AFTER@LHC
Luminosities, yields and tentative design

Cynthia Hadjidakis
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

SPRING 2012 AFTER Meeting
Grenoble, May 10th

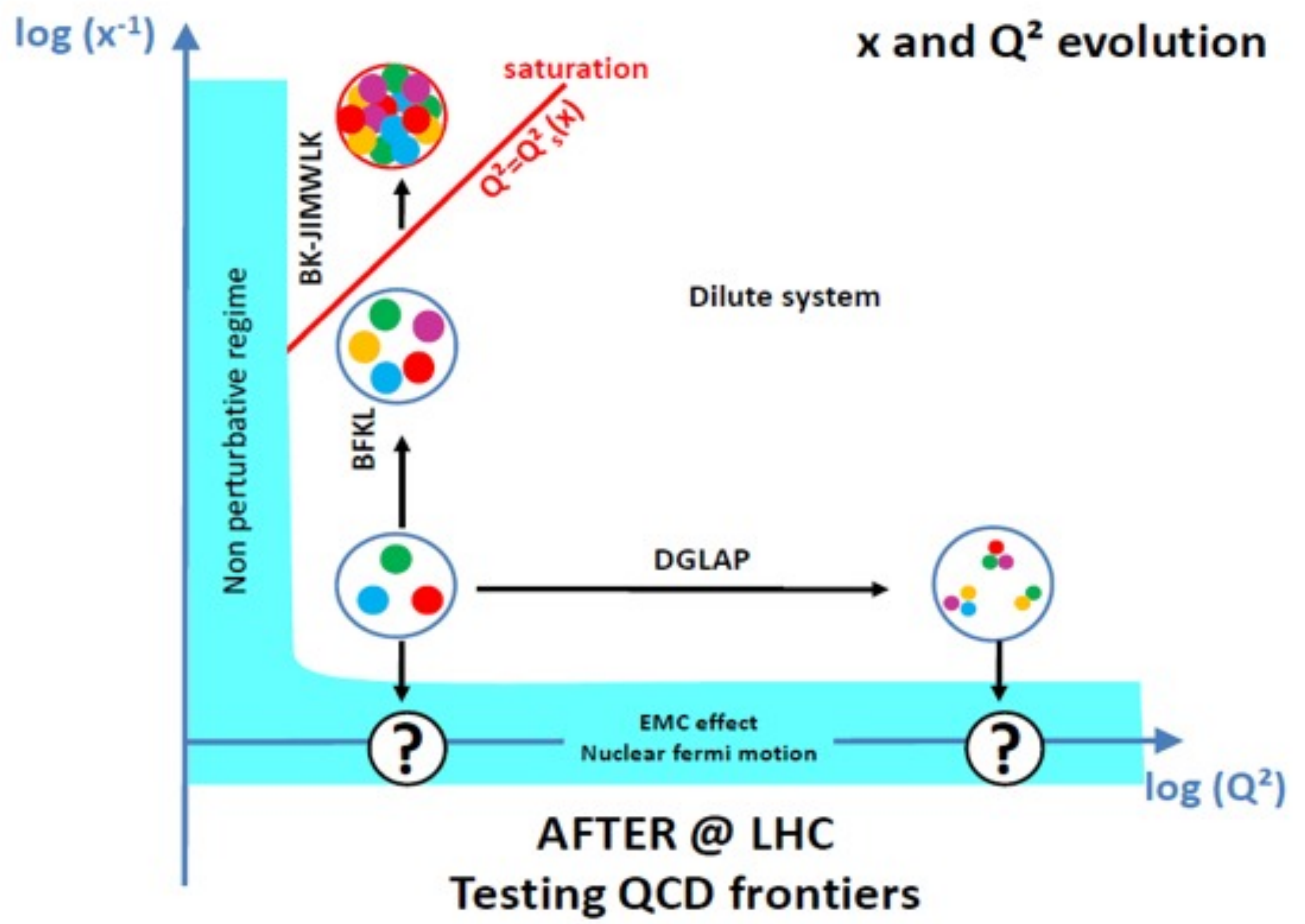
- Why and how a fixed target experiment at the LHC?
- Expected luminosities and quarkonium yields in pH, pA and PbA
  arXiv:1202.6585
- A tentative design for AFTER

Physics opportunities with A Fixed Target ExpeRiment (AFTER) @LHC

- **Idea: use LHC beam on fixed target**
  - 7 TeV proton beam ($\sqrt{s}$ ~115 GeV)
    - p+H, p+A
  - 2.75 TeV Pb beam ($\sqrt{s}$ ~72 GeV)
    - Pb+A, Pb+H

- **High boost and luminosity giving access to**
  - QCD at large *x*
  - nPDF and nuclear shadowing
  - QGP
  - Spin physics
  - Other ?

See Jean-Philippe's talk



LHC proton and lead beam extraction

- Proposal for the insertion of a bent crystal in the LHC beam

- Bent, single crystal of Si or Ge - 17cm long crystal
- Distance of 7 σ to the beam to intercept and deflect the beam halo

- Proton beam extraction

- Beam loss from LHC is ~ 10^9 p/s
- Extraction efficiency of 50% → $N_{beam} = 5\ 10^8$ p/s

- Ion beam extraction

- Ions extraction tested at SPS, is expected to be also possible at LHC

Available online at www.sciencedirect.com
SCIENCE @ DIRECT®
ELSEVIER
Nuclear Instruments and Methods in Physics Research B 234 (2005) 31–39
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Strong crystalline fields – a possibility for extraction from the LHC

E. Uggerhøj, U.I. Uggerhøj *

⇒ Next step: crystal will be installed in LS1 (2013) and tested at LHC to clean the beam (LUA9 Collaboration)

Luminosities in pH and pA @ 115 GeV

- **Intensity: $N_{beam} = 5.10^8$ protons.s^{-1}**
  - **Beam:** 2808 bunches of 1.15×10^{11} protons = **3.2×10^{14} protons**
  - **Bunch:** Each bunch passes IP at the rate: 3.10^5 km.s^{-1}/27 km ~ **11 kHz**
  - **Instantaneous extraction:** IP sees 2808 x 11000~3.10^7 bunches passing every second → extract $5.10^8/3.10^7$ ~ **extract 16 protons in each bunch at each pass**
  - **Integrated extraction:** Over a 10h run: extract 5.10^8p x 3600s.h^{-1} x 10h=1.8 10^{13}p.run^{-1} → extract 1.8 x 10^{13}/(3.2 x 10^{14})~**5.6% of the protons stored in the beam**

