Luminosity for Cross-section Calculations : A PHENIX Perspective

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PHENIX Cross-Sections

- Asymmetries are relative difference in cross-sections
- Cross-section measurements compared to theoretical estimates establishes the bona fide of the ability to probe the physics we claim to be probing
- These are useful and important on their own rights (to test pQCD, production mechanism models, as baselines or inputs for other purpose i.e. cosmic ray)
- Especially in early papers, PHENIX published cross-sections along with asymmetry results

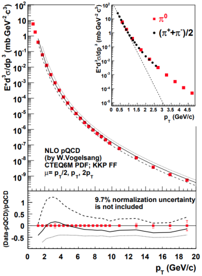


Figure: π^0 at 200 GeV

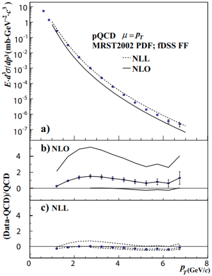


Figure: π^0 at 62 GeV

More Cross-Section Results

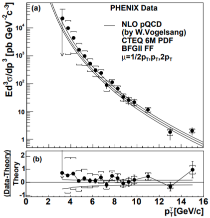


Figure: Direct γ at 200 GeV

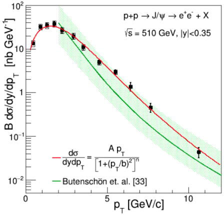


Figure: J/Ψ at 510 GeV

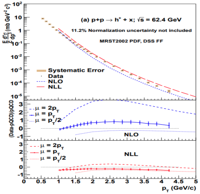


Figure: H^+ at 62 GeV

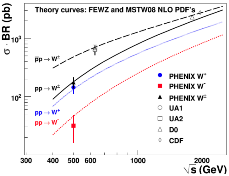


Figure: $W^{\pm}$ at 500 GeV

Cross-Section, Luminosity and Normalization

At PHENIX, cross-section is calculated as :

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\mathcal{L}^{int}_{eff}}\frac{1}{2\pi p_T}\frac{d^2N^{prod}}{dp_T d\eta}$$

where $N^{prod} = N^{det}/[\epsilon^{geom}\epsilon^{reco}\epsilon^{trig}]$ and $\mathcal{L}^{int}_{eff} = \frac{N_{BBC}}{\sigma_{BBC}}$

- **B**eam **B**eam **C**ounter used for MinBias trigger and as luminosity counter
- $\mathcal{L}^{int}_{eff}$ is the integrated lum. available to BBC trigger
- Different from 'delivered' int. lum. due to BBC z-vertex requirements
- N_{BBC} is number of collisions with BBC trigger
- σ_{BBC} is the p+p cross-section detected by BBC

A Few Thoughts

- Luminosity counter depends on the method of defining 'event' or $p + p$ collision in our case
- SPD does not have a hardware trigger and our events are essentially regular time slices (with a reconstructed primary vertex?)
- Most PHENIX analyses were done with a trigger requiring $-30cm \leq z_{vtx} \leq 30cm$ to ensure high quality tracks in mid-rapidity etc.
- SPD is free from such complications, as long as we can define a collision, we can count luminosity

BBC Cross-Section σ_{BBC}

σ_{BBC} is calculated as :

$$\sigma_{BBC} = \frac{R^{max}_{BBC}}{\mathcal{L}_{delivered} \times \epsilon_{BBC}}$$
$$\text{with} \quad \mathcal{L}_{delivered} = f_{beam} \times \sum_i \frac{N_1 \times N_2}{2\pi\sigma_x\sigma_y},$$

where R_{BBC} peak event rate detected by BBC, ϵ_{BBC} trigger efficiency, f_{beam} is the beam frequency (~ 78 kHz), $N_{1/2}$ number of protons in two colliding bunches and $\sigma_x(\sigma_y)$ is the transverse width of a Gaussian shape beam profile

- RHIC collider facility provides with f and N_1, N_2 measured using Wall Current Monitor and Direct Current Current Transformer (induction current in coils around beam)
- one fast (individual bunch) and less accurate, other slow but more accurate
- Beam profile is determined at PHENIX using Vernier Scan technique

