Review of Measurements with HERA-B

Prospects for Early Measurements with LHCb

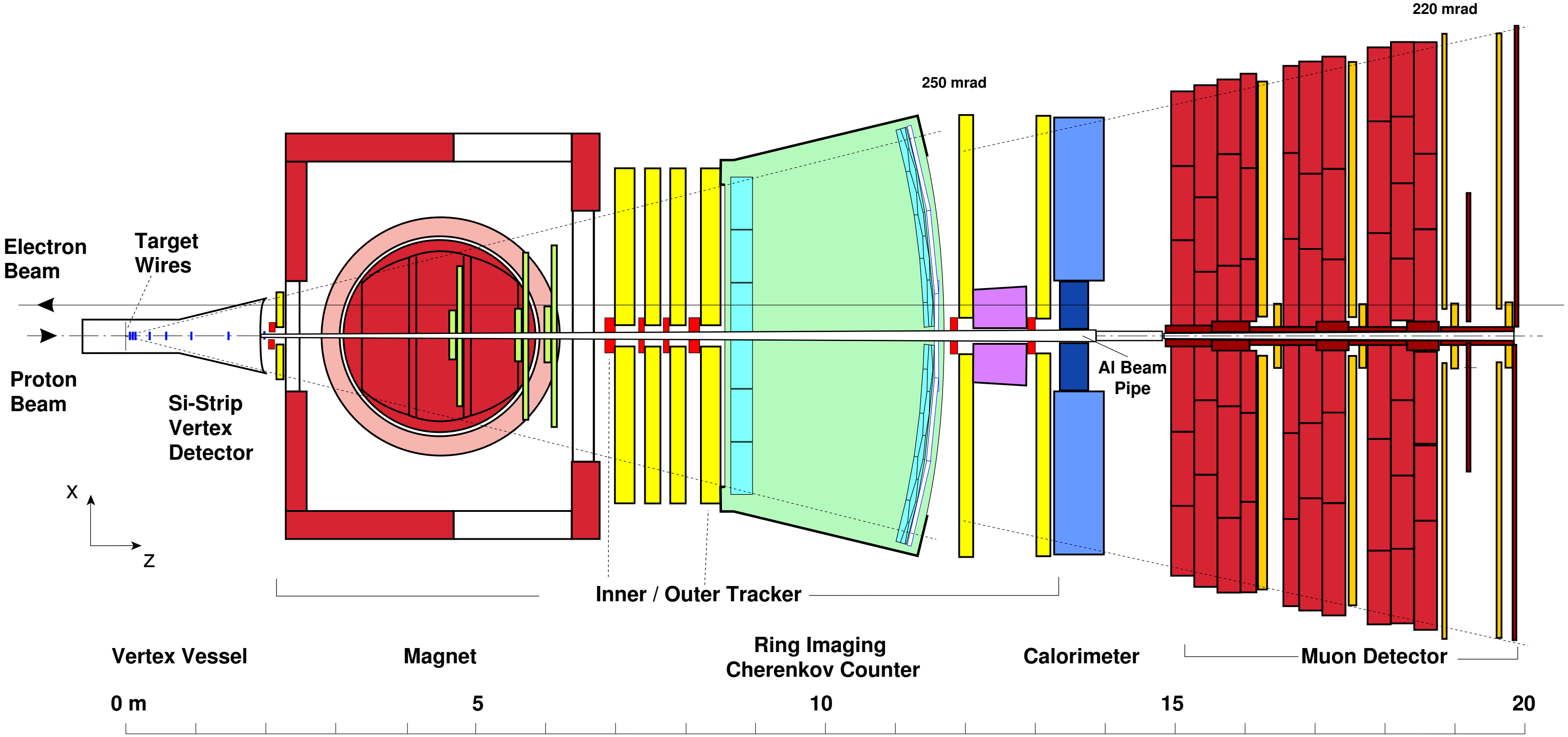
Michael Schmelling – MPI for Nuclear Physics
e-Mail: Michael.Schmelling@mpi-hd.mpg.de

Outline

- *The HERA-B Experiment*
- *Setting the Stage for LHCb*
- *Selected Physics Topics*
- *Summary and Conclusions*

Disclaimer

Cross sections and rates given below are order-of-magnitude estimates, (usually) NOT the result of detailed studies.



- fixed target experiment at the HERA proton ring
- C, Al, Ti, W target wires in the beam halo
- forward spectrometer - layout similar to LHCb, except . . .
  - ➜ only one RICH detector
  - ➜ simpler ECAL system (no PS, no SPD)
  - ➜ no HCAL

Kinematics

- angular coverage $10 - 220$ mrad
  - ➜ pseudorapidity very similar to range covered by LHCb

$$\eta = -\ln\tan\frac{\theta}{2} \sim [2.2 - 5.2] \sim 3.7 \pm 1.5$$

- energy of the proton beam $E = 920$ GeV
  - ➜ nucleon-nucleon center-of-mass energy

$$\sqrt{s_{NN}} = \sqrt{2 m_N E} \approx 42 \text{ GeV}$$

  - ➜ boost of center-of-mass system

$$\gamma = \frac{E}{M} \approx \frac{920}{42} \approx 22$$

  - ➜ rapidity of center-of-mass system

$$y = \frac{1}{2}\ln\frac{E+p}{E-p} = \frac{1}{2}\ln\frac{(E+p)^2}{(E+p)(E-p)} \approx \ln\frac{2E}{M} \approx \ln 44 \approx 3.8$$

- HERA-B is a central detector !
- study of pA collisions at $\sqrt{s_{NN}} = 42$ GeV

Particle Flux

❖ compare particle flux in LHCb and HERA-B

rule of thumb: $\Phi \sim \nu_{int} \cdot \ln s \cdot \Delta y$

	$\sqrt{s}$ /GeV	ν_{int} /MHz	Φ_{rel}
HERA-B nom.	42	40	1
HERA-B MinBias	42	2	0.05
LHCb 2008	14000	0.01 – 1	0.0006 – 0.06
LHCb nom.	14000	10	0.6

- similar radiation loads for both experiments
  - ➜ pile-up events in nominal HERA-B operation
  - ➜ "clean" conditions for nomimal LHCb running

❖ the very first HERA-B data sets:

Target	A	Wire	Run	triggers used	interactions	MC
Ti	48	Inner 1	14551	200,000	44,247 $\pm$ 464	21,489
C	12	Inner 2	14577	450,000	127,280 $\pm$ 414	39,997
Al	27	Upper 2	14606	150,000	21,928 $\pm$ 2069	13,679
W	184	Lower 2	14639	300,000	28,520 $\pm$ 367	22,553

2. Setting the Stage for LHCb

➜ *How quickly can LHCb collect Minimum Bias events?*

Lumi	nr-bunches	pp-int/xing	non-empty rate	L0-YES
1.1×10^{29}	* 4	0.15	6 kHz	3 kHz
2.3×10^{30}	* 16	0.76	94 kHz	47 kHz
2.6×10^{31}	936(75 ns)	0.15	1.4 MHz	0.7 MHz
2.0×10^{32}	2622 (25 ns)	0.4	10 MHz	1 MHz

❖ pessimistic/realistic scenario

- only 4 colliding bunches at $L = 1.1 \times 10^{29}$cm^{-2}s^{-1}
- no L0-trigger but proper timing
- 2 kHz random trigger on filled bunches
- 300 Hz non-empty minimum bias events to disk
- 10^8 events in approx. 100 hours of running
- approx. 15 hours with L0 interaction-trigger

Prospects for LHCb

❖ Conclusion:

Already in the first weeks after turn-on of the accelerator, LHCb should be able to log at least 10^8 minimum bias events. Even without triggering, those should provide 10 million charm and $500,000$ b-events.

- o enough statistics for publishable results already at 10^{-6} fb^{-1}!
- o examples will be discussed below
- o remember: 2 fb^{-1} per nominal LHCb year

➜ *physics analyses*

- no existing data at $\sqrt{s} = 14$ TeV – everything is new . . .
  - ➜ interesting in its own right
  - ➜ stepping stones towards the LHCb b-physics program

Note:

Harvesting the initial physics already needs a working experiment, although neither ultimate precision in calibration nor HLT is required.

Check list for first data

➜ *requirements*

- proper time alignment of all subdetectors
- data logging capabilities at the nominal rate of 2 kHz
- computing infrastructure for quasi-online reconstruction and analysis of 10^8 Events (0.5% of the nominal annual data volume)

➜ *calibration tasks*

- setting up and debugging of L0-trigger and HLT
  - ➜ initally run trigger offline or in transparent mode
- local and global alignment of tracking detectors
- calibration of the RICH detectors with identified particles
- ECAL calibration with π^0s
- systematic studies, for example
  - ➜ azimuthal symmetry of particle flow and charge ratios
- luminosity determination
- Monte Carlo tuning . . . not only for LHCb

Initial Physics Reach (I)

➜ general considerations

- σ_{mb}: pp inelastic minimum bias cross section
- N_{mb}: number of minimum bias events recorded/scrutinized
- σ: cross section for a given signal
- ε: efficiency for seeing a signal event, which includes
  - ➜ limited phase space coverage of the experiment
  - ➜ detector efficiencies
  - ➜ BR for a specific decay channels of final state particles
  - ➜ selection cuts to suppress background
- the number of signal events S then becomes

$$S = \frac{\sigma\varepsilon}{\sigma_{mb}} N_{mb}$$

- relation between signal and required minimum bias statistics

$$\log_{10} N_{mb} = \log_{10} S - \log_{10}\left(\frac{\sigma\varepsilon}{\sigma_{mb}}\right)$$

Initial Physics Reach (II)

- assume in the following $S = 100$ as "analysis threshold", i.e.

$$\log_{10} N_{mb} = 2 - \log_{10}\left(\frac{\sigma\varepsilon}{\sigma_{mb}}\right)$$

- significance K in units of standard deviations of such a measurement depends on the number of background events B

$$K = \frac{S}{\sqrt{S+B}} = \frac{\sqrt{S}}{\sqrt{1+B/S}}$$

  - ✘ $B/S = 0$ ➜ $K = 10$
  - ✘ $B/S = 3$ ➜ $K = 5$

- try to get some estimates for σ and ε in various channels
  - ➜ use published HERA-B data; apply scaling to cross sections
    - ✘ scale light flavours with inelastic pp-cross section
    - ✘ scale heavy flavours with σ_{cc} and σ_{bb}
  - ➜ LHCb DC04 results (mainly b-physics)