- **Instantaneous Luminosity**

  $L = N_{beam} \times N_{Target} = N_{beam} \times (\rho \times \mathbf{e} \times N_A)/A$
  - N_{beam}=5 x 10^8 p^+/s
  - **e** (target thickness) = 1 cm

- **Integrated luminosity**
  - 9 months running/year
  - 1 year ~ 10^7 s

Target (1 cm thick)	ρ (g cm^{-3})	A	$\mathcal{L}$ (μb^{-1} s^{-1})	$\int \mathcal{L}$ (pb^{-1} yr^{-1})
solid H	0.088	1	26	260
liquid H	0.068	1	20	200
liquid D	0.16	2	24	240
Be	1.85	9	62	620
Cu	8.96	64	42	420
W	19.1	185	31	310
Pb	11.35	207	16	160

⇒ Large luminosity in pH(A) ranging from 0.1 and 0.6 fb^{-1} for a 1 cm thick target

Luminosities in PbA @ 72 GeV

- **Intensity: N_{beam} = 2.10^5 Pb.s^{-1}**
  - **Beam:** 592 bunches of 7x10^7 ions = **4.1x10^{10} ions**
  - **Bunch:** Each bunch passes IP at the rate: 3.10^{5}km.s^{-1}/27 km ~ **11 kHz**
  - **Instantaneous extraction:** IP sees 592 x 11000~6.5.10^6 bunches passing every second → extract 2.10^5/6.510^6 ~ **extract 0.03 ions in each bunch at each pass**
  - **Integrated extraction:** Over a 10h run: extract 2.10^{5}Pb.s^{-1} x 3600s.h^{-1} x 10h=7.2 10^{9}Pb.run^{-1} → extract 7.2 x 10^9/(4.1 x 10^{10})~**15% of the ions stored in the beam**

- **Instantaneous Luminosity**

  $L = N_{beam} \times N_{Target} = N_{beam} \times (\rho \times e \times N_A)/A$
  - N_{beam}=2 x 10^5 Pb/s
  - **e** (target thickness) = 1 cm

- **Integrated luminosity**
  - 1 months running/year
  - 1 year ~ 10^6 s

Target (1 cm thick)	ρ (g cm^{-3})	A	$\mathcal{L}$ (mb^{-1} s^{-1})	$\int\mathcal{L}$ (nb^{-1} yr^{-1})
solid H	0.088	1	11	11
liquid H	0.068	1	8	8
liquid D	0.16	2	10	10
Be	1.85	9	25	25
Cu	8.96	64	17	17
W	19.1	185	13	13
Pb	11.35	207	7	7

⇒ AFTER provides a good luminosity to study QGP related measurements

Polarizing the hydrogen target

- **Instantaneous luminosity**

  $L = N_{beam} \times N_{Target} = N_{beam} \times (\rho \times \mathbf{e} \times N_A)/A$