Vernier Scan

- Vernier Scan or Van der Meer Scan is the technique of scanning one beam by the other by shifting one beam in steps across the other (in horizontal and vertical directions)
- Step sizes ($\sim 100\mu m$) measured by RHIC Beam Position Monitors (image charge in two plates on opposite sides of the beam of charged particles)
- Due to limited DAQ rate, PHENIX used pre-scaled triggers, but all triggered events are counted in 'scalers', used here to calculate BBC event rate R_{BBC}
- Event rate vs. beam step position plots are used to extract 'peak rate' (R_{BBC}^{max}) and widths (σ_x, σ_y)

Vernier Scan at RHIC/PHENIX

- Scan is taken a few times (5 - 10) during a certain p+p run period.
- Agreed upon between Collider Accelerator Dept (CAD), PHENIX and STAR
- Scan is done by CAD towards the end of lifetime ($\sim$ 8 hr) of a 'fill' to minimize loss of physics data

Scan Positions and Event Rates

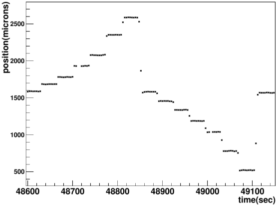


Figure: Step positions

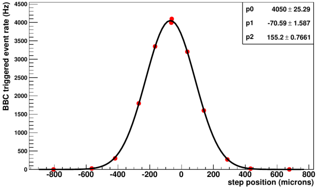


Figure: Horizontal profile

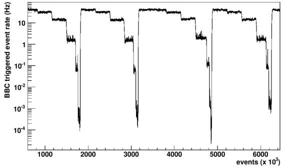


Figure: Event rates

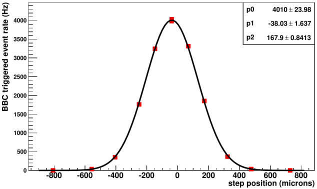


Figure: Vertical profile

Calculating Luminosity

- Using average beam size in x and y and average number of protons involved in bunch crossings, calculate average 'delivered' Luminosity for each crossing
- Done separately for each bunch crossing, take statistical mean
- Typical numbers from 2009 500 GeV p+p vernier scans :

$\frac{R_{max}}{bunch}$ (Hz)	σ_x (μm)	σ_y (μm)	N_1 ($\times 10^{11}$)	N_2 ($\times 10^{11}$)	$\mathcal{L}_{tot}$ ($\times 10^{29}$) (cm^{-2} s^{-1})
5327	181	187	0.988	1.079	3.92
4019	157	165	0.602	1.015	2.94
7656	139	143	0.992	0.851	5.29
4992	140	148	0.898	0.699	3.77

‘Effective’ vs. ‘Delivered’ Luminosity

- Triggered data used to determine this factor
- Ratio of BBC ‘narrow’ (30 cm zvtx) to ‘wide’ trigger to obtain factor
- Compare BBC wide and ZDC wide to correct for any z-dependence (ZDC being far enough to have prcatically no z-dependce)

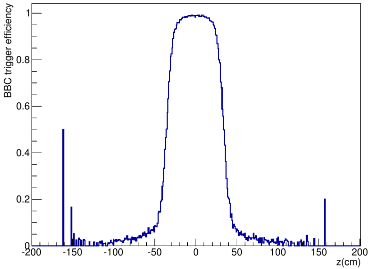


Figure: Ratio of BBC ‘narrow’ to ‘wide’ triggered event counts (ϵ_{BBC})

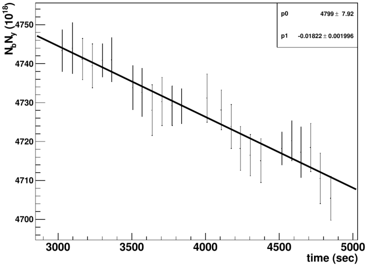
Calculating σ_{BBC}

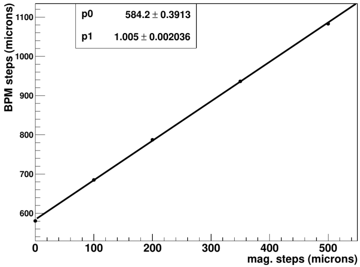
- Now we have all the information (slide 6) to calculate σ_{BBC}
- A number of large and small corrections are pending

R_{max}	$\mathcal{L}_{tot}$ $\times 10^{29}$	ϵ_{BBC}	σ_{BBC}^{uncor}
(Hz)	$(cm^{-2}\ s^{-1})$		(mb)
5327	3.92	0.559	24.3
4019	2.94	0.551	24.8
7656	5.29	0.574	25.2
4992	3.77	0.538	24.6

