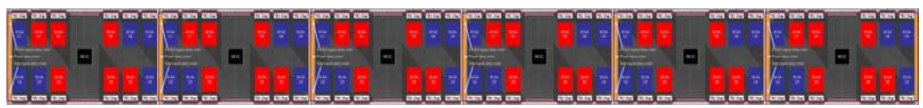
Made by HPK

Strip Read-Out card (ROC)



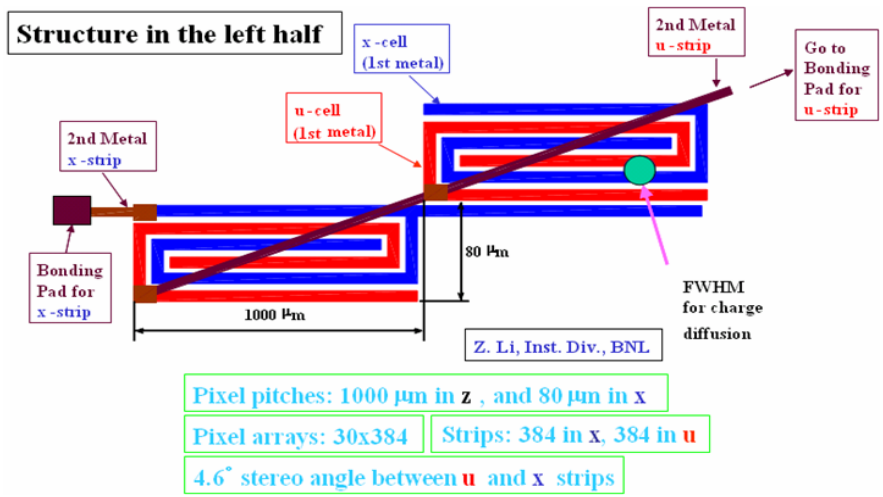
12 SVX4 per sensor
R&D at ORNL

Strip ladder: 5 (layer 3) or 6 (layer 4) sensor+ROC



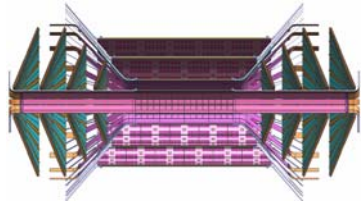
Stripixel Sensor : Principle

- Novel "stripixel" detector concept innovated by BNL Instr. Division: Z. Li, NIMA518, 738 (2004).
  - Single-sided sensor
  - 2-dimentional position sensitivity by charge sharing
  - Two independent electrodes interleaved in one pixel are projectively read out by strips
- Advantages (compared with a double-sided strip sensor)
  - Simple structure : reduce costs and integration issues
  - Radiation hard (cf. a complicated n^+ side structure in a double-sided strip sensor)

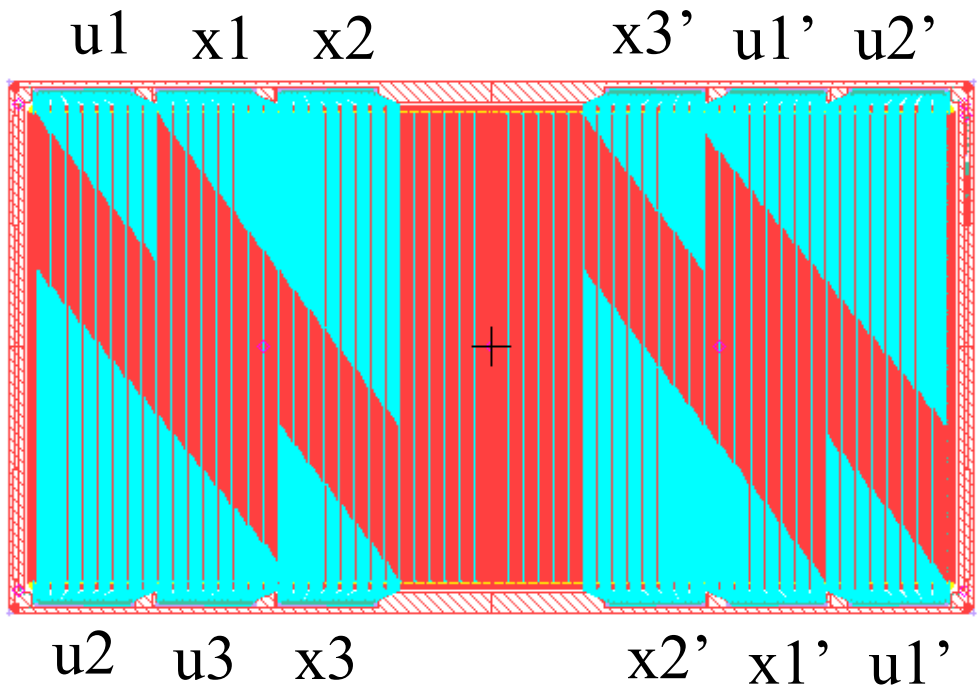


- Disadvantages
  - Large capacitance/strip due to the interleaving scheme
  - Decrease in S/N due to charge sharing

Design of Stripixel Sensor

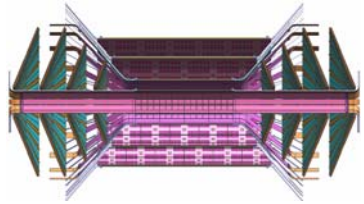


- $p^+/n/n^+$ diode structure w/ 5 mask steps (incl. double-metal process)
- High resistivity silicon wafer : ρ= 4 – 10 kΩ·cm
- Sensor size : 3.4×6.4 cm^2
- Pixel array : 80×1000μm^2 pitch, 384×30×2=23,040
- Spiral p^+ electrode : 5μm line, 3μm gap, 5 turns
- # readout strip
  - x-strip : 128×3×2
  - u-strip : 128×3×2
  - Total : 1536
- Two designs
  - "OLD" design : for prototyping
  - "NEW" design : our baseline now
  - Main diff. is in the location of readout pads.