  – $N_{beam} = 5 \times 10^8$ p^+/s

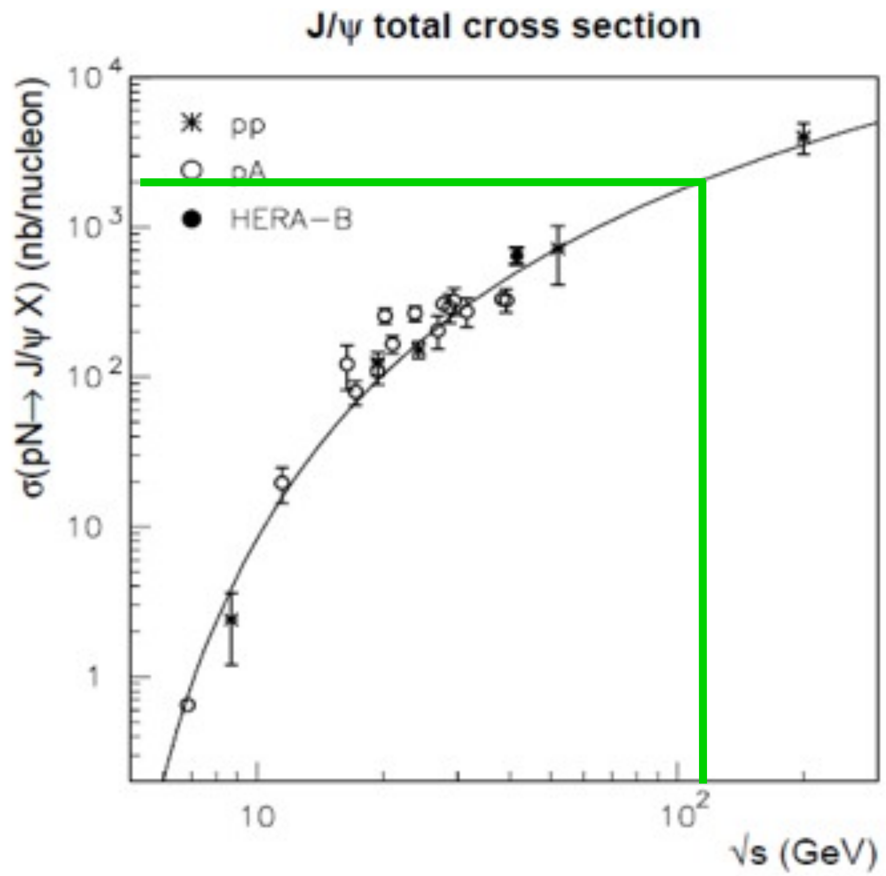
  – **e** (target thickness) = 50 cm

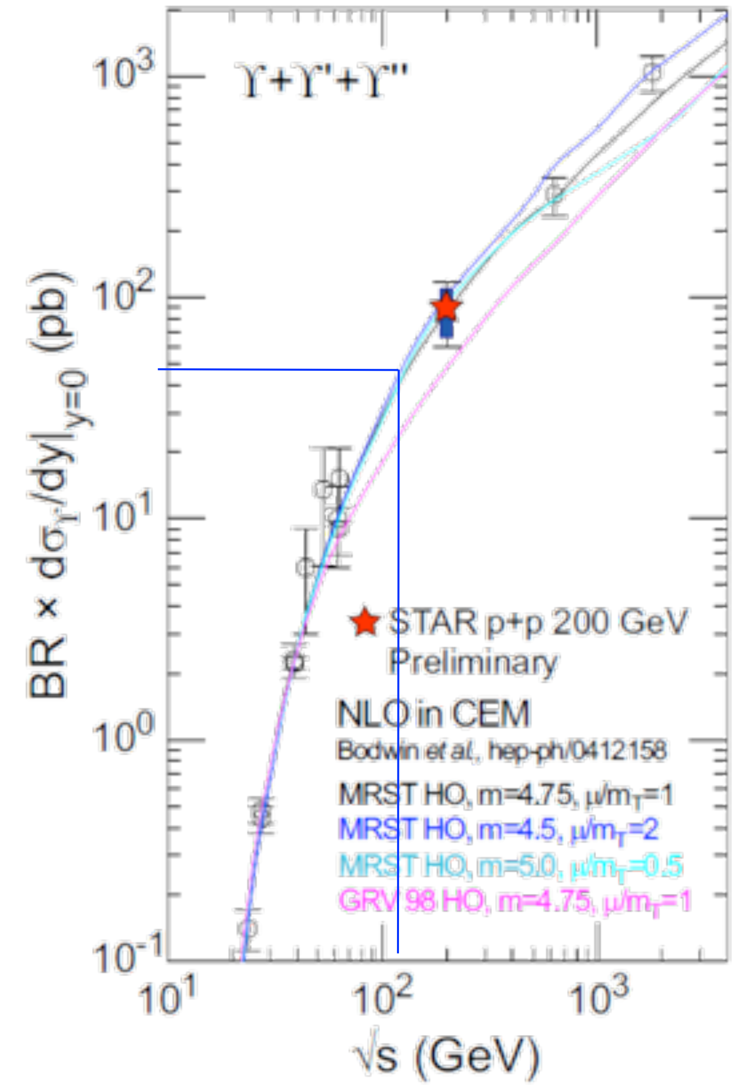
Experiment	particles	energy (GeV)	$\sqrt{s}$ (GeV)	$x_p^\uparrow$	$\mathcal{L}$ ($nb^{-1}s^{-1}$)
AFTER	$p + p^\uparrow$	7000	115	$0.01 \div 0.9$	1
COMPASS	$\pi^\pm + p^\uparrow$	160	17.4	$0.2 \div 0.3$	2
COMPASS (low mass)	$\pi^\pm + p^\uparrow$	160	17.4	~ 0.05	2
RHIC	$p^\uparrow + p$	collider	500	$0.05 \div 0.1$	0.2
J–PARC	$p^\uparrow + p$	50	10	$0.5 \div 0.9$	1000
PANDA (low mass)	$\bar{p} + p^\uparrow$	15	5.5	$0.2 \div 0.4$	0.2
PAX	$p^\uparrow + \bar{p}$	collider	14	$0.1 \div 0.9$	0.002
NICA	$p^\uparrow + p$	collider	20	$0.1 \div 0.8$	0.001
RHIC Int.Target 1	$p^\uparrow + p$	250	22	$0.2 \div 0.5$	2
RHIC Int.Target 2	$p^\uparrow + p$	250	22	$0.2 \div 0.5$	60

$x_p^\uparrow$ range corresponds to Drell-Yan measurements

⇒ AFTER provides a good luminosity to sudy target spin related measurements

Quarkonium yields





Inclusive pp cross-sections

$B_{ll}\, d\sigma/dy|_{y=0}$ @ 115 GeV

J/ψ = 20 nb

Y = 40 pb

Inclusive pp cross-sections

$B_{ll}\, d\sigma/dy|_{y=0}$ @ 72 GeV

J/ψ = 10 nb

Y = 15 pb

Quarkonium yields in pp and pA @ 115 GeV

In pp

⇒ RHIC @ 200 GeV x 100 with 10 cm thick H target

⇒ Comparable to LHCb if 1m H target

⇒ Detailed studies of quarkonium production (p_T, y, polarization, different quarkonium states, ...)

In pA

⇒ RHIC @ 200 GeV x 100 with 1 cm Pb target

⇒ Detailed studies of cold nuclear matter effect in pA (p_T, y, A, ...)

Target	$\int dt \mathcal{L}$	$\mathcal{B}_{\ell\ell} \frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$	$\mathcal{B}_{\ell\ell} \frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$
10 cm solid H	2.6	5.2 10^7	1.0 10^5
10 cm liquid H	2	4.0 10^7	8.0 10^4
10 cm liquid D	2.4	9.6 10^7	1.9 10^5
1 cm Be	0.62	1.1 10^8	2.2 10^5
1 cm Cu	0.42	5.3 10^8	1.1 10^6
1 cm W	0.31	1.1 10^9	2.3 10^6
1 cm Pb	0.16	6.7 10^8	1.3 10^6
pp low P_T LHC (14 TeV)	0.05	3.6 10^7	1.8 10^5
	2	1.4 10^9	7.2 10^6
pPb LHC (8.8 TeV)	10^{-4}	1.0 10^7	7.5 10^4
pp RHIC (200 GeV)	1.2 10^{-2}	4.8 10^5	1.2 10^3
dAu RHIC (200 GeV)	1.5 10^{-4}	2.4 10^6	5.9 10^3
dAu RHIC (62 GeV)	3.8 10^{-6}	1.2 10^4	1.8 10^1

Luminosity per year in fb^{-1}

Quarkonium yields in pH and pA @ 115 GeV

In pp

⇒ RHIC @ 200 GeV x 100 with 10 cm thick H target

⇒ Comparable to LHCb if 1m H target

⇒ Detailed studies of quarkonium production (p_T, y, polarization, different quarkonium states, ...)

In pA

⇒ RHIC @ 200 GeV x 100 with 1 cm Pb target

⇒ Detailed studies of cold nuclear matter effect in pA (p_T, y, A, ...)