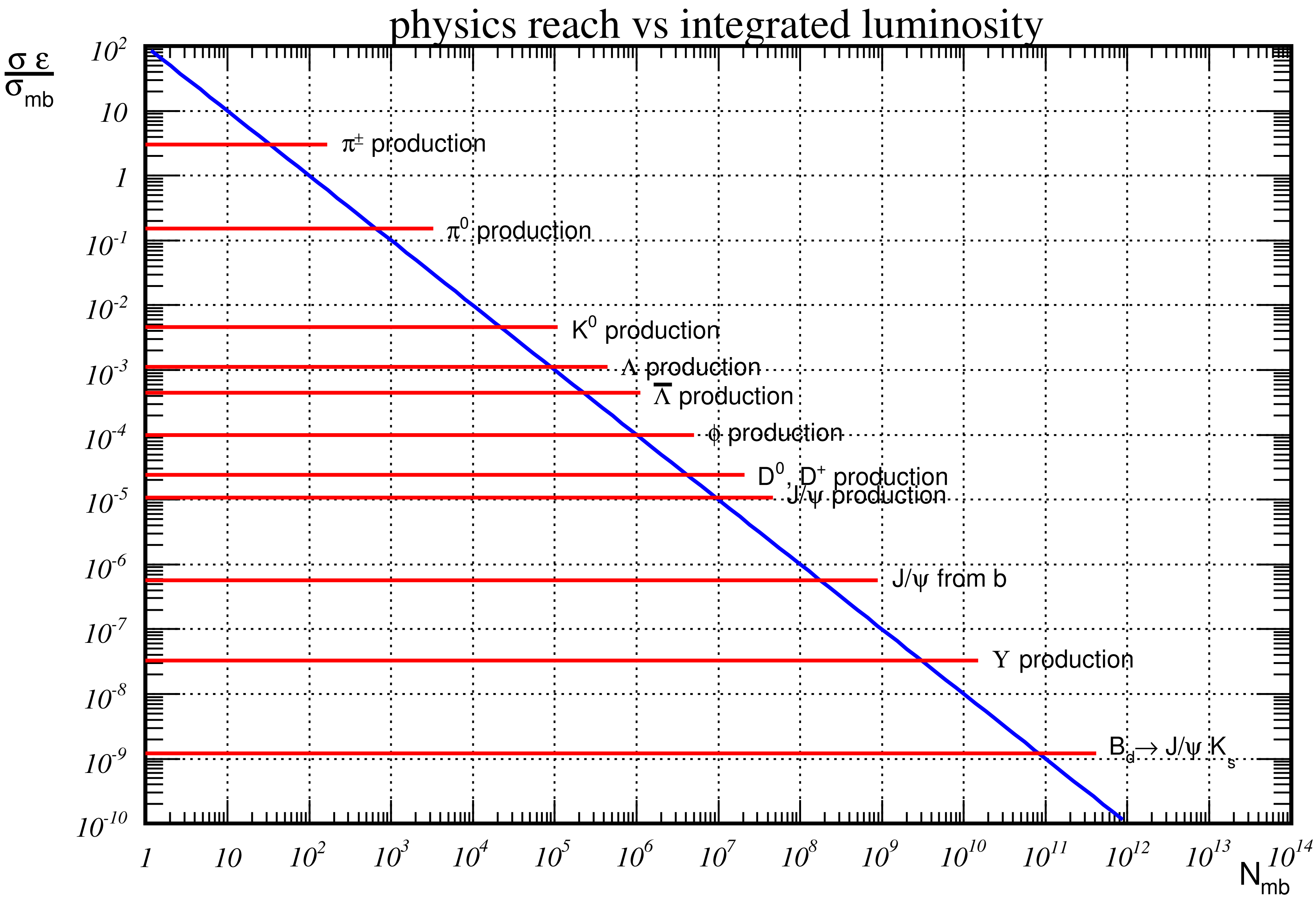
Initial Physics Reach (III)

➜ resulting (gu)estimates:

process	σ/mb	ε	$\log_{10}(\sigma\varepsilon/\sigma_{mb})$
$pp \to \pi^\pm X$	3000	0.1	0.48
$pp \to \pi^0 X$	1500	0.01	−0.82
$pp \to K^0 X$	23	0.02	−2.34
$pp \to \Lambda X$	11	0.01	−2.95
$pp \to \bar{\Lambda} X$	4.5	0.01	−3.35
$pp \to \Phi X$	2.5	0.004	−4.00
$pp \to D X$	6	0.0004	−4.62
$pp \to J/\psi X$	0.133	0.008	−4.97
$pp \to b\bar{b} \to J/\psi X$	0.133	0.008	−6.25
$pp \to \Upsilon X$	0.0002	0.01	−7.48
$pp \to B_d(J/\psi K_s)$	0.0002	0.0006	−8.92

with $\frac{\sigma_{mb}^{\mathrm{LHCb}}}{\sigma_{mb}^{\mathrm{HERA-B}}} = \frac{100\,mb}{40\,mb}$, $\frac{\sigma_{cc}^{\mathrm{LHCb}}}{\sigma_{cc}^{\mathrm{HERA-B}}} = \frac{10\,mb}{50\,\mu b}$ and $\frac{\sigma_{bb}^{\mathrm{LHCb}}}{\sigma_{bb}^{\mathrm{HERA-B}}} = \frac{500\,\mu b}{15\,nb}$

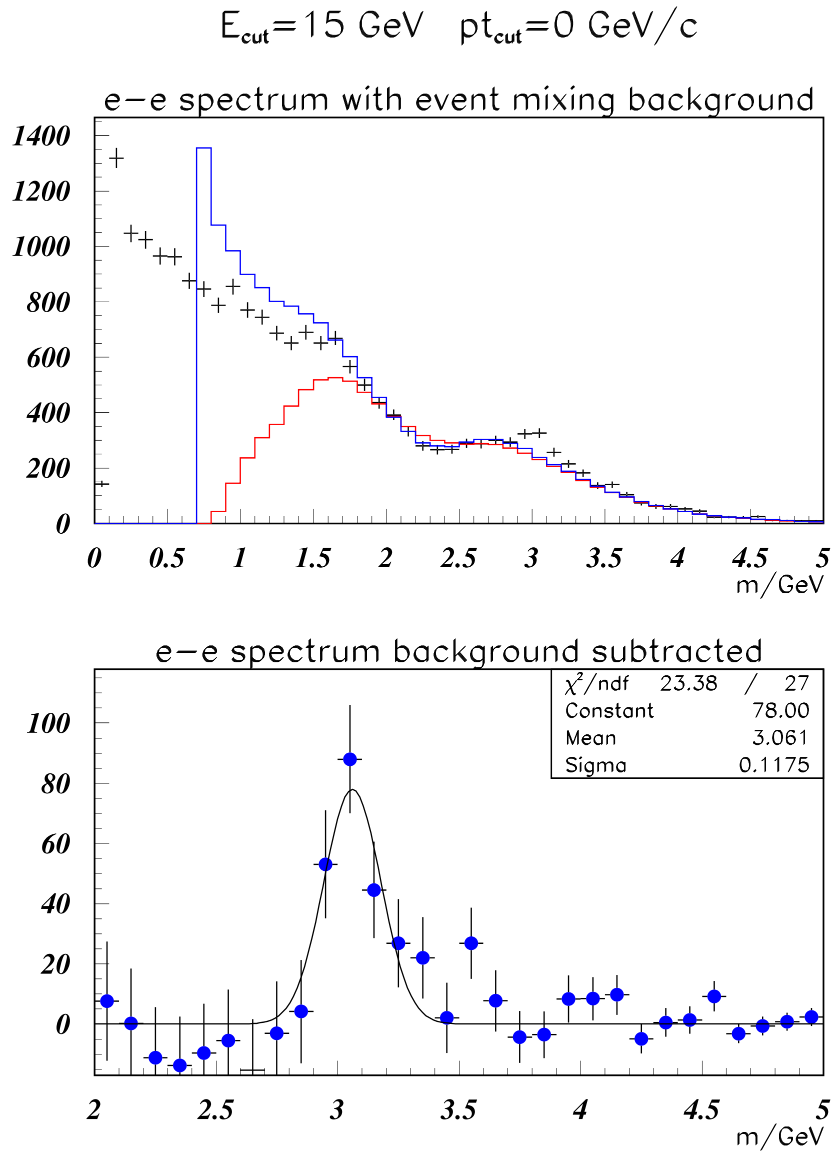
Overview



❖ trigger needed to go beyond 10^{11} events - i.e. to b-physics!

➜ Preliminaries: Measurements without B-Field

- π^0 reconstruction
  - ➜ first signal seen by HERA-B
  - ➜ ECAL was the first detector able to take data
  - ➜ calibration of ECAL
  - ➜ mapping of radiation length
    - ✘ cross check GEANT
  - ➜ basis for all studies using photons or π^0
- search for $J/\psi \to e^+e^-$ signals
  - ➜ use a high-p_T ECAL trigger
  - ➜ need at least partial coverage by ECAL plus overlap with some layers of the vtx-detector
  - ➜ use vertex-detector to veto photons
  - ➜ requires only lateral alignment in the sensitive coordinate