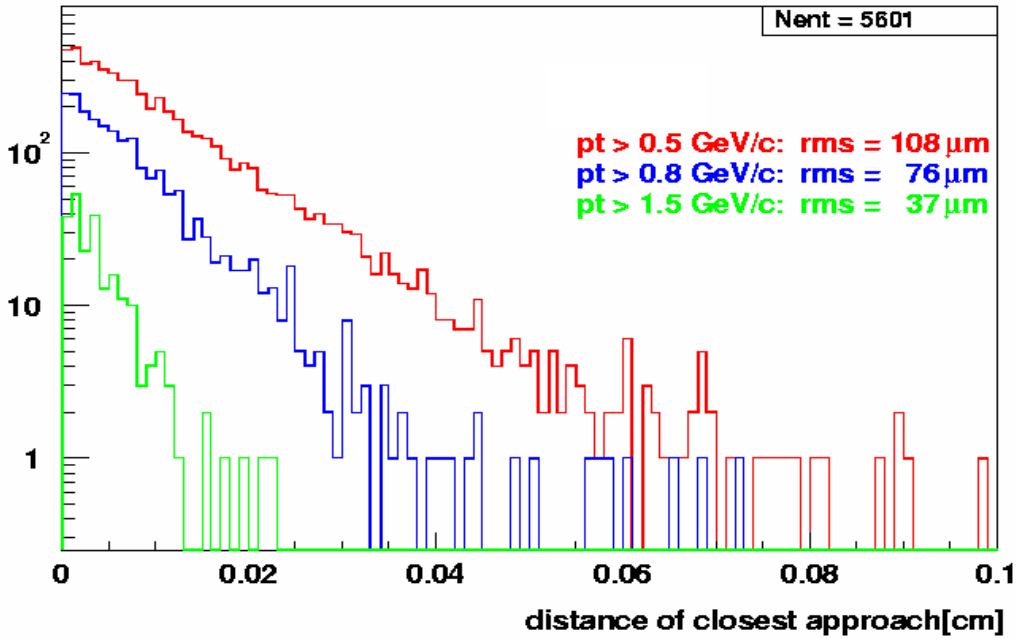
NEW design

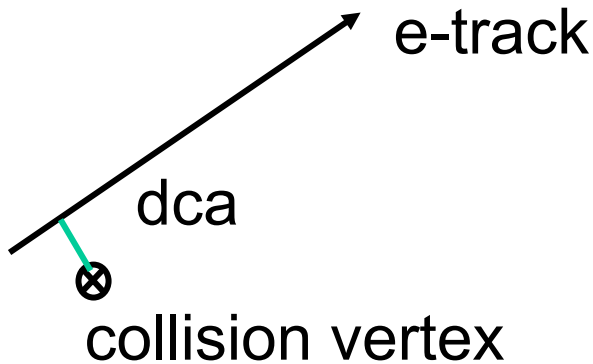
Electron DCA Resolution



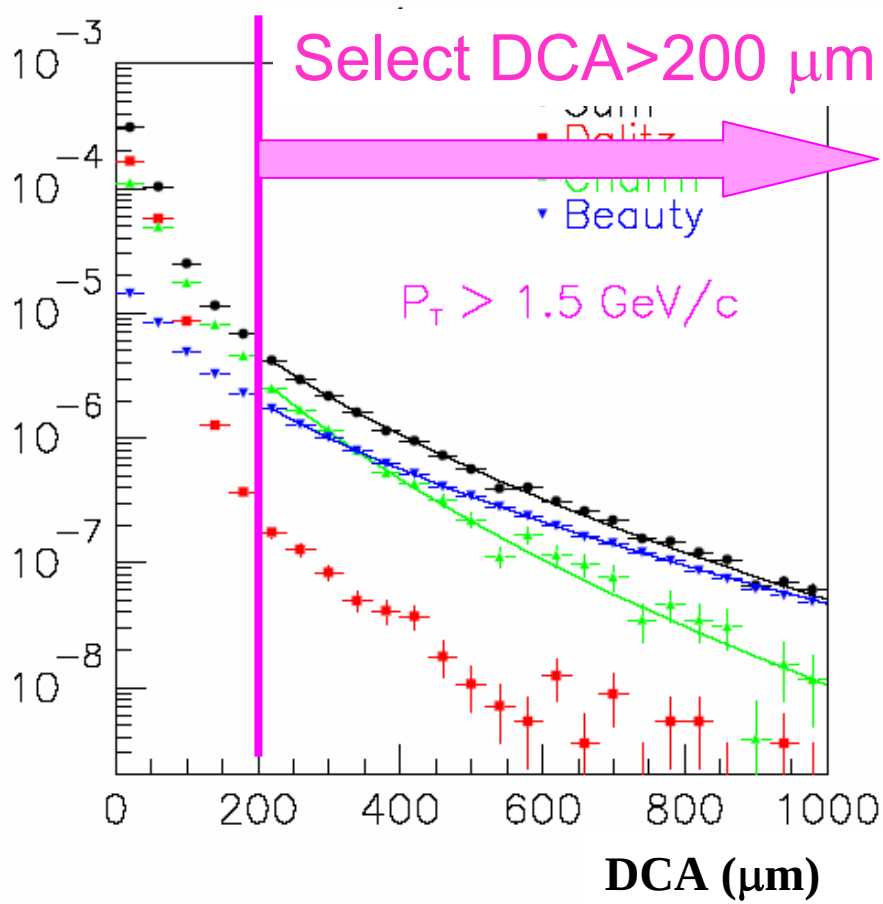
- Simulation for single electrons in central barrel
- Full multiple scattering included (X/X_0=1%/layer)
- DCA resolution < 50 μm at moderate p_T
- Less than $c\tau$, D^0: 125μm, $D^{\pm}$: 317 μm

→ Charm, Bottom ID

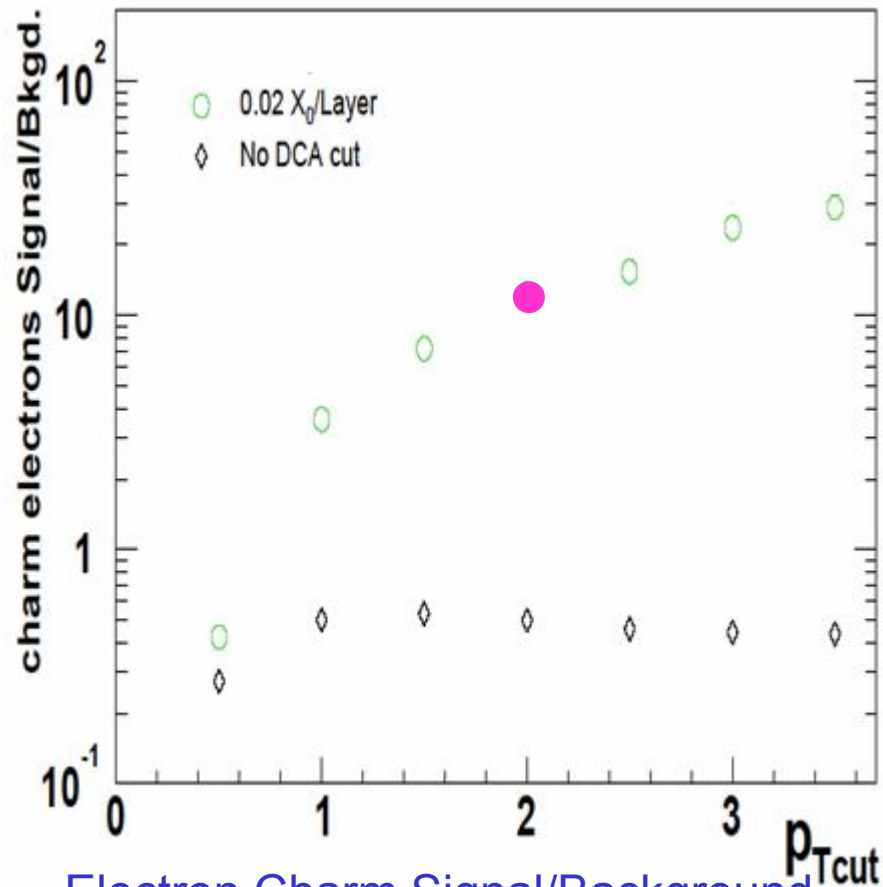




Barrel Tracker - Electron Performance



Electron DCA distribution from charm, beauty and p^0 Dalitz decay



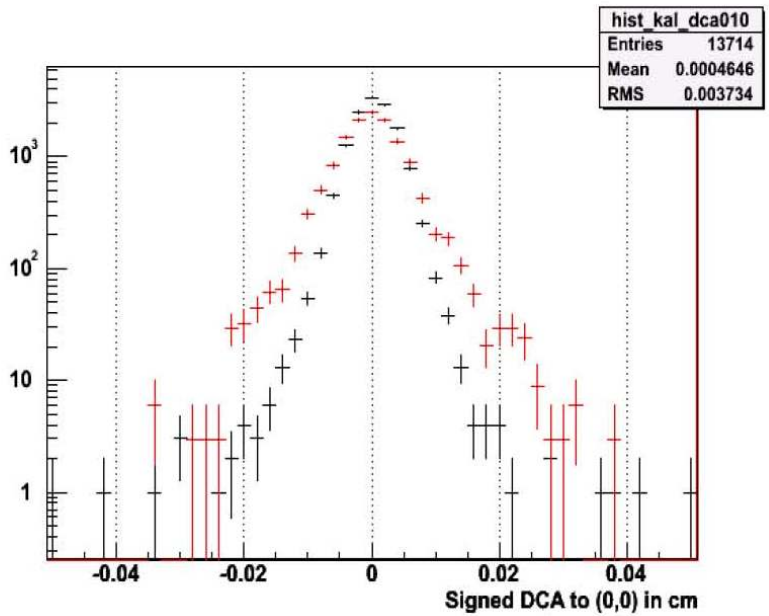
Electron Charm Signal/Background as a function of p_T cut >10 improvement with DCA cut at 2 GeV