Geometrical Acceptance

Simulations using ALICE as a fixed target experiment at LHC quotes a Geometrical Acceptance of 8% for J/ψ (4 π) → $\mu^+\mu^-$ (2.5< y < 4) using the Forward Muon Spectrometer @ 115 GeV

Target	$\int dt\mathcal{L}$	$\mathcal{B}_{\ell\ell}\frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$	$\mathcal{B}_{\ell\ell}\frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$
10 cm solid H	2.6	$5.2\ 10^7$	$1.0\ 10^5$
10 cm liquid H	2	$4.0\ 10^7$	$8.0\ 10^4$
10 cm liquid D	2.4	$9.6\ 10^7$	$1.9\ 10^5$
1 cm Be	0.62	$1.1\ 10^8$	$2.2\ 10^5$
1 cm Cu	0.42	$5.3\ 10^8$	$1.1\ 10^6$
1 cm W	0.31	$1.1\ 10^9$	$2.3\ 10^6$
1 cm Pb	0.16	$6.7\ 10^8$	$1.3\ 10^6$
pp low P_T LHC (14 TeV)	0.05	$3.6\ 10^7$	$1.8\ 10^5$
	2	$1.4\ 10^9$	$7.2\ 10^6$
pPb LHC (8.8 TeV)	10^{-4}	$1.0\ 10^7$	$7.5\ 10^4$
pp RHIC (200 GeV)	$1.2\ 10^{-2}$	$4.8\ 10^5$	$1.2\ 10^3$
dAu RHIC (200 GeV)	$1.5\ 10^{-4}$	$2.4\ 10^6$	$5.9\ 10^3$
dAu RHIC (62 GeV)	$3.8\ 10^{-6}$	$1.2\ 10^4$	$1.8\ 10^1$

Luminosity per year in fb^{-1}

Quarkonium yields in PbA @ 72 GeV

PbA

⇒ Same statistics than RHIC @ 200 GeV and LHC and 2 orders of magnitude larger than RHIC @ 62 GeV

⇒ Detailed studies possible for quarkonium states (ψ', χ_c, A, ...)

Target	$\int dt \mathcal{L}$	$\mathcal{B}_{\ell\ell} \frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$	$\mathcal{B}_{\ell\ell} \frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$
10 cm solid H	110	$4.3\ 10^5$	$8.9\ 10^2$
10 cm liquid H	83	$3.4\ 10^5$	$6.9\ 10^2$
10 cm liquid D	100	$8.0\ 10^5$	$1.6\ 10^3$
1 cm Be	25	$9.1\ 10^5$	$1.9\ 10^3$
1 cm Cu	17	$4.3\ 10^6$	$0.9\ 10^3$
1 cm W	13	$9.7\ 10^6$	$1.9\ 10^4$
1 cm Pb	7	$5.7\ 10^6$	$1.1\ 10^4$
*d*Au RHIC (200 GeV)	150	$2.4\ 10^6$	$5.9\ 10^3$
*d*Au RHIC (62 GeV)	3.8	$1.2\ 10^4$	$1.8\ 10^1$
AuAu RHIC (200 GeV)	2.8	$4.4\ 10^6$	$1.1\ 10^4$
AuAu RHIC (62 GeV)	0.13	$4.0\ 10^4$	$6.1\ 10^1$
*p*Pb LHC (8.8 TeV)	100	$1.0\ 10^7$	$7.5\ 10^4$
PbPb LHC (5.5 TeV)	0.5	$7.3\ 10^6$	$3.6\ 10^4$

Luminosity per year in fb^{-1}

Rapidity boost in a fixed target mode

- **Very high boost:**
  - With 7 TeV beam
    $\gamma = 61.1$ and $y_{CMS} = 4.8$
  - With 2.75 TeV beam
    $\gamma = 38.3$ and $y_{CMS} = 4.3$

- $\eta^* = \eta_{lab} - \mathbf{y_{CMS}}$
  forward region: $\eta^*>0$
  backward region: $\eta^*<0$

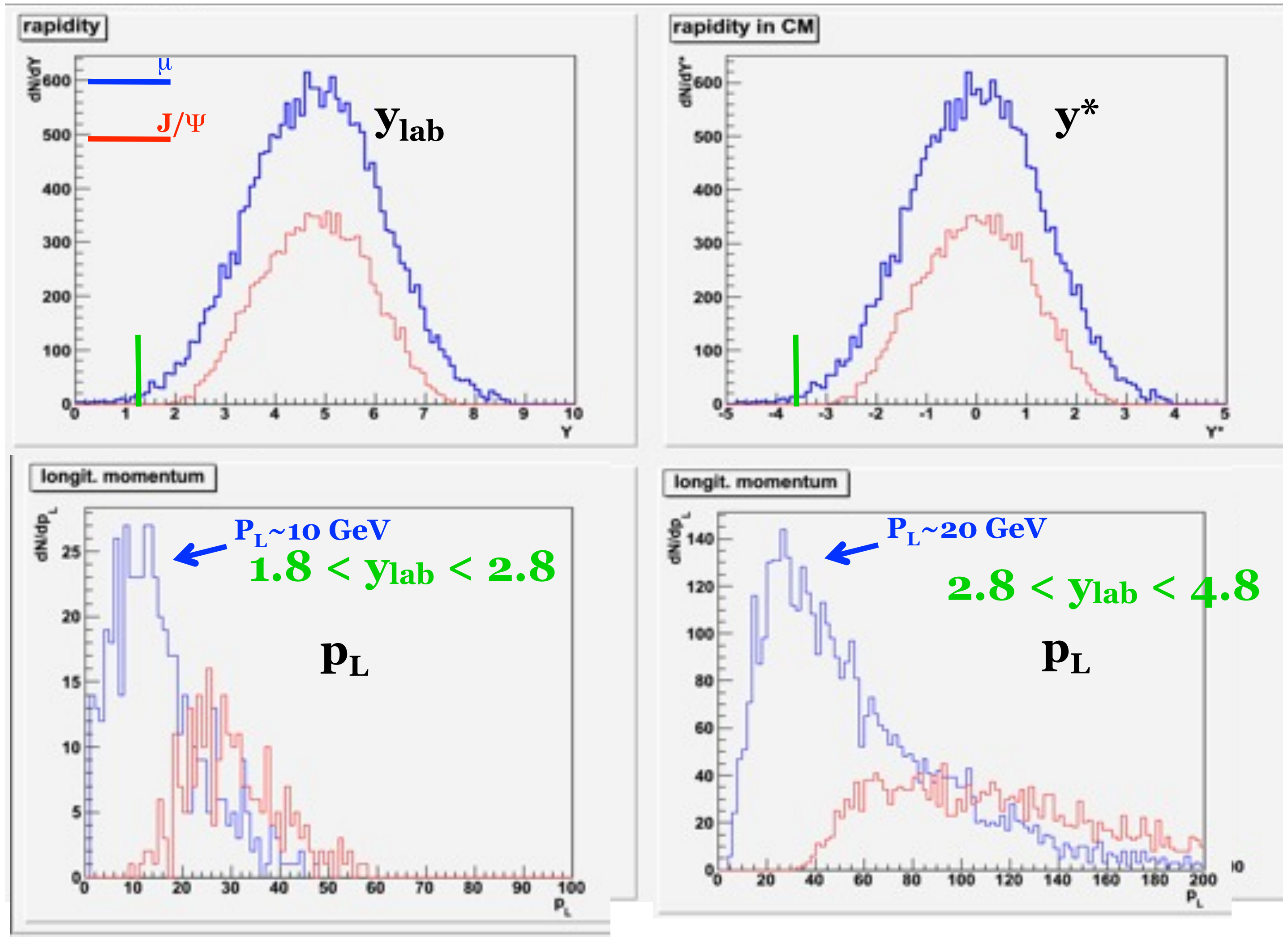
Quarkonium distributions in pp @ 115 GeV