Particle Ratios

➜ Compare production of positive and negative particles

- minimum requirement: working Main Tracker
- study ratios of single (or double) differential distributions

pseudorapidity $$R_\eta = \frac{dn^+/d\eta}{dn^-/d\eta}$$

transverse momentum $$R_{p_T} = \frac{dn^+/dp_T^2}{dn^-/dp_T^2}$$

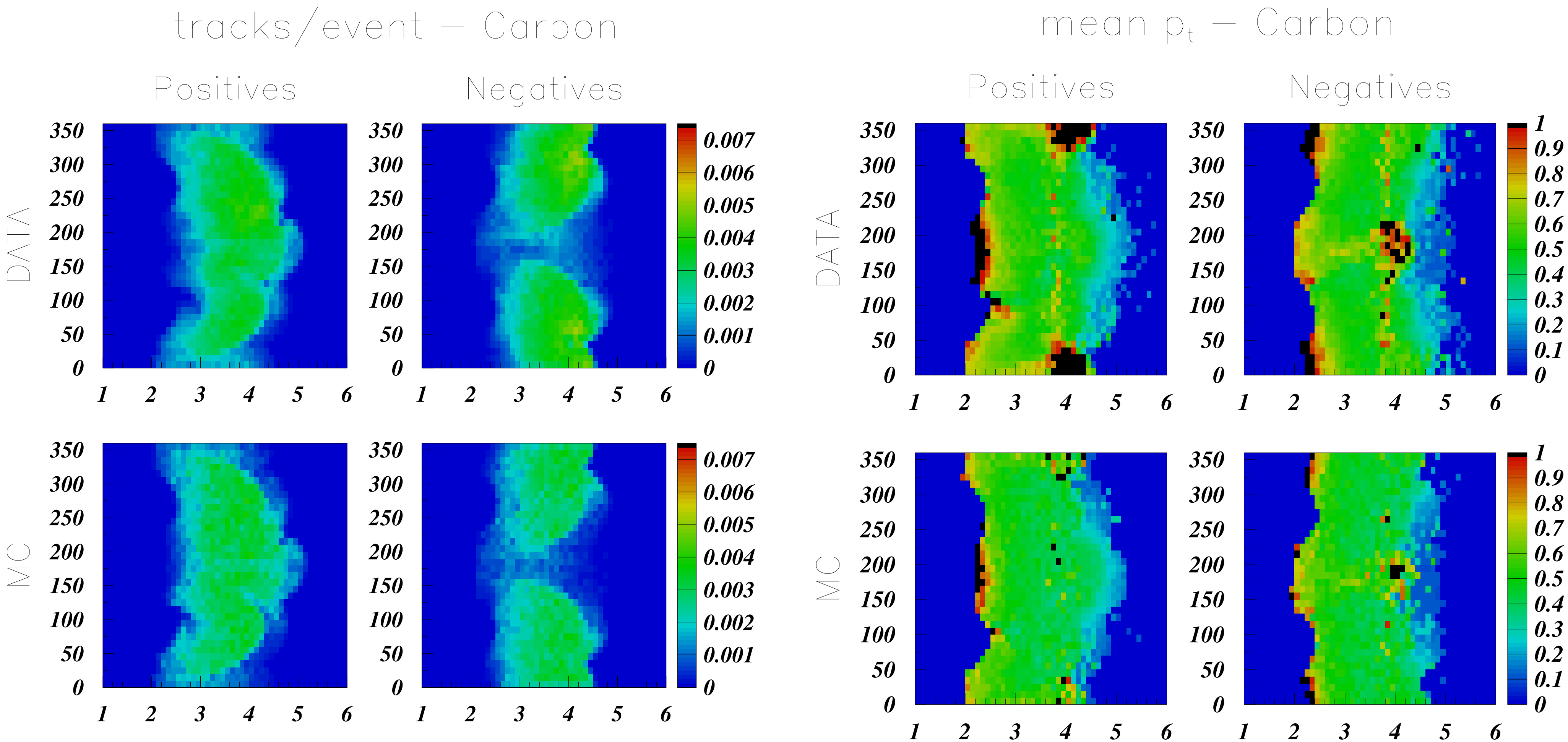
azimuthal angle $$R_\phi = \frac{dn^+/d\phi}{dn^-/d\phi}$$

- ➜ very simple measurement
- ➜ can be done with very low integrated luminosity
- ➜ vital for understanding charge asymmetries
- ➜ first check of the quality of the simulation
- ➜ important input for tuning of (minbias) Monte Carlo generators

illustration. . .

Phase Space Coverage of HERA-B

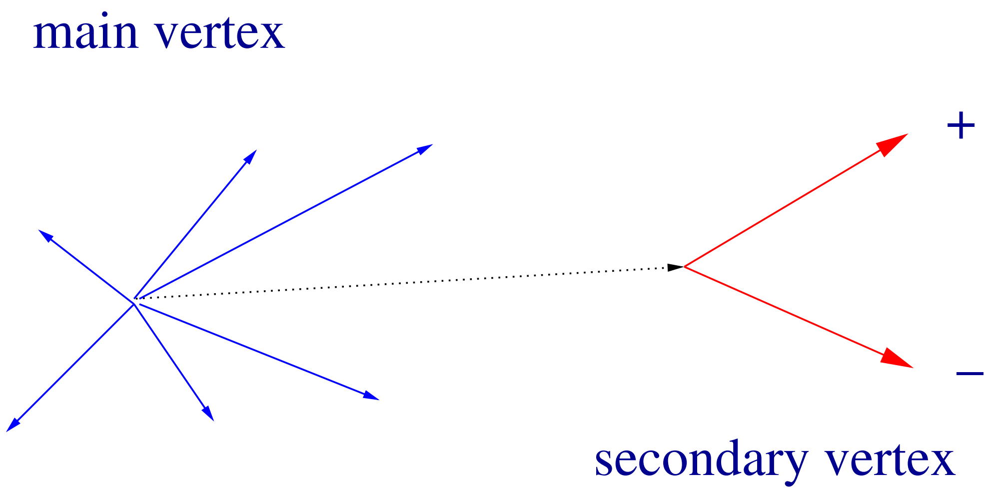
- phase space coverage ϕ vs η of charged tracks
  - average number of reconstructed tracks
  - average p_t of reconstructed tracks
  - comparison of data and Monte Carlo



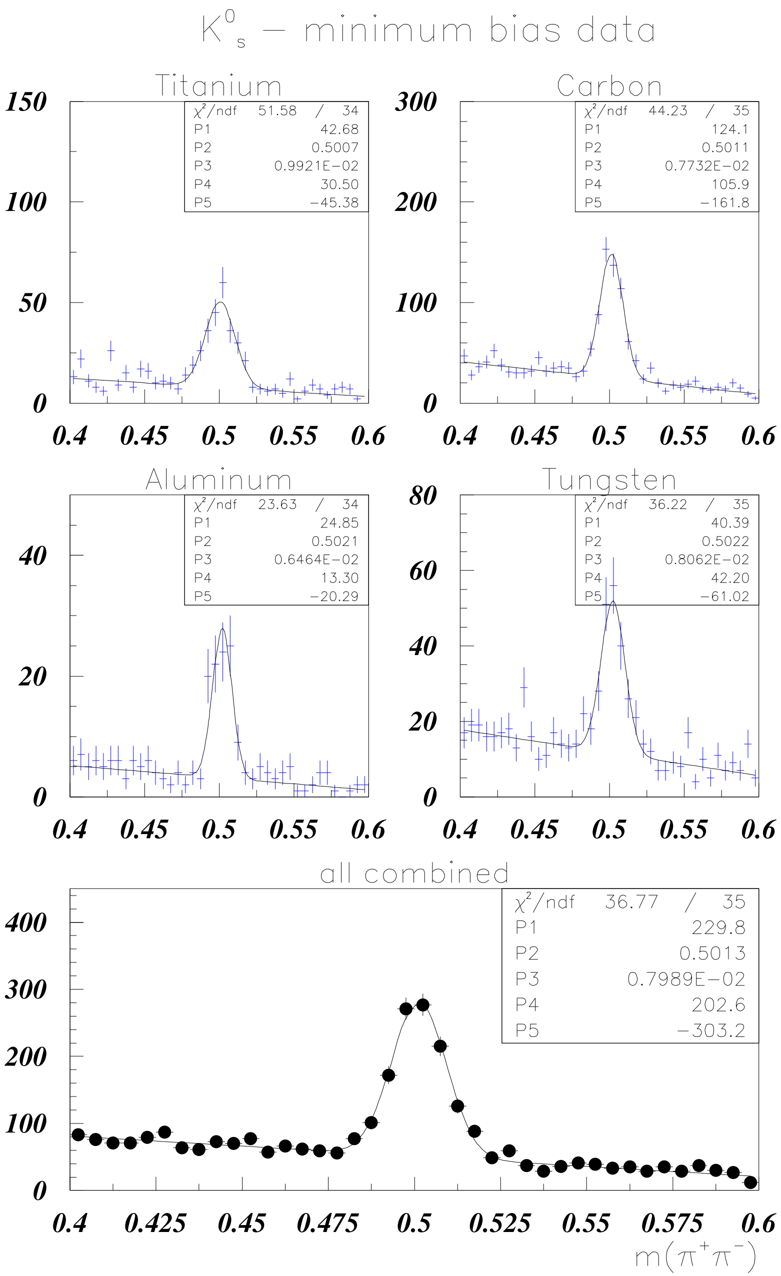
Measurements of V^0 Production

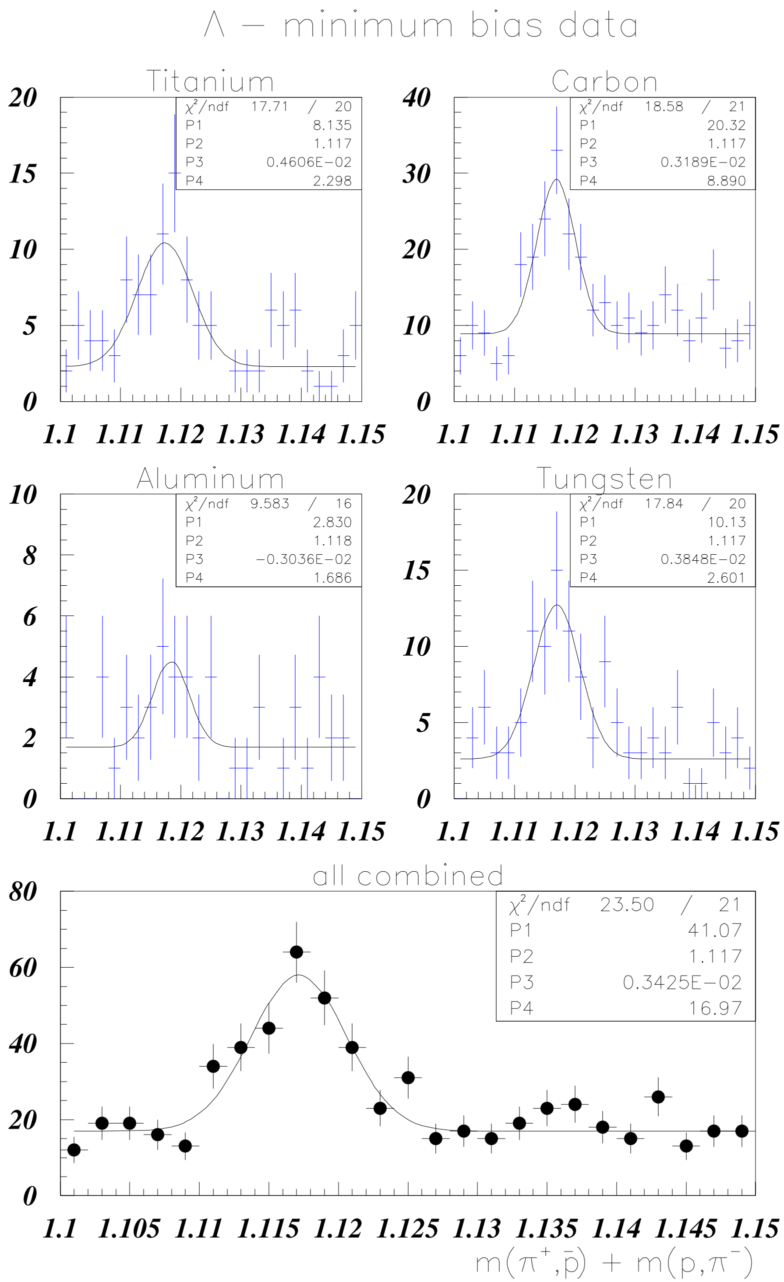
→ *neutral particles with weak decays into two charged tracks*