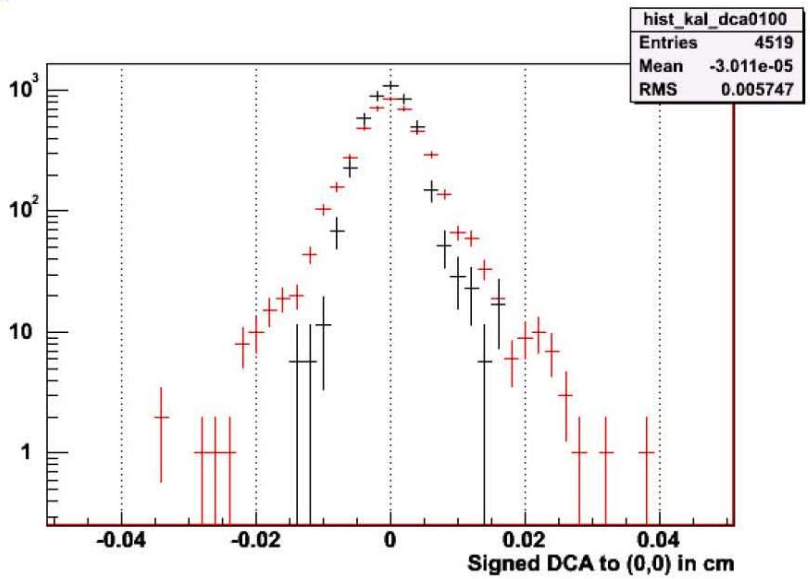
Kaon Pion - Barrel Performance

Single track
Black: particle from event vertex
Red: K/π from D meson decay

Tracks in Au+Au event
Black: particle from event vertex
Red: K/π from D meson decay

Chi2<3.0

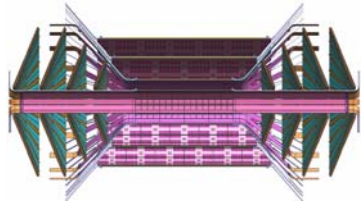


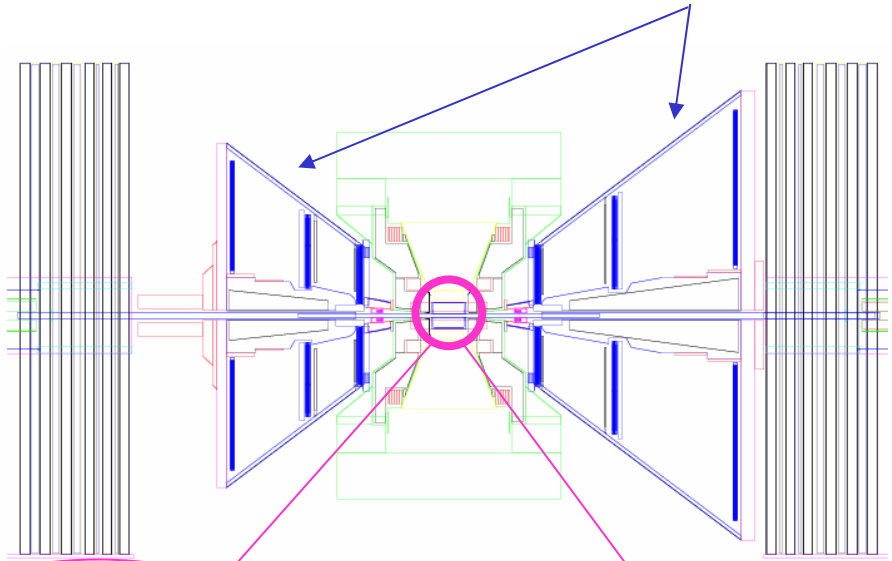


- Clear difference of Distance to Closest Approach (DCA) of K/π from D-meson decay and background particles
- The DCA resolution is almost unchanged when embedded in Au+Au collision

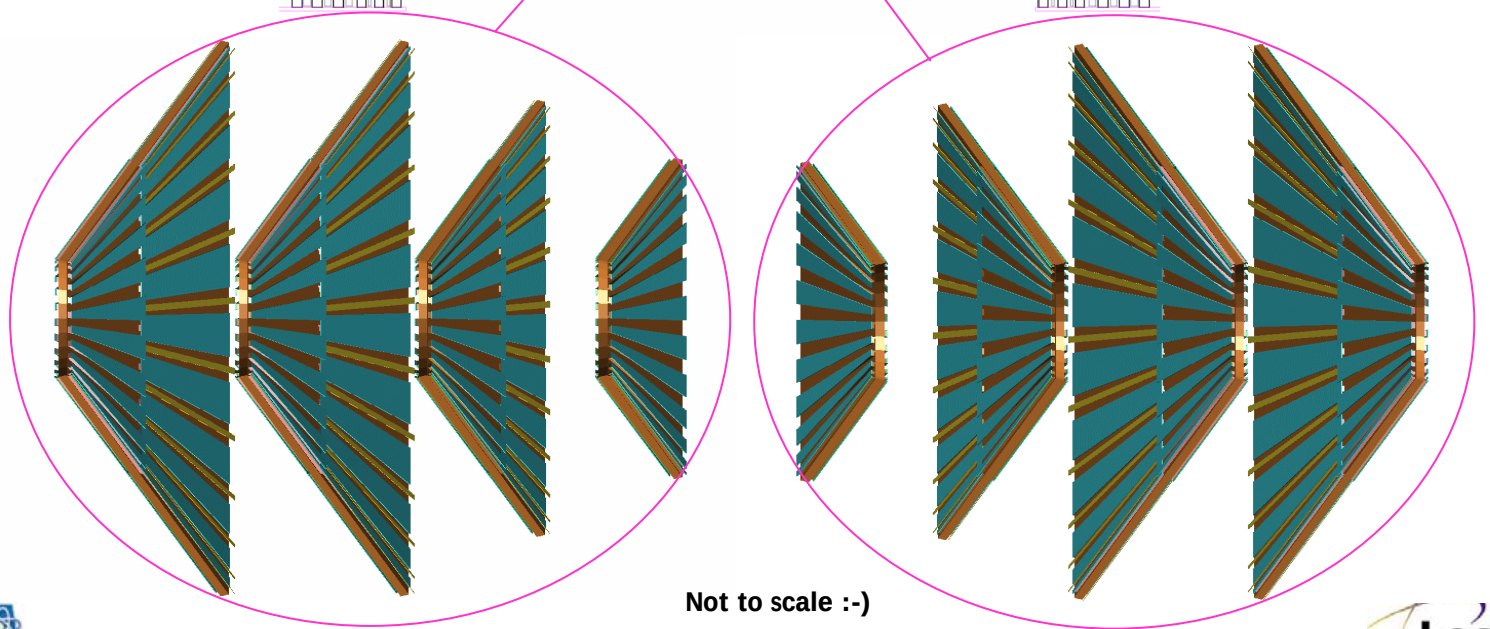
σ_{DCA} ~ 33 μ(single π) to 36 μ (in Au+Au)