- **Very high boost:**
  - With 7 TeV beam
    $\gamma = 61.1$ and $y_{CMS} = 4.8$
  - With 2.75 TeV beam
    $\gamma = 38.3$ and $y_{CMS} = 4.3$

- $\eta^* = \eta_{lab} - y_{CMS}$
  forward region: $\eta^* > 0$
  backward region: $\eta^* < 0$

- **Taking $x_2 = M/\sqrt{s}\, e^{-y^*}$**
  - $x_2(J/\Psi) = 1 \rightarrow y_{lab}(J/\Psi) \sim 1.2$
  - $x_2(\Upsilon) = 1 \rightarrow y_{lab}(\Upsilon) \sim 2.4$

Pythia: p (7 TeV) + p → J/Ψ (isub=86)
$J/\Psi \rightarrow \mu^+\mu^-$



J/Ψ for $1.3 < y < 5.3$
$\mu \rightarrow P_T \sim$ 1.7 GeV
$\mu \rightarrow P_L \sim$ 62 GeV

$1.3 < y < 3.3$ p_L (max) ~ 16 (50) GeV
$3.3 < y < 4.3$ p_L ~ 45 (150) GeV
$4.3 < y < 5.3$ p_L ~ 120 (300) GeV

Rapidity boost in a fixed target mode

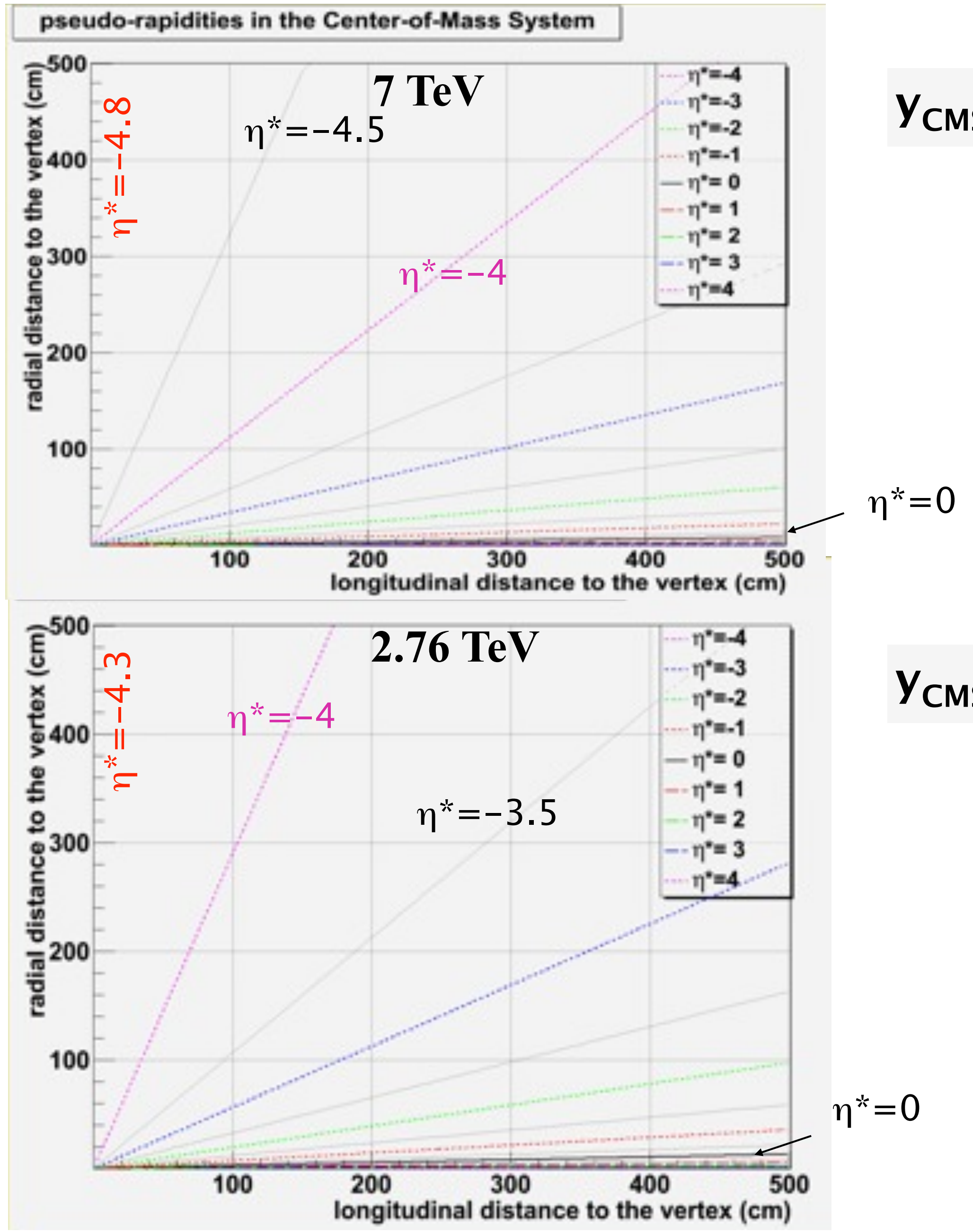
- **Very high boost:**
  - With 7 TeV beam
    $\gamma = 61.1$ and $y_{CMS} = 4.8$
  - With 2.75 TeV beam
    $\gamma = 38.3$ and $y_{CMS} = 4.3$