- minimum requirement: working VeLo and Main Tracker
- experimental signature:
  - ➜ secondary vertex
  - ➜ oppositely charged tracks
  - ➜ momentum pointing back to the primary vertex
- most important V^0-signals:
  - ➜ $K^0_{(s)} \to \pi^+\pi^-$
  - ➜ $\Lambda \to p\pi^-$
  - ➜ $\bar{\Lambda} \to \bar{p}\pi^+$
- analysis:
  - ➜ select oppositely charge tracks
  - ➜ require secondary vertex
  - ➜ require momentum to point back to the primary vertex
  - ➜ assign masses according to decay channel
  - ➜ histogram invariant masses



First V^0-Signals seen by HERA-B





V^0 Production at LHCb

➜ *good topic for a first physics paper*

- simple early measurement, though not trival
- can evolve quickly with improving understanding of alignment
- cross section ratios don't require luminosity

$$\frac{\sigma(\Lambda)}{\sigma(\bar{\Lambda})}(y, p_T)$$

  ➜ important input for models of strangeness production

  ➜ stepping stones towards c- and b-physics

- important for RICH calibration since particle-ID is done by relativistic kinematics

  ➜ consider $\pm$-pairs (with detached vertex)

  ➜ take the common direction of flight

  ➜ plot transverse momentum versus

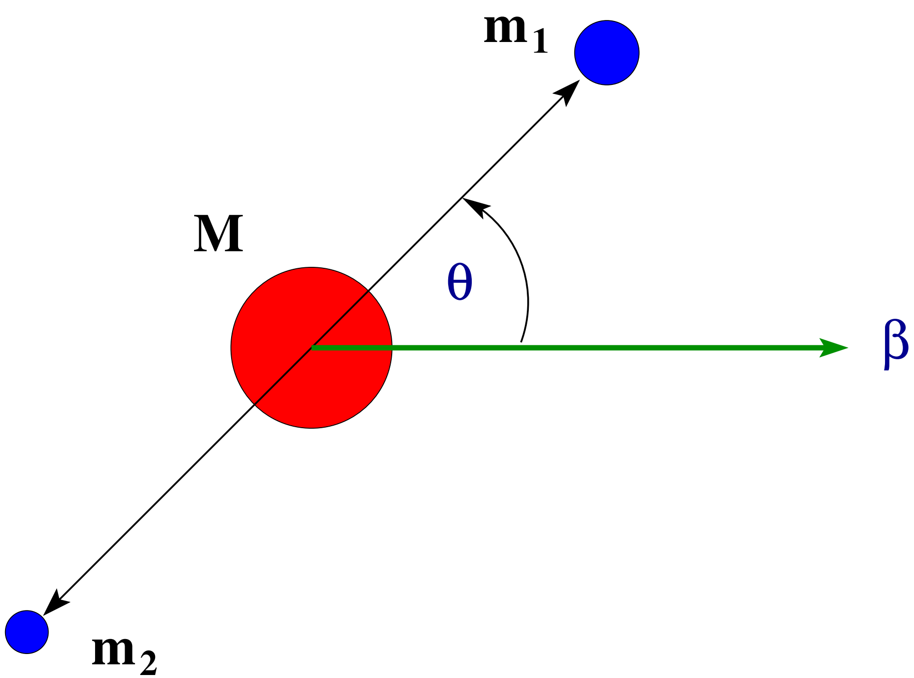
  ➜ asymmetry of longitudinal momenta

  ➜ identify regions of phase space with enhanced p or $\bar{p}$-content

➜ "Armenteros-Podolanski plot"

The Armenteros-Podolanski-Plot (I)

→ Particle identification by relativistic kinematics



- two-body decay of a heavy particle with mass M
- energy-momentum conservation determines the absolute value of the center-of-mass momenta of the daughter particles
- Lorentz-transformation yields lab-momenta of the daughter particles as a function of the decay-angle θ

❖ basic relations:

$$M = \sqrt{p_{cm}^2 + m_1^2} + \sqrt{p_{cm}^2 + m_2^2}$$

$$E_{cm}^2 = m^2 + p_{cm}^2$$

$$p_L = \gamma\, p_L^{cm} + \gamma\beta\, E^{cm}$$

$$p_L^{cm} = \pm p_{cm} \cdot \cos\theta$$

$$p_T = p_T^{cm}$$

$$p_T^{cm} = p_{cm} \cdot \sin\theta$$

The Armenteros-Podolanski-Plot (II)

❖ initial results:

$$p_{cm}^2 = \frac{1}{4M^2}(M^4 + m_1^4 + m_2^4 - 2m_1^2M^2 - 2m_2^2M^2 - 2m_1^2m_2^2)$$

$$E_1^{cm} = \frac{1}{2M}(M^2 + m_1^2 - m_2^2)$$

$$E_2^{cm} = \frac{1}{2M}(M^2 - m_1^2 + m_2^2)$$

❖ next, consider the asymmetry of the longitudinal momenta:

$$\alpha = \frac{p_L^{(1)} - p_L^{(2)}}{p_L^{(1)} + p_L^{(2)}} = \frac{(p_{cm}\cos\theta + \beta E_1^{cm}) - (-p_{cm}\cos\theta + \beta E_2^{cm})}{(p_{cm}\cos\theta + \beta E_1^{cm}) + (-p_{cm}\cos\theta + \beta E_2^{cm})}$$

$$= \frac{2\,p_{cm}\cos\theta + \beta(E_1^{cm} - E_2^{cm})}{\beta(E_1^{cm} + E_2^{cm})} = \frac{2\,p_{cm}}{\beta M}\cos\theta + \frac{E_1^{cm} - E_2^{cm}}{M}$$

$$= \frac{2\,p_{cm}}{\beta M}\cos\theta + \frac{m_1^2 - m_2^2}{M^2}$$

➜ result:

$$\alpha = \alpha_0 + \frac{r_\alpha}{\beta}\cos\theta \quad \text{with} \quad \alpha_0 = \frac{m_1^2 - m_2^2}{M^2} \quad \text{and} \quad r_\alpha = \frac{2\,p_{cm}}{M}$$

The Armenteros-Podolanski-Plot (III)

❖ consider the relativistic limit $\beta \rightarrow 1$

The asymmetry of the longitudinal momenta of the daughters is bounded:

$$\alpha_0 - r_\alpha < \alpha < \alpha_0 + r_\alpha$$

A combined view of α and p_T suggests itself. One has

$$\frac{\alpha - \alpha_0}{r_\alpha} = \cos\theta \quad \text{and} \quad \frac{p_T}{p_{cm}} = \sin\alpha$$

and thus

$$\frac{(\alpha - \alpha_0)^2}{r_\alpha^2} + \frac{p_T^2}{p_{cm}^2} = 1$$

i.e. in the (α, p_T)-plane particles from a two-body decay define an ellipse.

➜ center of the ellipse:

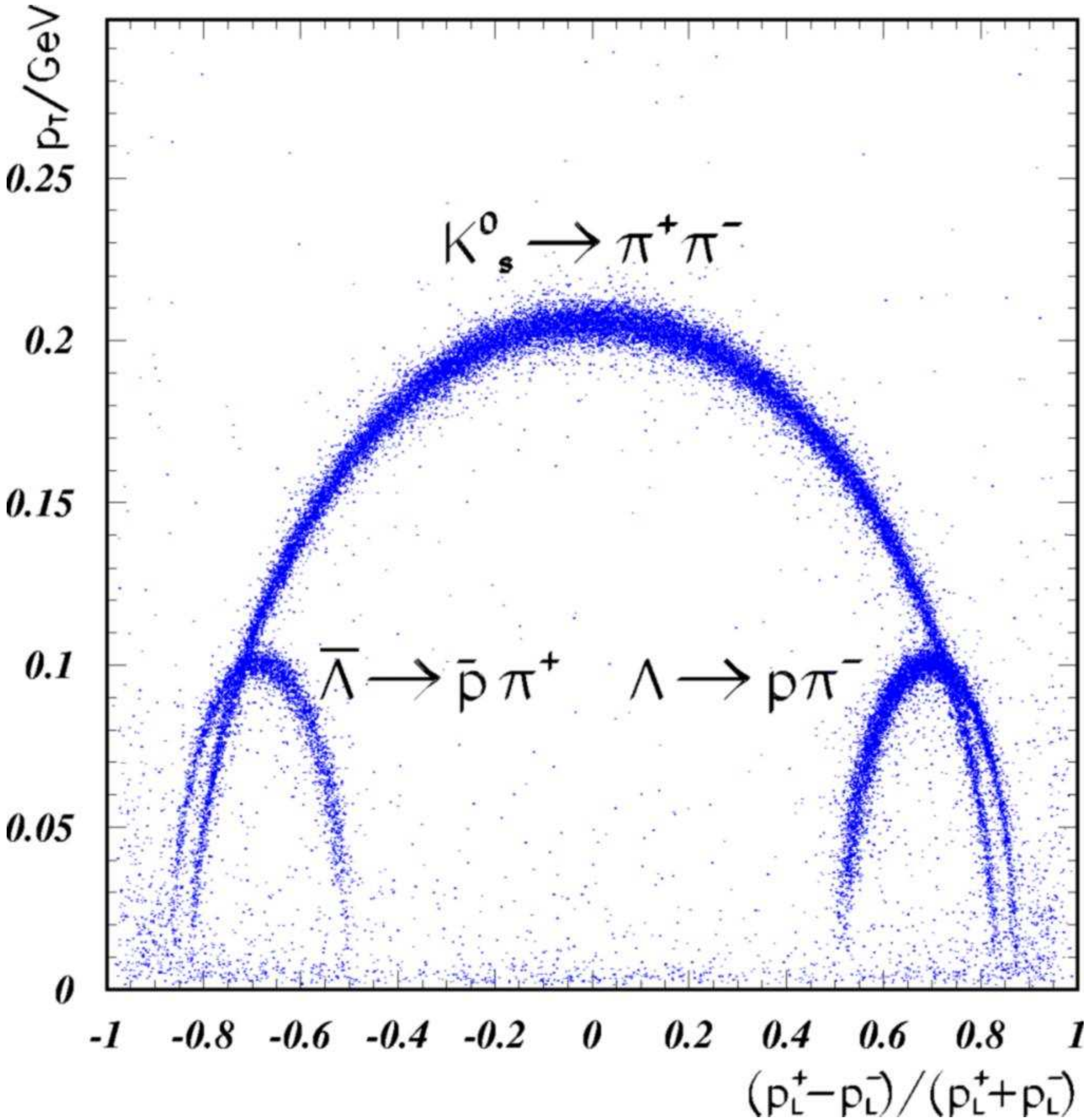
$$(\alpha_0, 0) = \left(\frac{m_1^2 - m_2^2}{M^2}, 0 \right)$$