‘Endcap’
A Silicon Tracker for the Muon-Arms



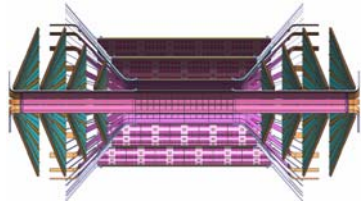


Adding displaced track and displaced vertex capability to Muon tracker

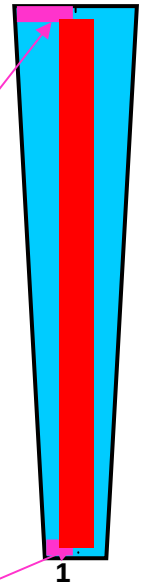


Not to scale :-)

Endcap Primer I



- 50 micron radial pitch (z reconstruction)
  - 4608 (4096) "mini-strips"
    - 3.5 cm < r < 18 (14) cm
    - < 1 % occupancy
  - 48 "double towers" in phi
    - mini-strips from
      13.0 mm
      to 2.2 mm
  - readout via one PHX chip row



Derived from FPIX3 (FNAL)

PHX R&D

PHX Chip Layout:

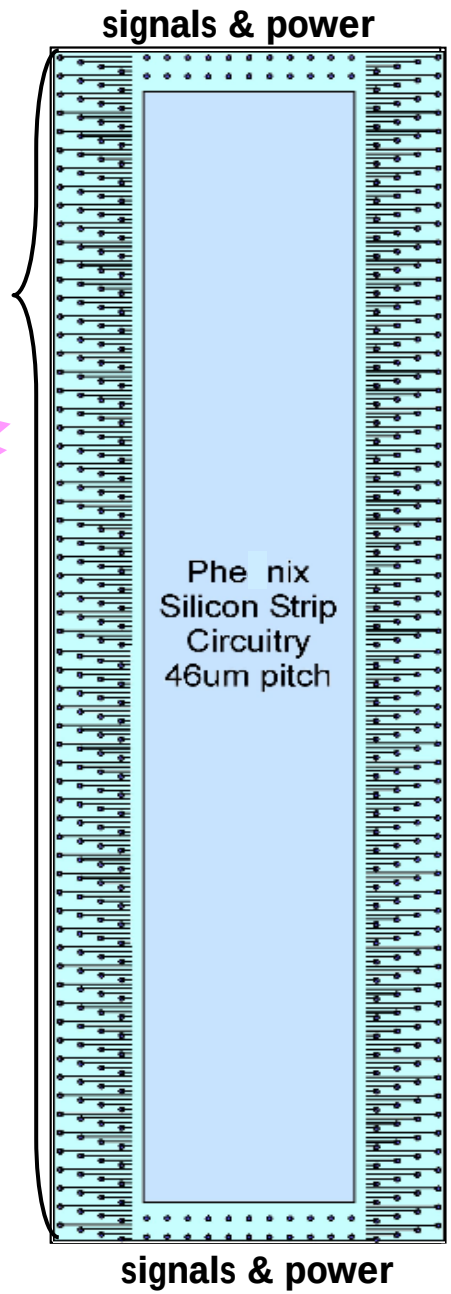
256 channels/2 column

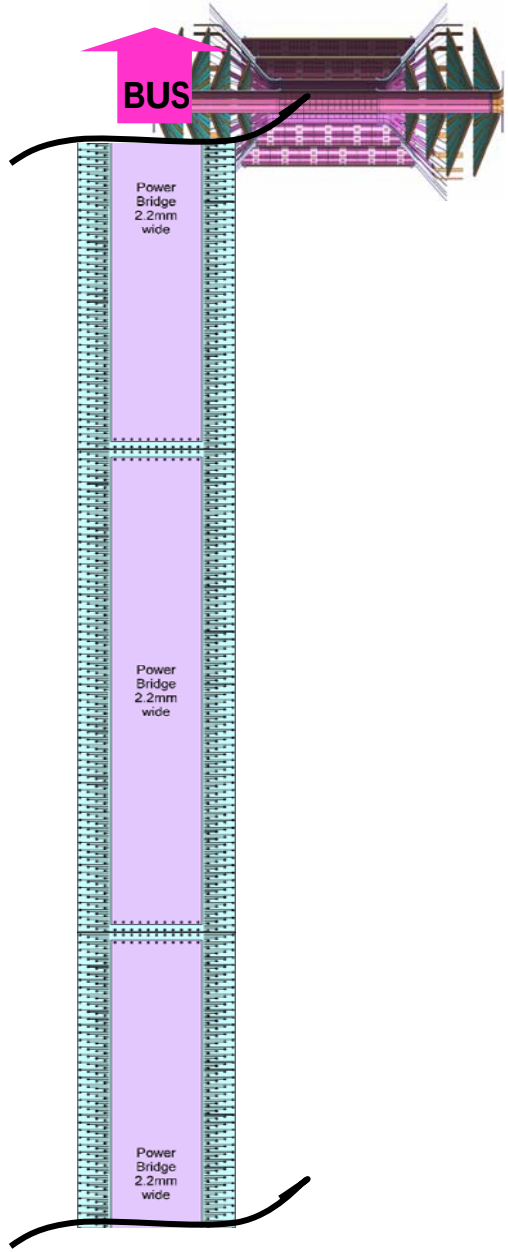
3.8 mm x 13 mm = 49.4 mm^2

Bump bonds on 200 um pitch

50 µm diameter bumps

Inter-chip bumps for the bus

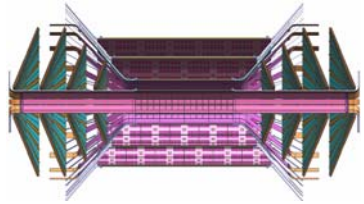




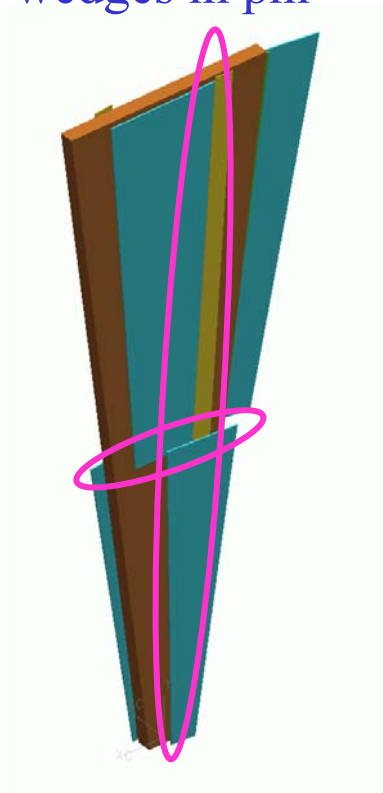
FPIX3

- Very advanced mixed analog/digital design
- Low power (1/10th of ALICE chip)
- 128 rows x 22 columns (2816 channels)
- 50 µm x 400 µm pixels
- High speed readout intended for use in Level 1 trigger. 840 Mbits/sec data output.
- Very low noise
- Excellent threshold matching
- DC coupled input (pixel standard)
- Fully programmable device
- 3 bit ADC