- $\eta^* = \eta_{lab} - y_{CMS}$
  forward region: $\eta^*>0$
  backward region: $\eta^*<0$

- **Taking $x_2 = M/\sqrt{s}\, e^{-y^*}$**
  - $x_2(J/\Psi) = 1 \rightarrow y_{lab}(J/\Psi) \sim 1.2$
  - $x_2(\Upsilon) = 1 \rightarrow y_{lab}(\Upsilon) \sim 2.4$

- $\eta = -\ln \tan \theta/2$
  $\rightarrow \theta_{y*=0} \sim 0.9°$ (16 mrad)
  - $y_{lab}(J/\Psi) \sim 4.8 \rightarrow x_2(J/\Psi) = 0.27$
  - $y_{lab}(\Upsilon) \sim 4.8 \rightarrow x_2(\Upsilon) = 0.5$

- **Very well placed to access backward physics**

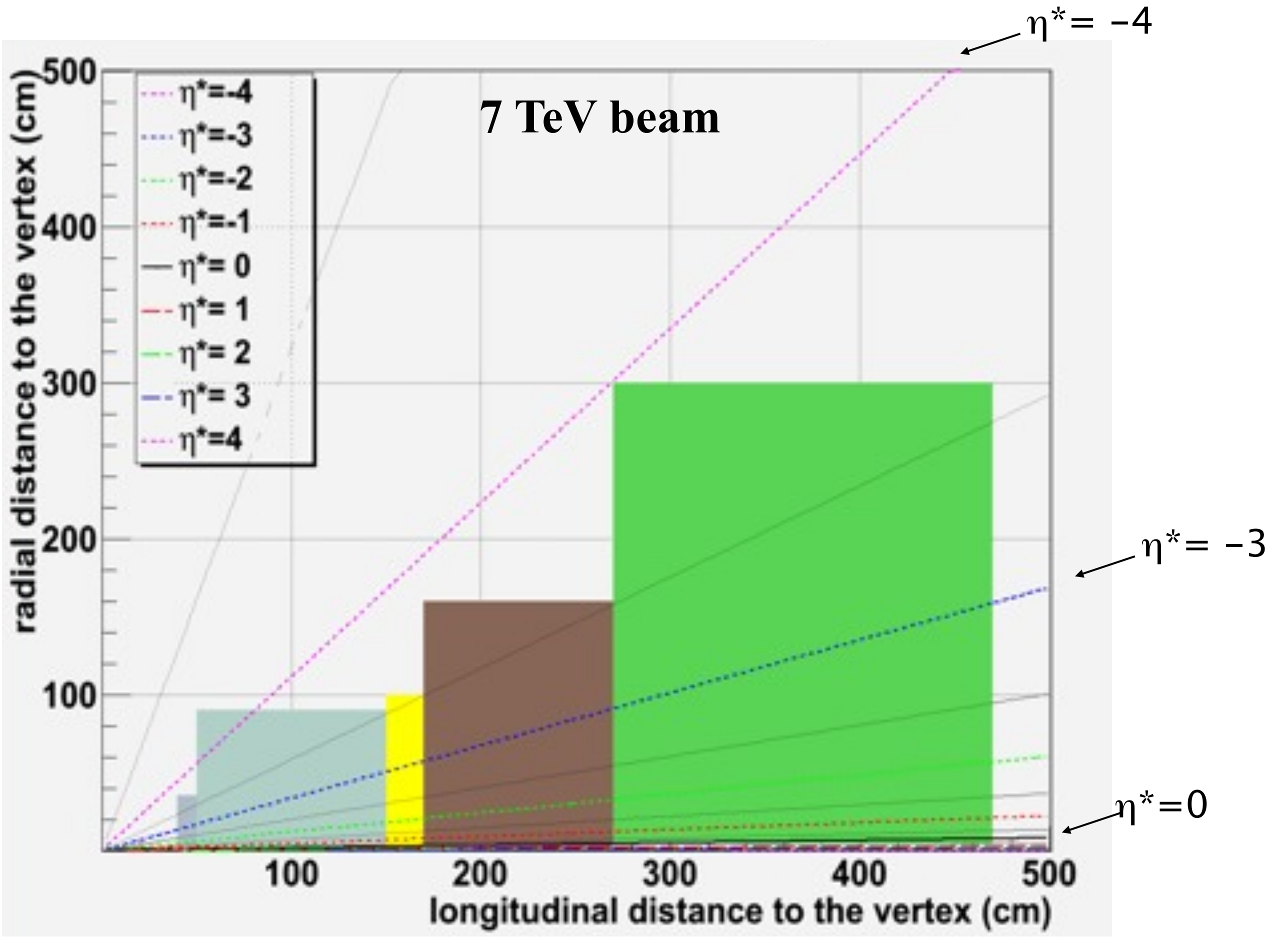