➜ radii of the ellipse:

$$(r_\alpha, r_{p_T}) = \left(\frac{2\, p_{cm}}{M}, p_{cm} \right)$$

The Armenteros-Podolanski-Plot (IV)

➜ *Example: V^0-decays*



❖ K^0-decay

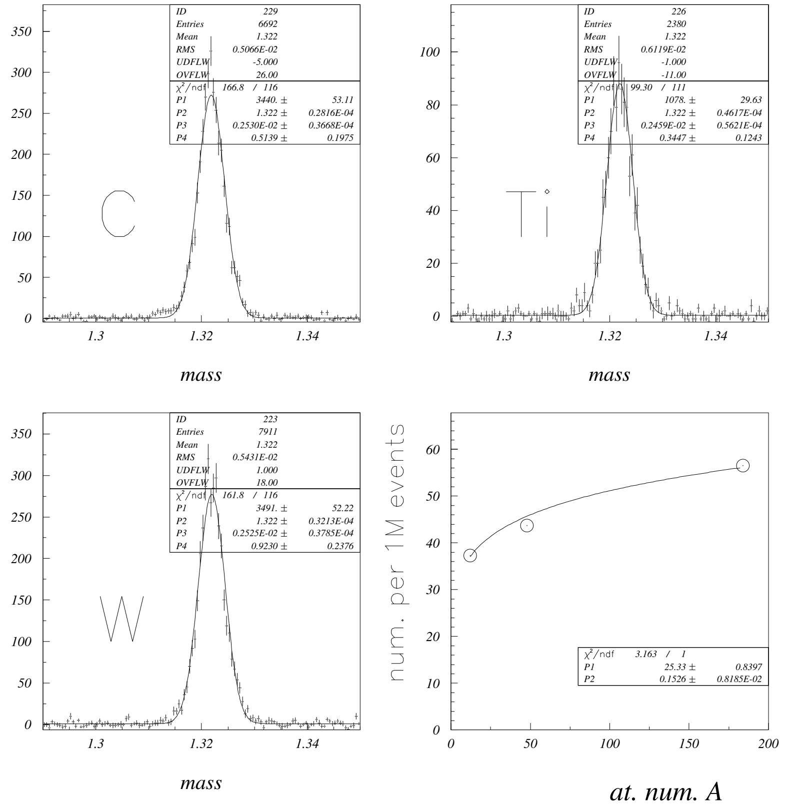
$$M = 0.498 \text{ GeV}$$
$$m_{1,2} = 0.140 \text{ GeV}$$
$$p_{cm} = 0.206 \text{ GeV}$$
$$\alpha_0 = 0$$
$$r_\alpha = 0.827$$

❖ Λ-decay

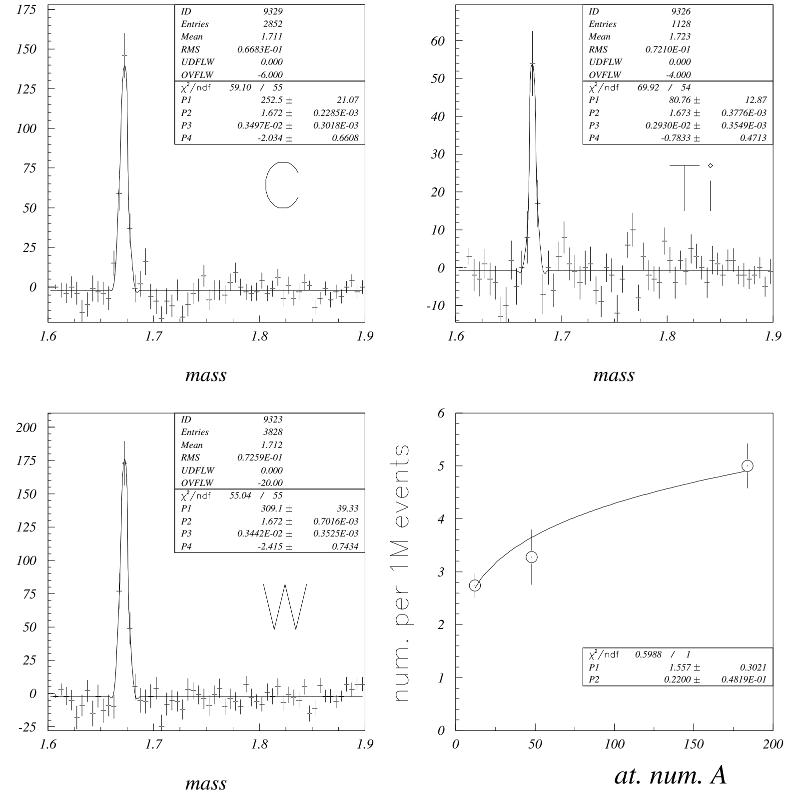
$$M = 1.116 \text{ GeV}$$
$$m_1 = 0.938 \text{ GeV}$$
$$m_2 = 0.140 \text{ GeV}$$
$$p_{cm} = 0.101 \text{ GeV}$$
$$\alpha_0 = \pm 0.691$$
$$r_\alpha = 0.181$$

Hyperon Production at HERA-B

$\Xi^- \to \Lambda\pi^-$

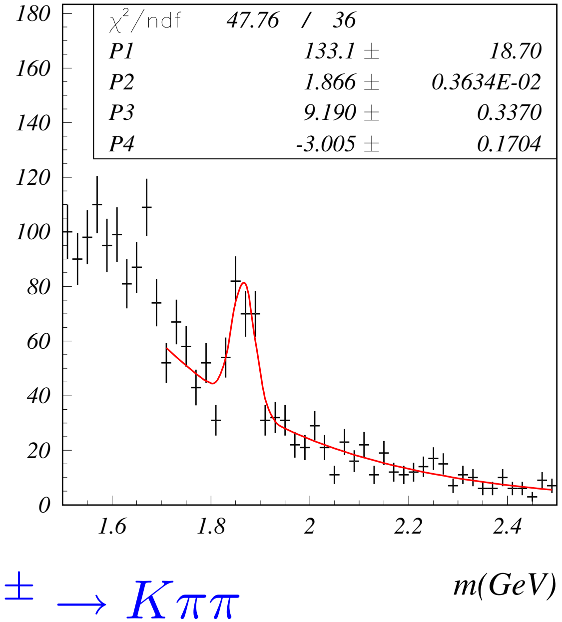


$\Omega^- \to \Lambda K^-$

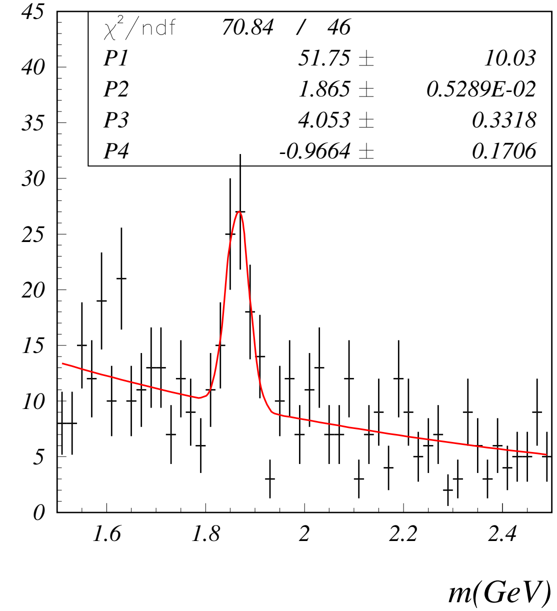


- systematic study of strangeness production
  - ➜ as a function of the number of strange quarks
  - ➜ as a function of target mass
  - ➜ as a function of the kinenatics x_F, y, p_T
- further topics: polarization, correlations between strange particles, . . .
- can also be done to LHCb