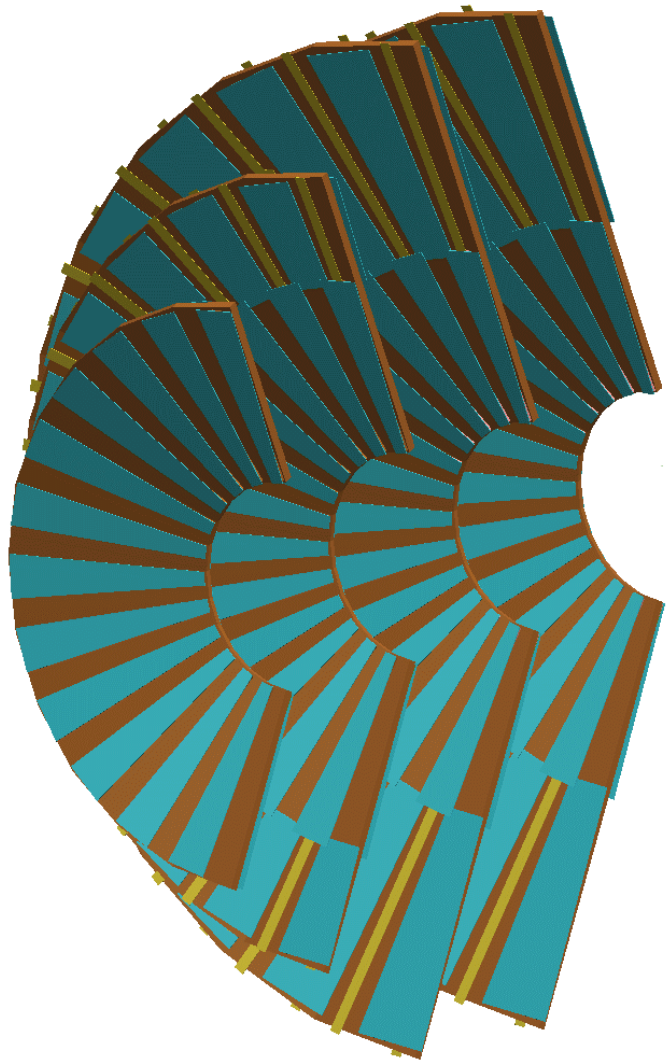
Endcap Primer II



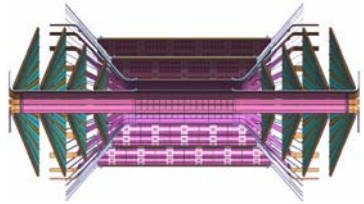
2 silicons each in front and back, 48 wedges in phi