Corrections 1

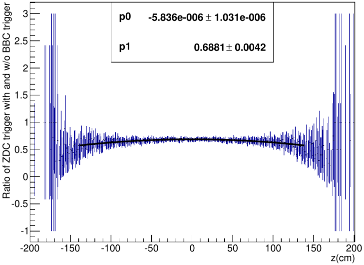
- Corrections due to intensity loss during the scan. $N_1 \times N_2$ plotted over duration of scan
- Event rates are corrected with this (significant corr.)
- Corrections to BPM set step size and actual steps (small corr.)





Corrections 2

- Correction to ϵ_{BBC} for z-dependence of BBC detection efficiency.
- BBC Wide triggered data is compared to ZDC Wide triggered data, z-dependence parameterized
- ϵ_{BBC} (a ratio) is recalculated after correcting both 'narrow' and 'wide' counts by z-dependence (small corr.)



Fill	ϵ_{BBC}^{uncor}	ϵ_{BBC}^{cor}
10276	0.559	0.550
10325	0.551	0.541
10478	0.574	0.566
10505	0.538	0.528

Corrections 3

- Correction to luminosity due to focusing (Hourglass Effect) : $\sigma_{x,y}(z) = \sigma^0_{x,y}\sqrt{1 + (\frac{z}{\beta^*})^2}$
- Correction to lum. due to crossing-angle between beams (calculation assumed head-on collisions)
- Combined corr. is the largest corr. to σ_{BBC} ($\sim 25 - 30\%$)

Hourglass Effect : With and Without Crossing Angle

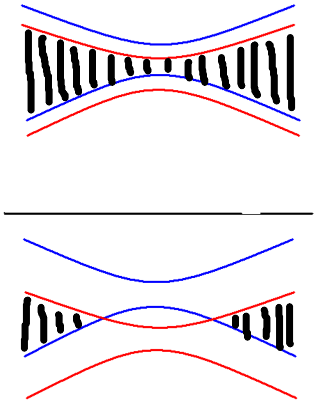


Figure: Head-on coll, scan steps

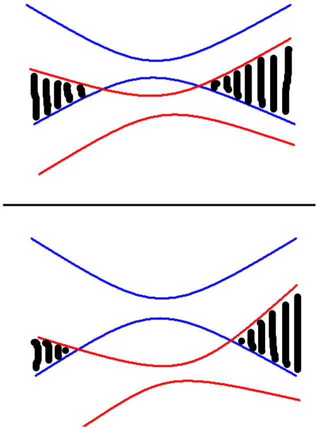


Figure: Crossing angle, scan steps

Hourglass+Angle Effect : Data

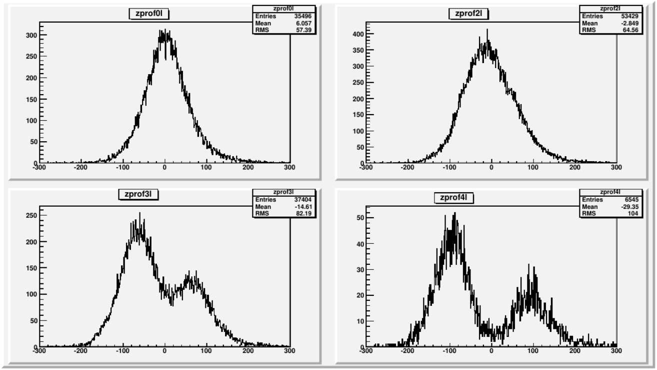


Figure: z_{vtx} profile, distinctive skewed double peak structures for crossing angles and scan steps

Hourglass+Angle Effect : Sim

- Based on collision rate, choose number of collisions in a given bunch crossing form a Poisson distribution
- For each collision, choose vertex position based on a realistic vertex distribution
- Choose collision type (elastic, single-diffraction, double-diffraction, hard scattering) based on probability (PYTHIA)
- Use z-dependence of detection probability by each side of BBC of a certain type of collision at a certain z
- Find mean reconstructed vertex position from difference between average time of hits in two BBCs. Smear reconstructed vertex by offline BBC resolution ($\sim$ 5 cm)
- Vary β^* parameter and crossing-angle in simulation to match data for different step sizes between the two beams