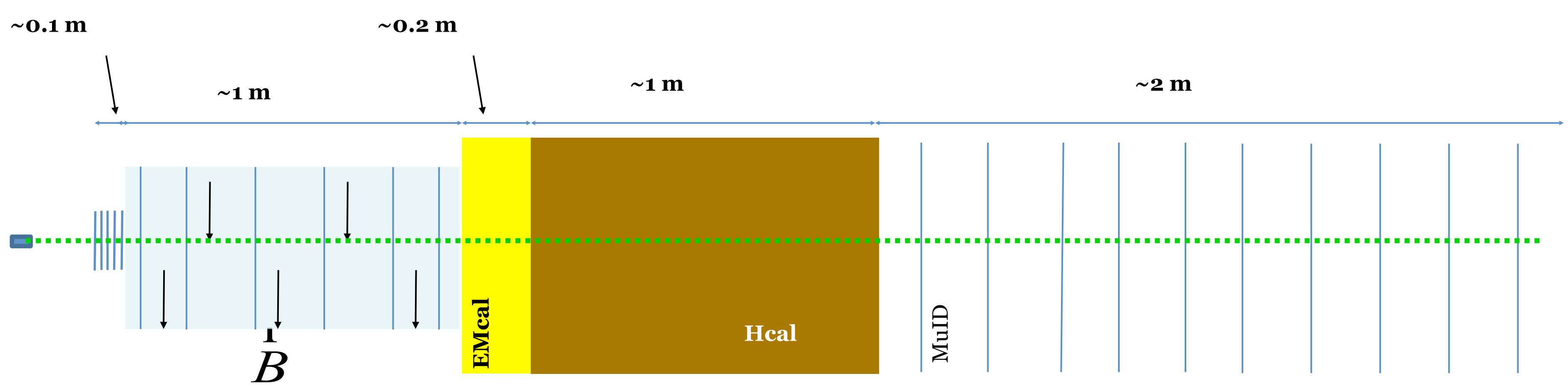
$y_{CMS} = 4.8$

$y_{CMS} = 4.3$

A tentative design for AFTER

- **Tentative design** $1.3 < y_{lab} < 5.3$
  - With 7 TeV beam : $-3.5 < y^* < 0.5$
  - With 2.75 TeV beam: $-3 < y^* < 1$
  - $\theta_{min} = 10$ mrad
- **Multi-purpose detector**
  - Vertex
  - Tracking (+ dipole magnet)
  - Calorimetry
  - Muons
  - PID (not yet considered)
- **High boost** → forward and compact detector

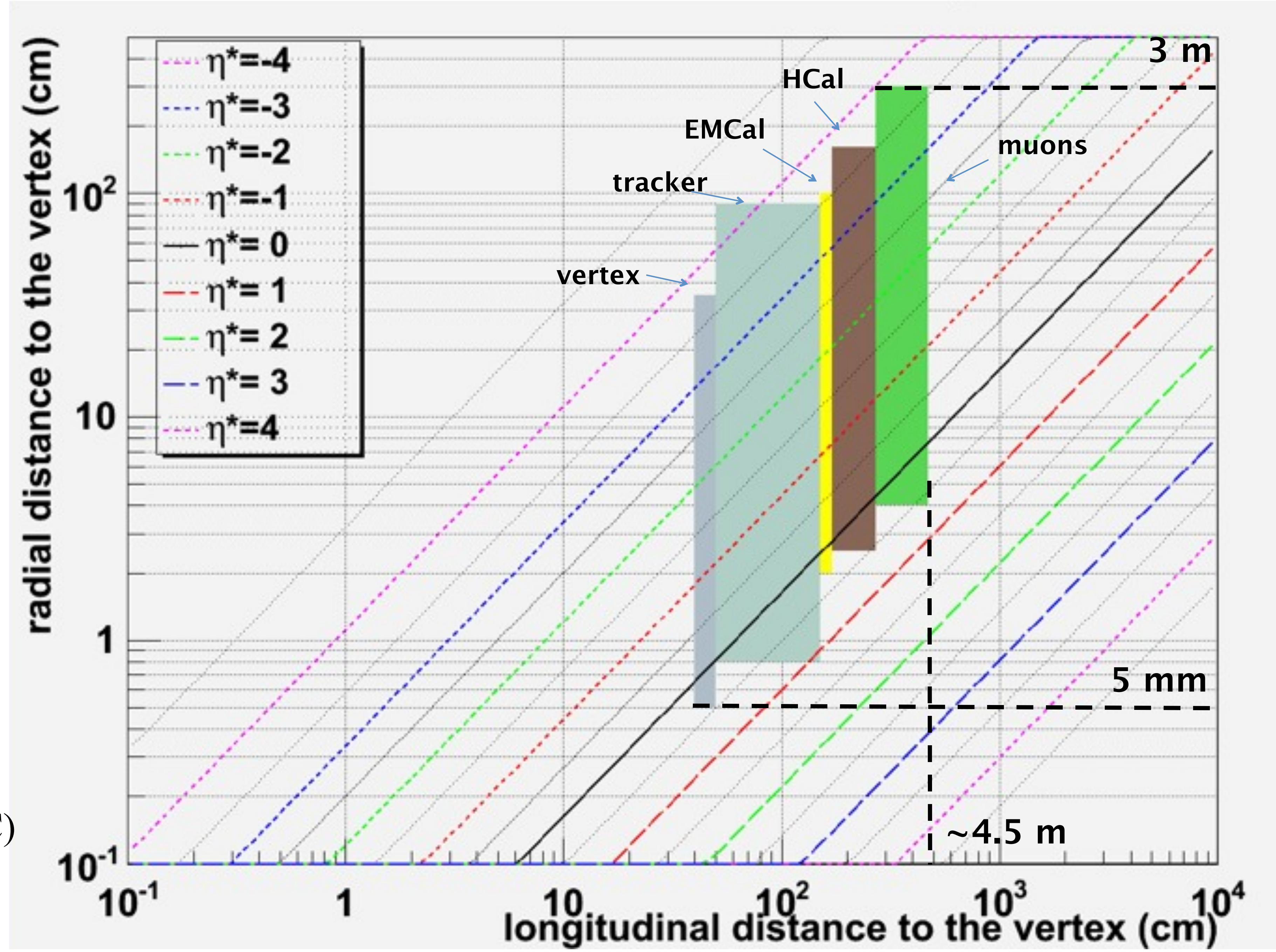




Detectors' dimension

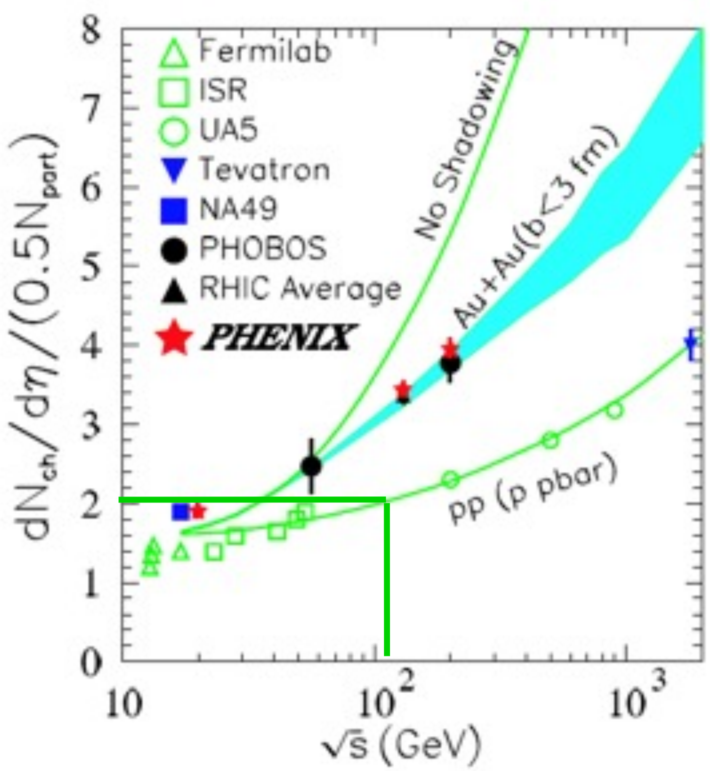
$1.3 < y_{lab} < 4.8$
$\theta_{min} = 16$ mrad