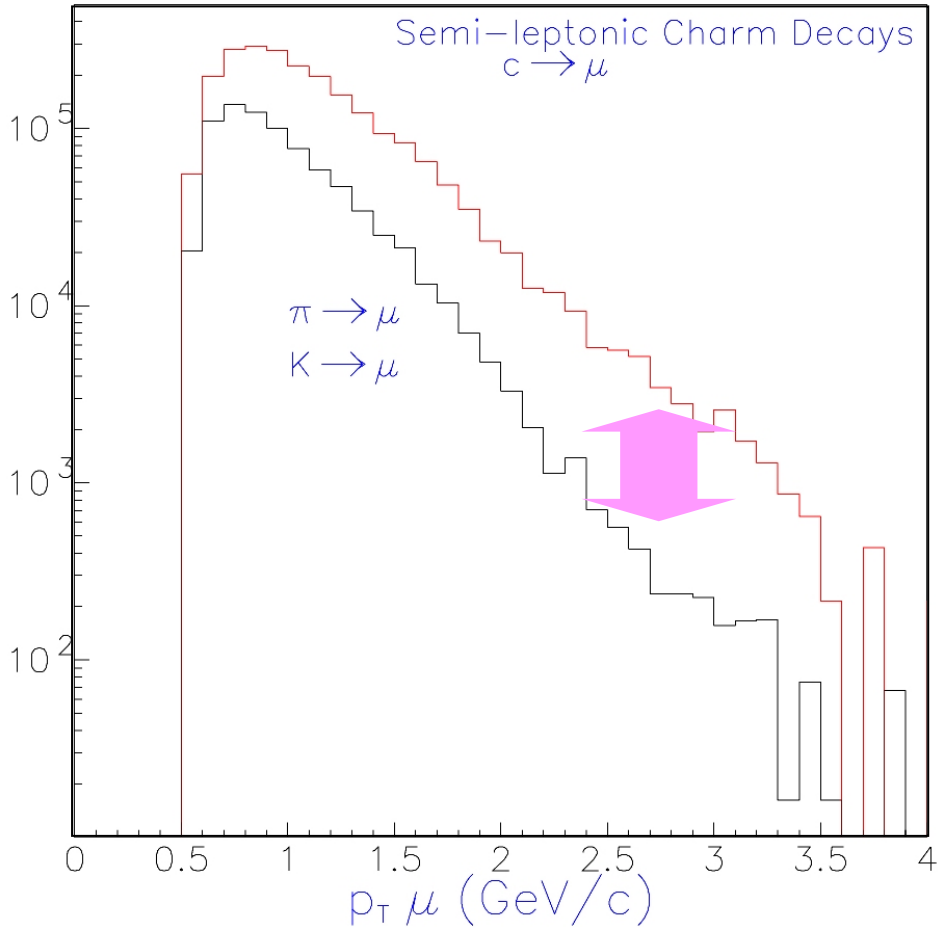


Overlap for complete acceptance



Open Charm Forward Rapidity Si Endcaps



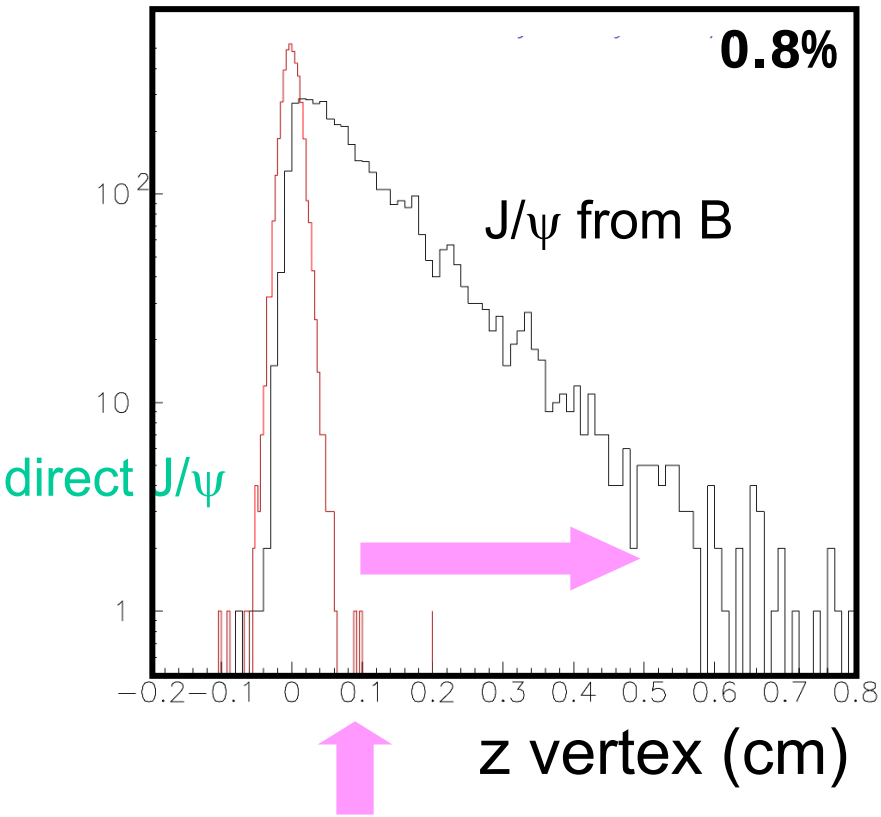


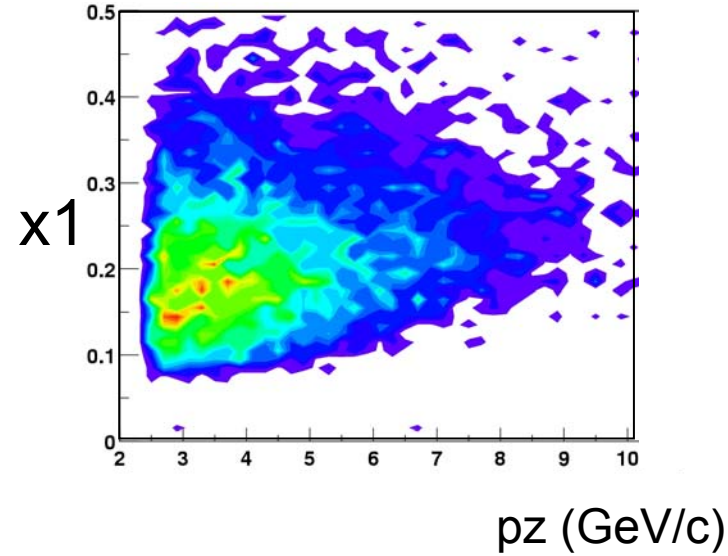
- Inclusive D=>μ+X dominated by π, K decays
  - Cut: muon from within 1cm of collision
  - removes most muons from π, K decay