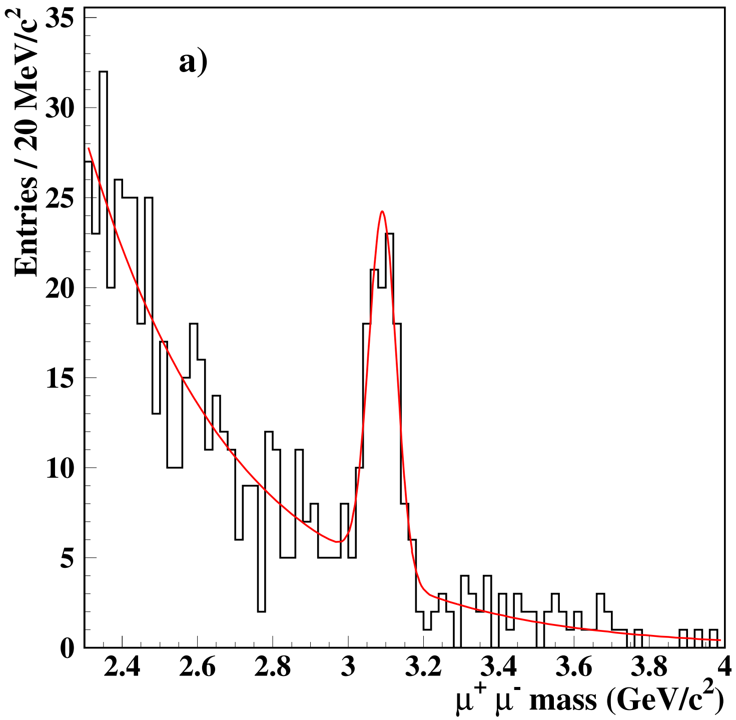
$D^0 \to K\pi$



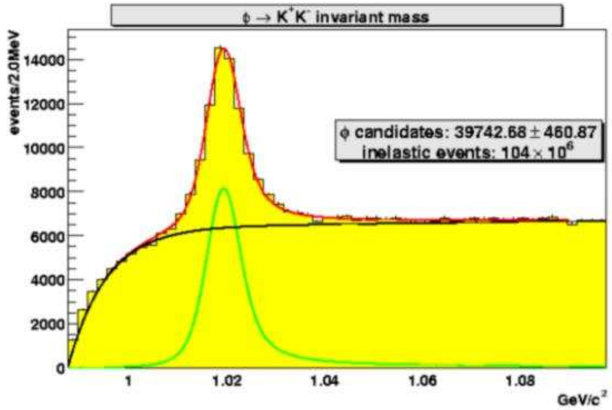
$D^\pm \to K\pi\pi$

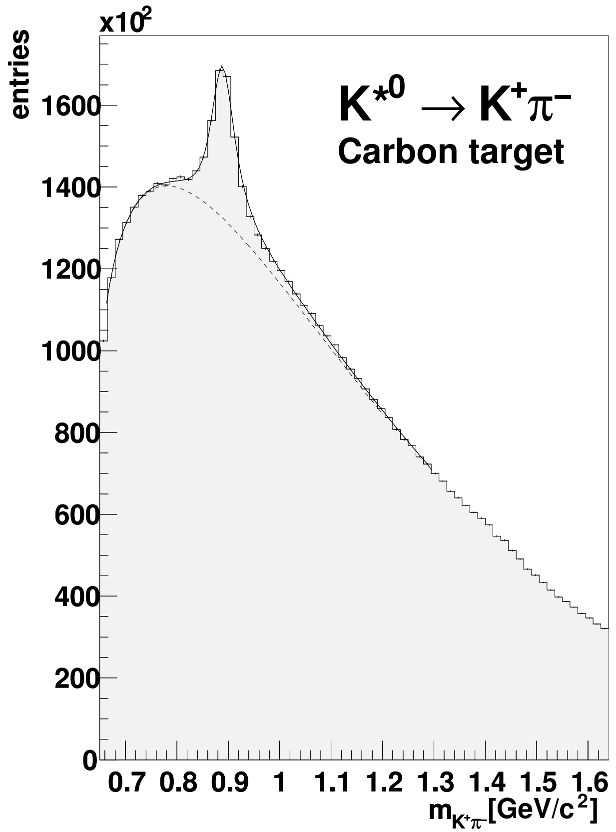


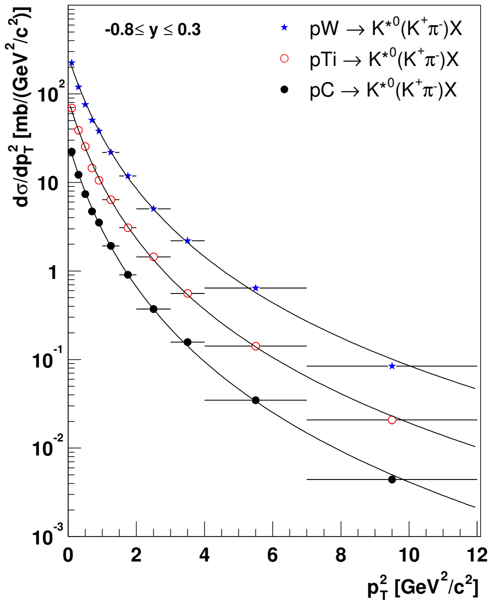
$J/\psi \to \mu^+\mu^-$

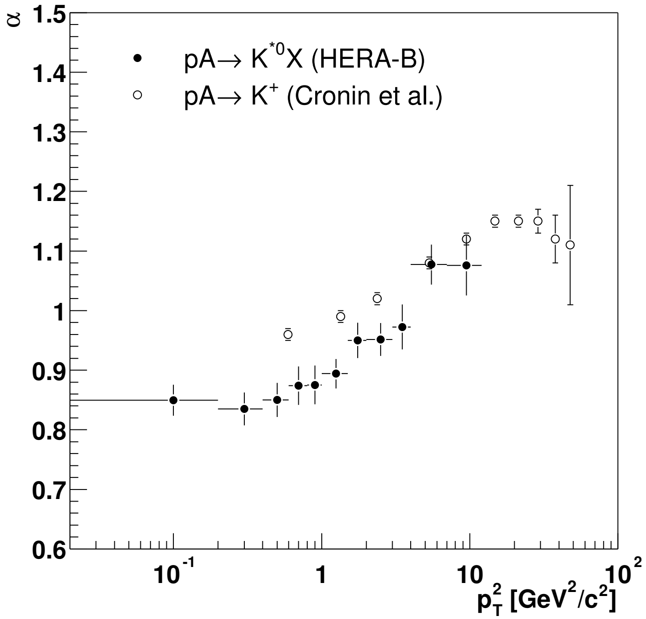


- 200 million minimum bias events recorded
- small, but significant signals seen
- D-signals require working RICH
- still among the best results for absolute cross sections
- needed as normalization e.g. for J/ψ triggered events









- requirement: working RICH and Main Tracker
- important building block for advanced analyses
- single Kaon tagging is sufficient to find the ϕ-signal
  - ➜ also interesting for RICH calibration
- at HERA-B first seen for K^*: Cronin-Effect

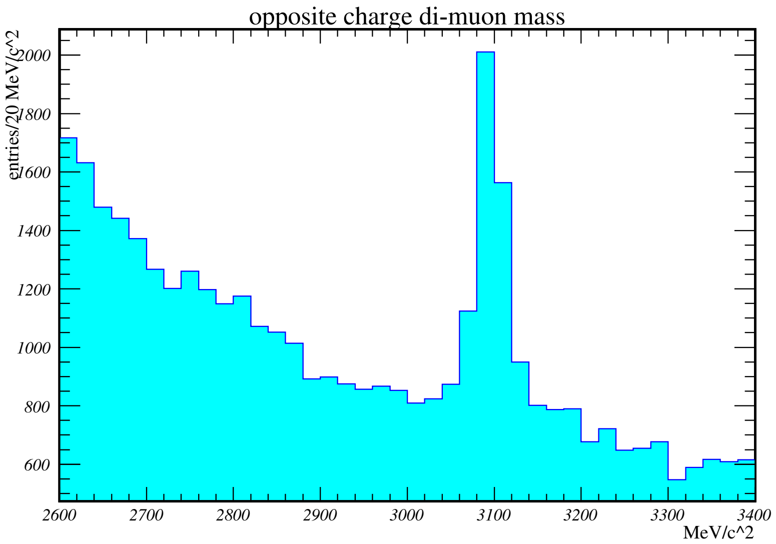
$$\sigma_{pA} = \sigma_{pp} A^{\alpha} \quad \text{with} \quad \alpha = f(p_T)$$

- only phenomological explanations
  - ➜ e.g. recattering in nucleus

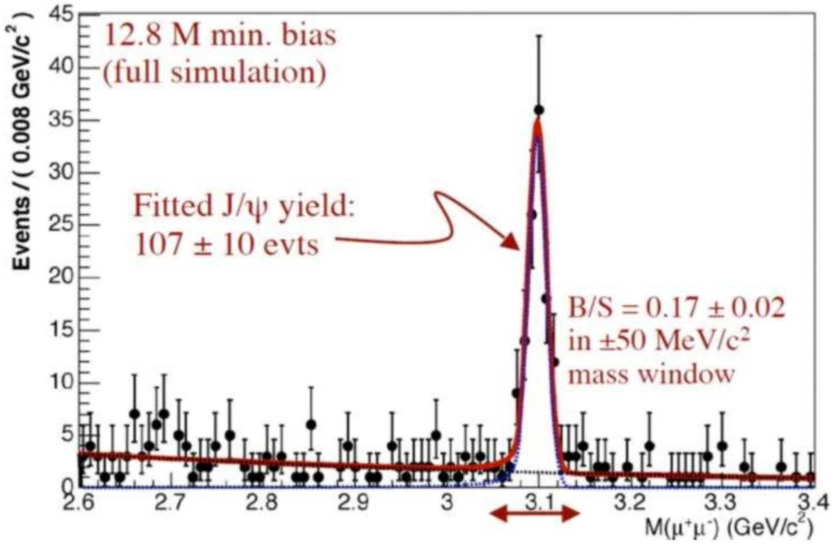
➜ Another good candidate for an early physics paper

- measurement of $J/\psi \to \mu^+\mu^-$-cross section
- minimum requirement: working MUON-system and Main Tracker
- production ratios for open charm, based on $D^0 \to K\pi$, $D^\pm \to K\pi\pi$
- requirement: RICH plus perfectly calibrated VeLo

❖ important building blocks for many CP and rare decay analyses!