Detector	Z_{min}/Z_{max}	R_{min}/R_{max}
Vertex	40/50 cm	0.5/35 cm
Tracker	50/150 cm	0.8/90 cm
EMCal	150/170 cm	2/100 cm
HCal	170/270 cm	2.5/160 cm
Muons	270/470 cm	4/300 cm

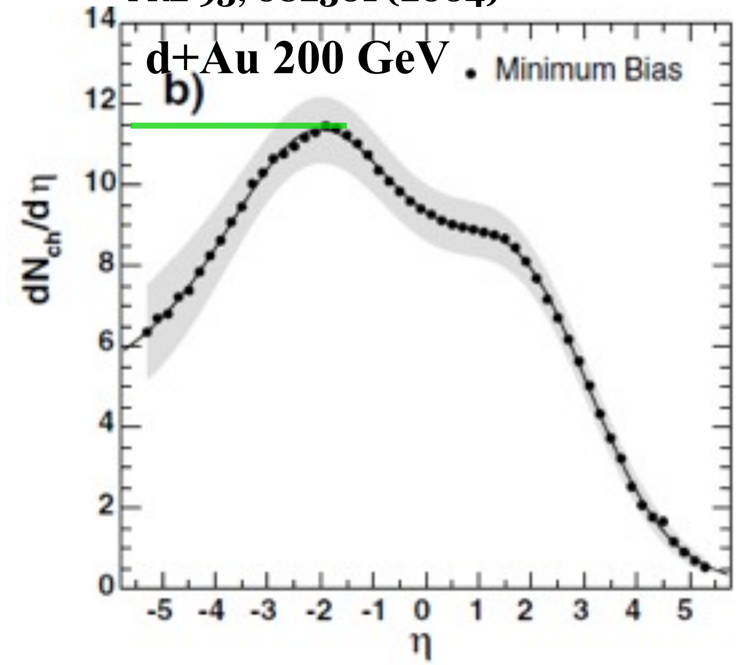


- **Technology**
- Vertex, tracker: pixel detectors
- EMCal: Tungsten/Si (Calice - ILC)
- Muons: Magnetize Fe (Minos)
- …

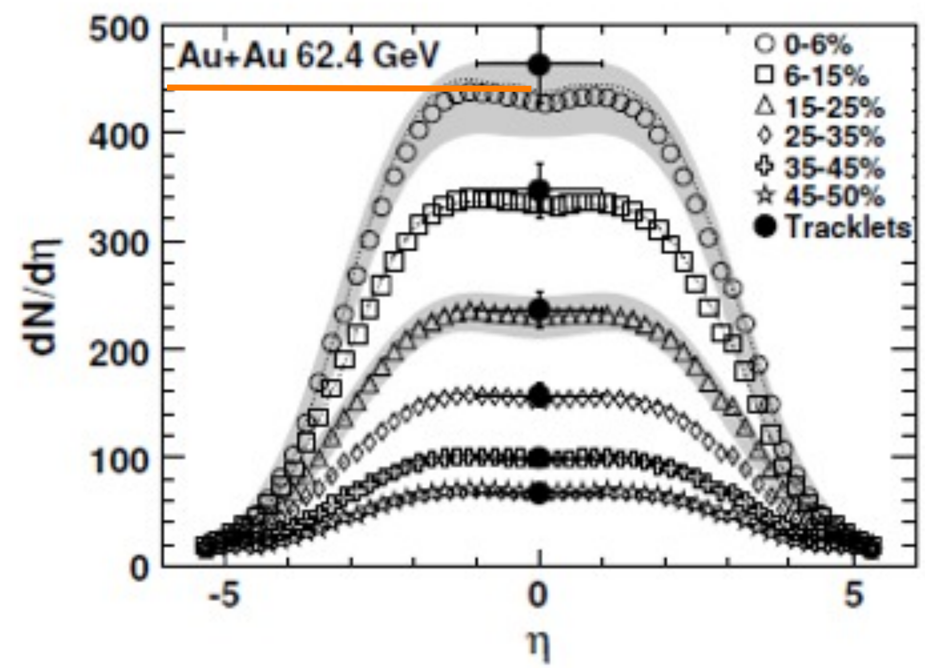
Multiplicity



PRL 93, 082301 (2004)



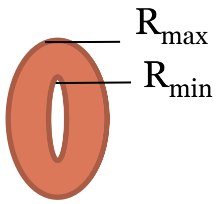
PRC 74, 021901(R) (2006)



Charged particles per unit of rapidity: (x 1.5 = charged+neutral)

p+p @ 115 GeV ~ 2 **d+Au @ 200 GeV : max ~11** **Au+Au @ 62.4 GeV : max ~ 450**

→ A highly granular detector is needed



y <|0.5|	R_{min} (cm)	R_{max} (cm)	Surface (cm²)
Vertex	1.5	10	~ 300
Calo	10	40	~4700

Vertex ~ 450 part.

$$1\% \sim \frac{450}{300\times\left(\frac{1}{0.8\times0.8\ \mathrm{mm}^2}\right)}$$

$$0.1\% \sim \frac{450}{300\times\left(\frac{1}{0.25\times0.25\ \mathrm{mm}^2}\right)}$$

Calo ~ 700 part.

$$\frac{700}{4700\times\left(\frac{1}{1\times1\ \mathrm{cm}^2}\right)} \sim 14\%$$

$$\frac{700}{4700\times\left(\frac{1}{0.5\times0.5\ \mathrm{cm}^2}\right)} \sim 3.7\%$$

Conclusion and outlook

- Extraction of p and Pb beam at LHC on a fixed target experiment offers many physics opportunities

- High luminosities are expected in pH, pA and $pH^{\uparrow}$ @ 115 GeV and PbA @ 72 GeV

- Large expected statistics (see quarkonium case) will allow precise measurements

- AFTER detectors should cope with the high rapidity boost and the large multiplicity expected in PbA: a highly granular and compact experimental setup is under consideration