high-statistics, robust charm

same y, pt range as J/ψ
=> critical for normalization

Example, B → J/ψ → μμ





-> Phenix high rate

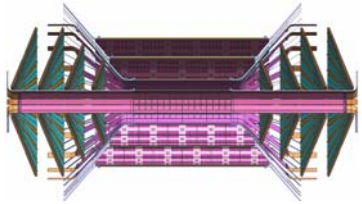
e.g. with z vertex > 0.1cm

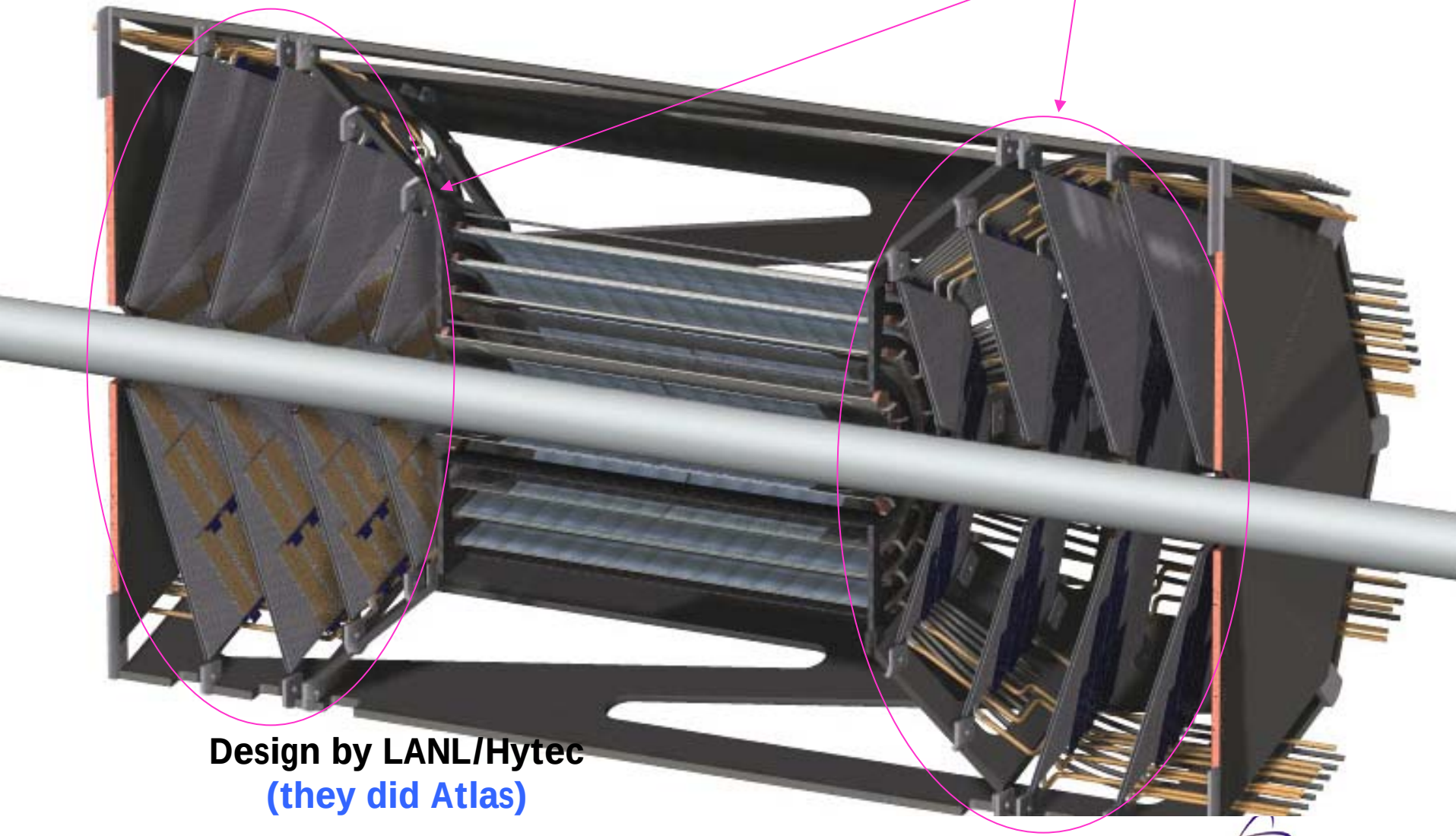
p+p: J/ψ ~20K/year

Au+Au: J/ψ ~7K/year

B => J/ψ, utilizing large acceptance muon arms

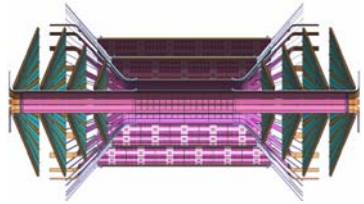
Conceptual Design Study

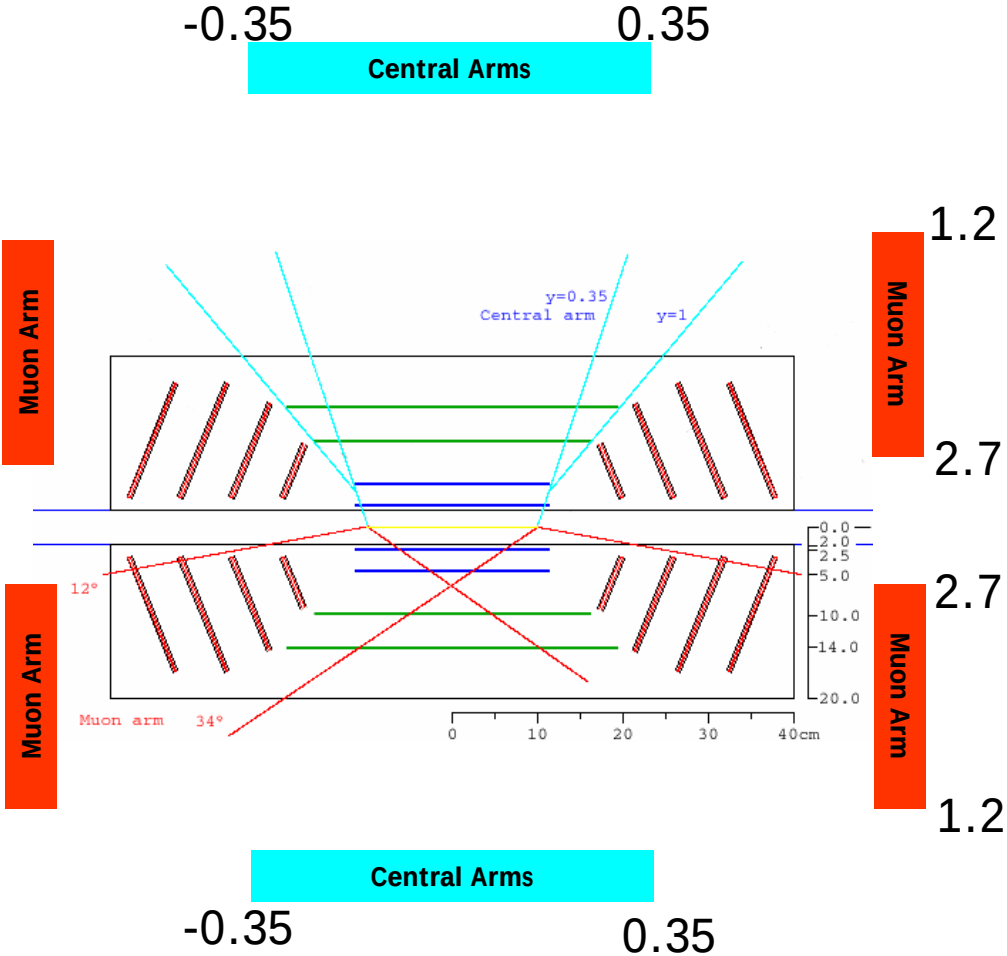




Design by LANL/Hytec
(they did Atlas)

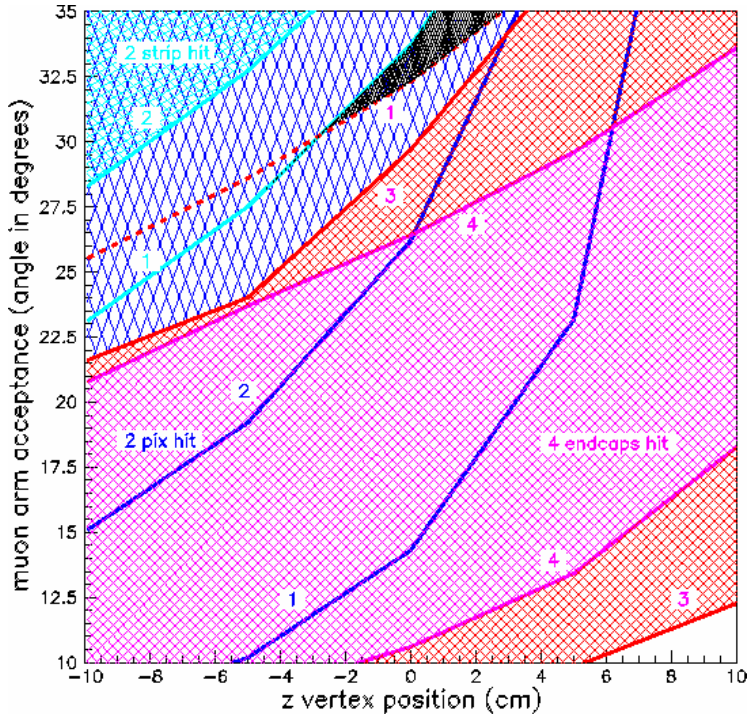
Barrel/Endcap Acceptance





Endcaps

Colored Area: 3 or more silicon hits

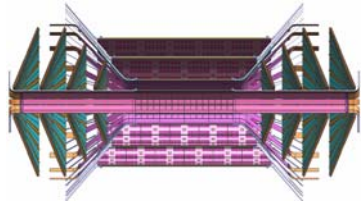


Yellow line in left figure

Barrel: 4 hits for Central Arm Acceptance

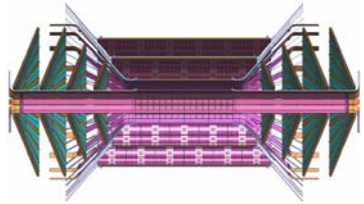
Endcap: 3 or more hits for Muon Arm Acceptance

Barrel Rate Estimates



Process	no VTX	Yield	Yield with DCA cuts
AuAu→c→e			
$1.0<p_T<2.0$ GeV/c	Yes	3M	150K (40K)
$2.0<p_T<3.0$ GeV/c	Limited	130K	6K
$3.0<p_T<4.0$ GeV/c	No	5K	0.3K
$4.0<p_T<5.0$ GeV/c	No	1K	50
$5.0<p_T<6.0$ GeV/c	No	0.2K	10
AuAu→b→e			
$1.0<p_T<2.0$ GeV/c	No	200K	50K (20K)
$2.0<p_T<3.0$ GeV/c	No	70K	15K
$3.0<p_T<4.0$ GeV/c	Limited	17K	3K
$4.0<p_T<5.0$ GeV/c	Limited	4K	0.7K
$5.0<p_T<6.0$ GeV/c	Limited	1K	0.2K
Au+Au→D→$K\pi$ (central)			
$p_T>2$ GeV/c	No	4900 (S/B~0.1%)	1000 (S/B~3%)
$p_T>3$ GeV/c	No	2900 (S/B~1%)	600 (S/B ~5%)
Au+Au→B→J/ψ→ee	No	100	50
$p+p$→c→e			
$1<p_T<3$ GeV/c	Yes	10M	0.5M
$p_T>3$ GeV/c	No	20 K	1K
$p+p$→b→e			
$p_T>1$ GeV/c	No	0.9M	0.2M
$p+p$→γ+jet			
$4<p_T<5$ GeV/c	No	300K	N.A.
$5<p_T<6$ GeV/c	No	150K	N.A.
$6<p_T<7$ GeV/c	No	70K	N.A.
$7<p_T<8$ GeV/c	No	40K	N.A.
$8<p_T<9$ GeV/c	No	20K	N.A.
$9<p_T<10$ GeV/c	No	12K	N.A.
$p+p$→B→J/ψ→ee	No	560	280

Summary: Physics Beyond Reach of PHENIX Baseline



2008 - barrel VTX will provide key measurements to PHENIX:

Detailed study of Heavy Quark production

- Beauty and Charm measurement in p+p, p-A and A-A collisions
- Energy loss of charm/beauty in hot matter
- ΔG (gluon polarization) measurement by heavy quark production over a wide Bjorken-x range
- Gluon shadowing over a wide x range