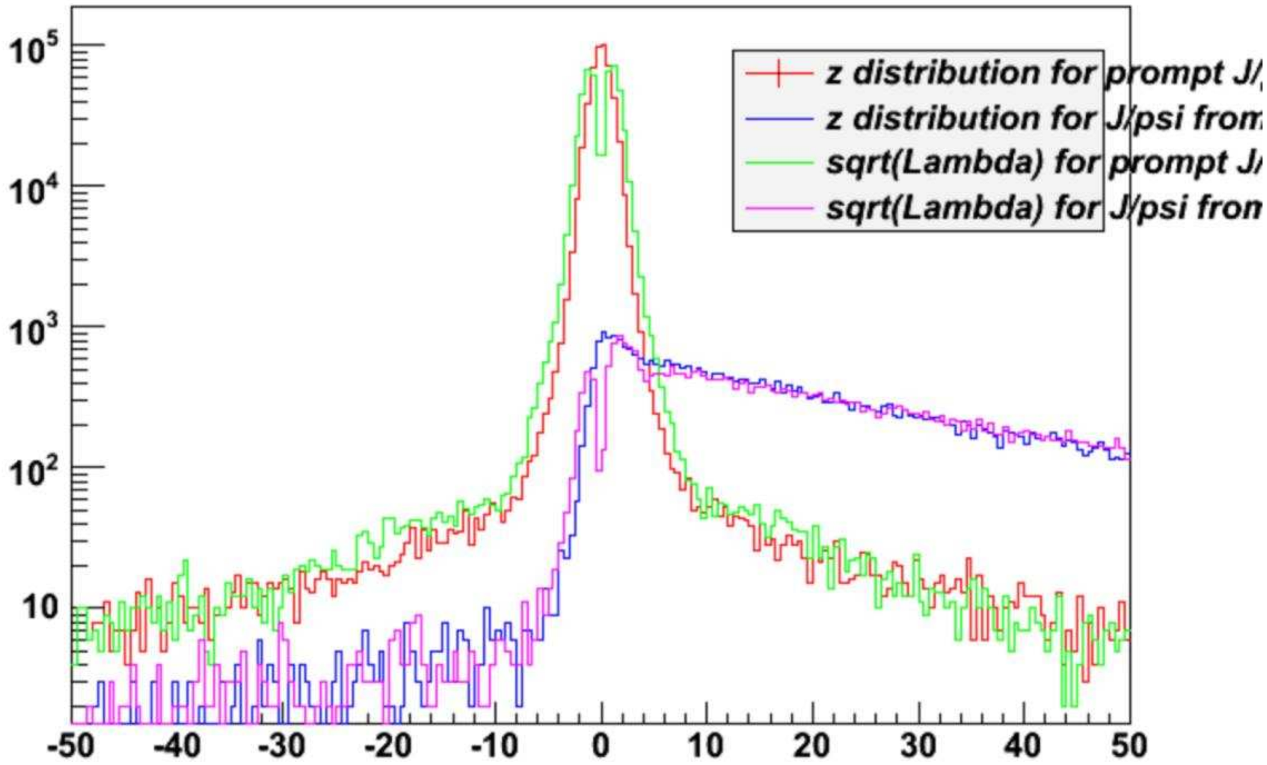


expected signal from opposite charge di-muon candidates in 10^8 min-bias events



DC04-analysis with tight cuts based on $1.28 \cdot 10^7$ min-bias events

- minimum requirement: working MUON-system, Main Tracker and VeLo
- reconstruct $J/\psi \to \mu^+\mu^-$
- disentangle fractions of prompt and detached J/ψs
- relate J/ψ yield to primary $c\bar{c}$ and $b\bar{b}$ cross sections, using as input fragmentation functions measured e.g. at LEP

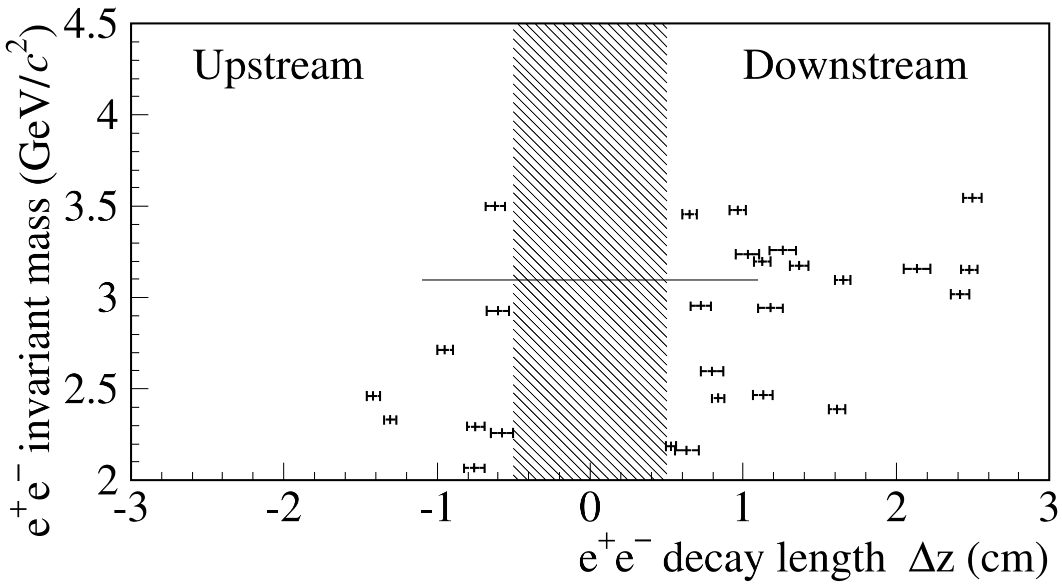


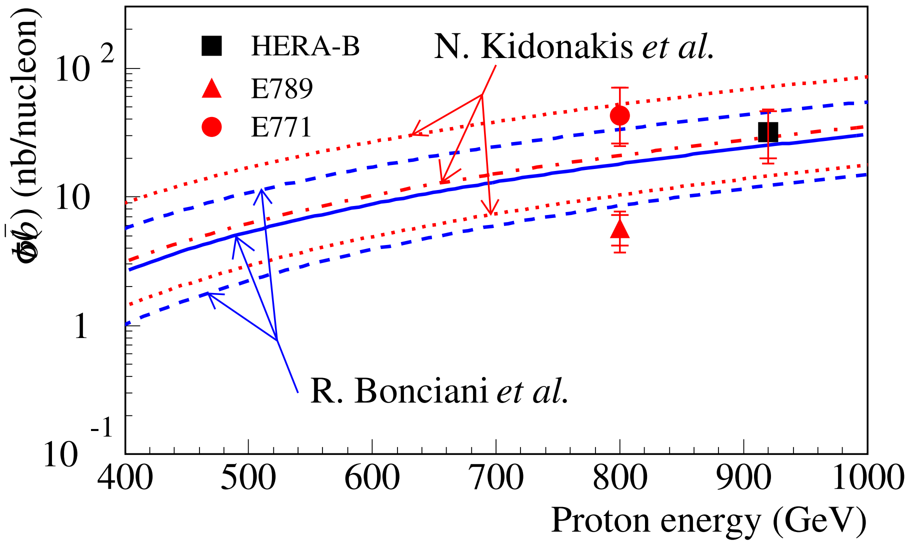
(plot by Wenbin Qian)

Result from HERA-B

➜ Measurement of $b\bar{b}$-cross section at $\sqrt{s} = 42$ GeV

scatter plot of invariant mass vs decay length and resulting cross section





➜ Other Measurements in the $c\bar{c}$ System

- J/ψ production via $\chi_c \to J/\psi\gamma$ decays ($J^{PC}(\chi_c) = \{0, 1, 2\}^{++}$)
- J/ψ spin alignment
- $\psi' \to J/\psi\gamma$

→ *proposed new states of 4-quarks and 1 antiquark*

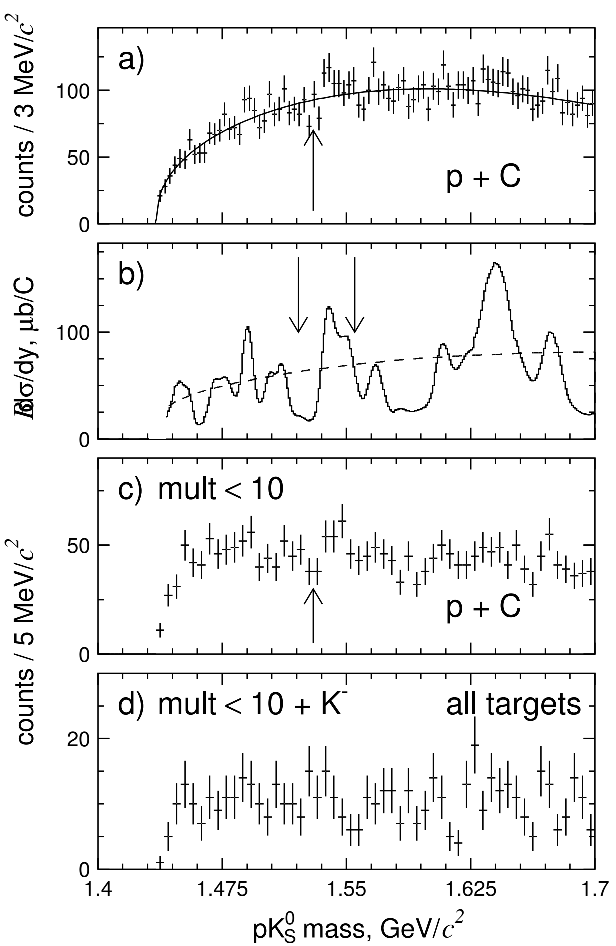
❖ for example:

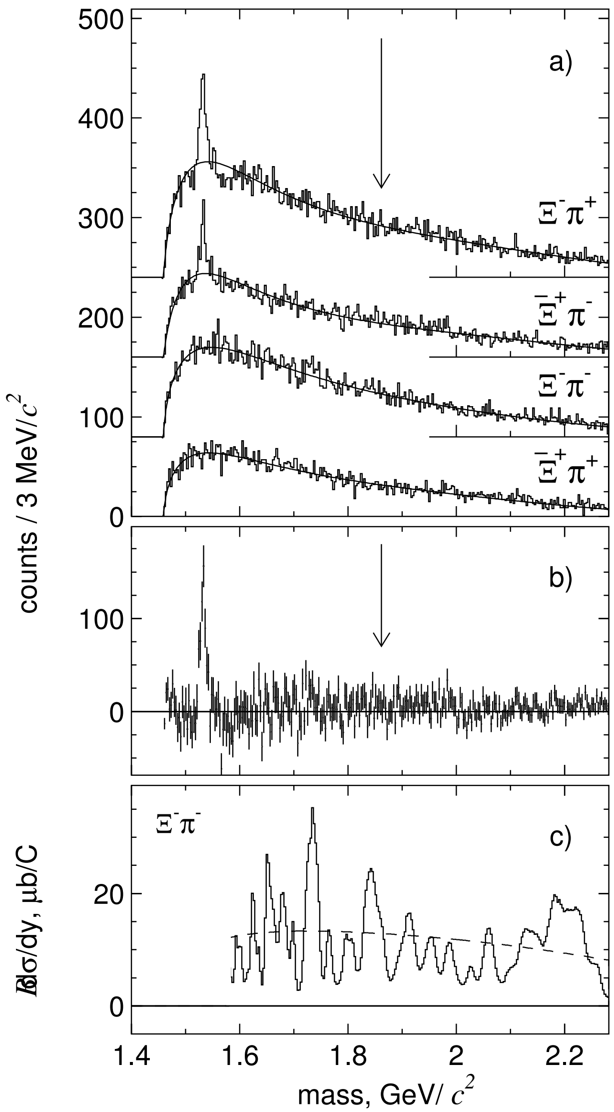
$$\Theta^+(uudd\bar{s}) \rightarrow pK_s^0$$

$$\Xi^{--}(ddss\bar{u}) \rightarrow \Xi^-\pi^-$$

❖ HERA-B results:

- based upon min-bias
  - → $200 \cdot 10^6$ events
  - → $2.2 \cdot 10^6\ K_s^0$
  - → $4.7 \cdot 10^3\ \Xi^-$
- no signal found!