Hourglass+Angle Effect : Data vs. Sim

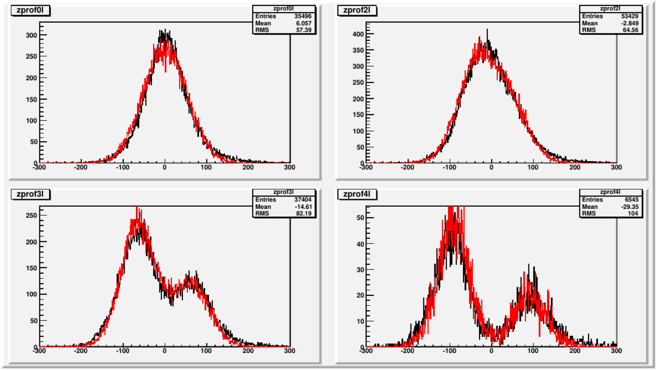


Figure: Matching sim with data

Corrections for Hourglass+Angle Effect

From the simulation correction factor is extracted as ratio of luminosity with infinite β^* and zero crossing-angle to that with the realistic (extracted) β^* and $\alpha_{crossing}$

Fill	β^*	$\alpha^{hor}_{crossing}$	$\alpha^{ver}_{crossing}$	Correction
	(cm)	(mrad)	(mrad)	
10276	70	-0.05	0.07	1.256
10325	70	0.11	0.06	1.320
10478	70	-0.05	0.06	1.279
10505	70	-0.06	0.07	1.325

Final σ_{BBC} and Uncertainties

- Systematic errors are estimated at every stage and for every correction and are propagated to the final corrected σ_{BBC}

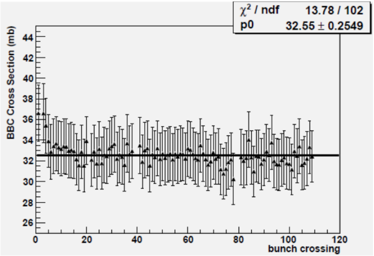


Figure: Sample variation of σ_{BBC} with bunch crossings

Final σ_{BBC} and Uncertainties

- Mean value of corrected σ_{BBC} and statistical uncertainty is obtained from all the bunch crossings from all the fills
- Final value for 2009 500 GeV p+p run :
  $32.51 \pm 3.01\ (\mathrm{sys}) \pm 1.19\ (\mathrm{stat})$ mb (used for integrated cross-section of $W^{\pm}$)

Fill	σ_{BBC}	$\delta\sigma_{BBC}$	$\delta\sigma_{BBC}$
	avg. (mb)	stat. (mb)	sys. (mb)
10276	30.86	1.08	2.80
10325	33.28	1.32	3.17
10478	32.55	0.96	3.08
10505	33.04	1.35	3.01

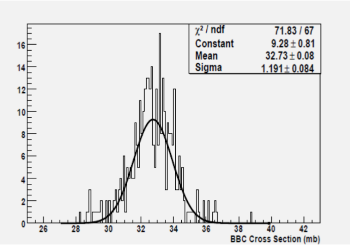


Figure: Distribution of all σ_{BBC}

Thoughts and Questions for SPD

- Unless we have vertex restrictions, we can use ‘delivered’ luminosity for crosss-ection measurements
- We still need no of protons in each colliding bunch, beam profile parameters, focussing parameter and crossing-angle
- How do we get these quantities and to what precision
- Do we need Vernier scans to determine beam profiles parameters, and crossing angles ourselves?

Thank You

Backup

- Luminosity calculation in all its glory : https://cds.cern.ch/record/941318/files/p361.pdf (Link)
- Example : with hourglass effect and crossing angle :
- $$\mathcal{L} = \left(\frac{N_1 N_2 f N_b}{8\pi \sigma_x^0 \sigma_y^0} \right) \frac{2 cos \frac{\phi}{2}}{\sqrt{\pi}\sigma_z} \int_{-\infty}^{+\infty} \frac{e^{-z^2 A}}{1 + \left(\frac{z}{\beta*} \right)^2} dz$$
- where $A = \frac{sin^2 \frac{\phi}{2}}{(\sigma_x^*)^2 \left[1 + (\frac{z}{\beta*})^2\right]} + \frac{cos^2 \frac{\phi}{2}}{\sigma_z^2}$