Measurements complement and enhance the physics program

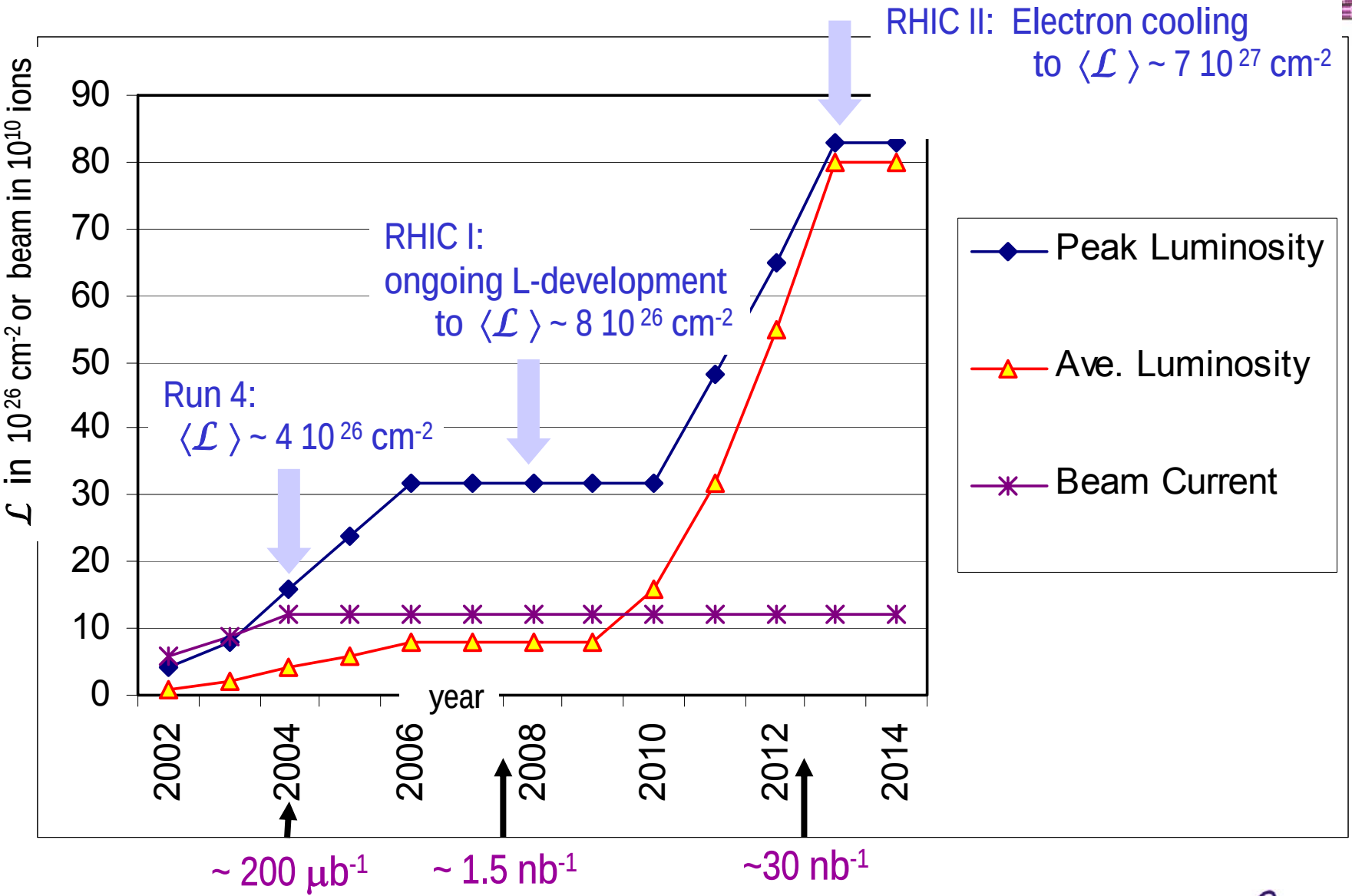
- Fully exploit existing rare event capabilities of PHENIX
- "Complete" the PHENIX central and muon spectrometers

‘Charm and Beauty’

will be seen by

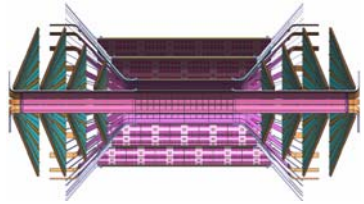
PHENIX VTX

BACKUP I : RHIC Au-Au Luminosity



Integrated Au-Au luminosity recorded by PHENIX

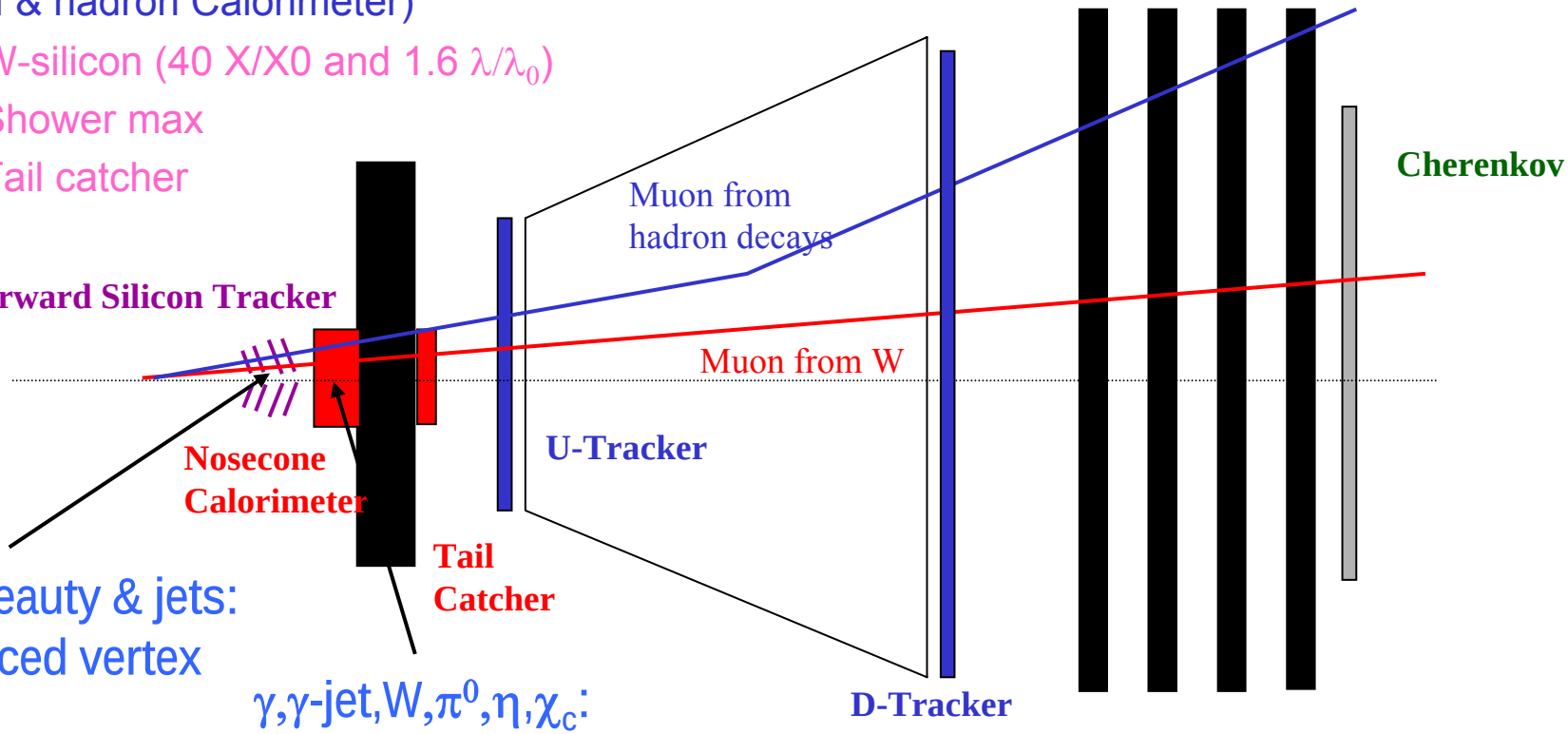
BACKUP II: Forward Upgrade



- Forward Silicon Vertex Tracker
  - Silicon ministrip detectors

NCC (EM & hadron Calorimeter)
  - W-silicon (40 X/X0 and 1.6 λ/λ_0)
  - Shower max
  - Tail catcher

- Muon trigger
  - U-tracker (MuTr or new)
  - D-tracker (timing with RPC's?)
  - Cherenkov



charm/beauty & jets:
displaced vertex

γ,γ-jet,W,π^0,η,χ_c:
calorimeter

W and quarkonium:
improved μ-trigger rejection