An Independent Study

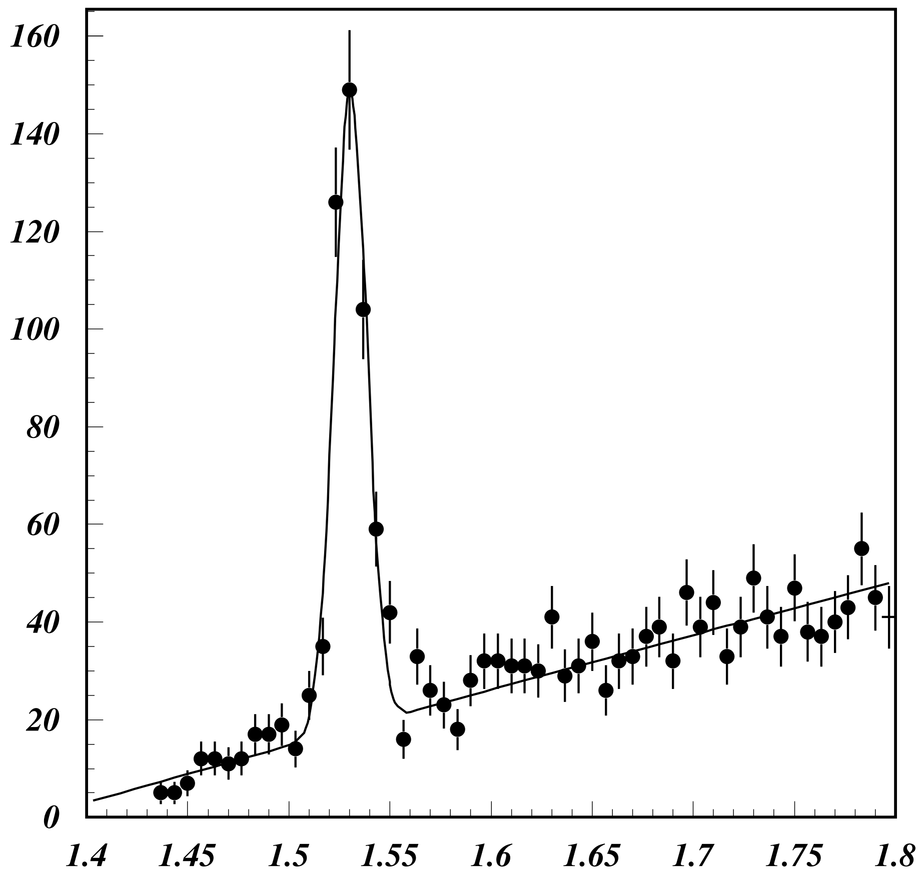
➜ *A quick look into single lepton triggered data. . .*

- select opposite charge pairs
  - ➜ secondary vertex downstream of the primary vertex
  - ➜ assigne pion masses
  - ➜ invariant mass consistent with K_s^0
- combine with another positive track
  - ➜ assign proton mass
  - ➜ construct invariant mass with the V^0
- highly significant signal at the Θ^+-mass

An Independent Study

➜ A quick look into single lepton triggered data. . .

- select opposite charge pairs
  - ➜ secondary vertex downstream of the primary vertex
  - ➜ assigne pion masses
  - ➜ invariant mass consistent with K_s^0
- combine with another positive track
  - ➜ assign proton mass
  - ➜ construct invariant mass with the V^0
- highly significant signal at the Θ^+-mass



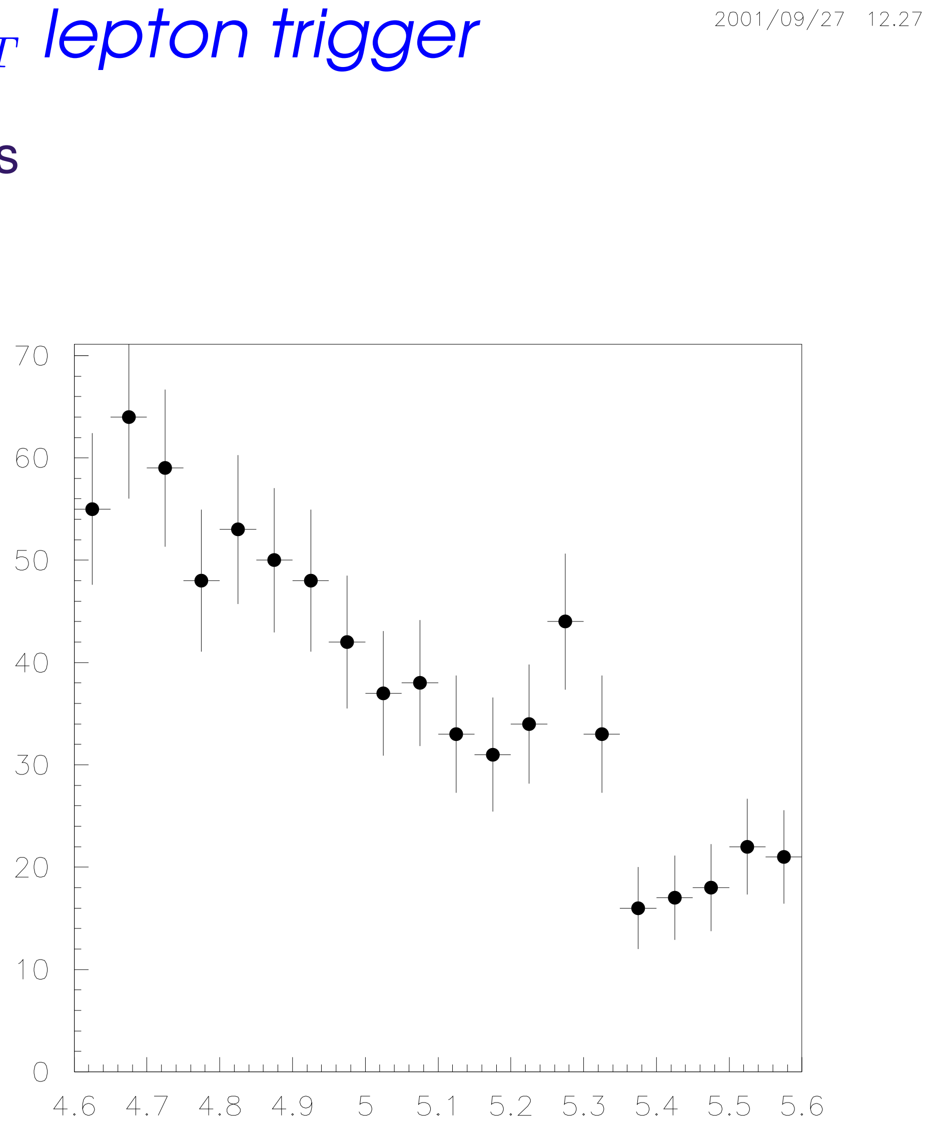
❖ but:

- the “signal” was fake
- the positive track was used twice
- could also be caused by a feature of the track finding program which splits a single true track into two independent ones . . .

Yet Another "Signal" . . .

➜ HERA-B data with a single high-p_T lepton trigger

- study invariant mass spectrum of $\pi^+\pi^-$-pairs
- "clear" $B_0 \rightarrow \pi^+\pi^-$ signal. . .
  - ➜ $m(B_0) = 5.279$ GeV
  - ➜ BR$(B_0 \rightarrow \pi^+\pi^-) = 4.6 \times 10^{-6}$
  - ➜ approx. 3 million triggered events. . .



❖ fluctuations do happen!

Prospects for B-Physics at LHCb

❖ integrated luminosity for first 5σ signals

based on DC04 studies (numbers by Olivier Schneider):

www.cern.ch/lhcb-phys/DC04_physics_performance

Lumi(pb^{-1})	Channel	MinBias events
0.009	$B_d \to D^{*-}\mu^+\nu$	$9.0 \cdot 10^8$
0.039	$B_u \to J/\psi(\mu^+\mu^-)K^+$	$3.9 \cdot 10^9$
0.046	$B_d \to D^+\pi^-$	$4.6 \cdot 10^9$
0.062	$B_d \to J/\psi(\mu^+\mu^-)K^{*0}$	$6.2 \cdot 10^9$
0.418	$B_d \to K^+\pi^-$	$4.2 \cdot 10^{10}$
0.427	$B_s \to J/\psi(\mu^+\mu^-)\phi$	$4.3 \cdot 10^{10}$
0.500	$B_s \to D_s^-\pi^+$	$5.0 \cdot 10^{10}$
1.176	$B_d \to K^*\gamma$	$1.2 \cdot 10^{11}$
1.490	$B_s \to K^+K^-$	$1.5 \cdot 10^{11}$
2.101	$B_d \to \pi^+\pi^-$	$2.1 \cdot 10^{11}$

➜ B-Physics with exclusive decays requires HLT

4. Summary and Outlook

Interesting LHC physics possible already with 10^8 minimum bias events

➜ *many use cases . . .*

- calibration of detector components
- (final) commissioning of trigger system
- first luminosity determination
- full test of computing model with real data
- first steps on the road to b-physics
- basis for tuning of (minbias) Monte Carlo
- first physics papers, such as
  - ➜ particle ratios and V^0-production and heavier hyperons
  - ➜ ϕ-crosss section and other vector meson resonances
  - ➜ studies of the charmonium system and open charm
  - ➜ measurement of $c\bar{c}$ and $b\bar{b}$ cross sections, . . .